Spectral and Energy Efficiency of Hybrid Precoding for mmWave Massive MIMO With Low-Resolution ADCs/DACs

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ABSTRACT In this paper, we investigate the spectral efficiency (SE) and energy efficiency (EE) of hybrid precoding in the point-to-point mmWave massive multiple-input multiple-output (MIMO) system with low-resolution analog-to-digital converters (ADCs) and digital-to-analog converters (DACs). First, considering the quantization noise of ADCs/DACs, an approximation expression for the SE is derived. Then, in order to solve the problem of non-convex hybrid precoding design, based on the derived analytical approximation expression, we propose a two-stage alternating minimization scheme to obtain the optimal hybrid precoder matrix. And the trade-offs between SE and EE with the full digital precoding and hybrid precoding are investigated. Numerical results verify that the system with the proposed scheme has nearly the same SE performance as with the full digital precoding. The fully connected hybrid precoding can be more energy-efficient compared to the full digital precoding, and the proposed hybrid precoding scheme can achieve the better trade-off between the SE and EE. Moreover, the increase in the resolution of ADCs/DACs can effectively improve the SE performance of the system, and 4-bits ADCs/DACs achieve the best EE performance for the hybrid precoding.

INDEX TERMS Massive MIMO, mmWave communication, hybrid precoding, spectral efficiency, energy efficiency, low resolution ADCs/DACs.

I. INTRODUCTION

Massive multiple-input multiple-output (MIMO) and mmWave have been emerged as promising technologies for the fifth generation (5G) wireless communicate systems thanks to the higher spectral efficiency (SE) and energy efficiency (EE) [1], [2]. Different from the traditional MIMO systems, massive MIMO systems should be built with low-cost components [3], and mmWave communication could achieve high data rates. However, in classical MIMO systems, the full digital precoding equipped with large-scale antennas is impractical for the power consumption and cost of multiple radio frequency (RF) chains [4].

Fortunately, in an effort to maintain reasonable hardware complexity an power consumption, the hybrid precoder for mmWave massive MIMO communications has been investigated with extensive interest in recent years [5]. The key challenge in designing the hybrid precoder is the non-convex constrain associated with digital precoder and analog precoder [6], [7]. In practical, the first popular category to design the optimal hybrid precoder of point-to-point transmission is to minimize the Euclidean distance between the hybrid precoder and full digital precoder [8], [9]. In [10], a sparse reconstruction problem was investigated to solve the hybrid beamforming design problem, and then the orthogonal matching pursuit (OMP) scheme was applied to obtain the optimal hybrid precoders and combiners for the fully connected structure. Inspired by it, based on the partially connected structure, the optimal analog precoding and digital precoding were found by using the single-stream optimal transmitter beamforming and water-filling algorithm, respectively [11]. Besides, a manifold optimization based
alternating minimization (MO-AltMin) scheme was proposed for hybrid precoding design by considering it as a matrix factorization problem [12].

Furthermore, the second category of hybrid precoding design based on codebooks was proposed, which involved joint iterative training scheme [13] and non-uniform quantization codebook scheme [14] to obtain the optimal hybrid preocoder with low-resolution phase shifters. Unfortunately, for a massive MIMO system, considering both hardware cost and power consumption of the high resolution analog-to-digital converters (ADCs) and digital-to-analog converters (DACs), it is unreasonable, or even impossible to implement in practical applications with the large number of antennas [15], [16].

Therefore, on the one hand, a promising solution for hybrid precoding architecture with low-resolution DACs at transmitter has been gained much interest [17], [18]. Using additive quantization noise model (AQNM), recent works in [17] investigated the EE of hybrid transmitters with DACs quantized based on an additive quantization noise and adopted the sub-optimal strategy to design optimal hybrid precoder. In [18], considering the mmWave large-scale MIMO system with low-resolution ADCs/DACs, an OMP method was used to maximize the achievable rate based on the Bussgang theorem [19] and AQNM [20], but the optimality of the precoder was not proven.

On the other hand, growing research efforts have been devoted to studying massive MIMO systems with low-resolution ADCs [21], [22]. By utilizing quantization models consisting of the additive Bussgang theorem and AQNM, low-resolution ADCs for hybrid precoding design at receiver were adopted as other energy-efficient approach for mmWave massive MIMO systems [23]–[25]. Considered a point-to-point MIMO system, an expression for the achievable rate was derived with one-bit ADCs. Then, the hybrid precoding was adopted as other energy-efficient approach for mmWave massive MIMO systems [23]–[25]. A generalized hybrid architecture was proposed with finite number of ADCs bits, and utilized the channel inversion and singular value decomposition (SVD) based transmission methods to derive the achievable rate of the system. Furthermore, by effectively managing the quantization error of low-resolution ADCs in [25], a two-stage analog combiner was adopted to optimize mutual information of the hybrid beamforming, which provided a near-optimal solution for hybrid precoding design.

Motivated by the above gaps, we investigate the performance of hybrid precoding of the point-to-point massive MIMO system with low-resolution ADCs/DACs. Specifically, our main contributions are summarized as follows:

- Based on the expression of SE, its approximate expression is derived by considering the approximate orthogonal characteristics of optimal analog precoder. The approximate expression of SE can reduce the complexity and difficulty of hybrid precoder design, which is useful for finding the optimal hybrid precoder.
- We propose an alternating minimization scheme through the use of a two-stage iterative procedure to find the optimal hybrid precoder matrix. Specifically, we separate the digital precoder and analog precoder into two subproblems to obtain the optimal hybrid precoding by using an alternative way. The simulation results indicate that the SE performance with the proposed hybrid precoding scheme outperforms OMP scheme [10] and MO-AltMin scheme [12] and approaches the full digital precoding [11].
- The spectral-energy efficiency trade-off with different precodings including the full digital and hybrid precoding is investigated to determine better efficient precoding strategies. It gives new insights on the choice between hybrid and full digital precoding structures.

**Notation:** In this paper, we use upper and lower case boldface to denote matrices and vectors, respectively. \( E[\cdot] \) denotes the expectation; \((\cdot)^H\), \((\cdot)^T\), \((\cdot)^{-1}\), \(||\cdot||\) denote the conjugate transpose, transpose, inversion, absolute operator, and Frobenius norm. The operator \( \langle x \rangle \) extracts the phase of the complex number \( x \). \( x_i \), \( \text{tr}(X) \) and \( [X]_{i,j} \) represents \( i \)th element of vector \( x \), the trace of matrix \( X \) and \((i,j)\)th element of matrix \( X \), respectively. Finally, \( I_M \) denotes the \((M \times M)\)-dimensional identity matrix.

**II. SYSTEM MODEL**

Consider the point-to-point mmWave massive MIMO system based on the fully connected architecture, in which a transmitter with \( N_t \) antennas transmits \( N_s \) data streams to a receiver with \( N_r \) antennas. Low-resolution ADCs/DACs are equipped at transmitter and receiver, respectively. To enable multi-stream communicate, the transmitter is equipped with \( N_{RF} \) chains, which is set \( N_{RF} = N_s \leq N_t \).

At the transmitter, \( N_s \) streams of data symbols are sent, represented by the vector \( s = [s_1, \ldots, s_{N_s}]^T \). They are assumed to be independent and Gaussian distributed with zero mean and unit variance, hence their covariance matrix is \( R_s = E[ss^H] = \frac{1}{N_s} I_{N_s} \). The transmitted symbols are first processed by a baseband digital precoder \( D \in \mathbb{C}^{N_{RF} \times N_s} \). Then, the data streams are precoded by the corresponding analog precoder \( A \in \mathbb{C}^{N_t \times N_{RF}} \) at the analog domain. Meanwhile, the data streams are processed by the phase shifters and satisfy \( |A_{i,j}| = 1 \). After passing through low-resolution DACs, we define the precoding operation as

\[ x = \sqrt{P} A Q_D (D s), \quad (1) \]

where \( Q_D (\cdot) \) represents the DAC process, and \( P \) represents transmit power. The power constraint is enforced by
normalizing \( \mathbf{D} \) such that \( \| \mathbf{AD} \|_F^2 = N_s \), \( \mathbf{d} \triangleq \mathbf{D}s \) is a vector precoded by digital precoder.

Assuming a narrow-band block-fading channel and perfect synchronization, there is no inter-symbol interference. The signal at the receive antennas is presented as

\[
y = \mathbf{H}x + \mathbf{n},
\]

where \( y = [y_1, y_2, \ldots, y_{N_t}]^T \) is the received signal, \( \mathbf{n} \sim \mathcal{C}\mathcal{N}(0, \mathbf{I}_{N_t}) \) is the additive white gaussian noise (AWGN) vector corrupting the received signal, and \( \mathbf{H} \in \mathbb{C}^{N_t \times N_t} \) denotes the mmWave channel matrix. Since we focus on the design of hybrid precoding with low-resolution ADCs/DACs, the channel state information (CSI) of \( \mathbf{H} \) is assumed to be perfect. In the future, we will extend the results of this paper to other conventional imperfect CSI.

The received signal after the low-resolution ADCs processing at receiver can be given as

\[
\mathbf{r} = \mathcal{Q}_{\mathbf{A}}(\mathbf{y}) = \mathcal{Q}_{\mathbf{A}}(\mathbf{Hx} + \mathbf{n}),
\]

where \( \mathcal{Q}_{\mathbf{A}}(\cdot) \) is the low-resolution quantization function.

The mmWave MIMO channel can be characterized by standard multipath models whose the number of propagation paths is \( L \). \( \beta_l \) is the complex gain of the path \( l \), which is the complex Gaussian distributed with zero-mean and unit-variance. The angle of arrival \( \{\theta_l^t\}_{l=1}^L \) and angle of departure \( \{\theta_l^r\}_{l=1}^L \) are uniformly distributed over \([0, 2\pi)\).

In particular, the discrete-time narrow-band mmWave channel \( \mathbf{H} \) is formulated as [10]

\[
\mathbf{H} = \sqrt{\frac{N_r N_t}{L}} \sum_{l=1}^L \beta_l \mathbf{f}_l(\phi_l^t, \theta_l^t) \mathbf{H}_l^{H}(\phi_l^r, \theta_l^r),
\]

where \( \mathbf{f}_l(\phi_l^r, \theta_l^r) \) and \( \mathbf{f}_l(\phi_l^t, \theta_l^t) \) are antenna array response vectors of the receiver and transmitter, respectively. The mmWave channel satisfies \( \mathbb{E}[\|\mathbf{H}\|_F^2] = N_t \times N_t \). For the uniform linear array (ULA) with \( N \) elements, the array response vector can be presented as

\[
\mathbf{f}_{t, ULA}(\phi) = \frac{1}{\sqrt{N}} \left[ 1, e^{j \mu d \sin(\phi)}, \ldots, e^{j (N-1) \mu d \sin(\phi)} \right]^T, \tag{5}
\]

where \( \mu = \frac{2\pi}{\lambda} \), where \( \lambda \) denotes the signal wavelength, and \( d \) is the antenna spacing. \( \theta \) is not included in (5) since the ULA response vector is independent of the elevation angle. \(^1\)

### III. QUANTIZED SIGNAL MODEL

At the transmitter, the transmission is converted to the analog domain by multiple DACs. We use the Bussgang theorem to decompose the signal \( \mathbf{t} = [t_1, \ldots, t_{N_{RF}}]^T \) after DAC processing into a desired signal component and a uncorrelated quantization error \( \mathbf{g} \in \mathbb{C}^{N_{RF} \times 1} \) as

\[
\mathbf{t} = \mathcal{Q}_D(\mathbf{d}) = \mathbf{F}d + \mathbf{g}, \tag{6}
\]

where \( \mathbf{d} = [d_1, \ldots, d_{N_{RF}}]^T \) is the input signal of quantizer, \( \mathbf{F} = (1 - \zeta)\mathbf{I}_{N_{RF}} \) represents the DAC processing matrix, where \( \zeta \) is the distortion factor of DACs. The covariance matrix of \( \mathbf{g} \) can be evaluated as

\[
\mathbf{R}_{\mathbf{gg}} = \mathbb{E}[(\mathbf{gg})^H] = \zeta(1 - \zeta) \text{diag}(\mathbf{R}_{\mathbf{dd}}), \tag{7}
\]

where \( \mathbf{R}_{\mathbf{dd}} \) presents the quantizer input covariance. It is given as

\[
\mathbf{R}_{\mathbf{dd}} = \mathbb{E}[(\mathbf{d}\mathbf{d})^H] = \mathbb{E}[(\mathbf{D}\mathbf{s}\mathbf{s}^H\mathbf{D}^H)] = \frac{1}{N_d}\mathbf{D}\mathbf{D}^H. \tag{8}
\]

Utilizing (1), (2) and (6), the signal after the DACs can be presented as

\[
y = (1 - \zeta)\sqrt{\frac{p}{N}}\mathbf{H}\mathbf{D}\mathbf{s} + \sqrt{\frac{p}{N}}\mathbf{H}A\mathbf{g} + \mathbf{n}. \tag{9}
\]

At the receiver, the detected signal is quantized by the ADCs. Considering the gain of the automatic gain control is set appropriately, we use the AQNM and formulate the quantizer outputs as

\[
\mathbf{r} = \mathcal{Q}_{\mathbf{A}}(\mathbf{y}) = (1 - \rho)\mathbf{y} + \mathbf{e}, \tag{10}
\]

where \( \mathbf{e} \in \mathbb{C}^{N_r \times 1} \) the statistically equivalent quantization noise, and \( \rho \) presents the ADCs quantization distortion factor and it depends on the resolution of ADCs. The quantization noise term \( \mathbf{e} \) follows \( \mathcal{C}\mathcal{N}(0, \mathbf{R}_{ee}) \), where

\[
\mathbf{R}_{ee} = \rho(1 - \rho) \text{diag}(\mathbb{E}(\mathbf{y}\mathbf{y}^H)). \tag{11}
\]

Substituting (9) into (10), the received quantized signal by low-resolution ADCs at the receiver is presented by

\[
\mathbf{r} = (1 - \rho)(1 - \zeta)\sqrt{\frac{p}{N}}\mathbf{H}\mathbf{D}\mathbf{s} + (1 - \rho)\sqrt{\frac{p}{N}}\mathbf{H}A\mathbf{g}.
\]

### IV. SPECTRAL EFFICIENCY ANALYSIS AND HYBRID PRECODER DESIGN

In this section, we investigate the SE of hybrid precoding MIMO system and derive an approximate expression of the SE for fully connected architecture with ADCs/DACs. Then, based on the derived analytical expression, we propose an alternating minimization scheme to obtain the optimal hybrid precoding matrix.

#### A. SPECTRAL EFFICIENCY ANALYSIS

In this subsection, we focus on the analysis SE of the point-to-point mmWave massive MIMO system. Assuming perfect decoding at the receiver, we aim to maximize the SE \( R \) of

1. Although we consider ULA configurations in this paper, the proposed scheme, which will be described in the subsequent section, can be applied to other antenna array topologies.
mmWave MIMO system with low-resolution ADCs/DACs. 

\[
R(A, D) = \log_2 \left( |N_t| + \frac{R_{SS}}{R_{gg} + R_{nn} + R_{ee}} \right),
\]  

(13)

where the desired signal power \(R_{SS} \in \mathbb{C}^{N_t \times N_t}\) and the AWGN power \(R_{nn}\) can be calculated as

\[
R_{SS} = \mathbb{E}[\{SS\}^{H}]
= (1 - \rho^2)(1 - \zeta^2) P \cdot \mathbb{E}[HA_{gg}A^H H^H]
= (1 - \rho^2) P R_{\text{ADD}} A^H H^H,
\]  

and

\[
R_{nn} = (1 - \rho^2) I_{N_t}.
\]  

(15)

From (7) and (8), the DACs distortion noise power \(R_{gg}\) can be expressed as

\[
R_{gg} = \mathbb{E}[\{gg\}^{H}]
= (1 - \rho^2) P \cdot \mathbb{E}[HA_{gg}A^H H^H]
= (1 - \rho^2) P HA_{rr}A^H H^H
= (1 - \rho^2) \zeta (1 - \zeta) \frac{P}{N_s} HA \text{diag}(D^{H}) A^H H^H.
\]  

(16)

Utilizing (9) and (11), the ADCs quantization noise \(R_{ee} \in \mathbb{C}^{N_t \times N_t}\) can be presented as

\[
R_{ee} = \rho (1 - \rho) \text{diag}\left( (1 - \zeta^2) \frac{P}{N_s} HA \mathbb{E}[\{s\}^{H} ] D^{H} A^H H^H ight)
+ \rho \mathbb{E}[HA_{gg}A^H H^H] + \mathbb{E}[\{mm\}^{H}]
= \rho (1 - \rho) \text{diag}\left( (1 - \zeta^2) \frac{P}{N_s} HADD^H A^H H^H ight)
+ \zeta (1 - \zeta) \frac{P}{N_s} HA \text{diag}(D^{H}) A^H H^H + I_{N_t}.
\]  

(17)

In order to obtain the maximum SE, the simplify approximation expressions including \(R_{gg}\) and \(R_{ee}\) are derived to reduce the difficulty of hybrid precoding design.

**Lemma 1:** For the hybrid precoding of the point-to-point mmWave massive MIMO system with low-resolution ADCs/DACs, the covariance matrix of DACs noise \(R_{gg}\) and ADCs noise \(R_{ee}\) can be expressed as

\[
\hat{R}_{gg} \approx \kappa (1 - \rho^2) \zeta (1 - \zeta) \frac{P}{N_s} H H^H,
\]  

(18)

and

\[
\hat{R}_{ee} \approx \rho (1 - \rho) \text{diag}\left( (1 - \zeta^2) \frac{P}{N_s} H H^H ight)
+ \kappa \zeta (1 - \zeta) \frac{P}{N_s} H H^H + I_{N_t},
\]  

(19)

respectively.

**Proof:** In [5], it has been verified that for large-scale mmWave MIMO systems, the optimal analog precoding is approximately orthogonal as

\[
AA^H \approx I_{N_t}.
\]  

(20)

After the SVD of channel matrix \(H\), the optimal unconstrained digital precoding is obtained from the unitary right singular vector of the \(H\). Moreover, the optimal unconstrained digital precoding matrix is orthogonal, i.e., \(W_{\text{opt}} H_{\text{opt}}^{H} = I_{N_t}\). The near-optimal hybrid design should also be exhibited the same orthogonality property as the optimal unconstrained digital precoding, which can be present as

\[
\hat{D} D^{H} \approx \kappa I_{N_{gf}},
\]  

(21)

where \(\kappa\) is the normalization factor. According to the equations (20) and (21), we have \(ADD^{H} A^H \approx \kappa I_{N_t}\). Substituting both (20) and (21) into (16) and (17), we finally obtain the desired results in (18) and (19) after simplifying the equations, respectively.

Thus, the SE in (13) can be approximately reformulated as

\[
\hat{R}(A, D) \approx \log_2 \left( |N_t| + \zeta \frac{P}{N_s} R_{n}^{-1} HADD^H A^H H^H \right),
\]  

(22)

where \(\zeta = (1 - \rho)^2 (1 - \zeta)^2\), and \(R_{n} = \hat{R}_{gg} + \hat{R}_{ee} + R_{nn}\) is the total noise power.

**B. HYBRID PRECODER DESIGN**

In this subsection, we discuss the optimization problem of maximizing the SE in (22), which can be reformulated as

\[
P1 : (A_{\text{opt}}, D_{\text{opt}}) = \arg \max_{A, D} \hat{R}(A, D),
\]

subject to \(\|AD\|^2_F = N_s, |A_{i,j}| = 1, \forall i, j\).  

(23)

Mathematically, based on [10], \(P1\) can be transformed into the hybrid precoding design problem as

\[
P2 : (A_{\text{opt}}, D_{\text{opt}}) = \arg \min_{A, D} \|W_{\text{opt}} - AD\|^2_F,
\]

subject to \(\|AD\|^2_F = N_s, |A_{i,j}| = 1, \forall i, j\).  

(24)

where \(W_{\text{opt}}\) represents the optimal hybrid precoding matrix. The problem \(P2\) is intractable due to the coupled \(A\) and \(D\) with the non-convex constraint set in (24), which motivates us to tackled \(P2\) through proposing a two-stage iterative procedure to find the optimal \(A\) and \(D\).

The proposed two-stage alternating minimization scheme for hybrid precoding design is shown in Algorithm 1. The main idea behind this alternating minimization scheme is to deal with two optimization problems. The algorithm starts by the SVD of \(H\) to get the optimal hybrid precoding matrix \(W_{\text{opt}}\). After that, in the first stage, we keep \(A\) fixed and use the linear least squares strategy to optimize \(\hat{D}\) as

\[
\hat{D} = \hat{A} H W_{\text{opt}}.
\]  

(25)

For the hybrid precoding design problem, the power constraint \(\|W\|^2_F = N_s\) in \(P2\) is temporarily removed. Unless otherwise mentioned, a least squares solution in (25) provides a global optimal solution.
In this subsection, we analyze the EE of point-to-point mmWave massive MIMO system. Based on the energy consumption model in [26], the total EE $\eta$ can be defined as

$$\eta = \frac{B \cdot R}{P_{tot}},$$

where $B$ is the available bandwidth of the system, $R$ is the SE defined in (13), and $P_{tot}$ is denoted as the overall power consumption of the point-to-point mmWave massive MIMO system with ADCs/DACs.

The total power consumption of full digital architecture and fully connected architecture of hybrid precoding is presented as

$$P_{tot}^{FD} = P_{LO} + P_{PA} + 2N_t P_{ADC} + N_t (2P_{DAC} + P_{RF}),$$

and

$$P_{tot}^{HP} = P_{LO} + P_{PA} + N_{RF} N_t P_{PS} + 2N_t P_{ADC} + N_{RF} (2P_{DAC} + P_{RF}),$$

respectively, where $P_{DAC} = c_1 N_t q + c_2 2^q$ is the power consumption of DACs, where $q$ is the resolution of DACs, $c_1 = 9 \times 10^{-12}$, which expresses a coefficient of static power consumption, $c_2 = 1.5 \times 10^{-5}$, which expresses a coefficient of dynamic power consumption, and $f_t$ is the sampling rate at transmitter, $P_{ADC} = k_f 2^b$ is the power consumption of ADCs, where $b$ is the resolution of ADCs, $k$ is the energy consumption per conversion step, e.g. $k = 494$ fJ [27], and $f_t$ is the sampling rate at receiver, $P_{RF}$ represents the power consumption of one RF chain as

$$P_{RF} = 2P_M + 2P_{LF} + P_{HB},$$

and both the notations and power consumptions of all the components are detailedly summarized in Table 1.

| Device          | Notation | Value   |
|-----------------|----------|---------|
| Local oscillator [28] | $P_{LO}$ | 22.5 mW |
| Hybrid with buffer [17] | $P_{HB}$ | 3 mW    |
| Power amplifier [29] | $P_{PA}$ | $P/0.25$ |
| Low-pass filter [30] | $P_{LP}$ | 14 mW   |
| Mixer [17]      | $P_M$   | 0.3 mW  |
| Phase shifter [17] | $P_{PS}$ | 21.6 mW |
| RF chain        | $P_{RF}$ | Equation (29) |
| DAC             | $P_{DAC}$ | $c_1 f_t q + c_2 2^q$ |
| ADC             | $P_{ADC}$ | $k_f 2^b$ |

V. ENERGY EFFICIENCY AND TRADE-OFF ANALYSIS

In this section, a study of EE of precoding for the point-to-point mmWave massive MIMO systems is presented, which includes the power consumption of both full digital architecture and fully connected architecture. Then, we analyze the trade-off between the SE and EE with the resolution of ADCs/DACs.

A. ENERGY EFFICIENCY ANALYSIS

In this subsection, we analyze the EE of point-to-point mmWave massive MIMO system. Based on the energy consumption model in [26], the total EE $\eta$ can be defined as

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$$P_{tot}^{FD} = P_{LO} + P_{PA} + 2N_t P_{ADC} + N_t (2P_{DAC} + P_{RF}),$$

and

$$P_{tot}^{HP} = P_{LO} + P_{PA} + N_{RF} N_t P_{PS} + 2N_t P_{ADC} + N_{RF} (2P_{DAC} + P_{RF}),$$

respectively, where $P_{DAC} = c_1 N_t q + c_2 2^q$ is the power consumption of DACs, where $q$ is the resolution of DACs, $c_1 = 9 \times 10^{-12}$, which expresses a coefficient of static power consumption, $c_2 = 1.5 \times 10^{-5}$, which expresses a coefficient of dynamic power consumption, and $f_t$ is the sampling rate at transmitter, $P_{ADC} = k_f 2^b$ is the power consumption of ADCs, where $b$ is the resolution of ADCs, $k$ is the energy consumption per conversion step, e.g. $k = 494$ fJ [27], and $f_t$ is the sampling rate at receiver, $P_{RF}$ represents the power consumption of one RF chain as

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| Phase shifter [17] | $P_{PS}$ | 21.6 mW |
| RF chain        | $P_{RF}$ | Equation (29) |
| DAC             | $P_{DAC}$ | $c_1 f_t q + c_2 2^q$ |
| ADC             | $P_{ADC}$ | $k_f 2^b$ |

B. TRADE-OFF ANALYSIS AND EFFECT OF QUANTIZATION

In this subsection, we investigate the trade-off between the SE and EE of the full digital architecture and fully connected architecture of hybrid precoding.

We consider comprehensively between the SE and EE by defining a parameter $\omega$, which satisfies $0 \leq \omega \leq 1$. For the point-to-point mmWave massive MIMO system, maximizing the joint objective function of EE and SE can be expressed as

$$\mathcal{P3} : \Theta = \max \left(1 - \omega \right) \eta + \omega R,$$

subject to $\omega \in [0, 1]$. (31)

It is clear that $\mathcal{P3}$ maximizes EE with $\omega = 0$ while maximizes SE with $\omega = 1$. Utilizing the exhaustive method for the different resolution of ADCs/DACs, we can obtain the solution for all values in the range $\omega \in [0, 1]$. 

| Device          | Notation | Value   |
|-----------------|----------|---------|
| Local oscillator [28] | $P_{LO}$ | 22.5 mW |
| Hybrid with buffer [17] | $P_{HB}$ | 3 mW    |
| Power amplifier [29] | $P_{PA}$ | $P/0.25$ |
| Low-pass filter [30] | $P_{LP}$ | 14 mW   |
| Mixer [17]      | $P_M$   | 0.3 mW  |
| Phase shifter [17] | $P_{PS}$ | 21.6 mW |
| RF chain        | $P_{RF}$ | Equation (29) |
| DAC             | $P_{DAC}$ | $c_1 f_t q + c_2 2^q$ |
| ADC             | $P_{ADC}$ | $k_f 2^b$ |
VI. NUMERICAL RESULTS

In this section, we provide the numerical results of SE and EE with the proposed hybrid precoding scheme presented. Unless otherwise mentioned, the point-to-point mmWave massive MIMO configuration with parameters $N_t = 64$, $N_r = 36$, and $N_s = N_{RF} = 2$ is considered in the simulations. The antenna arrays at transmitter and receiver are both ULA with antenna spacing $d = \lambda/2$. The sampling rate of DAC and ADC are set to $f_t = f_r = 1$ GHz. Further, we consider an environment with 6 clusters and 8 scatterers per cluster and the angles of arrival (departure) are generated according to Laplacian distribution with random mean cluster angels $\phi_t^l \in [0, 2\pi)$ ($\phi_r^l \in [0, 2\pi)$) and angular spreads of 5 degrees within each cluster. Besides, $B = 1$ GHz and all the results presented are averaged over 5000 random realizations, where the Algorithm 1 terminates after $S = 10$ iterations.

Fig. 1 shows the SE in different SNR at $q = \infty$, $b = \infty$ with various date streams $N_s$ and schemes including the proposed Algorithm 1, the OMP algorithm in [10], the full digital precoding in [11], and Mo-AltMin algorithm in [12]. Besides, Fig. 1 illustrates that the proposed algorithm outperforms the Mo-AltMin algorithm and OMP algorithm and achieves performance close to full digital precoding. This is because the optimization of the digital precoding matrix $D$ changes the amplitude of signal, while the analog precoding matrix can only adjust the phases, which impedes the performance of hybrid precoding improvement. Moreover, it can be observed that increasing the number of data streams can significantly improve the SE performance of the system.

In Fig. 2, we evaluate the performance of the different DAC resolutions and SNRs at $N_{RF} = N_s = 2$ and $b = \infty$. In the low SNRs (SNR $< -20$ dB), the SEs with different DAC resolutions are almost the same. This is because the power of Gaussian white noise is close to the power of transmitted signal, resulting in SE of different resolutions being close to each other. When $-20$ dB $\leq$ SNR $\leq -10$ dB, the SE of systems increases as SNR increasing. In the high SNRs (SNR $> -10$ dB), the SEs of resolutions at $q = 2$, 4, and 6 remain. Furthermore, the SE of the system increases and closes to the distortion-free quantization ($q = \infty$) as the number of resolutions increasing. Meanwhile, it can be seen that the SE of proposed scheme outperforms the others two hybrid precoding schemes.

Fig. 3 describes the SE versus data SNR with various schemes and ADC resolutions $b$ at $N_{RF} = N_s = 2$ and $q = \infty$. It is observed that increasing the number of ADC resolutions can increase the SE of the system. Meanwhile, increasing the number of ADC resolutions can be closer to the SE of the system without quantization distortion ($q = \infty$). Additionally the trends of SE for different ADC resolutions are similarly to DAC in Fig. 2.

Fig. 4 shows the SE with respect to the DAC resolution at SNR $= -5$ dB and $b = \infty$. In particular, full digital precoding is set to distortion-free quantization of DAC and ADC. Obviously, it can be seen that the two precoding
schemes have similar trends. Meanwhile, it can be observed that the trends of SE growth are relatively larger in all cases when DAC have very few quantized bits (e.g., $q < 5$). Therefore, it is obviously that the SE are more sensitive when the resolutions of DAC are small. However, the SE of proposed hybrid precoding grows quickly and gradually reaches the fully digital precoding as increasing the resolution of DAC. In addition, increasing the number of antennas at the transmitter and receiver can significantly improve the SE of the system.

Fig. 5 is mainly address the SE with respect to the ADC resolution at $\text{SNR} = -5 \text{ dB}$ and $q = \infty$. Meanwhile, the full digital precoding is set with $q = \infty$ and $b = \infty$. First, as expected, in the range 1-4 bits, the SE of finite-bit ADC increase with the ADC resolutions increasing. Second, when $b > 4$, the proposed hybrid precoding method achieves the performance similar to that of full digital architecture with $\infty$-bit ADC and the SEs with the two hybrid precoding schemes remain the fixed values finally. Compared to the resolution of DAC shown in Fig. 4, the SE increases slowly with quantization bits of ADC increasing in the range 1-4 bits. Therefore, the resolution of ADC is not sensitive to quantized bits at very low resolutions compared to the DAC.

FIGURE 5. Spectral efficiency versus DAC resolutions with SNR = -5 dB and $b = \infty$.

Fig. 6 shows the EE against DAC resolutions with various the number of antennas at transmitter at $\text{SNR} = -5 \text{ dB}$ and $q = \infty$. Meanwhile, the full digital precoding is set with $q = \infty$ and $b = \infty$. First, as expected, in the range 1-4 bits, the SE of finite-bit ADC increase with the ADC resolutions increasing. Second, when $b > 4$, the proposed hybrid precoding method achieves the performance similar to that of full digital architecture with $\infty$-bit ADC and the SEs with the two hybrid precoding schemes remain the fixed values finally. Compared to the resolution of DAC shown in Fig. 4, the SE increases slowly with quantization bits of ADC increasing in the range 1-4 bits. Therefore, the resolution of ADC is not sensitive to quantized bits at very low resolutions compared to the DAC.

FIGURE 6. Energy efficiency against DAC resolutions with various the number of antennas at transmitter at $\text{SNR} = -15 \text{ dB}$ and $b = 6$.

Fig. 7 presents that the EE curves of the two hybrid precoding schemes have a tendency to rise first but then decrease. Besides, Fig. 6 presents that the EE curves of the two hybrid precoding schemes have the peaks at $q = 4$. Meanwhile, when $q = 2$, the EE curve with the full digital precoding has a maximum and then gradually decreases. The EEs with full digital precoding and hybrid precoding reach the different peaks with different resolutions. This indicates that each antenna in the full digital precoding structure is configured with an RF chain, which is more sensitive to DAC resolutions.

FIGURE 7. Energy efficiency against ADC quantization bits with various the number of antennas at receiver at $\text{SNR} = -5 \text{ dB}$ and $q = 3$. Fig. 7 provides a EE comparison against the ADC quantization bits at the receiver. We find that the EE of all curves
with the number of antennas at receiver have the similar trend as the number of ADC quantization bits increasing. When \( b < 4 \), the EE of the full digital precoding and two hybrid precoding schemes increase with ADC quantization bits. Obviously, the EE with full digital precoding and two hybrid precoding schemes have different peaks when \( b = 4 \). When \( b > 4 \), all curves decline as the number of ADC quantization bits increasing. We observe that the two precoding schemes can achieve higher EE than the full digital precoding, and the EE of proposed hybrid precoding scheme shows the higher EE than the conventional OMP hybrid precoding. In addition, it can be observed that the EE of system decreases with the number of antennas increasing at receiver.

Fig. 8 depicts the EE vs SE for the proposed hybrid precoding scheme, OMP hybrid precoding scheme and full digital precoding. We can observe that as DAC resolution \( q \) increasing, the EE grows approximate linearly with SE, and then reaches the vertex corner and decreases exponentially while SE continues increasing. Meanwhile, the proposed precoding scheme maximizes SE (\( \omega = 1 \)) in the top corner corresponds to \( q = 8 \), whereas maximizes EE (\( \omega = 0 \)) corresponds to \( q = 4 \). It can be found that the proposed hybrid precoding scheme, OMP hybrid precoding scheme and full digital precoding scheme reach maximum EE with the highlighted green points at \( q = 4 \), \( 4 \), and \( 2 \), respectively. This indicates that full digital precoding is more sensitive to DAC resolution because it uses \( N_t \) DACs, while hybrid precoding uses only \( N_{RF} \). Besides, Fig. 8 shows that the proposed hybrid precoding scheme outperforms OMP scheme and can offer a spectral-energy efficiency trade-off. Based on the Table 1, we provide a constant component power consumption reference which is shown as gray dotted lines. If a power constraint is determined, the designers can choose points of different DAC resolutions above gray dotted line. Two hybrid precoding schemes are feasible below 6.5W, whereas proposed hybrid precoding scheme outperforms OMP scheme. When the power consumption below 15 W, both the proposed hybrid precoding scheme and OMP scheme can be applied at \( q \in \{ 1, \ldots, 8 \} \) but full digital precoding is only achieved at the points of \( q = 1, \ 2, \) and \( 3 \).

Fig. 9 illustrates the EE vs SE comparison for ADC resolution with quantization bits \( q = 3 \). All the curves have similarly trends that increasing approximate linearly and then have the vertex corner and decrease exponentially with SE continues increasing. We can see that the full digital precoding has advantages in SE while the proposed hybrid precoding strategy has advantages in terms of EE. The proposed hybrid precoding scheme always performs better than OMP hybrid precoding scheme for the same value of \( b \). Moreover, we observe that the optimal number of ADC resolution for the two hybrid precoding schemes and full digital precoding are same at the highlighted green points with \( b = 4 \). In addition, in the range 4.5-6.5 W, only hybrid precoding schemes can be selected for the designers. Besides, full digital precoding consumes power in the range of 8.2-10 W, which consumes more energy compared to hybrid precoding. When \( b = 4 \), the EE is maximum (\( \omega = 0 \)), whereas the SE is maximum (\( \omega = 1 \)) corresponds to \( b = 8 \).

VII. CONCLUSION
This paper investigated a general fully connected structure of hybrid precoding with low-resolution ADCs/DACs for the point-to-point mmWave massive MIMO system. An approximately analytical expression for the SE was derived with low-resolution ADCs/DACs to design hybrid precoding. Considering the non-convex hybrid precoding design problem, a hybrid precoding scheme was proposed based on alternating minimization, which solved the digital precoder and the analog precoder in an alternative way in two separate subproblems. Results from numerical simulations were presented to show that the proposed hybrid precoding could achieve a similar SE compared with full digital precoding. In terms of the trade-off between the SE and EE, the performance of the proposed scheme was significantly better than the OMP scheme. Furthermore, the fully connected hybrid
 precoding can be more energy-efficient compared to digital precoding. The system parameters, including the DAC and ADC resolutions, can be adjusted in order to balance the trade-off between the SE and EE.

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