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# Precoder and combiner design for dynamically sub-connected hybrid architecture with low-resolution DACs/ADCs in mmWave massive MIMO systems

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Dear editor,

The integration of mmWave and massive multiple-input multiple-output (mMIMO) becomes inevitable in future 5G wireless communication systems [1], in which the system throughput can be improved by several orders of magnitude owing to high spectrum utilization and large bandwidth [2]. In mmWave mMIMO systems, the excessive power consumption and the unacceptable hardware cost make the precoder with fully digital architecture (FD-A) no longer suitable. Aiming at reducing the power consumption and hardware cost, Ref. [3] proposed the precoder design for pure analog architecture (PA-A) by utilizing the low-cost and low-power analog phase shifters (APSs). Although PA-A was of low cost and low power, its performance was poor. Considering the advantages and disadvantages of FD-A and PA-A, hybrid architecture (HA) is widely adopted in mMIMO systems [4] or mmWave mMIMO systems [5]. The most of studies on precoder and/or combiner design for HA in mMIMO or mmWave mMIMO systems employ full precision digital-to-analog converters and analog-to-digital converters (DACs/ADCs), or low-resolution ADC at the receiver, or low-resolution DAC at the transmitter. The contributions of the related studies are discussed in Appendix A.

Based on those discussions, and motivated by the two facts of the low power consumption and hardware cost of the low-resolution DACs/ADCs, and the performance superiority of the dynamically sub-connected hybrid architecture (DSC-HA) [6] over fixed sub-connected hybrid architecture (FSC-HA), we propose a precoder and combiner design scheme with low-resolution DACs/ADCs for DSC-HA over mmWave multi-user mMIMO downlink based on the additive quantization noise model (AQNM). The contributions and key results of the work are listed as follows.

- Based on the AQNM, the mmWave multi-user mMIMO downlink model for DSC-HA with low-resolution ADCs/DACs is investigated. Most of the existing precoder and combiner designs for HA generally considered low-resolution DACs and ADCs separately in mMIMO and mmWave mMIMO systems.
- To realize the optimized design of the precoder and combiner for DSC-HA using low-resolution DACs/ADCs, the expression of the system sum rate of mmWave multi-user mMIMO downlink is theoretically derived, and further, the optimization problem with non-convex constraints is constructed aiming at maximizing the system sum rate.
- The optimization problem is relaxed to maximize the achievable rate of each user, and equivalently to maximize the received quantized signal to interference and noise ratio (SINR) of each user with non-convex constraints. To make the optimization problem solvable, maximizing the quantized SINR of each user is further relaxed into a series of subproblems without considering the user interference, and a suboptimal solution for designing the analog precoder and combiner with low-resolution DACs/ADCs is obtained. Finally, the zero-forcing (ZF)-based digital precoder is designed.
- Numerical results demonstrate that the precoder and combiner for DSC-HA with low-resolution DACs/ADCs have an obvious superiority over the corresponding FSC-HA in terms of the system sum rate, and meanwhile, achieve a good tradeoff between the system sum rate and energy efficiency when DACs/ADCs resolution is about 4 bits.

*System configuration and problem formulation.* Figure 1 illustrates DSC-HA in downlink mmWave multi-user mMIMO system consisting of an $M$-antenna basestation (BS) with $N_{\rm RF}^t$ DAC/radio frequency (RF) chain pairs and $K$ $N$-antenna users. Each user is equipped with one received RF chain with low-resolution ADCs for a practical purpose,

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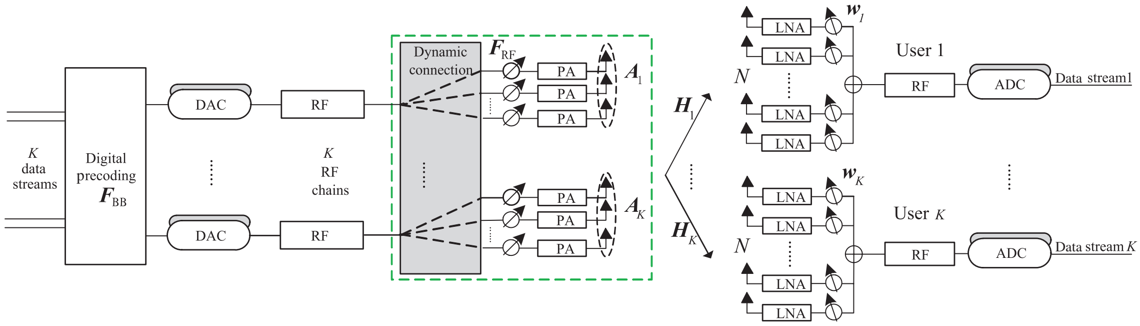


**Figure 1** (Color online) Multi-user mmWave mMIMO downlink for DSC-HA (PA and LNA represent the power and low noise amplifiers).

and let $U = \{1, 2, \ldots, K\}$ denote the set of $K$ users. Owing to the limited RF resources, $N^t_{\mathrm{RF}}$ is equal to $K$.

$$\mathrm{SINR}^q_k = \left\{ \frac{\alpha^3 P}{K} \left| (\boldsymbol{w}^k)^{\mathrm{H}} \boldsymbol{H}_k \boldsymbol{F}_{\mathrm{RF}} \boldsymbol{f}^k_{\mathrm{BB}} \right|^2 \right\} \Bigg/ \left\{ \frac{\alpha^2 P}{K} \sum_{j \neq k} \left| (\boldsymbol{w}^k)^{\mathrm{H}} \boldsymbol{H}_k \boldsymbol{F}_{\mathrm{RF}} \boldsymbol{f}^j_{\mathrm{BB}} \right|^2 + \frac{\eta \alpha^2 P}{K} \left| (\boldsymbol{w}^k)^{\mathrm{H}} \boldsymbol{H}_k \boldsymbol{F}_{\mathrm{RF}} \boldsymbol{f}^k_{\mathrm{BB}} \right|^2 + \sigma^2_{n_{q_D,k}} + \sigma^2_{n_k} \right\}. \quad (1)$$

For the $k$th user, the quantized SINR is denoted by (1), where the definitions of notations are presented in Appendix B.

The achievable rate of the $k$th user is $R_k = \log_2(1 + \mathrm{SINR}^q_k)$. Therefore, to maximize the system sum rate of the mmWave multi-user mMIMO system for DSC-HA, an optimization problem is formulated as

$$\mathbf{P1}: \arg \max_{\boldsymbol{F}_{\mathrm{RF}}, \boldsymbol{F}_{\mathrm{BB}}, \boldsymbol{W}} \sum_{k=1}^{K} R_k$$
$$\text{s.t. } |\boldsymbol{F}_{\mathrm{RF}}(m,k)| = \begin{cases} \frac{1}{\sqrt{N^k_{\mathrm{sub}}}}, & \text{if } \boldsymbol{F}_{\mathrm{RF}}(m,k) \neq 0, \\ 0, & \text{if } \boldsymbol{F}_{\mathrm{RF}}(m,k) = 0, \end{cases} \quad \forall m, k,$$
$$\sum_{k=1}^{K} |\boldsymbol{F}_{\mathrm{RF}}(m,k)| = \frac{1}{\sqrt{N^k_{\mathrm{sub}}}}, \ \forall m,$$
$$\sum_{m=1}^{M} |\boldsymbol{F}_{\mathrm{RF}}(m,k)|^2 = 1, \ \forall k,$$
$$|\boldsymbol{W}(n,k)| = \frac{1}{\sqrt{N}}, \ \forall n, k,$$
$$\|\boldsymbol{F}_{\mathrm{RF}} \boldsymbol{F}_{\mathrm{BB}}\|^2_F = K. \quad (2)$$

In the optimization problem **P1**, the second and third constraints respectively guarantee that each antenna is only connected to an RF chain, and that the $k$th RF chain is connected with $N^k_{\mathrm{sub}}$ transmit antennas in DSC-HA.

*Proposed precoder and combiner design scheme.* The direct solution of the maximization problem **P1** is neither practical nor tractable. First, it is hard to optimize the system sum rate in terms of many parameters, which will involve a huge computational complexity. Second, the equality constraints on $|\boldsymbol{F}_{\mathrm{RF}}(i,k)|$ and $|\boldsymbol{W}(n,k)|$ are non-convex and hard to deal with. Therefore, we decompose the original problem into a series of sub-problems and seek a suboptimal solution. First, joint implementation of the transmit antennas grouping and the candidate analog precoding vector design under constrained conditions is performed. After that, the candidate combining vector is designed, and further the ultimately optimized analog precoding and combining vectors are determined. Finally, with the equivalent channel matrix after analog precoding and combining, the digital precoder is obtained. The detailed solution process is provided in Appendix C, and the corresponding steps of the precoder and combiner design are also summarized in Algorithm C1 of Appendix C. Moreover, the system energy efficiency of the proposed precoder and combiner for DSC-HA with low-resolution DACs/ADCs is analyzed in Appendix D.

*Numerical results.* Numerical simulations and performance analysis are presented in Appendix E.

*Conclusion.* In this study, based on AQNM, the precoder and combiner designs for DSC-HA with low-resolution DACs/ADCs were investigated for mmWave multi-user mMIMO systems. In the proposed scheme, in order to ensure the reasonable system power consumption and hardware cost, DACs and ADCs with low resolution are considered at both the transmitter and receiver. Our results revealed that the proposed precoder and combiner design for DSC-HA with low-resolution DACs/ADCs achieves a good system sum rate and energy efficiency when the resolution is 4 (bits). At a relatively high signal-to-noise ratio (SNR), much higher energy efficiency is achieved for DSC-HA with low-resolution DACs/ADCs than that for FD-A and the corresponding FSC-HA, meanwhile, DSC-HA with low resolution DACs/ADCs has a significant superiority over the corresponding FSC-HA in terms of system sum rate.

In the present study, the dynamic connection network in DSC-HA is realized by an ideal switch network without considering the impedance matching problem required in the practical circuit design [7]. Thereby, introducing impedance matching problem into the optimization design of the precoder and combiner design for DSC-HA with low-resolution DACs/ADCs for mmWave multi-user mMIMO systems is envisioned as future work.

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**Supporting information** Appendixes A–E. The supporting information is available online at info.scichina.com and link.

springer.com. The supporting materials are published as submitted, without typesetting or editing. The responsibility for scientific accuracy and content remains entirely with the authors.

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