All-Analog Structures for AF Relaying in mmWave Massive MIMO Systems

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***Abstract*—Hybrid analog/digital (A/D) beamforming is preferred in the implementation of relays for mmWave massive multiple-input multiple-output (mMIMO) systems due to the smaller number of radio frequency (RF) chains required compared to fully digital (FD) beamforming. Although the hybrid structure reduces system cost and power consumption, it still requires expensive baseband processing while the unit-modulus constraint in the analog domain limits system performance. In this paper, motivated by these considerations, we propose and investigate the design of *all-analog* structures for amplify-and-forward (AF) half-duplex relaying in mMIMO systems, which are comprised of the conventional RF components, including: power dividers/combiners, phase-shifters, and delay elements. For the proposed structures, we consider a constrained data rate maximization problem and formulate the AF relay designs. The ensuing solution is not bound to the unit-modulus constraint and does not require RF chains for conversion between analog and baseband domains. Simulation results demonstrate that using the proposed analog structures for AF half-duplex relaying in mMIMO communications can achieve the same performance as the optimal FD relay design.**

***Index Terms*—mmWave, massive MIMO, hybrid beamforming, hybrid A/D signal processing, amplify-and-forward relay**

I. Introduction

A key feature of 5G wireless networks lies in the exploitation of high frequency millimeter wave (mmWave) bands (currently from 20 to 100 GHz) [1] [2]. While mmWave communications suffer from severe path loss and shadow fading, the short wavelengths of mmWaves accommodate a large number of antenna elements in a limited space [3]. Consequently, massive multiple-input-multiple-output (mMIMO) systems can be employed in mmWave communications to combat the channel impairments by exploiting beamforming gain [1] [4]. Neverthless, for mmWave systems equipped with large antenna arrays, it is difficult to provide each antenna element with a dedicated radio frequency (RF) chain due to high hardware complexity and power consumption [5]. To overcome this limitation, hybrid analog/digital (A/D) beamforming structures, which employ less RF chains than the number of antenna elements for linking the analog precoding/combining units and digital signal processing units, have been proposed for mMIMO systems[1] [6].

In order to extend coverage in non-line-of-sight (NLOS) scenarios, multi-hop relaying has also been adopted in mmWave systems [5]. In this regard, two major relaying strategies are available: decode-and-forward (DF) and amplify-and-forward (AF) [7] [8]. DF requires decoding, modulating and re-transmitting the received signal, which entails high processing complexity in the baseband (BB) or digital domain. In its basic form, AF only requires amplifying and re-transmitting the received signal without decoding. For MIMO relaying, however, some form of BB processing is still needed to optimize the transceiver operation. Our main focus in this work lies on the use of AF relaying in mmWave mMIMO systems, with an emphasis on simplifying BB processing.

Several hybrid beamforming designs have been proposed in the literature for the half-duplex AF mmWave mMIMO relay system. In [9], the authors develop a downlink single-user hybrid precoding scheme using an iterative orthogonal matching pursuit (OMP)-based sparse approximation algorithm. A method to jointly design the source and relay precoders using semi-definite programming is proposed in [10] for the single data stream scenario. In [11], hybrid solutions are proposed for the joint design of the source, relay and destination nodes precoders using the alternating direction method of multipliers algorithm. In [12], the hybrid precoder design for the relay is reformulated in terms of three convex subproblems which are solved using an iterative successive approximation algorithm. To reduce complexity, the RF and BB processors are separately designed in both [13] and [14]. After designing the RF precoders/combiners, a minimum mean squared error (MMSE)-based design is proposed for the BB processors in [13], but this algorithm does not optimize the sum-rate of the system. In [14], a weighted MMSE based design is employed for both the source and relay nodes BB processors, while a design based on successive interference cancellation (SIC) is employed for the BB combiner at the receiver node. This approach outperforms all the above algorithms, but still cannot achieve performance equivalent to a FD system.

Besides, attempts have been made at a structural level to reduce the number of RF chains in hybrid beamformers, in order to lower cost and increase energy efficiency while still achieving optimal performance [5]. In [15], the authors propose a heuristic hybrid beamforming design strategy for the critical case where the number of RF chains is equal to the number of data streams. In [16], a special hybrid

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[1] In this work, to simplify presentation, the term *beamforming* is used interchangeably to refer to transmit precoding, receive combining or both.

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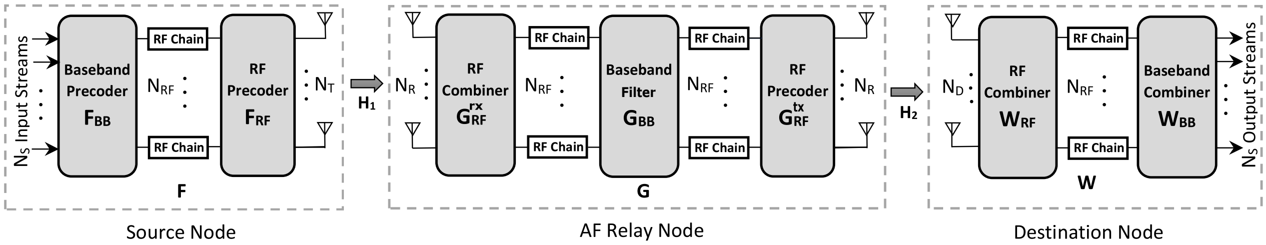

Fig. 1. Half-duplex AF relaying system with hybrid analog/digital transceiver architecture.

design for realizing a FD precoder in the hybrid architecture with a single RF chain is presented. In [17], the hybrid A/D structure is explored as a general framework for signal processing in mMIMO systems. In particular, a novel analog signal processing (ASP) structure, using conventional RF components and free from unit-modulus constraint, is proposed to facilitate hybrid A/D system design while achieving the FD performance.

In this paper, we propose and investigate the design of *all-analog* structures for AF half-duplex relaying in mmWave mMIMO systems. The new structures, whose derivation relies on the ASP framework introduced in [17], are comprised of basic RF components, i.e.: power combiners/dividers, phase-shifters, and delay elements. For the proposed structures, we consider a constrained data rate maximization problem and formulate the AF relay designs. The ensuing solution is not bound to the unit-modulus constraint and does not require RF chains for conversion between analog and BB domains, hence simplifying the implementation of the relay transceiver system. Simulation results demonstrate that by employing the proposed analog structures for AF half-duplex relaying in mmWave mMIMO communications, the same performance as the optimal FD relay design can be achieved.

The rest of the paper is organized as follows. In Section II, the hybrid AF relay system model is introduced and the ASP framework is reviewed briefly. In Section III, the proposed all-analog relay designs based on data rate maximization are developed. Section IV presents the supporting simulation results while Section V concludes the work.

II. System Model and Background

A. Conventional Hybrid Relay System Model

We consider a single-user AF relay-assisted mmWave mMIMO system consisting of a source node, destination node and AF relay node, as shown in Fig. 1. We let N_T, N_R and N_D denote the numbers of antennas at the source, relay, and destination nodes, respectively. We also let N_S and N_{RF} denote the numbers of transmitted data streams and RF chains at all nodes, respectively, such that $N_S \leq N_{RF} \leq \min(N_T, N_R, N_D)$. We consider a half-duplex relaying scenario in two phases or hops, i.e.: transmission from source to relay during the first time slot, followed by transmission from the relay to destination during the second time slot. The transmission channels from source to relay and from relay to destination are assumed to be flat-fading; there is no direct transmission path from source to destination.

Let $\mathbf{s} \in \mathbb{C}^{N_S}$ represent the input vector of complex information symbols to be communicated to the destination through the relay, with zero mean and normalized power, i.e., $\mathbb{E}[\mathbf{s}\mathbf{s}^H] = \mathbf{I}_{N_S}$. The signal transmitted from the source during the first time slot can be expressed as

$$\mathbf{x} = \mathbf{F}\mathbf{s}, \tag{1}$$

where $\mathbf{F} = \mathbf{F}_{RF}\mathbf{F}_{BB}$. Here, $\mathbf{F}_{RF} \in \mathbb{U}^{N_T \times N_{RF}}$ and $\mathbf{F}_{BB} \in \mathbb{C}^{N_{RF} \times N_S}$ are the analog RF and digital BB precoding matrices, respectively, and $\mathbb{U} = \{z \in \mathbb{C} : |z| = 1\}$. Denoting the available source transmit power by P_s, the hybrid precoding matrices should meet the following power constraint:

$$\mathbb{E}[\|\mathbf{x}\|^2] = \|\mathbf{F}\|_F^2 \leq P_s. \tag{2}$$

The received signal at the relay can be represented as

$$\mathbf{z}_1 = \mathbf{H}_1\mathbf{x} + \mathbf{n}_1, \tag{3}$$

where $\mathbf{H}_1 \in \mathbb{C}^{N_R \times N_T}$ is the channel matrix between the source and relay nodes, and $\mathbf{n}_1 \in \mathbb{C}^{N_R}$ is a complex Gaussian noise vector modeled as $\mathcal{CN}(0, \sigma_1^2\mathbf{I}_{N_R})$.

In the case of AF relaying with hybrid A/D architecture, the received signal $\mathbf{z}_1$ goes through the following sequence of processing steps: multiplication by RF combining matrix $\mathbf{G}_{RF}^{rx} \in \mathbb{U}^{N_{RF} \times N_R}$, conversion from analog to BB via RF chains, processing by BB filter matrix $\mathbf{G}_{BB} \in \mathbb{C}^{N_{RF} \times N_{RF}}$, conversion from BB to analog via RF chains, and finally, multiplication by RF precoding matrix $\mathbf{G}_{RF}^{tx} \in \mathbb{U}^{N_R \times N_{RF}}$. Hence, making abstraction of the RF chains, the signal transmitted by the relay during the second time slot can be expressed as

$$\mathbf{z}_2 = \mathbf{G}_{RF}^{tx}\mathbf{G}_{BB}\mathbf{G}_{RF}^{rx}\mathbf{z}_1 = \mathbf{G}\mathbf{z}_1, \tag{4}$$

where for convenience, we define the overall relay processing matrix $\mathbf{G} = \mathbf{G}_{RF}^{tx}\mathbf{G}_{BB}\mathbf{G}_{RF}^{rx}$. Denoting the available relay transmit power by P_r, the hybrid processing matrices at the AF relay should meet the following power constraint:

$$\mathbb{E}[\|\mathbf{z}_2\|^2] = \|\mathbf{G}\mathbf{H}_1\mathbf{F}\|_F^2 + \sigma_1^2\|\mathbf{G}\|_F^2 \leq P_r. \tag{5}$$

The signal received at the destination is given by

$$\mathbf{y} = \mathbf{H}_2\mathbf{z}_2 + \mathbf{n}_2, \tag{6}$$

where $\mathbf{H}_2 \in \mathbb{C}^{N_D \times N_R}$ is the channel matrix between the relay and the destination nodes, and $\mathbf{n}_2 \in \mathbb{C}^{N_D}$ is a noise vector modeled as $\mathcal{CN}(0, \sigma_2^2\mathbf{I}_{N_D})$. This signal is first processed by the RF combining matrix $\mathbf{W}_{RF} \in \mathbb{U}^{N_{RF} \times N_D}$ and then by the BB combining matrix $\mathbf{W}_{BB} \in \mathbb{C}^{N_S \times N_{RF}}$. Following these operations, the resulting signal can be expressed as

$$\hat{\mathbf{s}} = \mathbf{W}\mathbf{y} = \mathbf{W}\mathbf{H}_2\mathbf{G}\mathbf{H}_1\mathbf{F}\mathbf{s} + \mathbf{W}\mathbf{H}_2\mathbf{G}\mathbf{n}_1 + \mathbf{W}\mathbf{n}_2, \tag{7}$$

where $\mathbf{W} = \mathbf{W}_{BB}\mathbf{W}_{RF}$. Signal $\hat{\mathbf{s}}$ is finally passed on to the decoding stage, whose implementation falls outside the scope of this work.

In this paper, we consider a general mMIMO relaying system model which is not bound to the hybrid A/D factorization presented above. Accordingly, we represent the source, relay and destination nodes by the equivalent matrices $\mathbf{F} \in \mathbb{C}^{N_T \times N_S}$, $\mathbf{G} \in \mathbb{C}^{N_R \times N_R}$ and $\mathbf{W} \in \mathbb{C}^{N_S \times N_D}$, respectively.

B. ASP Network Architecture

A simple feed-forward ASP network that facilitates hybrid A/D system design by relaxing the analog beamforming weights from the constant-modulus constraint is proposed in [17]. This ASP network, illustrated in Fig. 2 for the case of M input and N output signals, consists of basic RF components, i.e., phase shifters and power dividers/combiners. Ideally, the phase shifters have infinite resolution with phase shift parameters $\varphi_{ij}^l \in [0, 2\pi)$. The power dividers can be implemented by means of Wilkinson devices with $2N+1$ ports; the same type of devices can be used as combiners by reversing the signal flow [18]. The input-output relationship for the proposed ASP network, implemented using M power dividers, N power combiners and $2NM$ phase shifters is given by

$$\mathbf{y} = \tfrac{1}{\sqrt{MN}}\mathbf{A}\mathbf{x}, \tag{8}$$

where $\mathbf{x} \in \mathbb{C}^M$ is the input signal vector and $\mathbf{y} \in \mathbb{C}^N$ is the output signal vector. The term $\frac{1}{\sqrt{MN}}$ in (8) is a normalization factor introduced as a result of the power dividers and combiners. A distinguishing feature of the ASP network is the use of $2NM$ phase shifters, as opposed to NM in a conventional fully-connected RF beamformer. The additional degrees of freedom allow the network to implement any matrix $\mathbf{A} \in \mathbb{V}^{N\times M}$, where $\mathbb{V} = \{z \in \mathbb{C} : |z| \leq 1\}$. In effect, the overall transformation matrix of the network is no longer restricted to the unit-modulus constraint, but instead bound to a convex set, which greatly simplifies the optimization problem involved in the design of hybrid A/D beamformers.

C. Motivation for All-analog Relay Design

While the complexity of the conventional hybrid architecture is less than that of a FD implementation with same number of antennas, the BB processing is still expensive and the conversion between the RF and BB domains by RF chains adds to the system cost and complexity. Moreover, relay transceiver design under the unit-modulus constraint in the analog domain results into non-convex optimization problems, which entail high complexity and limit attainable performance. In this work, we aim to design an all-analog AF relay transceiver by taking advantage of the ASP network introduced above, such that the data rate is maximized while the BB processing along with the associated RF chain complexity can be simplified.

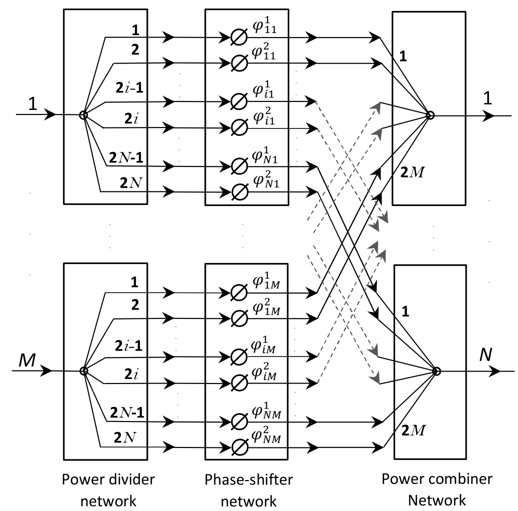

Fig. 2. ASP network.

III. Proposed Relay Design

In this section, we first present the constrained data rate maximization problem and the corresponding optimal FD solution for the AF relay design We then explain how the resulting solutions can be realized exactly by means of the ASP network in Fig. 2, along with additional delay and gain elements. Finally, we discuss certain practical considerations.

A. Fully Digital Optimization Problem

Our main goal in designing the AF relay assisted mMIMO system is to derive the optimal precoder/combiner matrices such that the overall system achieves maximum data rate while satisfying the power constraint. Since we intend to realize the resulting solution with the ASP network which is not bound to the unit-modulus constraint, we need not take into account additional structural constraints into our approach; in effect, this amounts to finding the FD solution.

The data rate R for the generic AF relay system with transformation matrices $\mathbf{F}$, $\mathbf{G}$, and $\mathbf{W}$ at the source, relay and destination nodes (see Section II-A) is defined as [19]

$$R = \tfrac{1}{2}\log_2 |\mathbf{I}_{N_S} + \mathbf{W}\mathbf{H}_2\mathbf{G}\mathbf{H}_1\mathbf{F}\mathbf{R}_n^{-1}\mathbf{F}^H\mathbf{H}_1^H\mathbf{G}^H\mathbf{H}_2^H\mathbf{W}^H|, \tag{9}$$

where $\mathbf{R}_n = \sigma_1^2\mathbf{W}\mathbf{H}_2\mathbf{G}\mathbf{G}^H\mathbf{H}_2^H\mathbf{W}^H + \sigma_2^2\mathbf{W}\mathbf{W}^H$ is the covariance matrix of the noise term in (7), i.e., $\mathbf{W}\mathbf{H}_2\mathbf{G}\mathbf{n}_1 + \mathbf{W}\mathbf{n}_2$, and the factor 1/2 is due to half-duplex operation. The constrained data rate maximization problem is formulated as

$$\begin{aligned}[\mathbf{F}^o, \mathbf{G}^o, \mathbf{W}^o] &= \arg\max_{\mathbf{F},\mathbf{G},\mathbf{W}} R \\ \text{s.t. } & \|\mathbf{F}\|_F^2 \leq P_s, \\ & \|\mathbf{G}\mathbf{H}_1\mathbf{F}\|_F^2 + \sigma_1^2\|\mathbf{G}\|_F^2 \leq P_r \end{aligned} \tag{10}$$

where P_s and P_r are the available transmit power at the source and relay nodes, respectively.

Let the singular value decomposition (SVD) of channel matrices $\mathbf{H}_1$ and $\mathbf{H}_2$ be given by $\mathbf{H}_1 = \mathbf{U}_1\mathbf{\Sigma_1}\mathbf{V}_\mathbf{1}^\mathbf{H}$ and $\mathbf{H}_2 = \mathbf{U}_2\mathbf{\Sigma_2}\mathbf{V}_\mathbf{2}^\mathbf{H}$, respectively, where $\mathbf{U}_1$, $\mathbf{U}_2$, $\mathbf{V}_1$ and $\mathbf{V}_2$ are unitary matrices of appropriate dimensions containing the left and right singular vectors, and $\mathbf{\Sigma_1}$ and $\mathbf{\Sigma_2}$ are the rectangular diagonal matrices with singular values on their main diagonal. The optimal solution to the constrained optimization problem in (10) can be found as [11]

$$\mathbf{F}^o = \sqrt{\rho_1}\,\mathbf{V}_{1a}, \;\; \mathbf{G}^o = \sqrt{\rho_2}\,\mathbf{V}_{2a}\mathbf{U}_{1a}^H \;\text{ and }\; \mathbf{W}^o = \mathbf{U}_{2a}^H, \quad (11)$$

where $\mathbf{U}_{1a}$, $\mathbf{U}_{2a}$, $\mathbf{V}_{1a}$ and $\mathbf{V}_{2a}$ contain the N_s columns of $\mathbf{U}_1$, $\mathbf{U}_2$, $\mathbf{V}_1$ and $\mathbf{V}_2$, respectively, corresponding to the N_s dominant singular values of channel matrices $\mathbf{H}_1$ and $\mathbf{H}_2$. The scaling variables ρ_1 and ρ_2 are set such that the transmit power constraints are satisfied.

When a similar data rate maximization problem is considered for the case of hybrid transceiver design, i.e., with the factorization $\mathbf{F} = \mathbf{F}_{RF}\mathbf{F}_{BB}$, $\mathbf{G} = \mathbf{G}_{RF}^{tx}\mathbf{G}_{BB}\mathbf{G}_{RF}^{rx}$, and $\mathbf{W} = \mathbf{W}_{BB}\mathbf{W}_{RF}$, we need to determine explicit solutions for all individual RF and BB processing matrices in the system. However, imposing the above mentioned power constraints on the system along with the unit-modulus constraint on all the RF processing matrices, results in a non-convex and intractable rate maximization problem. Hence, approximate solutions to design the hybrid transceivers have been proposed in the literature. For instance, in [14], a solution is obtained by first designing the RF precoding/combining matrices separately, and then transforming the non-convex optimization problem into a solvable weighted MMSE problem.

B. All-Analog Relay Design

Let $\mathbf{G}^o \in \mathbb{C}^{N_R \times N_R}$ denote the optimal FD solution for the overall matrix representing the relay node, as given in (11). Below, we present two different approaches for realizing matrix $\mathbf{G}^o$ using ASP networks along with additional gain and delay elements.

Our first approach, which uses two ASP networks, is based on the fact that the magnitudes of the entries of matrices $\mathbf{V}_{2a}$ and $\mathbf{U}_{1a}$ in (11) cannot exceed unity. Indeed, since the columns of these matrices are extracted from unitary matrices $\mathbf{V}_2$ in $\mathbf{U}_1$, they must have an Euclidean norm equal to 1. Denoting by V_{ij} and U_{ij} their respective entries, we have $\sum_{i=1}^{N_R}|V_{ij}|^2 = \sum_{i=1}^{N_R}|U_{ij}|^2 = 1$, which implies $|V_{ij}|$ and $|U_{ij}| \le 1$. Consequently, we can express $\mathbf{G}^o$ as

$$\mathbf{G}^o = \gamma_1\big(\alpha\mathbf{A}_T\big)\big(\alpha\mathbf{A}_R\big), \quad (12)$$

where we define $\alpha = 1/\sqrt{N_R N_S}$, $\gamma_1 = \sqrt{\rho_2}/\alpha^2$ and

$$\mathbf{A}_R = \mathbf{U}_{1a}^H \in \mathbb{V}^{N_S \times N_R}, \quad (13)$$

$$\mathbf{A}_T = \mathbf{V}_{2a} \in \mathbb{V}^{N_R \times N_S}. \quad (14)$$

According to (12), and based on our discussion in Section II-B, the overall matrix $\mathbf{G}^o$ for optimal operation of the relay node can be realized as a cascade of two feed-forward ASP networks as in Fig. 2, corresponding to the normalized factors $\big(\alpha\mathbf{A}_R\big)$ and $\big(\alpha\mathbf{A}_T\big)$, along with an overall system gain γ_1. In this realization, the first ASP network at the input, $\alpha\mathbf{A}_R$, can be interpreted as an RF combiner while the second ASP network at the output, $\alpha\mathbf{A}_T$, can be viewed as a complementary RF precoder. The overall system gain γ_1 can be distributed in different ways along the signal path to accommodate additional hardware requirements. A distinguishing feature of this first design approach is that phase parameters of the input and output ASP networks can be adjusted independently. This is important for applications where the estimates of channel matrices $\mathbf{H}_1$ and $\mathbf{H}_2$ are updated at different rates. Because it uses 2 ASP networks with sizes $N_R \times N_S$ and $N_S \times N_R$, this approach requires a total of $4N_R N_S$ phase shifters and $2(N_R + N_S)$ power dividers/combiners.

Our second approach seeks to realize the product $\mathbf{V}_{2a}\mathbf{U}_{1a}^H$ in (11) by means of a single ASP network. This is indeed possible since the magnitudes of the entries of this matrix cannot, as in the previous case, exceed unity. Specifically, denoting by A_{ij} the entry in the i^{th} row and j^{th} column of $\mathbf{V}_{2a}\mathbf{U}_{1a}^H$, and invoking Cauchy-Schwartz inequality, we can write

$$|A_{ij}|^2 = |\sum_{k=1}^{N_S} V_{ik}U_{jk}^*|^2 \le \sum_{k=1}^{N_R}|V_{ik}|^2 \sum_{k=1}^{N_R}|U_{jk}|^2 = 1 \quad (15)$$

since the rows of matrices $\mathbf{V}_2$ and $\mathbf{U}_1$ have unit norm. Hence we can express $\mathbf{G}^o$ as

$$\mathbf{G}^o = \gamma_2\big(\beta\mathbf{A}\big) \quad (16)$$

where we define $\beta = 1/N_R$, $\gamma_2 = \sqrt{\rho_2}/\beta$ and

$$\mathbf{A} = \mathbf{V}_{2a}\mathbf{U}_{1a}^H \in \mathbb{V}^{N_R \times N_R}. \quad (17)$$

According to (16), the optimal relay matrix $\mathbf{G}^o$ can be realized by a single feed-forward ASP network, corresponding to the normalized factor $\big(\beta\mathbf{A}\big)$, along with an overall system gain γ_2, which can be distributed along the signal path. This second realization is not as flexible as the previous one, in the sense that all its phase parameters must be updated whenever either one of the estimates of the channel matrices $\mathbf{H}_1$ or $\mathbf{H}_2$ changes. Because it uses a single ASP network with size $N_R \times N_R$, it requires a total of $2N_R^2$ phase shifters and $2N_R$ power dividers/combiners. The most economical realization will depend in general on the relative costs of the different types of RF components and values of N_R and N_S, although the first approach is preferable when $N_S \ll N_R$.

Next, we discuss the choice of the phase shift parameters in the proposed all-analog relay designs. For conciseness, we hereafter focus on the second approach (i.e., single ASP network), but the discussion extends forthrightly to the first approach. By denoting the input and output vectors of the ASP network $\beta\mathbf{A}$ in (16), as $\mathbf{x} = [x_1, \ldots, x_{N_R}]$ and $\mathbf{y} = [y_1, \ldots, y_{N_R}]$, respectively, the i^{th} output can be expressed in terms of the individual inputs as

$$y_i = \frac{1}{N_R}\sum_{k=1}^{N_R} A_{ij}x_j, \quad (18)$$

where $A_{ij} = \sum_{k=1}^{N_S} V_{ik}U_{jk}^*$ can be calculated following the SVD decomposition of the channel matrices $\mathbf{H}_1$ and $\mathbf{H}_2$. While the complex numbers A_{ij} generally do not have unit magnitude, they can be realized as a weighted sum of two phase terms. Specifically, since $|A_{ij}| \le 1$, it is always possible to find phase-shifter values φ_{ij}^1 and φ_{ij}^2 such that

$$A_{ij} = \tfrac{1}{2}(e^{j\varphi_{ij}^1} + e^{j\varphi_{ij}^2}), \quad (19)$$

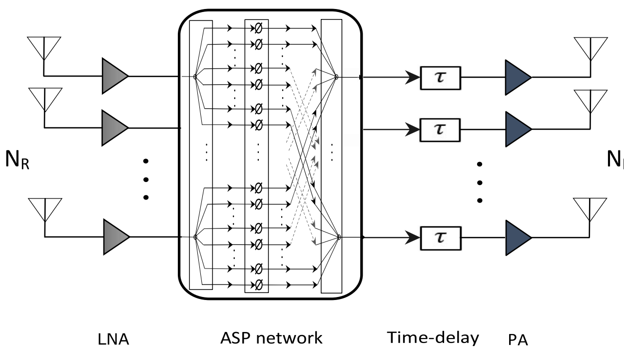

Fig. 3. Proposed all-analog AF relay structure.

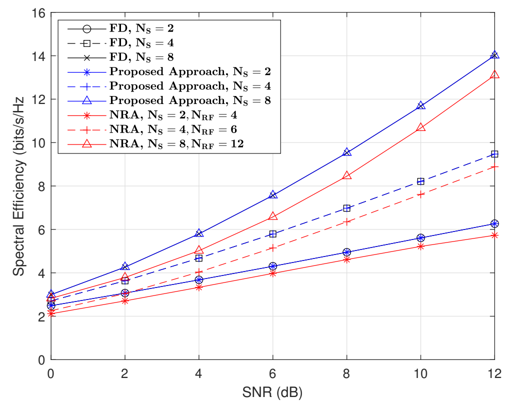

Fig. 4. Spectral efficiency vs SNR (N_T = 64, N_R = 32, N_D = 48).

where $j = \sqrt{-1}$ [17]. According to (19), while the overall transformation matrix $\mathbf{A}$ implemented by the ASP network in Fig. 2 is not restricted to the unit-modulus constraint, it can be realized by simple combinations of phase-shifters that individually satisfy this constraint. One possible solution for the phase-shifters is given as

$$\varphi_{ij}^1 = \angle A_{ij} + \cos^{-1}(|A_{ij}|), \tag{20a}$$

$$\varphi_{ij}^2 = \angle A_{ij} - \cos^{-1}(|A_{ij}|). \tag{20b}$$

C. Practical Considerations

Focusing on the second approach, the AF relay node can be realized using a single ASP network along with amplifiers and delay elements as shown in Fig. 3. The low-noise amplifiers (LNA) are used at the receiving end of the relay to amplify the antenna signals to a level suitable for RF processing. The amplified signals are processed by an ASP network implementing the linear transformation $\beta\mathbf{A}$ in (16). Here, we consider a half-duplex mMIMO relaying system, where the relay can communicate in both directions (i.e., from source to destination and vice-versa) but not simultaneously. Typically, once a relay begins receiving a signal, it must wait for the reception to complete and then switch to the transmitting mode. As only one way communication is possible at a time, a possible solution is to introduce a common time delay τ, equal to one symbol period, in the output lines of the ASP network. For example, assuming a 64-QAM modulation and transmission rate of 600Mbps in the 5G network, $\tau = (\log_2 64/600)10^{-6}$ sec = 10 nsec. This amount of delay is achievable for a RF frequency in the range 1-18 GHz using existing technologies [20]. Finally, the delayed signals are fed to power amplifiers (PA) driving the antennas for transmission.

From an RF perspective, as pointed out earlier, an ASP network requires twice as many phase shifters as a conventional fully-connected RF beamformer of similar dimensions, and additional power dividers/combiners. However, since BB processing is eliminated, RF chains for conversion between the analog and baseband domains are not required. From a signal processing perspective, the main complexity lies in the SVD decomposition of the channel matrices $\mathbf{H}_1$ and $\mathbf{H}_2$, which must be performed at regular intervals. We note however that SVD decomposition is a common step in several of the existing FD and hybrid AF relay design methods, e.g., [11], [14]. Besides the SVD, additional computations are required for the determination of the phase-shifter parameters, as given in (20a) and (20b). At the cost of these additional RF components and computations, the unit-modulus constraint the analog transformation can be lifted and FD performance can be achieved by both the proposed analog relay designs.

IV. Simulation Results

A. Methodologies

We adopt the clustered channel model given in [14], which is suitable for mmWave channels. Specifically, for N_c scattering clusters with each cluster contributing N_r propagation paths, the channel matrix $\mathbf{H}$ is given as

$$\mathbf{H} = \sqrt{\frac{N_T N_R}{N_c N_r}} \sum_{l=1}^{N_c} \sum_{n=1}^{N_r} \alpha_{l,n} \mathbf{a}_r(\theta_{l,n}^r) \mathbf{a}_t^H(\theta_{l,n}^t), \tag{21}$$

where $\theta_{l,n}^r$ and $\theta_{l,n}^t$ represent angles of arrival and departure (AoA and AoD), respectively, $\mathbf{a}_r(\theta_{l,n}^r)$ and $\mathbf{a}_t(\theta_{l,n}^t)$ are the array response vectors for the receiver and the transmitter, and $\alpha_{l,n}$ is the complex gain of the n^{th} path in the l^{th} cluster. The AoA and AoD are uniformly distributed in the interval $[0, 2\pi]$, while the path gains $\alpha_{l,n} \sim \mathcal{CN}(0,1)$; these random variables are independently generated. For simplicity, we consider the widely used uniform linear array (ULA) configuration with half-wavelength antenna spacing. For simulation, we use N_c = 20 and N_r = 1 and initially set the numbers of antennas as $N_T = 64$, $N_R = 32$, and $N_D = 48$. The signal-to-noise ratios (SNR) of the source-to-relay and relay-to-destination links are respecively defined as P_s/σ_1^2 and P_r/σ_2^2. Following [14], we set $P_s = 2P_r = 2N_S$ and adjust the noise powers so that the two SNRs are the same. All reported results are generated by averaging over 1,000 channel realizations.

The average spectral efficiency (bits/s/Hz) and bit error rate (BER) of the proposed all-analog relay design for mMIMO AF relaying system are examined through simulations. For comparison purposes, the performances of the non-robust approach in [14] (NRA) and the optimal FD solution (11) are also reported, with the FD method standing as the ultimate benchmark. For NRA with hybrid architecture, different number of RF chains, N_{RF}, are employed. For the proposed all-analog AF relaying mMIMO system, we employ FD precoder and combiner at the source and destination nodes.

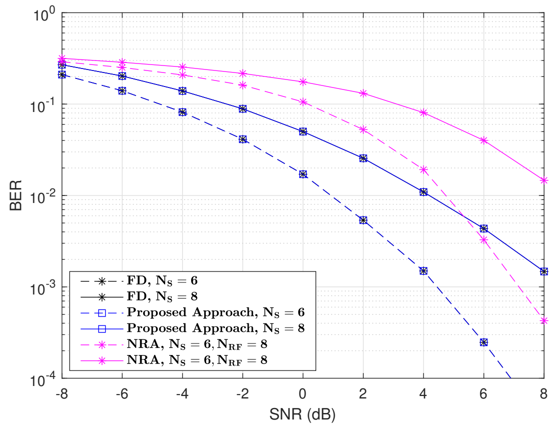

Fig. 5. BER versus SNR ($N_T = 64$, $N_R = 32$, $N_D = 48$).

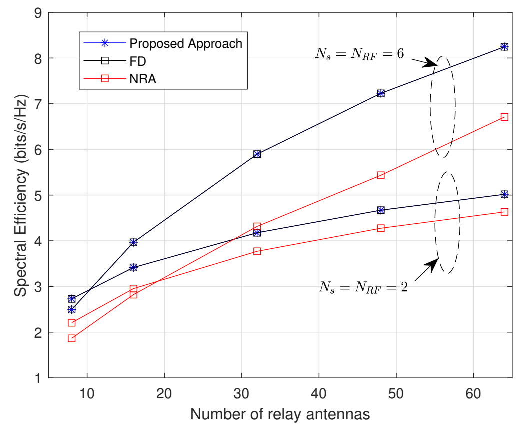

Fig. 6. Spectral efficiency vs N_R ($N_T = N_D = 64$, and SNR = $5dB$).

B. Results and Discussion

Fig. 4 shows the average spectral efficiency versus SNR simulation for different values of N_S and N_{RF}. The proposed design outperforms the NRA algorithm, and achieves the same performance as the FD beamforming solution. In Fig. 5, we examine the BER performance versus SNR of different algorithms for a mMIMO relay system. We compare our approach with the NRA and FD method in two scenarios: (i) $N_S = 6, N_{RF} = 8$; (ii) $N_S = 8, N_{RF} = 12$. It can be seen that in all the simulated scenarios, our proposed method matches the BER performance of the FD system, while the use of hybrid architecture with NRA entails a notable performance loss.

Finally, in Fig. 6 we compare the average spectral efficiency of the different approaches as a function of N_R, the number of antennas at the relay node. The value of SNR is fixed to 5dB while the other parameters are kept as in Fig. 4. The merits of the proposed all-analog approach over a traditional hybrid architecture are once again verified by the results. In effect, by relaxing the unit-modulus constraint through the use of an ASP network, performance equivalent to the optimal FD digital solution can be attained without the need of BB processing and associated RF chains for conversion between the analog and digital domains.

V. Conclusion

In this paper, we proposed and investigated the design of *all-analog* structures for AF half-duplex relaying in mMIMO systems, which are comprised of the conventional RF components, including: power dividers/combiners, phase-shifters, and delay elements. For these proposed analog structures, we considered a constrained data rate maximization problem and formulated the AF relay design. The ensuing solution is not bound to the unit-modulus constraint and does not require RF chains for conversion between analog and baseband domains. Simulation results demonstrated that using the proposed analog structures for AF half-duplex relaying in mMIMO communications, the same performance as the optimal FD relay design can be achieved.

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