

IA-Based Hybrid Beamforming Design in MIMO Interference Channel

Ji-Ho Lee*, Myeong-Jin Kim**, and Young-Chai Ko*

*School of Electrical Engineering, Korea University, Seoul, Korea

**Advanced Communication Technology Laboratory, LG Electronics, Seoul, Korea
arnoldjiho@korea.ac.kr, mjin.kim@lge.com, koyc@korea.ac.kr

Abstract— In this paper, we develop a hybrid beamforming design over multiple input multiple output (MIMO) interference channels. Since the performance of MIMO interference channels depends on the desired channel and the leakage of interference signals, the proposed hybrid beamforming design first selects radio frequency (RF) precoders/combiners and optimizes the corresponding baseband precoders/combiners to maximize the rate over the desired channel by adopting the concept of orthogonal matching pursuit (OMP). Then, by using interference alignment (IA), we modify the baseband precoders/combiners to suppress the interference. From simulation results, we demonstrate that the proposed hybrid beamforming design offers the better sum rate than the baseline scheme in signal to noise ratio (SNR) region of interest where the interference is the dominant factor to the performance while preserving the degrees of freedom (DOF).

Keywords— Hybrid beamforming, analog/RF beamforming, digital/baseband beamforming, interference channel, interference alignment.

I. INTRODUCTION

Due to the demand for high data rate, millimeter wave (mmWave) communication with large available spectrum has attracted tremendous interest [1]–[3]. However, to compensate for the performance degradation due to the high propagation loss on mmWave band, highly directional beamforming with large-scale antenna array (LSAA) is absolutely necessary to increase the transmission range and throughput [4]. Unfortunately, digital baseband beamforming is impracticable on account of the high cost and power consumption of mixed signal components since the same number of analog-to-digital converters (ADCs) and radio frequency (RF) chains as the number of antennas is required to realize the digital beamforming. To overcome such limitations, a hybrid (i.e., a mixture of analog and digital) beamforming was suggested in [5], [6].

On the other hand, there have been many researches about interference alignment (IA) to effectively manage the interference and improve the throughput of users in MIMO interference networks [7]–[9]. With IA, every user in interference networks can attain one half of the capacity free from interference at high signal to noise ratio (SNR) regardless of the number of users. However, a large overhead which can be a critical problem especially in LSAA system makes difficult

to apply IA for practical system because most of IA solutions require global channel state information (CSI). Also, IA with closed form solution can be only used in special cases. In general, it is difficult to obtain the closed form solution as the number of users in the network increases. In that case, iterative algorithms are proposed to solve the problem when the closed form solution of IA cannot be applied to system. One of the iterative algorithms, we use maximum signal to interference plus noise ratio (Max-SINR) algorithm in this paper, which is one of the distributed iterative IA algorithms requiring only the local CSI. Max-SINR algorithm considers the time division duplex (TDD) system exploiting channel reciprocity. We assume channel reciprocity always holds for simplicity, i.e., the forward link and reverse link are identical.

In this paper, we propose the hybrid beamforming design over MIMO interference channels to simultaneously maximize the rate over the desired channel and minimize the leakage of interference signals, which separates the design problem into two stages. First, based on the concept of orthogonal matching pursuit (OMP) [6], we select RF precoders/combiners and optimize the corresponding baseband precoders/combiners to maximize the rate over the desired channel. Subsequently, we modify the baseband precoders/combiners so that the leakage of the interference signal can be minimized by adopting the idea of IA [7]. From simulation results, we compare between proposed design and existing hybrid beamforming design algorithms. We show that the performance of the algorithm presented in [10] is degraded at high SNR region and cannot preserve DOF in certain case. Also we confirm that the proposed hybrid beamforming design improves the sum rate by preserving the DOF especially in high SNR region where the interference is the dominant contributor to the performance.

The remainder of this paper is organized as follows. Section II presents the system model under consideration. In Section III, we describe the proposed hybrid beamforming design. Simulation results are then given in Section IV. Finally, we draw some conclusions in Section V.

The following mathematical notations will be used throughout the paper. Upper case and lower case boldfaces are used to denote matrices and vectors, respectively. $(\cdot)^T$, $(\cdot)^H$, $(\cdot)^{-1}$, and $\mathbb{E}[\cdot]$ represent the transpose, conjugate transpose, inverse, and expectation operators, respectively. $\mathbf{I}_T$ signifies the $T \times T$ identity matrix. $\|\mathbf{A}\|$ and $\|\mathbf{A}\|_F$ denote the l^2 -norm and Frobenius norm of a matrix $\mathbf{A}$ respectively.

II. SYSTEM MODEL

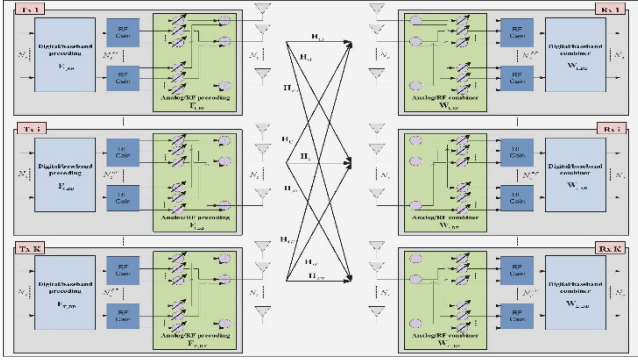


Figure 1. K -user MIMO interference channel where all transmitters and receivers have a hybrid beamforming system

In this section, we describe K -user MIMO interference channels as depicted in Fig. 1 where both the transmitters and receivers have a hybrid beamforming system. We consider symmetric systems that the i -th transmitter with N_t antennas sends N_s data streams to its corresponding i -th receiver with N_r antennas. Thus, each receiver undergoes interference from undesired transmitters. To support multiple data streams, each transmitter and receiver is equipped with N_t^{RF} and N_r^{RF} chains, respectively, which are subject to constraints $N_s \leq N_t^{\text{RF}} \leq N_t$ and $N_s \leq N_r^{\text{RF}} \leq N_r$. This hybrid beamforming structure enables the i -th transmitter to apply a baseband precoder, $\mathbf{F}_{i,\text{BB}} \in \mathbb{C}^{N_t^{\text{RF}} \times N_s}$, followed by an RF precoder, $\mathbf{F}_{i,\text{RF}} \in \mathbb{C}^{N_t \times N_t^{\text{RF}}}$. Then, the transmitted signal at the i -th transmitter is given by

$$\mathbf{x}_i = \mathbf{F}_{i,\text{RF}} \mathbf{F}_{i,\text{BB}} \mathbf{s}_i, (1)$$

where $\mathbf{s}_i \in \mathbb{C}^{N_s \times 1}$ is data symbol vector for the i -th transmitter such that $\mathbb{E}[\mathbf{s}_i \mathbf{s}_i^H] = \mathbf{I}_{N_s}$. Note that the transmit power constraint of the i -th transmitter is $\|\mathbf{F}_{i,\text{RF}} \mathbf{F}_{i,\text{BB}}\|_F^2 = P_i$, where P_i is the transmit power for the i -th transmitter. The received signal at the i -th receiver can be written as

$$\mathbf{y}_i = \mathbf{H}_{ii} \mathbf{F}_{i,\text{RF}} \mathbf{F}_{i,\text{BB}} \mathbf{s}_i + \sum_{j=1, j \neq i}^K \mathbf{H}_{ij} \mathbf{F}_{j,\text{RF}} \mathbf{F}_{j,\text{BB}} \mathbf{s}_j + \mathbf{n}_i,$$

where $\mathbf{H}_{ij} \in \mathbb{C}^{N_r \times N_t}$ is the channel matrix from the j -th transmitter to the i -th receiver and $\mathbf{n}_i \in \mathbb{C}^{N_r \times 1}$ is the additive white Gaussian noise (AWGN) vector at the i -th receiver with zero mean and variance σ^2 per entry. The output signal after the receiver combining for the i -th receiver can be written as

$$\bar{\mathbf{y}}_i = \mathbf{W}_{i,\text{BB}}^H \mathbf{W}_{i,\text{RF}}^H \mathbf{y}_i,$$

where $\mathbf{W}_{i,\text{RF}} \in \mathbb{C}^{N_r \times N_r^{\text{RF}}}$ is the RF combiner and $\mathbf{W}_{i,\text{BB}} \in \mathbb{C}^{N_r^{\text{RF}} \times N_s}$ is the baseband combiner for the i -th receiver.

Hybrid beamforming system is mainly designed to overcome the unfavorable channel characteristic of mmWave band such

as a large path-loss which reduces service coverage and impairs communication performance. Therefore, in this paper, we consider the geometric channel model where the channel has L limited scatters as a mmWave channel model [6], [11]. Under this assumption, the channel $\mathbf{H}_{ij}$ can be expressed as

$$\mathbf{H}_{ij} = \sqrt{\frac{N_t N_r}{L}} \sum_{m=1}^L \alpha_m^{ij} \mathbf{a}_r(\theta_m^{r(i)}) \mathbf{a}_t^H(\theta_m^{t(j)}),$$

where α_m^{ij} is the complex gain of the m -th path with $\mathbb{E}[|\alpha_m^{ij}|^2] = 1$. The variables $\theta_m^{r(i)} \in [0, 2\pi]$ and $\theta_m^{t(j)} \in [0, 2\pi]$ are the azimuth angles of arrival or departure (AoAs/AoDs) of m -th path of the receiver and transmitter, respectively. $\mathbf{a}_t(\theta_m^{t(j)})$ and $\mathbf{a}_r(\theta_m^{r(i)})$ are the antenna array response vectors at the transmitter and receiver, respectively. Although our proposed algorithm can be applied to arbitrary antenna arrays, we adopt uniform linear arrays (ULAs). If ULAs are assumed, $\mathbf{a}_t^H(\theta_m^{t(j)})$ can be written as

$$\mathbf{a}_t(\theta_m^{t(j)}) = \frac{1}{\sqrt{N_t}} \left[1, e^{j \frac{2\pi}{\lambda} d \sin(\theta_m^{t(j)})}, \dots, e^{j \frac{2\pi}{\lambda} (N_t-1) d \sin(\theta_m^{t(j)})} \right]^T,$$

where λ is the signal wavelength and d is the distance between antenna elements.

III. HYBRID BEAMFORMING DESIGN

A. Problem formulation

Consider that the baseband precoder $\mathbf{F}_{i,\text{BB}}$ can be composed into two matrices $\mathbf{F}_{i,\text{BB}}^{\text{OMP}} \in \mathbb{C}^{N_t^{\text{RF}} \times N_t^{\text{IA}}}$ and $\mathbf{F}_{i,\text{BB}}^{\text{IA}} \in \mathbb{C}^{N_t^{\text{IA}} \times N_s}$, i.e., $\mathbf{F}_{i,\text{BB}} = \mathbf{F}_{i,\text{BB}}^{\text{OMP}} \mathbf{F}_{i,\text{BB}}^{\text{IA}}$, which are subject to $N_s \leq N_t^{\text{IA}} \leq N_t^{\text{RF}}$. Similarly, the baseband combiner $\mathbf{W}_{i,\text{BB}}$ can be decomposed into the product of $\mathbf{W}_{i,\text{BB}}^{\text{OMP}} \in \mathbb{C}^{N_r^{\text{RF}} \times N_r^{\text{IA}}}$ and $\mathbf{W}_{i,\text{BB}}^{\text{IA}} \in \mathbb{C}^{N_r^{\text{IA}} \times N_s}$, which are subject to $N_s \leq N_r^{\text{IA}} \leq N_r^{\text{RF}}$. Then, the output signal in (4) can be rewritten as

$$\bar{\mathbf{y}}_i = \mathbf{W}_{i,\text{BB}}^{\text{IA}H} \mathbf{H}_{ii}^{\text{eff}} \mathbf{F}_{i,\text{BB}}^{\text{IA}} \mathbf{s}_i + \mathbf{W}_{i,\text{BB}}^{\text{IA}H} \sum_{j=1, j \neq i}^K \mathbf{H}_{ij}^{\text{eff}} \mathbf{F}_{j,\text{BB}}^{\text{IA}} \mathbf{s}_j + \bar{\mathbf{n}}_i,$$

where $\bar{\mathbf{n}}_i = \mathbf{W}_{i,\text{BB}}^{\text{IA}H} \mathbf{W}_{i,\text{RF}}^H \mathbf{n}_i$ and $\mathbf{H}_{ij}^{\text{eff}}$, defined as $\mathbf{H}_{ij}^{\text{eff}} = \mathbf{W}_{i,\text{BB}}^{\text{OMP}H} \mathbf{W}_{i,\text{RF}}^H \mathbf{H}_{ij} \mathbf{F}_{j,\text{RF}} \mathbf{F}_{j,\text{BB}}^{\text{OMP}}$, is the effective channel matrix between the j -th transmitter and the i -th receiver.

First, we design $\mathbf{F}_{i,\text{BB}}^{\text{OMP}}$ and $\mathbf{W}_{i,\text{BB}}^{\text{OMP}}$ to maximize the rate over the desired effective channel, which can be formulated as

$$\begin{aligned} & \max_{(\mathbf{F}_{i,\text{RF}}, \mathbf{F}_{i,\text{BB}}^{\text{OMP}}, \mathbf{W}_{i,\text{RF}}, \mathbf{W}_{i,\text{BB}}^{\text{OMP}})} \log_2 \left(\left| \mathbf{I} + \mathbf{H}_{ii}^{\text{eff}} \mathbf{H}_{ii}^{\text{eff}H} \right| \right), \\ & \text{s.t. } \mathbf{F}_{i,\text{RF}} \in \mathbb{F}, \mathbf{W}_{i,\text{RF}} \in \mathbb{W}, \\ & \quad \|\mathbf{F}_{i,\text{RF}} \mathbf{F}_{i,\text{BB}}\|_F^2 = P_i. \end{aligned}$$

After finding a solution of maximizing the rate over the desired effective channel, we calculate $\mathbf{F}_{i, \text{BB}}^{\text{IA}}$ and $\mathbf{W}_{i, \text{BB}}^{\text{IA}}$ based on IA to satisfy the following conditions:

$$\begin{aligned} \mathbf{W}_{i, \text{BB}}^{\text{IA}} \mathbf{H}_{ij}^{\text{eff}} \mathbf{F}_{j, \text{BB}}^{\text{IA}} &= 0, \forall i \neq j, \\ \text{rank}(\mathbf{W}_{i, \text{BB}}^{\text{IA}} \mathbf{H}_{ii}^{\text{eff}} \mathbf{F}_{i, \text{BB}}^{\text{IA}}) &= N_s. \end{aligned}$$

B. OMP-based Effective Channel Selection

As shown in [6], maximizing the objective function approximately leads to the minimization of $\|\mathbf{F}_{i, \text{opt}} - \mathbf{F}_{i, \text{RF}} \mathbf{F}_{i, \text{BB}}^{\text{OMP}}\|_F$ and $\|\mathbf{W}_{i, \text{opt}} - \mathbf{W}_{i, \text{RF}} \mathbf{W}_{i, \text{BB}}^{\text{OMP}}\|_F$, where $\mathbf{F}_{i, \text{RF}}$ and $\mathbf{W}_{i, \text{RF}}$ denotes the optimal fully-digital precoder and combiner respectively. The unconstrained optimal precoder and combiner can be obtained from the singular value decomposition (SVD) of the desired channel matrix. The problem is equivalent to a sparsity constrained matrix reconstruction problem, which can be solved by using an OMP algorithm [6].

C. IA-Based Interference Mitigation

Designing $\mathbf{F}_{i, \text{BB}}^{\text{IA}}$ and $\mathbf{W}_{i, \text{BB}}^{\text{IA}}$ based on the concept of IA is presented in this subsection. In this paper, we will focus on Max-SINR algorithm which achieves a better performance than other IA algorithms. Note that Max-SINR iteratively optimizes the receiver beamforming vectors in terms of receiver SINR [12]. The SINR of the l -th stream of the i -th receiver over the effective channel $\mathbf{H}_{ii}^{\text{eff}}$ is

$$\text{SINR}_i^{(l)} = \frac{|\mathbf{W}_{i, \text{BB}}^{\text{IA}}(l)^H \mathbf{H}_{ii}^{\text{eff}} \mathbf{F}_{i, \text{BB}}^{\text{IA}}(l)|^2 P_i}{\mathbf{W}_{i, \text{BB}}^{\text{IA}}(l)^H \mathbf{B}_i^{(l)} \mathbf{F}_{i, \text{BB}}^{\text{IA}}(l) N_s},$$

Where $\mathbf{F}_{i, \text{BB}}^{\text{IA}}(l)$ and $\mathbf{W}_{i, \text{BB}}^{\text{IA}}(l)$ are the l -th column of $\mathbf{F}_{i, \text{BB}}^{\text{IA}}$ and $\mathbf{W}_{i, \text{BB}}^{\text{IA}}$ respectively. Also, $\mathbf{B}_i^{(l)}$ is interference plus noise covariance matrix expressed as

$$\begin{aligned} \mathbf{B}_i^{(l)} &= \sum_{j=1}^K \frac{P_j}{N_s} \sum_{l=1}^{N_s} \mathbf{H}_{ij}^{\text{eff}} \mathbf{F}_{j, \text{BB}}^{\text{IA}}(l) \mathbf{F}_{j, \text{BB}}^{\text{IA}}(l)^H \mathbf{H}_{ij}^{\text{eff}H} \\ &\quad - \frac{P_i}{N_s} \mathbf{H}_{ii}^{\text{eff}} \mathbf{F}_{i, \text{BB}}^{\text{IA}}(l) \mathbf{F}_{i, \text{BB}}^{\text{IA}}(l)^H \mathbf{H}_{ii}^{\text{eff}H} + \mathbf{I}_{N_t^{\text{IA}}}. \end{aligned}$$

For the given matrix $\mathbf{F}_{i, \text{BB}}^{\text{IA}}$, the unit vector $\mathbf{W}_{i, \text{BB}}^{\text{IA}}(l)$ that maximizes $\text{SINR}_i^{(l)}$ is

$$\mathbf{W}_{i, \text{BB}}^{\text{IA}}(l) = \frac{(\mathbf{B}_i^{(l)})^{-1} \mathbf{H}_{ij}^{\text{eff}} \mathbf{F}_{i, \text{BB}}^{\text{IA}}(l)}{\|(\mathbf{B}_i^{(l)})^{-1} \mathbf{H}_{ij}^{\text{eff}} \mathbf{F}_{i, \text{BB}}^{\text{IA}}(l)\|}.$$

In the reciprocal network, the computed $\mathbf{W}_{i, \text{BB}}^{\text{IA}}$ is chosen to use as a precoder. As a result, we obtain $\mathbf{F}_{i, \text{BB}}^{\text{IA}}$ and $\mathbf{W}_{i, \text{BB}}^{\text{IA}}$ iteratively until they converge or the number of iterations reaches a pre-specified limit.

IV. NUMERICAL RESULTS

In this section, we demonstrate simulation results to evaluate the performance of our proposed hybrid beamforming design. The performance is measured in terms of sum rate of users over interference channel. We consider a symmetric interference with $K = 3$. We assume each node uses the same power as $P_i = P$, $i = 1, 2, 3$ for simplicity. Then, SNR is given as $\frac{P}{\sigma^2}$. We consider the geometric channel model where the generated channel has 10 limited scatters with uniformly random angle of arrival and departure [11].

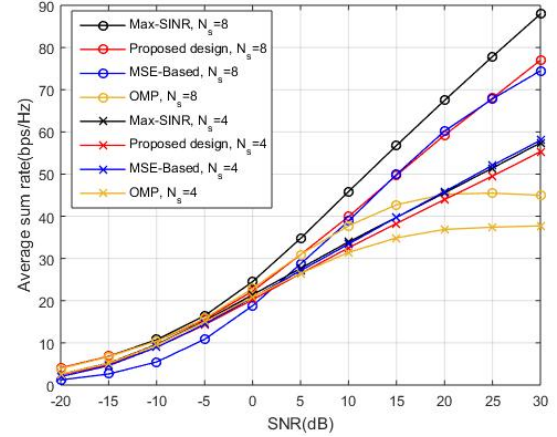


Figure 2. Comparison of average sum rate versus SNR for 32×32 mmWave system with linear arrays at each transmitter and receiver pair. Where $N_t^{\text{RF}} = N_r^{\text{RF}} = 16$ and $N_t^{\text{IA}} = N_r^{\text{IA}} = 16$

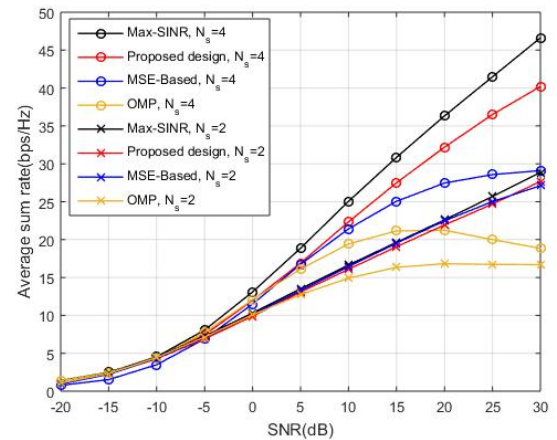


Figure 3. Comparison of average sum rate versus SNR for 16×16 mmWave system with linear arrays at each transmitter and receiver pair. Where $N_t^{\text{RF}} = N_r^{\text{RF}} = 8$ and $N_t^{\text{IA}} = N_r^{\text{IA}} = 8$

Figs. 2 and 3 show the average sum rate for 4 different schemes with respect to SNR. In low SNR region, the DOF of OMP algorithm is preserved since each transmitter sends a signal by forming a narrow beam towards each desired receiver. However, the sum rate of OMP algorithm becomes saturated as SNR increases since the interference is the dominant factor to the performance. For finite resolution of phase shifter, hybrid beamforming matrix calculated by OMP algorithm over Max-SINR algorithm cannot be the same as the fully-digital

beamforming matrix and interference from other nodes still remain at high SNR region. As shown in Fig. 2, the performance between proposed hybrid beamforming design and MSE-based algorithm is almost the same at high SNR. However, the performance gain of MSE-Based algorithm described in [10], [13] is saturated which is described in Fig. 3. On the contrary, the proposed hybrid beamforming design not only preserves the DOF and but also improves the sum rate by mitigating the interference in SNR region. In contrast to the main purpose of the MSE-based hybrid beamforming design that approximates the hybrid beamforming matrix to the fully-digital beamforming matrix, the main purpose of our proposed design is to eliminate the interference from other users perfectly. The interference mitigation process of the proposed design is performed only with digital beamforming at baseband, the proposed hybrid beamforming design is not a sparse approximation problem. Thus, the proposed hybrid beamforming design always preserves the DOF without saturation.

V. CONCLUSIONS

In this paper, we proposed a hybrid beamforming design based on OMP and IA for hybrid beamforming system over MIMO interference channel. To eliminate the interference from other nodes perfectly, we add an additional baseband precoder/combiner. The proposed algorithm is designed to simultaneously maximize the rate over the desired channel and minimize the leakage of interference signals while using only local CSI. Thus, the proposed hybrid beamforming design enhances the sum rate with reduced overhead in SNR region where the interference is the dominant contributor to the performance by maintaining the DOF, as shown in the simulation results.

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Ji-Ho Lee (S'15) received the B.S. and M.S. degrees in electrical engineering from Korea University, Seoul, Korea, in 2014 and 2016, respectively. He is currently working toward the Ph.D. degree in the School of Electrical Engineering at Korea University. His current research interests include hybrid beamforming system, interference mitigation techniques.



Myeong-Jin Kim (S'13-M'16) received the B.S., M.S., and Ph.D. degrees in electrical engineering from Korea University, Seoul, Korea, in 2010, 2012 and 2016, respectively. Since March 2016, he has been with the Advanced Communication Technology Laboratory, LG Electronics, Seoul, Korea as a Senior Research Engineer. His research interests include communication theory and signal processing techniques for wireless cellular networks.



Young-Chai Ko (S'97-M'01-SM'06) received the B.Sc. degree in electrical and telecommunication engineering from the Hanyang University, Seoul, Korea, and the M.S.E.E. degree and the Ph.D. degree in electrical engineering from the University of Minnesota, Minneapolis, in 1999 and 2001, respectively. In March 2001, he joined Texas Instruments, Inc., San Diego Wireless Center, San Diego, CA, where he worked on WCDMA MODEM system design. Since March 2004, he has been with School of Electrical Engineering at Korea University, Seoul, Korea, where he is currently a full Professor. His research focus is on the performance analysis and the design of wireless communication systems in the physical layer.