Analog Zero-Forcing Combining in mmWave Massive-MIMO Systems

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***Abstract*—Large-scale antenna arrays are used to acquire high array gain in millimeter-wave (mmWave) massive multiple-input multiple-output (MIMO) communication systems. With hybrid precoding, the inter-user interference could be suppressed by the base station (BS). But for receivers, interference comes not only from the serving BS, but also from neighboring BSs and other device-to-device users. Although more antennas could be integrated into the receiving device with mmWave, usually only one radio frequency (RF) chain is employed due to the limitation of complexity and power consumption. This restriction forces the receivers that can only use analog combiner to improve signal power and eliminate interference. In this paper, an analog combining method is proposed, where the interference is forced to zero by a geometric construction algorithm. We shift the phases of each element of the interference channel vector, and construct a polygon with these elements as sides. From many construction possibilities, we choose a set of phase shifts that improve the beam gain greatly. This analog zero-forcing method is then extended to eliminate multiple interferences by layered construction strategy. Simulation results show that the proposed method greatly outperforms other analog processing methods, especially in scenarios with strong interference and high channel correlation.**

I. Introduction

Millimeter wave (mmWave) spectrum can potentially provide the bandwidth required for future mobile broadband applications [1], and has been considered as a key technology in the fifth generation (5G) mobile communication systems [2]. MmWave offers higher throughput with its rich spectrum resource, and makes it easier to integrate antennas because of its tiny wavelength. However, suffering severe penetration loss and rain fading [3], the signal has poor scattering and diffraction abilities. Large-scale antenna arrays will be equipped at BS to compensate the severe path loss with large array gains [4], [5].

For mmWave system with large-scale antenna arrays, full-digital processing (precoding or detection) brings inhibited complexity and power consumption. Thus hybrid precoding, working with less RF chains at the transmitter, are generally considered at the base stations (BSs) [6]–[8]. At the mobile terminals, especially the cell phones, usually only one RF chain is allowed. However, the receiving ends confront more complicated interference environments, such as the inter-user interference from the same serving BS, the inter-cell interference from neighboring BSs, and variable interference from device-to-device (D2D) users. With only one RF chain, the interference suppression capability must be achieved by the analog combiners, where the combining element has constant envelop (CE) and we can only operate its phase shift.

The optimal solution of CE combining is hard to obtain due to its nonlinear property [9]. In previous researches, the gradient descent method, the cross-entropy optimization method and the Riemannian manifold based method can only find local optimal solutions [10]–[12], and these optimization based methods have high implementation complexity. In [13], a geometric perspective is proposed and the inteference is suppressed by shifting the phases of the channel elements and constructing a triangle with those summed elements as sides. But the method might lose receiving gain and sacrifice data rate seriously. In practice, beamsteering is still widely used, where all directions are searched to find an angle with the highest gain. However, beamsteering only performs well in scenarios with one dominant path, it will become helpless under strong interferences.

In this paper, an analog zero-forcing (ZF) scheme is proposed, which can be implemented with only phase shifters. The interference is forced to zero by a geometric construction algorithm. We construct a polygon with interference channel vector elements by phase shifting. Then choose a solution that improve the expected signal gain greatly from many construction possibilities. This method have significantly improved the data rate performance of analog combining methods, even under strong interference. Then we designed a layered construction strategy to extend the analog ZF method to accommodate multiple interferences. The algorithm has low complexity, and approaches the digital ZF scheme with increasing number of antennas.

The rest of this paper is organized as follows. Section II introduces the system model. Section III proposes the analog ZF method. Simulation results and discussions of data rate on signal to noise ratio (SNR), antenna number, channel correlation and interference strength are presented in Section IV, and conclusions are given in Section V.

II. System Model

Consider a system where a BS equipped with N_t antennas communicates with a receiver equipped with N_r antennas, and one data stream is considered.

Then signal is received as

$$\boldsymbol{r} = \boldsymbol{H}\boldsymbol{f}s + \boldsymbol{n}, \tag{1}$$

where s is the data symbol and $\boldsymbol{f}$ is the $N_\mathrm{t}\times 1$ precoding vector at BS. $\boldsymbol{H}$ is the $N_\mathrm{r} \times N_\mathrm{t}$ matrix that represents the mmWave channel between BS and the user, and $\boldsymbol{n}$ is the Guassian noise vector with zero mean and covariance matrix $\sigma^2\boldsymbol{I}$.

Actually, what we really care about is the arriving signal $\boldsymbol{r}$. No matter what $\boldsymbol{f}$ and $\boldsymbol{H}$ are, their product is equivalent to an $N_\mathrm{r}\times 1$ channel vector $\boldsymbol{h}$, i.e.,

$$\boldsymbol{r}=\boldsymbol{h}s+\boldsymbol{n}. \tag{2}$$

With N_r antennas, the receiver calculates $\boldsymbol{w}\in\mathbb{C}^{N_\mathrm{r}\times 1}$ to produce the scalar decision statistic

$$y=\boldsymbol{w}^H\boldsymbol{r}=\boldsymbol{w}^H\boldsymbol{h}s+\boldsymbol{w}^H\boldsymbol{n}. \tag{3}$$

With just one RF chain, the receiver implements $\boldsymbol{w}$ via a network of analog phase shifters [7], bringing the constraint of constant envelope amplitude: $w_k=\frac{1}{\sqrt{N_\mathrm{r}}}e^{j\phi_k}$, where ϕ_k is the phase of the k-th element in the combining vector, and $\frac{1}{\sqrt{N_\mathrm{r}}}$ is for power normalization.

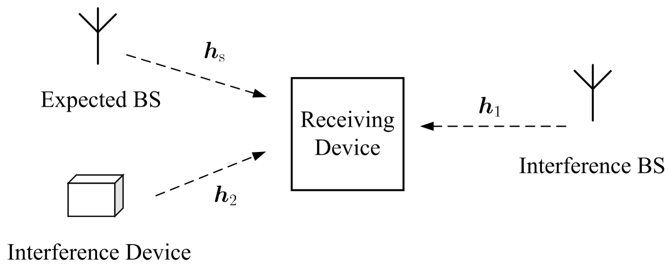


Fig. 1: A user with an expected signal and two interference signals.

As is shown from the example in Fig. 1, the received signal, including the expected signal and interference from N devices, can be expressed as

$$\begin{aligned}y&=y_\mathrm{s}+\sum_{k=1}^{N}y_k+n\\&=\boldsymbol{w}^H\boldsymbol{h}_\mathrm{s}s_\mathrm{s}+\sum_{k=1}^{N}\boldsymbol{w}^H\boldsymbol{h}_k s_k+\boldsymbol{w}^H\boldsymbol{n},\end{aligned} \tag{4}$$

where s_s and $\boldsymbol{h}_\mathrm{s}$ are the expected data symbol and equivalent channel response, respectively, and s_k and $\boldsymbol{h}_k$ are those of interference.

Thus the achievable rate for this user is calculated by [7]

$$R=\log_2\left(1+\frac{P_\mathrm{s}|\boldsymbol{w}^H\boldsymbol{h}_\mathrm{s}|^2}{\sum_{k=1}^{N}P_k|\boldsymbol{w}^H\boldsymbol{h}_k|^2+\sigma^2}\right). \tag{5}$$

As is shown in Fig. 1, the interference might come from the serving BS, neighboring BSs or other D2D users. Since the designs of precoding in transmitter and combining in receiver are dual, the proposed method also applies to precoding for the D2D user with only one transmit RF chain.

III. Analog Zero-Forcing Method

Analog ZF method is proposed in this part, which is a design that taking into account the maximization of signal power and the elimination of various interference simultaneously. We will first discuss the specific schemes for the scenarios with one interference and two interferences, and generalize the method into scenarios with N interferences afterwards.

A. One-Interference Scenario

For a single user, the received signal including an expected signal and an interference can be expressed as

$$y=\boldsymbol{w}^H\boldsymbol{h}_\mathrm{s}s_\mathrm{s}+\boldsymbol{w}^H\boldsymbol{h}s+\boldsymbol{w}^H\boldsymbol{n}. \tag{6}$$

The optimization objective and constraints of the receiving vector are

$$\begin{aligned}&\max_{\boldsymbol{w}}|\boldsymbol{w}^H\boldsymbol{h}_\mathrm{s}|\\&\text{s.t. } |w_k|=\frac{1}{\sqrt{N_\mathrm{r}}},0<k\leqslant N_\mathrm{r},\\&\quad \boldsymbol{w}^H\boldsymbol{h}=0.\end{aligned} \tag{7}$$

We first focus on a simplified scenario without interference

$$\begin{aligned}&\max_{\boldsymbol{w}}|\boldsymbol{w}^H\boldsymbol{h}_\mathrm{s}|\\&\text{s.t. } |w_k|=\frac{1}{\sqrt{N_\mathrm{r}}},0<k\leqslant N_\mathrm{r}.\end{aligned} \tag{8}$$

The global optimal solution is easy to obtain, which is similar to the maximal ratio combining (MRC) method. Channel response elements correspond to vectors in a complex plane. The received power of the expected signal can be maximized if we take the phases of channel response elements to generate the combining matrix, which means in-phase superposition of channel elements, i.e.,

$$\begin{aligned}w_{\mathrm{MRC},k}&=\frac{1}{\sqrt{N_\mathrm{r}}}e^{-j\cdot\arg(h_{\mathrm{s},k})},0<k\leqslant N_\mathrm{r},\\\boldsymbol{w}_\mathrm{MRC}&=[w_{\mathrm{MRC},1},w_{\mathrm{MRC},2},...,w_{\mathrm{MRC},N_\mathrm{r}}]^T,\end{aligned} \tag{9}$$

where $h_{\mathrm{s},k}$ is the k-th element of the channel response between the expected BS and the user, $\boldsymbol{w}_\mathrm{MRC}$ is the analog MRC response, and $\arg(\cdot)$ is to take phase.

Reasonably, there is no correlation between the interference channel and expected channel in a scenario where interference sources distribute randomly. So with $\boldsymbol{w}_\mathrm{MRC}$, the expected signal gets maximal beam gain, and the interference elements are just superimposed in random phases, as shown in Fig. 2.

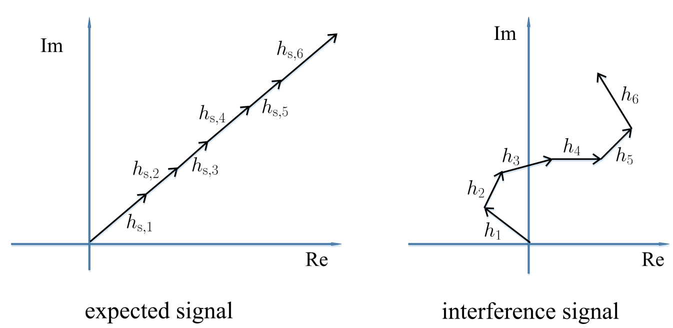


Fig. 2: The expected signal and interference signal after analog MRC.

Then we consider how to suppress the interference. Given the interference channel response $\boldsymbol{h}=[h_1,h_2,...,h_{N_\mathrm{r}}]^T$, they can form a polygon when the length of each element is shorter than the sum length of others, i.e.,

$$\forall k,\ |h_k|<\sum_{n\neq k}|h_n|. \tag{10}$$

We choose proper phase shifts $\boldsymbol{w} = [w_1, w_2, ..., w_{N_\mathrm{r}}]^T$ for $\boldsymbol{h}$ to make an end-to-end connection. The method is shown in Fig. 3. The combiner design with the constant envelop constraint is transformed into a geometric problem

$$\boldsymbol{w}^H \boldsymbol{h} = \sum_{k=1}^{N_\mathrm{r}} w_k h_k = 0. \tag{11}$$

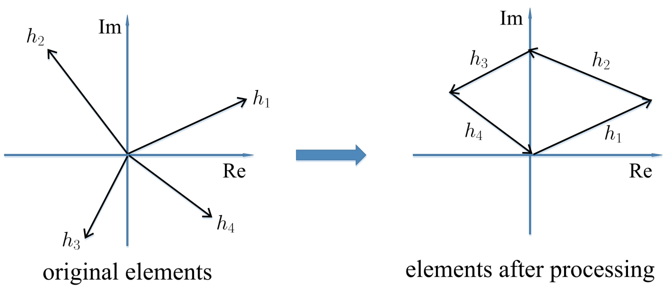


Fig. 3: The combining method for interference elimination.

Given channel vectors, the polygon can be formed in many ways. As is shown in Fig 4, a method to construct a triangle, called Geometric Constant Envelop Precoding (GCEP), is proposed in [13], and the algorithm is presented in Algorithm 1.

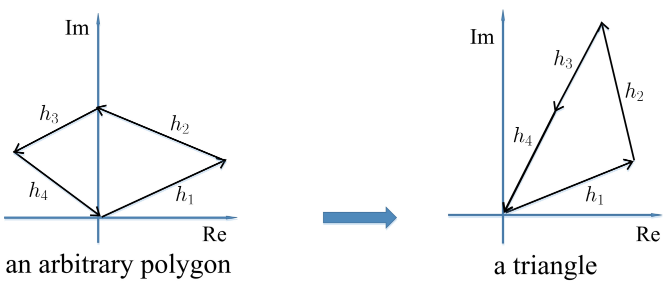


Fig. 4: A method to construct a triangle.

Algorithm 1 Geometric Constant Envelop Precoding (GCEP)

1: List channel response elements in a descending order of their modulus, $p(\cdot)$ is the mapping relation, $|h_{p(1)}| \geqslant |h_{p(2)}| \geqslant ... \geqslant |h_{p(N_\mathrm{r})}|$.

2: Initialize variables: $l_1 = 0, l_2 = \sum_{k=2}^{N_\mathrm{r}} |h_{p(k)}|, \gamma_k = \arg(h_{p(k)})$.

3: If $|h_{p(1)}| > l_2$, no solution, return.

4: Find a minimum n that $|l_1 - l_2| \leqslant |h_{p(1)}|$, where $l_1 = \sum_{k=2}^{n} |h_{p(k)}|$ and $l_2 = \sum_{k=n+1}^{N_\mathrm{r}} |h_{p(k)}|$.

5: Phase calculation:
$\beta = \arccos\frac{l_1^2+|h_{p(1)}|^2-l_2^2}{2l_1|h_{p(1)}|}$, $\alpha = \arccos\frac{l_2^2+|h_{p(1)}|^2-l_1^2}{2l_2|h_{p(1)}|}$
$\phi_1 = -\gamma_1$;
$\phi_k = -\gamma_k - \pi + \beta, (k = 2, 3, ..., n)$;
$\phi_k = -\gamma_k + \pi - \alpha, (k = n+1, n+2, ..., N_r)$.

6: Combining matrix: $w_{p(k)} = \frac{1}{\sqrt{N_\mathrm{r}}} e^{j\phi_k}$.

In the GCEP algorithm, the largest element is selected out and is taken as one side of the triangle with zero phase shift in Step 1, which supports the triangle formation with the most possibility. In Step 4, another two sides are formed through an iterative searching. Phase shifts are calculated through Cosine Theorem in Step 5.

Although GCEP can eliminate interference completely, it may lose beam gain seriously since there is no mechanism to preserve the signal power. To keep an eye on the signal power, we propose a new combiner design method called analog ZF. When constructing the polygon for interference channel, we leave as many elements as possible to make in-phase superposition of the expected channel. Thus the power of the expected signal is improved in parallel with the interference elimination procedure.

One construction example is shown in Fig. 5. In this example, the elements of interference channel h_1, h_2, h_3, h_4 keep phase shifts as in analog MRC, which means the in-phase superposition of the expected channel elements $h_{\mathrm{s},1}, h_{\mathrm{s},2}, h_{\mathrm{s},3}, h_{\mathrm{s},4}$. The combined effect of h_1, h_2, h_3, h_4 is $\overline{h}$, and the phase shifted $\overline{h}, h_5, h_6$ form a triangle to eliminate the interference. In scenarios with massive antennas, most of the phase shifts can be kept as in analog MRC, usually only several phase shifts are specially designed to construct the polygon for interference channel, like the roles of h_5, h_6 in Fig. 5. The sacrifice of beam gain is minimized.

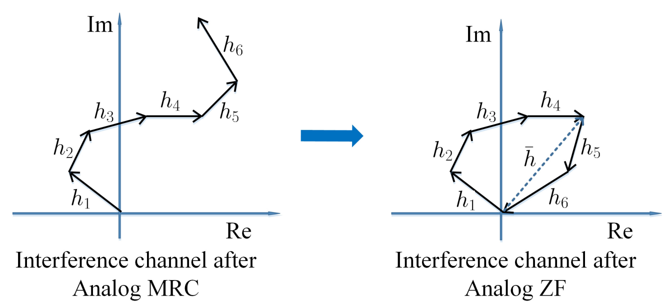


Fig. 5: The interference channel after analog ZF combining.

The complete procedure of the proposed analog ZF algorithm is given in Algorithm 2. First, Step 1 is to obtain analog MRC matrix. In Step 2, the elements of interference channel response are sorted in ascending order to leave as many elements as possible in l_2. Step 4 is to look for the maximum number of elements that can combine in MRC principle. The equivalent interference channels are acquired in Step 5. The first n elements are combined to one, which together with other $(N_\mathrm{r} - n)$ elements contribute zero to the final decision. The algorithm only involves linear searching, and thus has low implementation complexity.

B. Two-Interference Scenario

In this case, the received signal consists of one expected signal and two interferences,

$$y = \boldsymbol{w}^H \boldsymbol{h}_\mathrm{s} s_\mathrm{s} + \boldsymbol{w}^H \boldsymbol{h}_1 s_1 + \boldsymbol{w}^H \boldsymbol{h}_2 s_2 + \boldsymbol{w}^H \boldsymbol{n}. \tag{12}$$

The objectives are to eliminate interference and to maximize the expected power. The difficulty is to eliminate two

Algorithm 2 Analog ZF for one-interference scenario

1: Analog MRC for $\boldsymbol{h}_{\text{s}}$: $\boldsymbol{w}_{\text{MRC}} = [w_{\text{MRC},1}, ..., w_{\text{MRC},N_{\text{r}}}]^T$.
2: List interference channel elements in an ascending order of modulus, $p(\cdot)$ is the mapping relation:
$|h_{p(1)}| \leqslant |h_{p(2)}| \leqslant ... \leqslant |h_{p(N_{\text{r}})}|$.
3: Initialize variables: $l_1 = 0, l_2 = \sum_{k=1}^{N_{\text{r}}} w_{\text{MRC},p(k)}^H h_{p(k)}$.
4: Find a maximum n that $|l_1| \geqslant |l_2|$.
$l_1 = \sum_{k=n+1}^{N_{\text{r}}} |h_{p(k)}|$, $l_2 = \sum_{k=1}^{n} w_{\text{MRC},p(k)}^H h_{p(k)}$.
5: Equivalent channel:
$\overline{h}_1 = \sum_{k=1}^{n} w_{\text{MRC},p(k)}^H h_{p(k)}$,
$\overline{h}_m = h_{p(m+n)}, m = 2, ..., N_{\text{r}} - n + 1$.
6: Apply GCEP on $\overline{h}_1, ..., \overline{h}_{N_{\text{r}}-n+1}$, and obtain the combining elements $\overline{w}_1, \overline{w}_2, ..., \overline{w}_{N_{\text{r}}-n+1}$.
7: Analog ZF Method:
$w_{p(k)} = \sqrt{N_{\text{r}}}\overline{w}_1 w_{\text{MRC},p(k)}, k = 1, 2, ..., n$,
$w_{p(k)} = \sqrt{N_{\text{r}}}\overline{w}_{k-n+1}, k = n+1, ..., N_{\text{r}}$.

interferences simultaneously.

$$\begin{aligned} &\max_{\boldsymbol{w}} |\boldsymbol{w}^H \boldsymbol{h}_{\text{s}}| \\ &\text{s.t. } |w_k| = \frac{1}{\sqrt{N_{\text{r}}}}, 0 < k \leqslant N_{\text{r}}, \\ &\quad \boldsymbol{w}^H \boldsymbol{h}_1 = 0, \\ &\quad \boldsymbol{w}^H \boldsymbol{h}_2 = 0. \end{aligned} \tag{13}$$

In the geometric perspective, to satisfy the two constraints means that the two set of channel elements from $\boldsymbol{h}_1$ and $\boldsymbol{h}_2$ could form polygons simultaneously with the same phase shifting vector $\boldsymbol{w}$. We propose a layered construction strategy, where the interferences from different sources will be eliminated in different layers. The elements of each channel are divided into groups, promising that the number of groups and the number of elements in each group are both larger than three. In the first layer, the elements of $\boldsymbol{h}_1$ in each group form a different polygon after phase shifts, i.e., the equivalent group values for $\boldsymbol{h}_1$ are all zeros. In the second layer, the equivalent group values for $\boldsymbol{h}_2$ form another polygon after phase shifts, thus the interference from $\boldsymbol{h}_2$ is also eliminated. We see that in the second layer the elements in the same group share the same phase shift.

More concretely, assume that N_{r} elements are divided into G groups, and the g-th group contains M_{g} elements. The channel response of the k-th interference and the combiner in the first layer are respectively denoted as

$$\begin{aligned} \boldsymbol{h}_k &= [\boldsymbol{h}_{k,1}^T, ..., \boldsymbol{h}_{k,G}^T]^T \\ &= [h_{k,1,1}, ..., h_{k,1,M_1}, ..., h_{k,G,1}, ..., h_{k,G,M_{\text{g}}}]^T, \end{aligned} \tag{14}$$

$$\begin{aligned} \boldsymbol{w}_1 &= [\boldsymbol{w}_{1,1}^T, ..., \boldsymbol{w}_{1,G}^T]^T \\ &= [w_{1,1,1}, ...w_{1,1,M_1}, ..., w_{1,G,1}, ...w_{1,G,M_{\text{g}}}]^T. \end{aligned} \tag{15}$$

The interference of $\boldsymbol{h}_1$ is eliminated in the first layer, that in each group the elements of $\boldsymbol{h}_{1,g}$ form a polygon after corresponding phase shifts, i.e.,

$$\boldsymbol{w}_{1,g}^H \boldsymbol{h}_{1,g} = 0, \; g = 1, 2, ..., G. \tag{16}$$

For the interference of $\boldsymbol{h}_2$, with the first layer phase shifting vector $\boldsymbol{w}_{1,g}$, the elements of $\boldsymbol{h}_{2,g}$ are combined to get an equivalent group value

$$\overline{h}_{2,g} = \boldsymbol{w}_{1,g}^H \boldsymbol{h}_{2,g}, \; g = 1, 2, ..., G. \tag{17}$$

Then the polygon is constructed based on $\overline{h}_{2,g}$,

$$\sum_{g=1}^{G} w_{2,g} \overline{h}_{2,g} = 0, \tag{18}$$

where $w_{2,g}$ is the second layer phase shift for the g-th group.

Combined with these two layers, the final phase shifting vector is

$$\boldsymbol{w} = [w_{2,1}\boldsymbol{w}_{1,1}^T, ..., w_{2,G}\boldsymbol{w}_{1,G}^T]^T. \tag{19}$$

Algorithm 2 is applied in both layers to design the phase shifting vector. Moreover, as in the one-interference case, we still attempt to keep in-phase superposition of the elements in $\boldsymbol{h}_{\text{s}}$. Therefore, the grouping is uneven, that the group 1 contains the most possible elements to increase beam gain, and other groups contain the fewest possible elements to eliminate interference. Since the channel elements are random, three elements are not always enough to form a polygon. It is similar for the second layer, sometimes three groups are not enough. We use iterative searching to keep the group number minimum. The complete procedure is listed in Algorithm 3.

Algorithm 3 Analog ZF for two-interference scenario

1: Obtain analog MRC vector $\boldsymbol{w}_{\text{MRC},1}$ of $\boldsymbol{h}_{\text{s}}$.
2: Rank the first interference channel elements in ascending order, $p(\cdot)$ is the mapping relation:
$|h_{p(1)}| \leqslant |h_{p(2)}| \leqslant ... \leqslant |h_{p(N_r)}|$.
3: Initialize group number $G = 1$ and the rest element number $M_{\text{rest}} = N_{\text{r}}$.
4: **do:**
$G = G + 1$.
Search minimum M_G to satisfy:
$\sum_{k=M_{\text{rest}}-M_G+1}^{M_{\text{rest}}-1} |h_{p(k)}| \geqslant |h_{p(M_{\text{rest}})}|$.
Group G: $\boldsymbol{h}_{2,G} = [h_{p(M_{\text{rest}}-M_G+1)}, ..., h_{p(M_{\text{rest}})}]$.
Update Group 1: $\boldsymbol{h}_{2,1} = [h_{p(1)}, ..., h_{p(M_{\text{rest}}-M_G)}]$.
For group g, $g = 1, 2, ..., G$:
Calculate $\boldsymbol{w}_{1,g}$ by Algorithm 2.
Calculate equivalent channel: $\overline{h}_{2,g} = \boldsymbol{w}_{1,g}^H \boldsymbol{h}_{2,g}$.
Update rest element number $M_{\text{rest}} = M_{\text{rest}} - M_G$.
while: $\forall g, \sum_{k \neq g}^{G} |\overline{h}_{2,k}| \geqslant |\overline{h}_{2,g}|$.
5: Apply Algorithm 2 to $\overline{h}_{2,1}, ..., \overline{h}_{2,G}$ and obtain the combiner in the second layer: $w_{2,1}, ..., w_{2,G}$.
6: Calculate the whole $N_{\text{r}} \times 1$ analog combiner:
$\boldsymbol{w}_p = [w_{2,1}\boldsymbol{w}_{1,1}^T, w_{2,2}\boldsymbol{w}_{1,2}^T, ..., w_{2,G}\boldsymbol{w}_{1,G}^T]^T$.
7: Final combining vector $\boldsymbol{w}$ is obtained based on $p(k)$.

If three elements could form a triangle in both layers, 6 elements are involved in group 2 and 3. Then group 1 could contain $(N_{\text{r}} - 6)$ elements at most and $(N_{\text{r}} - 8)$ elements are used to make in-phase superposition. In massive MIMO system with more than 32 antennas, this scheme can actually grab the most part of the possible beam gain and keep interference nulling simultaneously.

C. N-Interference Scenario

In the N-interference scenario, we can use N layers to eliminate the interference. Firstly, we group the elements of each channel response into N layers and each layer has certain number of groups or elements. Each layer of the phase shift design will eliminate one interference, and the final combined phase shifting vector can remove all the interferences.

The complete algorithm is not listed here due to the limit of space. It is similar with Algorithm 3 but with more tedious details. Since the elements in each group should be no less than three, at least 3^N antennas should be equipped to control N interferences. Hence we can see that this algorithm is not appropriate for too many interferences.

IV. Simulation Results

In this part, the analog ZF scheme is compared with the full-digital and other analog combining methods. We will show the data rate of different methods along with SNR, number of antennas and interference strength. The compared methods are listed in Table 1.

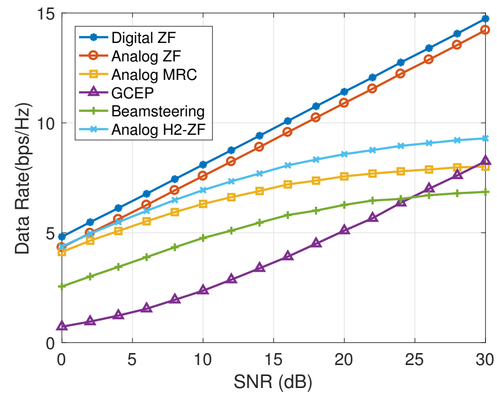
TABLE I: The Compared Methods

Order	Method
1	**Digital ZF:** Obtain the Moore-Penrose pseudo-inverse of channel matrix.
2	**Analog MRC:** Take phases of the expected channel to produce the combiner.
3	**GCEP:** Eliminate interference by geometric construction method.
4	**Beamsteeing:** Searching all rays to find an angle with the highest gain.
5	**Analog H2-ZF [14]:** Calculate the digital ZF combining matrix and take the corresponding phase of the expected vector.

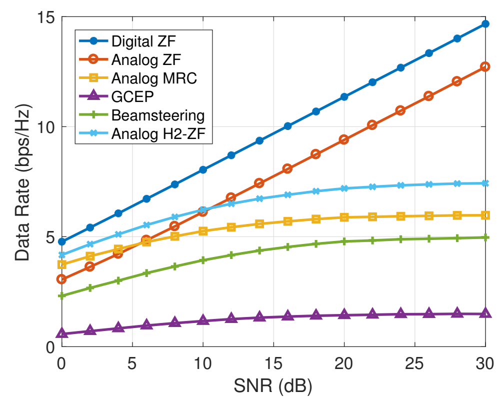
In our simulation, the interference sources distribute randomly in a radius between 100 m and 200 m. The antennas at the receiver stay as uniform linear array, and the distance between two array elements is half the wavelength. The carrier frequency is set as 28 GHz, and channel parameters are generated according to 3GPP TR 38.900 in UMa/LOS scene [15], where 12 clusters and 20 rays in each cluster are assumed.

A. The Effect of SNR

In this part, the receiver is equipped with 32 antennas. The data rates along with the increasing of SNR are shown in Fig. 6. Among the six schemes, only the data rates of digital ZF and analog ZF grow linearly with the increasing of SNR. The gap between them and other analog methods becomes larger when the SNR is high. The methods of analog H2-ZF, analog MRC and beamsteering are interference-limited, while the GCEP method loses a lot of beam gain. Compared with digital ZF method, the SNR loss of the analog ZF method is less than 2 dB with one interference and about 6 dB with two interferences. Given fixed antenna numbers, the proposed scheme performs worse with more interferences.



(a) one-interference scenario



(b) two-interference scenario

Fig. 6: Data rate with the increasing of SNR.

B. The Effect of Receiving Antenna Number

The effect of receiving antenna number is shown in Fig. 7, where the SNR in each antenna is 20 dB, and the number of antennas increases from 16 and grows with the integer power of 2. We can see that the analog ZF performs better than other analog methods. With the increasing number of receiving antennas, the gap between the analog ZF and digital ZF gradually shrinks. Given certain interferences, the number of antennas used to eliminate interference is almost fixed. Thus with the increase of antenna number, more antennas could be used to improve the signal power.

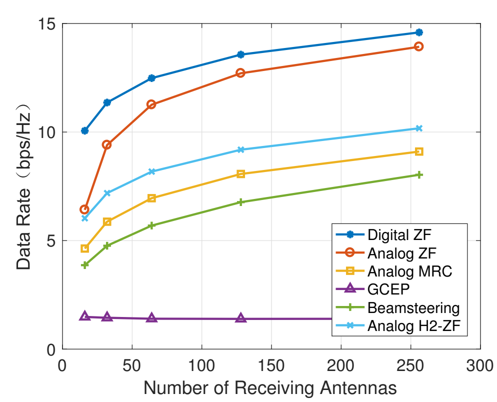


Fig. 7: Data rate with increasing number of antennas in two-interference scenario.

C. The Effect of Channel Correlation

In this part of simulation, N_r is 32 and SNR in each antenna is 20 dB. One-interference scenario is considered, and the separation angle between the signal and interference is increased from 0 to 180 degrees. The channel correlation is maximized when the directions of signal and interference are aligned, i.e., the separation angle is 0 or 180 degrees. The data rate results are shown in Fig. 8. We can see that, when the channel correlation increases, the analog ZF scheme performs closely after the digital ZF scheme, and is robust to the strong correlation.

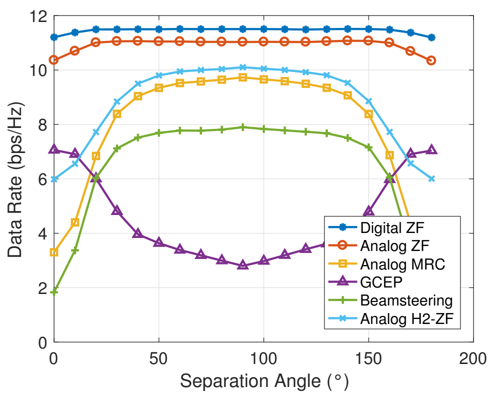


Fig. 8: Data rate with the increasing of separation angle between the signal and interference.

D. The Effect of Interference Power

In this part of simulation, we still set N_r is 32 and SNR in each antenna is 20 dB. The interference to noise power ratio (INR) ranges from 10 dB to 50 dB. The results are shown in Fig. 9. With the increasing of interference power, the data rates of analog H2-ZF, analog MRC, beamsteering and GCEP decrease seriously, while that of analog ZF keeps invariant, as well as the digital ZF scheme. Thus the analog ZF scheme is very promising in the scenario of strong interference.

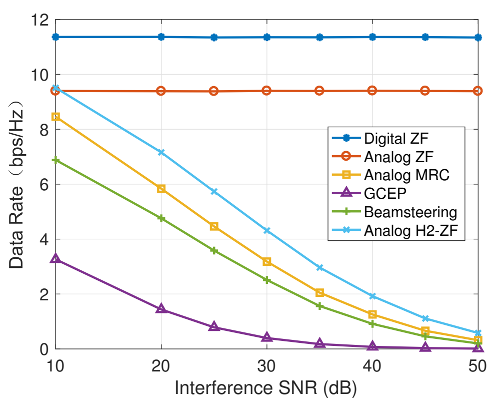


Fig. 9: Data rate with the increasing of interference power in two-interference scenario.

V. Conclusion

In this paper, an analog ZF combining method is proposed, which considers both the interference suppression and signal power maximization. The interference is mitigated by rotating interference channel elements to construct a polygon. From many possibilities of polygon construction solution, we propose an algorithm to improve the beam gain of expected signal greatly. The method can simultaneously suppress two interferences through layered construction strategy, and can be generalized into scenarios with more interferences. Simulation results show that our proposed method is better than other existing analog combiners and has a close performance to digital ZF. Besides, it is robust to strong channel correlation and high interference power. This method is also applicable in precoding design for the transmitter with only one RF chain.

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