Analog Beamformer Design for Interference Exploitation based Hybrid Beamforming

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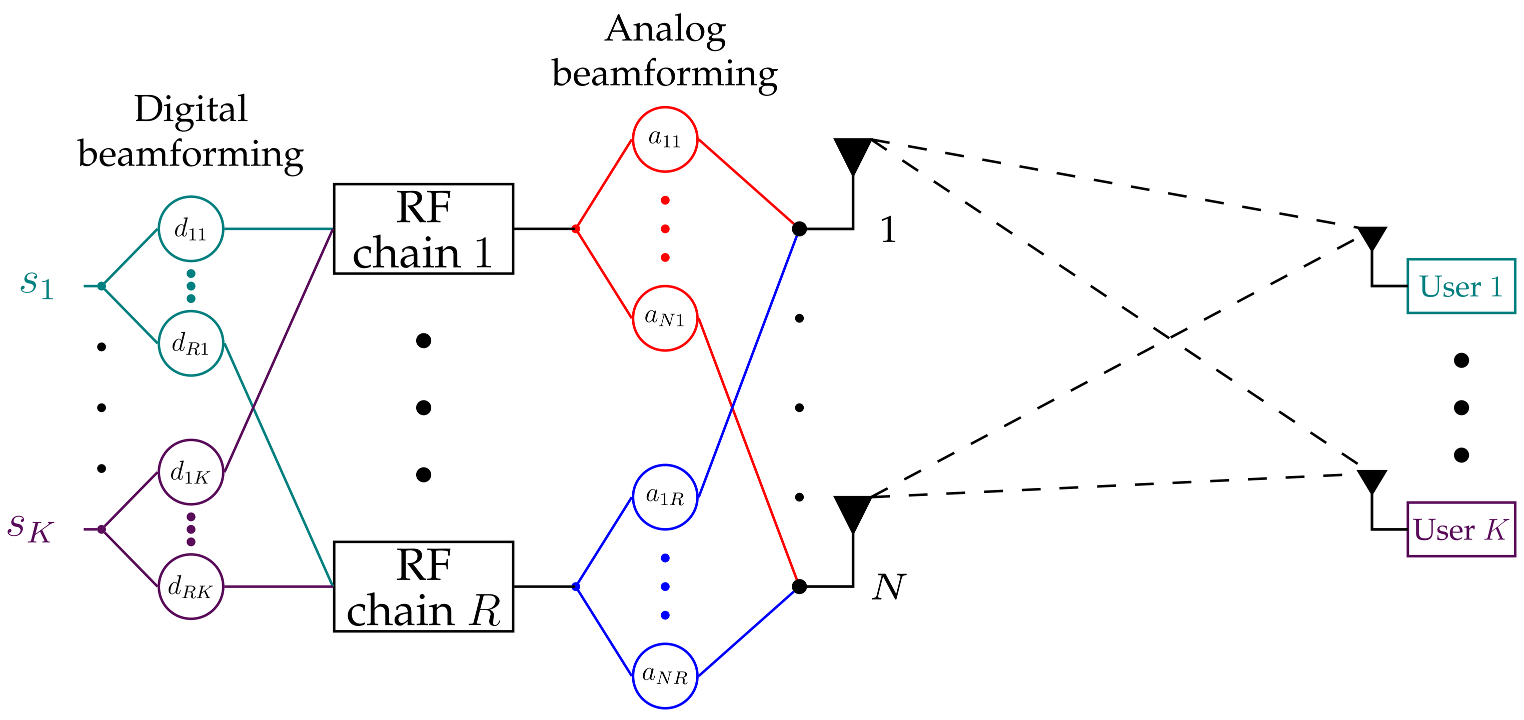
1 Motivation

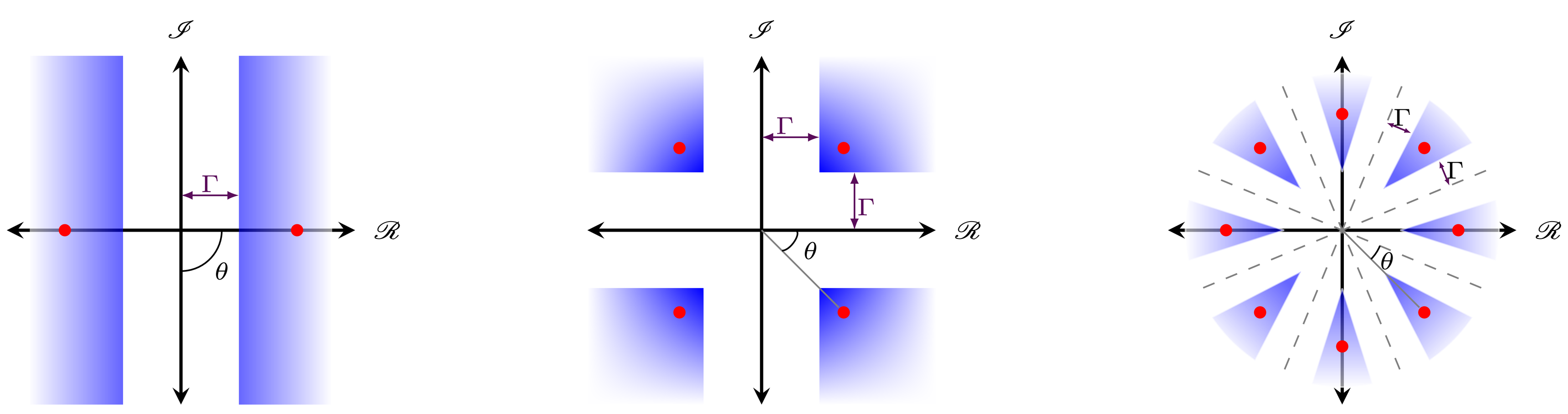
- Massive MIMO with the conventional fully-digital beamforming:
  - Extremely high hardware cost
  - Unwieldy operational power
- Hybrid beamforming with the conventional SINR maximization approach:
  - Reduced control over interference ⇒ increased transmit power
- **Proposed solution:** Massive MIMO system comprising the following features:
  - Hybrid analog-digital beamforming
  - Symbol-level beamforming
  - Interference exploitation using constructive interference (CI) phenomena

2 System Model



- Co-channel multi-user downlink system with K single antenna users
- Each users has a maximum allowable symbol-error-rate (SER) requirement
- Base station (BS) equipped with N antennas and R RF chains, where $R \leq N$
- Transmit symbols belong to M-PSK constellation, with $s_k = e^{j\phi_k}$
- The digital beamformer (DBF) $\mathbf{d}_k$ applied to transmit symbol s_k
- Analog beamformers (ABF) $\mathbf{a}_r$ are chosen from a predefined codebook $\mathcal{C} = \{\mathbf{c}_1, \ldots, \mathbf{c}_L\}$, where $L \geq R$. ABF matrix $\mathbf{A} = [\mathbf{a}_1, \ldots, \mathbf{a}_R]$
- The channel vector of the kth user $\tilde{\mathbf{h}}_k$ is known at the BS
- The received signal y_k at the kth user is given by: $y_k = \tilde{\mathbf{h}}_k^\top \mathbf{A} \sum_{i=1}^K \mathbf{d}_i s_i + n_k$

3 CI-based Hybrid Beamforming



(a) BPSK (b) QPSK (c) 8-PSK

- *Desired-region:* Complex space that is a threshold-margin Γ away from the corresponding decision boundaries
- CI-based beamforming enforces the received signals to the desired-regions of the corresponding transmit symbols
- Determine the threshold-margin Γ_k that ensure the SER requirement of the kth user
- CI-based joint analog-digital beamforming problem (nonconvex):

$$\underset{\mathbf{A},\, \{\mathbf{d}_k\}_{k\in\mathcal{K}}}{\text{minimize}} \left\| \mathbf{A} \sum_{i=1}^{K} \mathbf{d}_i s_i \right\|^2 \quad (1a)$$

$$\text{subject to} \left| \text{Im}\left(s_k^* \tilde{\mathbf{h}}_k^\top \mathbf{A} \sum_{i=1}^{K} \mathbf{d}_i s_i \right) \right| \leq \left(\text{Re}\left(s_k^* \tilde{\mathbf{h}}_k^\top \mathbf{A} \sum_{i=1}^{K} \mathbf{d}_i s_i \right) - \gamma_k \right) \tan\theta, \quad \forall k \in \mathcal{K} \quad (1b)$$

$$\mathbf{a}_r \in \mathcal{C}, \quad \forall r \in \mathcal{R} \quad (1c)$$

where • $\gamma_k = \Gamma_k / \sin(\theta)$ • $\theta = \pi/M$

- Equivalent single-group multicast problem (nonconvex):

$$\underset{\mathbf{A},\, \mathbf{b}}{\text{minimize}} \ ||\mathbf{A}\mathbf{b}||^2 \quad (2a)$$

$$\text{subject to} \left| \text{Im}\left(\mathbf{h}_k^\top \mathbf{A}\mathbf{b} \right) \right| - \left(\text{Re}\left(\mathbf{h}_k^\top \mathbf{A}\mathbf{b} \right) - \gamma_k \right) \tan\theta \leq 0, \quad \forall k \in \mathcal{K} \quad (2b)$$

$$\mathbf{a}_r \in \mathcal{C}, \quad \forall r \in \mathcal{R} \quad (2c)$$

where • The effective channel $\mathbf{h}_k = \tilde{\mathbf{h}}_k s_k^*$ • The digital beamformer $\mathbf{d}_k = \frac{\mathbf{b}}{K} s_k^*$

- The problem is combinatorial and needs exhaustive search over the codebook $\mathcal{C}$ to obtain the optimal solution

4 Proposed Suboptimal Solution

- Decompose the problem into two parts: ABF design and DBF design
  1. **ABF design:** Select ABFs from the predefined codebook, employing the proposed methods
  2. **DBF design:** For the fixed ABF matrix $\mathbf{A}$, design the optimal DBFs by solving problem (2) (convex quadratic problem)

5 Analog Beamformers Design Techniques

Method 1: Margin widening and selection operator (MWASO)

- Define ABF codebook matrix $\mathbf{C} = [\mathbf{c}_1, \ldots, \mathbf{c}_L] \in \mathbb{C}^{N \times L}$
- Solve the convex problem

$$\underset{\bar{\mathbf{b}}\in\mathbb{C}^L,\, \delta\in\mathbb{R}}{\text{minimize}} \ \epsilon \left|\left| \bar{\mathbf{b}} \right|\right|_1 + \delta \quad (3a)$$

$$\text{subject to} \ \left| \text{Im}\left(\mathbf{h}_k^\top \mathbf{C}\bar{\mathbf{b}} \right) \right| - \left(\text{Re}\left(\mathbf{h}_k^\top \mathbf{C}\bar{\mathbf{b}} \right) - (\gamma_k - \delta) \right) \tan\theta \leq 0, \quad \forall k \in \mathcal{K} \quad (3b)$$

- The ℓ_1-norm term $||\bar{\mathbf{b}}||_1$ promotes sparsity over vector $\bar{\mathbf{b}}$
- δ controls the margin between received signals and corresponding decision boundaries
- The optimization variable δ also facilitates achieving any desired sparsity on vector $\bar{\mathbf{b}}$ by relaxing threshold-margin constraint
- Columns of matrix $\mathbf{C}$ corresponding to the non-zero elements of $\bar{\mathbf{b}}$ form the ABF matrix
- ABFs dependent on transmit symbols ⇒ need to be reselected at every time-slot

Method 2: Best matching code selection (BMCS) method

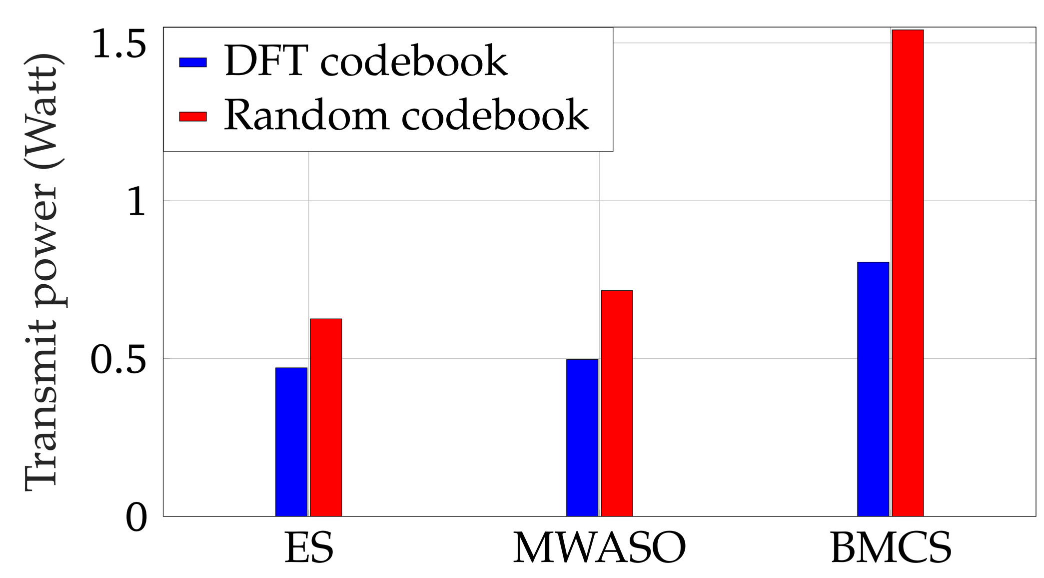
- For each user, select an ABF from the codebook $\mathcal{C}$ that maximizes the absolute value of inner product with its channel vector (array gain)

1: Initialization: $\bar{\mathcal{C}} = \mathcal{C}$
2: **for** $k = 1 : K$ **do**
3: $\quad \mathbf{a}_k = \underset{\mathbf{c}\in\bar{\mathcal{C}}}{\text{argmax}} \left| \mathbf{c}^\top \tilde{\mathbf{h}}_k \right|$
4: $\quad \bar{\mathcal{C}} \leftarrow \bar{\mathcal{C}} \setminus \mathbf{a}_k$
5: **end for**

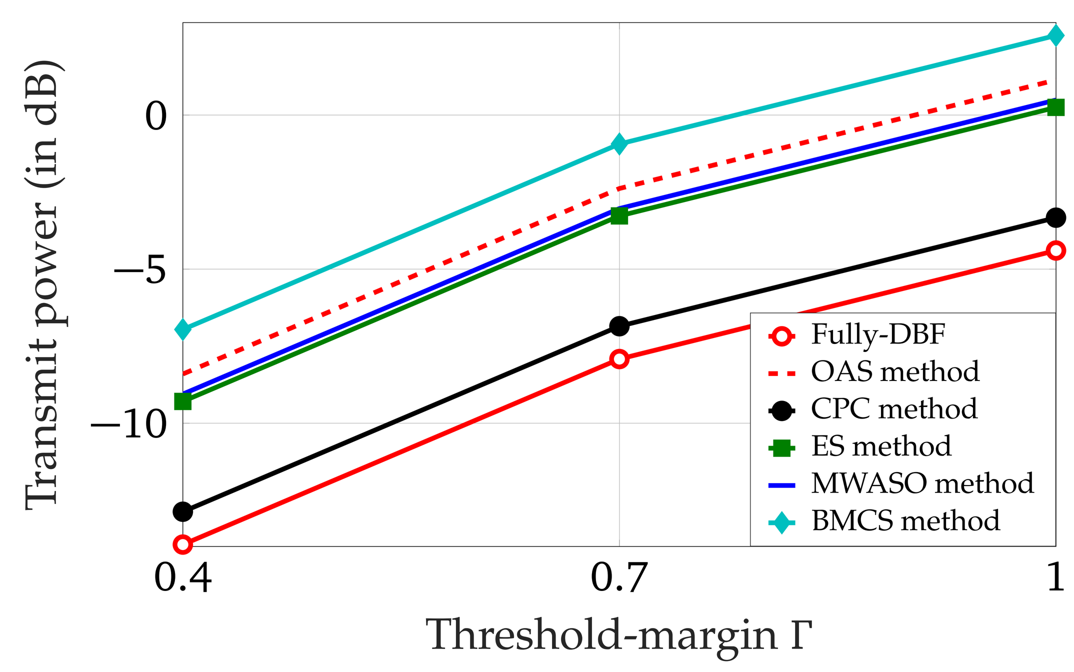
- ABFs independent of transmit symbols ⇒ can be fixed for multiple time-slots
- Significantly reduced computational complexity when compared to MWASO

6 Numerical Results

- Simulation settings: $N = L = 16$, $R = K = 2$, $M = 4$, $\Gamma = 0.7$
- Comparison of 1) DFT codebook, 2) random phase constant magnitude codebook



- Comparison of different ABF design techniques



- Fully-DBF: CI-based fully-digital beamforming, with $R = N$
- OAS method: Optimal R antenna selection (exhaustive search) with CI-based fully-digital beamforming for $N = R$
- CPC method: Conjugate phase of channel method [Liang *et al*-14] with expensive high-resolution continuous-valued phase shifters
- ES method: Optimal ABFs selection employing exhaustive search over codebook $\mathcal{C}$ and subsequent optimal DBF design