Semi-Distributed Hybrid Beamforming Design for Cooperative Cell-Free Dual-Function Radar-Communication Networks

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Bowen Wang[1], Lingyun Xu[1,2], Ziyang Cheng[1], Zishu He[1]

[1]School of Information and Communication Engineering (SICE),
University of Electronic Science and Tech. of China

[2]School of Electronics & Electrical Engineering (SEEE),
University of Glasgow, Scotland, UK

Presenter: Ziyang Cheng

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Why DFRC?

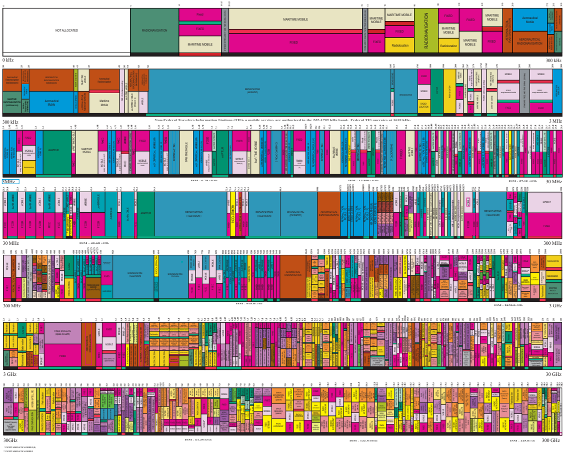
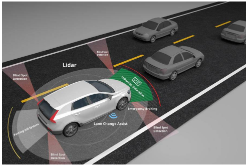


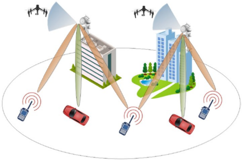
Figure: U.S. Frequency Allocation Chart from Data as of September 2015

How to make efficient use of spectrum resources?

Why DFRC?

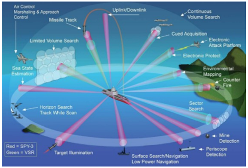


(a)



(b)

(c)



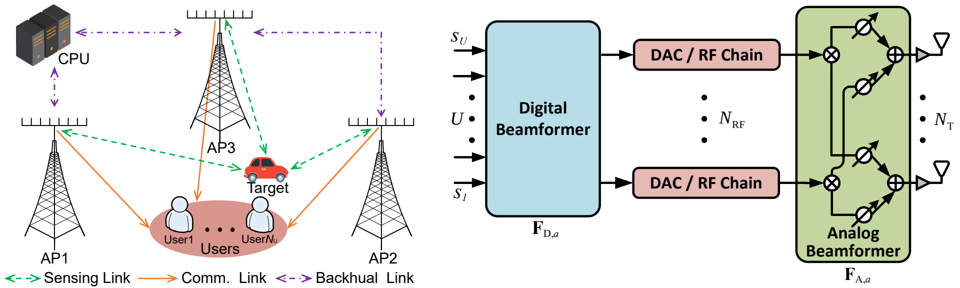
(d)

Figure: Practical application of DFRC technology

DFRC has broad application scenarios!

Motivation

- Existing works on DFRC
  1. Communication-Centric
  2. Radar-Centric
  3. **Joint Radar-Communication Waveform Design**
- Drawbacks
  1. Fully digital beamforming: Requires one high-resolution RF chain per antenna element.
  2. Single base station: *1)* Limits performance of sensing and communication; *2)* Limits the DFRC coverage area.
- Motivation
  1. Cooperative cell-free (CCF) transmission based HBF enhances the radar and communication performance.
  2. Distributed optimization framework enables the practical HBF design.



(a) (b)

Figure: (a) Diagrams of proposed CCF-DFRC network; (b) Overview of transmit HBF architecture at the AP a.

The transmit signal $\mathbf{x}_a \in \mathbb{C}^{N_T}$ at the AP a can be expressed as

$$\mathbf{x}_a = \mathbf{F}_{\mathrm{A},a}\mathbf{F}_{\mathrm{D},a}\mathbf{s} = \mathbf{F}_{\mathrm{A},a} \sum_{u \in \mathcal{U}} \mathbf{f}_{\mathrm{D},a,u} s_u, \tag{1}$$

where $\mathbf{F}_{\mathrm{D},a} = [\mathbf{f}_{\mathrm{D},a,1}, \cdots, \mathbf{f}_{\mathrm{D},a,U}]$, $\mathcal{A} = \{1, \cdots, A\}$, $\mathcal{U} = \{1, \cdots, U\}$.

Comm. Model

- Communication Precoding Design **Main Idea**:
  1. High Quality of Service (QoS) communication.
- **Downlink Communication Model**:
  1. Received signal at the legitimate user u is given by

$$y_u^{\mathrm{C}} = \sum_{a\in\mathcal{A}} \mathbf{h}_{a,u}^H \mathbf{F}_{\mathrm{A},a} \mathbf{f}_{\mathrm{D},a,u} s_u + \sum_{a\in\mathcal{A}} \sum_{j\in\mathcal{U},j\neq u} \mathbf{h}_{a,u}^H \mathbf{F}_{\mathrm{A},a} \mathbf{f}_{\mathrm{D},a,j} s_j + n_{\mathrm{C},u}, \quad (2)$$

  2. Signal-to-interference-plus-noise-ratio (SINR) at user u is

$$\mathrm{SINR}_u = \frac{\left| \sum_{a\in\mathcal{A}} \mathbf{h}_{a,u}^H \mathbf{F}_{\mathrm{A},a} \mathbf{f}_{\mathrm{D},a,u} \right|^2}{\sum_{j\in\mathcal{U},j\neq u} \left| \sum_{a\in\mathcal{A}} \mathbf{h}_{a,u}^H \mathbf{F}_{\mathrm{A},a} \mathbf{f}_{\mathrm{D},a,j} \right|^2 + \sigma_{\mathrm{C},u}^2}, \quad (3)$$

- **Communication Performance**: Achievable transmission rate at user u can be written as

$$\mathrm{Rate}_u = \log\left(1 + \mathrm{SINR}_u\right). \quad (4)$$

Radar Model

- Radar Waveform Design **Main Idea**:
  1. Forming mainlobes towards the targets
  2. Achieving the notch towards other APs.

- **Radar Performance**: Weighted mean square error (MSE) between transmit beampattern and desired $P_a(\theta)$ is defined as

$$\mathrm{MSE}_a\left(\mathbf{F}_{\mathrm{A},a}, \mathbf{F}_{\mathrm{D},a}, \Psi_a\right) = \sum_{l=1}^{L} \mu_l \left| \left\| \mathbf{a}_{\mathrm{T}}^H(\theta)\, \mathbf{F}_{\mathrm{A},a} \mathbf{F}_{\mathrm{D},a} \right\|_F^2 - \Psi_a P_a\left(\theta_l\right) \right|^2, \tag{5}$$

where $\mathbf{p}_a = [P_a(\theta_1), \cdots, P_a(\theta_L)]^T$ denotes the pre-defined spectrum. Ψ_a is a scaling parameter to be optimized, and μ_l is a user-defined parameter.

Problem Formulation

Problem of interest:

$$
\begin{aligned}
&\max_{\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\},\boldsymbol{\Psi}} \sum_{u\in\mathcal{U}} w_u \mathrm{Rate}_u\left(\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\}\right) && \text{(6a)}\\
&\text{s.t.} \quad \mathrm{MSE}_a\left(\mathbf{F}_{\mathrm{A},a},\mathbf{F}_{\mathrm{D},a},\Psi_a\right) \le \gamma_a, \forall a, && \text{(6b)}\\
&\qquad \left\|\mathbf{F}_{\mathrm{A},a}\mathbf{F}_{\mathrm{D},a}\right\|_F^2 \le E, \forall a, && \text{(6c)}\\
&\qquad \left|\left[\mathbf{F}_{\mathrm{A},a}\right]_{m,n}\right| = 1, \forall m,n,\forall a, && \text{(6d)}
\end{aligned}
$$

- High dimension and non-convex problem.

Three-Step Transformation

- **STEP 1**: Deal with the sum-logarithms objective (6a)

  Applying the quadratic transform-based fractional programming method and introducing auxiliary variables $\mathbf{r} \triangleq [r_1, \cdots, r_U]^T$ and $\boldsymbol{\eta} \triangleq [\eta_1, \cdots, \eta_U]^T$ [1], the function (6a) can be further derived as

$$
\begin{aligned}
\mathcal{G}\left(\{\mathbf{F}_{\mathrm{A},a}\}, \{\mathbf{F}_{\mathrm{D},a}\}, \mathbf{r}, \boldsymbol{\eta}\right) = & \sum_{u\in\mathcal{U}} w_u \log\left(1 + r_u\right) - \sum_{u\in\mathcal{U}} w_u r_u \\
& + \sum_{u\in\mathcal{U}} 2\sqrt{w_u\left(1+r_u\right)} \Re\{\eta_u^* \sum_{a\in\mathcal{A}} \mathbf{h}_{a,u}^H \mathbf{F}_{\mathrm{A},a} \mathbf{f}_{\mathrm{D},a,u}\} \\
& - \sum_{u\in\mathcal{U}} |\eta_u|^2 \left(\sum_{j\in\mathcal{U}} \left| \sum_{a\in\mathcal{A}} \mathbf{h}_{a,u}^H \mathbf{F}_{\mathrm{A},a} \mathbf{f}_{\mathrm{D},a,j} \right|^2 + \sigma_{\mathrm{C},u}^2 \right)
\end{aligned} \tag{7}
$$

[1] Kaiming Shen and Wei Yu, "Fractional programming for communication systems—Part I: Power control and beamforming," IEEE Transactions on Signal Process- ing, vol. 66, no. 10, pp. 2616–2630, 2018.

Three-Step Transformation

- **STEP 2**: Deal with the quartic constraint (6b)

1. **Proposition:** For the quartic optimization $\min_{\mathbf{X}} \|\mathbf{X}\mathbf{X}^H - N\mathbf{I}\|_F^2$, it can be approximately solved by optimizing the following simpler quadratic problem [3].

$$\min_{\mathbf{X},\mathbf{Z}} \left\|\mathbf{X} - \sqrt{N}\mathbf{Z}\right\|_F^2, \qquad \text{s.t. } \mathbf{Z}^H\mathbf{Z} = \mathbf{I}, \tag{8}$$

where $\mathbf{Z}$ is a semiunitary matrix.

2. We approximately reformulate the radar beampattern weighted MSE as

$$\overline{\text{MSE}}_a\left(\mathbf{F}_{\text{A},a}, \mathbf{F}_{\text{D},a}, \mathbf{V}_a, \zeta_a\right) = \sum_{l=1}^{L} \mu_{a,l} \left\|\mathbf{a}_T^H\left(\theta_l\right)\mathbf{F}_{\text{A},a}\mathbf{F}_{\text{D},a} - \zeta_a \mathbf{v}_{a,l}^H\right\|_F^2 \leq \gamma_a, \tag{9}$$

where $\mathbf{V}_a = [\mathbf{v}_{a,1}, \cdots, \mathbf{v}_{a,L}] \in \mathbb{C}^{U\times L}, \forall a$ is the auxiliary variables, satisfying $\|\mathbf{v}_{a,l}\|_F^2 = P_a(\theta_l), \forall a, l$, and $\zeta_a = \sqrt{\Psi_a}$.

[3] Joel A Tropp, Inderjit S Dhillon, Robert W Heath, and Thomas Strohmer, "Designing structured tight frames via an alternating projection method," IEEE Transactions on Information Theory, vol. 51, no. 1, pp. 188–209, 2005.

Three-Step Transformation

- **STEP 3**: Decouple the analog beamformer $\mathbf{F}_{\mathrm{A},a}$ and digital beamformer $\mathbf{F}_{\mathrm{D},a}$

1. Introducing the linear equality constraints $\mathbf{T}_a = \mathbf{F}_{\mathrm{A},a}\mathbf{F}_{\mathrm{D},a}$, the original problem is equivalently converted into

$$
\begin{aligned}
\max_{\substack{\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\},\boldsymbol{\zeta} \\ \mathbf{r},\boldsymbol{\eta},\{\mathbf{V}_a\},\{\mathbf{T}_a\}}} \quad & \mathcal{G}\left(\{\mathbf{T}_a\},\mathbf{r},\boldsymbol{\eta}\right) && \text{(10a)} \\
\text{s.t.} \quad & \overline{\mathrm{MSE}}_a\left(\mathbf{T}_a,\mathbf{V}_a,\zeta_a\right) \le \gamma_a, \forall a, && \text{(10b)} \\
& \|\mathbf{T}_a\|_F^2 \le E, \forall a, && \text{(10c)} \\
& \left|\left[\mathbf{F}_{\mathrm{A},a}\right]_{m,n}\right| = 1, \forall m,n,\forall a, && \text{(10d)} \\
& \mathbf{T}_a = \mathbf{F}_{\mathrm{A},a}\mathbf{F}_{\mathrm{D},a}, \forall a, && \text{(10e)}
\end{aligned}
$$

where $\mathbf{T}_a = [\mathbf{t}_{a,1},\cdots,\mathbf{t}_{a,U}]$, and $\boldsymbol{\zeta} = [\zeta_1,\ldots,\zeta_A]$.

Three-Step Transformation

- **STEP 3**: Decouple the analog beamformer $\mathbf{F}_{\mathrm{A},a}$ and digital beamformer $\mathbf{F}_{\mathrm{D},a}$

  2. To determine $\{\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\},\boldsymbol{\zeta},\mathbf{r},\boldsymbol{\eta},\{\mathbf{V}_a\},\{\mathbf{T}_a\}\}$, we apply **alternating direction optimization method**. The corresponding augmented Lagrangian (AL) minimization problem is

$$\begin{aligned} \min_{\substack{\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\},\boldsymbol{\zeta} \\ \mathbf{r},\boldsymbol{\eta},\{\mathbf{V}_a\},\{\mathbf{T}_a\}}} \quad & \mathcal{L}\left(\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\},\mathbf{r},\boldsymbol{\eta},\{\mathbf{T}_a\}\right) \\ \text{s.t.} \quad & \text{(10b)} - \text{(10e)}, \end{aligned} \tag{11}$$

  where the AL function:
  $\mathcal{L}(\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\},\mathbf{r},\boldsymbol{\eta},\{\mathbf{T}_a\}) = -\mathcal{G}(\{\mathbf{T}_a\},\mathbf{r},\boldsymbol{\eta}) + \sum_{a\in\mathcal{A}} \frac{\rho_a}{2}\|\mathbf{T}-\mathbf{F}_{\mathrm{A},a}\mathbf{F}_{\mathrm{D},a}+\mathbf{D}_a\|_F^2.$

Variables $\{\mathbf{F}_{\mathrm{A},a}\}$, $\{\mathbf{F}_{\mathrm{D},a}\}$, $\boldsymbol{\zeta}$, $\mathbf{r}$, $\boldsymbol{\eta}$, $\{\mathbf{V}_a\}$ are separated with each other!

Proposed Semi-Distributed Hybrid Beamforming Algorithm

- **Fully distributed** joint design is unrealizable [4]:
  1. $\{\mathbf{T}_a\}$ are still coupled in the objective function.
- Main ideas of the **semi-distributed** design:
  1. Avoid CPU undertaking too much computational complexity.
  2. Take advantage of distributed APs.
- Split the variables into **two blocks**:
  1. **CPU** takes responsibility for large-dimensional $\{\mathbf{r}, \boldsymbol{\eta}, \{\mathbf{T}_a\}\}$
  2. **AP** locally optimize its small-dimensional $\{\{\mathbf{F}_{\mathrm{A},a}\}, \{\mathbf{F}_{\mathrm{D},a}\}, \boldsymbol{\zeta}, \{\mathbf{V}_a\}\}$

[4] Tsung-Hui Chang, Mingyi Hong, Wei-Cheng Liao, and Xiangfeng Wang, "Asynchronous distributed ADMM for large-scale optimization—Part I: Algorithm and con- vergence analysis," IEEE Transactions on Signal Pro- cessing, vol. 64, no. 12, pp. 3118–3130, 2016.

Optimization in CPU: $\{\mathbf{r}, \boldsymbol{\eta}, \{\mathbf{T}_a\}\}$

- With the fixed $\{\{\mathbf{F}_{\mathrm{A},a}\}, \{\mathbf{F}_{\mathrm{D},a}\}, \boldsymbol{\zeta}, \{\mathbf{V}_a\}\}$, the block $\{\mathbf{r}, \boldsymbol{\eta}, \{\mathbf{T}_a\}\}$ are updated by solving

$$\min_{\mathbf{r},\boldsymbol{\eta},\{\mathbf{T}_a\}} \mathcal{L}\left(\mathbf{r}, \boldsymbol{\eta}, \{\mathbf{T}_a\}\right), \quad \text{s.t. (10b) and (10c).} \tag{12}$$

- The problem (12) can be settled by the **block coordinate descent (BCD)** method. Taking the first-order derivatives, optimal solutions to auxiliary variables $\mathbf{r}$ and $\boldsymbol{\eta}$ can be directly derived as

$$r_u = \left|\sum_{a\in\mathcal{A}} \Xi_{a,u}\right|^2 \Big/ \Big\{ \sum_{j\in\mathcal{U}, j\neq u} \left|\sum_{a\in\mathcal{A}} \Xi_{a,j}\right|^2 + \sigma_{\mathrm{C},u}^2 \Big\}, \tag{13}$$

$$\eta_u = \sqrt{\kappa_u} \sum_{a\in\mathcal{A}} \Xi_{a,u} \Big/ \Big\{ \sum_{j\in\mathcal{U}} \left|\sum_{a\in\mathcal{A}} \Xi_{a,j}\right|^2 + \sigma_{\mathrm{C},u}^2 \Big\}, \tag{14}$$

where $\Xi_{a,u} = \mathbf{h}_{a,u}^H \mathbf{t}_{a,u}$ and $\kappa_u = w_u(1 + r_u)$.

- The update of $\{\mathbf{T}_a\}$ can be obtained by solving

$$\min_{\{\mathbf{T}_a\}} \mathcal{L}\left(\{\mathbf{T}_a\}\right), \quad \text{s.t. (10b) and (10c).} \tag{15}$$

Optimization in CPU: $\{\mathbf{r}, \boldsymbol{\eta}, \{\mathbf{T}_a\}\}$

- Define $\mathbf{T} \triangleq [\mathbf{T}_1^T, \cdots, \mathbf{T}_A^T]^T$, problem (15) can be equivalently reformulated as

$$\begin{aligned} \min_{\mathbf{T}} \quad & \left\|\mathbf{B}\mathbf{T} - \bar{\mathbf{D}}\right\|_F^2 - 2\Re\left\{\mathsf{Tr}\left[\mathbf{B}_2\mathbf{T}\right]\right\} \\ \text{s.t.} \quad & \|\mathbf{G}_{a,1}\mathbf{E}_a\mathbf{T} - \mathbf{G}_{a,2}\|_F^2 \le \gamma_a, \forall a, \\ & \|\mathbf{E}_a\mathbf{T}\|_F^2 \le E, \forall a, \end{aligned} \tag{16}$$

  where we define $\mathbf{t} = \mathsf{Vec}(\mathbf{T})$, $\mathbf{A}_{\rm all} = [\mathbf{a}_{\rm T}(\theta_1), \cdots, \mathbf{a}_{\rm T}(\theta_L)]$, $\mathbf{b}_{1,u} = [\eta_u^*\mathbf{h}_{1,u}^H, \cdots, \eta_u^*\mathbf{h}_{A,u}^H]^H$, $\mathbf{b}_{2,u} = [\sqrt{w_u(1+r_u)}\eta_u^*\mathbf{h}_{1,u}^H, \cdots, \sqrt{w_u(1+r_u)}\eta_u^*\mathbf{h}_{A,u}^H]^H$, $\mathbf{G}_{a,1} = \mathsf{diag}(\sqrt{\mu_{a,1}}, \cdots, \sqrt{\mu_{a,L}})\mathbf{A}_{\rm all}^H$, $\mathbf{G}_{a,2} = \zeta_a\mathsf{diag}(\sqrt{\mu_{a,1}}, \cdots, \sqrt{\mu_{a,L}})\mathbf{V}_a^T$, $\mathbf{B}_1 = [\mathbf{b}_{1,1}, \cdots, \mathbf{b}_{1,U}]^H$, $\mathbf{B}_2 = [\mathbf{b}_{2,1}, \cdots, \mathbf{b}_{2,U}]^H$, $\mathbf{B}_3 = [\sqrt{\rho_1/2}\mathbf{I}_{N_{\rm T}}, \cdots, \sqrt{\rho_A/2}\mathbf{I}_{N_{\rm T}}]$, $\mathbf{B} = [\mathbf{B}_1^H, \mathbf{B}_3^H]^H$, $\tilde{\mathbf{D}} = \mathbf{B}_3[\tilde{\mathbf{D}}_1^H, \cdots, \tilde{\mathbf{D}}_A^H]^H$, $\tilde{\mathbf{D}}_a = \mathbf{F}_{{\rm A},a}\mathbf{F}_{{\rm D},a} - \mathbf{D}_a$, $\bar{\mathbf{D}} = [\mathbf{0}; \tilde{\mathbf{D}}]$, $\mathbf{E}_a = [\mathbf{0}_{(a-1)N_{\rm T}\times N_{\rm T}}; \mathbf{I}_{N_{\rm T}}; \mathbf{0}_{(A-a)N_{\rm T}\times N_{\rm T}}]$.

- Problem (16) is a convex quadratically constrained quadratic program (QCQP), which can be optimally solved by adopting the interior point method.

Optimization in APs: $\{\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\},\zeta,\{\mathbf{V}_a\}\}$

- With the fixed $\{\mathbf{r},\boldsymbol{\eta},\{\mathbf{T}_a\}\}$, the block $\{\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\},\boldsymbol{\zeta},\ \{\mathbf{V}_a\}\}$ are updated by solving

$$\min_{\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\},\boldsymbol{\zeta},\{\mathbf{V}_a\}} \mathcal{L}\left(\{\mathbf{F}_{\mathrm{A},a}\},\{\mathbf{F}_{\mathrm{D},a}\}\right) \qquad \text{s.t. (10b), (10d) and (10e).} \tag{17}$$

- Analyzing **KKT** conditions, the closed-form solutions can be given by

$$\zeta_a = \left\{\sum_{l=1}^{L} \mu_l \Re\{\mathbf{a}_{\mathrm{T}}^H(\theta_l)\,\mathbf{T}_a\mathbf{v}_{a,l}^*\}\right\} / \left\{\sum_{l=1}^{L} \mu_l \|\mathbf{v}_{a,l}\|_F^2\right\},$$

$$\mathbf{v}_{a,l} = \sqrt{P_a(\theta_l)}\mathbf{T}_a^H\mathbf{a}_{\mathrm{T}}(\theta_l) / \left\|\mathbf{T}_a^H\mathbf{a}_{\mathrm{T}}(\theta_l)\right\|_F,\ \mathbf{F}_{\mathrm{D},a} = \left\{\mathbf{F}_{\mathrm{A},a}^H\mathbf{F}_{\mathrm{A},a}\right\}^{-1}\mathbf{F}_{\mathrm{A},a}^H\left(\mathbf{T}_a + \mathbf{D}_a\right),$$

where $\mathbf{V}_a = [\mathbf{v}_{a,1},\cdots,\mathbf{v}_{a,L}]$.

- The update of $\mathbf{F}_{\mathrm{A},a}$ can be equivalently rewritten as

$$\min_{\mathbf{F}_{\mathrm{A},a}} \|\mathbf{F}_{\mathrm{A},a}\mathbf{F}_{\mathrm{D},a} - \mathbf{T}_a - \mathbf{D}_a\|_F^2,\ \text{s.t.} |[\mathbf{F}_{\mathrm{A},a}]_{m,n}| = 1. \tag{18}$$

- Problem (18) is a constant modulus constrained quadratic program (QP) problem, whose solution can be obtained by majorization minimization (MM) approach [5].

[5] Ying Sun, Prabhu Babu, and Daniel P Palomar, "Majorization-minimization algorithms in signal pro- cessing, communications, and machine learning," IEEE Transactions on Signal Processing, vol. 65, no. 3, pp. 794–816, 2016.

Proposed Algorithm

Algorithm 1: Proposed Algorithm.

Input: System parameters, $k = 0$.
Output: $\{\mathbf{F}_{\mathrm{A},a}\}_{\forall a}$, and $\{\mathbf{F}_{\mathrm{D},a}\}_{\forall a}$.

```
while No Convergence do
    k = k + 1;
    CPU side
        Update r^k and η^k by (10) and (11);
        Update {T_a^k} by solving (13);
    Exchange CPU side information to AP sides;
    AP side (a ∈ A), \\In Parallel
        Update ζ_a^k and V_a^k by (15) and (16);
        Update F_{D,a}^k by closed-form solution (17) ;
        Update F_{A,a}^k by solving (18);
        D_a^k = D_a^{k-1} + (T_a^k − F_{A,a}^k F_{D,a}^k);
    Exchange AP sides information to CPU side;
```

Parameters Setting

Parameter	Value	Parameter	Value
N_{T}	32	U	4
N_{RF}	4	E	100mW
$\sigma^2_{\mathrm{C,u}}$	-40dBm	μ_l	1

Table: Collection of parameters values

- $A = 3$ APs are located at $(0\mathrm{m},\ 0\ \mathrm{m})$, $(90\ \mathrm{m},\ 0\mathrm{m})$, and $(45\mathrm{m},\ 45\sqrt{3}\mathrm{m})$.
- Saleh-Valenzuela (SV) channel model: $\mathbf{h}_{a,u} = \mathrm{L}(d) \times (\sqrt{\varrho}\mathbf{h}^{\mathrm{LoS}}_{a,u} + \mathbf{h}^{\mathrm{NLoS}}_{a,u})/\sqrt{N_{\mathrm{T}}(\varrho+1)}$. LoS channel: $\mathbf{h}^{\mathrm{LoS}}_{a,u} = \mathbf{a}_{\mathrm{T}}(\phi^0_{a,u})$; NLoS channel: $\mathbf{h}^{\mathrm{NLoS}}_{a,u} = \sum_{p=1}^{N_{\mathrm{P}}-1} \kappa^p_{a,u}\mathbf{a}_{\mathrm{T}}(\phi^p_{a,u})$, where $\mathrm{L}(d) = C_0(d/d_0)^{-\varpi}$, $C_0 = -30\mathrm{dB}$, $d_0 = 1\mathrm{m}$, $\varpi = 1.6\mathrm{dB}$, $\varrho = 6\mathrm{dB}$.
- Two radar targets are located in $(30\mathrm{m},\ 30\mathrm{m})$ and $(40\mathrm{m},\ 5\mathrm{m})$.
- The ideal beampattern $P_a(\theta_l)$ is given by $P_a(\theta_l) = 1$ when $\theta_l \in [\theta_{a,k} - \Delta, \theta_{a,k} + \Delta]$, otherwise $P_a(\theta_l) = 0$, where $\theta_{a,k}$ denotes the angle of k-th target for AP a, and $\Delta = 4^\circ$.
- The radar MSE thresholds of different APs are the same, i.e., $\gamma_a = \gamma$.

Comm. Performance

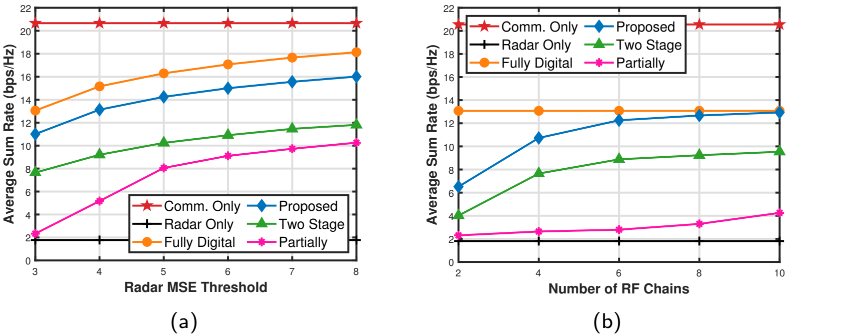
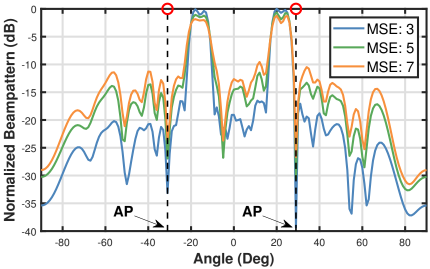


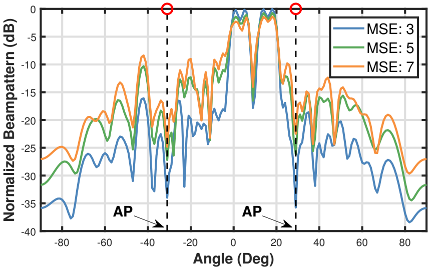
Figure: Performance achieved by CCF-DFRC. (a) Sum-rate vs. radar MSE γ; (b) sum-rate vs. number of RF chains N_{RF} with radar MSE $\gamma = 3$.

- The average sum rate increases along with the radar MSE γ.
- $N_{\mathrm{RF}} \leq 2U$: the average sum rate increases with the number of RF chains; $N_{\mathrm{RF}} > 2U$: the achievable rates are nearly unchanged.
- The proposed method is better than the "two-stage" method and close to the conventional "FD".

Radar Performance



(a) AP 1



(b) AP 3

Figure: Transmit beampattern achieved by CCF-DFRC.

- The main beam is allocated to the target directions.
- The transmit beampattern achieves the notch at other AP directions to avoid interfering with other APs.
- With radar MSE increasing, the gain at the mainlobe slightly decreases, and the sidelobe level becomes high.

Conclusions

- In this paper, we propose a novel **cooperative cell-free DFRC** network with **HBF** architecture.
  - The distributed APs cooperatively perform radar sensing and provide communication service.
- The corresponding problem of the joint HBF design is formulated via maximizing the weighted sum rate while guaranteeing radar beampattern similarity.
  - A **semi-distributed** algorithm is proposed to settle the optimization problem.
- The simulation results show that:
  - The CCF-DFRC can obtain significant gains in radar and communication performance.

Thank you !!

Email: B_W_Wang@163.com

Regular Paper:

B. Wang *et al*, "A Distributed Hybrid Beamforming Design Framework for Cooperative Cell-Free Dual-Function Radar-Communication Networks," submitted to *IEEE Trans. on Signal Process.*.