RIS-Assisted Joint Radar and Communications Beamforming Design

Zhaolin Wang

Communications and Signal Processing Group
Department of Electrical and Electronic Engineering
Imperial College London

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Communication and Radar Spectrum Sharing

- **Motivation**[1]
  - Radar systems utilize numerous spectrum bands below 10 GHz, leading to sever spectrum congestion with future wireless communications systems.
- **Communication and Radar Spectrum Sharing (CRSS)**[2]
  - Coexistence of existing radar and communications.
  - Co-design for dual-functional radar and communications (DFRC)
    1. Radar-centric (information embedding)
    2. Communication-centric (joint beamforming design)

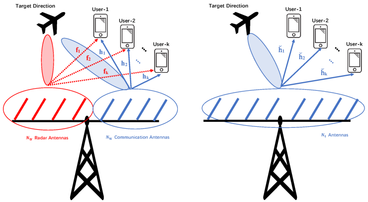


Figure: Schematic diagram for separated and shared multi-antenna joint RadCom[3]

[1] F. Liu et al. "Joint Radar and Communication Design: Applications, State-of-the-Art, and the Road Ahead". In: *IEEE Transactions on Communications* 68.6 (2020), pp. 3834–3862. DOI: 10.1109/TCOMM.2020.2973976.

[2] F. Liu and C. Masouros. "A Tutorial on Joint Radar and Communication Transmission for Vehicular Networks—Part I: Background and Fundamentals". In: *IEEE Communications Letters* 25.2 (2021), pp. 322–326. DOI: 10.1109/LCOMM.2020.3025310.

[3] C. Xu, B. Clerckx, and J. Zhang. "Multi-Antenna Joint Radar and Communications: Precoder Optimization and Weighted Sum-Rate vs Probing Power Tradeoff". In: *IEEE Access* 8 (2020), pp. 173974–173982. DOI: 10.1109/ACCESS.2020.3025156.

Trade-off between Radar and Communication

$$\max_{\mathbf{P},\mathbf{R}_x} \rho \sum_{k=1}^{K} \mu_k R_k(\mathbf{P},\mathbf{R}_x) +$$
$$\mathbf{a}_1^H(\varphi_m)\mathbf{R}_x\mathbf{a}_1(\varphi_m) + \mathbf{a}_2^H(\varphi_m)\mathbf{P}\mathbf{P}^H\mathbf{a}_2(\varphi_m)$$
$$\textbf{s.t.} \quad \mathrm{diag}(\mathbf{R}_x) = \frac{P_r \mathbf{1}^{M_r\times 1}}{M_r}$$
$$\mathrm{Tr}(\mathbf{P}\mathbf{P}^H) \le P_c$$
$$\mathbf{R}_x \succeq 0$$

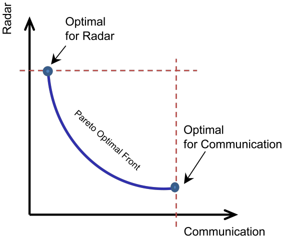


Figure: Pareto Optimal Front

- What if the channel is totally controllable?
  - Precoder (beamforming) is only for Radar
  - Control the channel to meet the Communication requirement
- Reconfigurable Intelligent Surface (RIS)[4]
  - Composed of many small and low-cost reflecting elements
  - Achieve the desired propagation characteristics

[4] Y. Liu et al. "Reconfigurable intelligent surfaces: Principles and opportunities". In: *arXiv preprint arXiv:2007.03435* (2020).

RIS-Assisted Joint RadCom Beamforming Design

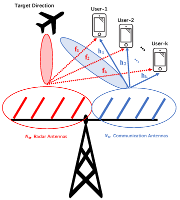
- System Model
  - M_r antennas for the radar, M_c antennas for the communication
  - N reflecting elements at RIS
  - K users with single antenna; 1 target
  - Observation at user k

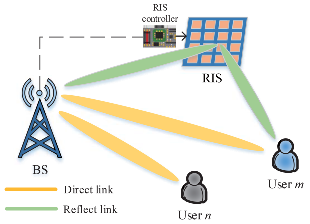
$$y_k = \mathbf{h}_k^H \boldsymbol{\Theta}^H \mathbf{H}_c \sum_{k=1}^{K} \mathbf{p}_j s_j + \mathbf{h}_k^H \boldsymbol{\Theta}^H \mathbf{H}_r \mathbf{r} + n_k$$

  - SINR and Achievable Rate at user k

$$\gamma_k(\mathbf{P}, \mathbf{R}_x, \boldsymbol{\Theta}) = \frac{|\mathbf{h}_k^H \boldsymbol{\Theta}^H \mathbf{H}_c \mathbf{p}_k|^2}{\sum_{j=1, j\neq k}^{K} |\mathbf{h}_k^H \boldsymbol{\Theta}^H \mathbf{H}_c \mathbf{p}_j|^2 + \mathbf{f}_k^H \mathbf{R}_x \mathbf{f}_k + 1}$$

$$R_k(\mathbf{P}, \mathbf{R}_x, \boldsymbol{\Theta}) = \log_2(1 + \gamma_k(\mathbf{P}, \mathbf{R}_x, \boldsymbol{\Theta}))$$





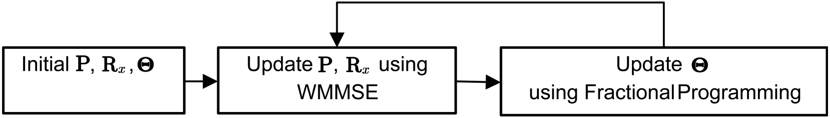
RIS-Assisted Joint RadCom Beamforming Design

- Optimization Problem

$$\max_{\mathbf{P},\mathbf{R}_x,\boldsymbol{\Theta}} \rho \sum_{k=1}^{K} \mu_k R_k(\mathbf{P},\mathbf{R}_x,\boldsymbol{\Theta}) + \mathbf{a}_1^H(\varphi_m)\mathbf{R}_x\mathbf{a}_1(\varphi_m) + \mathbf{a}_2^H(\varphi_m)\mathbf{P}\mathbf{P}^H\mathbf{a}_2(\varphi_m)$$

$$\begin{aligned}
\textbf{s.t.} \quad & \mathrm{diag}(\mathbf{R}_x) = \frac{P_r \mathbf{1}^{M_r\times 1}}{M_r} \\
& \mathrm{Tr}(\mathbf{P}\mathbf{P}^H) \leq P_c \\
& \mathbf{R}_x \succeq 0 \\
& |\theta_n| \leq 1, n = 1, ..., N
\end{aligned}$$

- Block Coordinate Descent, WMMSE[5,6], Fractional Programming[7]



[5] S. S. Christensen et al. “Weighted Sum-Rate Maximization Using Weighted MMSE for MIMO-BC Beamforming Design”. In: *2009 IEEE International Conference on Communications*. 2009, pp. 1–6. DOI: 10.1109/ICC.2009.5199574.

[6] C. Xu, B. Clerckx, and J. Zhang. “Multi-Antenna Joint Radar and Communications: Precoder Optimization and Weighted Sum-Rate vs Probing Power Tradeoff”. In: *IEEE Access* 8 (2020), pp. 173974–173982. DOI: 10.1109/ACCESS.2020.3025156.

[7] K. Shen and W. Yu. “Fractional Programming for Communication Systems—Part I: Power Control and Beamforming”. In: *IEEE Transactions on Signal Processing* 66.10 (2018), pp. 2616–2630. DOI: 10.1109/TSP.2018.2812733.

RIS-Assisted Joint RadCom Beamforming Design

- Update $\mathbf{P}$, $\mathbf{R}_x$ using WMMSE → Semi-definite Programming

$$\begin{aligned}
\min_{\mathbf{P},\mathbf{R}_x} \ & \rho \sum_{k=1}^{K} \mu_k \xi_k(\mathbf{P},\mathbf{R}_x) - \mathbf{a}_1^H(\varphi_m)\mathbf{R}_x\mathbf{a}_1(\varphi_m) + \sum_{k=1}^{K} \mathbf{p}_k^H \mathbf{Z}(\varphi_m)\mathbf{p}_k \\
\textbf{s.t.} \quad & \mathrm{diag}(\mathbf{R}_x) = \frac{P_r \mathbf{1}^{M_r \times 1}}{M_r} \\
& \mathrm{Tr}(\mathbf{P}\mathbf{P}^H) \le P_c \\
& \mathbf{R}_x \succeq 0
\end{aligned}$$

- Update $\boldsymbol{\Theta}$ using Fractional Programming → Quadratic Programming

$$\begin{aligned}
\max_{\mathbf{y},\boldsymbol{\theta}} \ & \sum_{k=1}^{K} \left(2\Re\left\{ y_k^* \sqrt{\tilde{\alpha}_k} \mathbf{a}_{k,k}^H \boldsymbol{\theta} \right\} - |y_k|^2 \left(\sum_{j=1}^{K} |\mathbf{a}_{j,k}^H \boldsymbol{\theta}|^2 + \boldsymbol{\theta}^H \mathbf{B}_k \boldsymbol{\theta} + 1 \right) \right) \\
\textbf{s.t.} \quad & |\theta_n| \le 1, n = 1, \ldots, N \\
& y_k \in \mathbb{C}
\end{aligned}$$

RIS-Assisted Joint RadCom Beamforming Design

Algorithm WMMSE-FP Algorithm

Input: $t \leftarrow 0,\ \mathbf{P}^{[t]},\ \mathbf{\Theta}^{[t]}$

$\mathrm{WSR}^{[t]}$ is calculated from $\mathbf{P}^{[t]}$ and $\mathbf{\Theta}^{[t]}$

repeat

$\boldsymbol{\omega}^{*} = \boldsymbol{\omega}^{\mathrm{MMSE}}(\mathbf{P}^{[t]}, \mathbf{\Theta}^{[t]})$

$\mathbf{g}^{*} = \mathbf{g}^{\mathrm{MMSE}}(\mathbf{P}^{[t]}, \mathbf{\Theta}^{[t]})$

update $\mathbf{P}^{[t+1]}$, $\mathbf{R}_x^{[t+1]}$ by solving the SDP with updated $\boldsymbol{\omega}^{*}$ and $\mathbf{g}^{*}$.

$\boldsymbol{\alpha}^{*} = \gamma\left(\mathbf{P}^{[t+1]}, \mathbf{R}_x^{[t+1]}, \mathbf{\Theta}^{[t]}\right)$

$y_k^{*} = \frac{\sqrt{\tilde{a}_k \mathbf{a}_{j,k}^H \boldsymbol{\theta}_k}}{\sum_{j=1}^{K} |\mathbf{a}_{j,k}^H \boldsymbol{\theta}_k|^2 + \boldsymbol{\theta}_k^H \mathbf{B}_k \boldsymbol{\theta}_k + 1}, k = 1, \ldots, K$

update $\mathbf{\Theta}^{[t+1]}$ by solving the QP with updated $\boldsymbol{\alpha}^{*}$ and y_k^{*}.

$t++$

until $\left|\mathrm{WSR}^{[t]} - \mathrm{WSR}^{[t+1]}\right| \leq \epsilon$

Challenges

- If the discrete phase shift of RIS is considered, the constraint set is non-convex
    - Discrete set
- If the shared deployment is considered, the constraint set is also non-convex
    - Quadratic equality constraint

Thanks