Imperial College London

# RIS-aided Dual-Functional Radar and Communications Beamforming Design

*Author:* Zhaolin Wang *Supervisor:* Prof Bruno Clerckx

## Motivation

### CRSS

- Enable two systems perform in the same frequency band with tiny performance loss
- Long-term solution for the spectrum management of communications and radar.

### RIS

- Modify wireless channel via passive beamforming.
- Provide extra capability for the CRSS system.

### Group/fully connected RIS

- A novel RIS model wherein elements are connected mutually.
- Lead to higher received power than single connected RIS in Rayleigh channel.

### WSR maximization

- The most representative communication metric.
- Has not been investigated in this field.
- WSR maximization is non-convex and hard to solve

## System Model

- **Separated:** received signal at user $k$

$$y_k = (\mathbf{h}_k^H \boldsymbol{\Theta}^H \mathbf{H}_c + \mathbf{d}_{c,k}^H) \sum_{j=1}^{K} \mathbf{p}_j s_j + (\mathbf{h}_k^H \boldsymbol{\Theta}^H \mathbf{H}_r + \mathbf{d}_{r,k}^H)\mathbf{q} + n_k$$

➢ $s_j$: data symbol; $\mathbf{p}_j$: linear precoder; $\mathbf{q}$: radar signal; $\mathbf{d}_{c,k}, \mathbf{d}_{r,k}$: direct channel; $\mathbf{H}_c, \mathbf{H}_r$: BS $\rightarrow$ RIS channel; $\mathbf{h}_k$: RIS $\rightarrow$ user channel; $\boldsymbol{\Theta}$: passive beamforming matrix;

- **Shared:** received signal at user $k$

$$y_k = (\mathbf{h}_k^H \boldsymbol{\Theta}^H \mathbf{H} + \mathbf{d}_k^H) \sum_{j=1}^{K} \mathbf{p}_j s_j + n_k$$

➢ $s_j$: data symbol; $\mathbf{p}_j$: linear precoder; $\mathbf{q}$: radar signal; $\mathbf{d}_k$: direct channel; $\mathbf{H}$: BS $\rightarrow$ RIS channel; $\mathbf{h}_k$: RIS $\rightarrow$ user channel; $\boldsymbol{\Theta}$: passive beamforming matrix;

- **WSR:** $R = \sum_{k=1}^{K} \mu_k \log_2(1 + \mathrm{SINR}_k)$

- **Probing power:** $d(\varphi) = \mathbf{a}^H(\varphi)\mathbf{C}\mathbf{a}(\varphi)$

➢ $\mathbf{a}(\varphi)$: steering vector; $\mathbf{C}$: covariance matrix of overall transmit signal;

- **Radar constant-modulus constraint:**

➢ power fed to each antenna is the same

Separated: $\mathrm{diag}(\mathbf{R}_\mathbf{q}) = \frac{P_r}{M_r} \mathbf{1}^{M_r \times 1}$

Shared: $\mathrm{diag}\left(\sum_{k=1}^{K} \mathbf{p}_k \mathbf{p}_k^H\right) = \frac{P}{M} \mathbf{1}^{M \times 1}$

## Contribution

The first work that studies WSR maximization and group/fully connected RIS in CRSS

### A new framework

- A BS with separated or shared setup probing one target and serving multiple users.
- The users receive signal from BS plus reflected signal from RIS

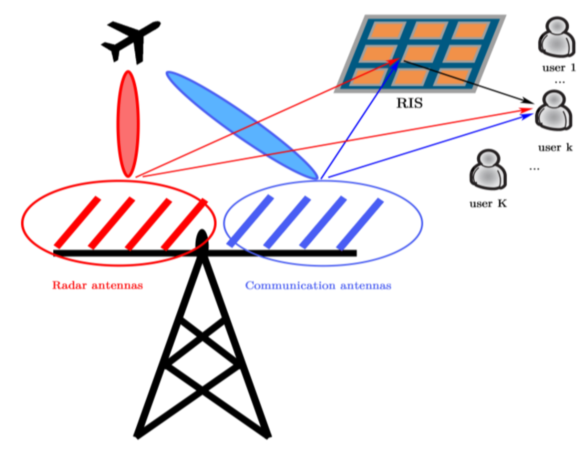
### An algorithm for *separated* deployment

- Non-convexity from WSR is tackled by WMMSE framework and Fractional Programming (FP)
- Non-convexity from group connected RIS is tackled by scattering-reactance relationship.

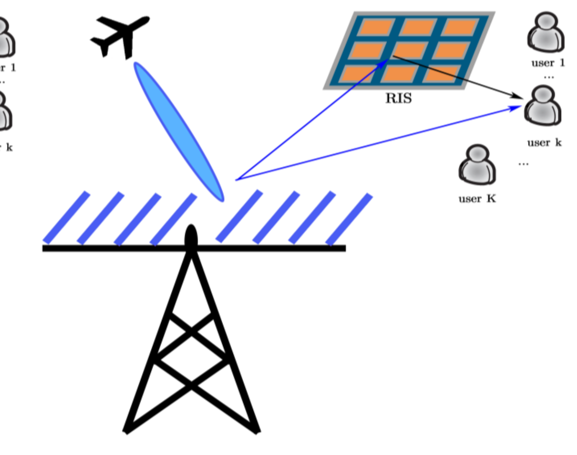
### An algorithm for *shared* deployment

- Similar as separated deployment, but additional non-convexity from radar constant-modulus constraint
- Lower complexity SDR method than the existing Majorization-Minimization (MM) method.

## Separated/Shared Deployment




*a) Separated Deployment*




*b) Shared Deployment*

**Separated:** two groups of antennas transmit radar and communication signals

**Shared:** all antennas transmit communication signal under radar constraint.

**Tradeoff between complexity and performance**

## Algorithm for WSR and Probing Power Maximization

### 1) WMMSE: fix passive beamforming, optimize active beamforming

➢ Calculate MMSE receiver for each user $k$ as $g_k^{\mathrm{MMSE}} = \arg\min_{g_k} \mathbf{E}[\| g_k y_k - s_k \|^2]$

➢ According to WMMSE to framework, the WSR maximization w.r.t. active beamforming can be converted to weighted MSE minimization problem with MMSE receiver.

$$\underbrace{\max_{\mathbf{p}_k, \mathbf{R}_\mathbf{q} \in \mathcal{F}} \sum_{k=1}^{K} \mu_k \log_2(1 + \mathrm{SINR}_k)}_{\text{non-convex}} \Rightarrow \underbrace{\min_{\mathbf{p}_k, \mathbf{R}_\mathbf{q} \in \mathcal{F}} \sum_{k} w_k \mathbf{E}\left[\left\| g_k^{\mathrm{MMSE}} y_k - s_k \right\|^2\right]}_{\text{convex}}$$

- Separated
  - Feasible set $\mathcal{F}$ is convex
  - Directly solved using CVX toolbox
- Shared
  - Feasible set $\mathcal{F}$ is non-convex
  - Using SDR technique and dominant eigenvalue approximation

### 2) FP: fix active beamforming, optimize passive beamforming

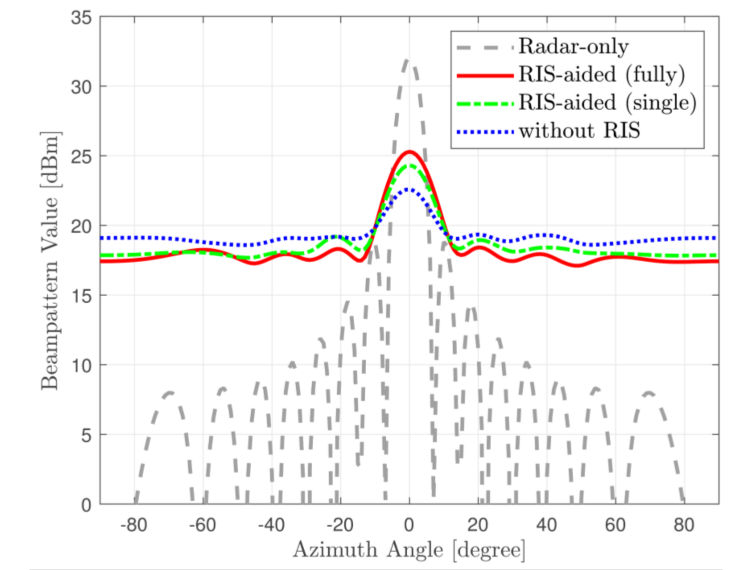
➢ Based on FP, the WSR maximization w.r.t. passive beamforming can be reformulated as a minimization problem with a convex objective function through *Largrangian dual transform* and *quadratic transform*

$$\underbrace{\max_{\boldsymbol{\Theta} \in \mathcal{Q}} \sum_{k=1}^{K} \mu_k \log_2(1 + \mathrm{SINR}_k)}_{\text{non-convex}} \Rightarrow \underbrace{\min_{\substack{\boldsymbol{\theta} = \mathrm{vec}(\boldsymbol{\Theta}^H) \\ \boldsymbol{\Theta} \in \mathcal{Q}}} \boldsymbol{\theta}^H \mathbf{U} \boldsymbol{\theta} - 2\mathrm{Re}\{\boldsymbol{\theta}^H \mathbf{v}\}}_{\text{convex}}$$

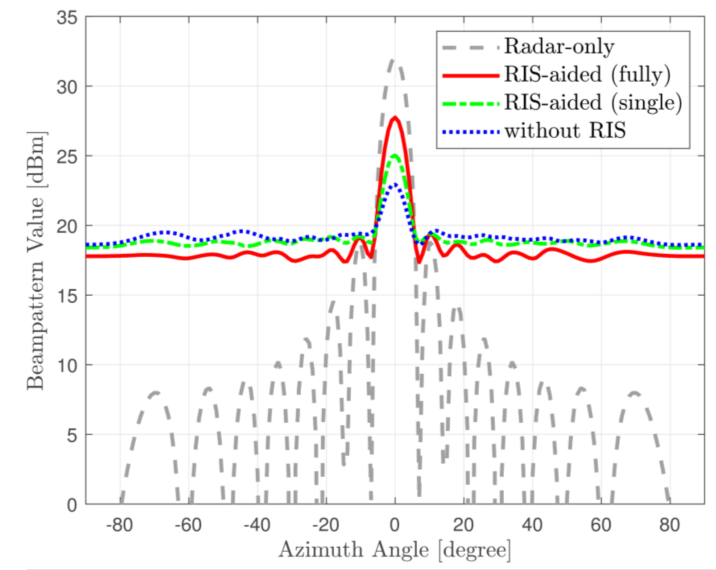
- Single connected RIS
  - Feasible set $\mathcal{Q}$ is convex
  - Directly solved using CVX toolbox
- Group/fully connected RIS
  - Feasible set $\mathcal{Q}$ is non-convex
  - Using scattering-reactance relationship to formulate an equivalent unconstrained problem, which can be addressed by Quasi-Newton method.

### 3) Alternating between 1) and 2) until convergence

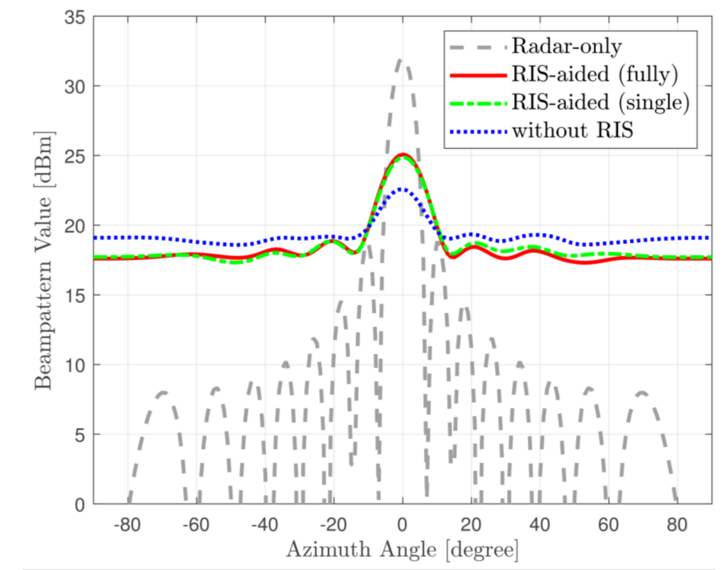
## Simulation Rsults



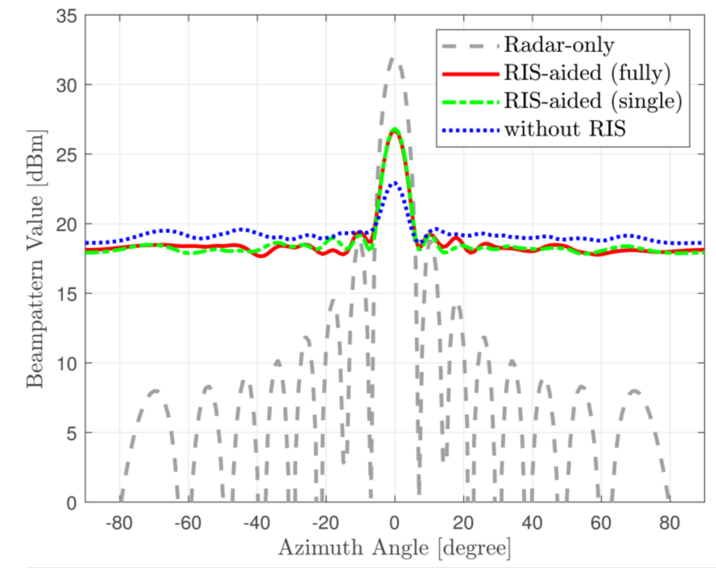

*a) Separated, Rayleigh, WSR = 5.4 bps/Hz*



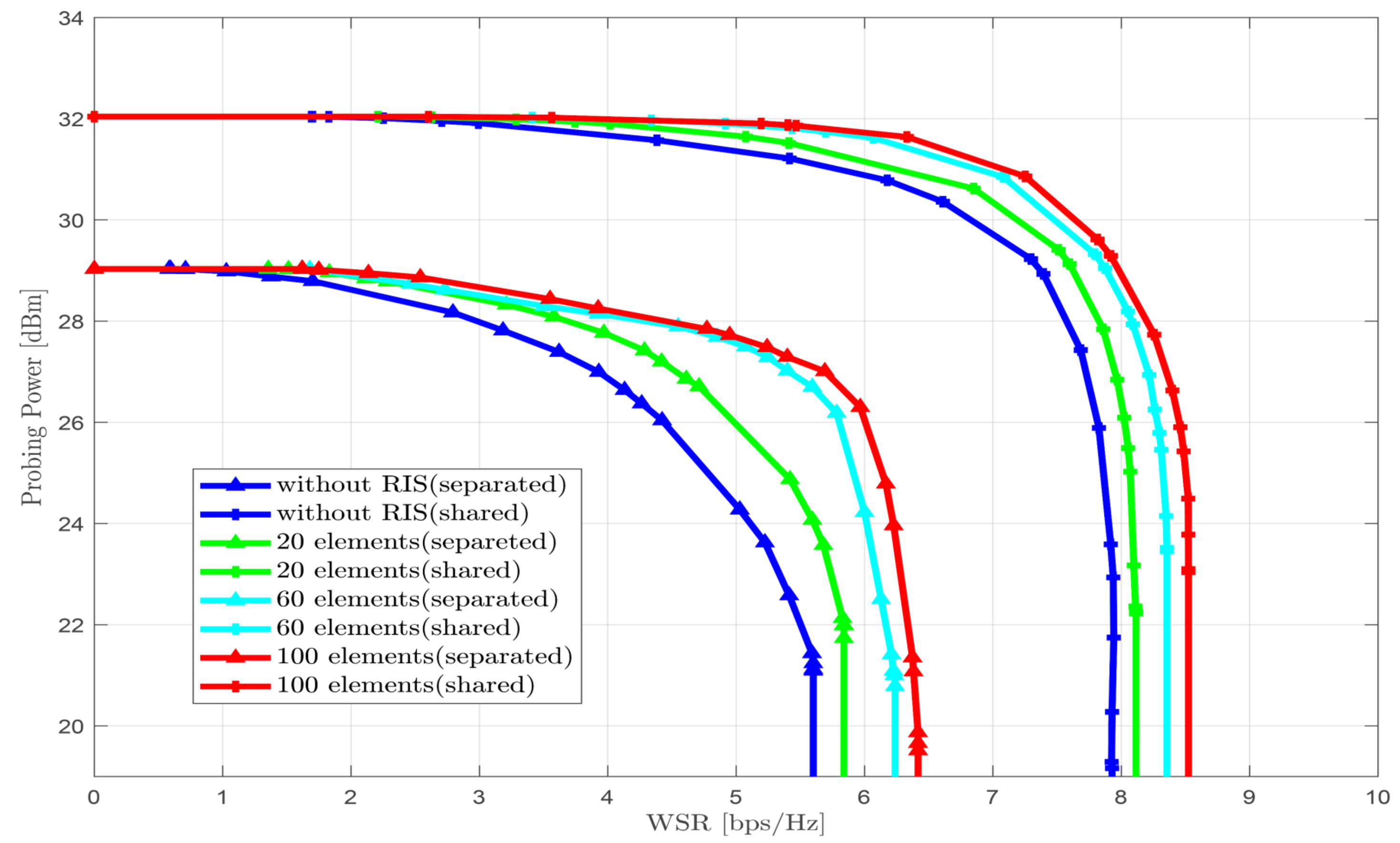

*b) Shared, Rayleigh, WSR = 7.9 bps/Hz*




*c) Separated, LOS, WSR = 5.4 bps/Hz*




*d) Shared, LOS, WSR = 7.9 bps/Hz*




*e) Effect of the number of reflecting elements*

- In both separated and shared deployments, the RIS aids the system in achieving improved radar beampatterns and achievable region.
- The fully connected RIS brings more improvements in terms of radar beampattern and achievable region than single connected RIS in Rayleigh channel, while its performance is the same as single connected RIS in LOS channel.
- Compared with separated deployment, the shared deployment achieves better beampattern and larger achievable region because the antennas are fully exploited.