# Radar Target Detection Aided by Reconfigurable Intelligent Surfaces

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## Context

- Reconfigurable Intelligent Surfaces (RIS's) are planar structures of reflecting units capable of changing the phases of incoming signals
- No power amplification is undertaken in RIS's
- The overall power consumption of an $L$-element RIS is in the order of $LP_n(b)$, where $P_n(b)$ is the power consumption of a single unit with a $b$-bits phase resolution. Typical values are:

| $b$ | 3 | 4 | 5 | 6 |
|---|---|---|---|---|
| $P_n(b)$ (mW) | 1.5 | 4.5 | 6 | 7.8 |

- Thus RIS's have become popular as energy-efficient alternatives to classical Amplify-and-Forward in terrestrial wireless networks.



## Problem Formulation

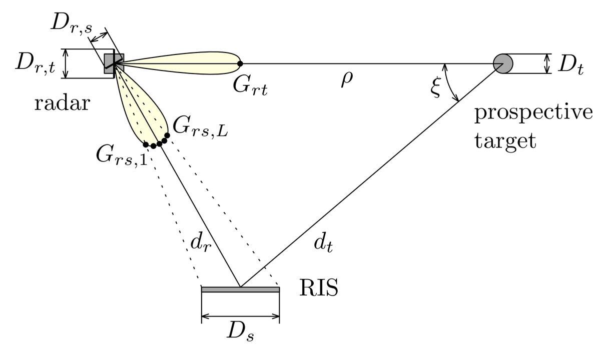
Given
- A radar system, possibly capable of forming multiple transmit/receive beams
- An $L$-element RIS placed at distance $d_r$ from the radar transceiver
- A prospective target at distance $\rho$ from the radar and at distance $d_t$ from the RIS

Determine

If and under what conditions is the RIS helpful in target detection.



## Geometry and Parameters




- $D_{rt}$, $D_{rs}$ are the sizes of the radar antennas pointing toward the target and the RIS, respectively, while $D_s$ is the size of the RIS
- $G_{rt}$ is the gain of the radar beam towards the target, and $G_{rs,\ell}$ the corresponding gain towards the $\ell$-th element of the RIS



## Assumptions

- The radar is narrowband, i.e. its bandwidth $W$ satisfies $\max\{D_{rt}, D_{rs}, D_s\} \ll \frac{c}{W}$;
- All of the antennas are *directive*: $\min\{D_{rt}, D_{rs}, D_s\} \gg \lambda$;
- The wavefield is a plain wave in the paths between radar and target, target and RIS, radar and each element of the RIS, i.e.:

$$\begin{cases} \rho \geq 2\max\{D_{rt}^2, D_{rs}^2\}/\lambda \\ \min\{d_{t,\ell}^2\}_{\ell=1}^L \geq 2\max\{D_t^2, D_s^2\}/\lambda \\ \min\{d_{r,\ell}^2\}_{\ell=1}^L \geq 2\max\{D_{rs}^2\}/\lambda \end{cases}$$

Remark: the whole RIS and the radar may not be in the far field of each other!



## A case study

The radar has

One single transmit beam pointing at the target
Two receive beams pointing at the target and the RIS

We have a direct path (radar → target → radar) and an indirect path (radar → target → RIS → radar)
We examine two situations:
- Radar and RIS view the target with the same angle of view (co-located radar and RIS)
- Radar and RIS are widely spaced (different angles of view)

Remark: A different architecture would be possible, i.e. the radar splits its power between two transmit beams and has one receive beam. We do not consider this situation here.



## Signal model

Let $x_1$ be the observable generated by the direct path, and $x_2$ be the one generated by the indirect path. We have:

$$\begin{cases} x_1 = \alpha\sqrt{\sigma}e^{j\beta} + w_1 \\ x_2 = \sum_{\ell=1}^L \alpha_{sr,\ell}\sqrt{\sigma_s}e^{j(\psi_{t,\ell}+\phi_\ell+\psi_{r,\ell})} + w_2 \end{cases}$$

- $\sigma$ and $\sigma_s$ are the unknown target RCS's ($\sigma = \sigma_s$ for co-located case)
- $\{\psi_{r,\ell}\}_{\ell=1}^L$ are the phases of the radar-RIS channel
- $\{\phi_\ell\}_{\ell=1}^L$ are the adjustable RIS phases
- $\{\psi_{t,\ell}\}_{\ell=1}^L$ are the unknown phases of the target-RIS channel
- $\alpha$ is the target attenuation (target → radar hop)
- $\alpha_{sr,\ell}$ is the attenuation between the $\ell$-th RIS unit and the radar receive antenna



## RIS phases choice and receiver design

For known RIS-radar channel phases, the RIS phases can be designed so as to phase-align all of the signal terms. In fact:
- If they are closely-spaced, then

$$\sigma = \sigma_s \quad \text{and} \quad \psi_{t,\ell} = \underbrace{\beta}_{\text{unknown}} + \underbrace{\psi'_{t,\ell}}_{\text{known}}$$

- If they are widely-spaced, then

$$\sigma \neq \sigma_s \quad \text{and} \quad \psi_{t,\ell} = \underbrace{\beta_s}_{\text{unknown}} + \underbrace{\psi''_{t,\ell}}_{\text{known}}$$

- For the closely-spaced case, the receiver is a coherent energy integrator
- For the widely-spaced case, it incoherently integrates the energy along the two available channels



## SNR Gain of the Radar+RIS system

Let $\text{SNR}_0$ be the SNR in absence of RIS, we have:
- Closely-spaced RIS and Radar

$$\text{SNR} = \text{SNR}_0\,(1 + K_{sr}) \qquad K_{sr} = \frac{\alpha_{sr}^2}{\alpha^2} = \frac{\sum_{\ell=1}^L \alpha_{sr,\ell}^2}{\alpha^2}$$

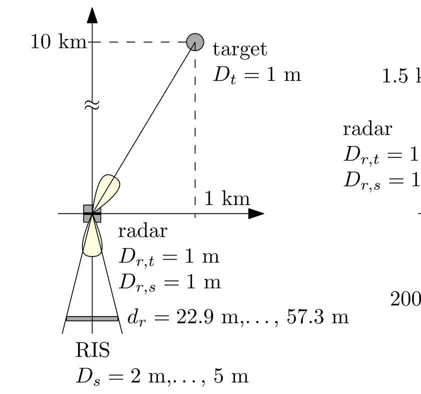
- Widely-spaced RIS and radar. Here we have two independent paths and two different SNR's:

$$\begin{cases} \text{SNR}_1 = \text{SNR}_0 \\ \text{SNR}_2 = \text{SNR}_0 K_{sr} \frac{\mathbb{E}[\sigma_s]}{\mathbb{E}[\sigma]} \end{cases}$$

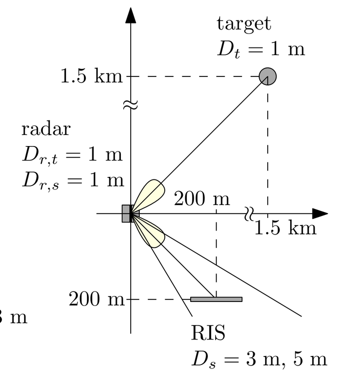
Preliminary conclusion: This scheme *always* results in an SNR gain.
Remark: The relevance of this gain depends on the system geometry and will be investigated later on.



## Performance assessment




Closely-spaced




Widely-spaced

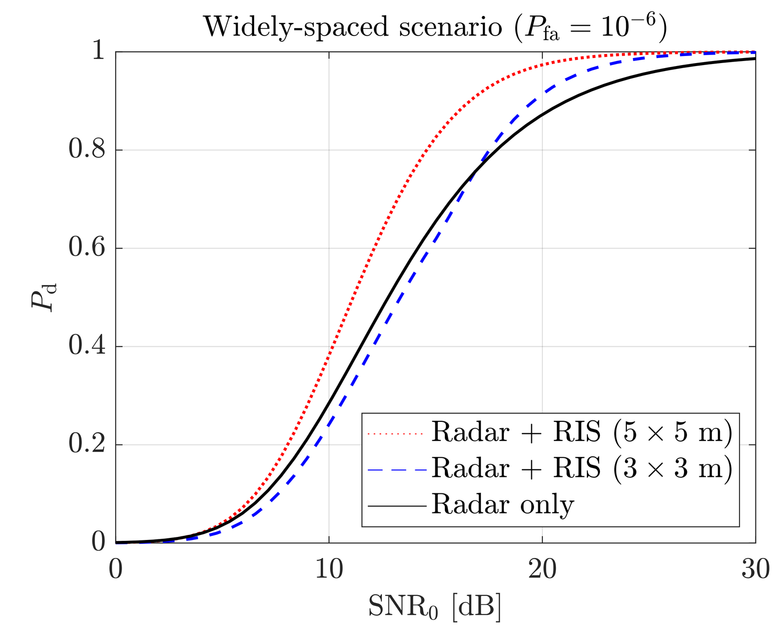
- Carrier at 3 GHz
- Radar Antennas: uniform square arrays of area 1 $m^2$ and $\frac{\lambda}{2}$ spacing
- Two transmit bandwidths: 1 and 10 MHz
- RIS sizes range from 2 to 5 meters, and $d_r$ is such that the area covered by the radar 3-dB bandwidth equals the RIS surface



## Performance

Closely-spaced scenario

| $D_s$ [m] <br> $d_r$ [m] | 2 <br> 22.9 | 2.5 <br> 28.6 | 3 <br> 34.4 | 3.5 <br> 40.1 | 4 <br> 45.8 | 4.5 <br> 51.5 | 5 <br> 57.3 |
|---|---|---|---|---|---|---|---|
| SNR gain [dB] | 4.78 | 6.17 | 7.41 | 8.53 | 9.54 | 10.5 | 11.3 |






## Comments and Conclusions

- In a closely-spaced scenario, the system Radar+RIS is seen as a unique *large* array, which explains the substantial SNR gains
- In a widely-spaced scenario, the RIS is just a source of angular diversity, whereby a visible advantage is observed only for high detection probabilities
- The results and the conclusions established here carry over (more or less) to the case of a power split between two transmit antennas (one pointed at the target, the other at the RIS) with a single receive beam pointed at the target