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 \( d_t \) from the RIS

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

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 are co-located (same angle of view)
- 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.

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 \( LP_{\ell}(b) \), where \( P_{\ell}(b) \) is the power consumption of a single unit with a 6-bit phase resolution. Typical values are:
  - \( b = 1, 3, 4, 5, 6 \)
    - \( P_{\ell}(b) \) (mW): 1.4, 4.5, 6, 7.8
- Thus RIS’s have become popular as energy-efficient alternatives to classical Amplify-and-Forward in terrestrial wireless networks.

Assumptions

- The radar is nanometer-sized, i.e. its bandwidth \( W \) satisfies \( \max(D_x, D_y, D_z) < \frac{W}{2\pi} \)
- All of the antennas are directive: \( \min(D_x, D_y, D_z) > \lambda \)
- The maxfield is a plane wave in the paths between radar and target, radar and RIS, and RIS and each element of the RIS, i.e.:
  \[
  \left\{ \begin{array}{ll}
  \rho \geq 2 \max(D^x, D^y, D^z) / \lambda \\
  \min(D^x, D^y, D^z) \geq 2 \max(D^x, D^y, D^z) / \lambda \\
  \min(D^x, D^y, D^z) \geq 2 \max(D^x, D^y, D^z) / \lambda
  \end{array} \right.
  \]
- \( \xi \) is the target attenuation (target → radar hop)
- \( \psi \) is the attenuation of the \( \ell \)-th RIS unit and the radar receive antenna

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

Radar Target Detection Aided by
Reconfigurable Intelligent Surfaces

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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:

\[
\begin{align*}
  x_1 &= \sigma_1 \mathcal{A} \mathcal{H} + \nu_1 \\
  x_2 &= \sum_{\ell=1}^{L} \sigma_\ell \mathcal{A} \mathcal{H}_\ell \mathcal{G} + \nu_2
\end{align*}
\]

\( \sigma_\ell \) and \( \sigma_1 \) are the unknown target RIS’s (\( \sigma_\ell \) for co-located case)

\( \{ \mathcal{A} \mathcal{H}_\ell \} \) are the phases of the radar-RIS channel

\( \{ \mathcal{A} \mathcal{G} \} \) are the adjustable RIS phases

\( \alpha \) is the target attenuation (target → radar hop)

\( \psi_\ell \) is the attenuation between the \( \ell \)-th RIS unit and the radar receive antenna

Performance assessment

- Carrier at 3 GHz
- Radar antennas: uniform square arrays of area \( 1 \text{ m}^2 \) 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

SNR Gain of the Radar+RIS system

Let \( \text{SNR}_R \) be the SNR in absence of RIS, we have:

- Closely-spaced Radar and RIS

\[
\text{SNR} = \text{SNR}_R (1 + K_r) \quad K_r = \frac{\gamma^2}{\gamma^2 + \frac{\sigma^2}{\text{SNR}_R}}
\]

- Widely-spaced Radar and RIS

Here we have two independent paths and two different SNR’s:

\[
\begin{align*}
  \text{SNR}_R &= \text{SNR}_R \\
  \text{SNR}_L &= \text{SNR}_R \frac{K_r}{K_\ell + K_r}
\end{align*}
\]

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.

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