RIS-aided monostatic MIMO Radar with co-located antennas

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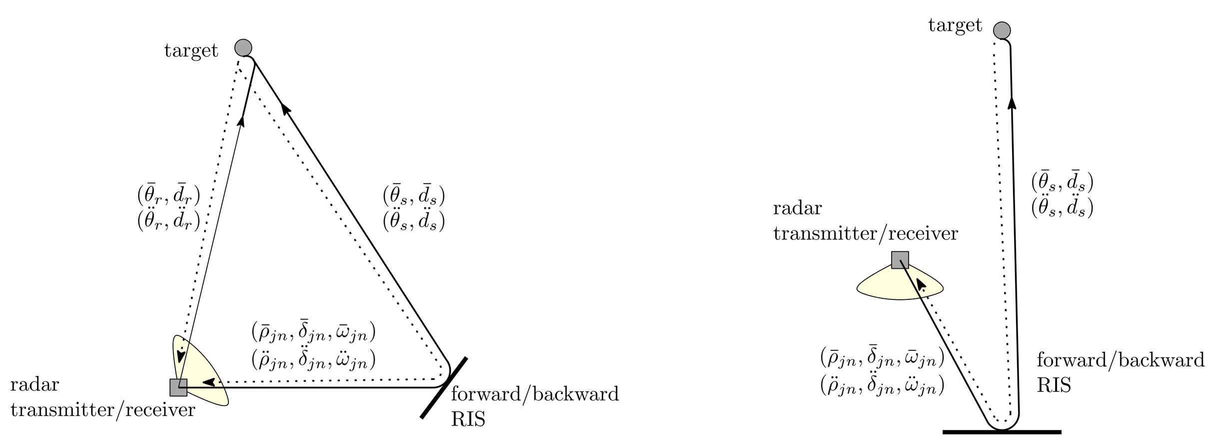
Basic contribution

- Co-located MIMO Radars emit (isotropically) orthogonal waveforms. The receiver undertakes space-time processing in order to sense the surrounding scene
- Thus an RIS—i.e., a low-consumption surface with reflecting unit capable of changing the phase of the incoming signal—placed anywhere *around* the MIMO transceiver is hit by *astray signals*, and may vary their phases in order to help the receiver exploit such an otherwise lost energy
- The basic question we want to answer is whether or not the achievable gains are worth the additional hardware required by such an architecture.

Possible configurations



(a) LOS monostatic configuration

(b) NLOS monostatic configuration

Comments

- LOS: up to four rays can be exploited to increase the target detectability, i.e. *direct radar/target paths*:
  a. Radar→Target→Radar
  b. Radar→RIS→Target→Radar

  and *indirect paths*:
  c. Radar→Target→RIS→Radar
  d. Radar→RIS→Target→RIS→Radar
- NLOS: Here the Radar may only rely on the RIS (in both forward and backward scattering modes) in order to capture the target echo

System Geometrical parameters

- The radar and the RIS are in the target far field. We thus define
  - $\bar{\boldsymbol{v}}_r$ and $\ddot{\boldsymbol{v}}_r$ the steering vectors between target and radar transmitter and receiver, respectively
  - $\boldsymbol{v}_s$ is the steering vector between the RIS and the target
- $\boldsymbol{\varphi} = [\varphi_1, \dots, \varphi_{N_s}]^T$ are the RIS phase shifts;
- $\bar{\boldsymbol{G}}$ and $\ddot{\boldsymbol{G}}$ are the normalized channel matrices between radar transmitter/receiver and RIS, respectively
- $\bar{\gamma}_r$ and $\bar{\gamma}_s$ are the complex amplitudes of the forward paths between radar and target/RIS
- $\ddot{\gamma}_r$ and $\ddot{\gamma}_s$ are the complex amplitudes of the backward paths between target and radar/RIS
- $\boldsymbol{X}(\boldsymbol{\varphi}) = \mathrm{diag}(\boldsymbol{\varphi}) \in \mathbb{C}^{N_s \times N_s}$
- α encapsulates the unknown target response.

Received signal model

- For each of the $\ddot{N}_r$ spatial channels separation between the $\bar{N}_r$ orthogonal waveforms is undertaken
- Sampling at approximately $\frac{1}{W}$ thus yields, for each cell, $N_r = \ddot{N}_r \bar{N}_r$ space-time samples, arranged in $\boldsymbol{r} \in \mathbb{C}^{N_r}$ as

$$\boldsymbol{r} = \underbrace{\left(\bar{\gamma}_r \bar{\boldsymbol{v}}_r + \bar{\gamma}_s \bar{\boldsymbol{G}} \boldsymbol{X}(\boldsymbol{\varphi}) \boldsymbol{v}_s\right) \otimes \left(\ddot{\gamma}_r \ddot{\boldsymbol{v}}_r + \ddot{\gamma}_s \ddot{\boldsymbol{G}} \boldsymbol{X}(\boldsymbol{\varphi}) \boldsymbol{v}_s\right)}_{\boldsymbol{e}(\boldsymbol{\varphi})} \alpha + \boldsymbol{w}$$

Remark: The RIS phase vector $\boldsymbol{\varphi}$ is the degree of freedom that can be exploited for optimization purposes

Optimization

- Let $\boldsymbol{f} \in \mathbb{C}^{N_r}$ be the unit-norm (space-time) filter employed at the receiver
- The SNR available at the radar receiver is obviously

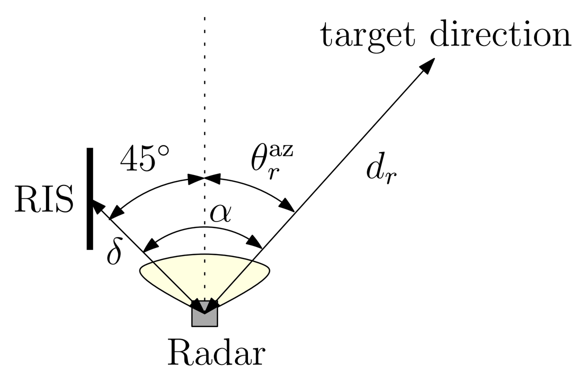
$$\mathrm{SNR} = \left|\boldsymbol{f}^H \boldsymbol{e}(\boldsymbol{\varphi})\right|^2 \sigma_\alpha^2 / \sigma_w^2$$

  which is maximized for $\boldsymbol{f} = \frac{\boldsymbol{e}(\boldsymbol{\varphi})}{\|\boldsymbol{e}(\boldsymbol{\varphi})\|}$
- The problem is now to find out the N_s optimum phases whereupon the above solution depends
- Lacking a closed-form solution, we resort to a sub-optimum solution based on optimizing one phase shift at a time (alternating maximization)

Performance assessment: simulated scenario

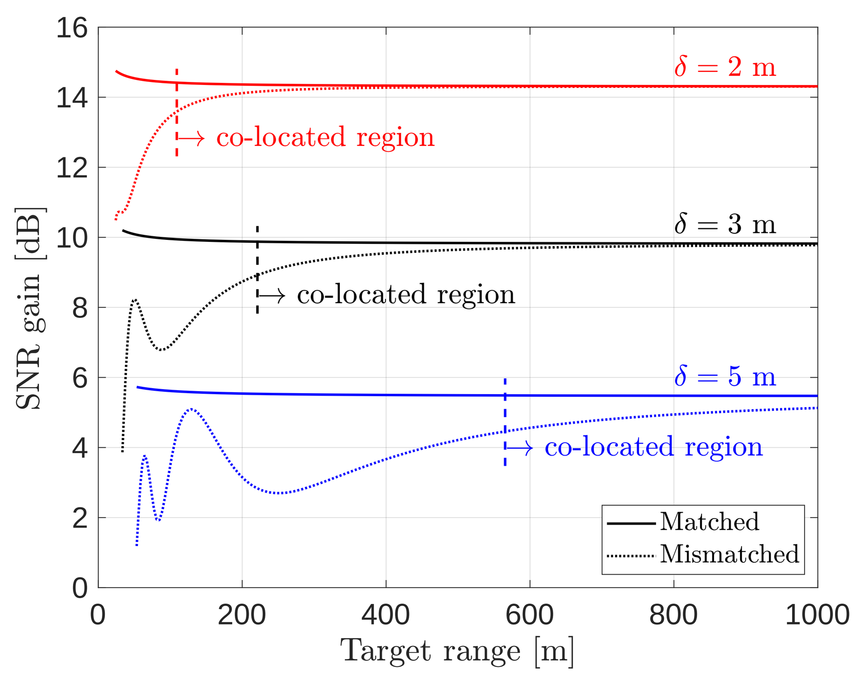
The geometry we focus upon is outlined in the figure

- Wavelength $\lambda = 10$ cm (3 GHz);
- $\ddot{N}_r = \bar{N}_r = 4$, $N_s = 225$ (15×15);
- Each antenna element has a power beampattern with 3-dB width 120° in azimuth and of 60° in elevation.
- The target is a square of size 50×50 cm^2.



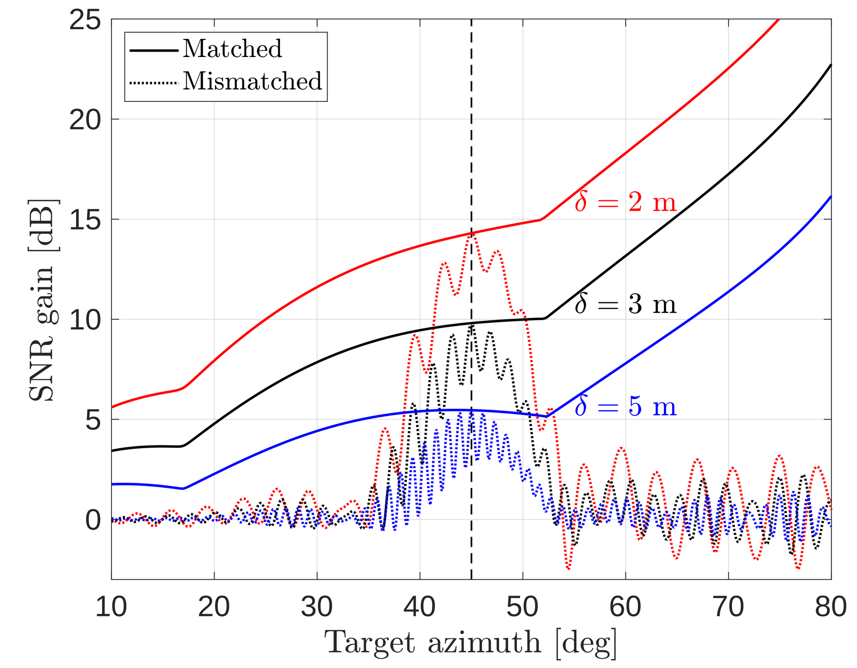
SNR gain vs target range

Matched: Nominal and true target azimuth coincide
Mismatched: Optimization is conducted at infinity

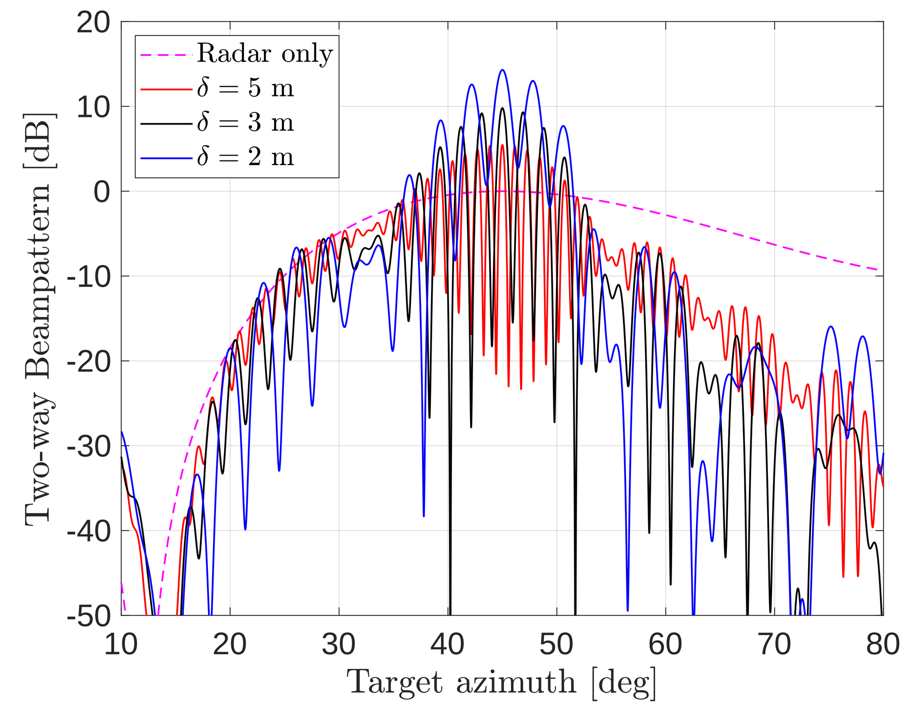


SNR gain vs target azimuth

Matched: Nominal and true target azimuth coincide
Mismatched: nominal azimuth = 45°, true azimuth on the abscissa



Two-way beampattern (nominal azimuth 45°)



Comments and Conclusions

- The RIS must be placed in close proximity (in the order of meters) to the radar, since attenuation would otherwise eat out indirect rays
- if $D_{\max}$ is the maximum distance between any element of the RIS and any element of the transmit/receive radar array the two are seen as co-located if $r > 2D_{\max}^2/\lambda$: beyond this distance the optimum RIS focusing is range-independent (focusing at infinity)
- Co-located Radar and RIS yield the most significant gains
- In regard to azimuth, the largest gain is for $\theta_r^{az} = 90°$, since the target *sees* the whole RIS aperture, while seeing smaller and smaller parts thereof as θ_r^{az} approaches 0
- If there is mismatch between the nominal and the actual target azimuth the gain takes on an oscillatory behavior; in any case the presence of the RIS is almost always beneficial, since the SNR Gain (in dB) is almost always > 0