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Performance Analysis for RIS Assisted Wireless Sensing

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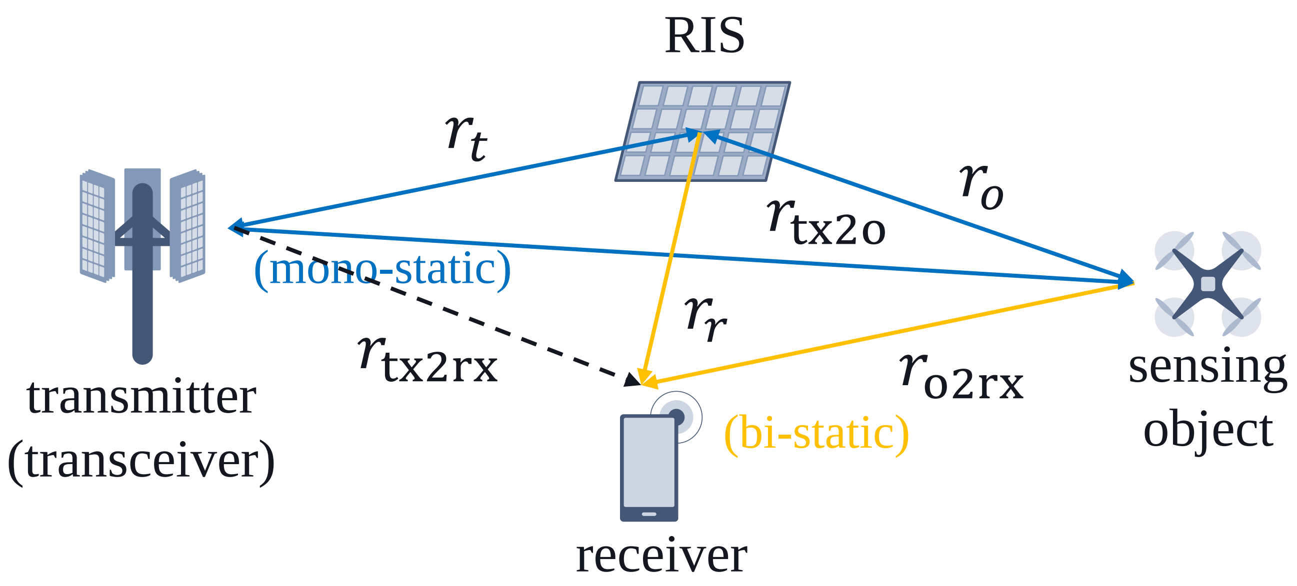
Outline

- System model
- Pathloss and SNR analysis
- Evaluation

System Model

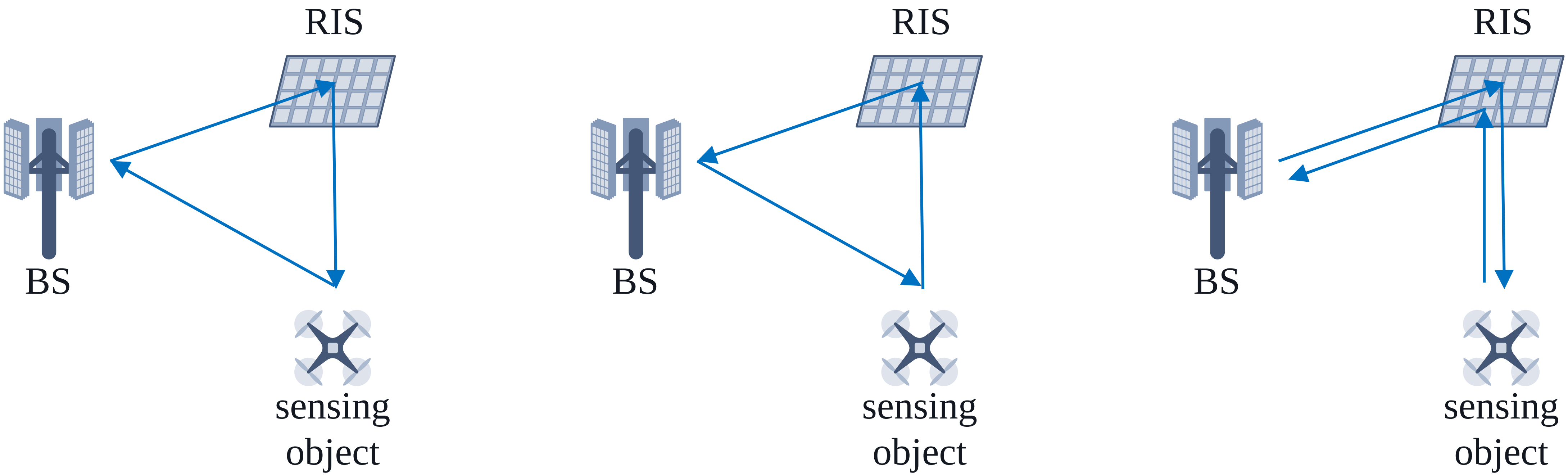


- RIS-assisted communications
  - RIS enhances the communication link btw Tx and Rx.
- RIS-assisted sensing: mono-static and bi-static
  - Enhancing power of indirect links which are reflected by RISs, to exceed power of direct link.
  - Bypassing blockage in direct links.

System Model

- Paths of RIS-assisted mono-static sensing

BS→RIS→object→BS BS→object→RIS→BS BS→RIS→object→RIS→BS



Receive Power of Sensing Assisted by RIS

Monostatic Sensing: BS → RIS → object → RIS → BS

[Ref] W. Tang et al., "Wireless Communications With Reconfigurable Intelligent Surface: Path Loss Modeling and Experimental Measurement," in IEEE Transactions on Wireless Communications, vol. 20, no. 1, pp. 421-439, Jan. 2021. (SEU)

- Reflected power at the object: BS → RIS → object

Unit cell radiation pattern

$$P_{\text{object,rf}} = P_t G_t G_{\text{cell}} \frac{l_M l_N \,\text{RCS}}{(4\pi)^2} \left| \sum_{m=1}^{M} \sum_{n=1}^{N} \frac{\sqrt{F(\theta_{m,n}^{\text{BS}}) F\left(\theta_{m,n}^{\text{object}}\right)}\, a_{m,n} e^{j\left(\phi_{m,n} - 2\pi \frac{r_{m,n}^{\text{BS}} + r_{m,n}^{\text{object}}}{\lambda}\right)}}{r_{m,n}^{\text{BS}} r_{\text{m,n}}^{\text{object}}} \right|^2$$

- Received power at BS: object → RIS → BS
  - General model:

$$P_{\text{BS,rx}} = P_{\text{object,rf}}\, G_r G_{\text{cell}} \frac{l_M l_N \lambda^2}{(4\pi)^3} \left| \sum_{m=1}^{M} \sum_{n=1}^{N} \frac{\sqrt{F\left(\theta_{m,n}^{\text{object}}\right) F(\theta_{m,n}^{\text{BS}})}\, a_{m,n} e^{j\left(\phi_{m,n} - 2\pi \frac{r_{m,n}^{\text{object}} + r_{m,n}^{\text{BS}}}{\lambda}\right)}}{r_{m,n}^{\text{object}} r_{m,n}^{\text{BS}}} \right|^2$$

Maximize (RIS beam forming): $\phi_{m,n} = 2\pi \frac{d_{m,n}^{\text{BS}} + d_{m,n}^{\text{object}}}{\lambda}$

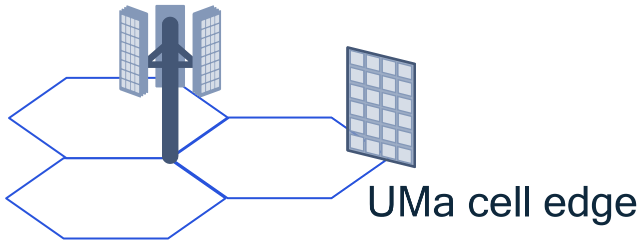
Far field approximate

$\boxed{K = MN}$

$$P_{\text{BS,rx}}^{\text{max, farField}} = P_t G_t G_r \frac{\text{RCS}\left(G_{\text{cell}} \lambda l_M l_N F(\theta^{\text{BS}}) F\left(\theta^{\text{object}}\right)\right)^2 (aK)^4}{(4\pi)^5 (r^{\text{BS}} r^{\text{object}})^4}$$

Receive power increases with the fourth power of the number of RIS unit cells

Power Gain of RIS in Monostatic Sensing



Comparison of RIS in Communications and Sensing

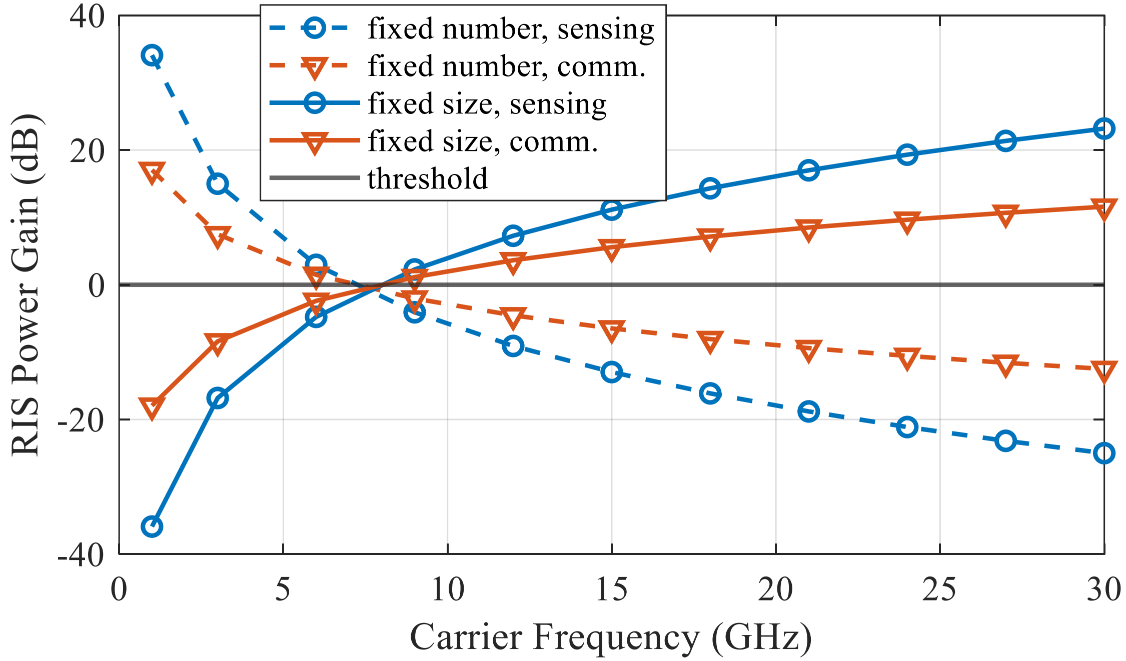
$$\eta_{\mathrm{sens}} = \frac{(GF^{\mathrm{sens,t}})^2 (a r_{\mathrm{tx2o}})^4}{(4\pi F^{\mathrm{tx}}(\theta_{\mathrm{tx2o}})\beta)^2 (r_t r_o \lambda)^4} A_{\mathrm{RIS}}^4,$$

$$\eta_{\mathrm{comm}} = \frac{GF^{\mathrm{comm}} (a r_{\mathrm{tx2rx}})^2}{4\pi F^{\mathrm{tx}}(\theta_{\mathrm{tx2rx}})\beta (r_t r_r \lambda)^2} A_{\mathrm{RIS}}^2,$$

$$A_{\mathrm{RIS}} = MNA_{\mathrm{cell}} = MN\beta\lambda^2, \;\; \beta = 1/16$$

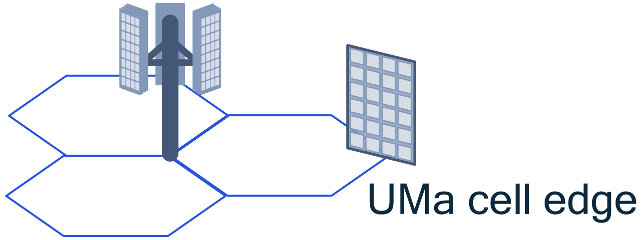
Amplitude of RIS reflection coefficient $a = 0.7$

Power gains brought by RISs in sensing and communications with the fixed unit cell number (100x100) or the fixed RIS size (1 m^2)



- Higher carrier frequency
  - Fixed unit cell number: the advantage of RIS assisted sensing over communications reduces
  - Fixed RIS size: the advantage of RIS assisted sensing over communications grows

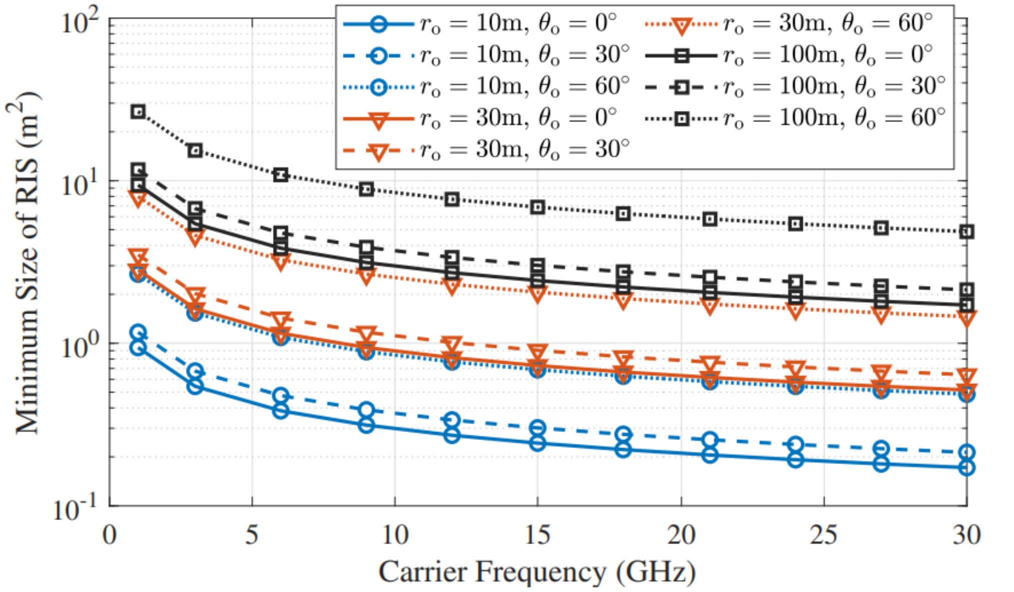
Required RIS Size in Monostatic Sensing



The minimum size of RIS in mono-static sensing to achieve the receiver sensitivity

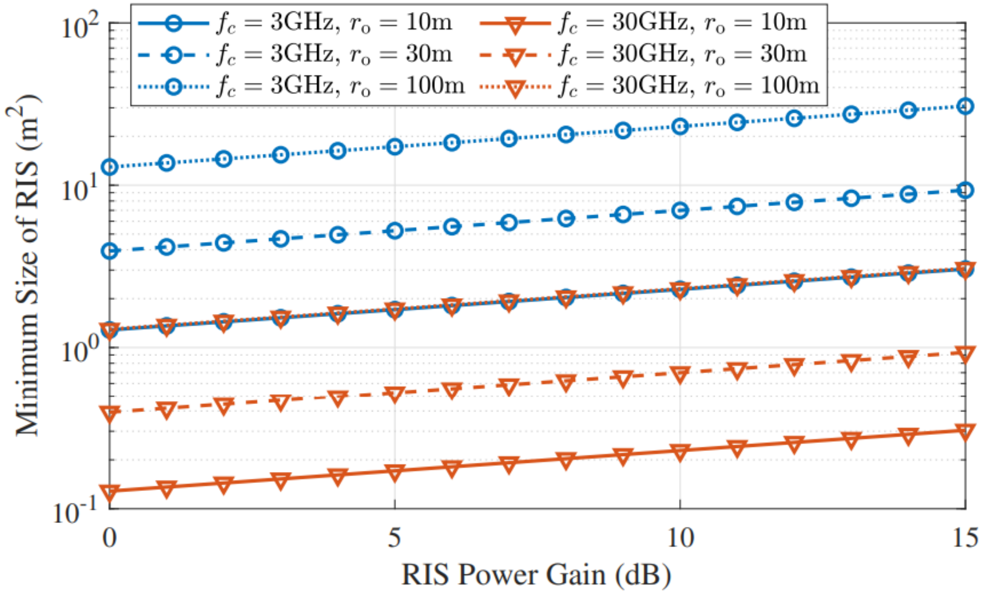
SNR sensitivity −16.5 dB

$$A_{\text{RIS}} \geq \left(\frac{\rho_0 P_n (4\pi)^5 \beta^2 \lambda^2}{P_t G_t G_r \sigma (G F^{\text{sens},t})^2} \right)^{\frac{1}{4}} \frac{r_t r_o}{a}.$$



The minimum size of RIS in mono-static sensing to achieve a given power gain

$$A_{\text{RIS}} > \frac{(4\pi F^{\text{tx}}(\theta_{\text{tx2o}})\beta)^{\frac{1}{2}} r_t r_o \lambda}{(G F^{\text{sens,t}})^{\frac{1}{2}} a r_{\text{tx2o}}} \eta_{\text{sens}}^{\frac{1}{4}}.$$

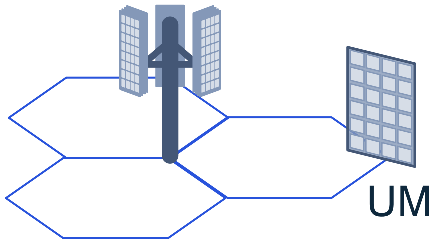


- Higher carrier frequency → Smaller required RIS size
- RIS size grows slowly with the increasing of target power gain

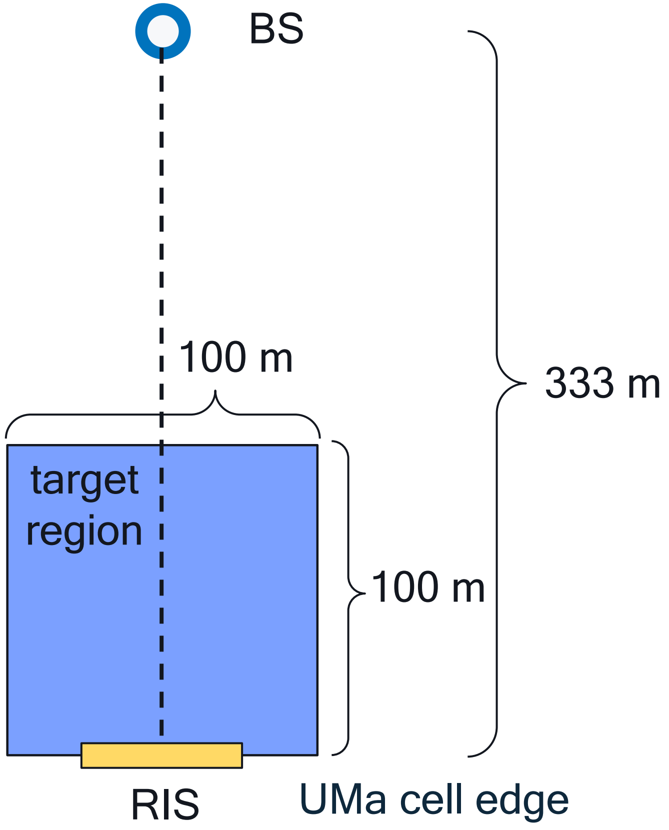
SNR for Sensing Assisted by RIS

Monostatic Sensing: BS → RIS → object → RIS → BS

- System Parameters
  - Carrier frequency = 3.5 GHz, BW = 100MHz, comb 4 RS
  - BS:
    - $P_t = 49$ dBm (TR 38.855), $G_t = G_r = 8$ dBi,
    - Antenna uptilt 0°, beamforming gain = 12 dB
    - Noise figure = 8 dB, noise density -174 dBm/Hz
  - RIS:
    - Surface size $M = N = \sqrt{K}$
    - Unit cell size $l_M = l_N = \lambda/4$, amplitude of coefficient $\alpha = 0.7$
    - Varactor-diode or 2-bitquantized PIN-diode
- SNR = $\frac{P_{\mathrm{BS,rx}}}{kT_0BF_n}$
  - Paths other than the direct link can be neglected
    - Non-target reflections assumed removed by radar processing
    - TR36.777 (target UAV): 15 dB for the target LOS/NLOS ratio over Rician channels



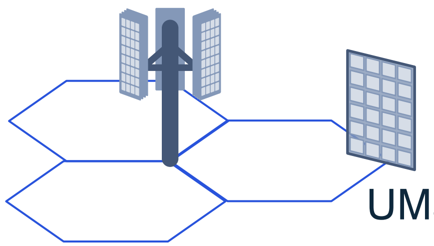
Geometry (top view):



Assume BS, RIS and objects are same in height for in the initial analysis

SNR for Sensing Assisted by RIS

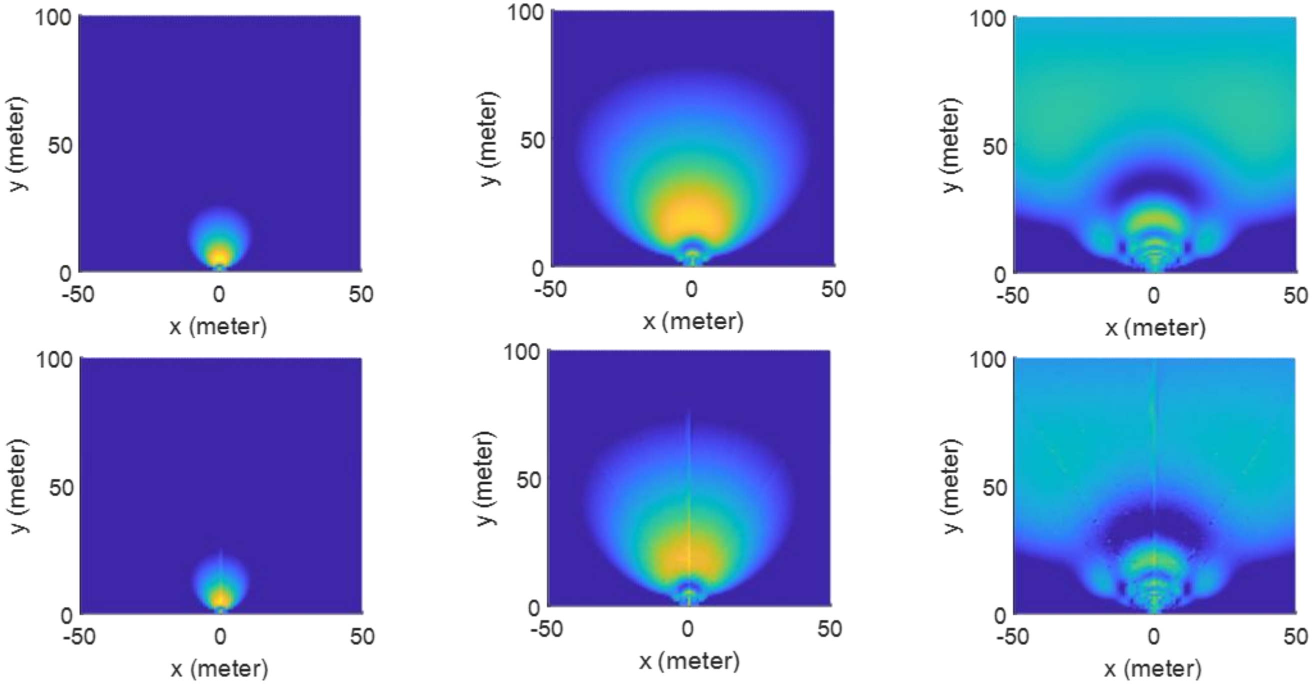
Comparison RIS size and quantization



- **Color shows** SNR of BS → RIS → object → RIS → BS **minus** SNR of BS → object → BS

Unit Cell Number K: **50x50** (1mx1m) **100x100** (2.1mx2.1m) **200x200** (4.3mx4.3m)

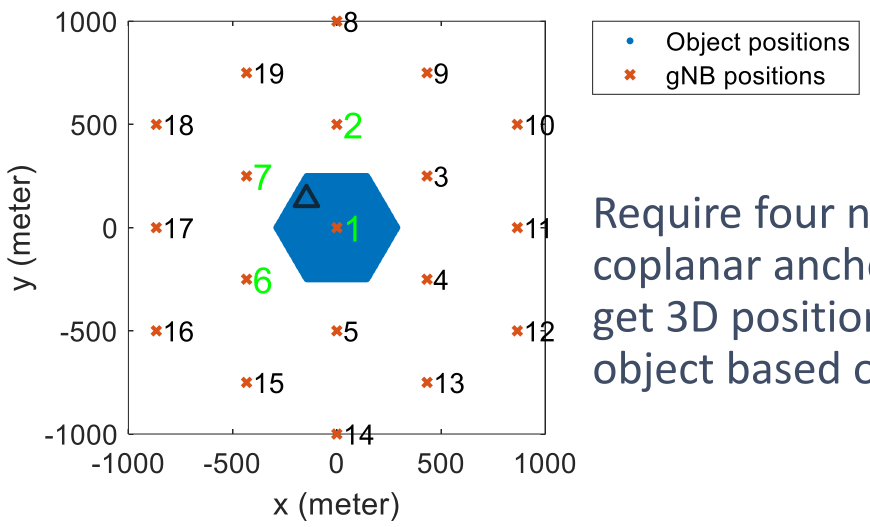
- 2D beamforming
  - Coefficients by the far field model
  - Varactor-based RIS
- 2-bit quantized 2D beamforming
  - Coefficients by the far field model
  - PIN-diode RIS



- Impact of the quantization of two bits and more on the RIS beamforming gain could be neglected.

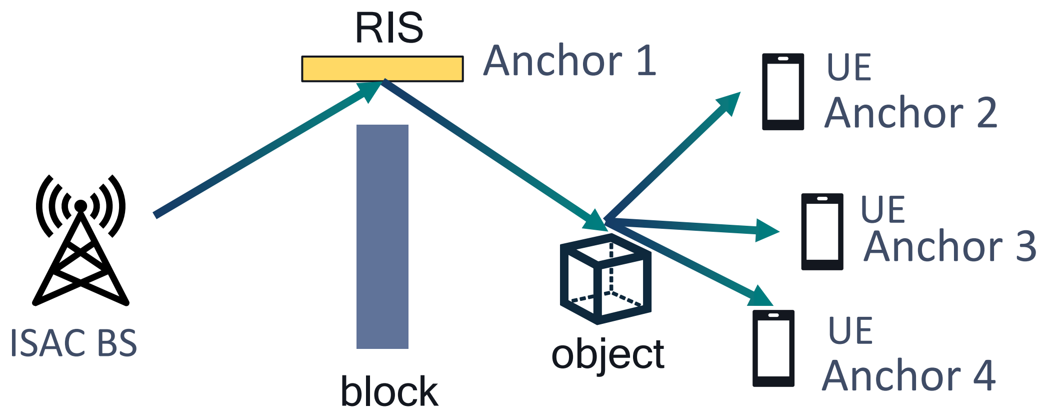
Utilization of RIS in Sensing

- New anchor node
  - New anchor by RIS to replace the 4th largest SNR BS in the object 3D locating with higher SNR
    - For the object position denoted by the triangle, the four largest SNR BS is BS 1, 2, 6 and 7, where the 4th largest SNR BS is BS 6.
    - RIS can reflect signals from BS 1 to exceed the SNR of BS 6 at the object position.



Require four non-coplanar anchors to get 3D position of object based on ToF.

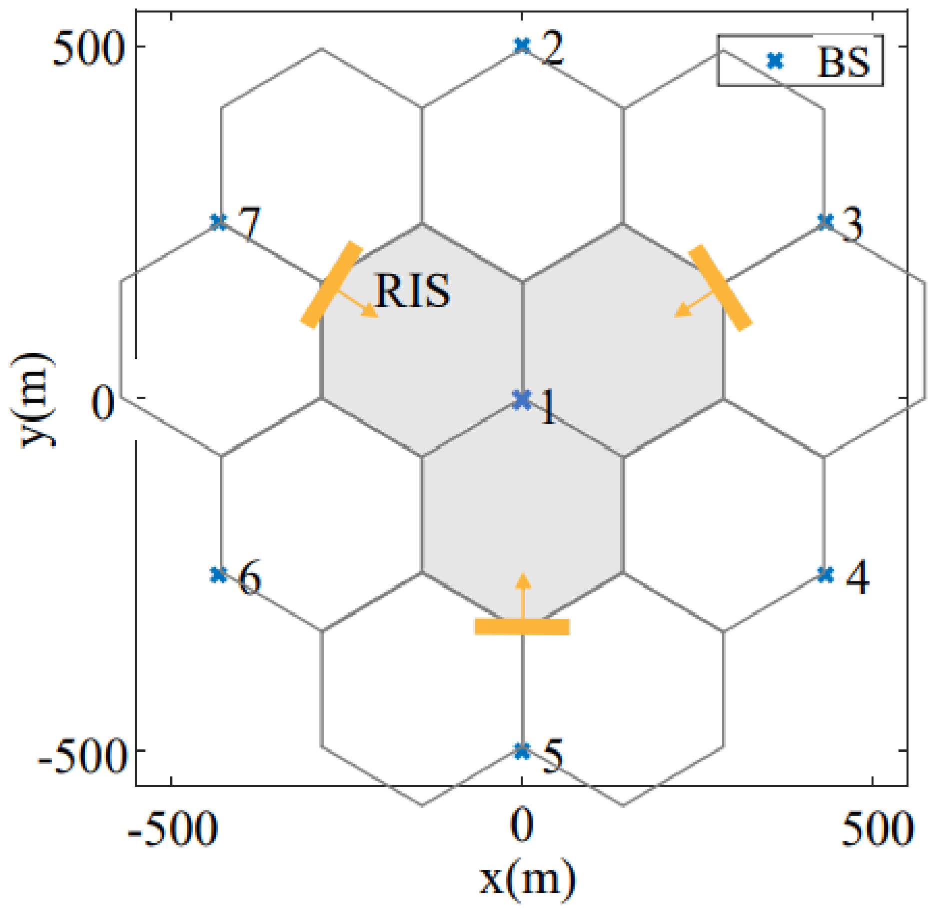
- RIS to provide additional sensing/positioning RS
  - RIS can extend the coverage to the area with LOS blockage between the BS
  - UEs in the blockage can be served by RIS for communications and serve as sensing RS receivers.



System Setup

Four-Point Localization in 3D

- Baseline: BS monostatic
  - Require four reference BSs not in the same plane
    - Height of the 19 BSs is uniformly distributed in [20,50] m (38.855 UMa outdoor)
    - **Four reference point**: Select the four largest SNR BSs, not in the same plane.
- RIS-based: BS + RIS
  - RIS provide a new reference point
    - Height of all RISs is 10 m
    - **Four reference point**: Select the three largest SNR BSs and RIS



Simulation Results

UAV Sensing as an Example

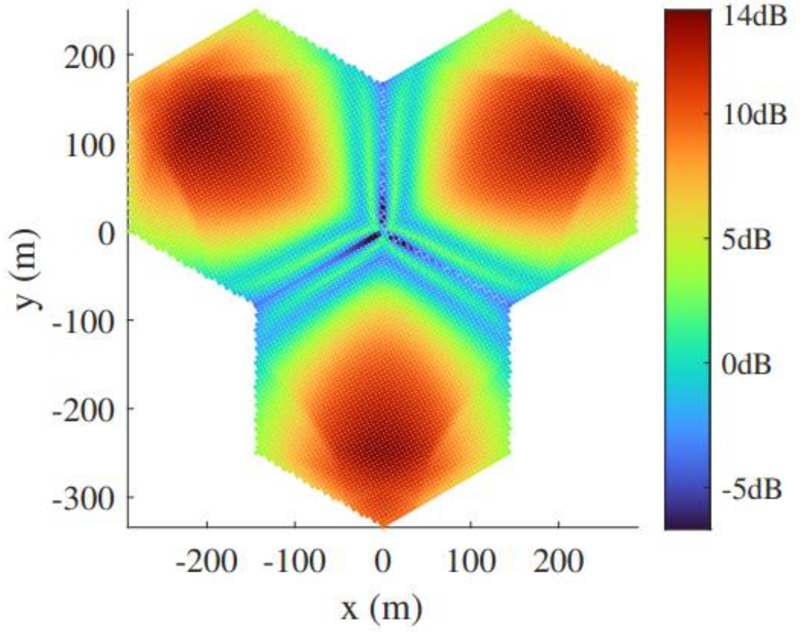
Simulation settings

- Carrier frequency is 3.5 GHz
- RIS size is $M = N = 100$, $\alpha = 0.7$, RISs adopt far-field beamforming and the BSs have a beamforming gain of 12 dB
- Sensing object is assumed as drones with RCS $\sigma = 0.01\ m^2$ at the height of 120 m
- RIS-based sensing: RIS height is 10 m with uptilting of 20°, and the BS height is 25 m with uptilting of 0°
- Sensing w/o RIS: BS height is uniformly distributed in the range of 20~50m
- Algorithm: Gauss-Newton

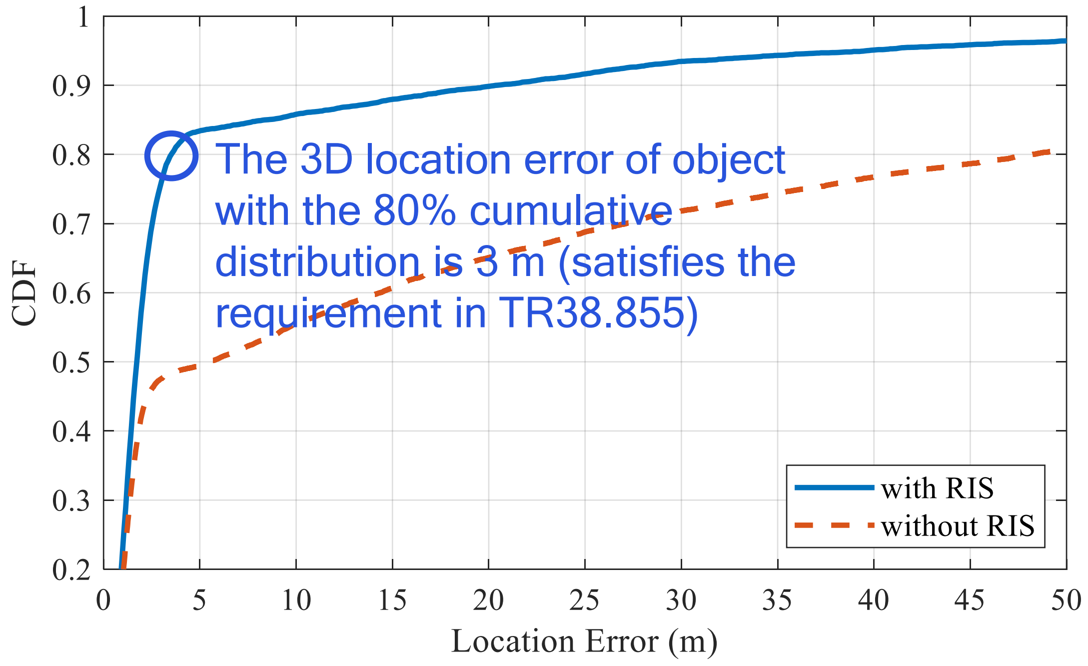
- SNR Gain by RIS
  - Achieve an average SNR gain of 6.7 dB compared to the 4th-highest SNR BSs.

- Localization Error
  - Bottleneck is the 4th-highest-SNR device → much smaller error in sensing assisted by RISs

SNR Gain by RIS in the coverage of a BS



CDF of Localization Error



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