PRISM: Practical Design and Orchestration of Frequency-Shifting RIS for NLoS mmWave Sensing

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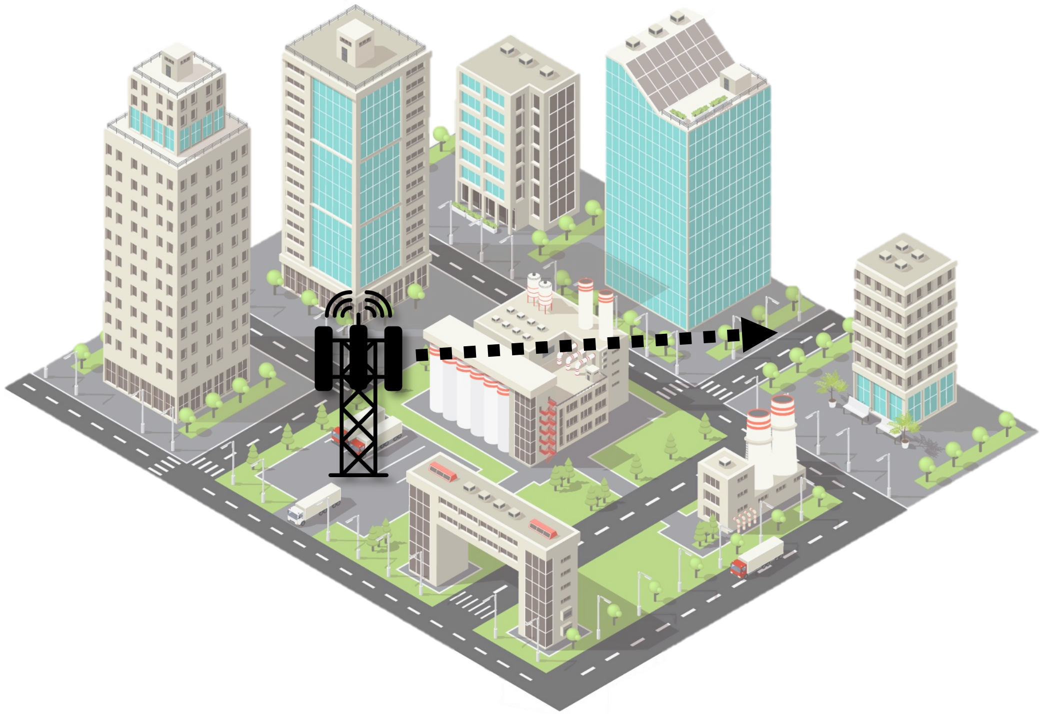
NLoS mmWave Sensing

- mmWave sensing deployments suffer due to lack of LoS in most environments

Indoor: Walls and furniture obstruct LoS for commodity radars



Outdoor: Buildings cause large-scale shadowing for dual-function radar-communication systems

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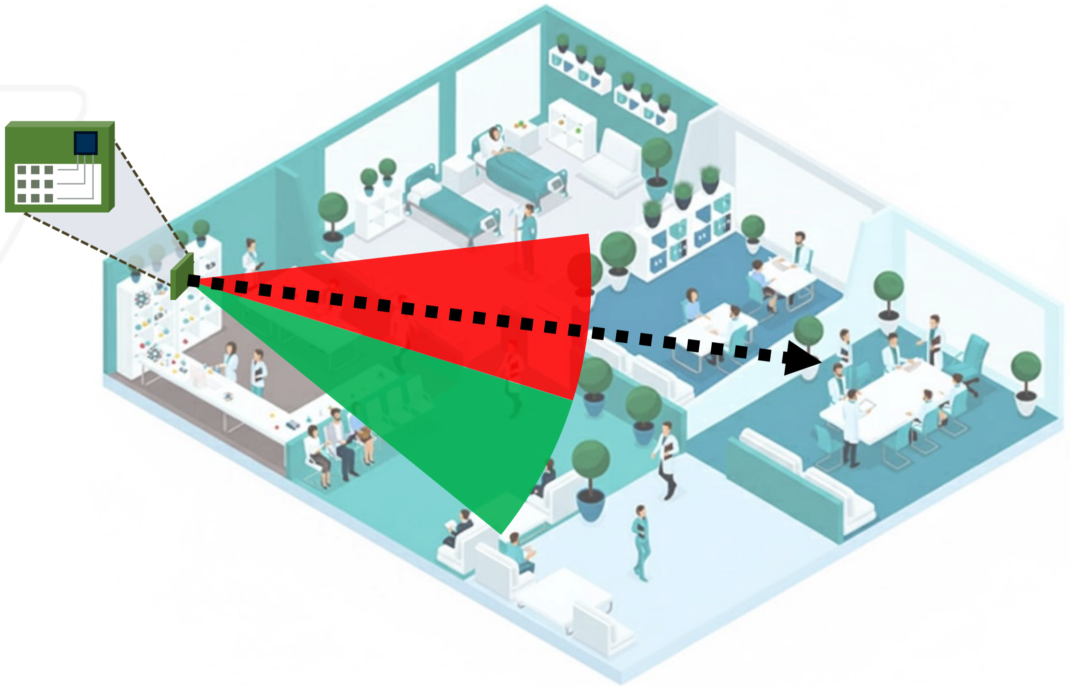

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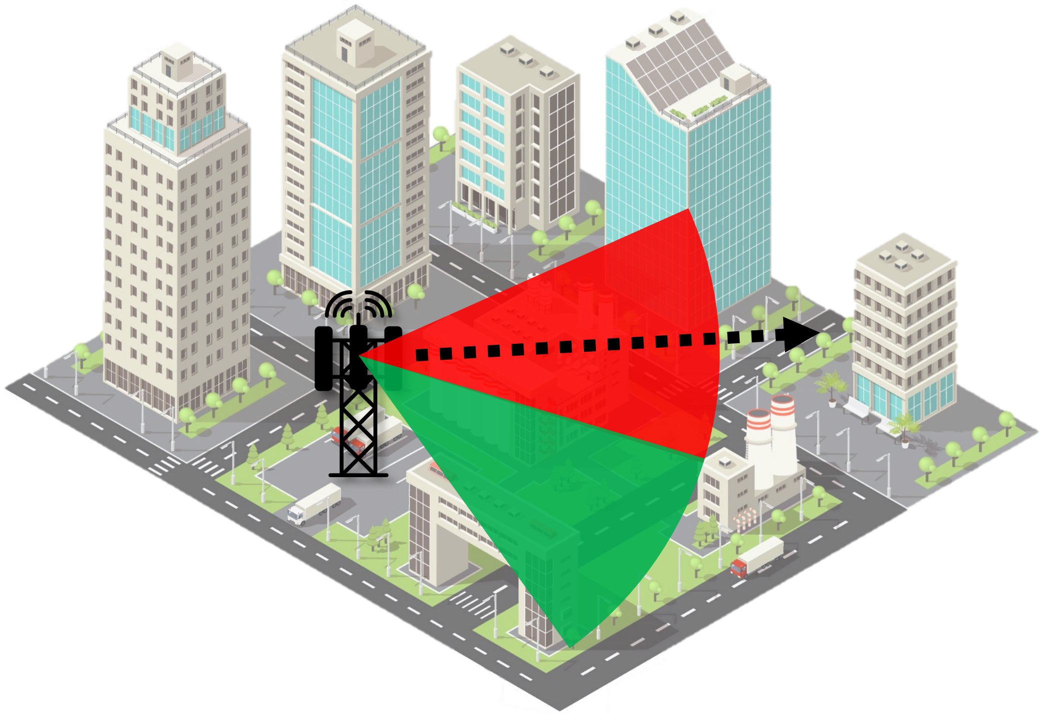

Outdoor: Buildings cause large-scale shadowing for dual-function radar-communication systems

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Existing Solutions

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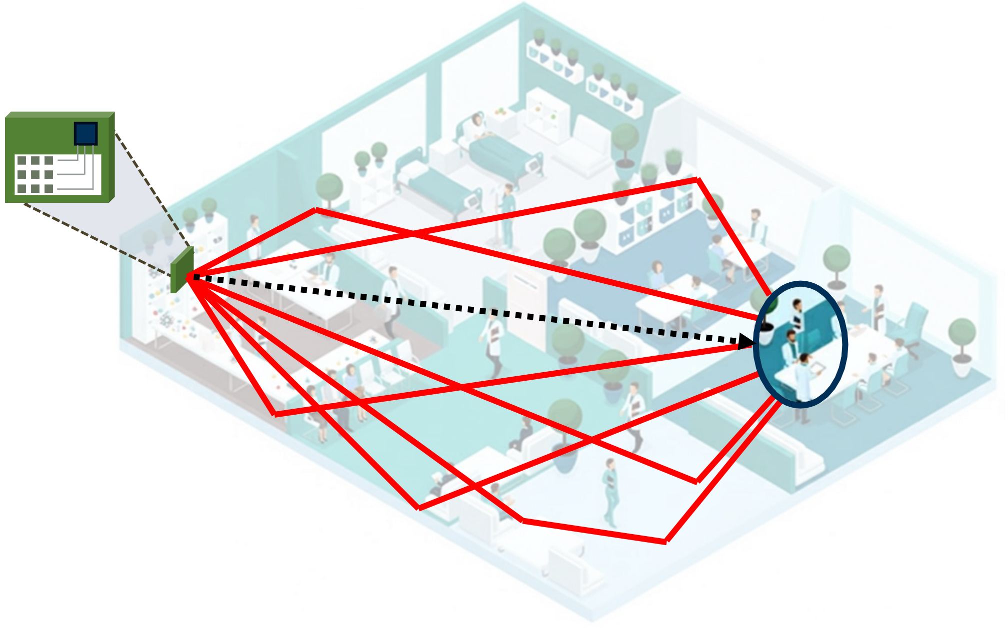
- Rely on effective **geometric modeling** of the environment

Ray tracing-based approaches

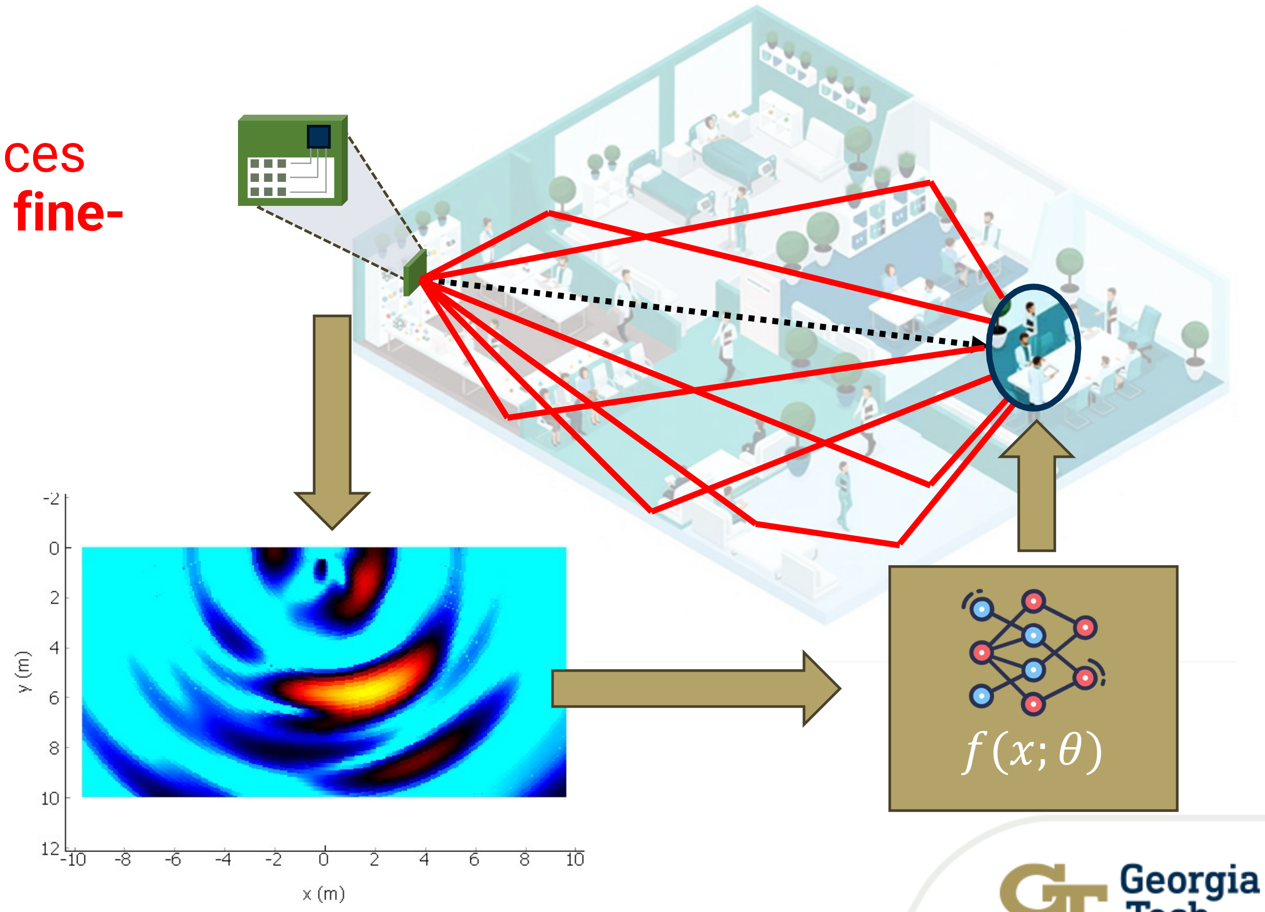


Existing Solutions

- Rely on effective **geometric modeling** of the environment

- Deployment of ML models on commodity devices requires **high compute**; ML models need to be **fine-tuned to specific environments**

Machine learning-based approaches



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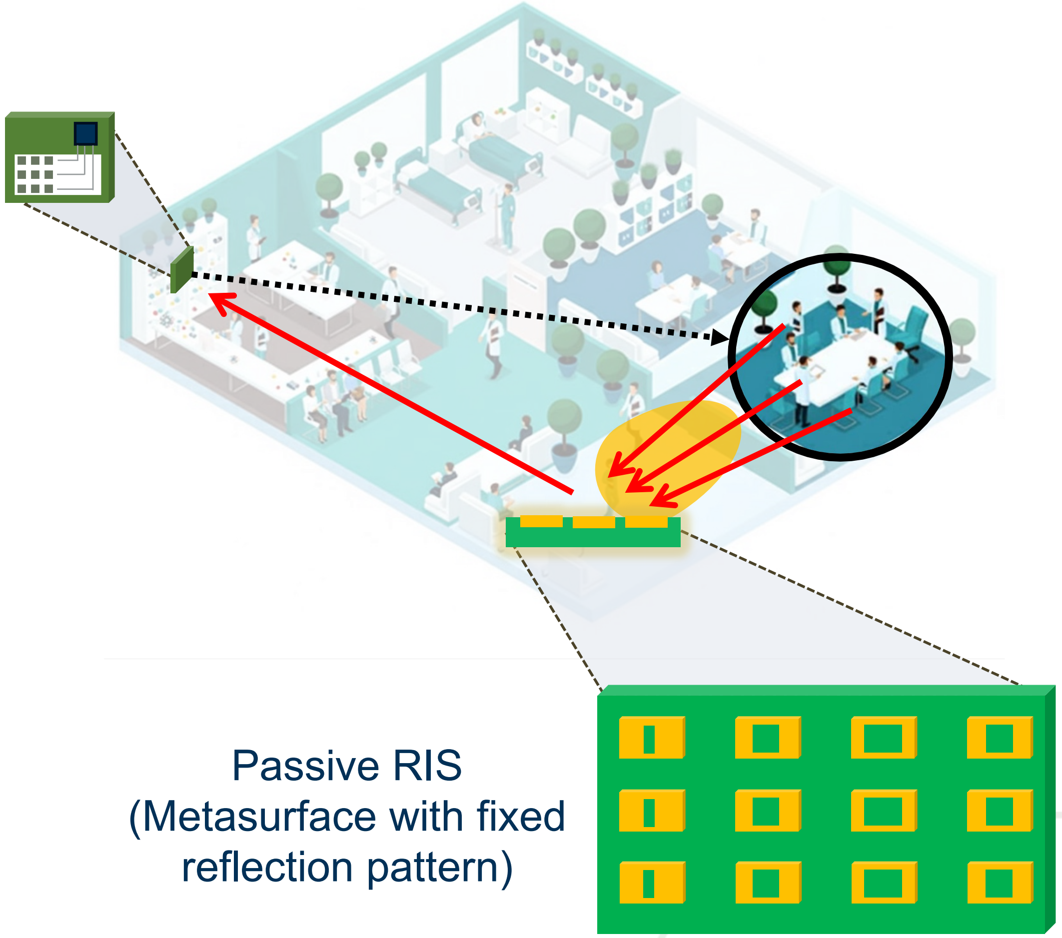
- **Poor** (or no) **angular resolution** with passive reflector in NLoS regions with large multipath effects

RIS-based approaches



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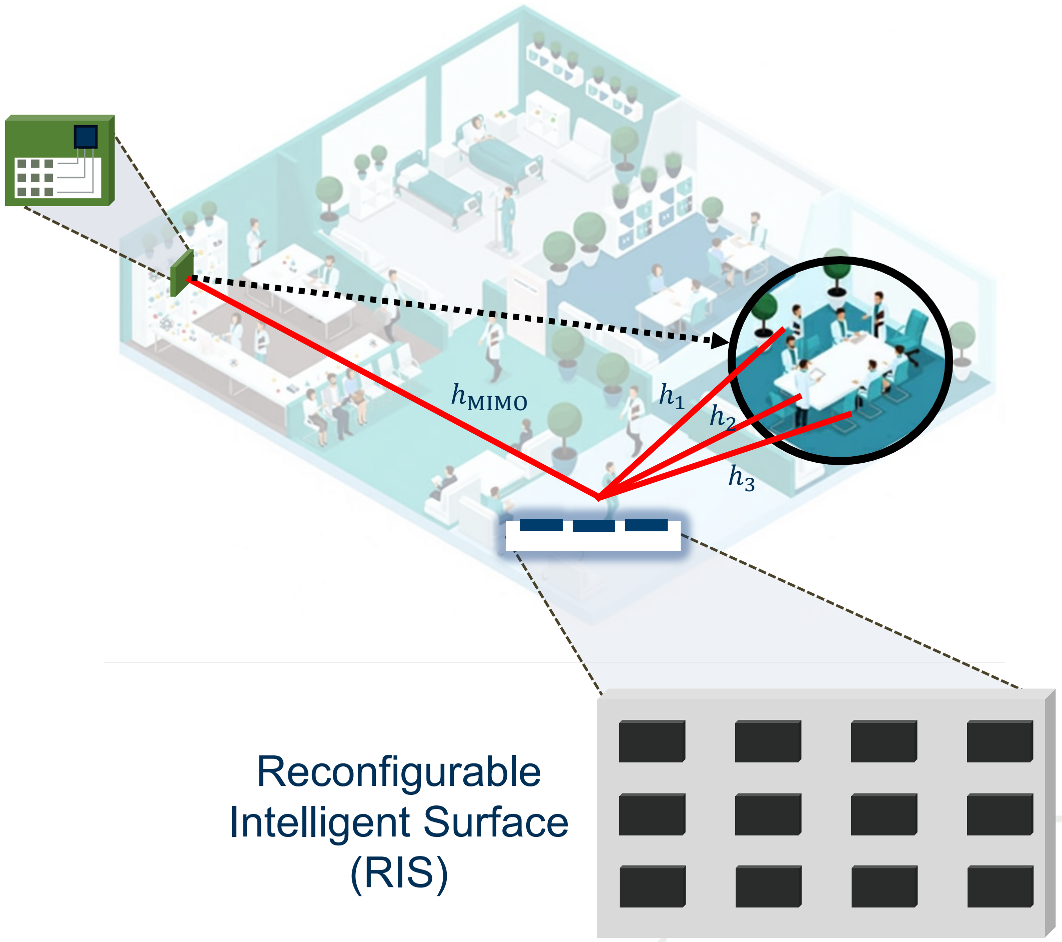
RIS-based approaches



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- Active RIS **require MIMO and/or fine-time co-ordination** with radar

Key Requirements

1. Resolve angles of incidence signals **simultaneously**
2. Enable **beamforming** for multipath suppression
3. No **active components / time synchronization** with the radar
4. **Seamlessly integrate** into the radar's signal processing

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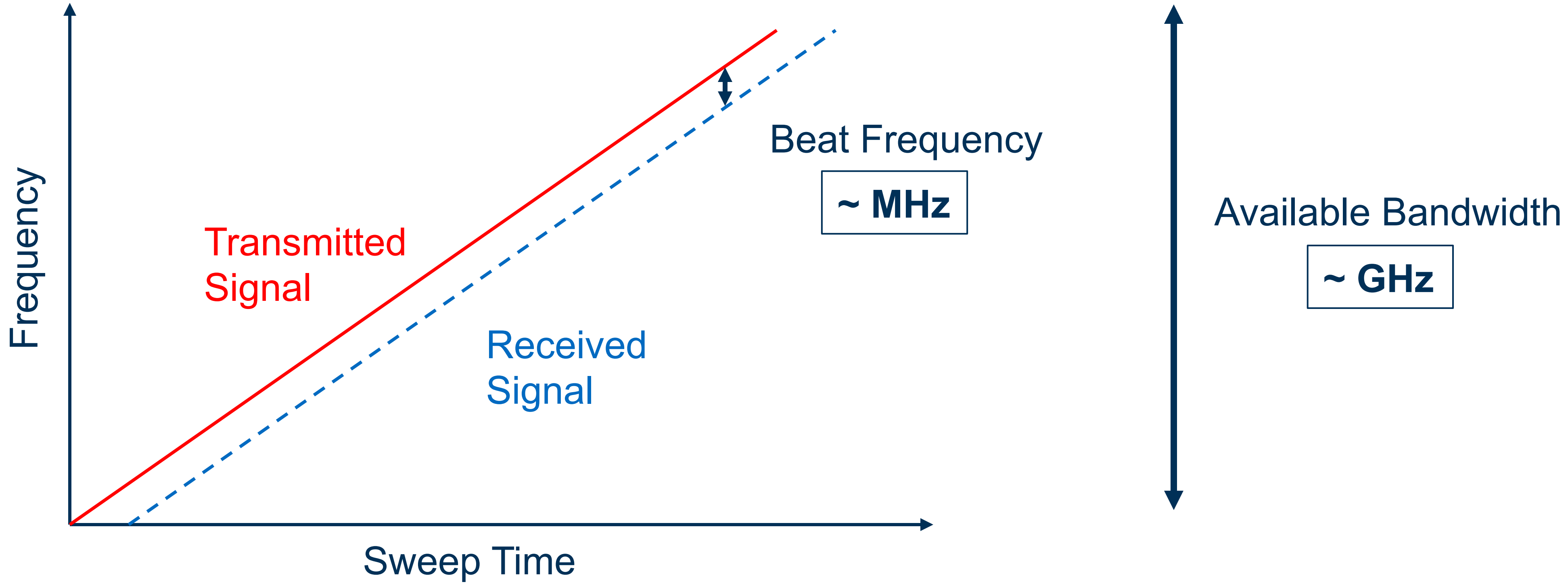
Basics of FMCW/Chirp Radars

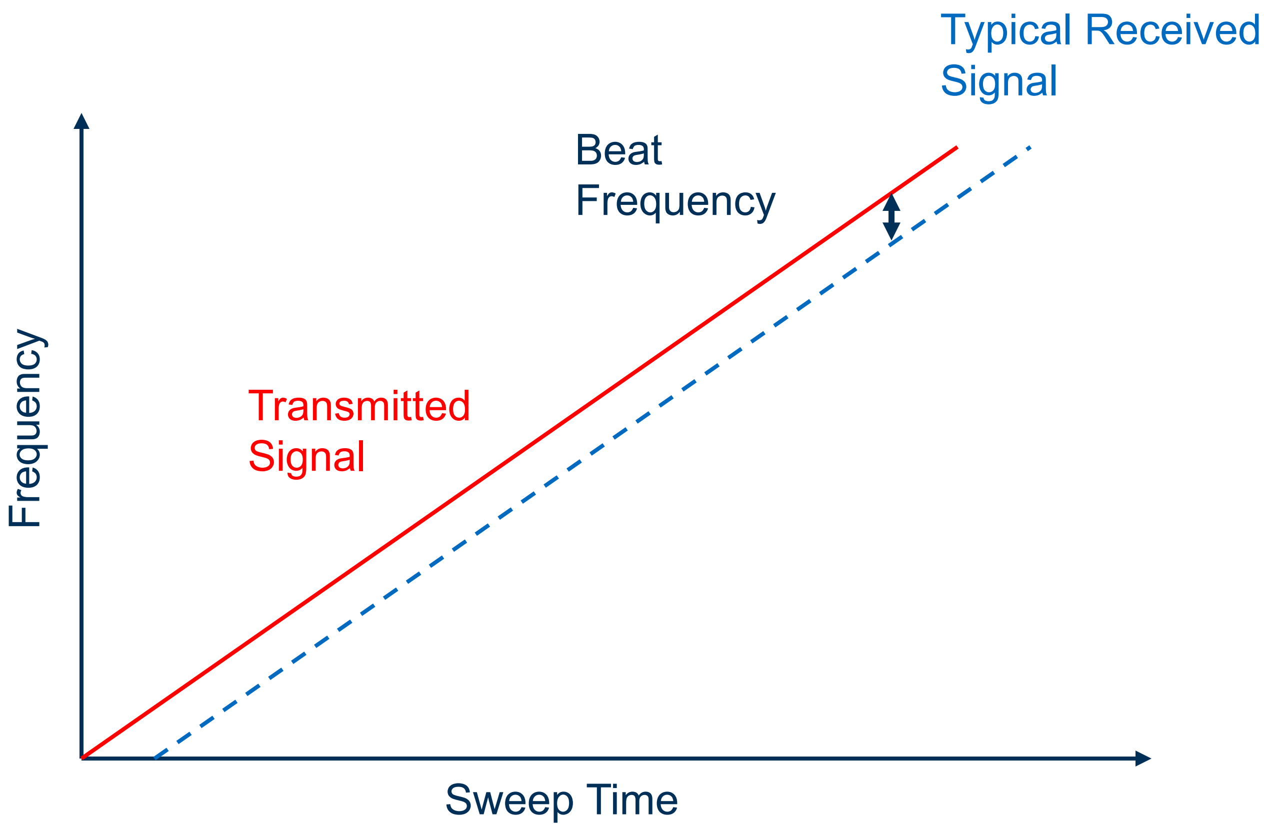
- Frequency Modulated Continuous Wave (FMCW)

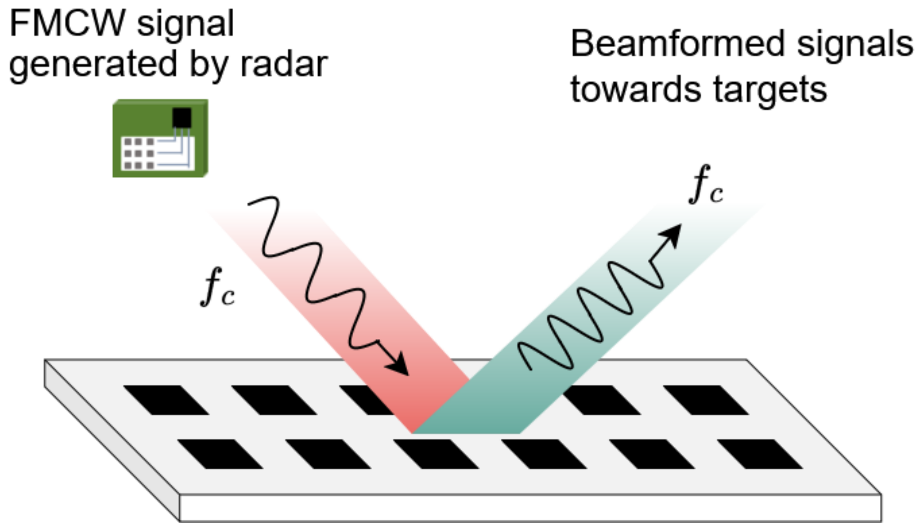


Can we exploit the unused bandwidth?

Basics of FMCW/Chirp Radars

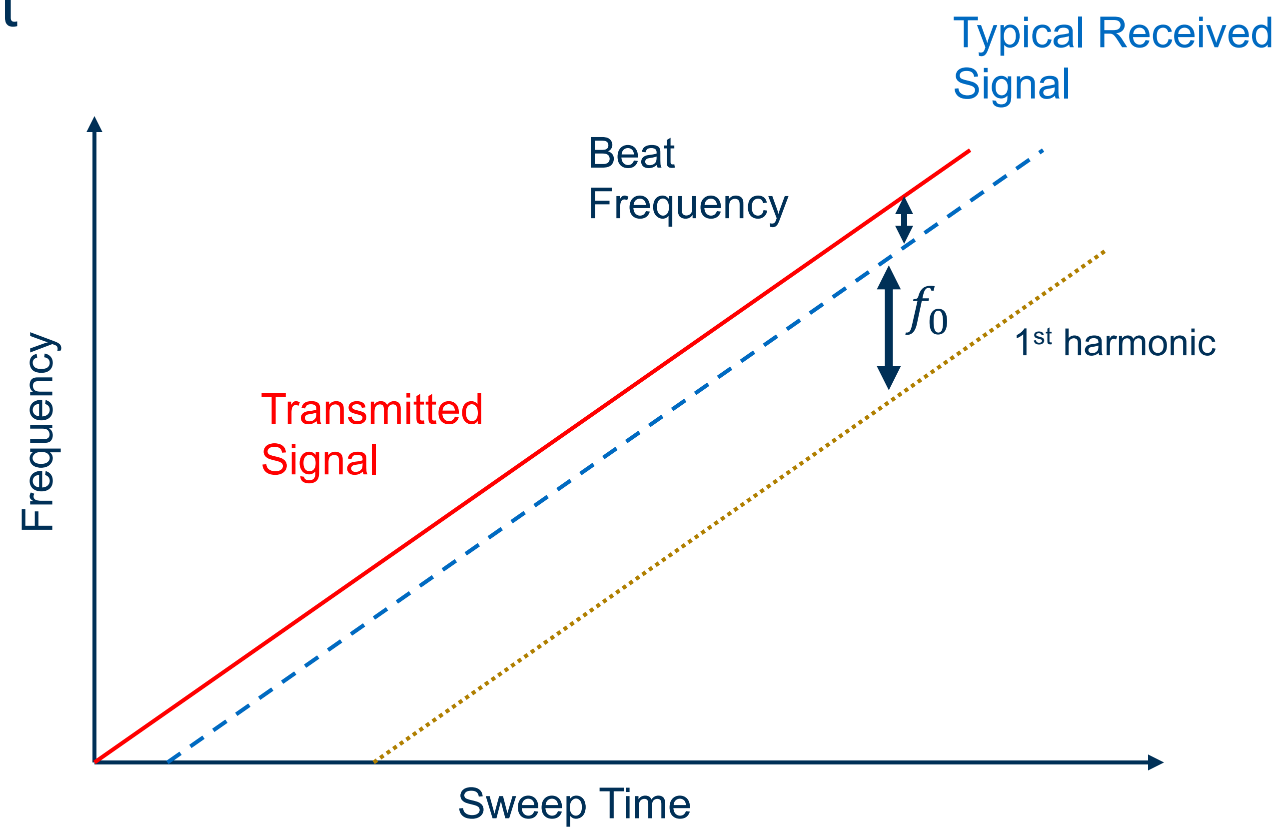
- Static RIS only redirects the energy towards the target (beamforming)

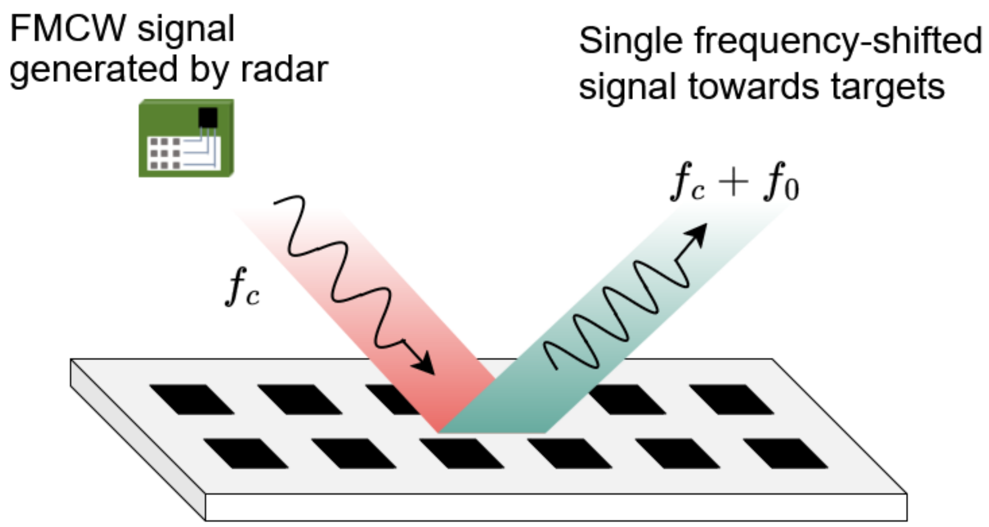




Key Idea: Frequency-shifting with RIS

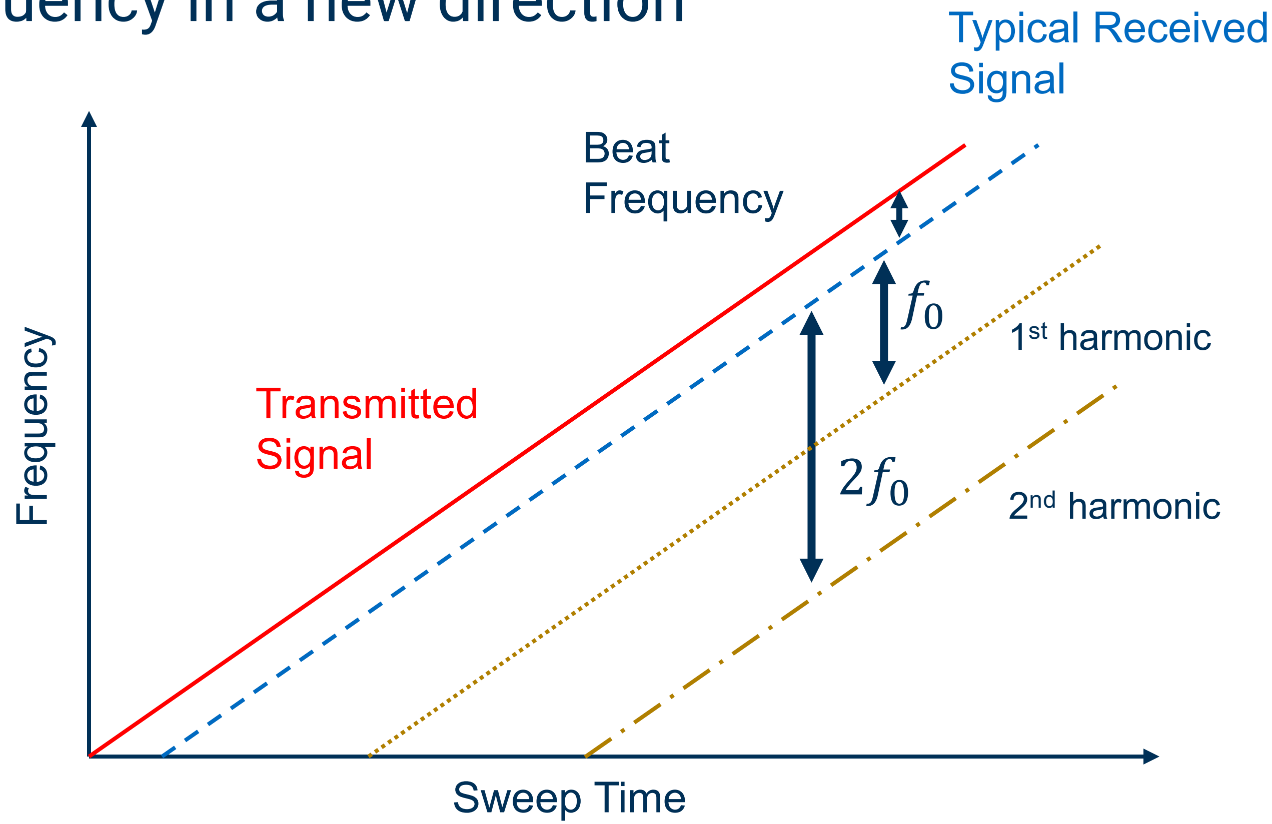
- Periodically alternating the RIS configuration creates a predictable frequency-shift

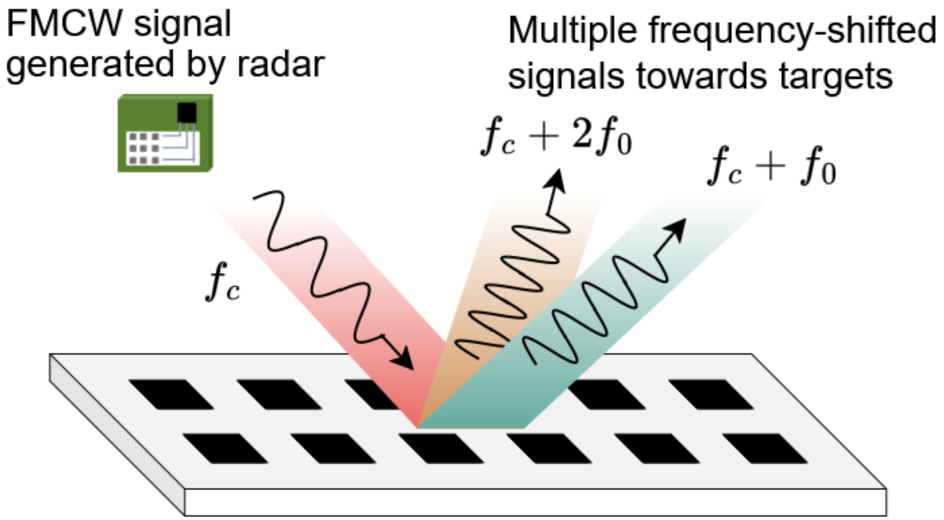




Key Idea: Frequency-shifting with RIS

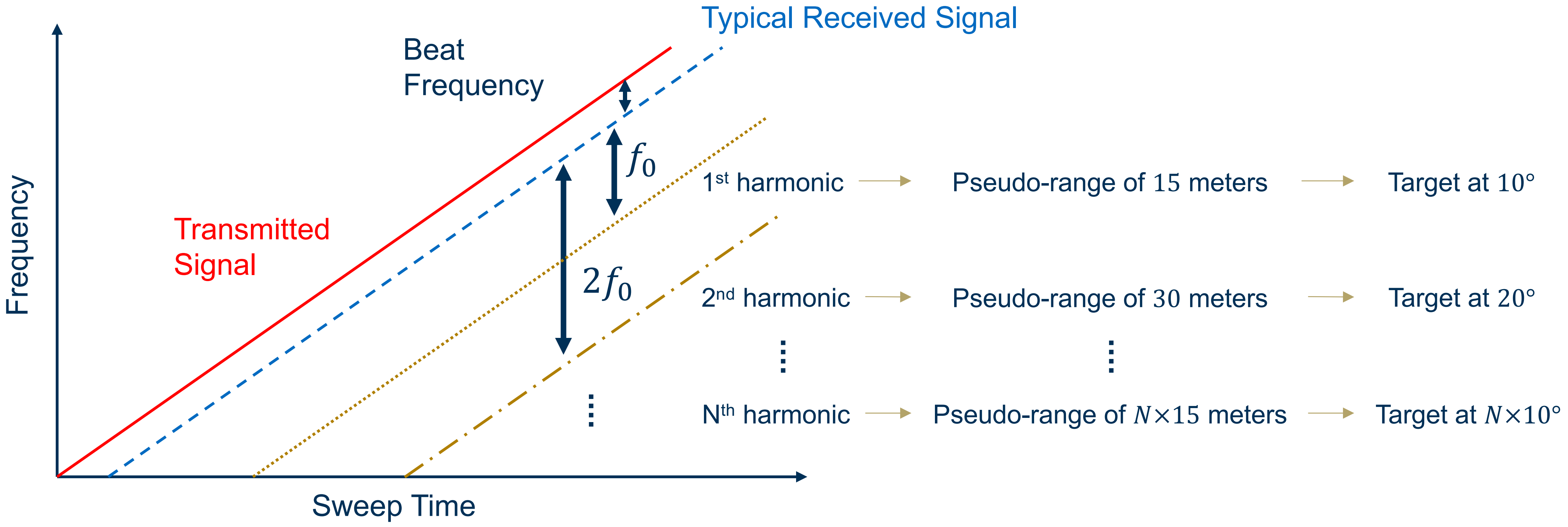
- Varying the RIS configuration at finer time-scales can create a second harmonic frequency in a new direction





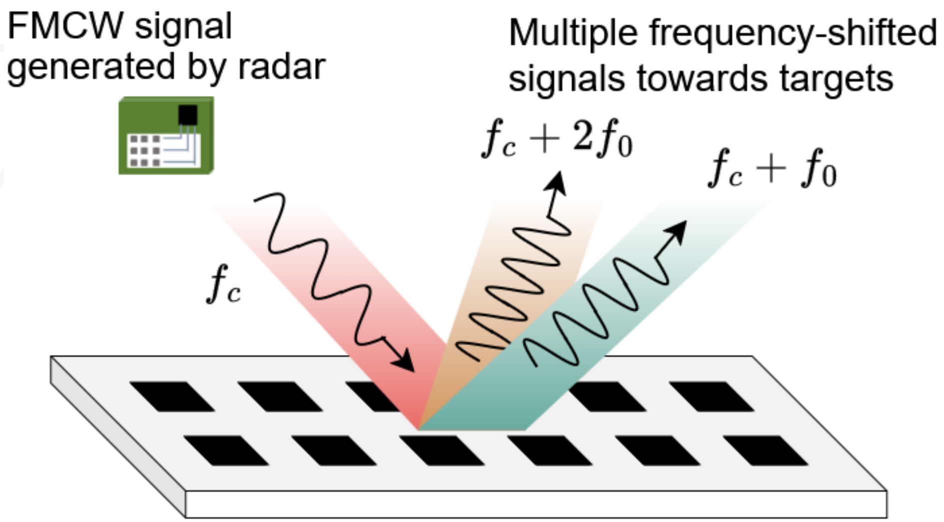
Key Idea: Frequency-shifting with RIS

- Precisely controlling the RIS configuration has the potential to create beams in several directions, each with a different frequency-shift



Key Idea: Frequency-shifting with RIS

Simultaneous frequency-shifting and beamforming with RIS satisfies all the key requirements!

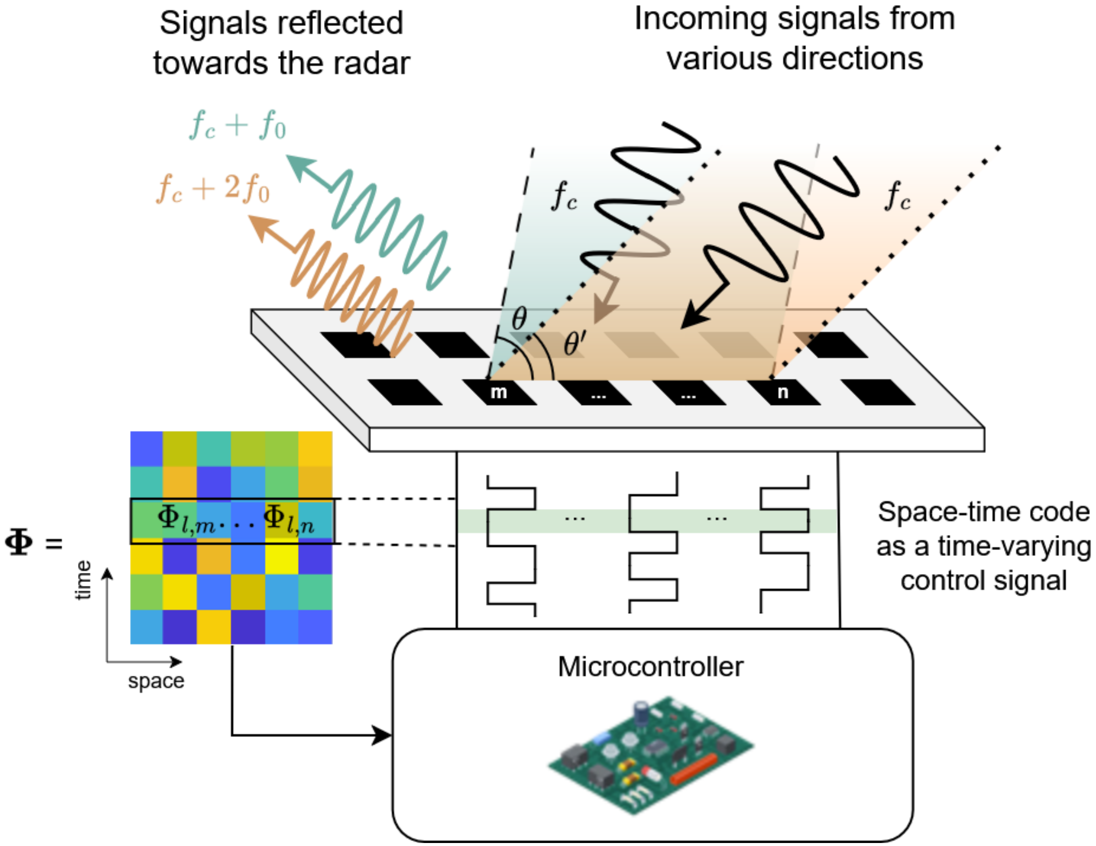


- ✓ Resolve angles of incidence signals **simultaneously**
- ✓ Enable **beamforming** for multipath suppression
- ✓ No **active components / time synchronization** with the radar
- ✓ **Seamlessly integrate** into the radar's signal processing

Challenge of Joint Frequency-Shifting and Beamforming

Problem: How to obtain reliable frequency shifting in multiple directions simultaneously?

"Space-Time" Modulation



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Space-Time Modulation Framework

- Analytical model for joint frequency-shifting and beamforming in wideband operation
  - **RIS Model**: S_{11} parameters
  - **Channel Model**: Wideband delay-line model
  - **Space-Time Code**: Possible reflection coefficients (RIS configurations)

RIS Model
$\Gamma(f)$

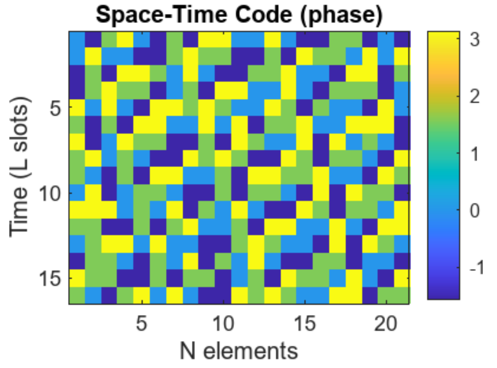
Channel Model
$\boldsymbol{H}(f)$

Space-Time Code
$\boldsymbol{\Phi}$

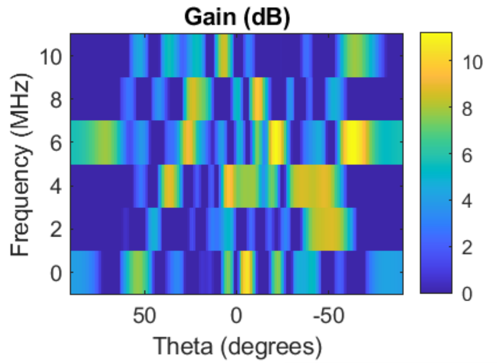
$$\boldsymbol{G}(\boldsymbol{\Phi}) = \int |\boldsymbol{W}\boldsymbol{\Phi}\mathbf{H}(\mathrm{f})|^2 \mathrm{df}$$

Wideband Integral

$\boldsymbol{\Phi}$:



$\boldsymbol{G}(\boldsymbol{\Phi})$:



Space-Time Modulation Framework

- What <u>time-varying RIS configuration</u> produces frequency-shifts in the desired directions?
- Using a global optimization framework, we solve for the optimal space-time code

Space-Time Code
$\mathbf{\Phi}$

Frequency-Space Encoding
$\boldsymbol{G}^*$

Global Optimization

$$argmin_{\Phi}\ |\boldsymbol{G}^* - \mathbf{G}(\mathbf{\Phi})|$$

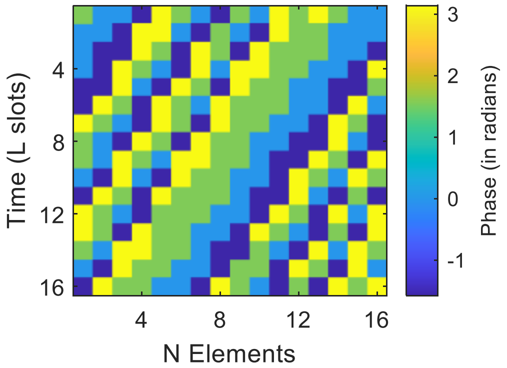
where $\mathbf{\Phi} \in \{\pm 1, \pm j\}^{L \times N}$

Optimal Space-Time Code

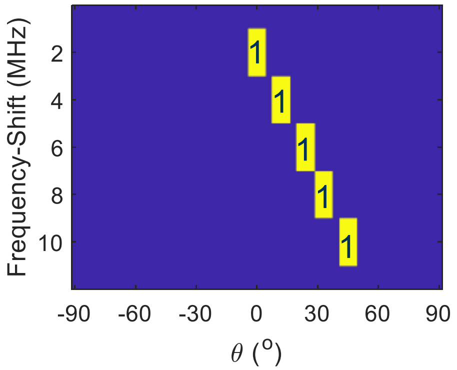
$\mathbf{\Phi}^*$

Hard to compute, non-convex, very high-dimensional problem

$\mathbf{\Phi}^*$:



$\mathbf{G}^*$:



Space-Time Coding Framework

- **Problem:** Computing the wideband integral is the bottleneck
- **Solution:** Approximate the wideband integral with a narrowband matrix approximation
  - Modified low-rank approximation methodology (Theorem 1)

$$\hat{\mathbf{G}}(\mathbf{\Phi}) = |\mathbf{W}\mathbf{\Phi}\hat{\mathbf{H}}|^2 \approx \int |\mathbf{W}\mathbf{\Phi}\mathbf{H}(f)|^2 df$$

Narrowband Approximation

Wideband Integral

- Solve using a global optimizer (like genetic algorithm)

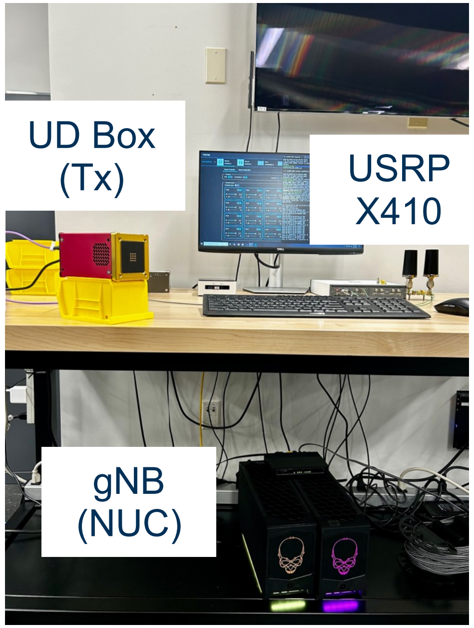
$$\mathbf{\Phi}^* = \mathrm{argmin}_{\Phi \in \{\pm 1, \pm j\}^{L \times N}} \underbrace{|\mathbf{G}^* - \mathbf{G}(\mathbf{\Phi})|_F}_{\text{difficult to compute}}$$

$$\approx \mathrm{argmin}_{\Phi \in \{\pm 1, \pm j\}^{L \times N}} \underbrace{|\mathbf{G}^* - \hat{\mathbf{G}}(\mathbf{\Phi})|_F}_{\text{easy to compute}}$$

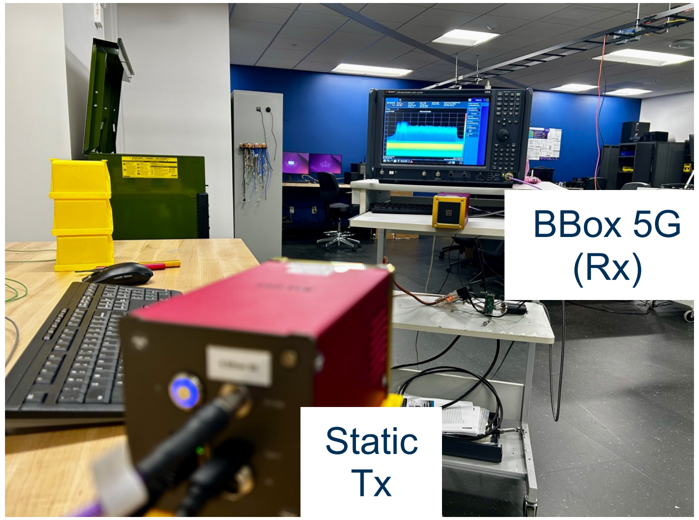
Easier to compute, non-convex, very high-dimensional problem

Evaluations

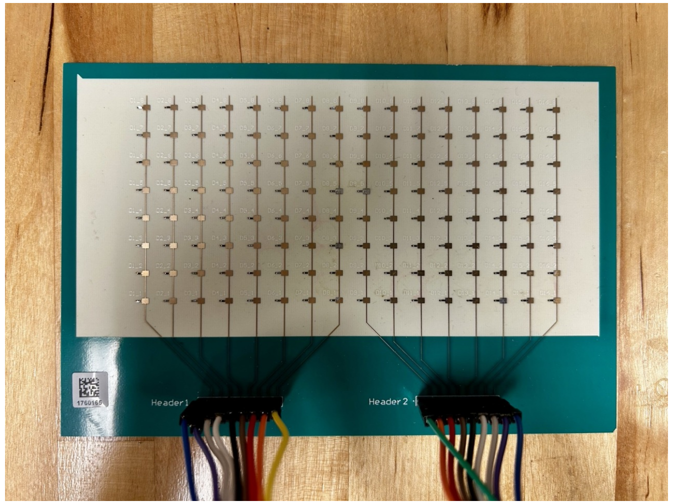
- Channel traces collected in indoor setup (real-world environment)
  - TYMTEK devices at 39 GHz (up-, down-converters, phased array)
  - 5G-compliant waveform generated using Open Air Interface
- Evaluations supplemented with additional test environments in Wireless InSite



Mobile Rx Setup



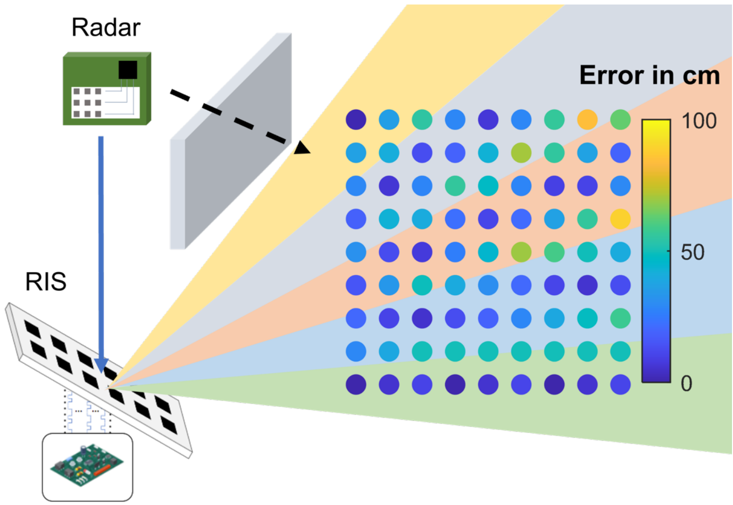
RIS Model

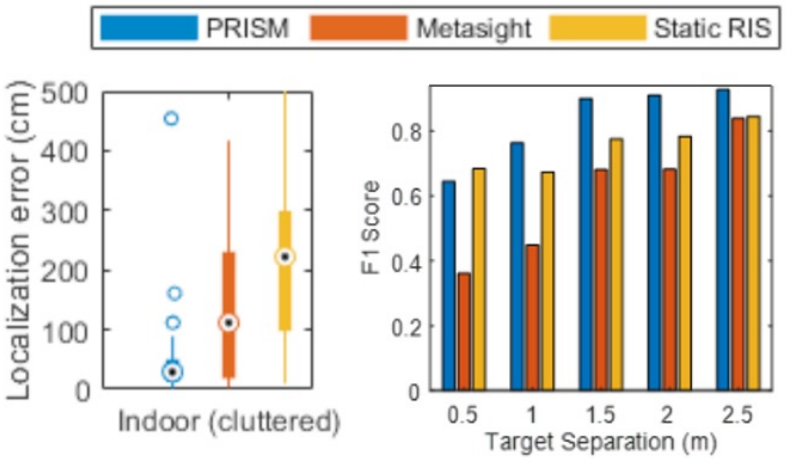


Evaluations

Non-line-of-sight evaluation study

- *PRISM (our work)*: 5 beams from 0º to 45º; harmonic frequency $f_0 = 2$ MHz
- *Metasight*: Multi-reflector setup with gray-coding for angular resolution
- *Static RIS*: Single-reflector setup without angular resolution





Median localization error is 31 cm

Two-target resolution F_1 score > 0.9 for separation > 1.5 m

Conclusions and Future Directions

Summary

- In mmWave sensing, angular resolution in NLoS regions is a problem
- *PRISM* proposes to encode the angles of the targets in NLoS regions using *pseudo-ranges*
- *PRISM* uses “space-time codes” to jointly beamform and create frequency shifts which translates to the desired *pseudo-ranges*
- *PRISM* seamlessly works with a radar, does not depend on any active components, and resolves all angles simultaneously

Future Directions

- Encoding angles in frequency-shifts is useful from the perspective of tracking NLoS users in a mmWave communication setup

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Thank You!