

Practical Null Steering in Millimeter Wave Networks

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* IMDEA Networks



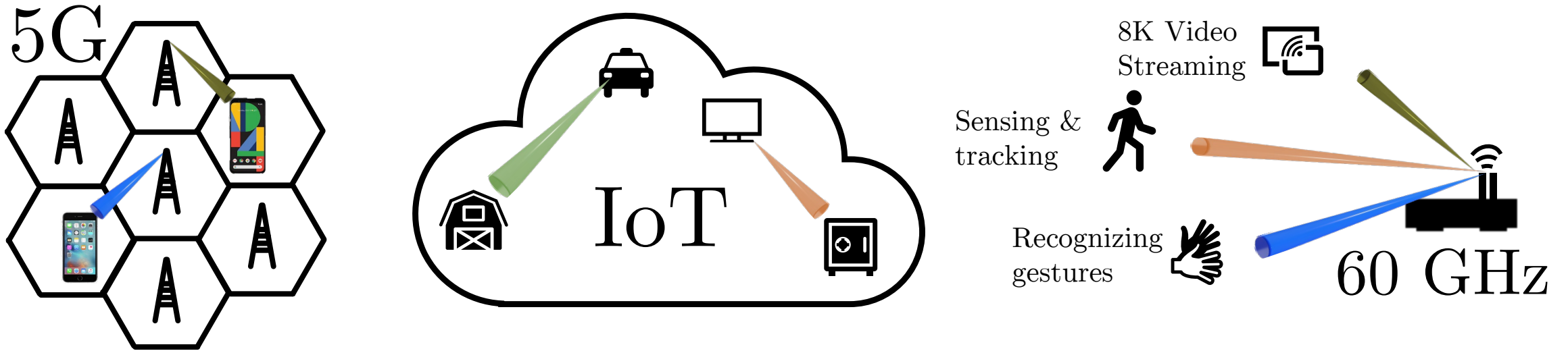
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Millimeter Wave

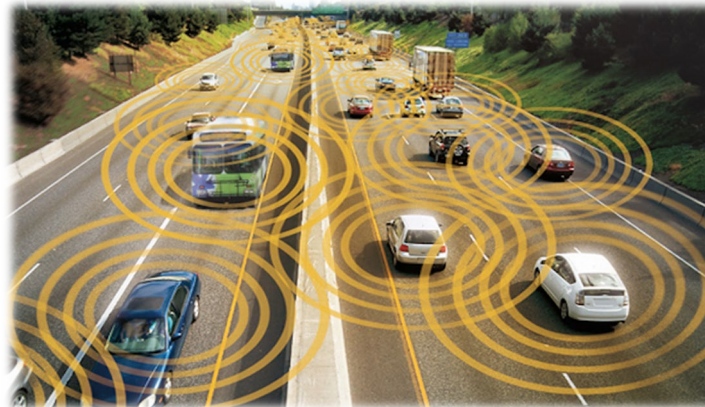
High Frequency > 24 GHz, Huge Bandwidth



Virtual Reality

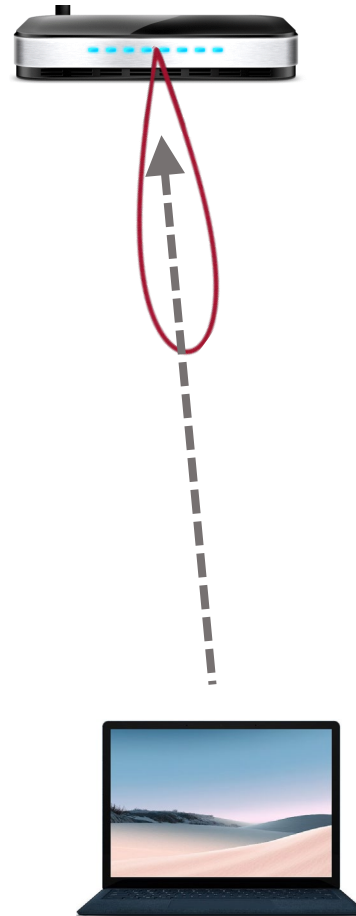


Connected Vehicles



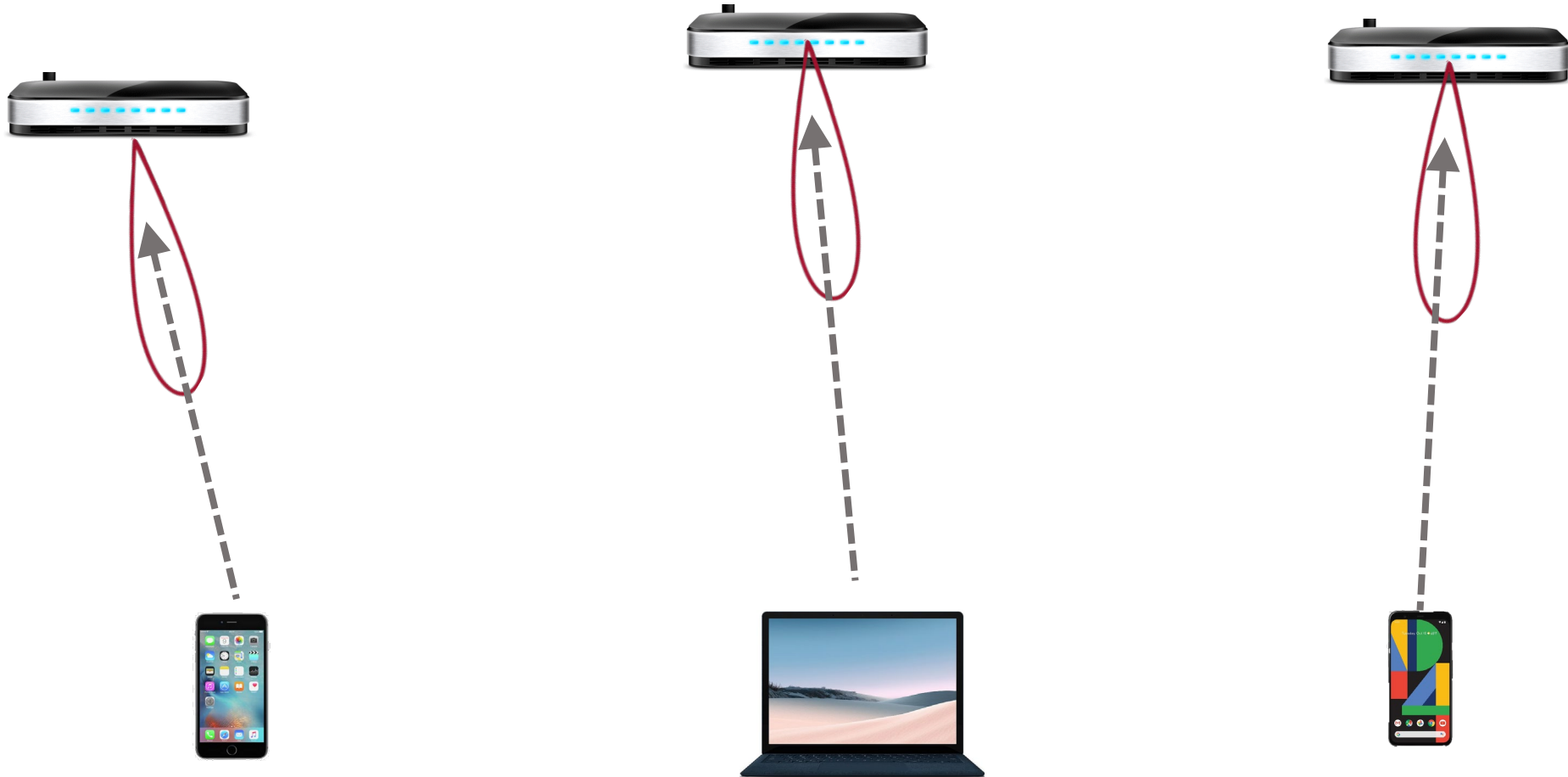
Millimeter Wave Networks

Use Directional Narrow Beams



Millimeter Wave Networks

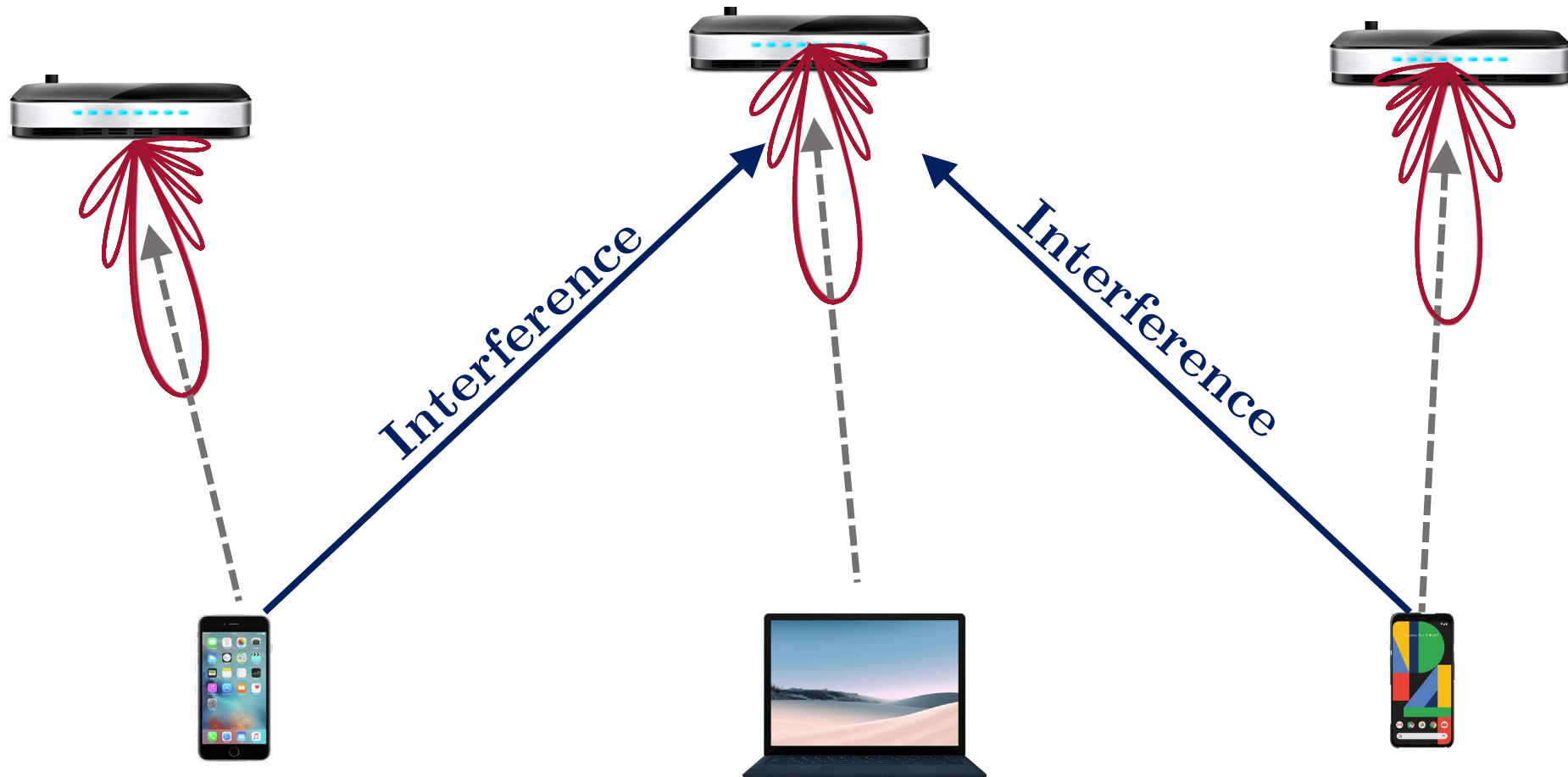
Use Directional Narrow Beams \longrightarrow Multiple Links operate concurrently



Millimeter Wave Networks

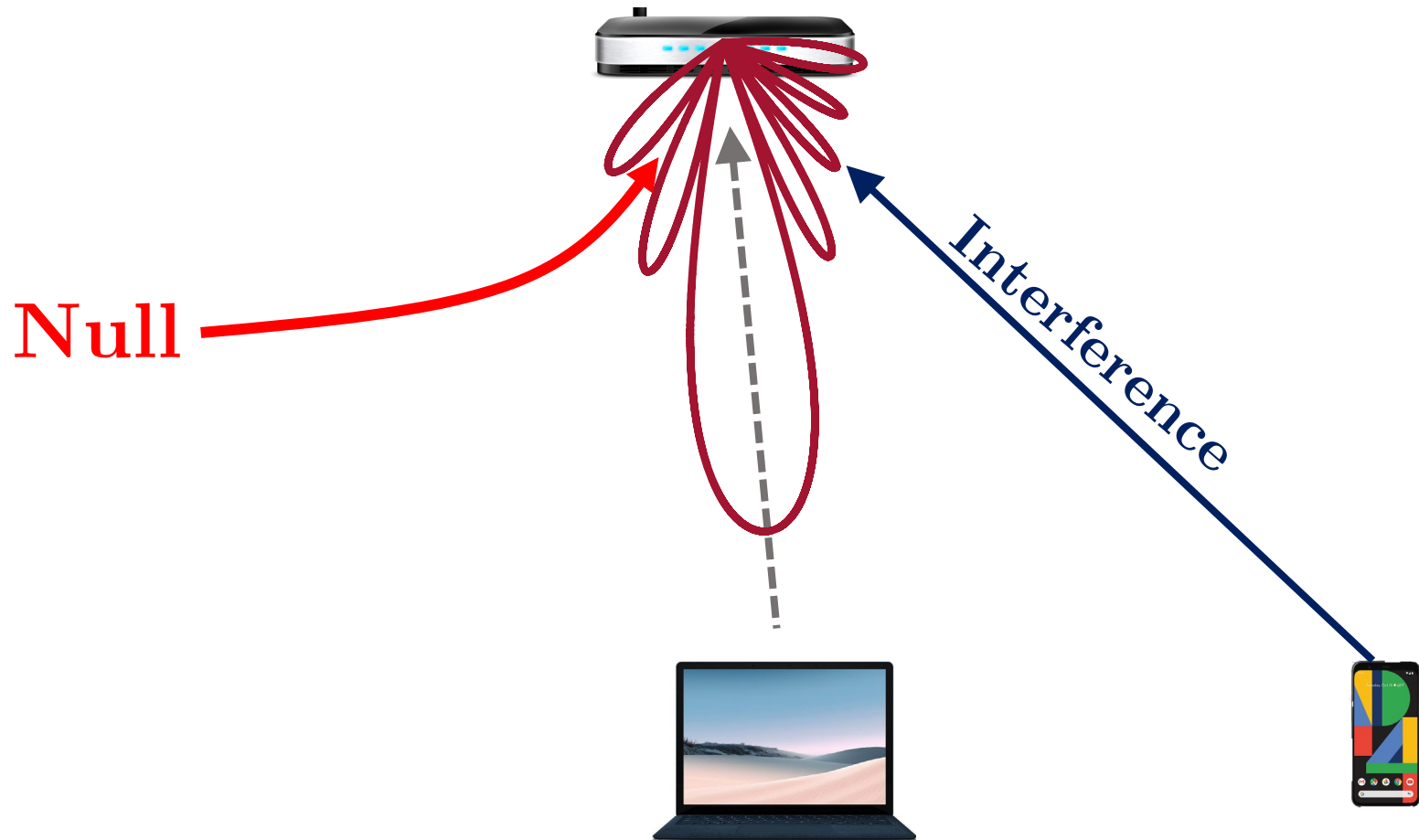
Use Directional Narrow Beams  Multiple Links operate concurrently

Interference



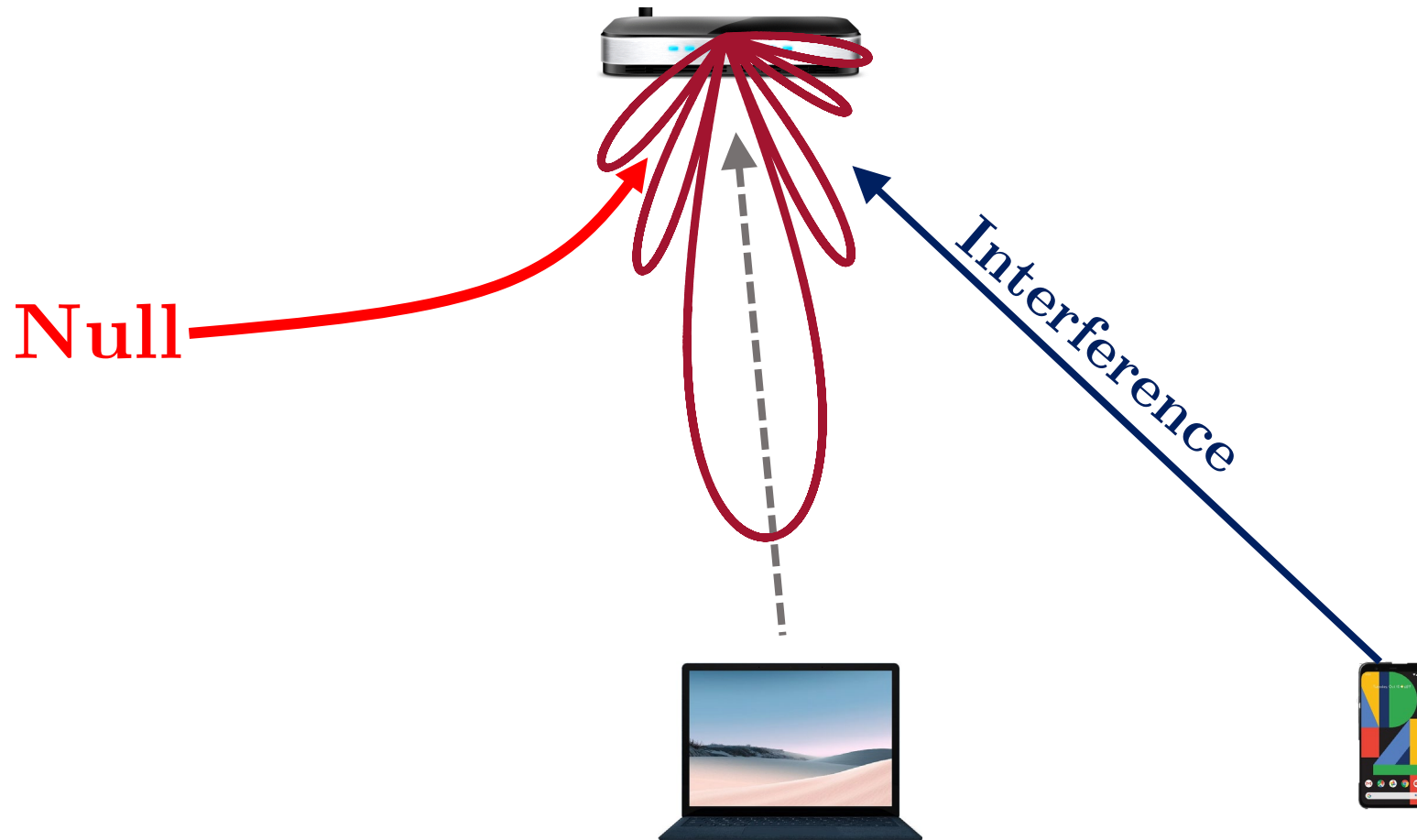
Millimeter Wave Networks

Nulls: Directions with no signal power.



Millimeter Wave Networks

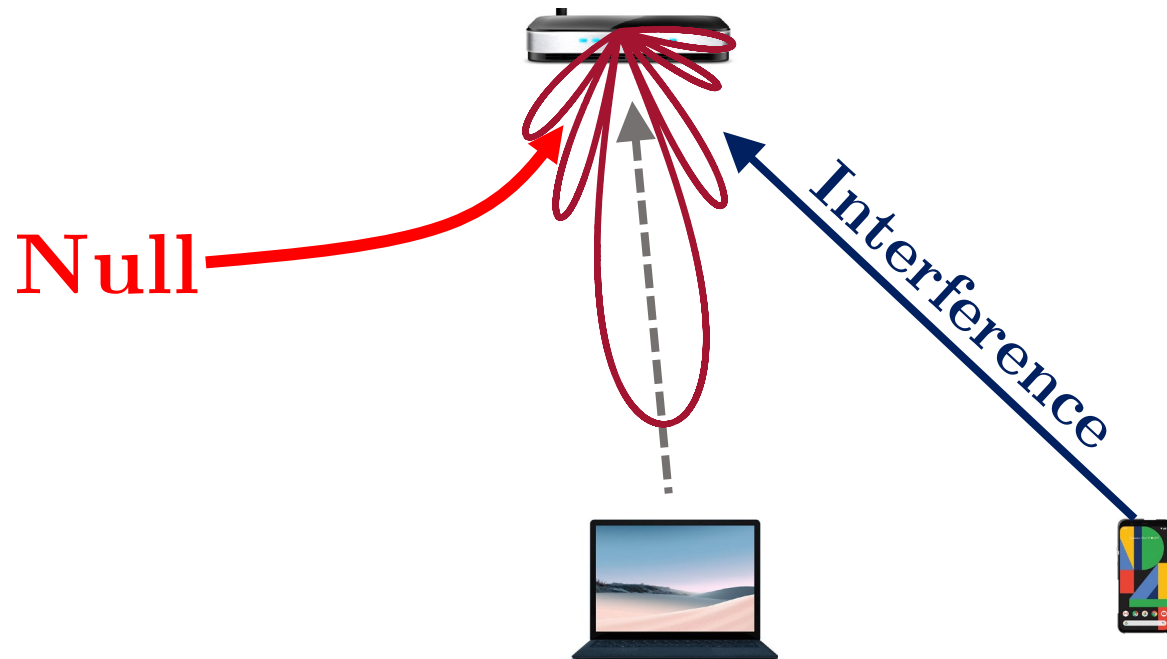
Nulls: Directions with no signal power.



Millimeter Wave Networks

Nulls: Directions with no signal power.

Can we align a null towards the interferer while preserving the main beam?



Creating Nulls in Practice is Challenging

Network-Level

Need Fast Null Steering

Quickly find the direction of interferer

Need Wide Nulls

Direction of interferer not accurate!

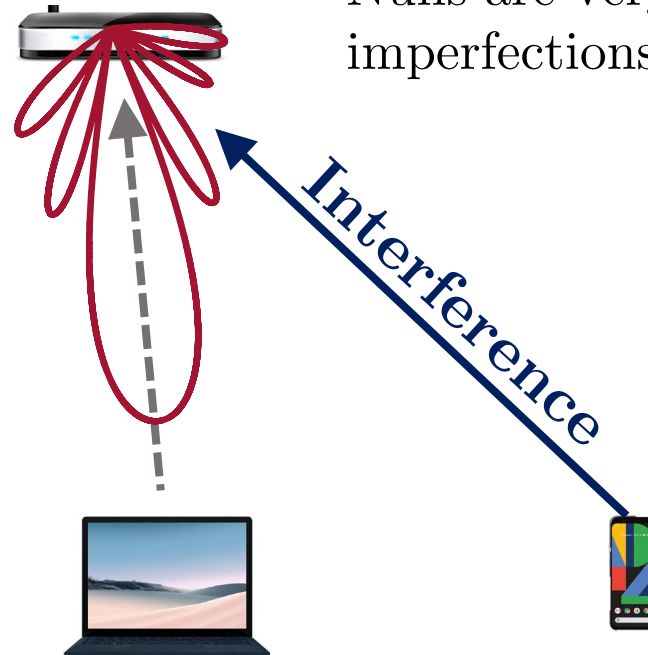
Hardware-Level

Limited Control Over Hardware

e.g. 802.11ad 60 GHz radios offer only 2 bits of control

Hardware Imperfections & Errors

Nulls are very sensitive to hardware imperfections



Creating Nulls in Practice is Challenging

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Need Fast Null Steering

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Need to Align Multiple nulls

Multiple interferers and multipath

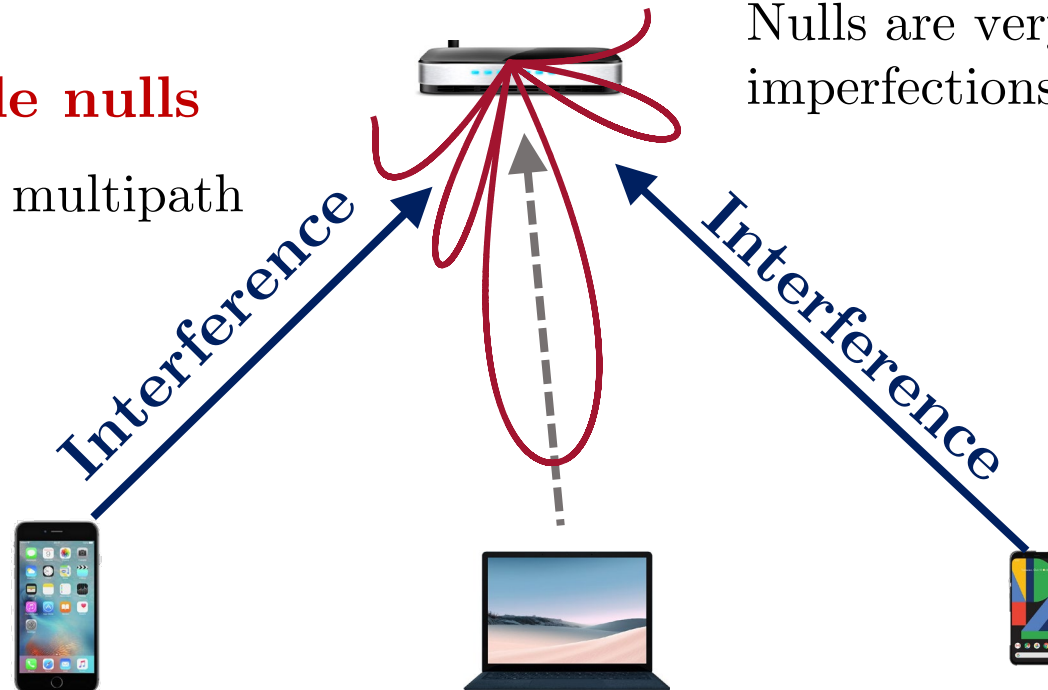
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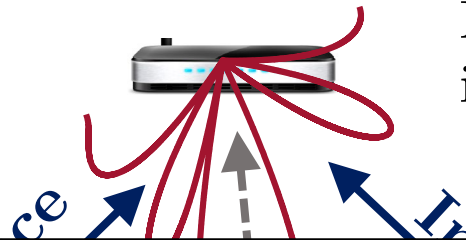
Hardware-Level

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Hardware Imperfections & Errors

Nulls are very sensitive to hardware imperfections



Past work on aligning the nulls does not address these challenges and remains simulation based.

[Steyskal '82, '83, Schreiber '86, Haupt '94,'97, Bower '01, Day '07,'09, Haupt 2010]



Nulli-Fi

First practical mmWave null steering system that addresses both hardware and network level challenges.

Nulli-Fi is implemented on commercial mmWave radios and can find interference directions in less than 300 ns and suppress them by 15 dB.

Nulli-Fi

Creating nulls in the
beam pattern

Nulling Algorithm



Initialize

Discrete Optimization
Framework

Steering the null
towards the interferer

Fast null steering
protocol

Nulli-Fi



The diagram illustrates the Nulli-Fi system architecture. It is divided into two main functional areas under the 'Nulli-Fi' header. The left area, 'Creating nulls in the beam pattern', contains a red 'Nulling Algorithm' box that leads via a downward arrow labeled 'Initialize' to a green 'Discrete Optimization Framework' box. The right area, 'Steering the null towards the interferer', contains a green 'Fast null steering protocol' box.

Creating nulls in the
beam pattern

Nulling Algorithm



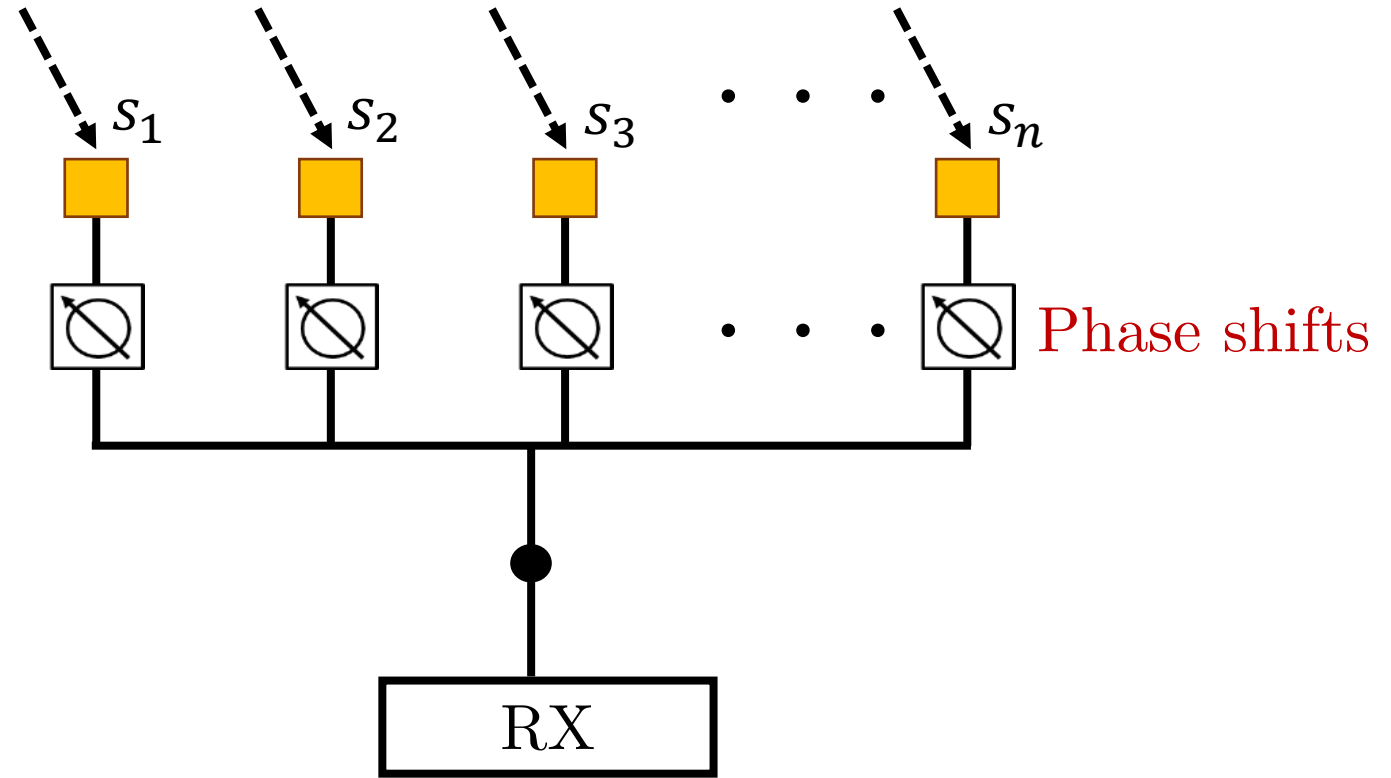
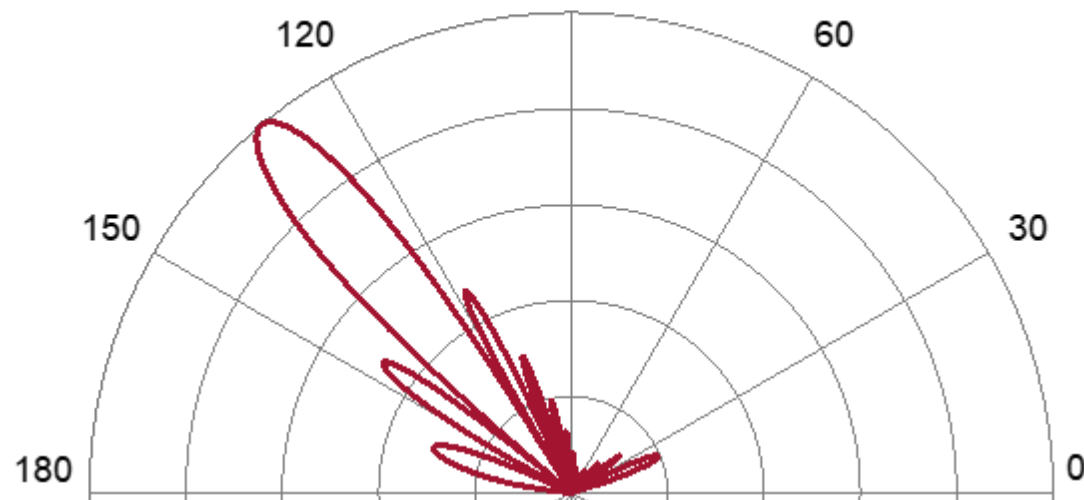
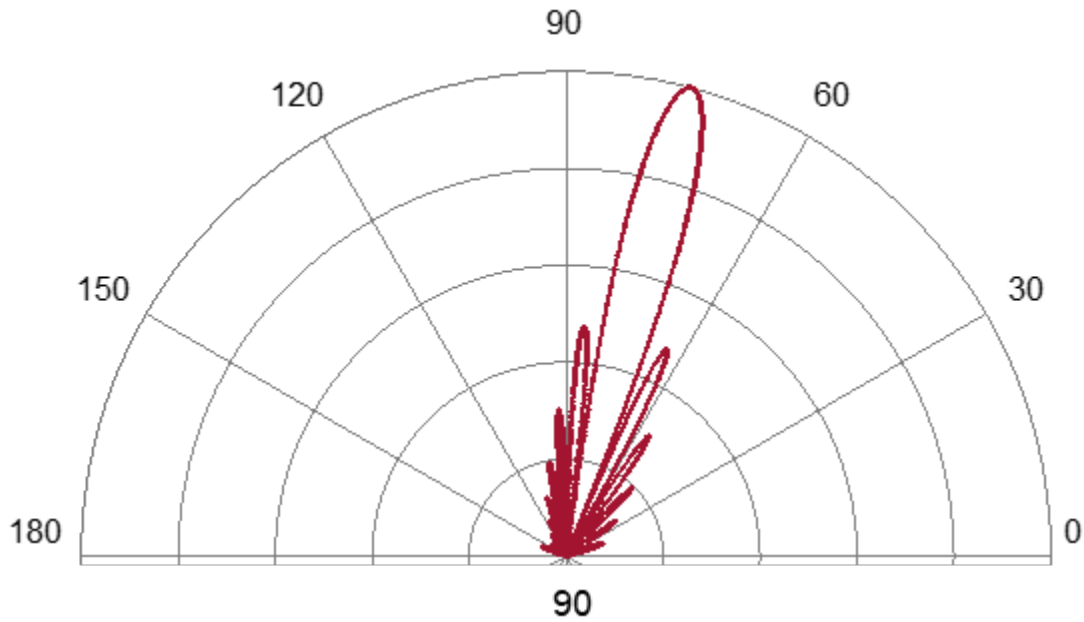
Initialize

Discrete Optimization
Framework

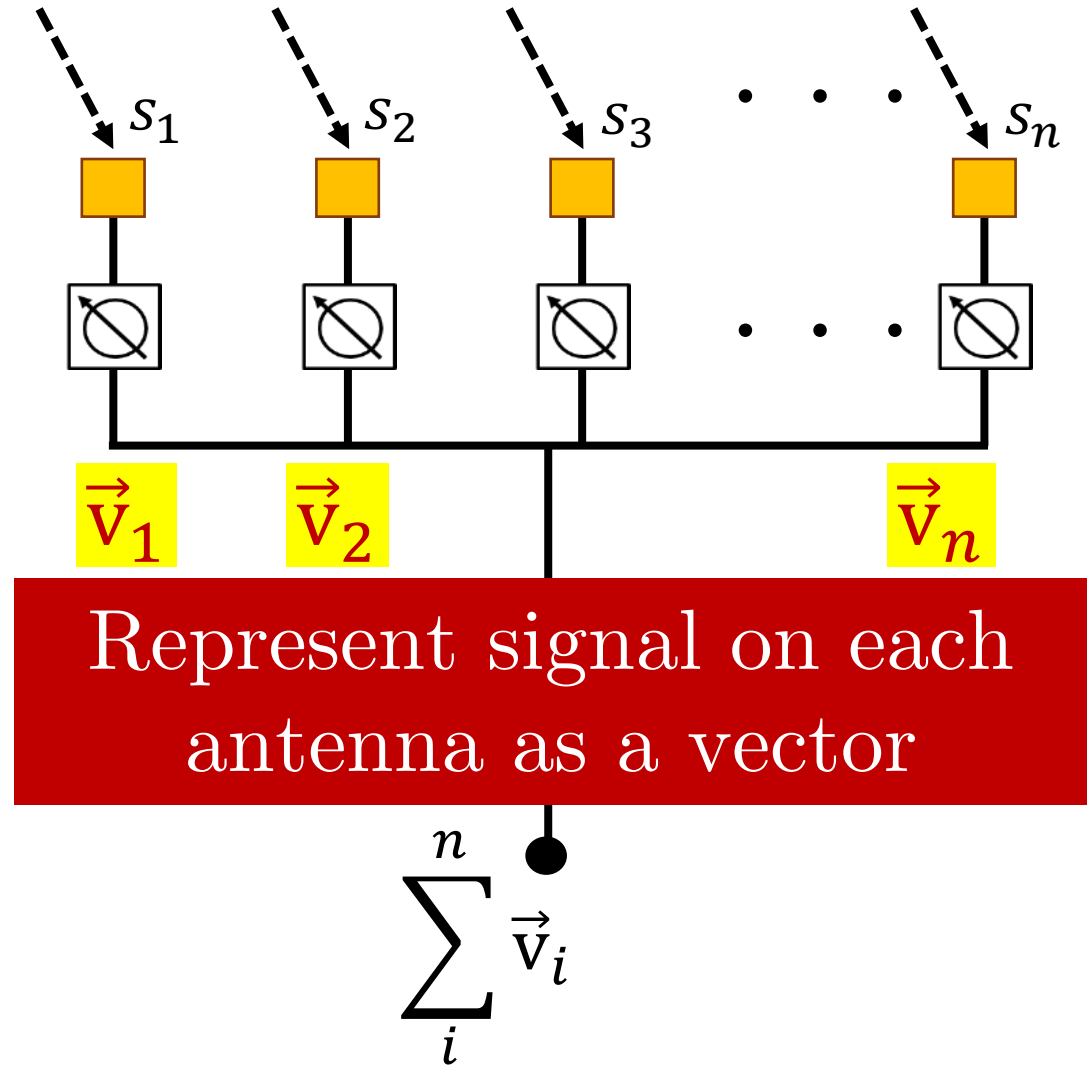
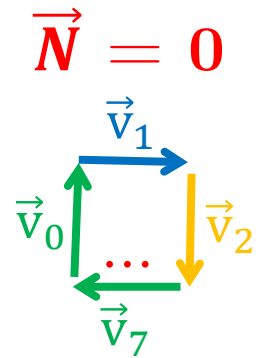
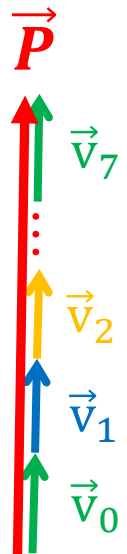
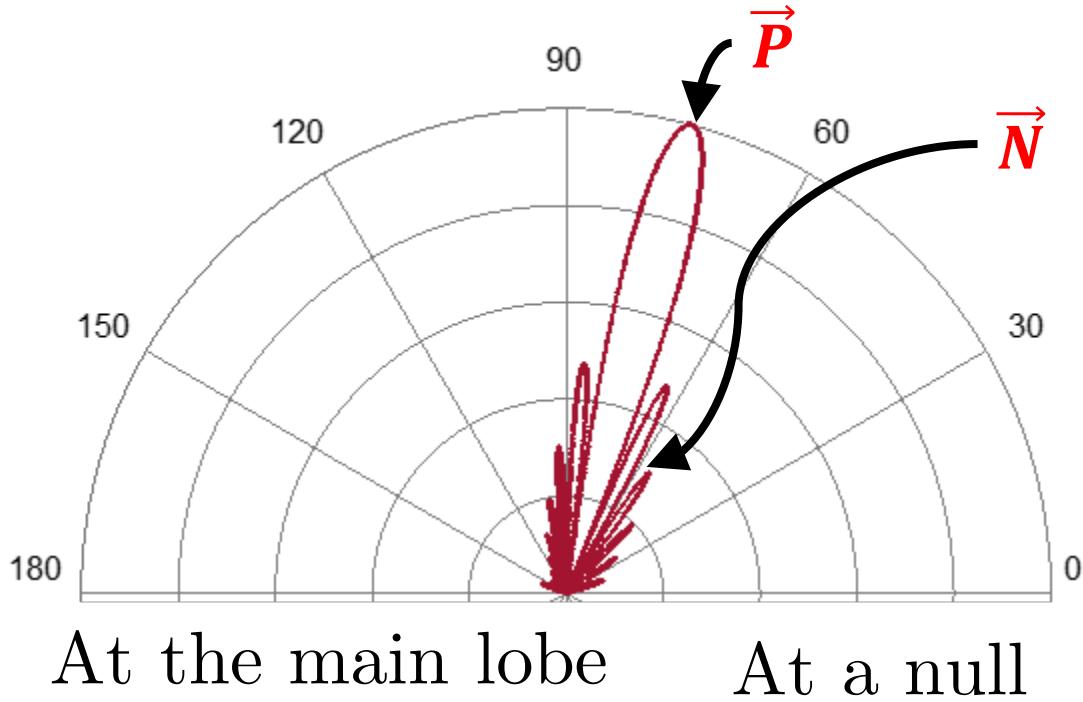
Steering the null
towards the interferer

Fast null steering
protocol

How to control the beam pattern?



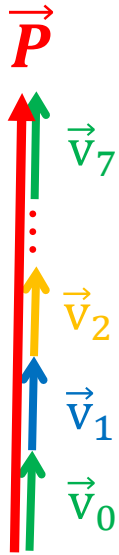
Representing Signals as Vectors



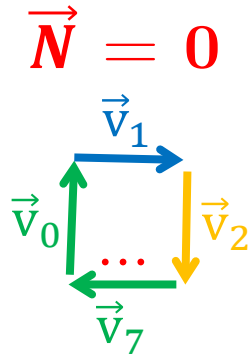
Nulli-Fi's Algorithm

Key Observation:

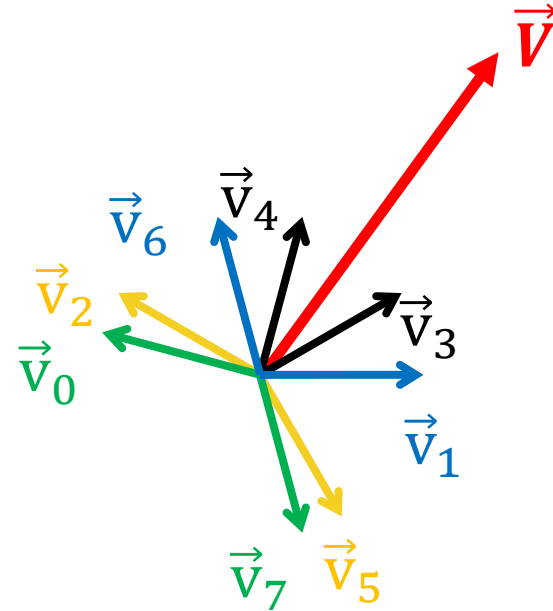
At any angle, the vectors summing up to the signal V come in *symmetric pairs* around V .



At the main lobe

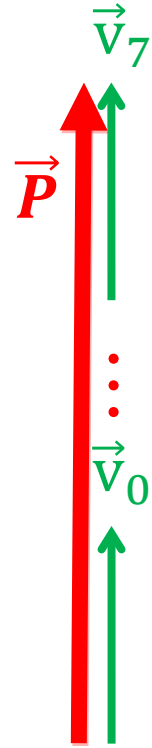


At a null

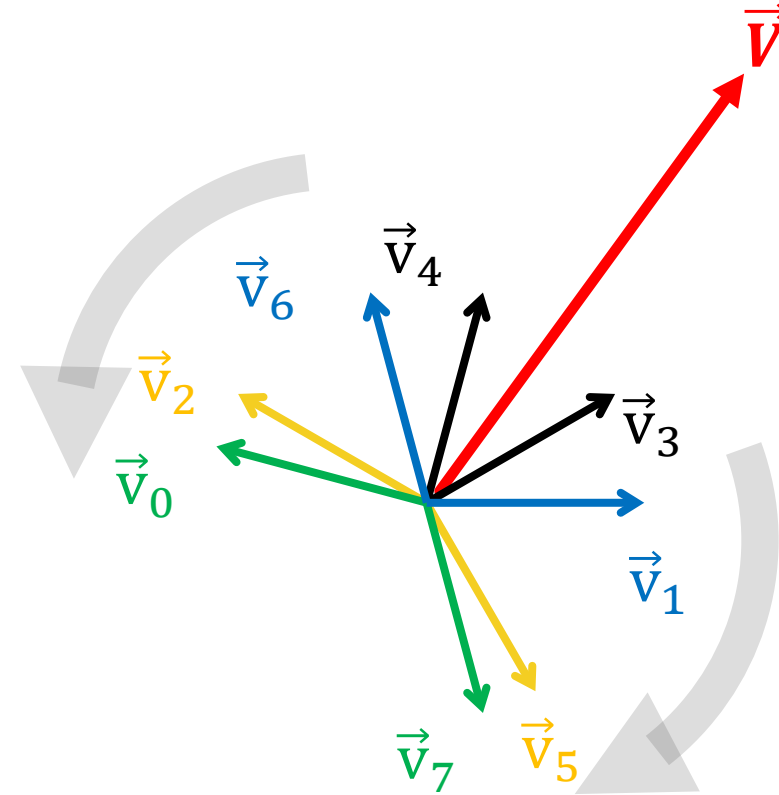


At any angle

Nulling Example



At main lobe (90°)



At null point (ϕ)

Restrict maximum phase shift on each antenna to $\pm\alpha$ to keep the main lobe intact.

Nulli-Fi's Algorithm

Theorem:

Given an angle ϕ , a beam pointing towards θ , and a restriction of $\pm \alpha$ on the phase shift, the algorithm creates the best possible null along ϕ while ensuring the loss in the main lobe is at most $\sin^2 \alpha$.

Nulli-Fi



```
graph TD; subgraph Nulli-Fi; direction LR; subgraph Left; direction TB; L1[Creating nulls in the beam pattern]; L2[Nulling Algorithm]; L3[Discrete Optimization Framework]; L2 -- Initialize --> L3; end; subgraph Right; direction TB; R1[Steering the null towards the interferer]; R2[Fast null steering protocol]; end; end;
```

Creating nulls in the
beam pattern

Nulling Algorithm



Initialize

Discrete Optimization
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Steering the null
towards the interferer

Fast null steering
protocol

Nulli-Fi



The diagram illustrates the Nulli-Fi system architecture. It is divided into two main functional areas under the 'Nulli-Fi' header. The left area, titled 'Creating nulls in the beam pattern', shows a workflow starting with the 'Nulling Algorithm' (in a red box), followed by an 'Initialize' step indicated by a downward arrow, leading to the 'Discrete Optimization Framework' (also in a red box). The right area, titled 'Steering the null towards the interferer', contains a 'Fast null steering protocol' (in a light green box).

Creating nulls in the
beam pattern

Nulling Algorithm



Initialize

Discrete Optimization
Framework

Steering the null
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Fast null steering
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Nulli-Fi



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Creating nulls in the
beam pattern

Nulling Algorithm



Initialize

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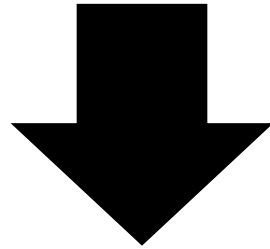
Steering the null
towards the interferer

Fast null steering
protocol

Fast Null Steering Protocol

Key Idea:

Interference is likely coming from a side lobe.



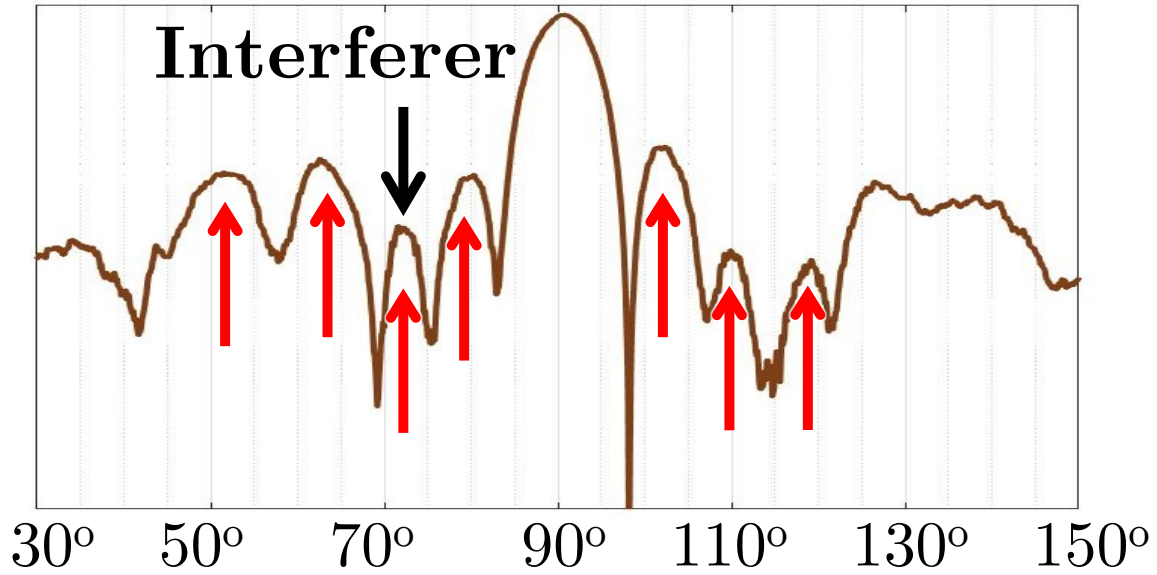
No need to scan all possible directions looking for the interferer.

Transmitter

Fast Null Steering Protocol

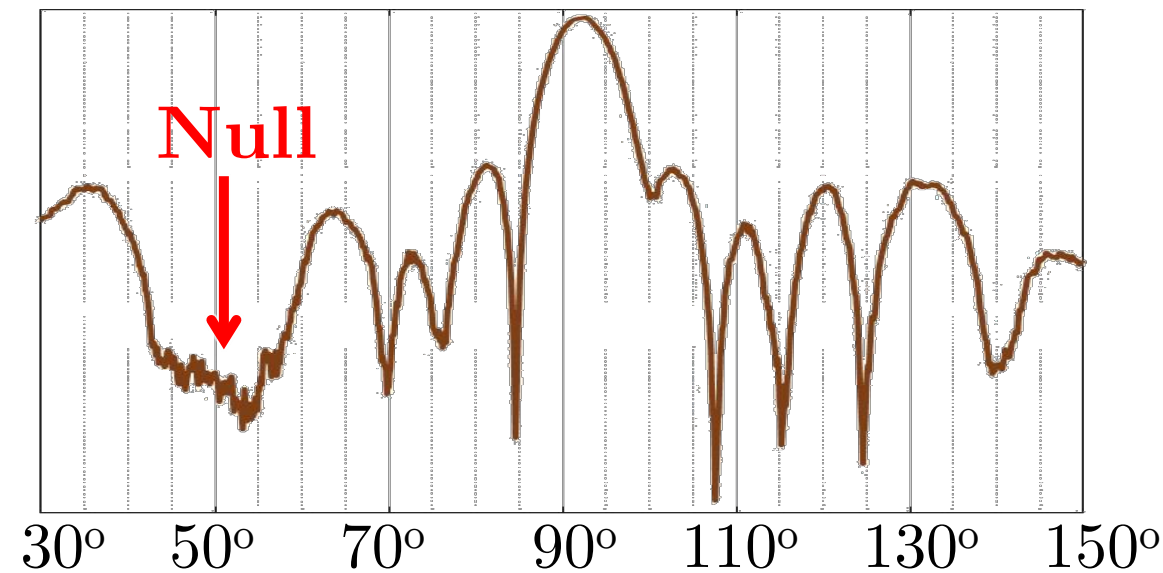
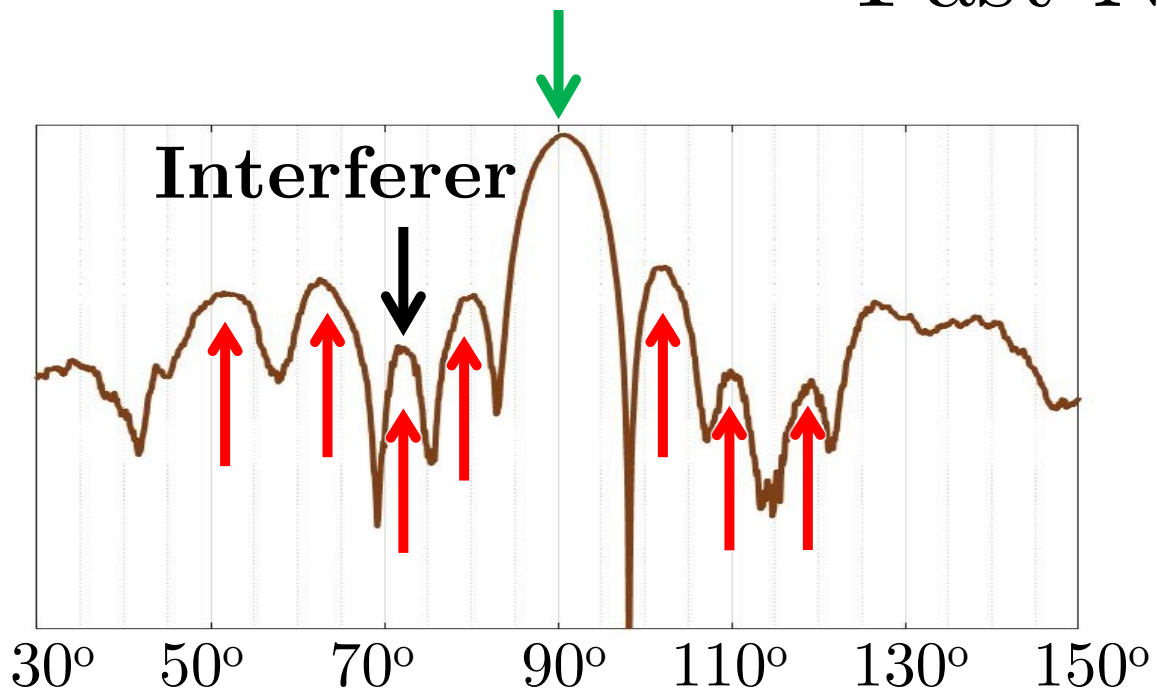


Interferer



Transmitter

Fast Null Steering Protocol



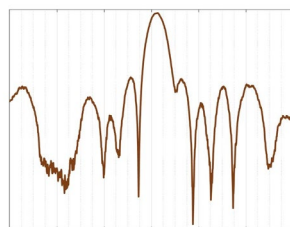
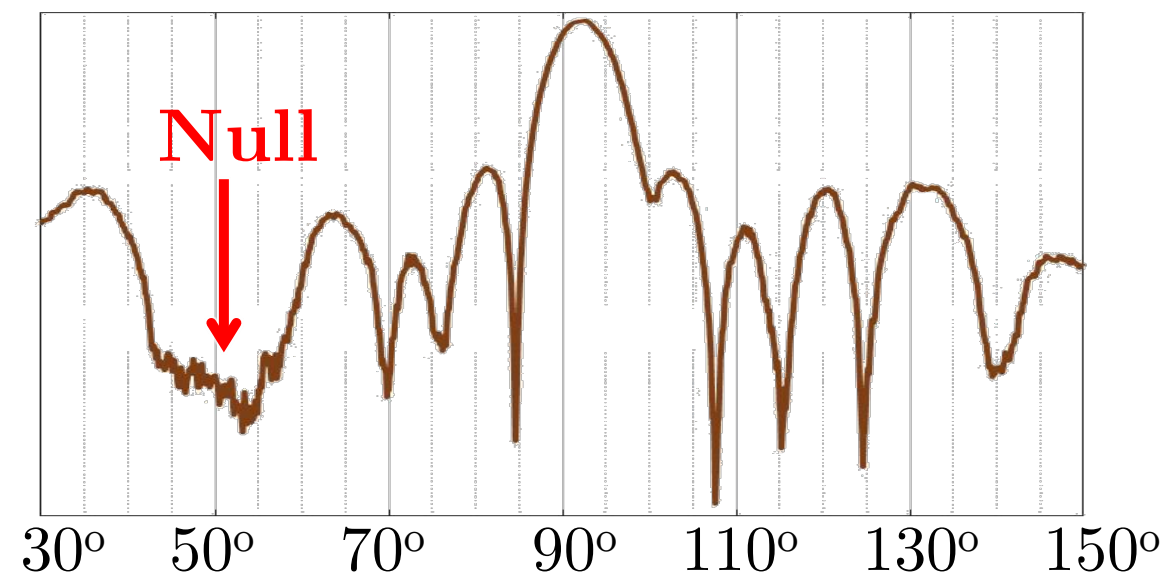
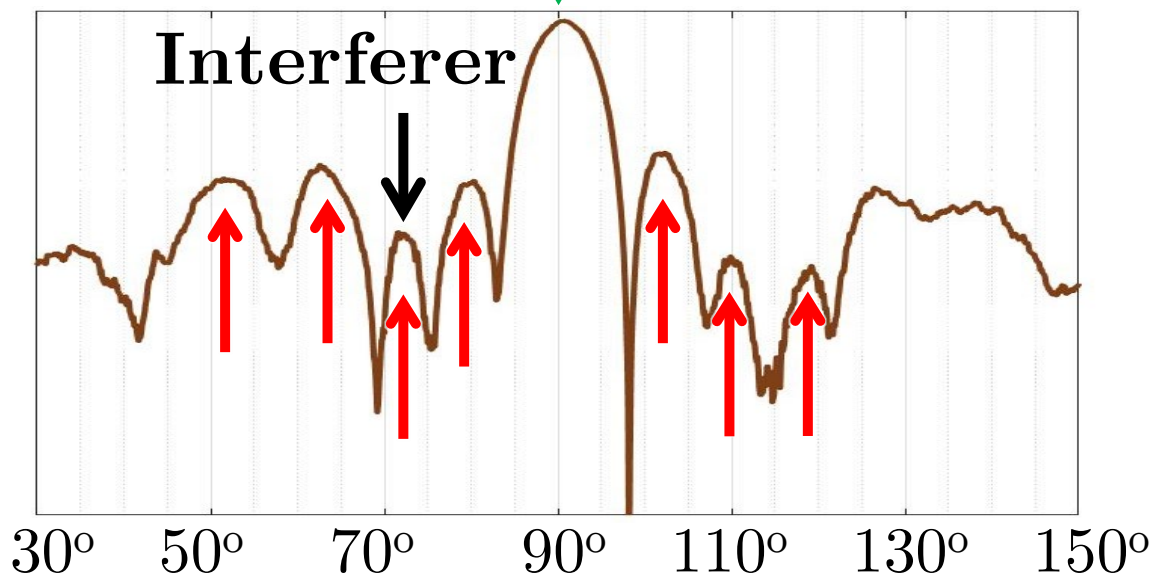
Interference

Signal



Transmitter

Fast Null Steering Protocol



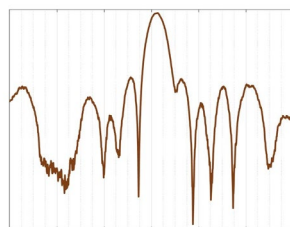
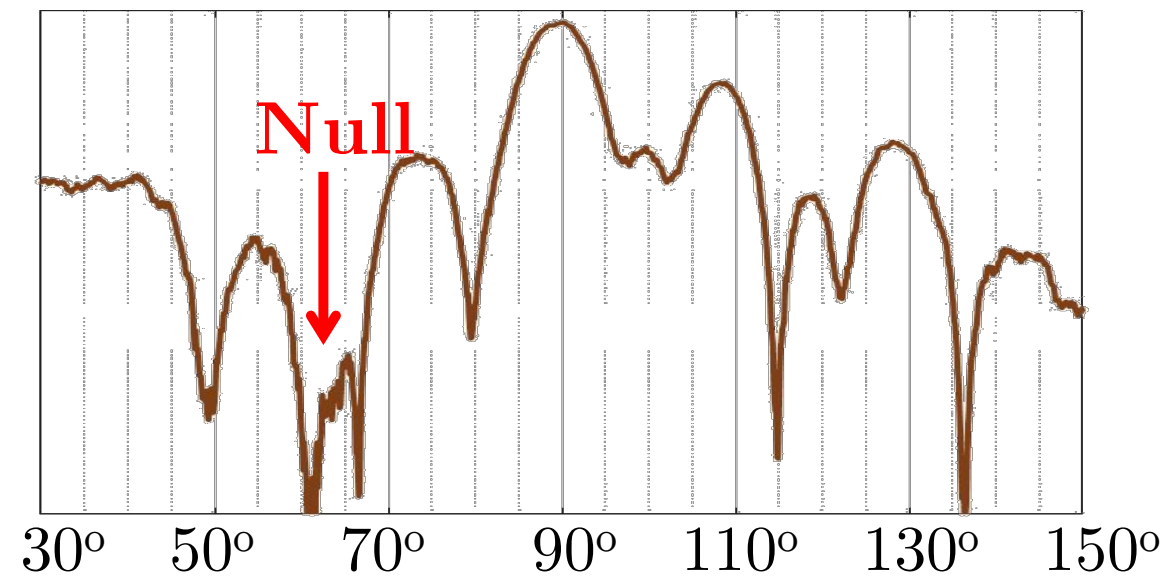
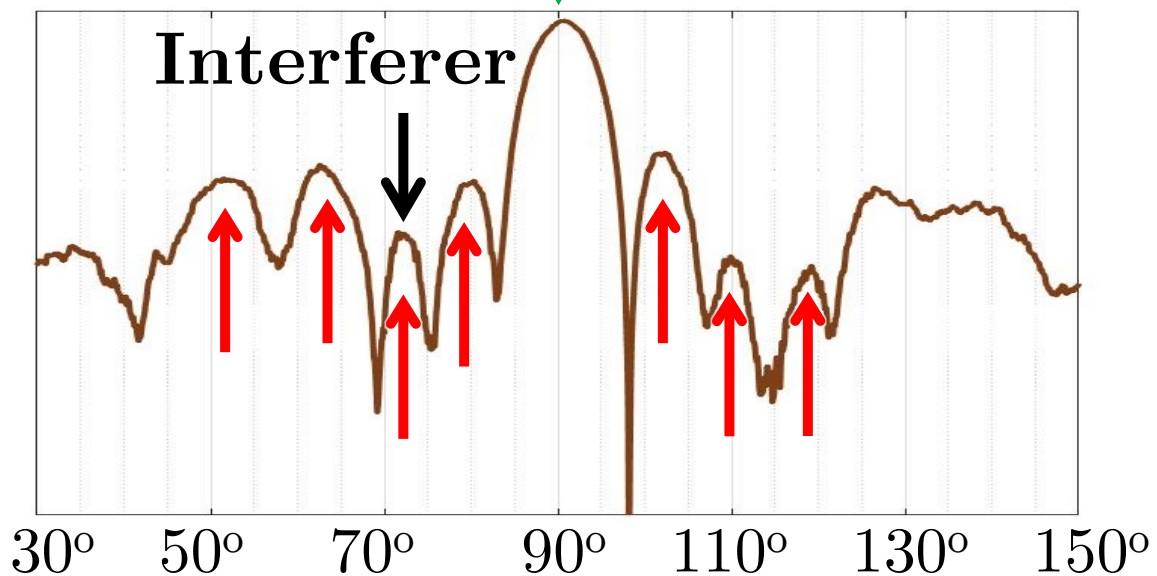
Interference

Signal



Transmitter

Fast Null Steering Protocol



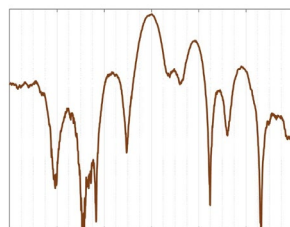
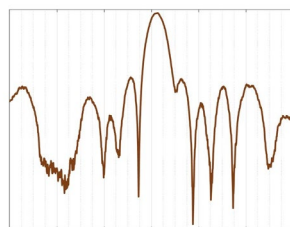
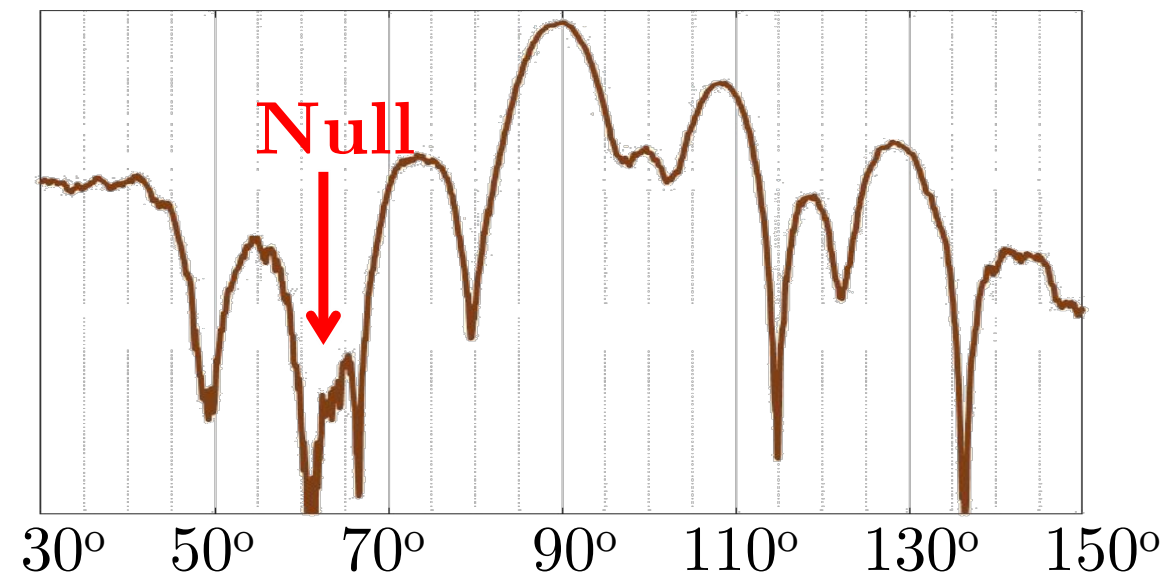
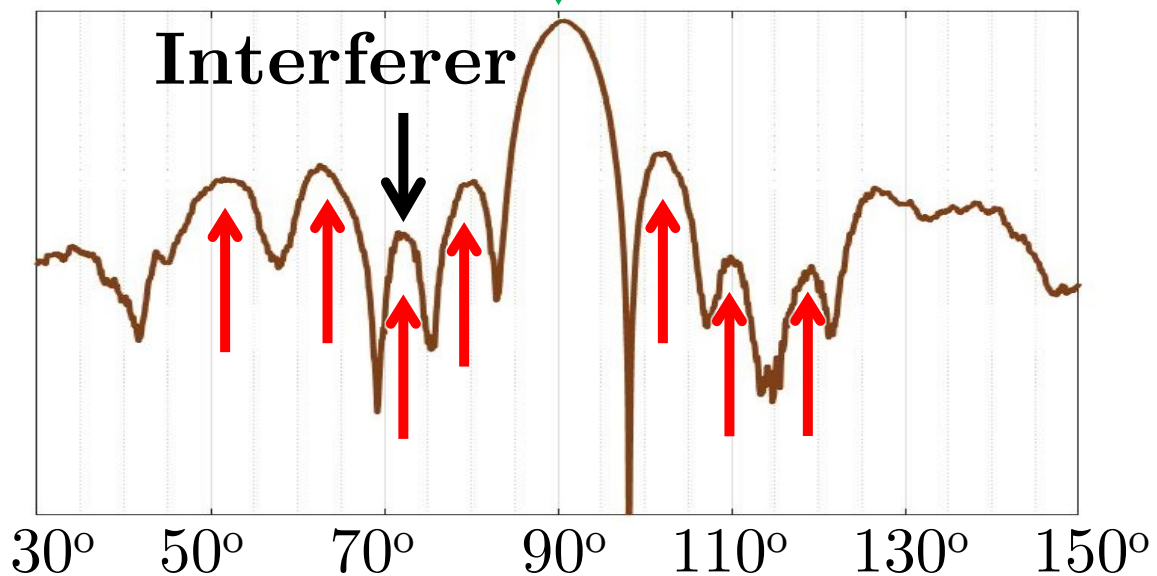
Interference

Signal



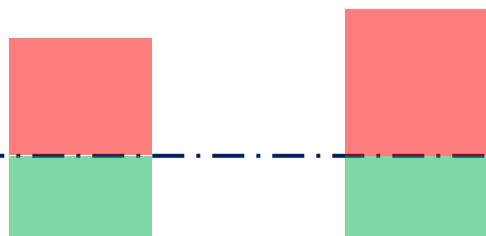
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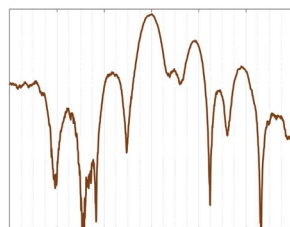
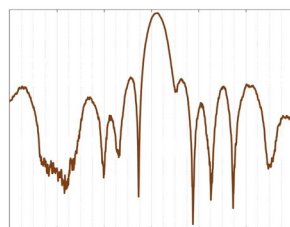
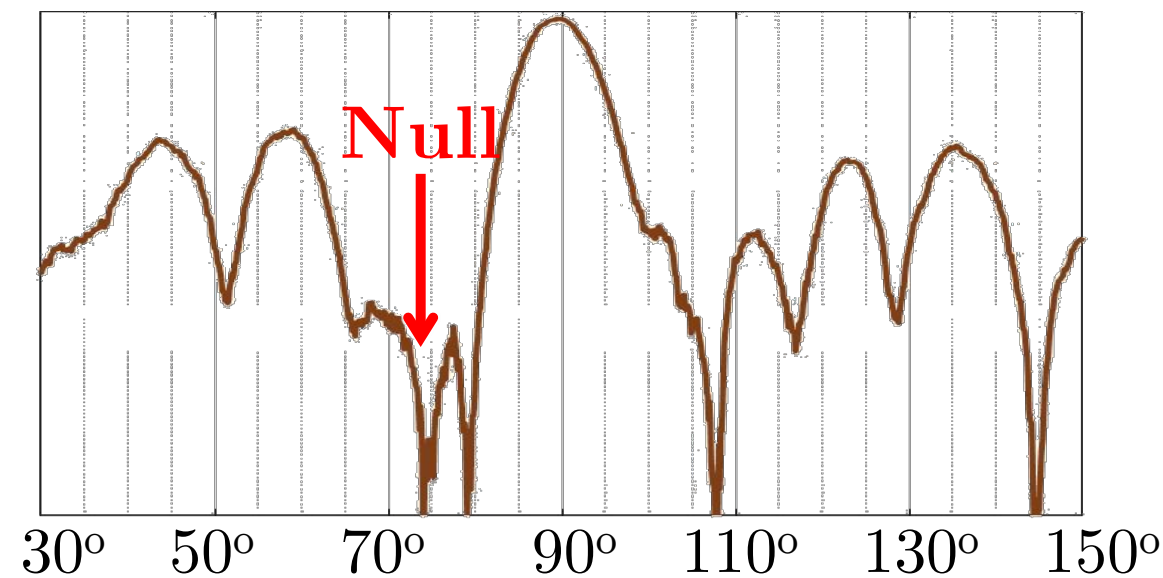
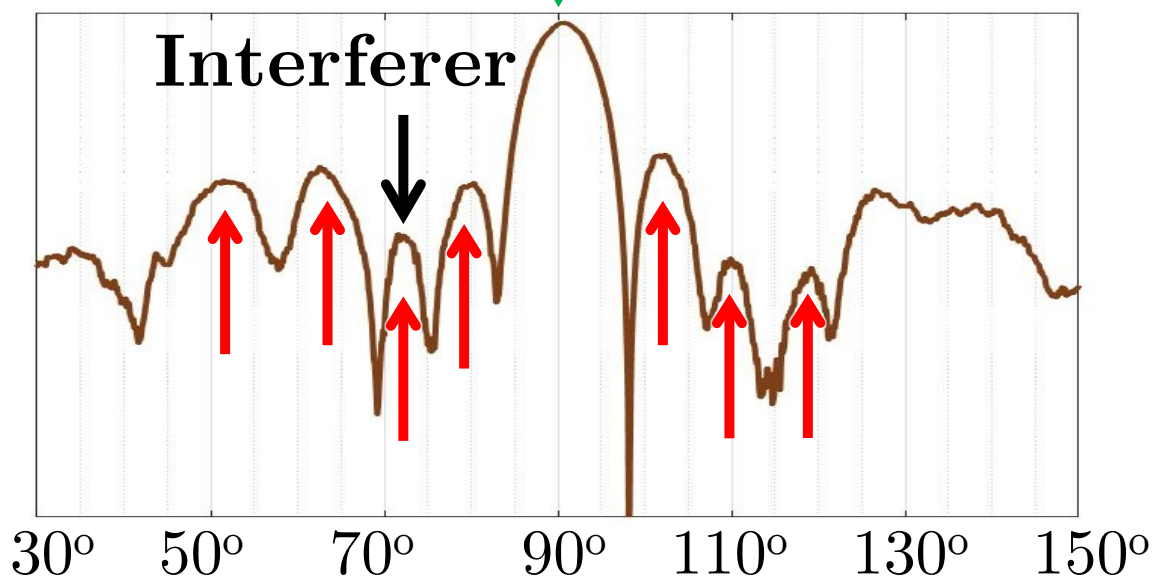
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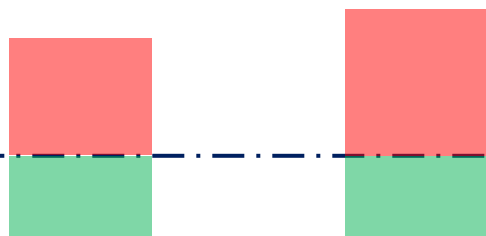
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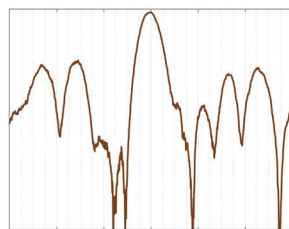
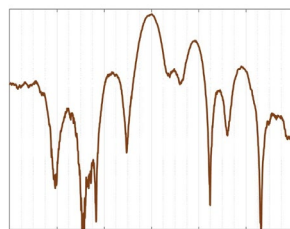
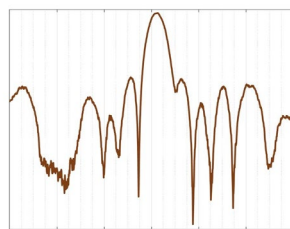
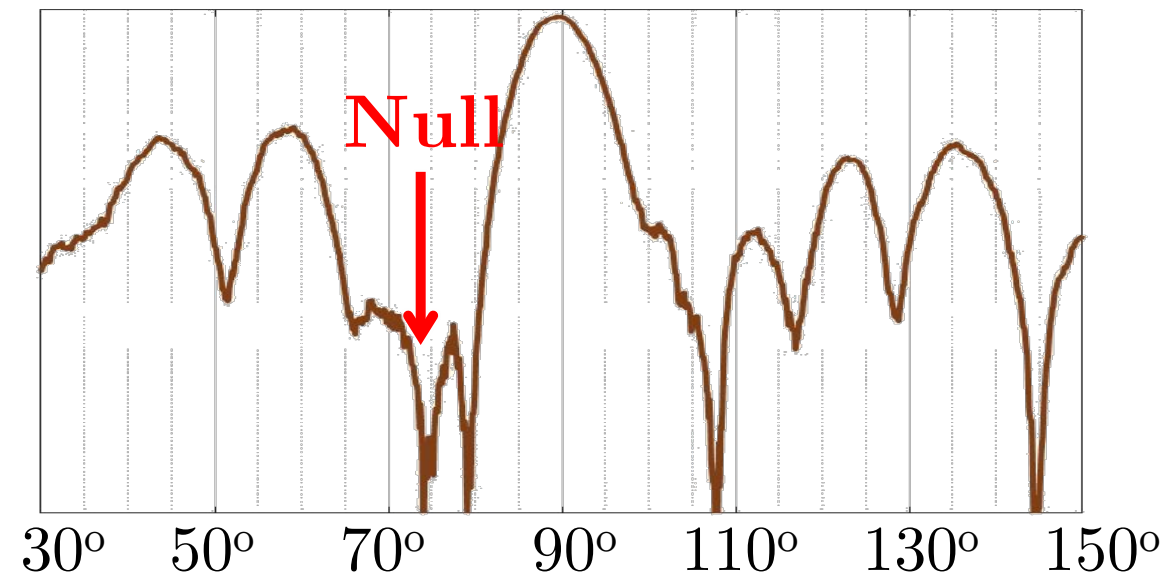
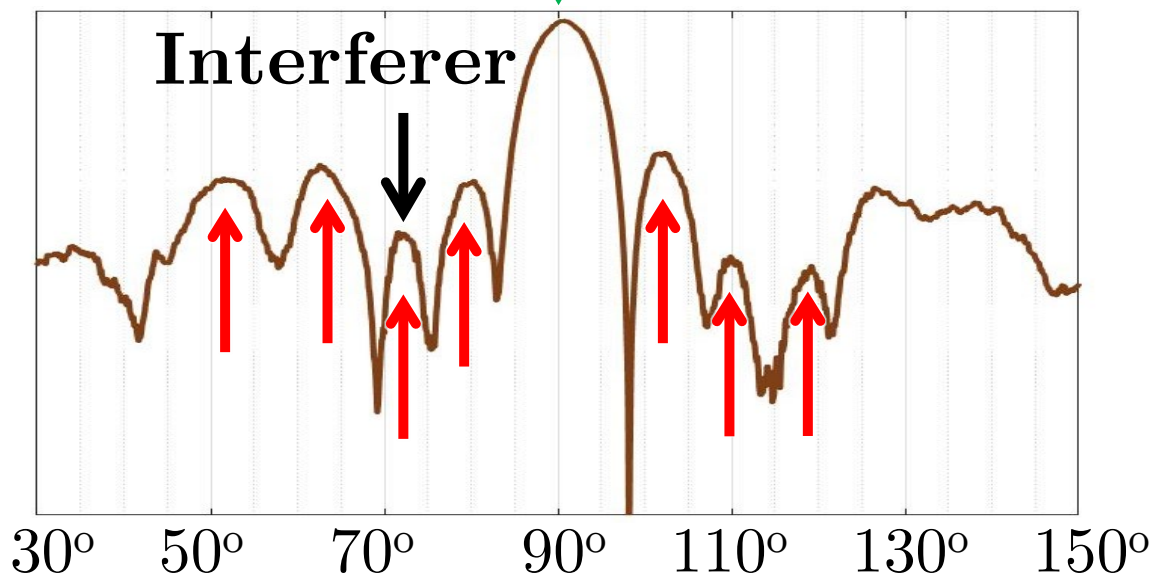
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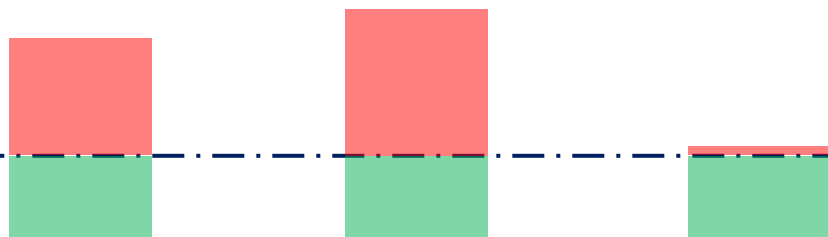
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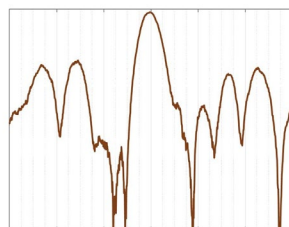
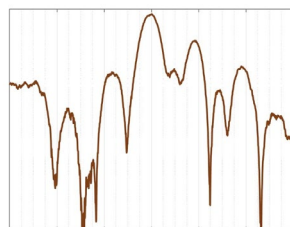
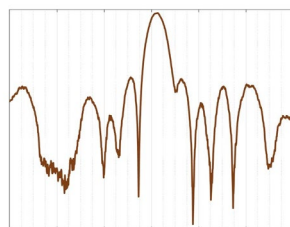
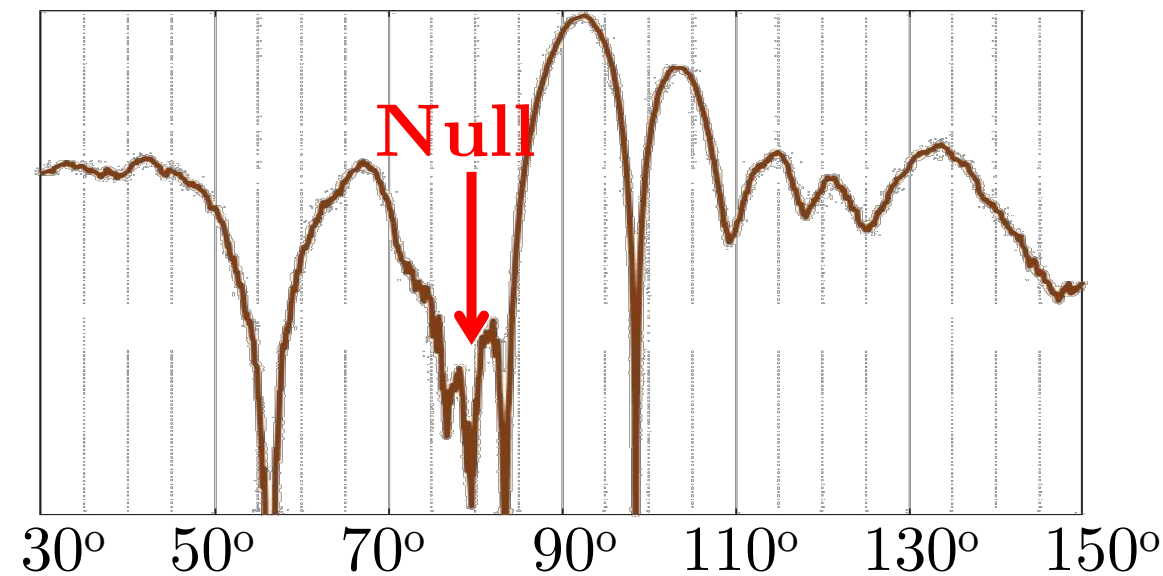
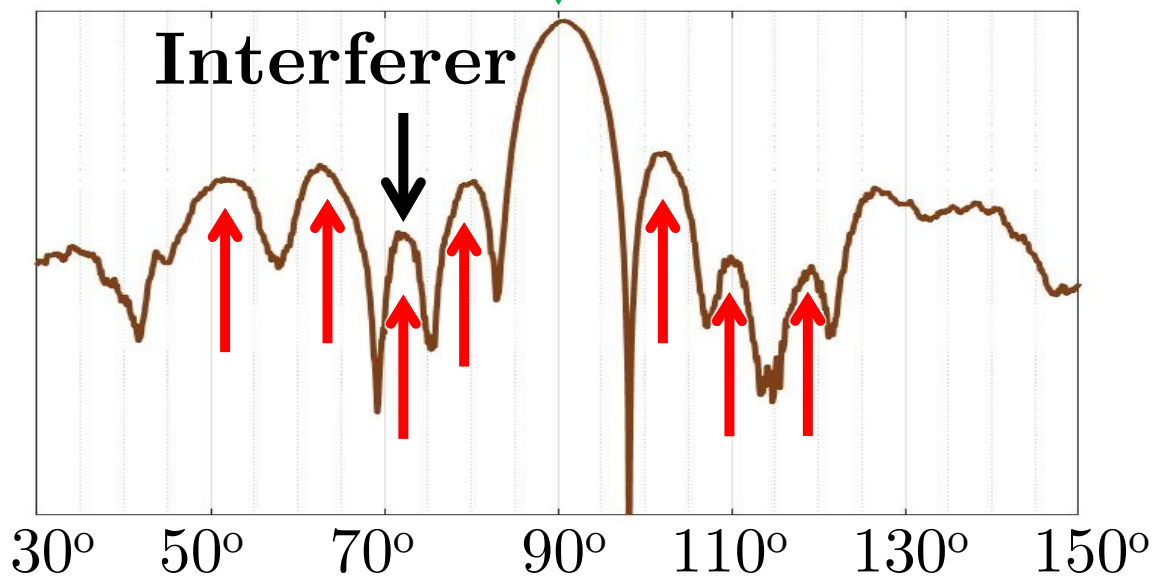
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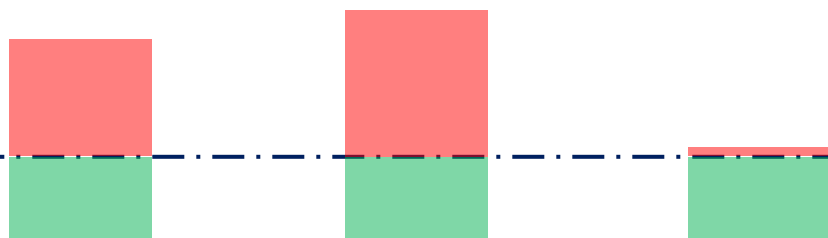
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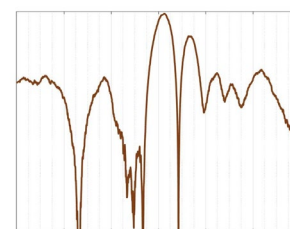
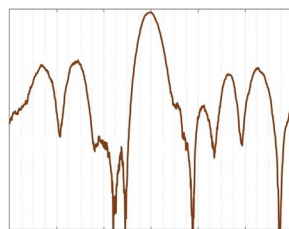
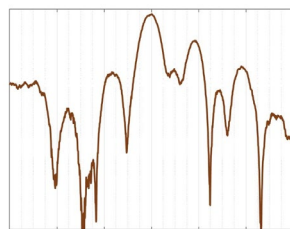
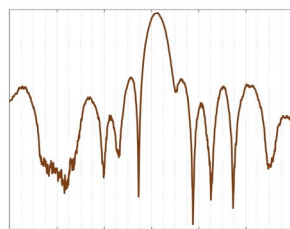
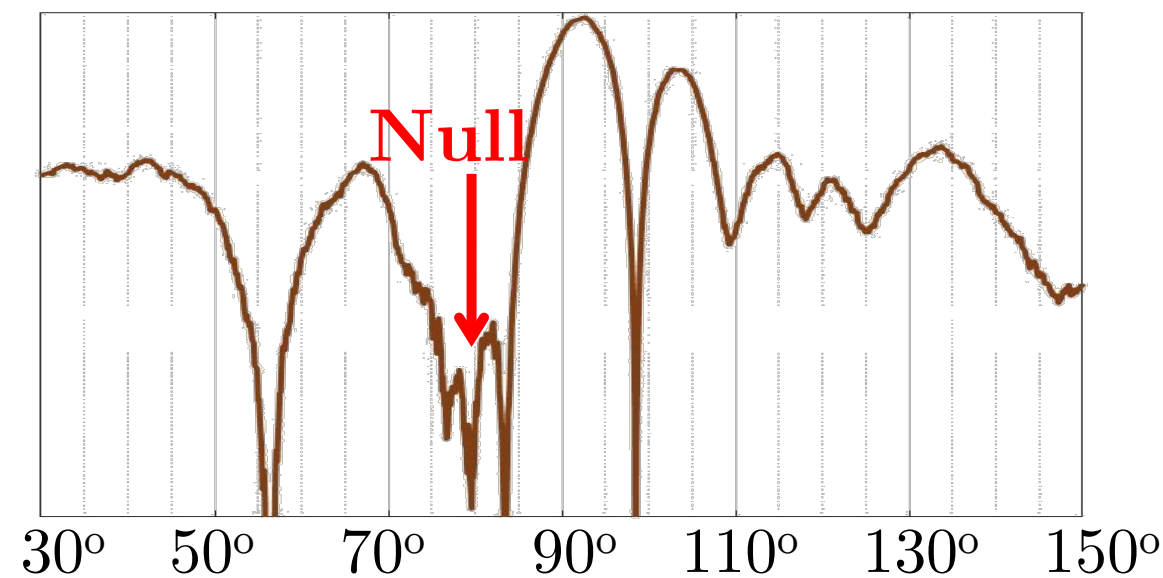
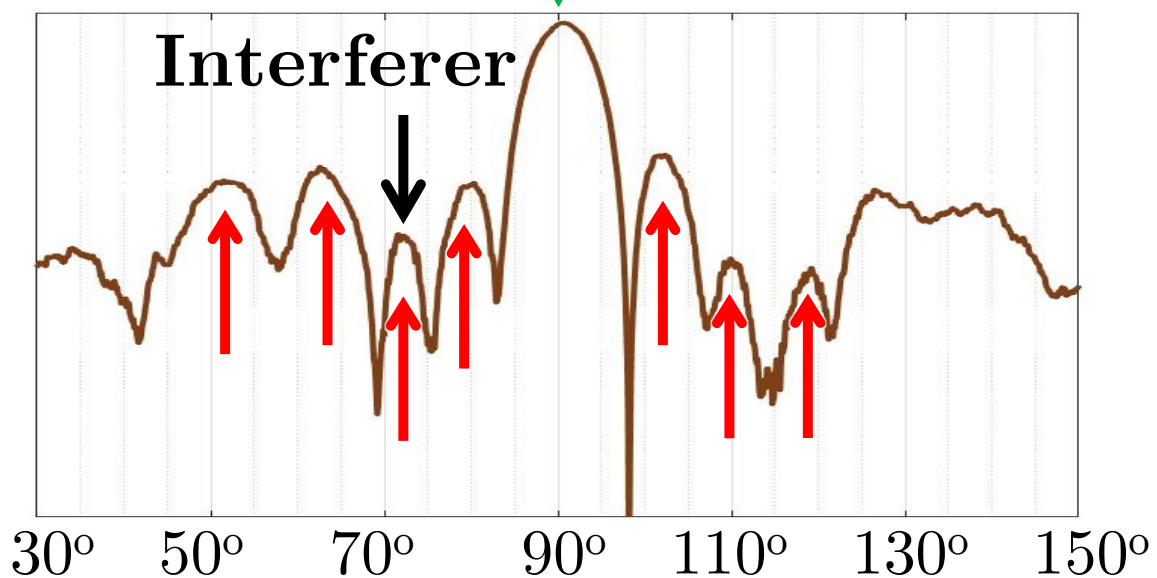
Interference

Signal



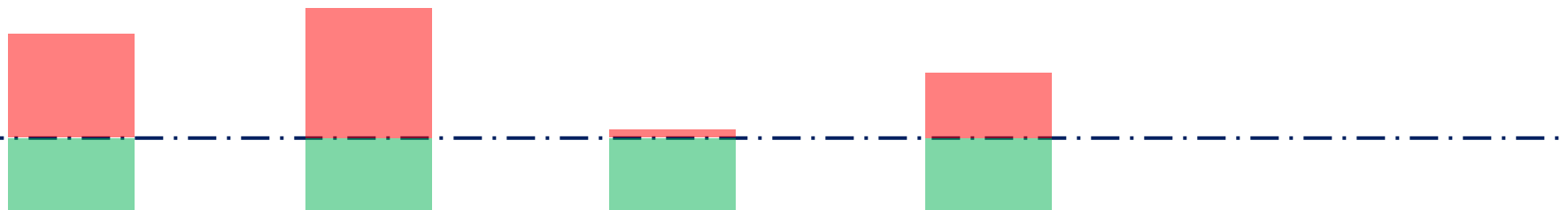
Transmitter

Fast Null Steering Protocol



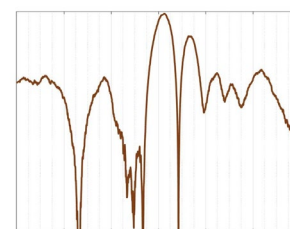
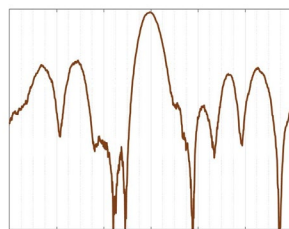
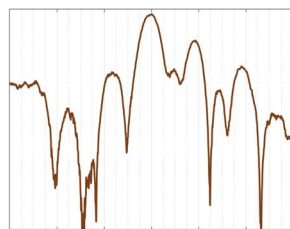
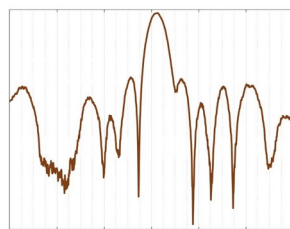
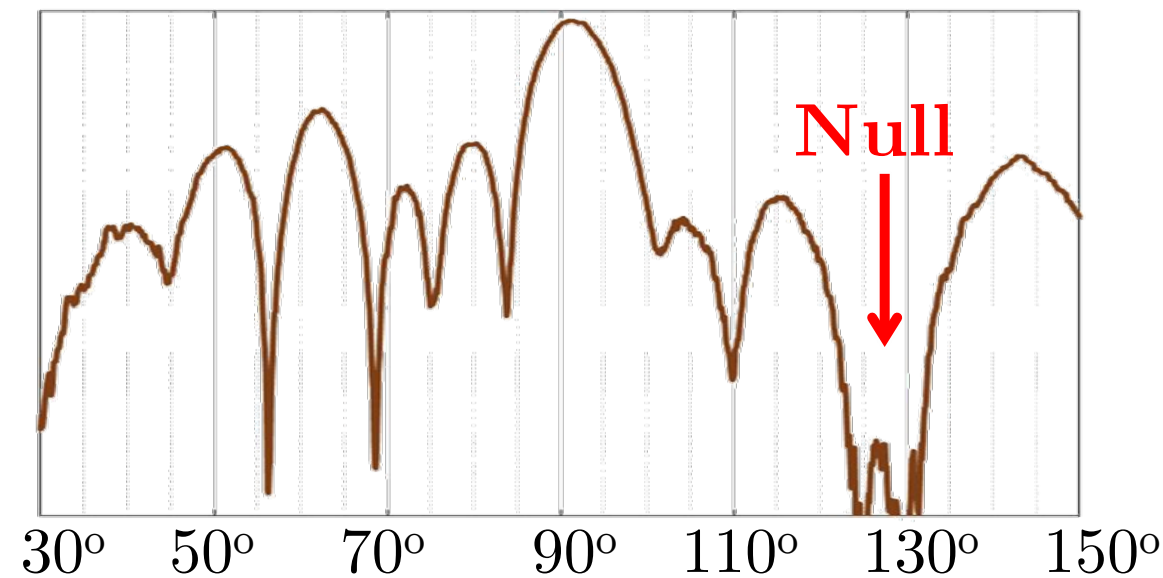
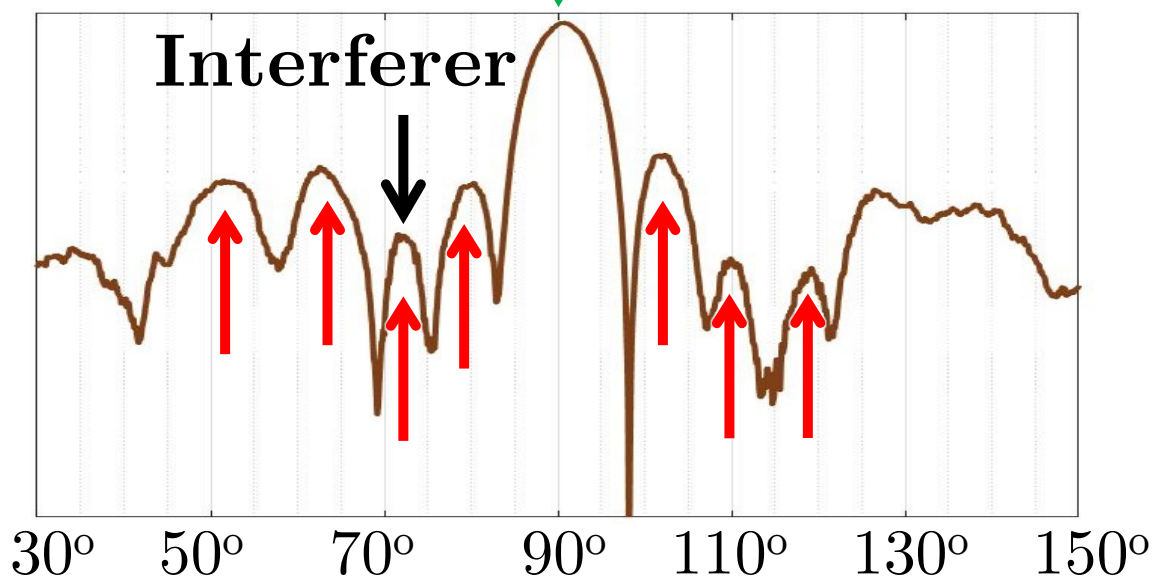
Interference

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Transmitter

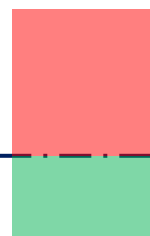
Fast Null Steering Protocol



...

Interference

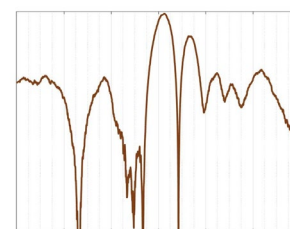
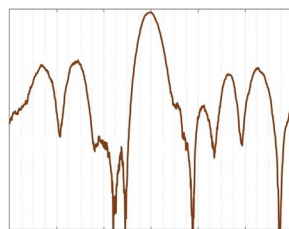
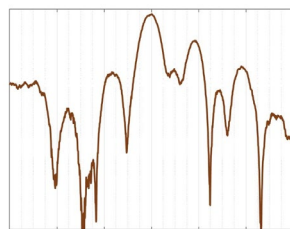
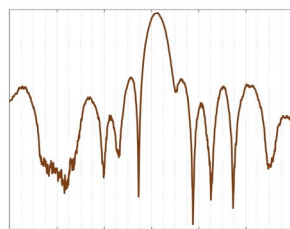
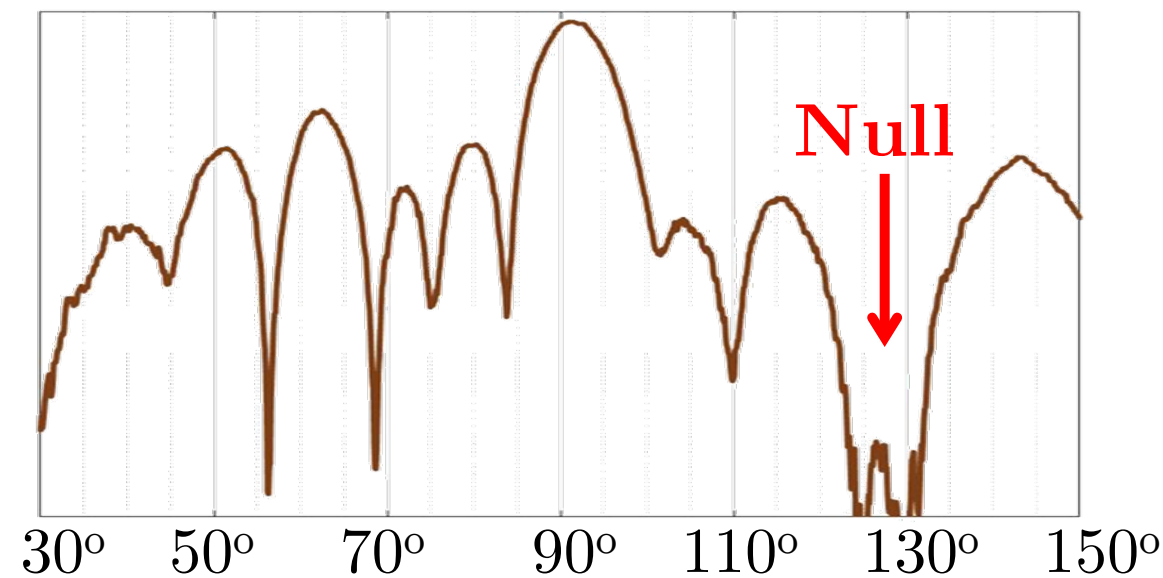
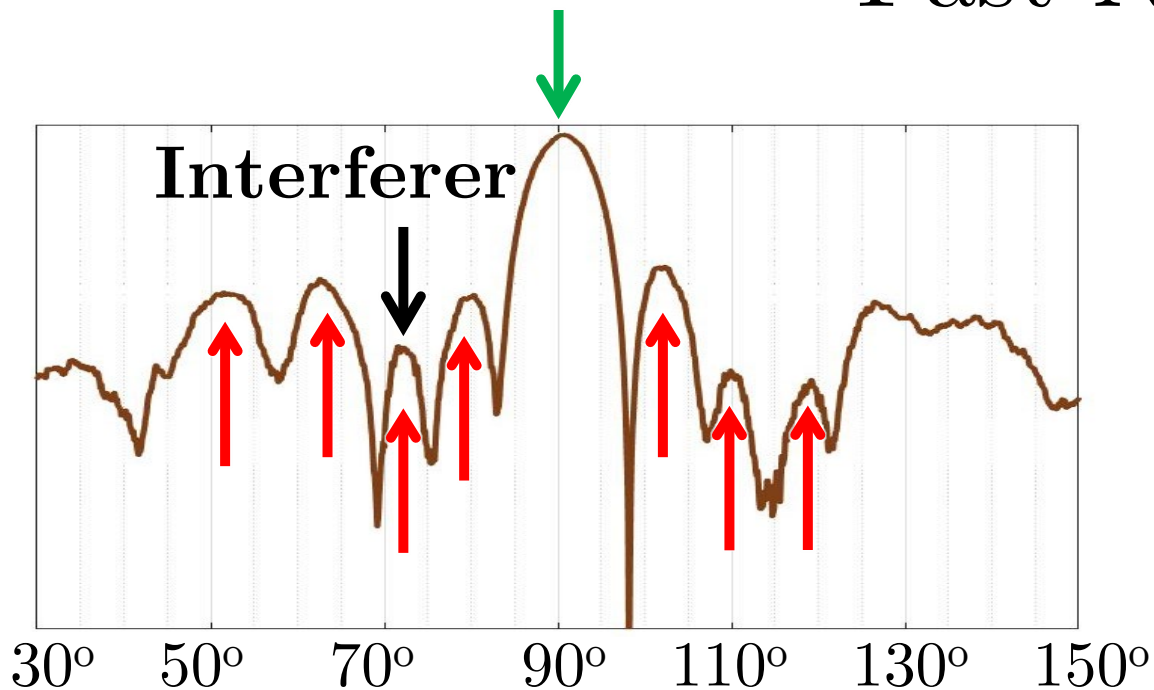
Signal



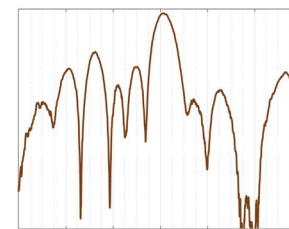
...

Transmitter

Fast Null Steering Protocol

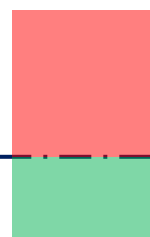


...

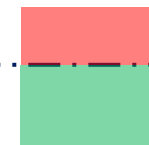


Interference

Signal

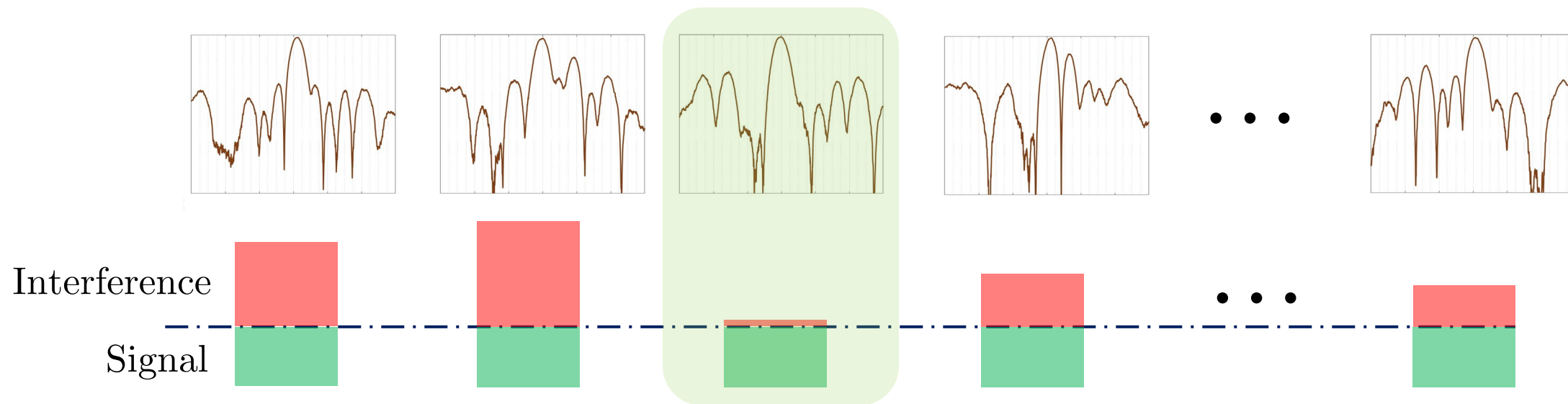
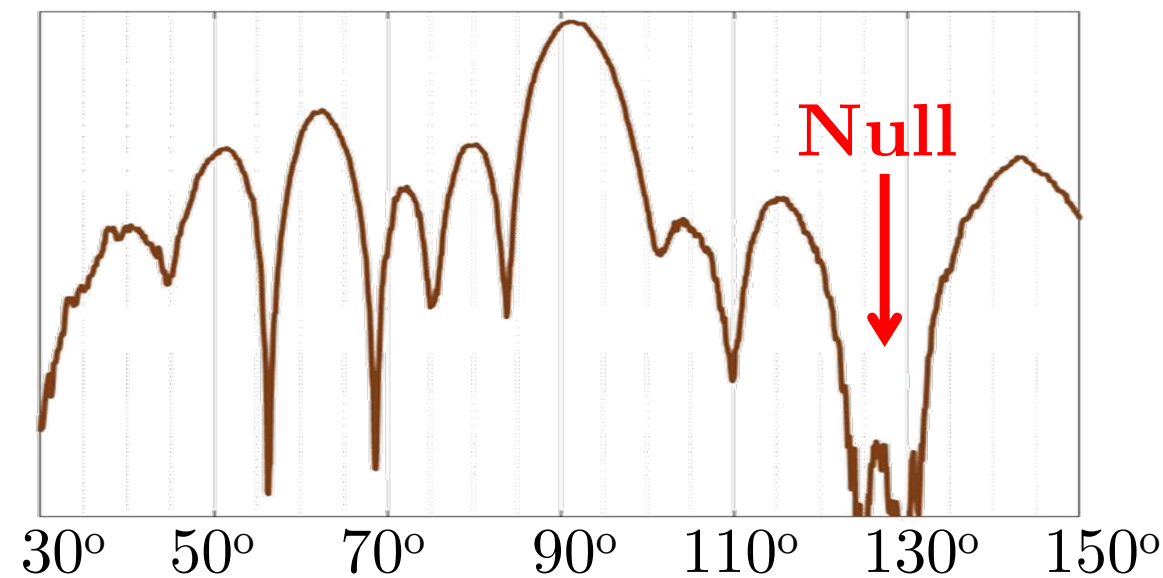
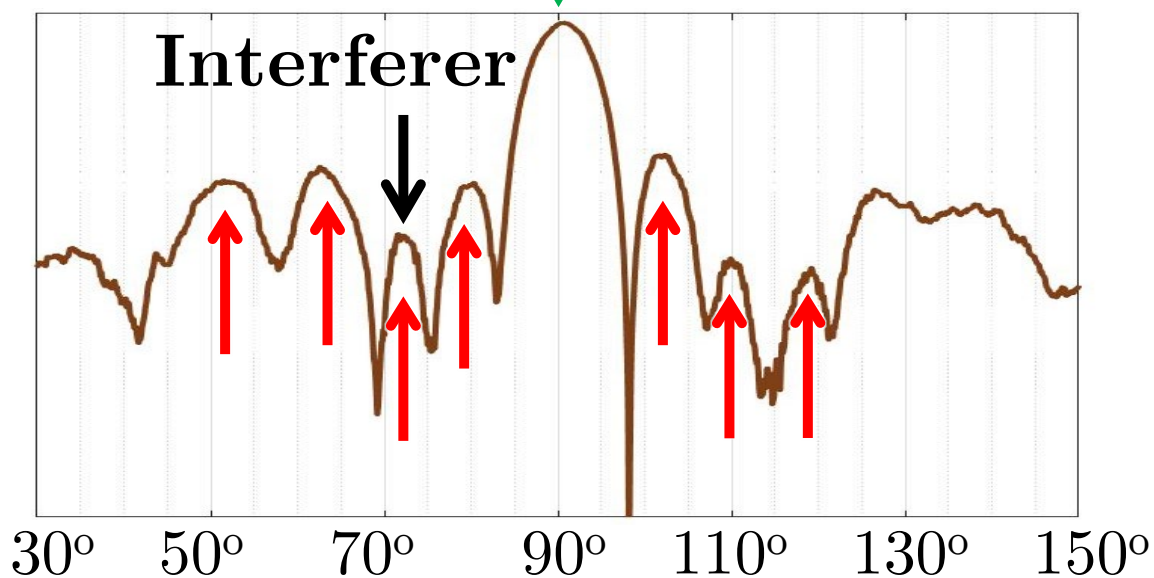


...



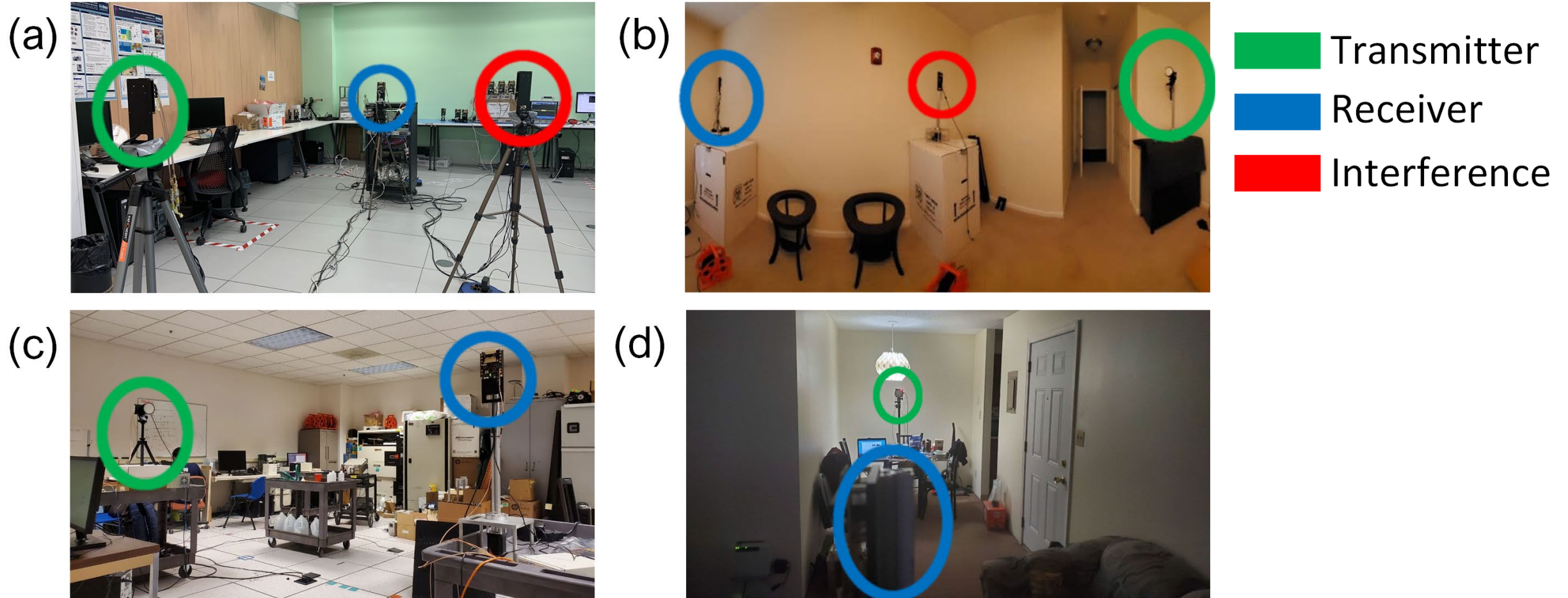
Transmitter

Fast Null Steering Protocol

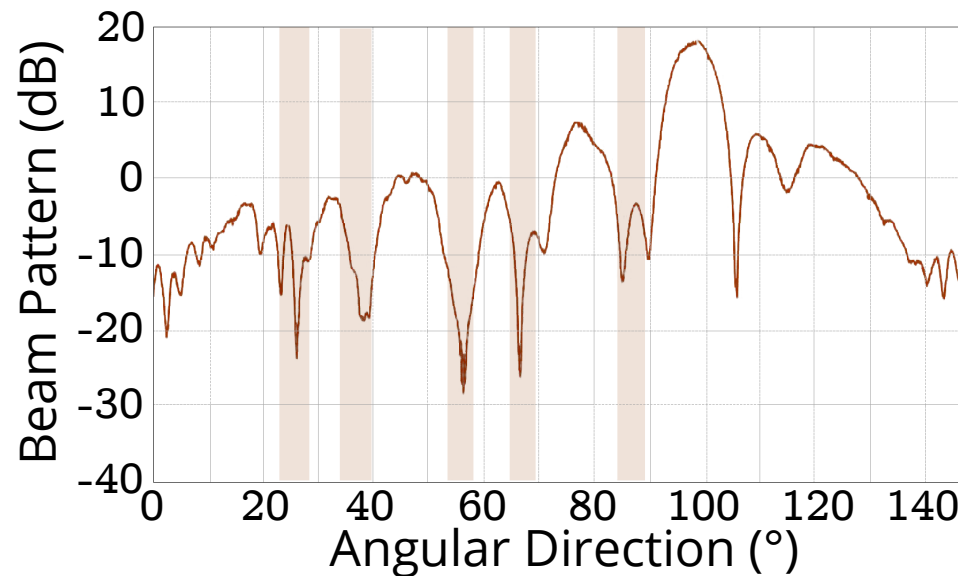
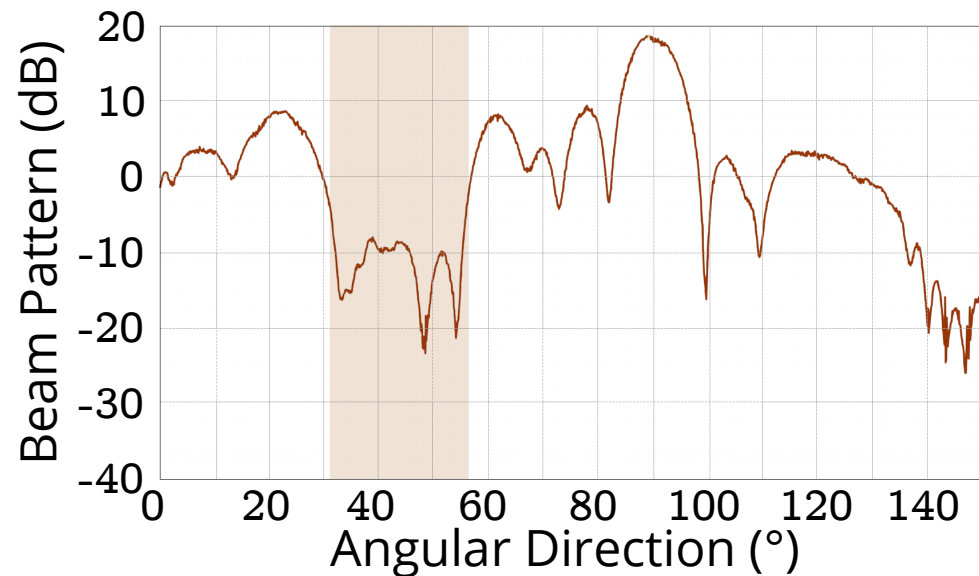
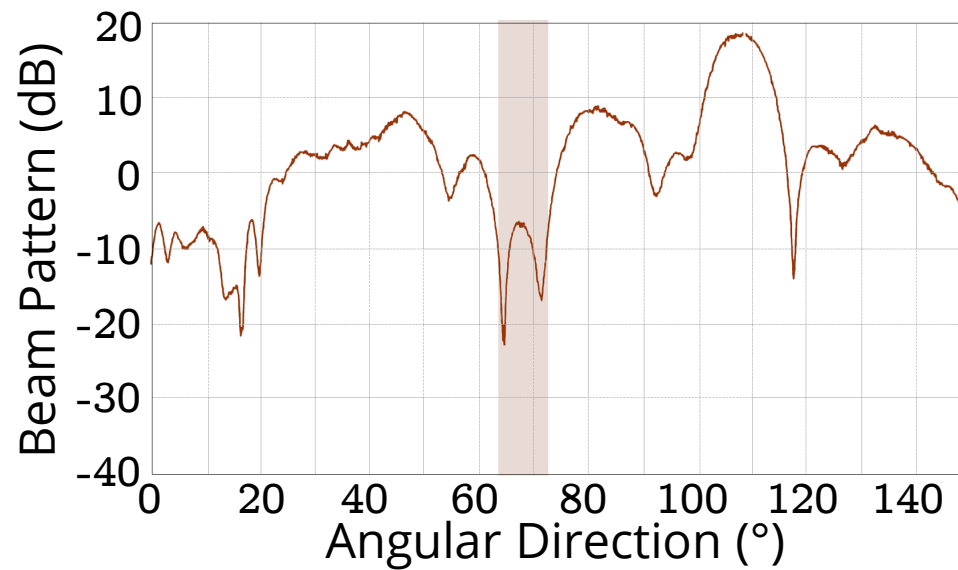
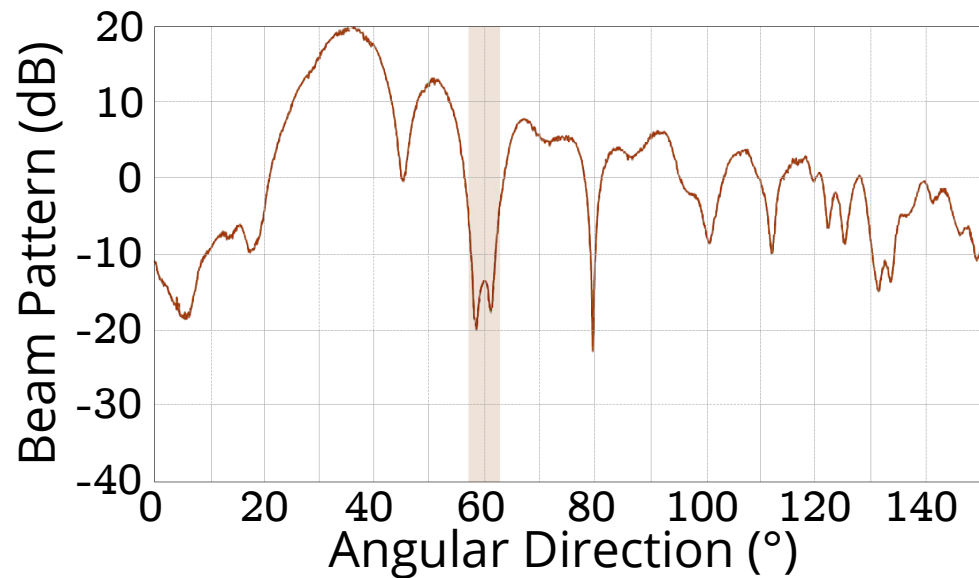


Implementation

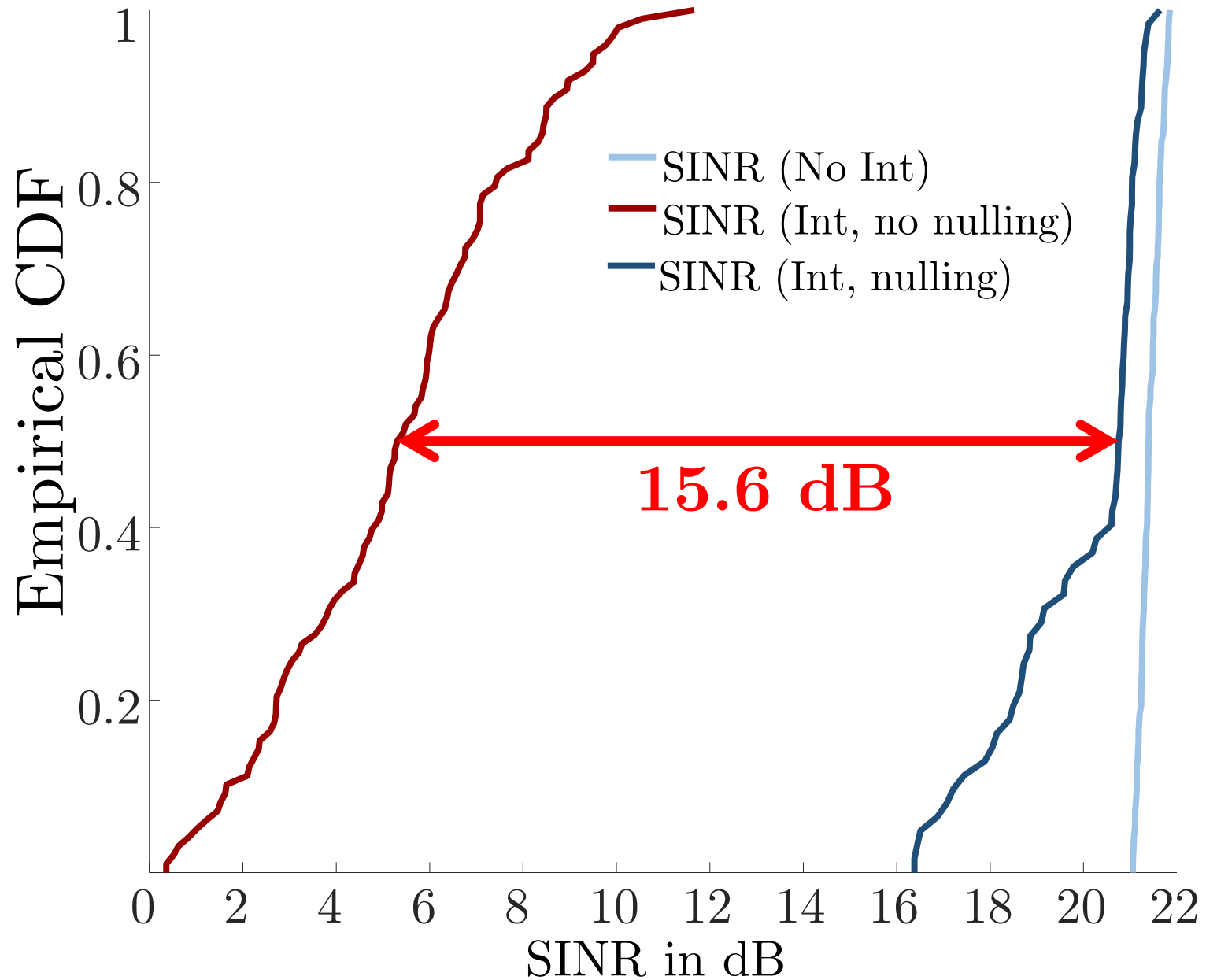
Implemented on mmFlex: 60 GHz, 16 element antennas, sending 802.11ad packets



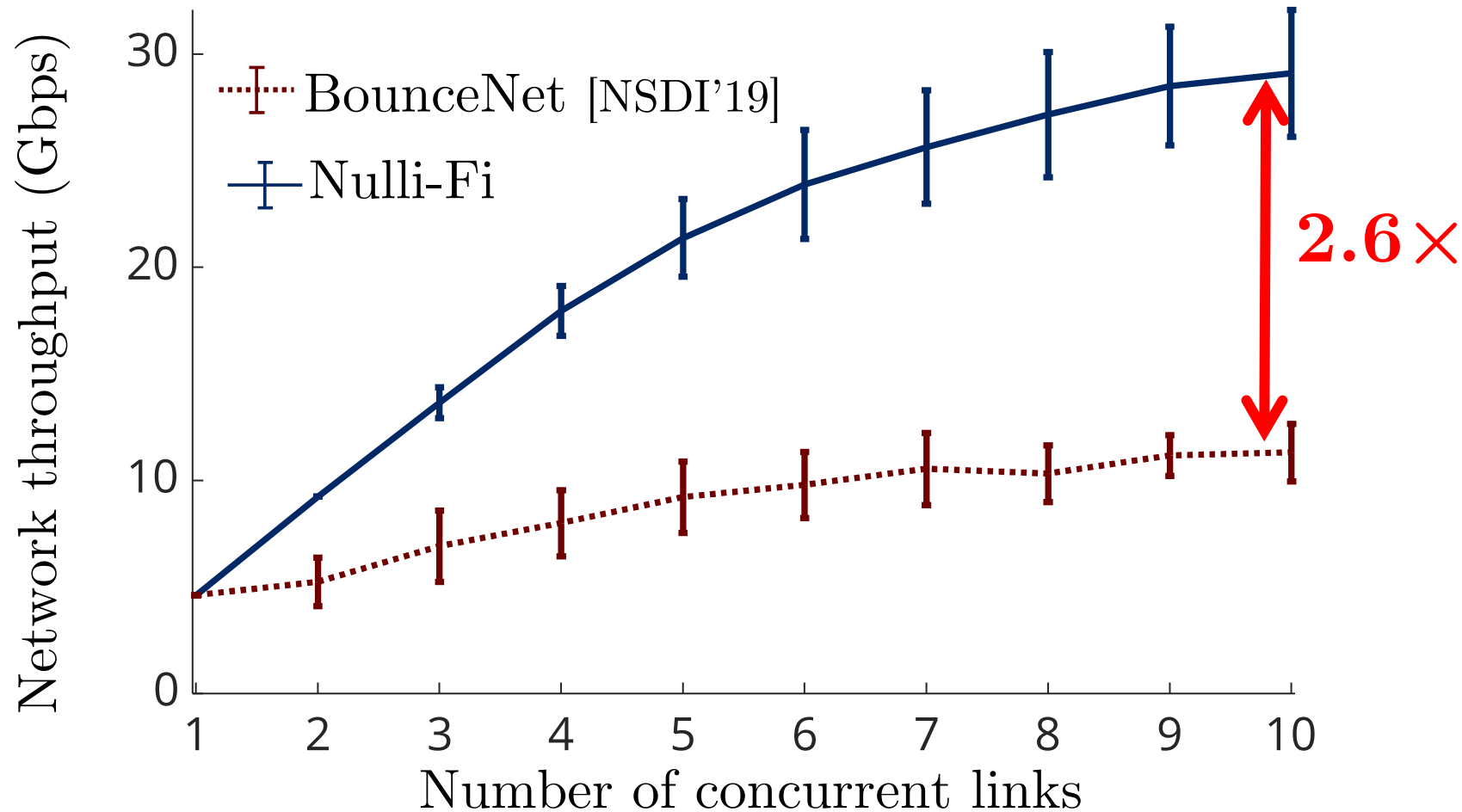
Qualitative Results



Restoring SINR using Nulli-Fi



Throughput Gains



Conclusion

- Nulli-Fi is the first practical millimeter wave null steering system.
- Millimeter wave offers a new way of interference management, opening up the opportunity of designing protocols using nulling as another primitive in our toolbox.
- We have open-sourced our algorithms on our GitLab page at <https://gitlab.engr.illinois.edu/smadani2/nulling-python>