Millimeter Wave Spectrum Sharing using Analog True-Time-Delay Array-based Wideband Nulling

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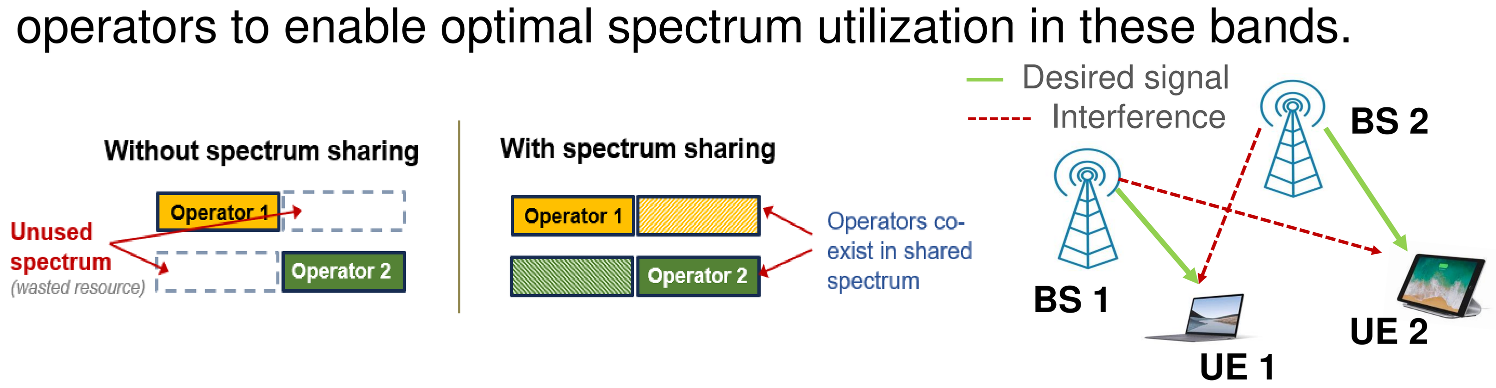
BACKGROUND

Spectrum sharing has been identified as the key solution to the spectrum crunch problem in sub-6 GHz bands. With the evolution of cellular technologies to millimeter wave (mmWave), it is crucial to identify spectrum sharing opportunities among mmWave cellular operators to enable optimal spectrum utilization in these bands.



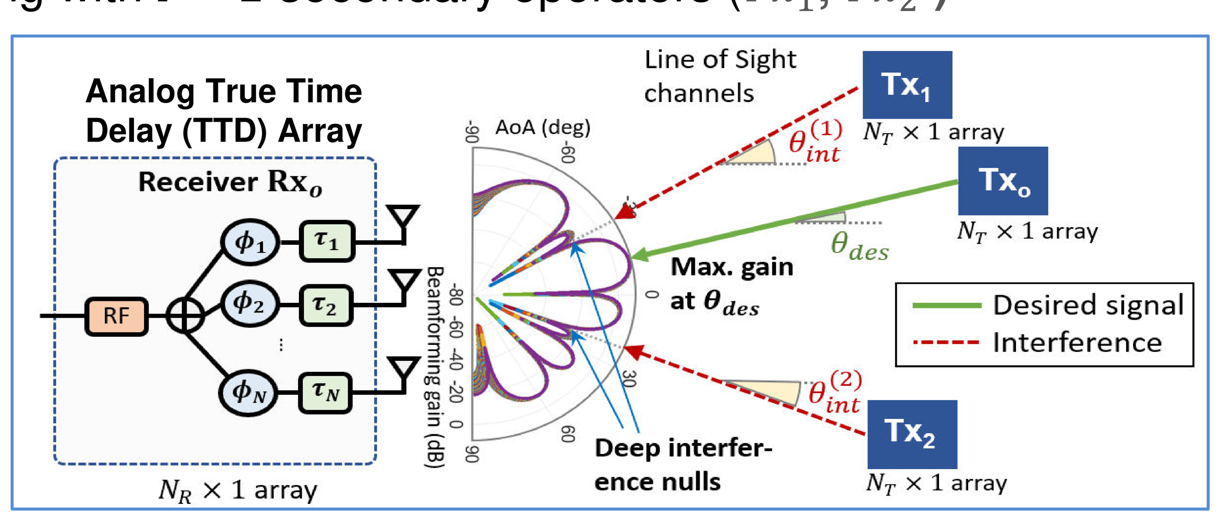
RESEARCH PROBLEM

Non-cooperating cellular operators sharing spectrum suffer from capacity degradation due to wideband interference. To facilitate dynamic spectrum sharing in mmWave bands, we need to devise low-cost and low-complexity interference suppression methods that

- Compatible with the analog antenna array architecture
- Do not require strict coordination.
- Exploit spatial sparsity of mmWave channels to circumvent explicit channel estimation

SYSTEM MODEL

An mmWave receiver Rx_o (paired with Tx_0) in a cellular network, co-existing with $I = 2$ secondary operators (Tx_1, Tx_2)



- Rx_o uses $N_R \times 1$ analog TTD array with combiner $\boldsymbol{w}_{TTD}[m]$

$$\boldsymbol{w}_{TTD}[m] = e^{j(2\pi f_m \tau + \phi)} / \sqrt{N_R}$$

- Both interferers have equal strength.

Downlink training pilots

- Each Tx_i transmits time-domain pilots $[\mathbf{b}_i\ 1] \in \mathbb{C}^{1\times(L+1)}$ in downlink.
- $\mathbf{b}_i \in \mathbb{C}^{1\times L}$ is the orthonormal pilot known to the respective Rx

PROBLEM STATEMENT

1. Given the AoAs θ_{des} and $\theta_{int}^{(1)}, \theta_{int}^{(2)}$, design the analog TTD combiner $w_{TTD}[m]$ to steer perfect wideband nulls at $\theta_{int}^{(1)}, \theta_{int}^{(2)}$ while maximizing gain at θ_{des}
2. Obtain low-latency and accurate estimates of AoAs θ_{des}, $\theta_{int}^{(1)}, \theta_{int}^{(2)}$ using dispersive TTD rainbow beam codebook.

PART I – AGILE WIDEBAND NULLING

Kronecker Decomposition based null steering

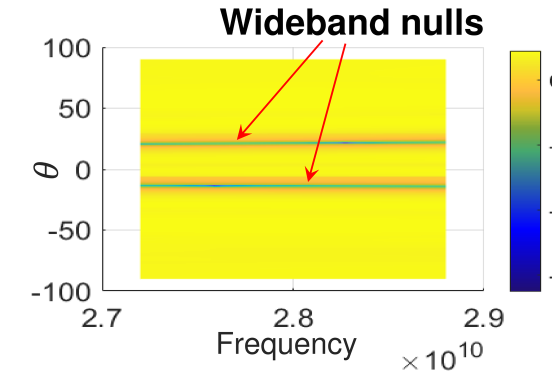
The TTD combiner is decomposed into $K = \log_2 N_R$ Kronecker factors. Each factor is either used for nulling or desired signal enhancement.

$$\boldsymbol{w}_{TTD}[m] = \begin{bmatrix} 1 \\ e^{j2\pi f_m \tilde{\tau}_1} e^{j\varphi_1} \end{bmatrix} \otimes \begin{bmatrix} 1 \\ e^{j2\pi f_m \tilde{\tau}_2} e^{j\varphi_2} \end{bmatrix} \otimes \ldots \otimes \begin{bmatrix} 1 \\ e^{j2\pi f_m \tilde{\tau}_K} e^{j\varphi_K} \end{bmatrix}$$

TTD codebook design

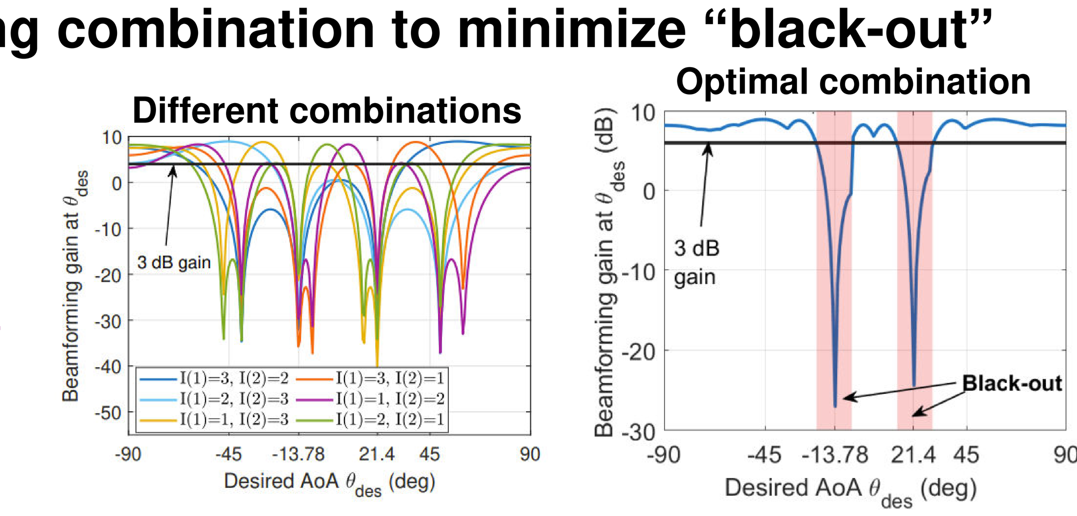
$$\tilde{\tau}_i = \frac{2^{K-i}\sin\theta_i}{2f_c}; \quad \varphi_i = \begin{cases} 0, & desired \\ \pi, & nulling \end{cases}$$

Upto $(\log_2 N_R - 1)$ nulls possible



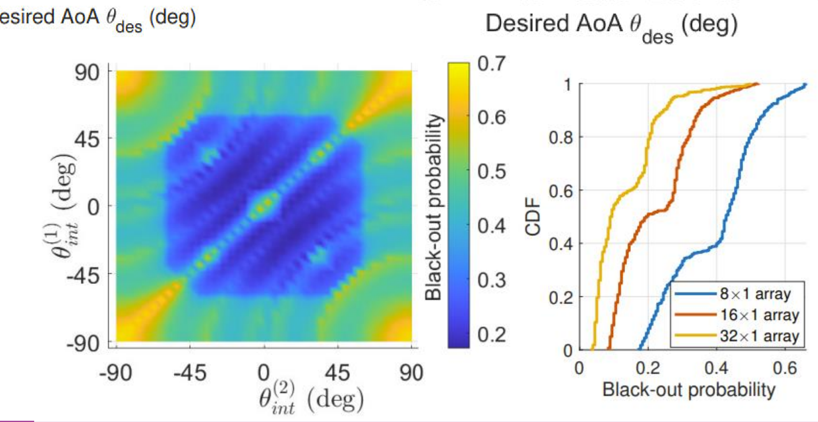
Optimal nulling combination to minimize "black-out"

Each nulling combination has unfavourable regions that suffer gain degradation



Width of black-out region depends on

- Array size
- Relative position of interferers



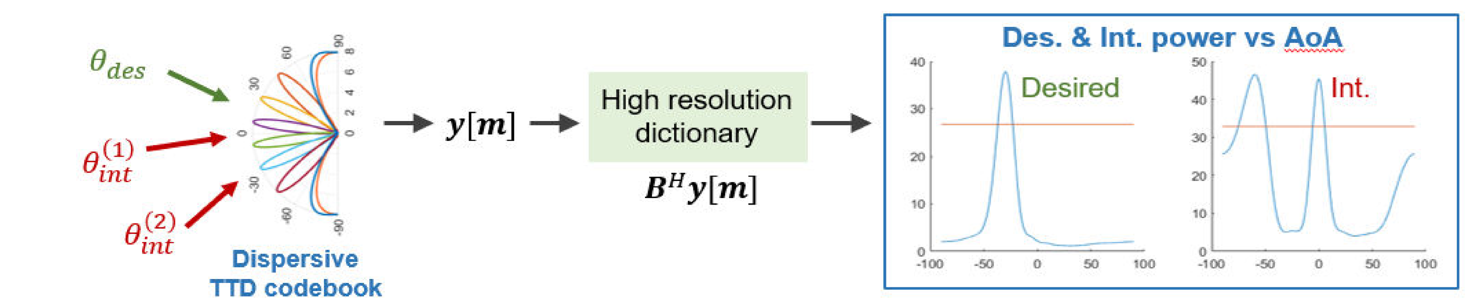
PART II –AOA ESTIMATION

Segregate desired and interference signal using known pilot sequence $\boldsymbol{b}_0$

$$y_{des}[m] = \mathbf{w}_{TTD}^H[m]\mathbf{Y}[m] \begin{bmatrix} \mathbf{I}_L \\ \mathbf{0}_{1\times L} \end{bmatrix} \boldsymbol{b}_0^H$$

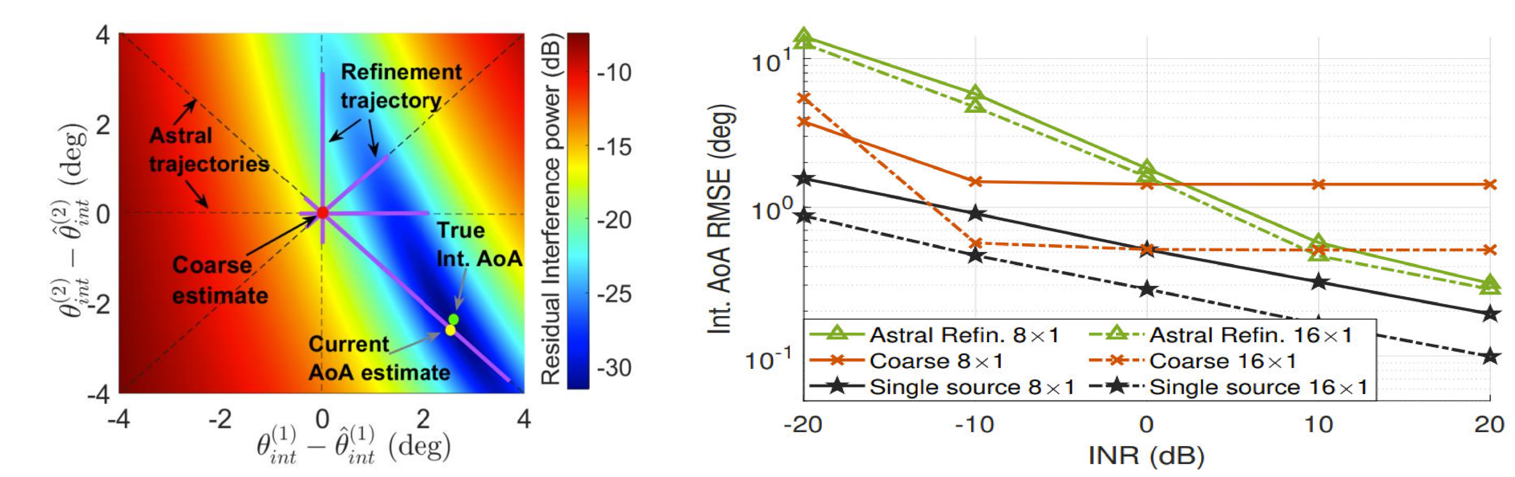
$$y_{int}[m] = \mathbf{w}_{TTD}^H[m]\mathbf{Y}[m] \left(\begin{bmatrix} \mathbf{0}_{L\times 1} \\ 1 \end{bmatrix} - \begin{bmatrix} \mathbf{I}_L \\ \mathbf{0}_{1\times L} \end{bmatrix} \boldsymbol{b}_0^H \right)$$

Dispersive rainbow beam codebook based AoA estimation



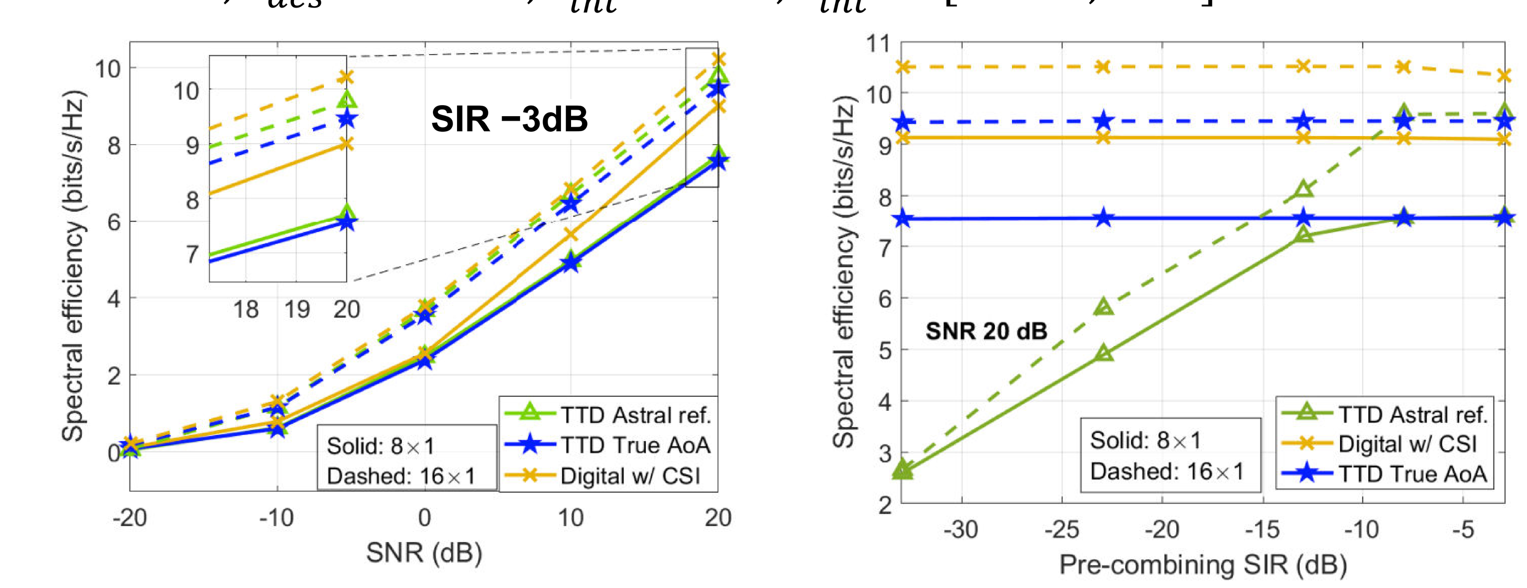
Step 1: Coarse AoA estimation via peak detection

Step 2: Iterative Astral refinement for Int. AoA estimation



RESULTS & CONCLUSIONS

$I = 2, \theta_{des} = -30^\circ, \theta_{int}^{(1)} = 0^\circ, \theta_{int}^{(2)} \in [-60^\circ, 60^\circ]$



- TTD Astral ref performs comparable to Digital w/ CSI for SNR ≤ 0dB but is marginally outperformed by the latter at high SNR.
- Larger array (eg 16x1) reduces the performance gap between TTD Astral ref and Digital w/ CSI at high SNR.
- In interference rich channels (SIR<-15dB), TTD Astral ref suffers significant degradation, whereas TTD True AoA does not.
- This shows that the sensitivity of TTD Astral Ref to AoA RMSE increases as interference becomes stronger.

ACKNOWLEDGEMENT

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[1] A. Wadaskar, S. Sarkar, and D. Cabric, "Millimeter Wave Spectrum Sharing using Analog True Time Delay Array based Wideband Nulling," in 2024 IEEE International Symposium on Dynamic Spectrum Access Networks, 2024.