Nonuniform Array Design for Robust Millimeter-Wave MIMO Links

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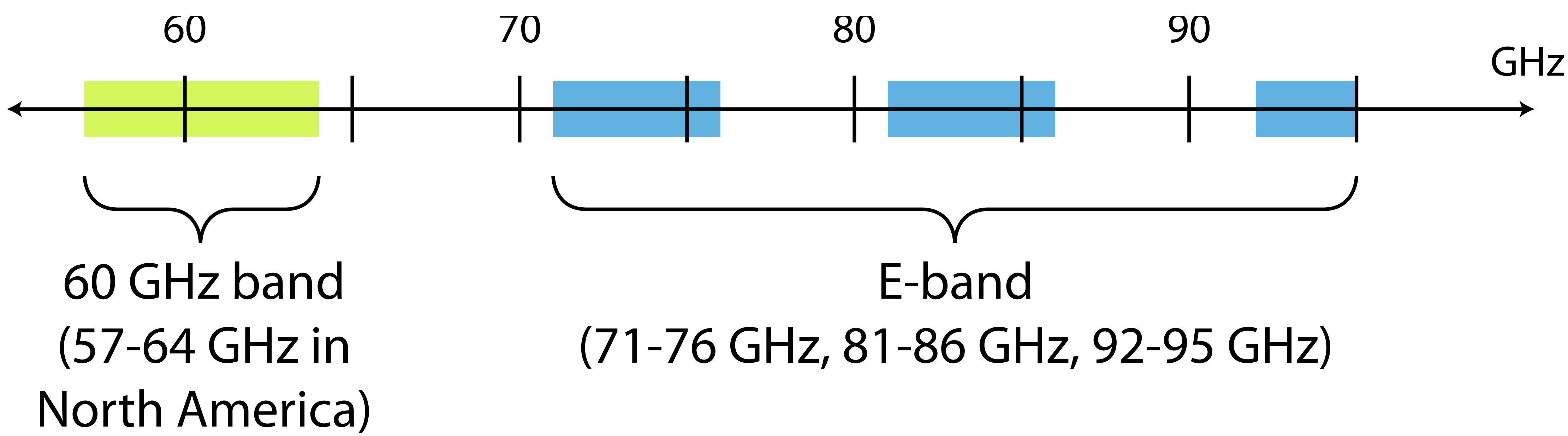
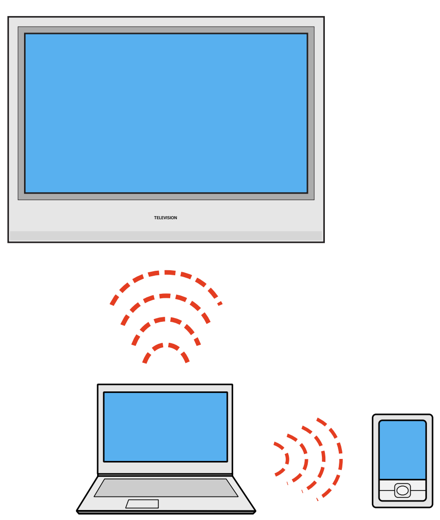
Outline

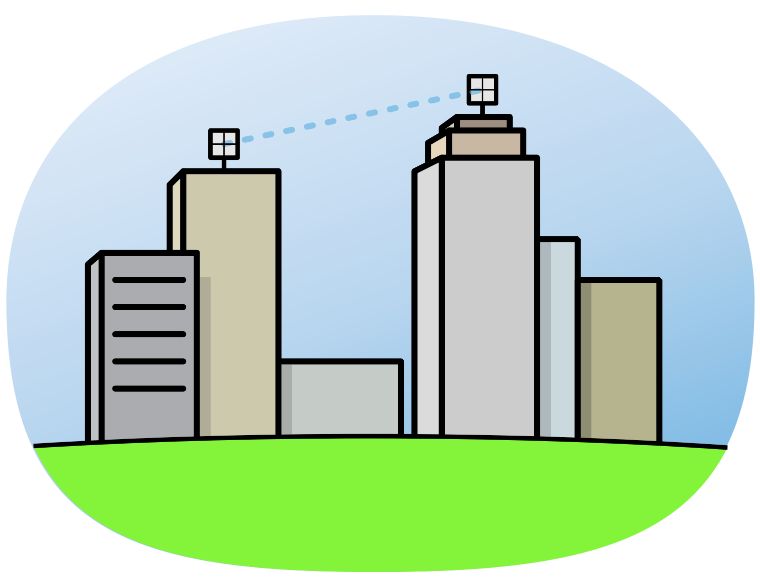
- Millimeter-wave Spatial Multiplexing
- Rayleigh Spacing Criterion
- Rayleigh-Spaced Arrays at Non-Optimal Link Range
- Performance of Nonuniform Arrays
- Conclusions

Potential of mm-Wave Communications





Streaming HD multimedia
and high speed data sync



Outdoor point-to-point links
as fiber alternative

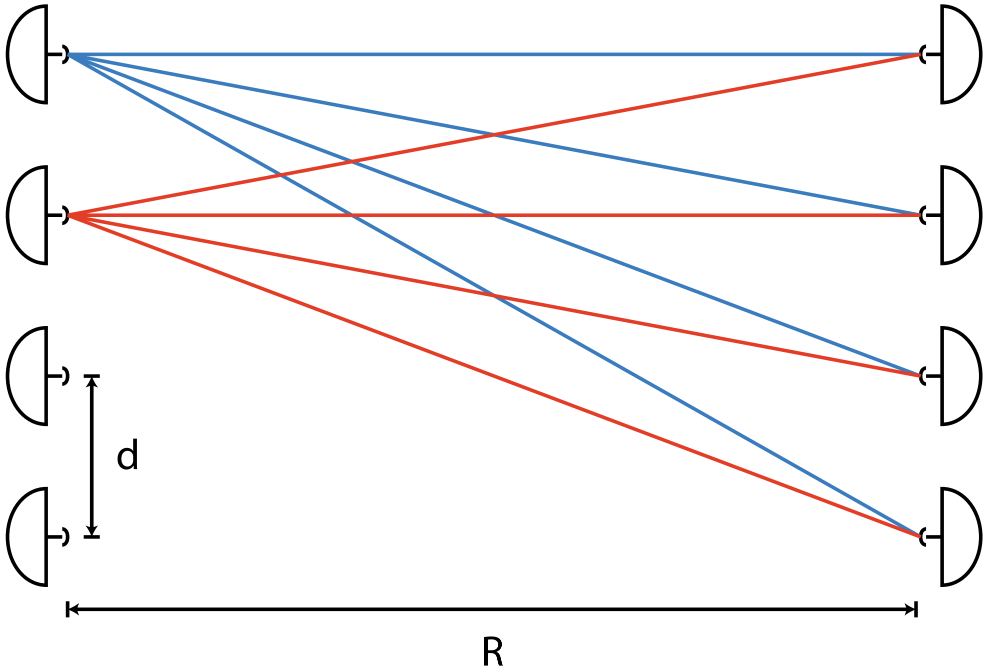
Spatial Multiplexing at mm-Waves

- Abundant bandwidth, but hardware constraints limit spectral efficiency
- Spatial multiplexing allows us to close gap with wired/fiber data rates

Ex. 4 x 10 Gbps = 40 Gbps

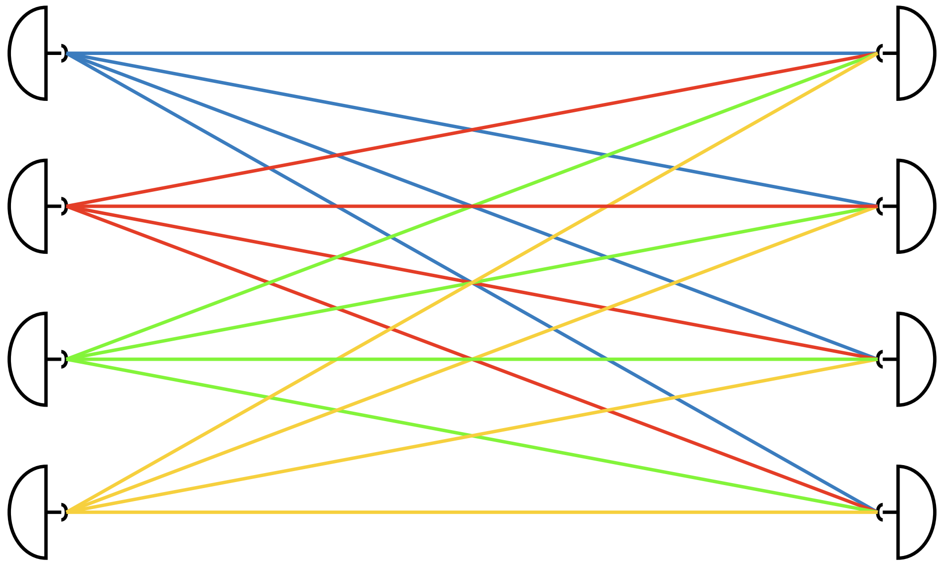
LOS MIMO Channel

At lower frequencies, multipath relied on for uncorrelated channel.



At mm-wave, LOS component dominates. LOS channel is determined by array geometry.

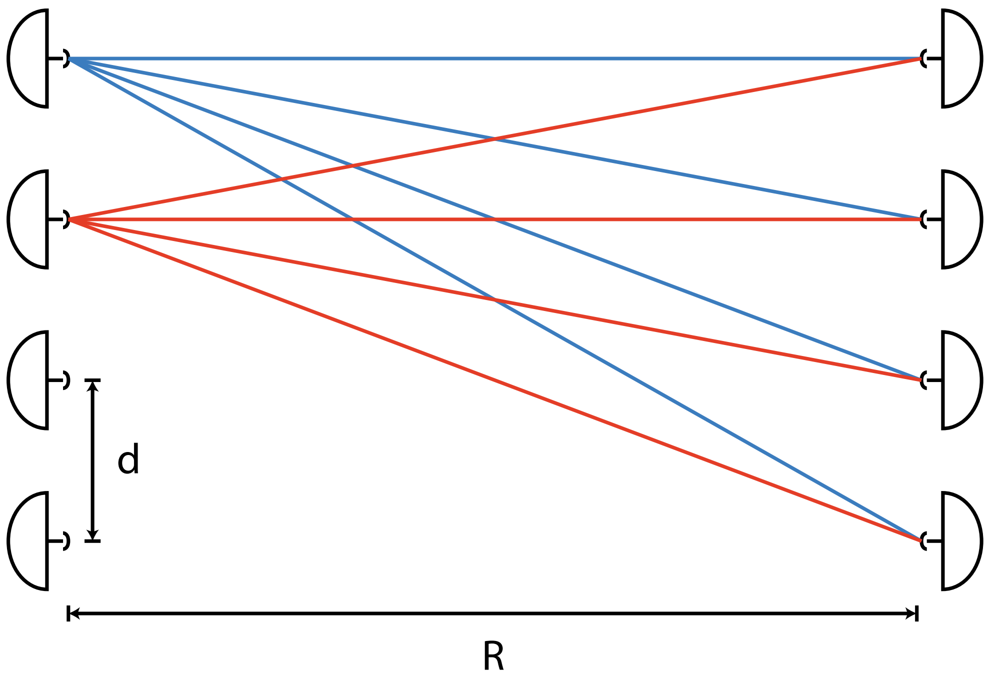
LOS MIMO Channel



$$\mathbf{H} = \begin{bmatrix} h_{11} & h_{12} & h_{13} & h_{14} \\ h_{21} & h_{22} & h_{23} & h_{24} \\ h_{31} & h_{32} & h_{33} & h_{34} \\ h_{41} & h_{42} & h_{43} & h_{44} \end{bmatrix}$$

Ideally, RX array responses to various TX elements (columns of **H**) are orthogonal

Rayleigh Spacing Criterion



Phase difference:

$$\phi = \frac{2\pi}{\lambda}\Delta L \approx \frac{\pi d^2}{\lambda R}$$

$$\mathbf{h}_1 = (1, e^{j\phi}, e^{j2^2\phi}, \ldots, e^{j(N-1)^2\phi})$$

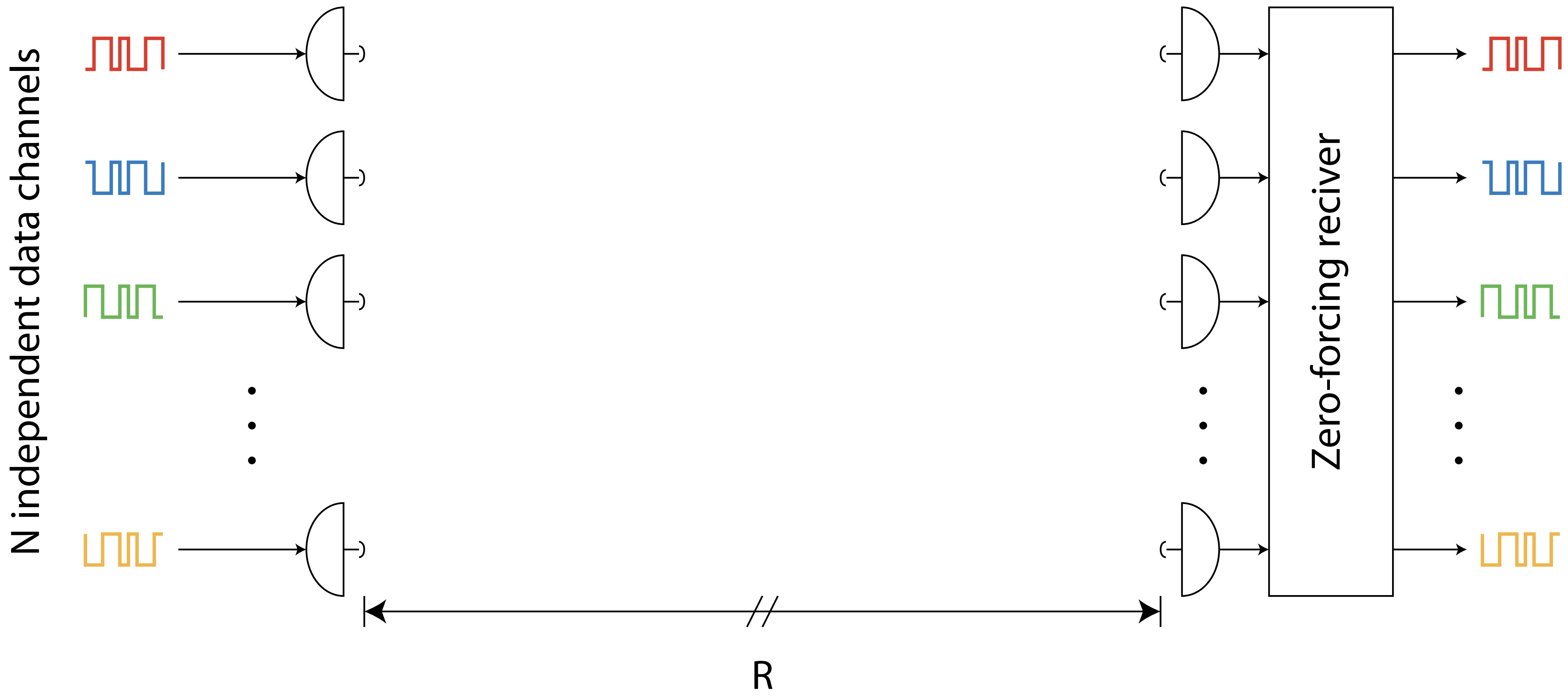
$$\mathbf{h}_2 = (e^{j\phi}, 1, e^{j\phi}, \ldots, e^{j(N-2)^2\phi})$$

Correlation: $\rho = \frac{|\mathbf{h}_1^H \mathbf{h}_2|}{||\mathbf{h}_1|| \, ||\mathbf{h}_2||} = \left| \frac{\sin(N\phi)}{N \sin\phi} \right|$

$$\rho = 0 \text{ when } N\phi = \pi$$

$$d = \sqrt{\frac{\lambda R}{N}}$$

System Diagram



- ZF receiver coefficients: $\mathbf{C}_{\mathrm{zf}} = \mathbf{H}^{-1}$

The Penalty of Spacing-Range Mismatch

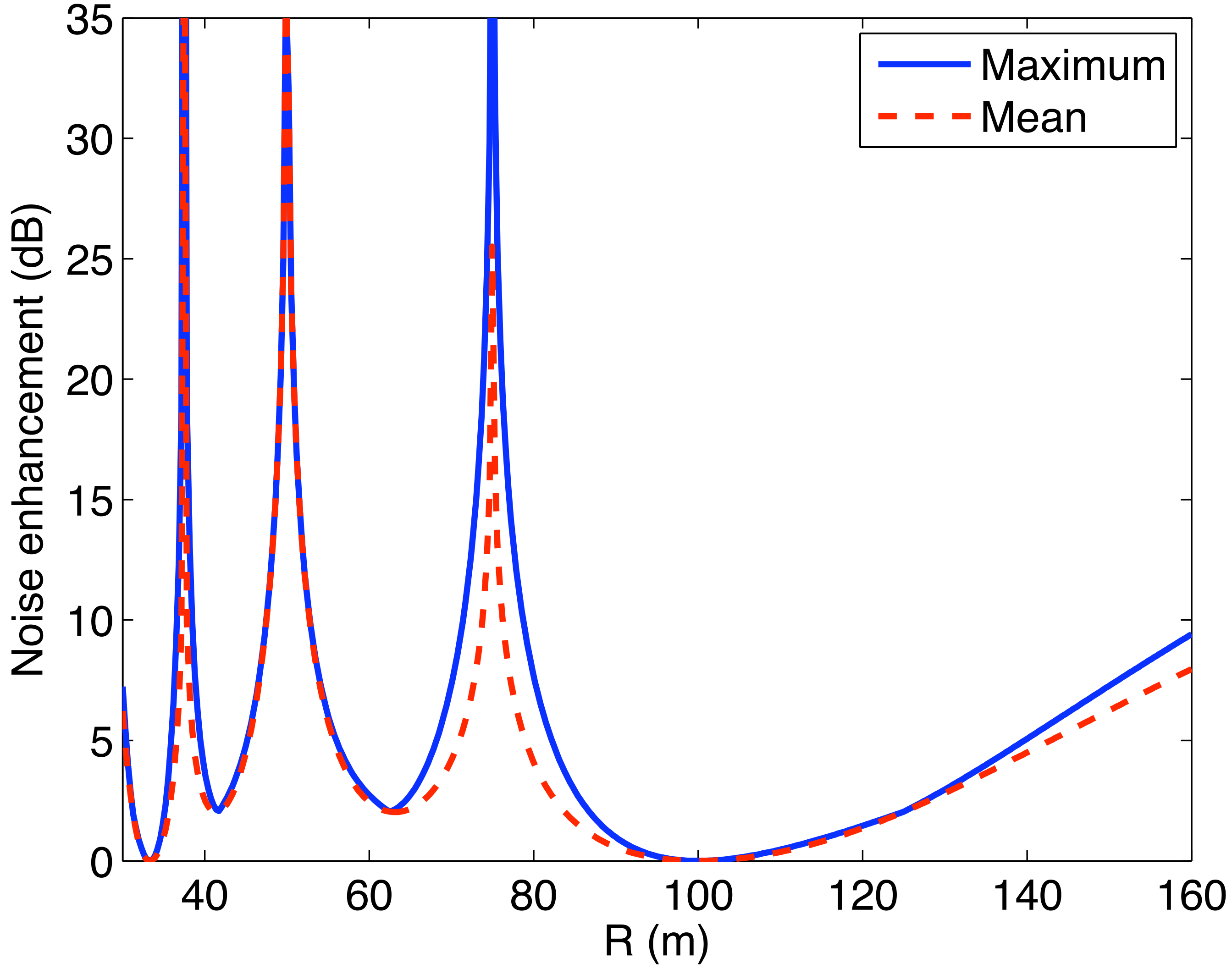
- The output of the *n*-th channel of ZF receiver

$$y_n = \mathbf{c}_{\mathrm{zf},n}^T \mathbf{r} = x_n + \mathbf{c}_{\mathrm{zf},n}^T \mathbf{w} = x_n + \hat{w}_n$$

$$\hat{w}_n \sim N(0, 2\sigma^2 ||\mathbf{c}_{\mathrm{zf},n}||^2)$$

- Noise enhancement: the SNR penalty when the Rayleigh criterion is not met
  - $\mathrm{NE} = ||\mathbf{h}_{\mathrm{n}}||^2 ||\mathbf{c}_{\mathrm{zf,n}}||^2 = \mathrm{N} \cdot ||\mathbf{c}_{\mathrm{zf,n}}||^2$

Noise Enhancement



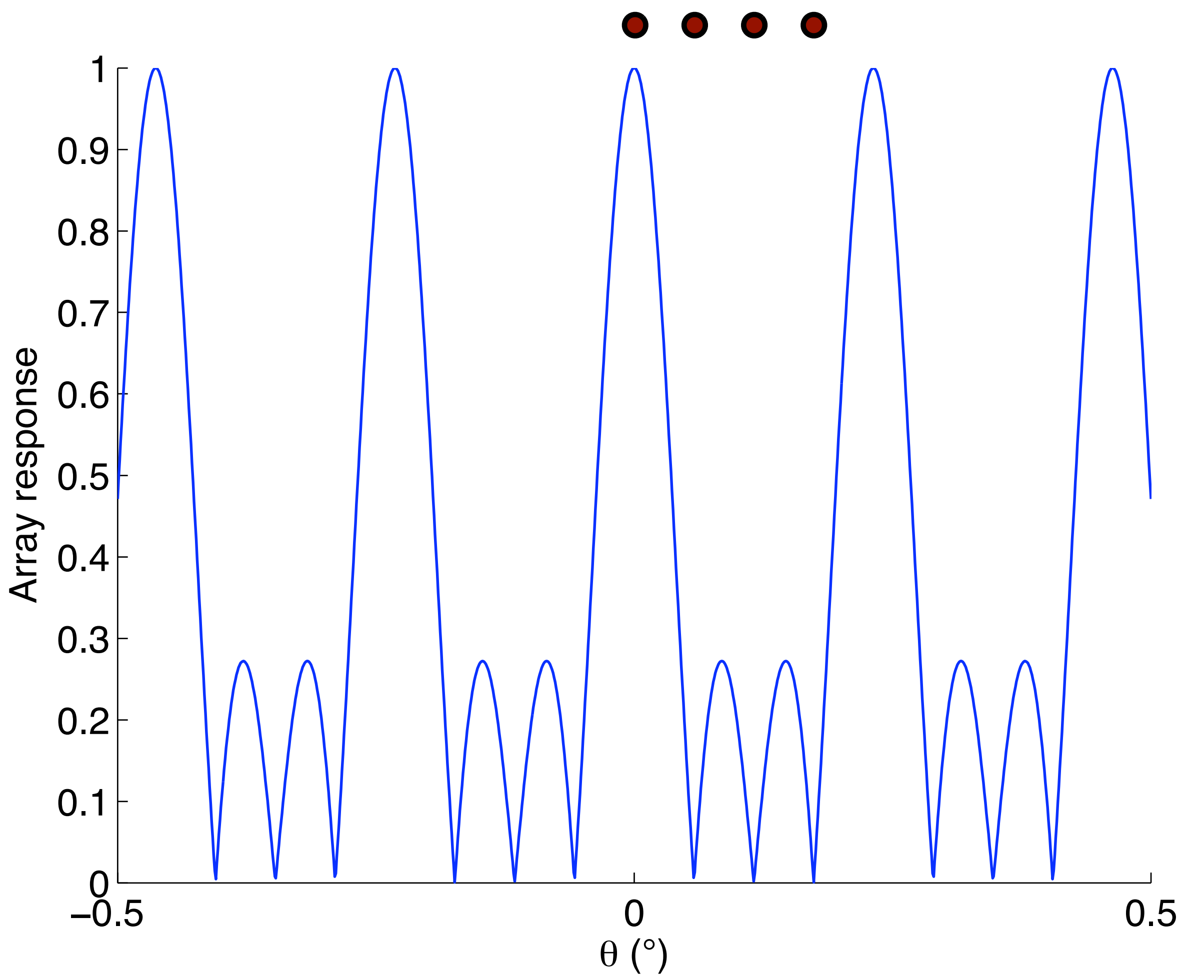
4x4 link

R_o = 100 m

- Noise enhancement spikes occur when rows of channel matrix become highly correlated
- First spike occurs at R= $R_o(N-1)/N$

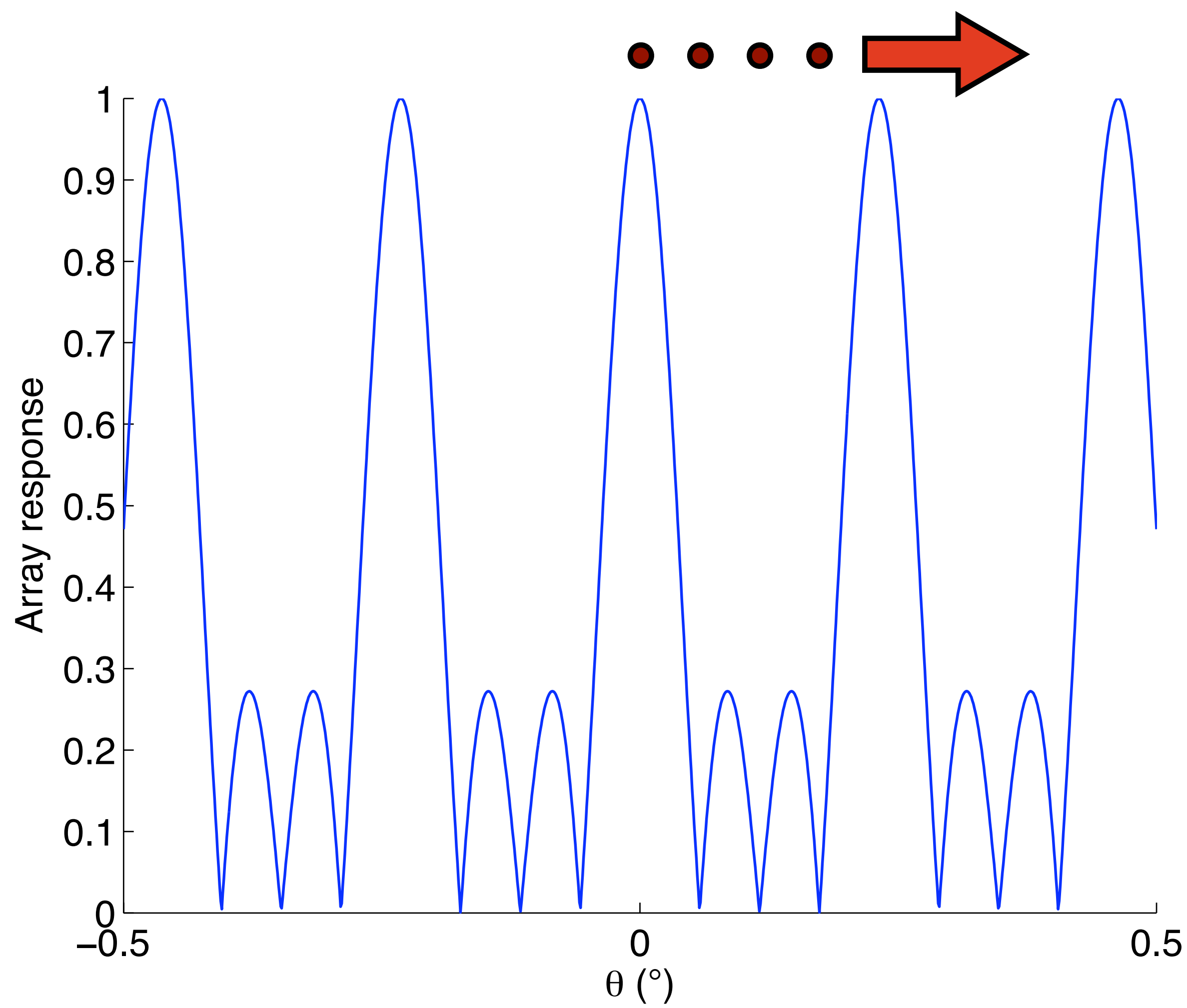
Physical Interpretation: Grating Lobes

- Large antenna spacing results in grating lobes
- At Rayleigh spacing, TX antennas coincide with nulls in RX array pattern



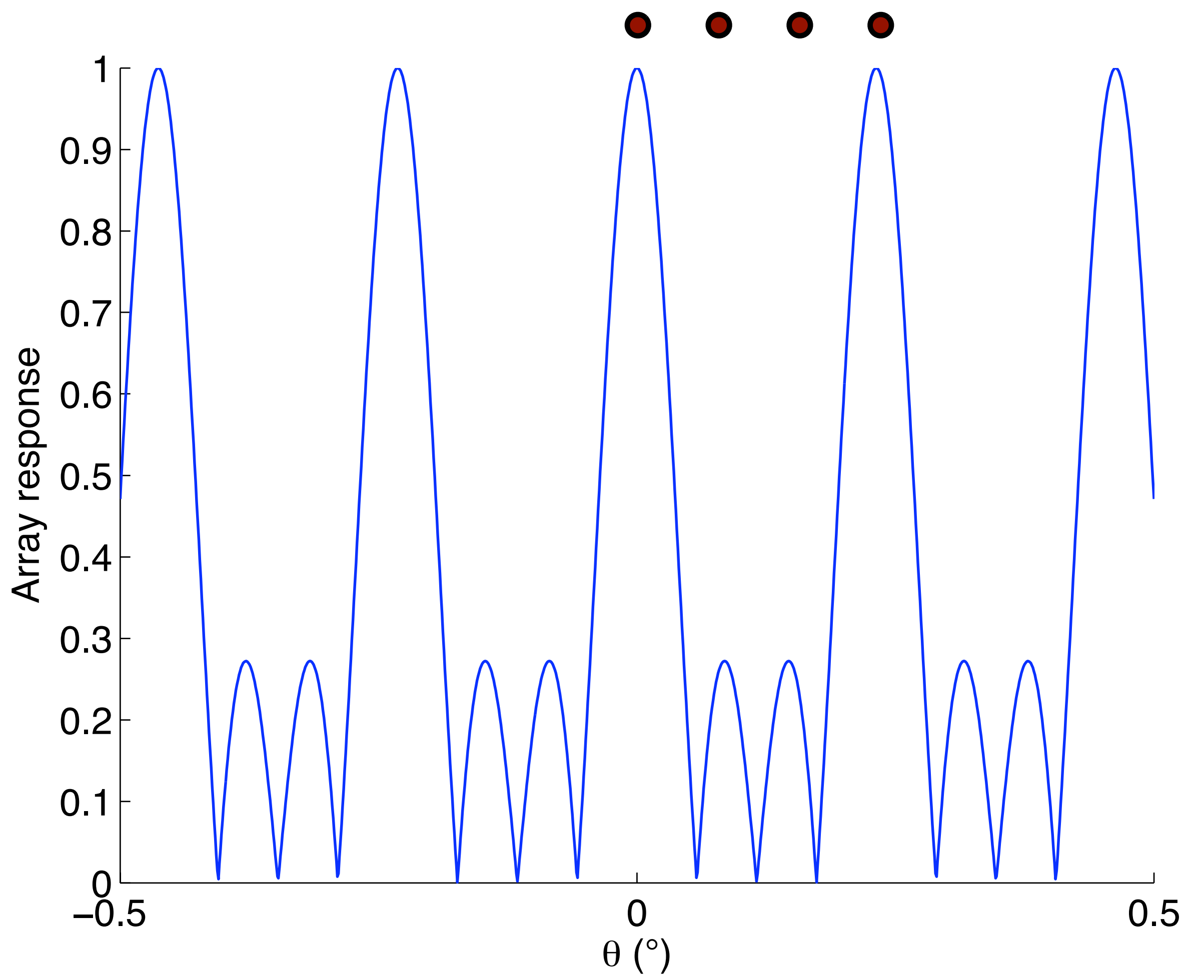
Physical Interpretation: Grating Lobes

- When arrays moved closer together, angular separation between TX elements increases



Physical Interpretation: Grating Lobes

- Eventually, outermost TX elements cannot be distinguished at receiver
- This accounts for first NE spike

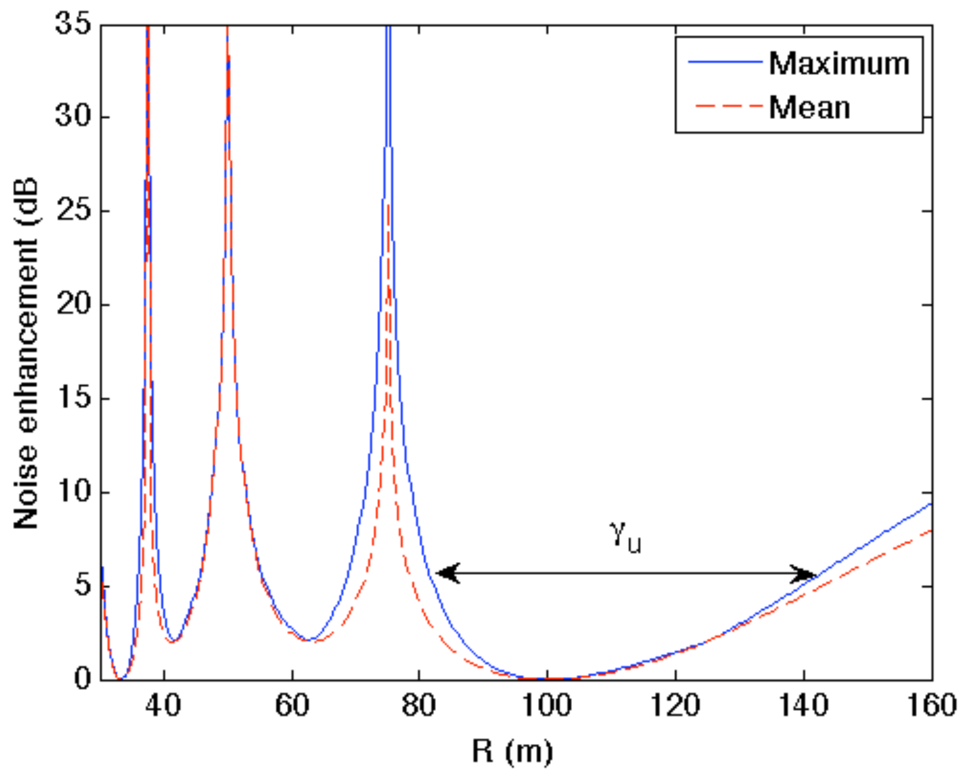


How can we increase link robustness?

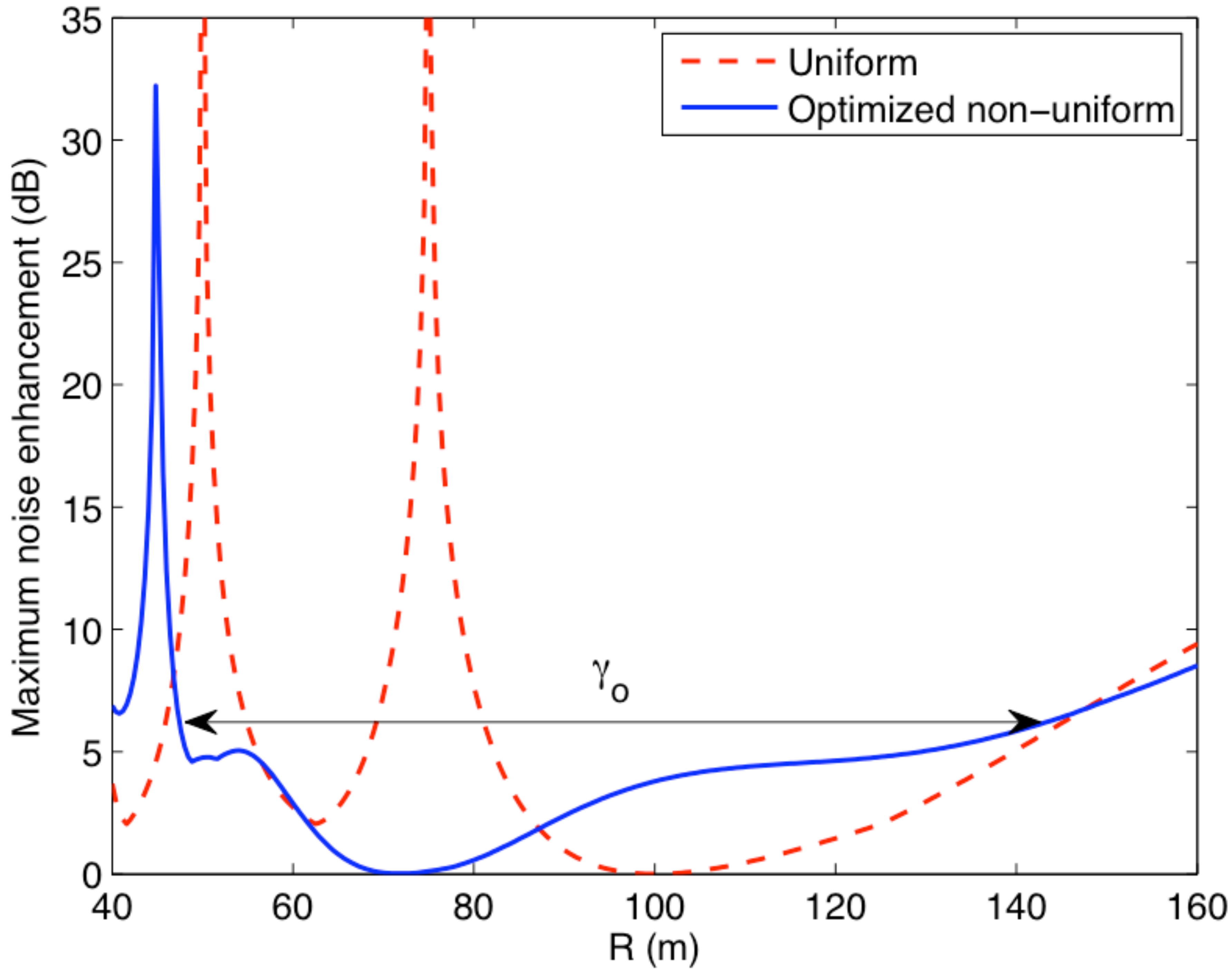
- Increase number of array elements
  - Substantial increase in cost
  - Additional RF chain for each antenna
- Use non-uniform arrays
  - Reduce grating lobes
  - Keep cost/complexity to a minimum

Array Optimization

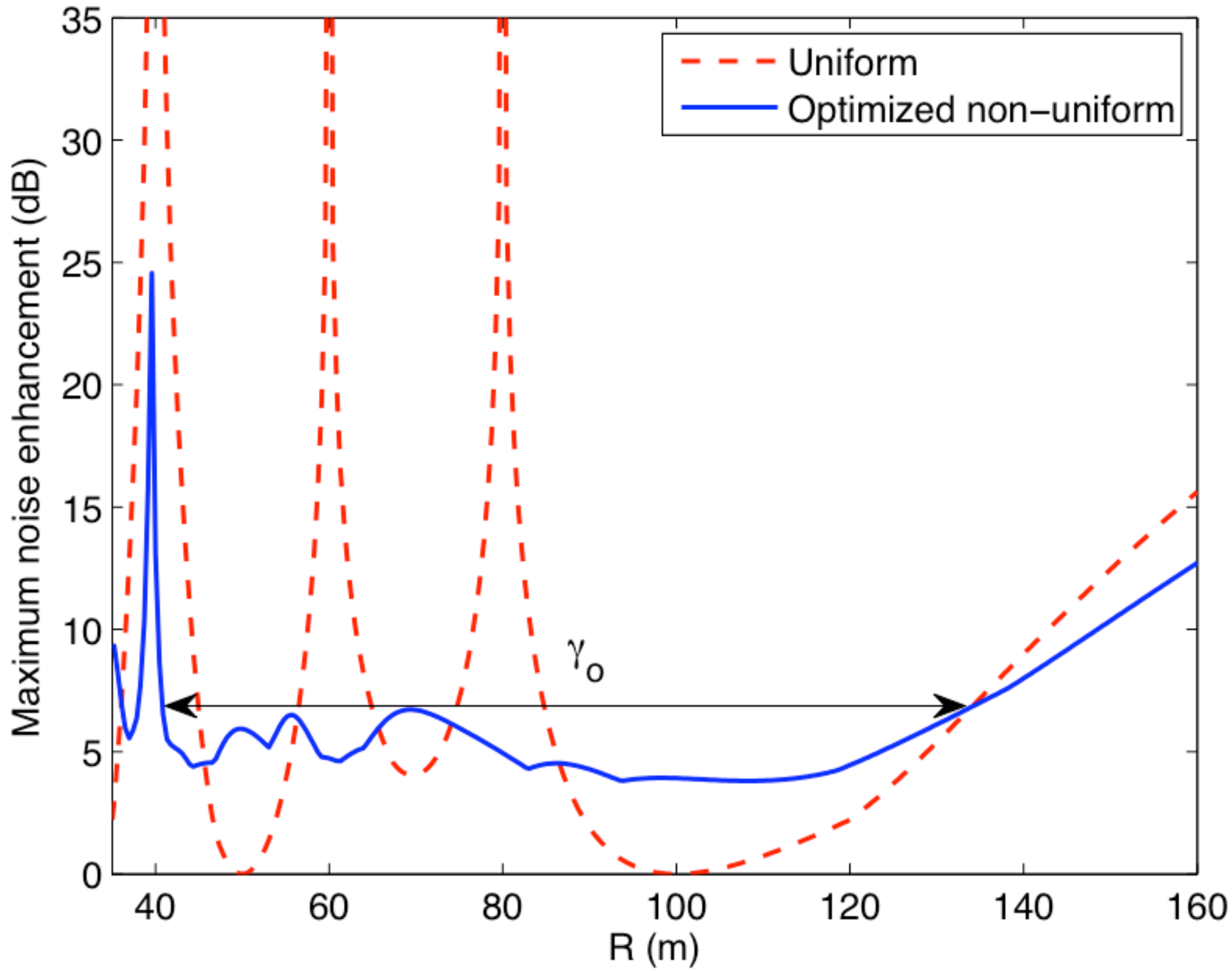
- Keeping total array length fixed, vary inner element positions
- **Objective:** maximize continuous span of link ranges around R_o for which maximum NE remains below a given threshold



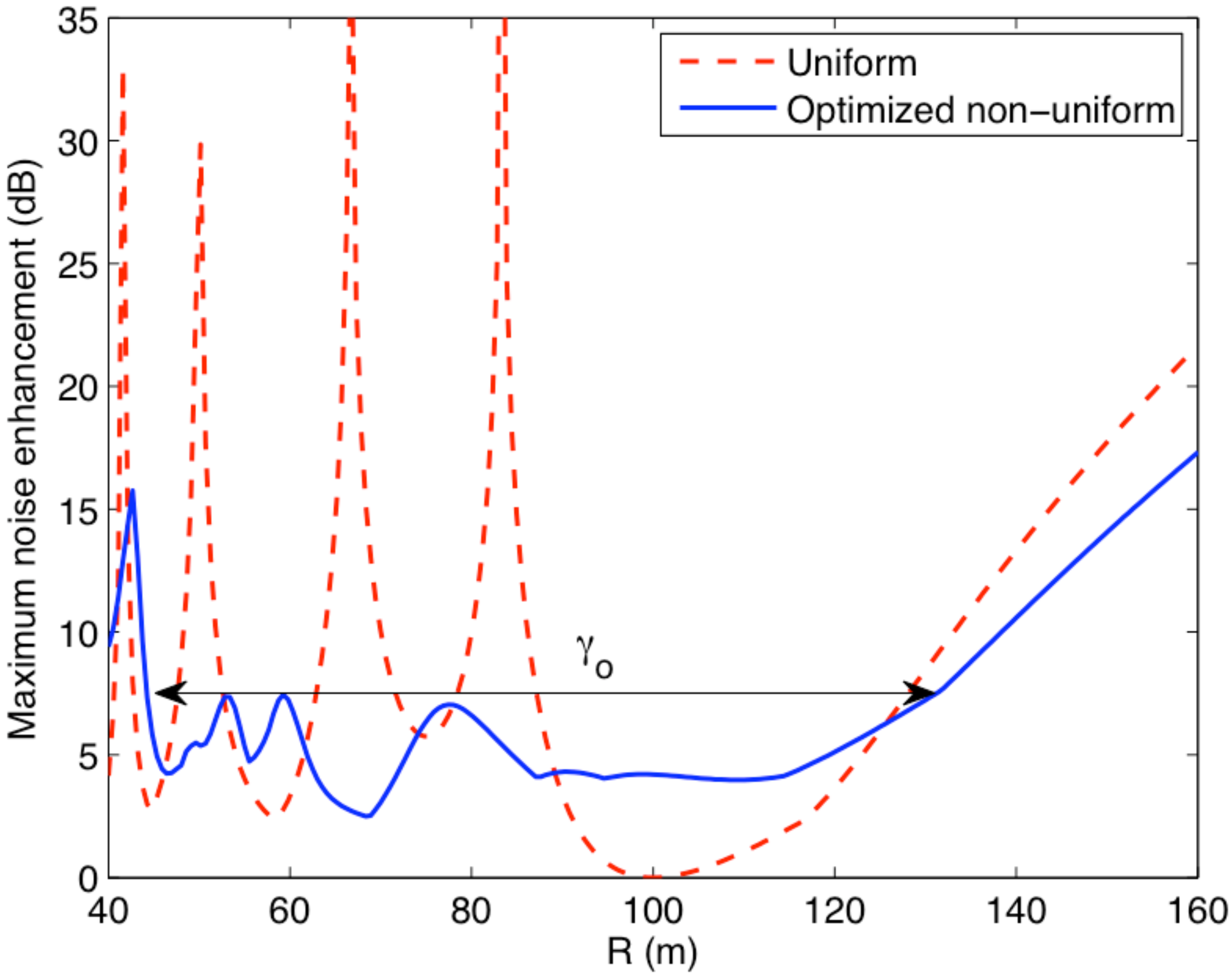
Optimized 4-Element Array



Optimized 5-Element Array



Optimized 6-Element Array



Results

N	γ_u	γ_o	Improvement
4	63 m	94 m	49%
5	50 m	92 m	85%
6	42 m	91 m	121%

- Heuristic optimization methods can improve robustness for larger N
  - In practical scenarios, N will be small due to constraints on array size

Summary

- mm-Wave spatial multiplexing allows order of magnitude increase in wireless data rates
- Rayleigh spacing criterion is optimal when link range is known a priori
  - But if actual link range differs from nominal link range, potential huge SNR penalty.
- Non-uniform arrays sacrifice optimality at R_o to increase robustness to uncertainty

Thank you. Any questions?

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