Millimeter wave MIMO
Wireless Links at Optical Speeds

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The Goal

- Seamless interface of wireless to optical
  - Key to a fail-safe, rapidly deployable infrastructure
- Problem: A Huge Wireless/Optical Capacity Gap
  - Wireless can do 10s of Mbps, optical 10s of Gbps
- *How do we get to 40 Gbps wireless?*
  - How would you process passband signals so fast?
  - Where is the bandwidth?

The promise of mm wave

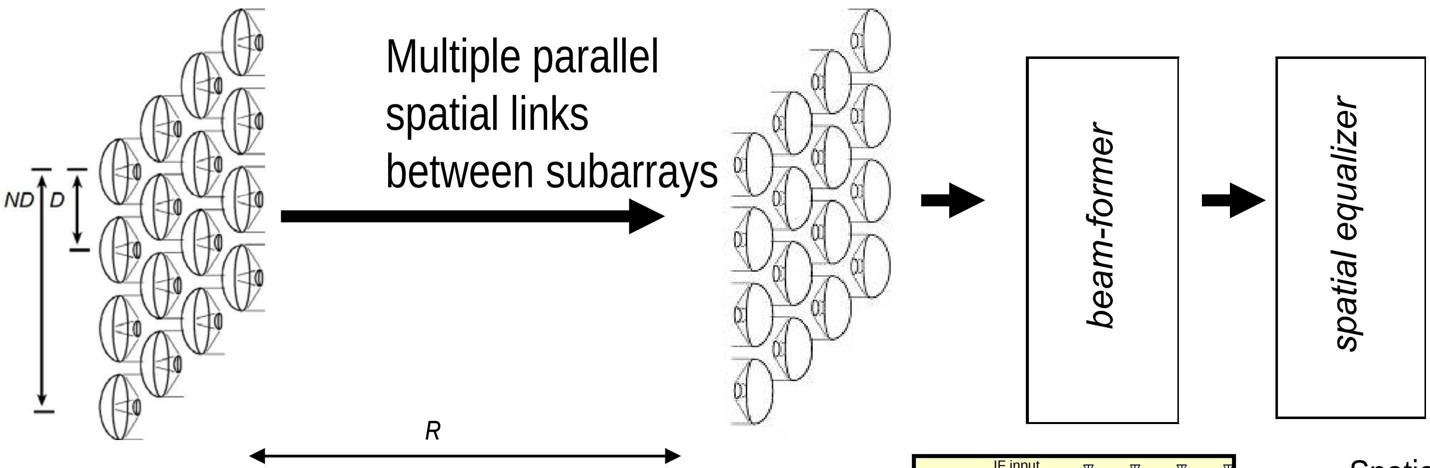
- 13 GHz of E-band spectrum for outdoor point-to-point links
  - 71-76 GHz, 81-86 GHz, 92-95 GHz
  - Semi-unlicensed
  - Narrow beams required
- CMOS and SiGe are getting fast enough
  - Low-cost mm wave RF front ends within reach
- Application requirements
  - Required range of kilometers
  - Highly directive antennas
  - High power transmission not possible
  - Ease of instalment

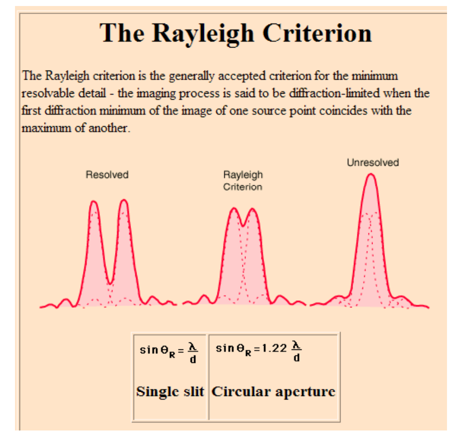
From constraints to design choices

- Tight power budget with low-cost silicon RF realizations
  - small constellations
  - Singlecarrier modulation
- Eliminate need for highly skilled installers
  - Electronic beamsteering
- 5 GHz of contiguous spectrum
  - 5 Gbps with QPSK and 100% excess bandwidth

But how do we scale from 5 Gbps to 40 Gbps?

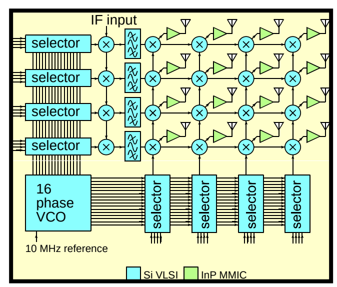
Millimeter-wave MIMO in one slide





4 x 4 array
of subarrays

IC realization for
subarray beamformer



Spatial equalizer handles crosstalk between subarray transmitters due to spacing closer than Rayleigh criterion

Example system: 40 Gbps over 1 km using 5 GHz of E-band spectrum
4 x 4 array of subarrays at each end
Overall array size with sub-Rayleigh spacing ~ 2 x 2 meters
8 out of 16 transmit at 5 Gbps for aggregate of 40 Gbps
QPSK with 100% excess bandwidth over the 75-80 GHz band
Level 1 signal processing: Transmit and receive subarray beamforming
Level 2 signal processing: 16-tap receive spatial equalizer (each receive subarray corresponds to one equalizer tap)

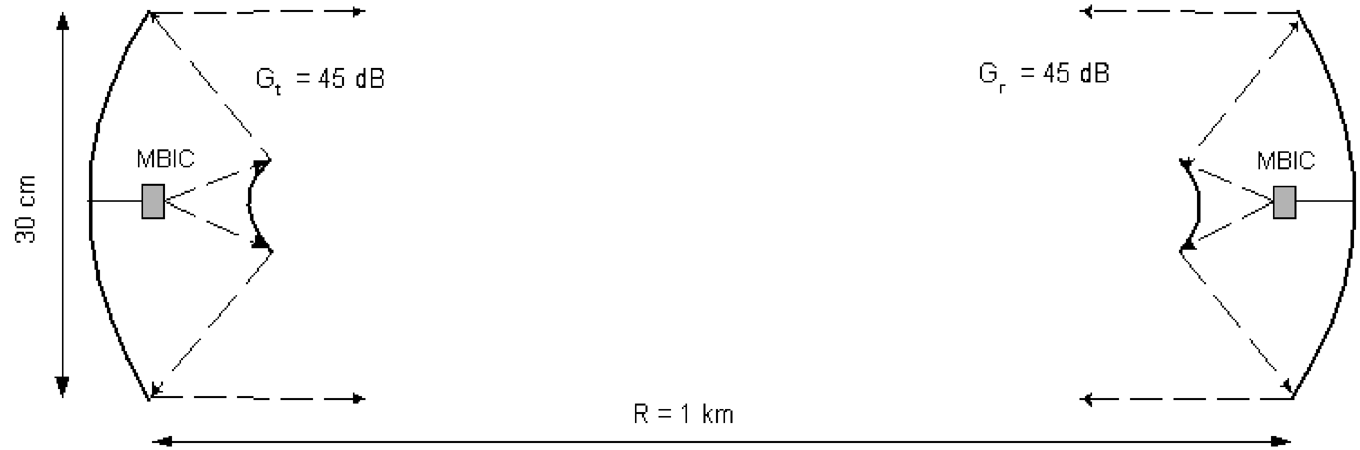
Millimeter wave MIMO: key features

- Parallel spatial links at 1-5 Gbps to get 10-40 Gbps aggregate
- Low cost realization of large beamsteering arrays for accurately pointing each parallel link
- Spatial interference suppression across parallel links
- Signal processing/hardware co-design to handle ultra-high speeds
  - Level 1: beamforming reduces subarrays to virtual elements
  - Level 2: Spatial multiplexing using virtual elements
- CMOS RFIC design for low-cost realization

The rest of this talk

- Link budget benchmark
- Level 1 beamforming
  - Possible geometries
  - Joint upconversion/beamsteering: row-column design
- Level 2 spatial multiplexing
  - Model
  - Spatial multiplexing configurations
  - Performance with zero-forcing solution
  - Gap to capacity
- Conclusions

Link budget benchmark

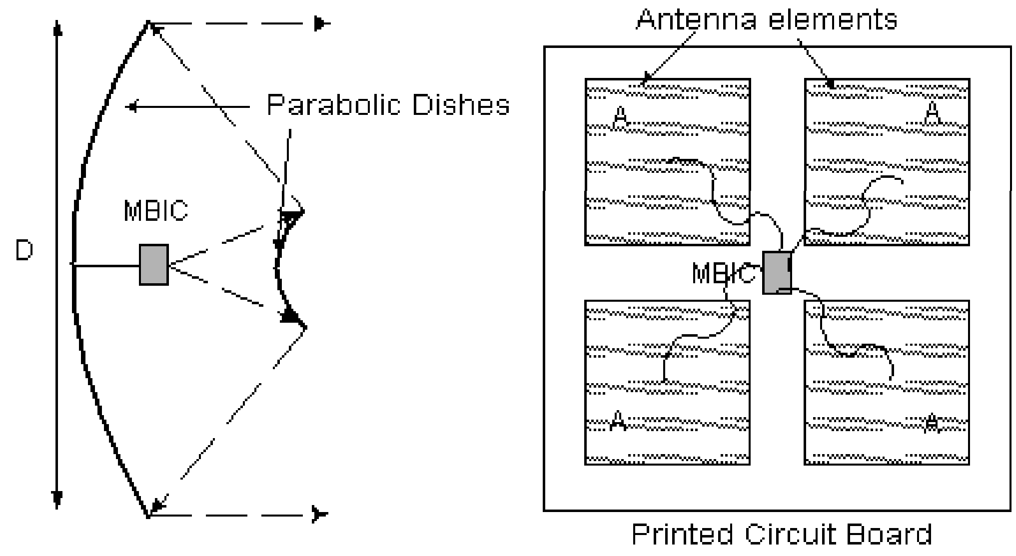


- $f_{carrier}$ = 75 GHz (λ = 4 mm) with W = 5 GHz
- MBIC controls 4x4 square array
- $G_{trans} = G_{receive}$ = 45 dB and
- 3-dB antenna beamwidth = 2^o
- Receiver Noise Figure = 6.5 dB
- Desired Bit Rate = 5 Gbps using QPSK
- Design BER = 10^{-9}

Even in 25mm/hr rain, and transmitting only 10 mW / MBIC element, we get a 25 dB link margin

From fixed to steerable beams

$A_{eff} = \pi D^2/4$



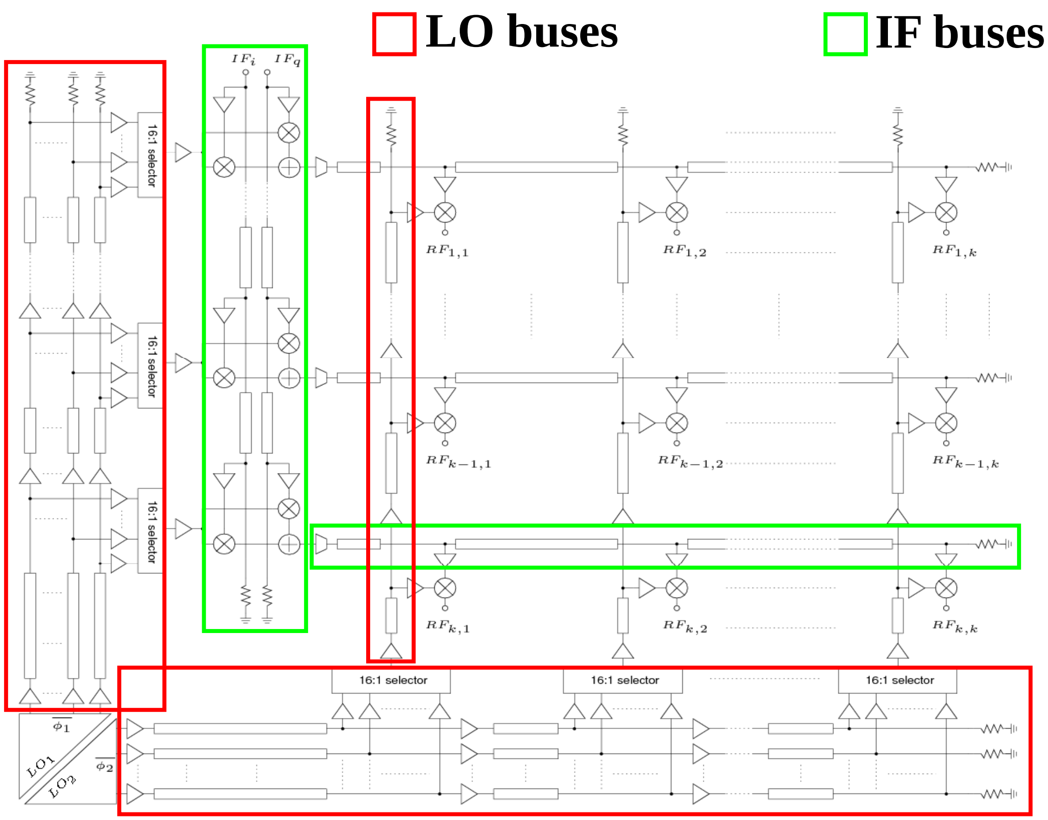
(a) Telescopic Dish Configuration

(b) Planar Configuration

$A_{eff} = 4A$

- The Directivity Gain of each subarray is $G = \frac{4\pi A_{eff}}{\lambda^2}$
- The effective aperture A_{eff} of half-length spaced square array at mm-wave is small
- The A_{eff} can be increased using (a) parabolic dish (like a telescope) or (b) antenna elements on printed circuit board with a larger area

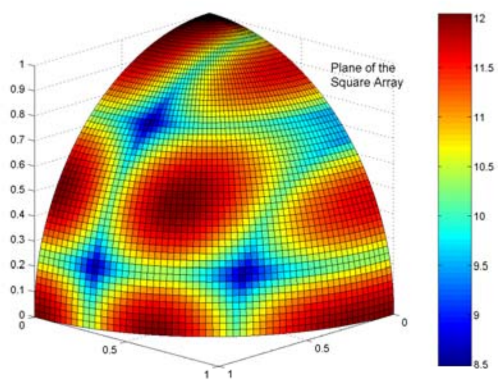
Row-column beamsteering



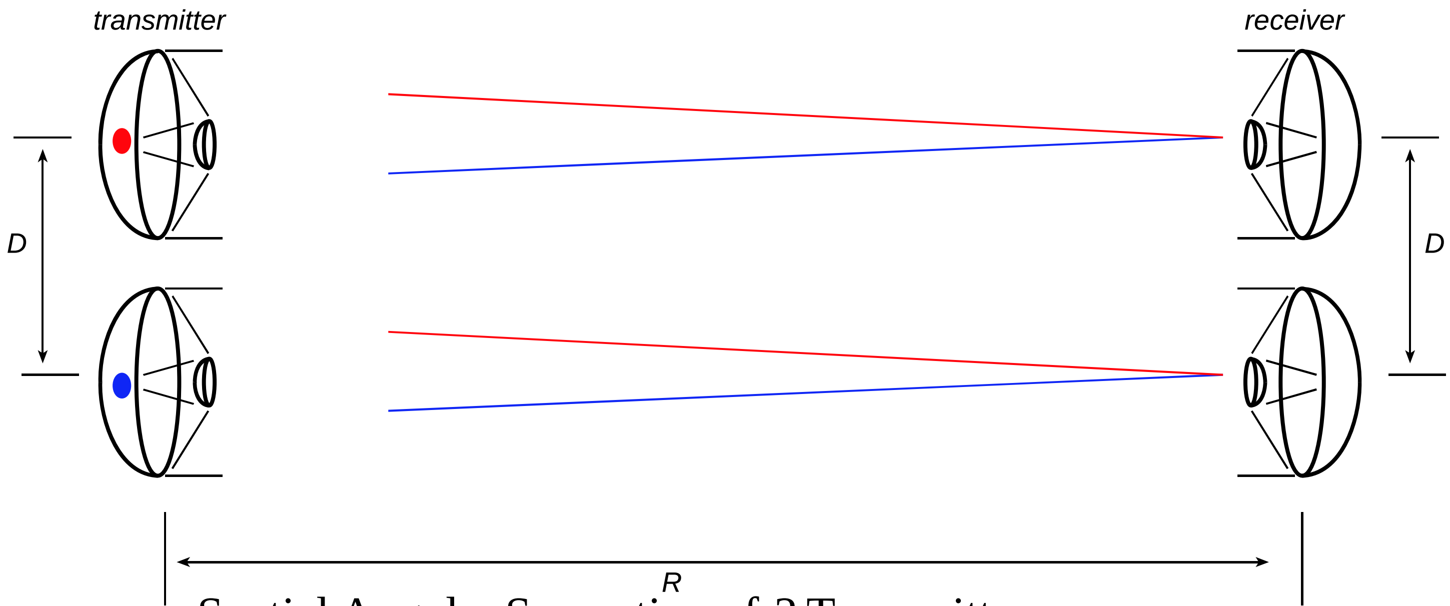
- 16 discrete phases of two LOs
- Phase on each element is set by row first, then by column
- 2D steerability close to unconstrained weights
- Limit on IF and LO buses (frequency and max N)

Performance of Row-Column Beamsteerer

- 4x4 subarray, λ/2 spacing
- 4 quantized phases along vertical and horizontal
- Plots show beamforming gain available along any direction
  - Max gain is 12 dB
  - Quantization loss can be up to 3.5 dB
  - Easily remedied by finer quantization (e.g., 8 phases)



Level 2 geometry: intuition



Spatial Angular Separation of 2 Transmitters

$\delta\theta = D / R$

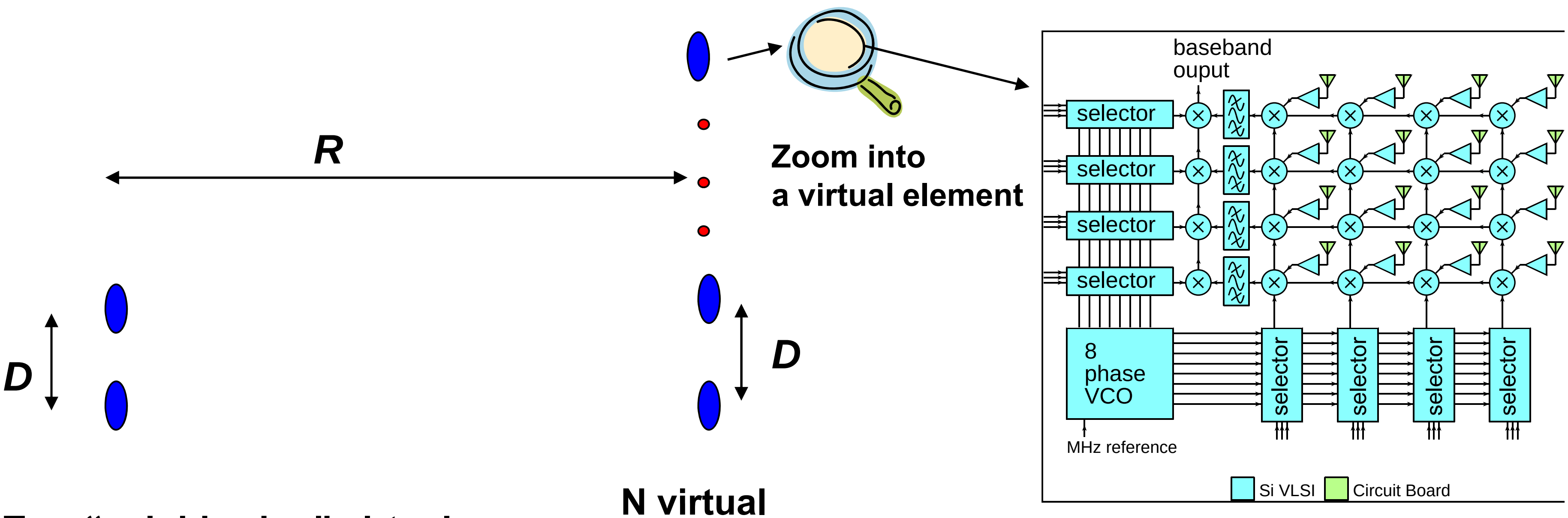
Signal Phase Separation of 2 Transmitters at the Receivers

$\delta\phi_e = \delta\theta \cdot 2\pi D / \lambda$

- If $\delta\phi_e = \pi$, e.g. $D = \sqrt{\lambda R / 2}$, then simple in-phase combining of receiver signals to aim receiver array at desired transmitter will result in 100% suppression of signal from undesired transmitter.

- This corresponds to the Rayleigh criterion in diffraction-limited imaging

Level 2 geometry: details



Two “neighboring” virtual transmit elements should have different enough receive array responses

N virtual receive elements

Each virtual element is a subarray providing beamforming gain

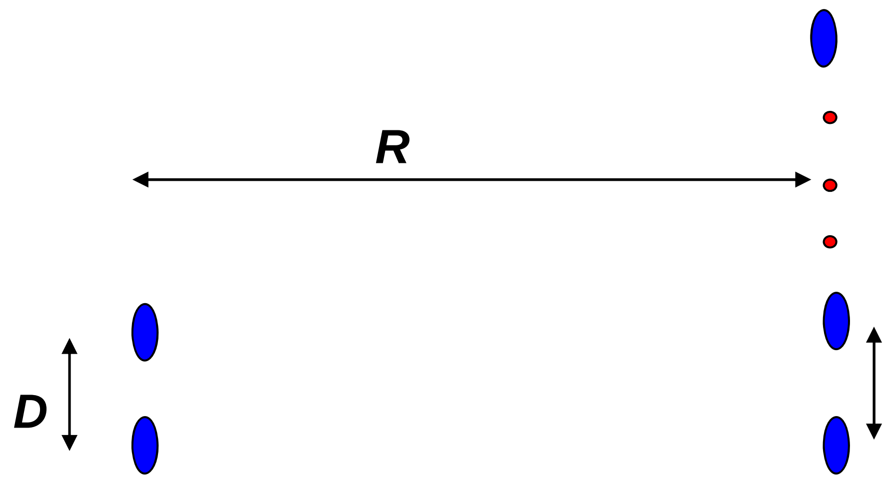
$$\sqrt{(R+D)^2} - R \approx \frac{D^2}{2R}$$

Path difference between signals reaching adjacent receive elements from a transmit element

$$\phi = \frac{2\pi}{\lambda}\frac{D^2}{2R} = \frac{\pi D^2}{R\lambda}$$

Phase difference between adjacent receive elements due to one transmit element

Level 2: Criterion for zero interference



Receive array responses

$$\mathbf{a}_1 = (1, e^{j\phi}, e^{j2^2\phi}, e^{j3^2\phi}, \ldots)$$

$$\mathbf{a}_2 = (e^{j\phi}, 1, e^{j\phi}, e^{j2^2\phi}, \ldots)$$

$$\phi = \frac{2\pi}{\lambda}\frac{D^2}{2R} = \frac{\pi D^2}{R\lambda}$$

$$\rho = \frac{|\mathbf{a}_1^H \mathbf{a}_2|}{\|\mathbf{a}_1\| \|\mathbf{a}_2\|} = \frac{\sin(N\phi)}{N \sin\phi}$$

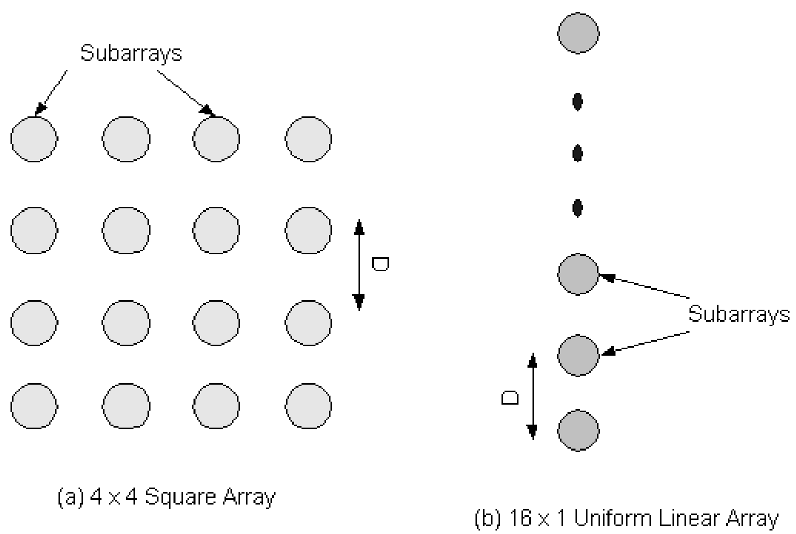
Normalized correlation

No interference if $N\phi = \pi$ *or* $D = \sqrt{\frac{R\lambda}{N}}$ *Rayleigh criterion*

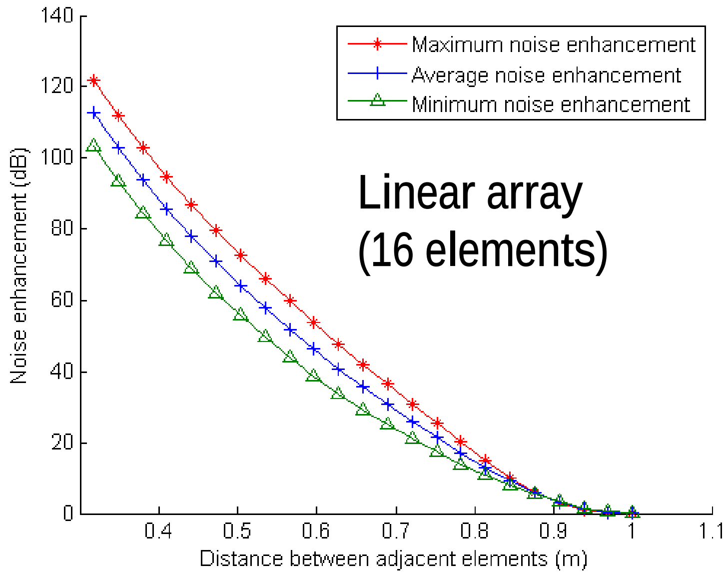
Example: 75 GHz carrier, 1 km range, 8 receive subarrays
Array dimension is about 5 meters
Too big?

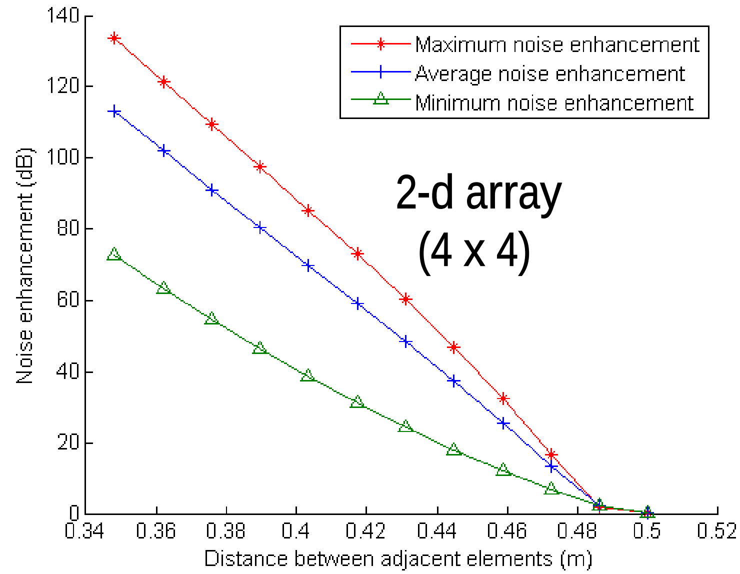
Size reduction techniques

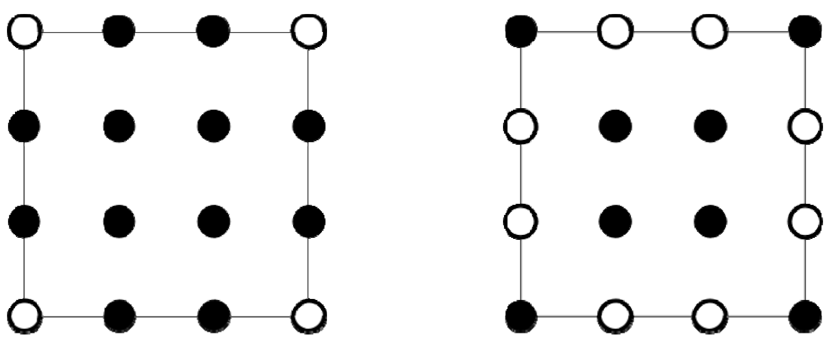
- Sub-Rayleigh spacing between virtual elements
  - Combat interference using spatial equalizer at level 2
- Two-dimensional array instead of linear array
  - The rayleigh spacing for NxN array is $N^{1/2}$ larger than N^2 ULA
  - But side dimension is N times for N^2 ULA than NxN array



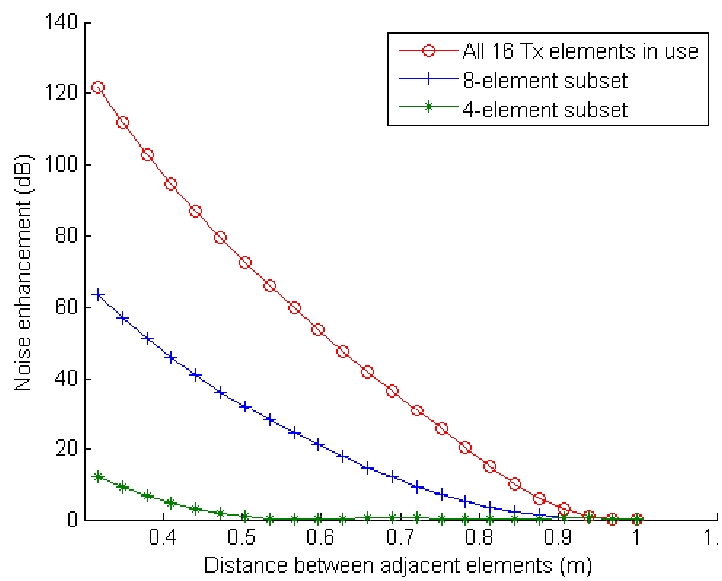
Noise enhancement due to ZF equalizer







Tx Subset selection: 4 (left) and 8 (right) antennas



Gap to capacity

- Uncoded system with QPSK
  - Gap to Shannon capacity about 11 dB at BER of 10^{-9}
  - Constellation expansion + coding unlikely in near future
  - Expect this gap to remain
- Suboptimal zero-forcing reception
  - MIMO capacity realized by transmitting along orthog eigenmodes
  - Gap is mainly due to noise enhancement
  - May be able to reduce gap using decision feedback

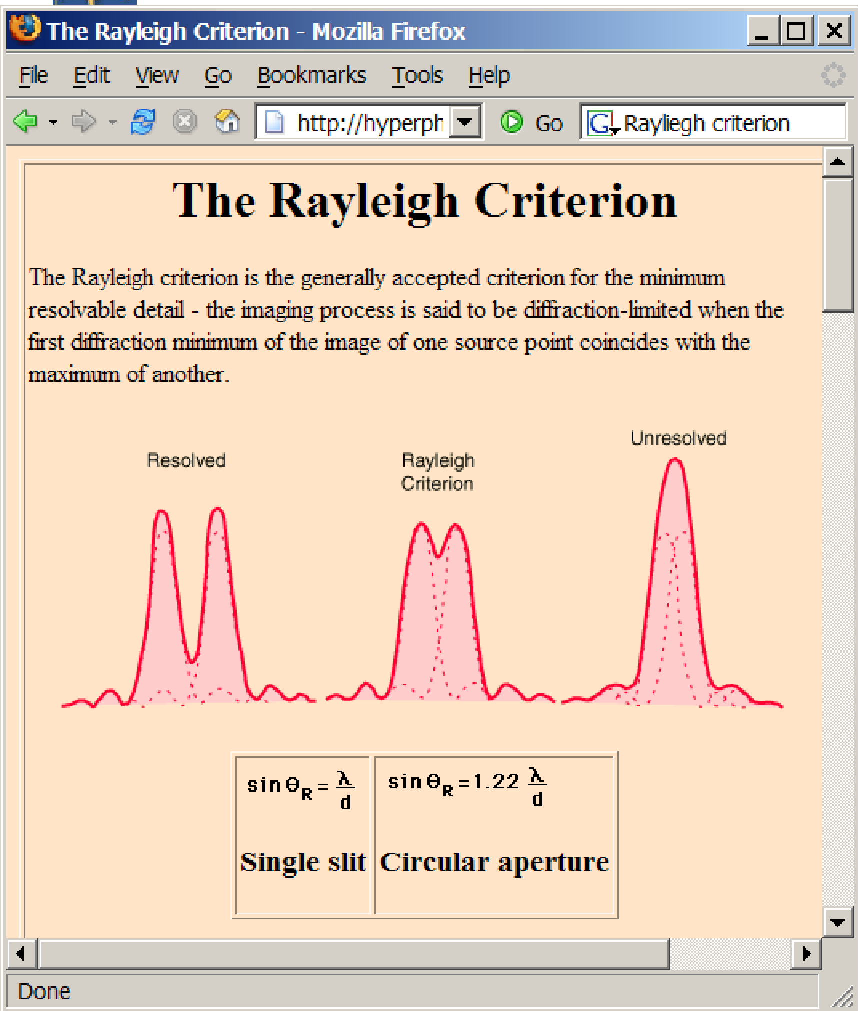
The potential is huge

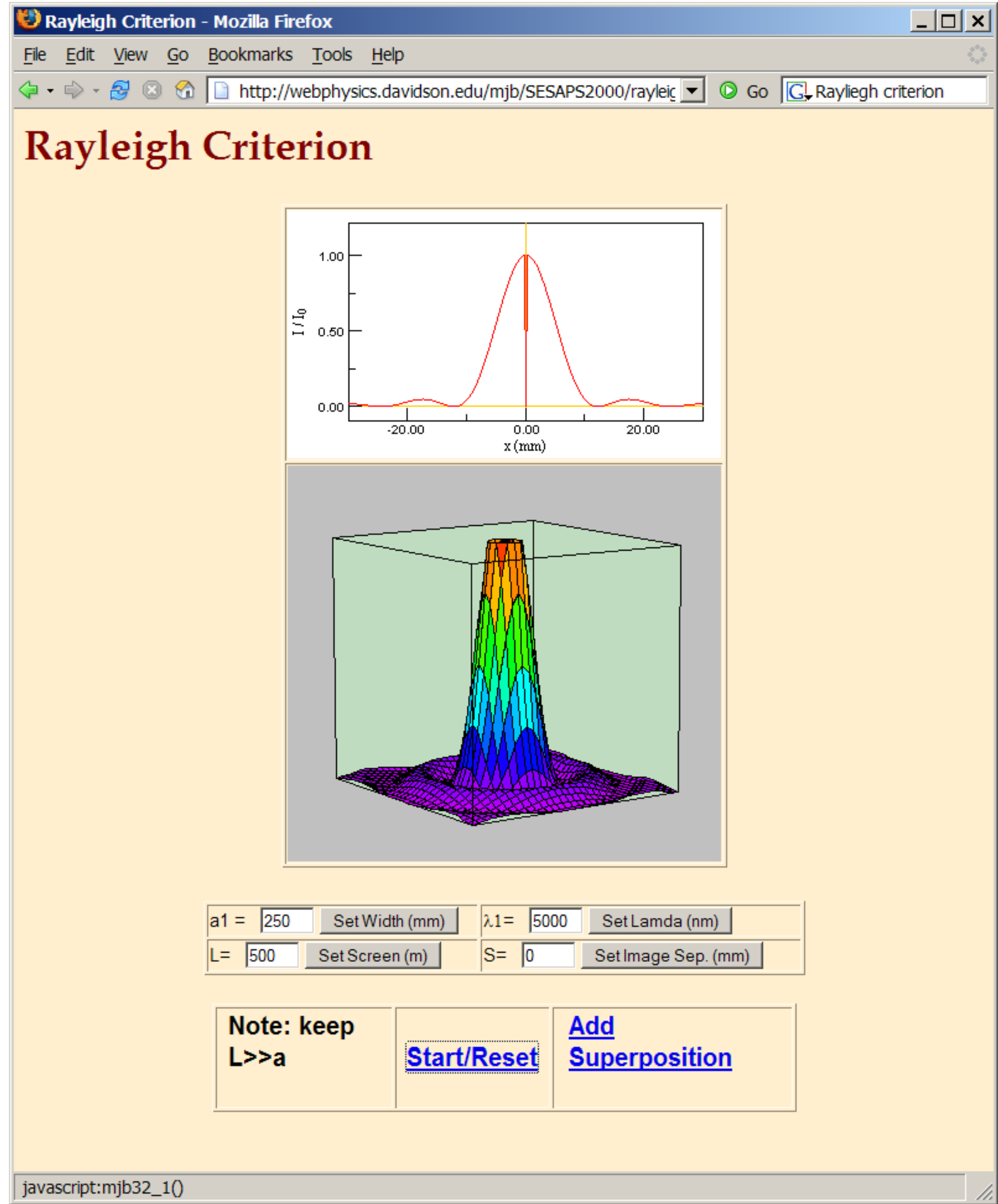
- “Wireless Fiber” is now truly within reach
  - All weather 40 Gbps wireless links with kilometers range
- Applications galore
  - Last mile
  - Disaster recovery using hybrid optical/wireless backbone
  - WiMax backhaul
  - Avoiding right-of-way issues

But much work remains…

- We have an architecture and systems level analysis
- Now comes the hard work
  - Cutting edge mm wave RFIC design (90 nm CMOS)
  - Hybrid digital/analog baseband algorithms
  - High-speed baseband CMOS ICs
  - Subarray design: IC realization, physical antenna
  - Protocols incorporating transmit and receive beamforming
  - Handling multipath

The Rayleigh criterion in imaging





The Rayleigh criterion gives exactly zero crosstalk. Sub Rayleigh spacing results in crosstalk which must be corrected by a spatial equalizer