LoS MIMO

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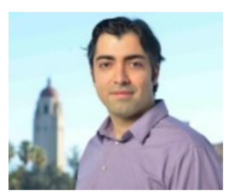
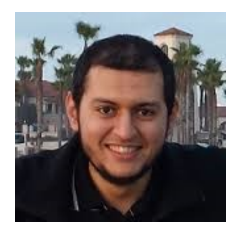
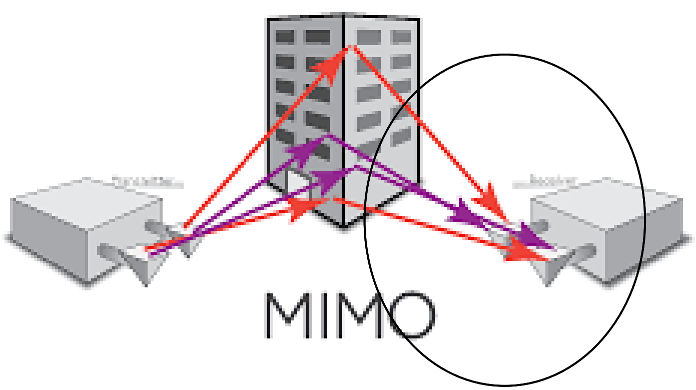


Prof. Amin Arbabian
(Stanford)



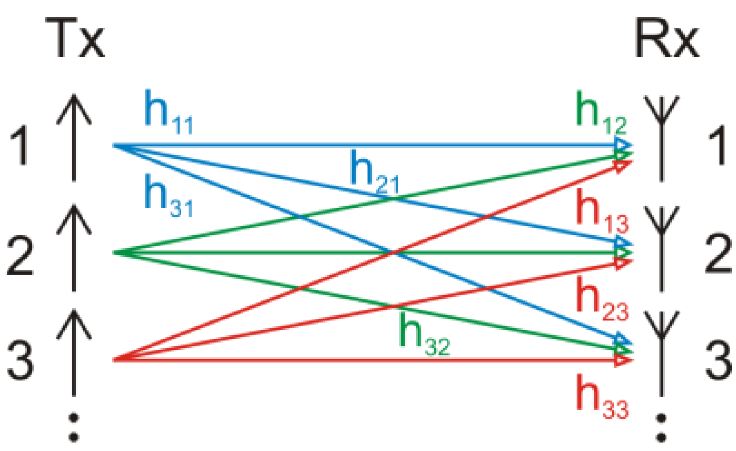
Mahmoud Sawaby (Stanford)

MIMO spatial multiplexing



"Rich scattering" environment (more prevalent indoors)
--many paths from TX to RX
--direct, multiple bounce reflection, diffraction, scattering)

Number of independent data streams that can be sent: DoF



Mathematical model
--Vector response to TX1 linearly independent of response to TX2
--Data streams from different TXs can be separated out at RX

But mm wave channels are sparse
(the opposite of “rich scattering”)

Can we get spatial multiplexing gains?

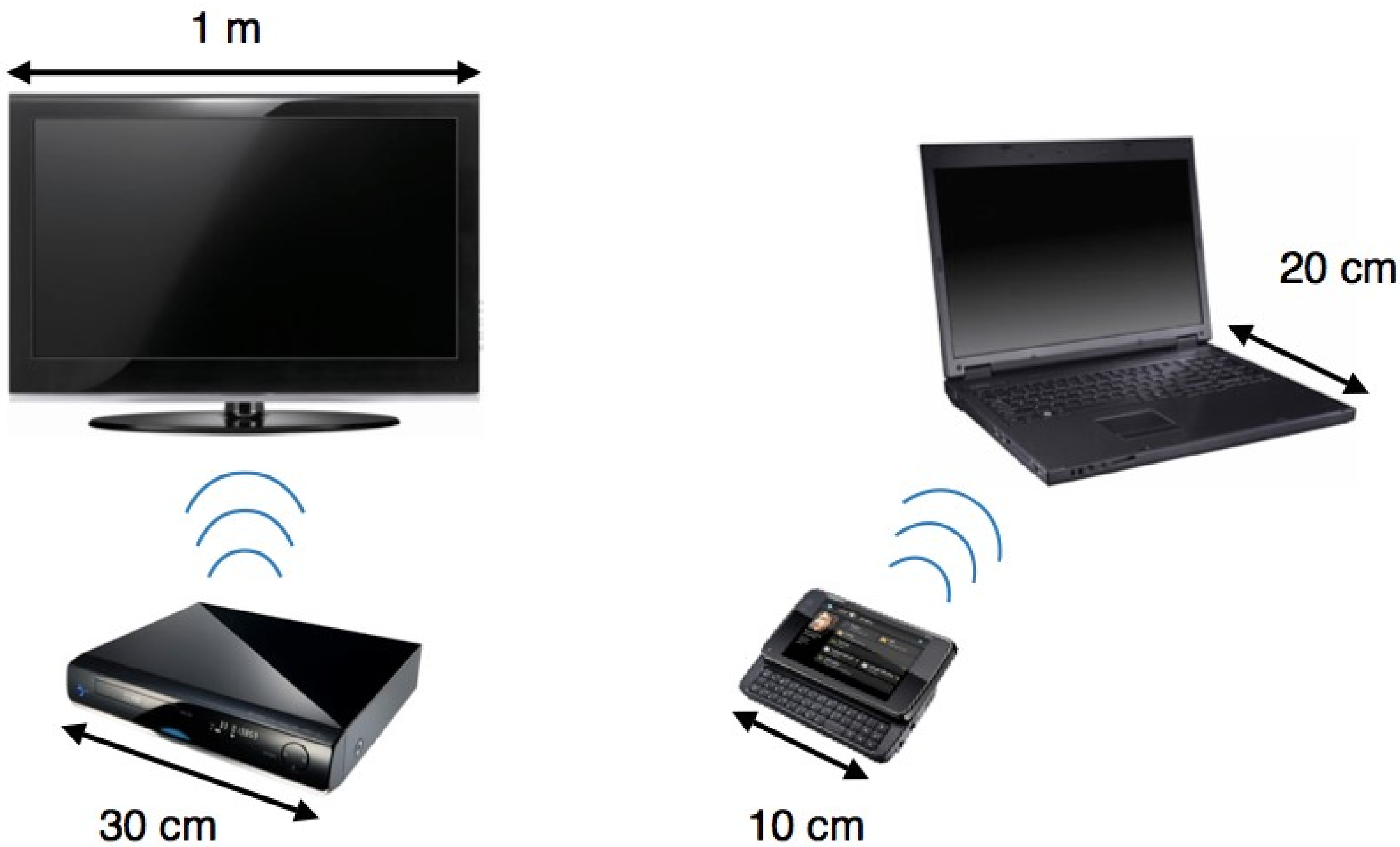
But mm wave channels are sparse
(the opposite of "rich scattering")

Can we get spatial multiplexing gains?

Yes we can.

Spatial multiplexing can happen even in LoS settings
But the antenna separations must scale with wavelength
→ Can do it with compact form factors at tiny wavelengths

How many degrees of freedom are available?

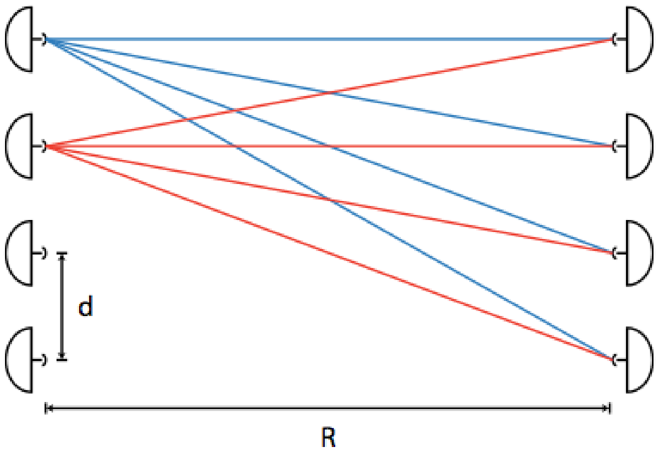


As usual, we need a geometric approach

The Geometry of LoS MIMO

UCSB

Rayleigh criterion



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

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

$$|\langle \mathbf{h}_1, \mathbf{h}_2 \rangle| = \left| \frac{\sin(N\phi)}{\sin\phi} \right|$$

Vectors are orthogonal when $N\phi = N\dfrac{\pi d^2}{\lambda R} = \pi$

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

Example

R=10 m, λ=5 mm, N=4

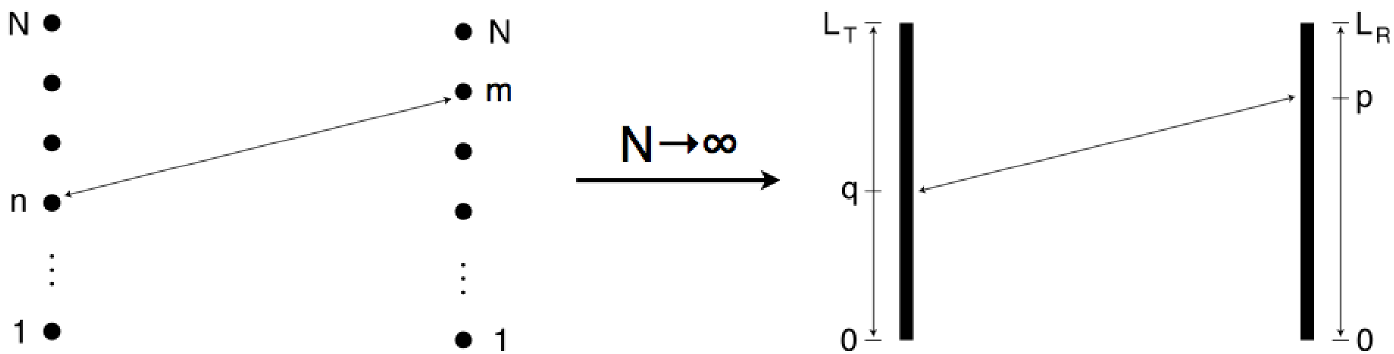
d =11 cm

Information-theoretic analysis

➔

DoF depends on form factor

Rayleigh spaced antennas near-optimal for DoF

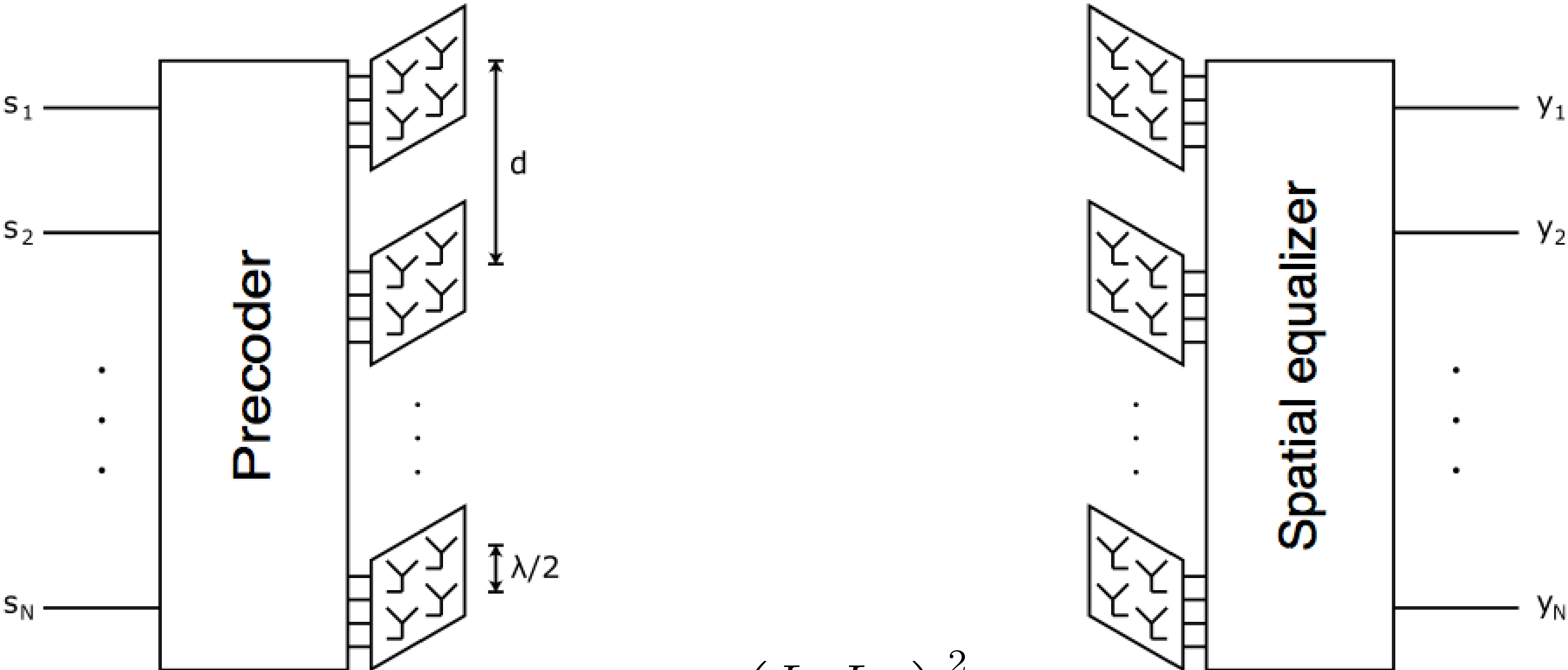


$$y_m = \frac{1}{N} \sum_{n=1}^{N} \underbrace{\exp\left(-i\frac{\pi}{\lambda R}(nd_T - md_R)^2\right)}_{h_{m,n}} x_n \qquad y(p) = \frac{1}{L_T}\int_{-L_T/2}^{L_T/2} \underbrace{\exp\left(-i\frac{\pi}{\lambda R}(q-p)^2\right)}_{h(q,p)} x(q)\mathrm{d}q$$

Packing in more antenna elements does not increase DoF

But provides beamforming (SNR) gain

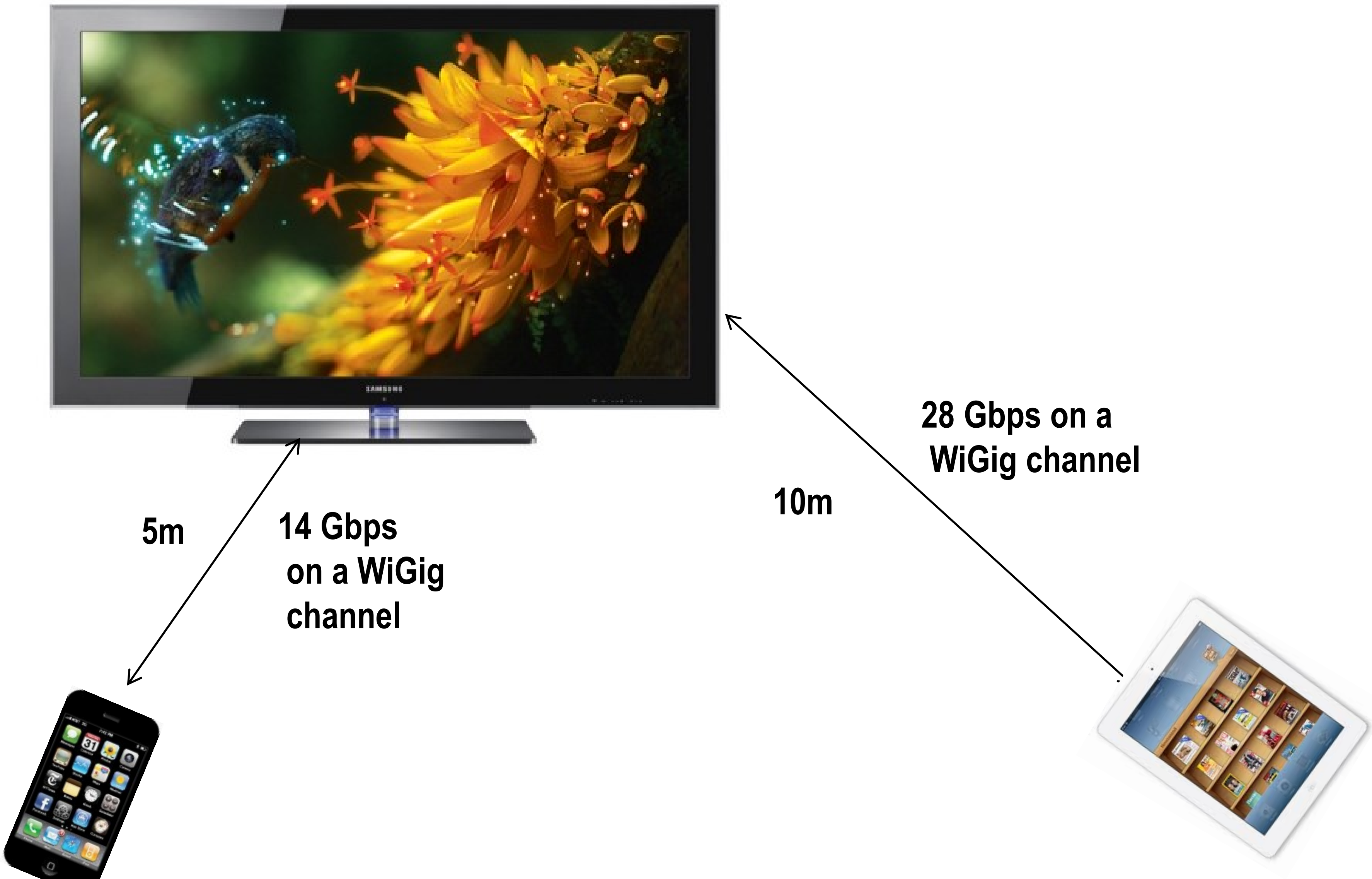
Array of subarrays architecture



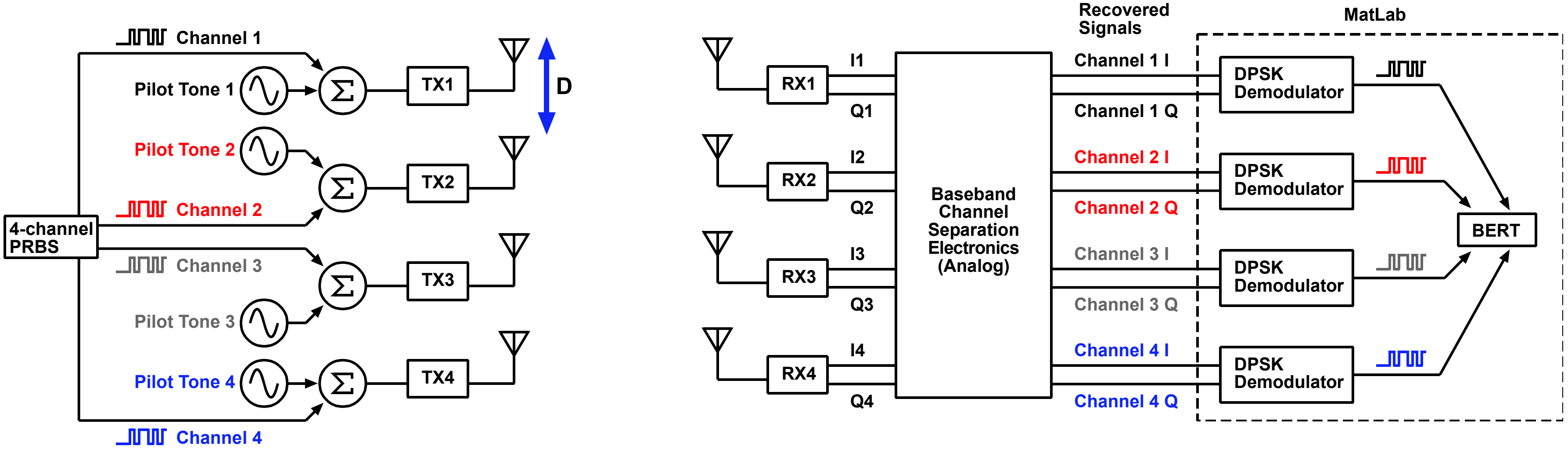
$$\mathrm{DoF} \approx \left(\frac{L_T L_R}{R\lambda}\right)^2$$

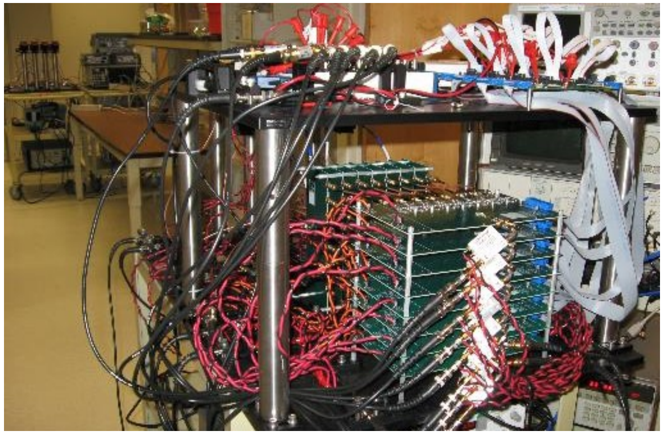
Rayleigh-spaced arrays: spatial multiplexing
Each array is a sub-wavelength spaced subarray: beamforming

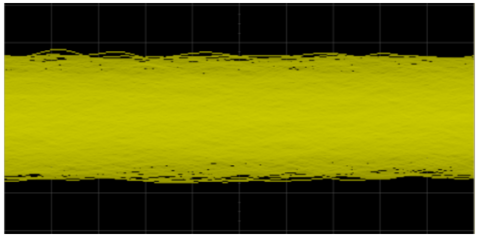
Implications for WiGig



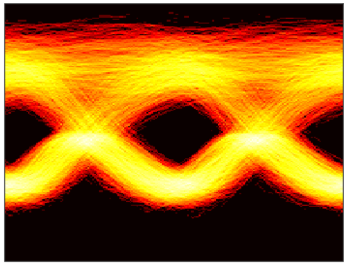
Demos in indoor & outdoor settings







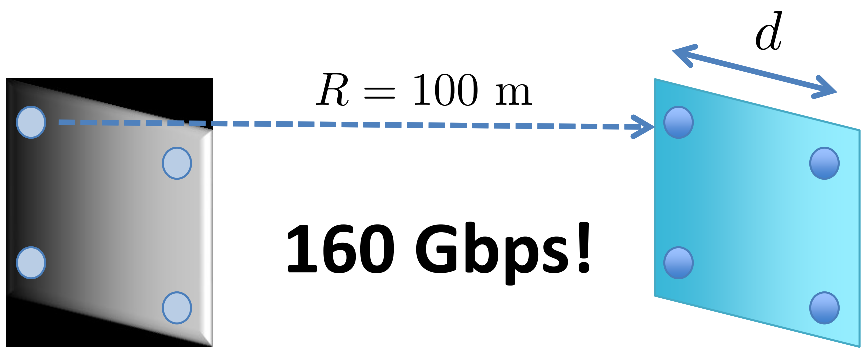
Received superposition



After separation

Far more ambitious goal today

4 x 4 MIMO
130 GHz carrier frequency
40 Gbps per stream



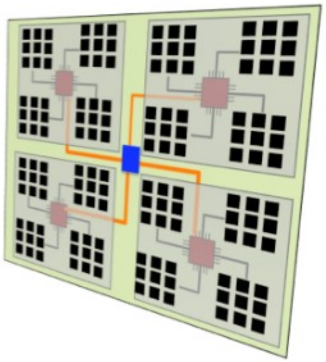
Significant challenges
--Even slight misalignment changes the channel
--"Mostly analog" processing needed because of ADC bottleneck

Take-aways

- LoS MIMO enables multiplicative increase in data rates
  - For fixed form factor, DoF increases with frequency, decreases with link distance
- For typical consumer device form factors, 2-4X increase possible at 60 GHz
  - 802.11ad → 802.11ay
- For outdoor links, need to go beyond 60 GHz
  - "Wireless fiber:" 100 Gbps @ 100 m using 130 GHz

LoS MIMO is severely constrained by geometry

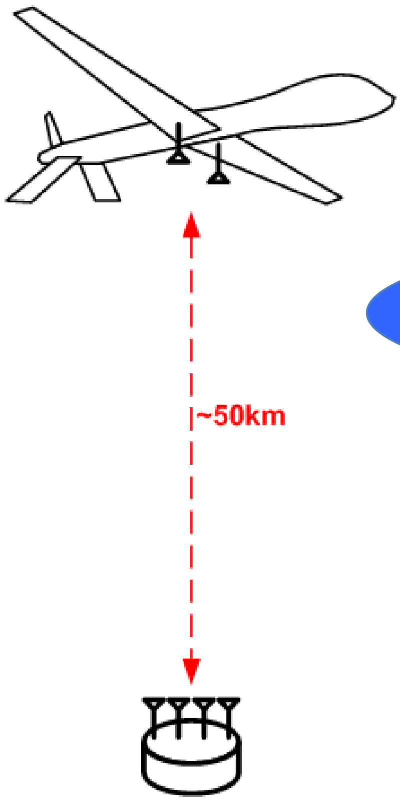
$$\mathrm{DoF} \approx \left(\frac{L_T L_R}{R\lambda}\right)^2$$



Can we manipulate the geometry to increase the # DoF?

(without requiring giant antenna arrays)

DARPA 100G program
How to get 100 Gbps wireless over 50 km?



Must throw everything we know at it

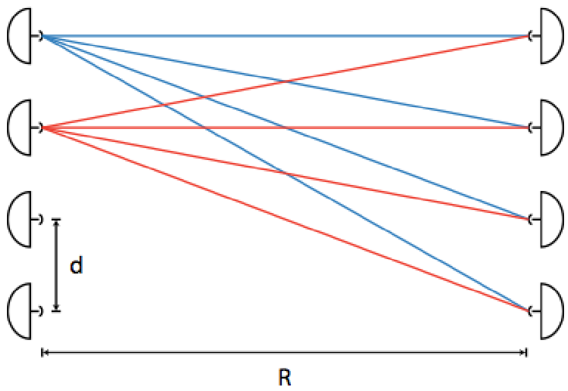
Bandwidth → mm wave band or higher

Power → not THz or optics

Directivity → mm wave band or higher

Polarimetric multiplexing → no conceptual hurdles, modulo hardware/signal processing design

Recall the Rayleigh criterion



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Vectors are orthogonal when $N\phi = N\frac{\pi d^2}{\lambda R} = \pi$

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

Example
R=10 m, λ=5 mm, N=4
d =11 cm

Perfect for short-range indoor 60 GHz comms

Generalizes to different spacing at TX and RX $d_T d_R = \frac{\lambda R}{N}$

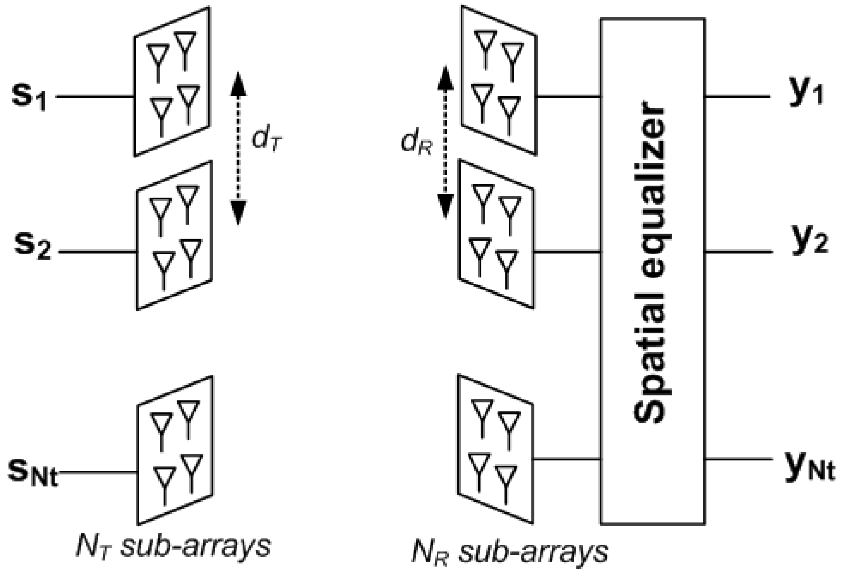
Achieves the spatial degrees of freedom promised by continuous Shannon limit

Array of subarrays architecture

Discrete array suffices to attain Shannon limit on degrees of freedom

Each element in the array can be a subarray providing beamforming gain

➔ Array of subarrays architecture providing spatial multiplexing + beamforming



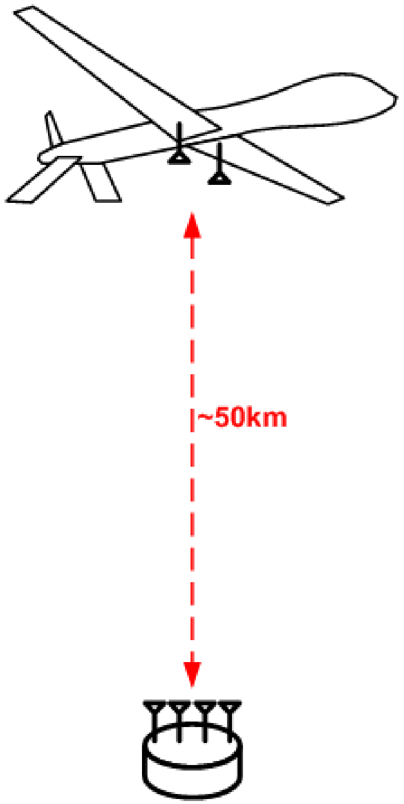
$$d_T d_R = \frac{\lambda R}{N}$$

Back to 100 Gbps long-range link

Andrew Irish

Francois Quitin
(now at ULB, Belgium)

We have a problem



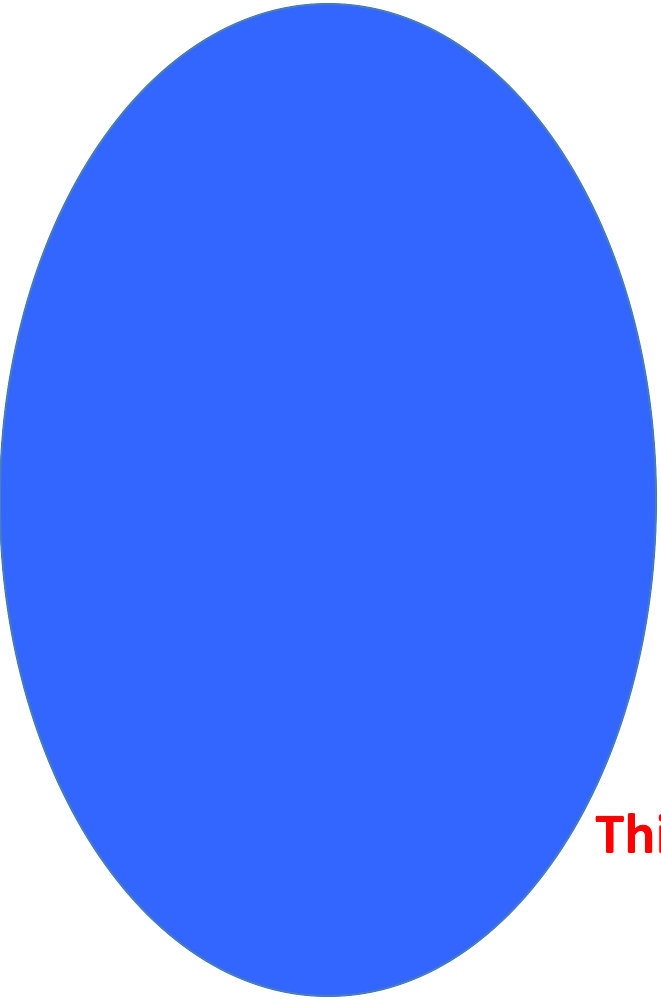
Example

75 GHz carrier frequency, 50 km range

Two-fold spatial multiplexing

$$d_T d_R = 100\ m^2$$

A dealbreaker?



Example

75 GHz carrier frequency, 50 km range

Two-fold spatial multiplexing

$$d_T d_R = 100\ m^2$$

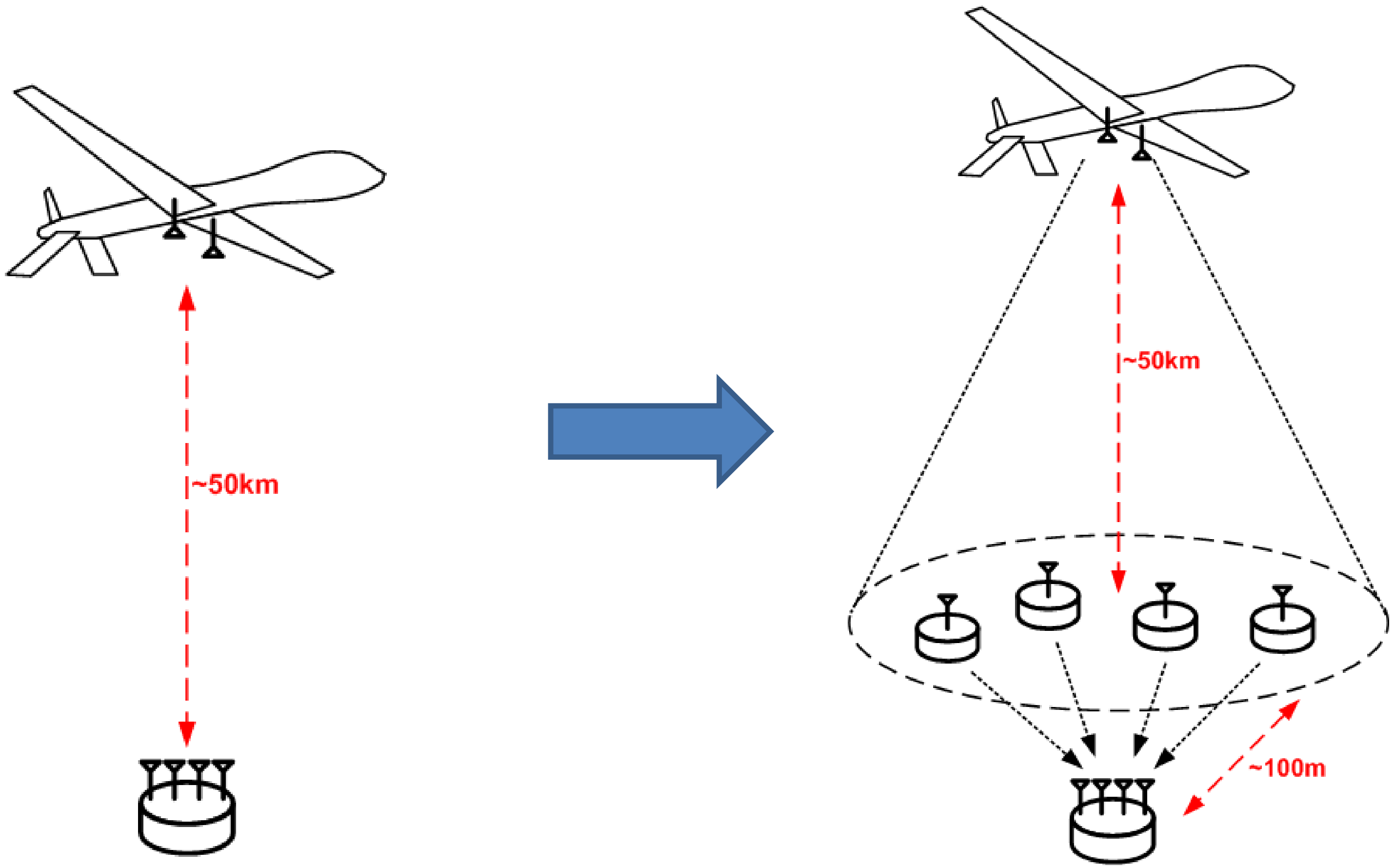
Subarrays 1 m apart on aircraft

➔ Need subarrays 100 m apart on the ground!

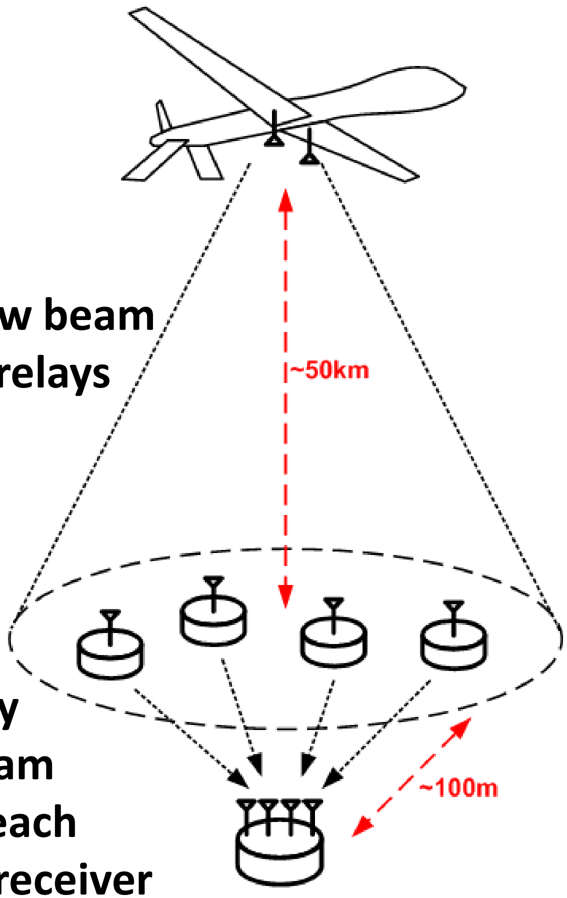
This picture does not work!

Distributed MIMO to the rescue

Synthesize full rank channel by spreading the receiver out



Anatomy of full rank DMIMO



Very narrow beam covers all relays

Moderately narrow beam between each relay and receiver

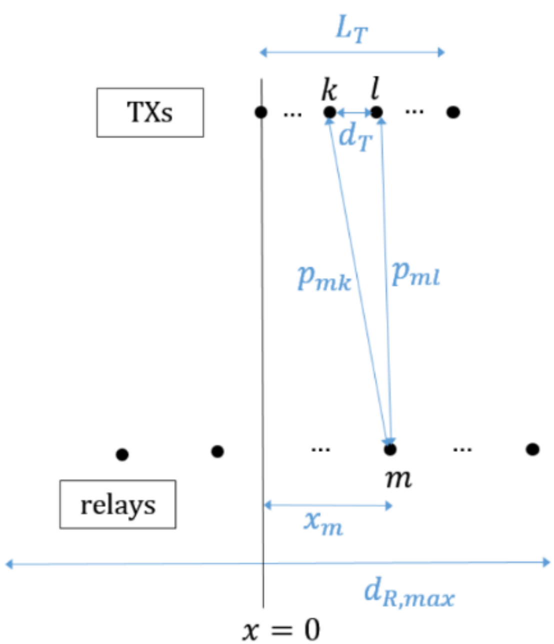
$\mathbf{H_1}$ full-rank thanks to spatial spread of relays

$\mathbf{H_2}$ diagonal => full-rank

Composite channel full-rank

How much do the relays need to be spread out?

Relay spread design via geometry + statistics



Want zero inter-TX correlation

Since $p_{mk} \gg x_m$ we get

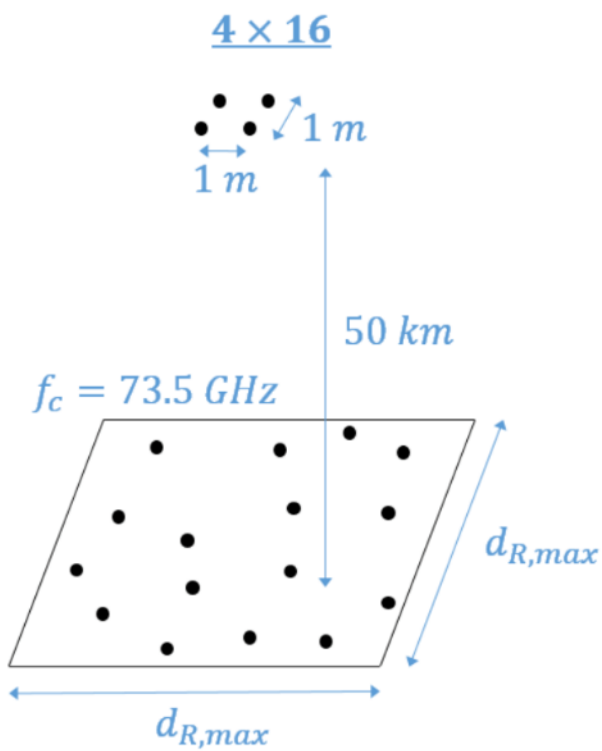
$$\langle \mathbf{h}_k \mathbf{h}_l \rangle \propto \sum_{m=0}^{N_R-1} e^{j\frac{2\pi}{\lambda}(p_{mk}-p_{ml})}$$

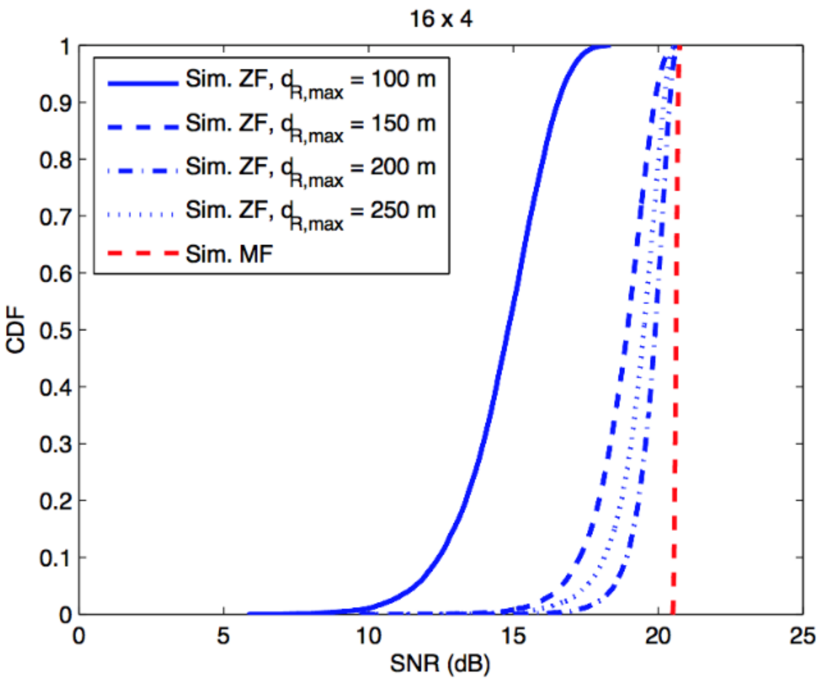
$$\approx \sum_{m=0}^{N_R-1} e^{j\frac{2\pi}{\lambda R}(l-k)d_T x_m}$$

Uniform phases yield 0 corr, so:

$$x_m \sim U\left(-\frac{\lambda R}{2(l-k)d_T}, \frac{\lambda R}{2(l-k)d_T}\right)$$

Design matches simulations





$\Rightarrow$ "best" $d_{R,max} = \frac{\lambda R}{d_T} = 200$ m

LoS MIMO take-aways

- Potential for 2-4X increase for indoor 60 GHz links
- Wireless fiber is within reach
- Can get around form factor limitations using relays
- Novel geometries → novel system concepts
  - Explore via combination of geometry & statistics