Networking @ 60GHz
The Emergence of MultiGigabit Wireless

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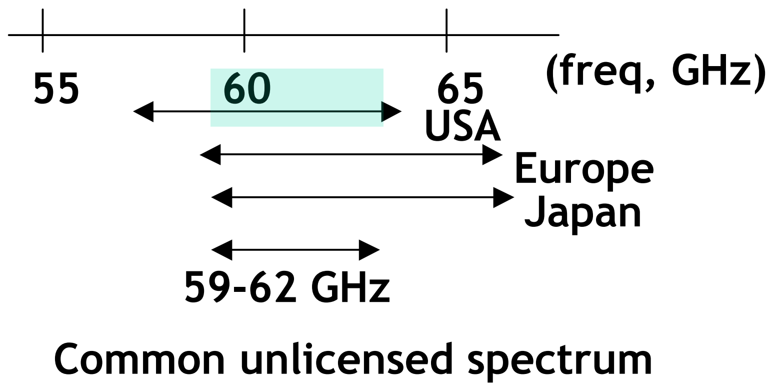
The next phase of the wireless revolution?

60 GHz: 7 GHz of unlicensed spectrum in US, Europe, Japan



Oxygen absorption band

Ideal for short-haul multihop

(Semi-unlicensed mm wave spectrum avoiding oxygen absorption available in E-band)

Industry is getting serious about 60 GHz

ECMA, Wireless HD, WiGig

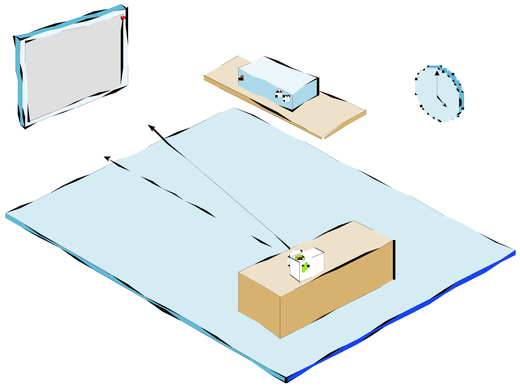
No dearth of catchy slogans to describe the opportunity

Wireless catches up with wires

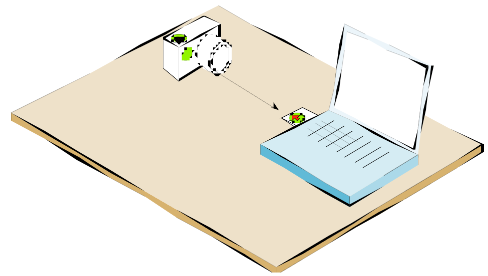
Combat world hunger for spectrum

***BUT**: Harnessing 60GHz spectrum while respecting cost and physics constraints requires both hardware and system-level innovations*

Indoor mm wave systems at 60 GHz



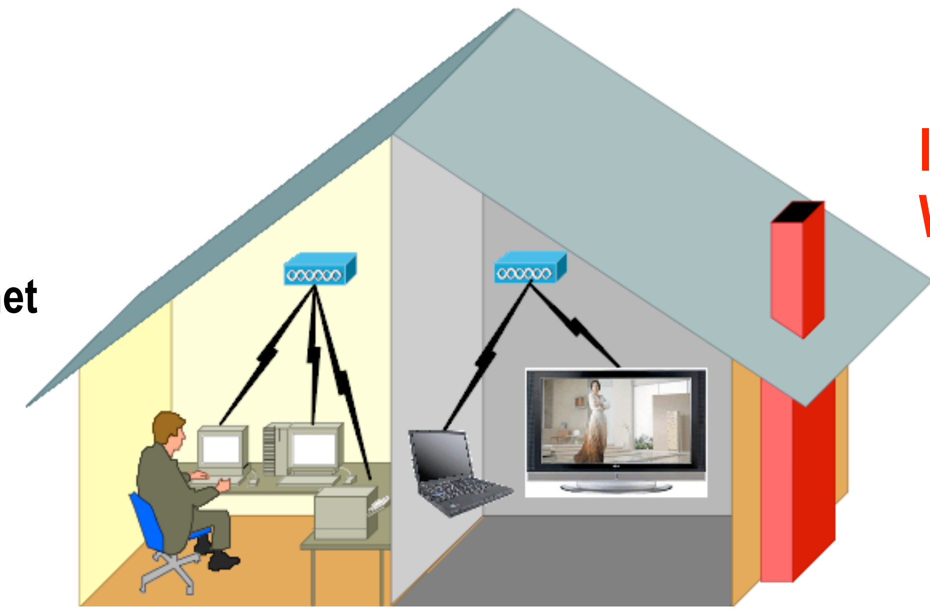
WirelessHD



Wireless USB/Touch and Go

IEEE 802.15.3c
WPAN

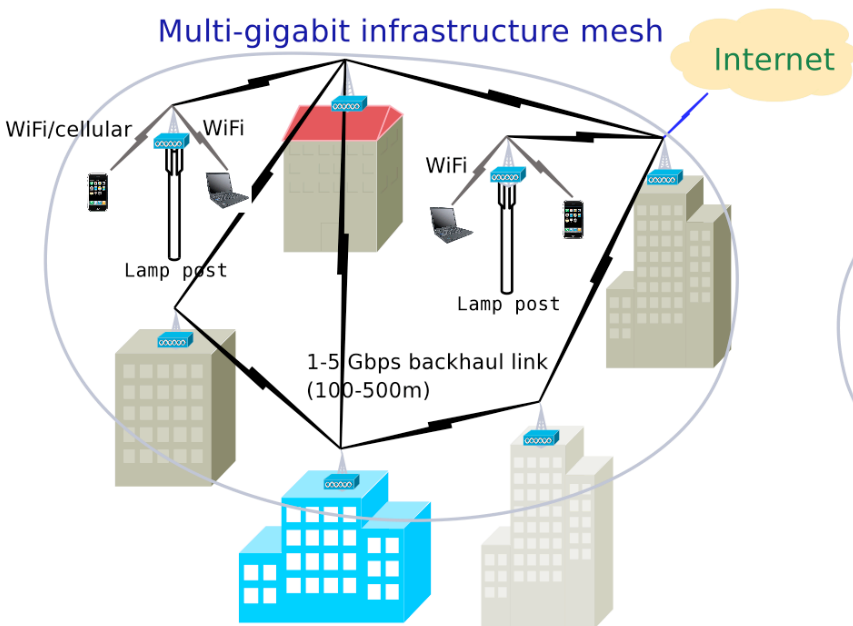
Wireless Gigabit Ethernet

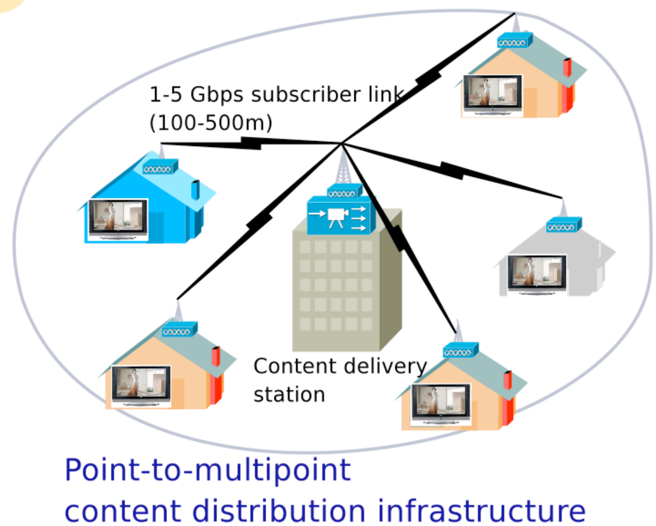


IEEE 802.11 VHT
WLAN

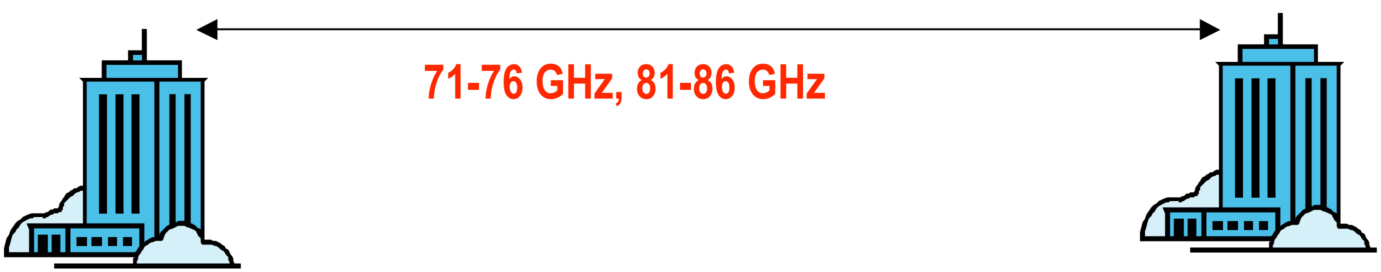
Outdoor mm wave systems

60 GHz mesh networks for "instant" broadband connectivity, 1-5 Gbps at 100 meters





True "Wireless Fiber," 10-40 Gbps Ethernet at 1 km



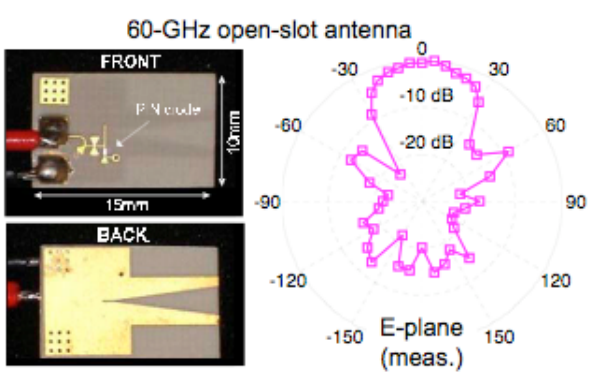
Today's talk

- Big picture: mm wave comm is fundamentally different!
- Directional Networking
  - Principles
  - Indoor WPAN
  - Outdoor multiGigabit mesh
- Millimeter wave MIMO
- Conclusions

What's different about mm wave comm?

Mm wave links are inherently directional

- Omnidirectional links are a truly bad idea!
  - λ^2 scaling of path loss unacceptable: too expensive to produce power at mm wave frequencies
  - MultiGigabit transceivers hard to implement with significant multipath
  - Spatial reuse gets compromised
- Directional transmit and receive are necessary and feasible
  - $1/\lambda^2$ scaling of path loss, 20 dB less TX power than 5 GHz
  - Circuit board antenna arrays can produce highly directive links
  - Electronic steerability usually essential, but need not be perfect



Slot antenna designed at UCSB for imaging sensor nets project

New design considerations

- Blockage kills
  - Obstacles look bigger at small wavelengths
  - Need to steer around, not burn through
- Cannot count on carrier sense for MAC
  - Highly directional links make it hard to snoop on neighbors
  - Must use explicit coordination mechanisms
- Can exploit reduced spatial interference to simplify MAC
- Spatial multiplexing available even for LoS environments
  - Small path length differences enough to provide full rank MIMO channel

Directional Networking

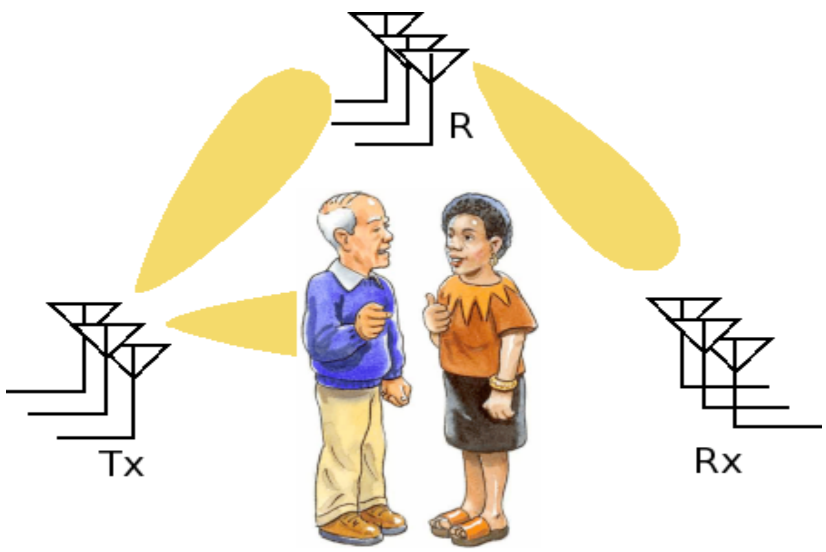
Multihop Indoor Networking

Multihop indoor WPAN

- LOS blockage occurs routinely
  - Furniture, humans
  - Is this a showstopper?
- Worst-case model with relays
  - Directional transmission using only LOS component
  - Small link margin: cannot burn through obstacles
  - Can we preserve network connectivity?
  - Don't rely on wall reflections
- Do we need a lot of relays?

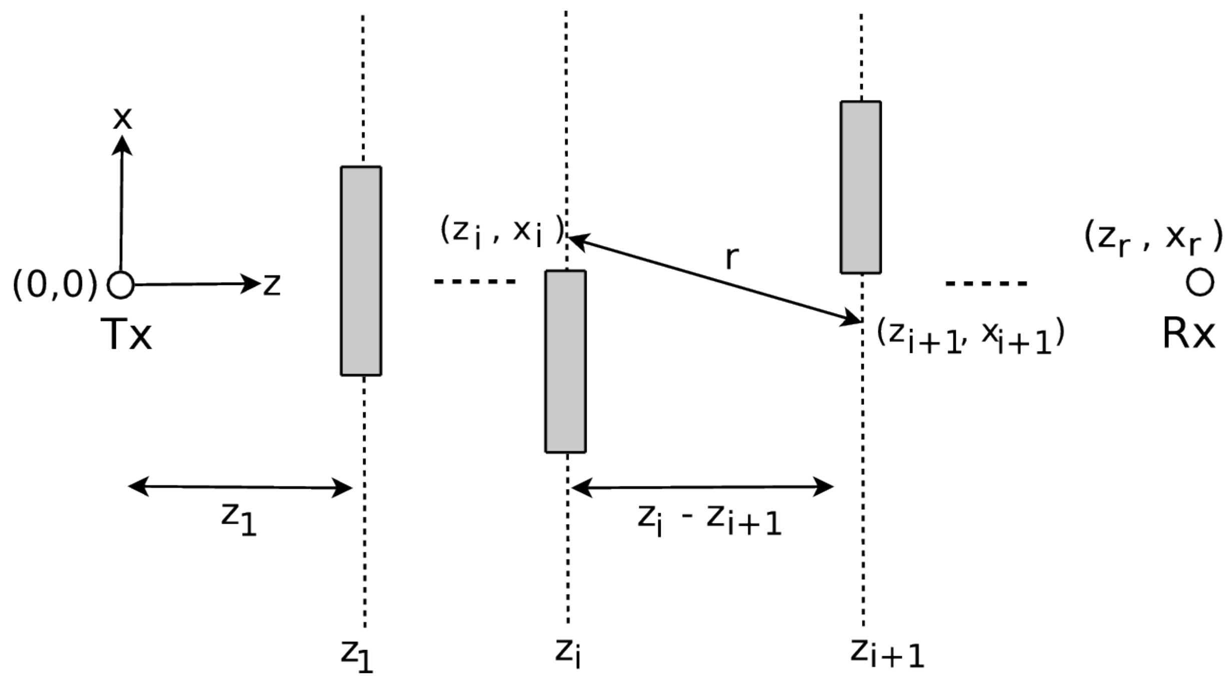
Multihop WPAN Architecture

- In-room multihop WPAN architecture
  - Directional Tx/Rx links
  - Multihop routing based on directional, LOS links
- Diffraction-based link connectivity model
- Multihop relay directional MAC protocol



Link Loss: Obstacle Modeling

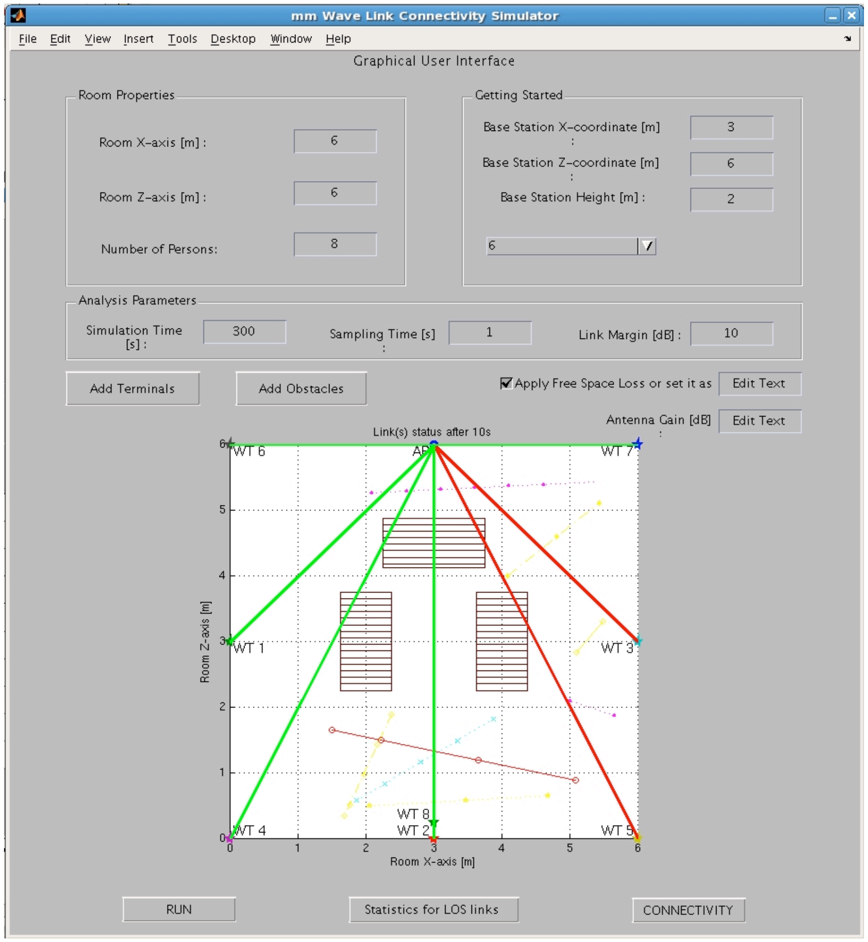
- Received signal strength
  - Signal energy only from the LOS components
  - (In practice, multipath reflections can provide virtual relays)
- Recursive algorithm to evaluate total signal attenuation
  - Diffraction model based on Huygen's principle
  - Diffraction loss for multiple obstacles found by convolution



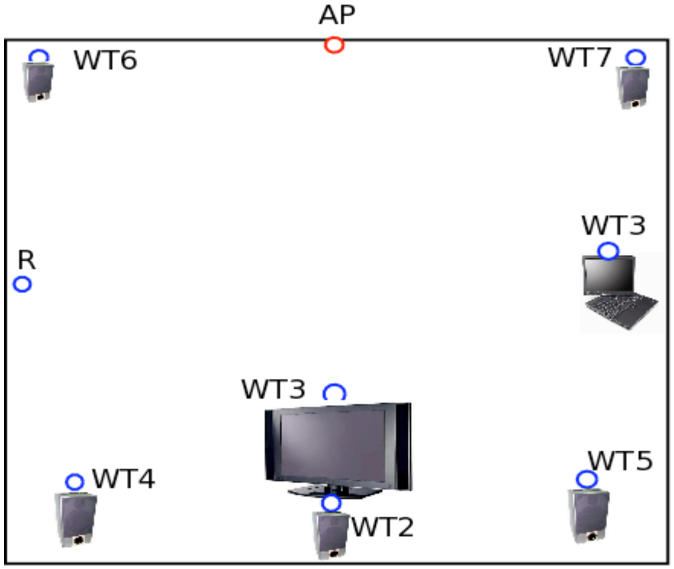
2-D illustration of a multiple obstacle scenario between an AP and a WT

Simulation Tools

- Site-specific time evolution of link loss: Matlab tool
- Packet level network simulations: QualNet Network Simulator - 60 GHz mm-wave "plugins"

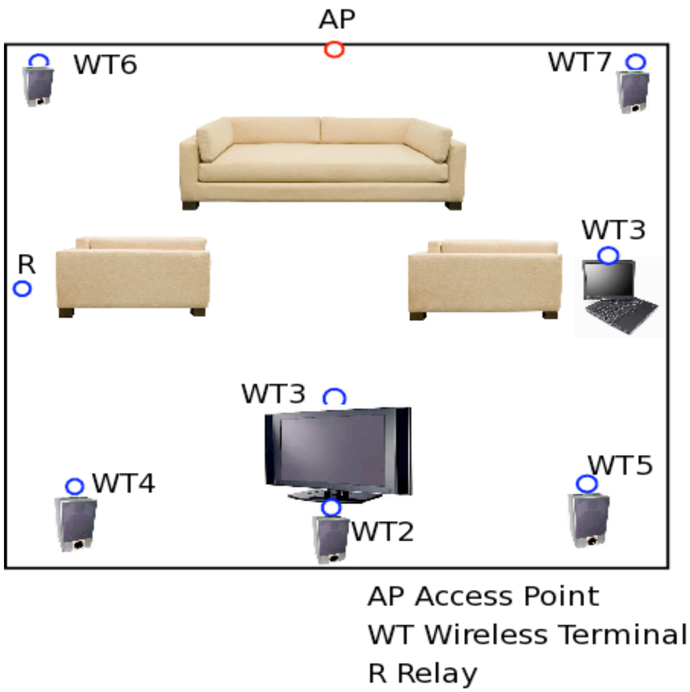


Example evaluation scenario



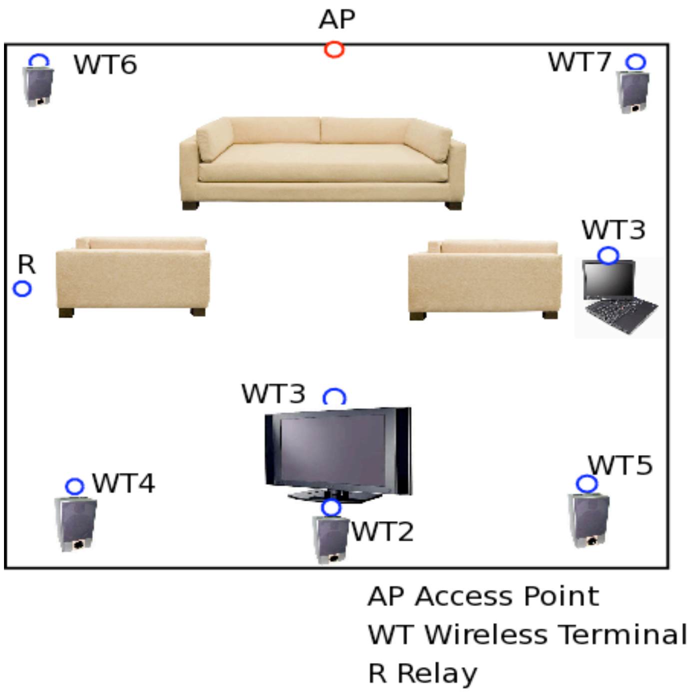
AP Access Point
WT Wireless Terminal
R Relay

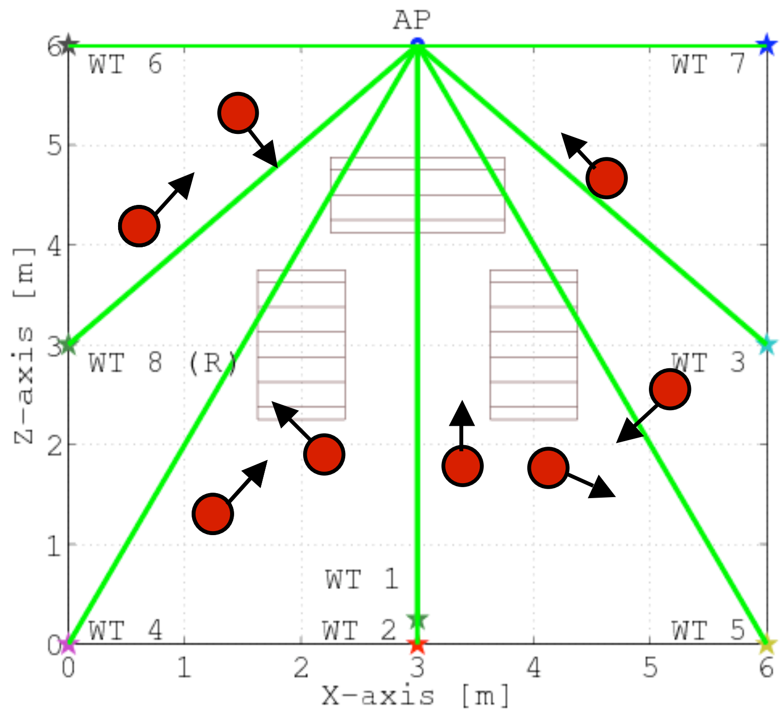
Example evaluation scenario



- Stationary obstacles: furniture
- Mobile obstacles: human beings

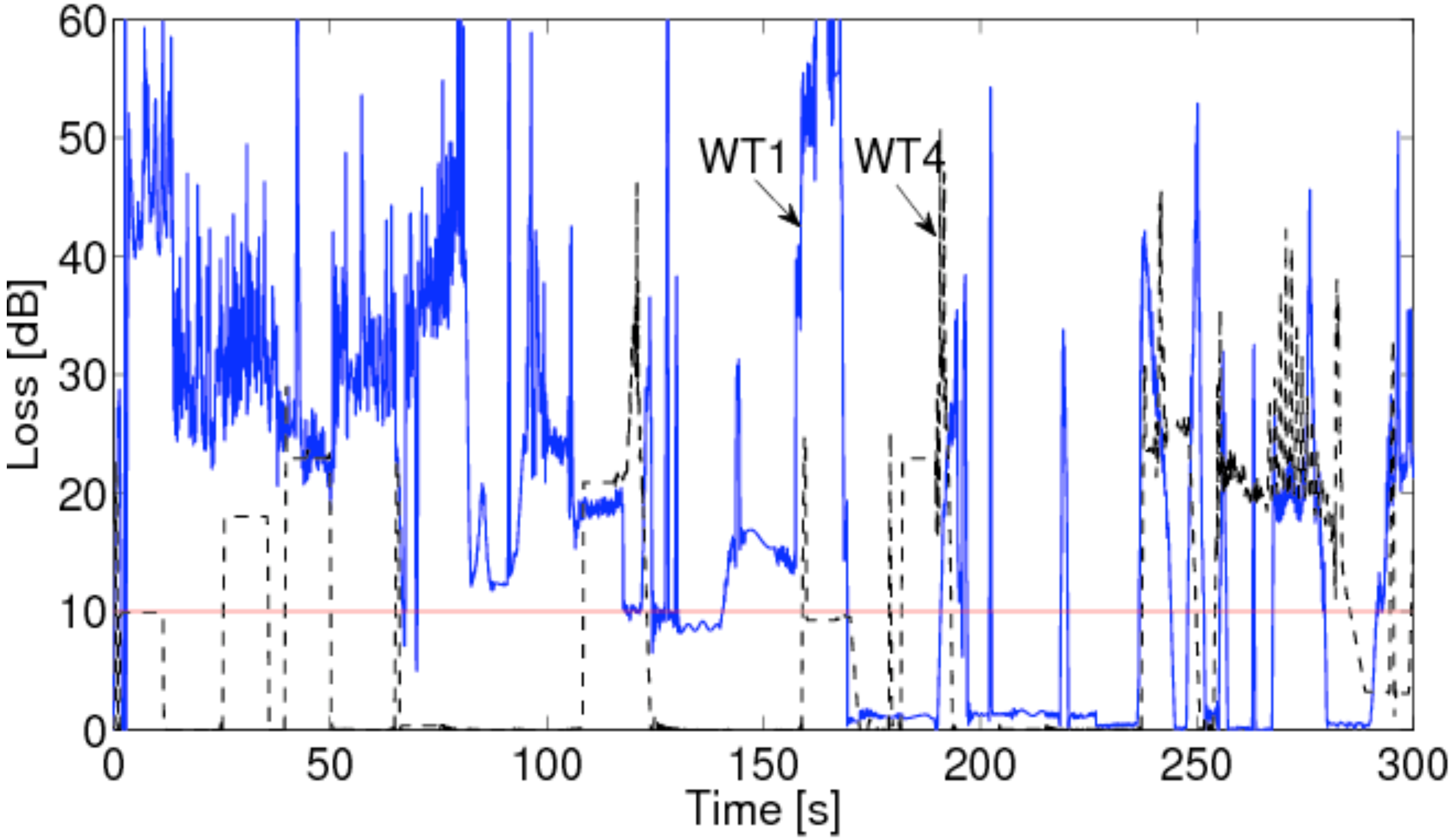
Example evaluation scenario



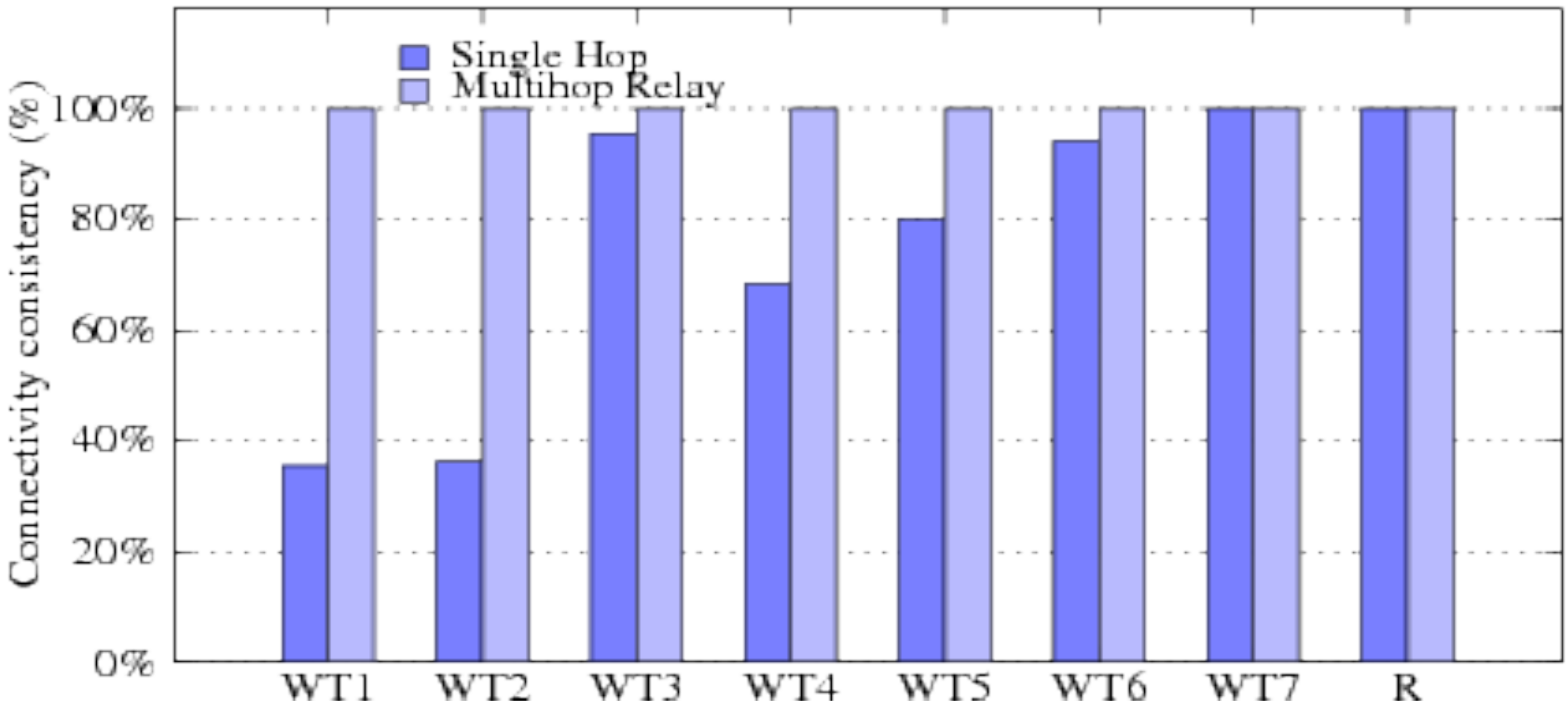


- Stationary obstacles: furniture
- Mobile obstacles: human beings

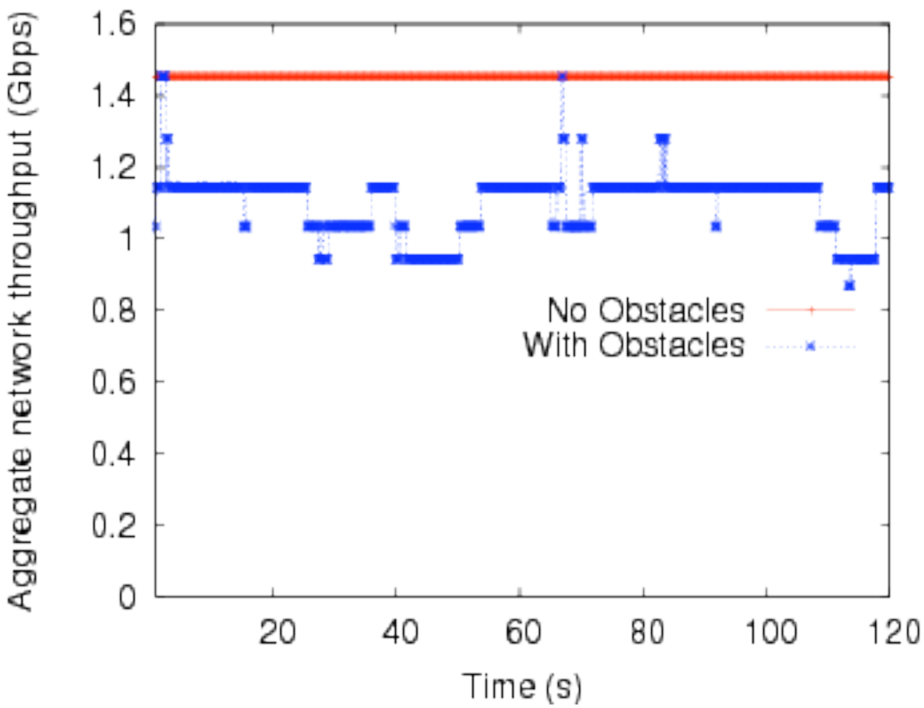
AP to WT Link Loss Profile



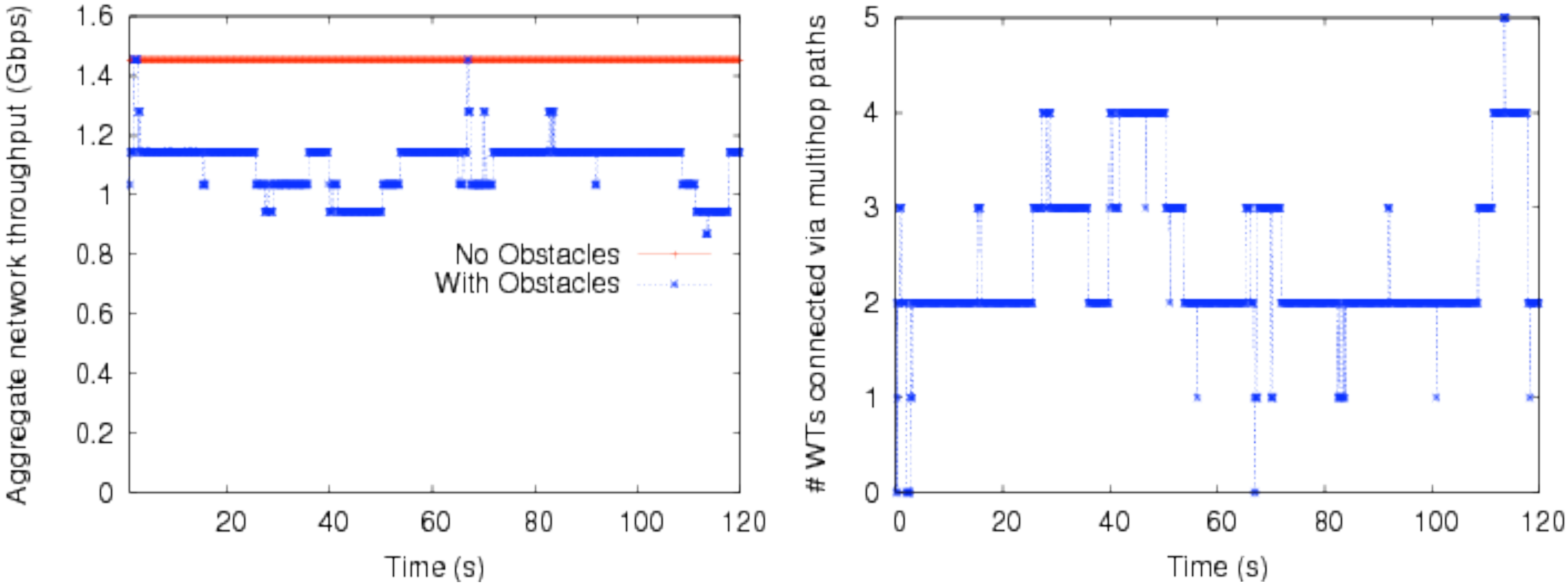
Connectivity Consistency



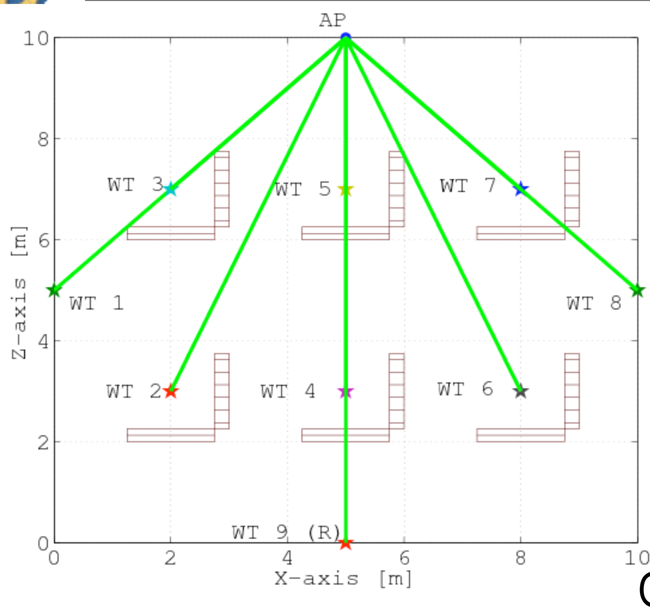
Aggregate Network Throughput



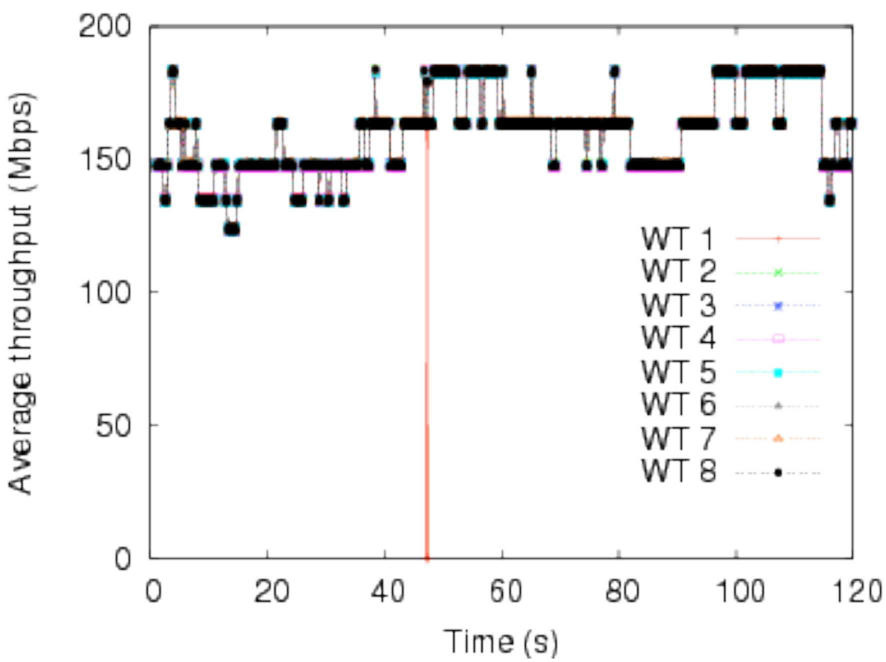
Aggregate Network Throughput



Relays: Position and Number Matter



Office Scenario



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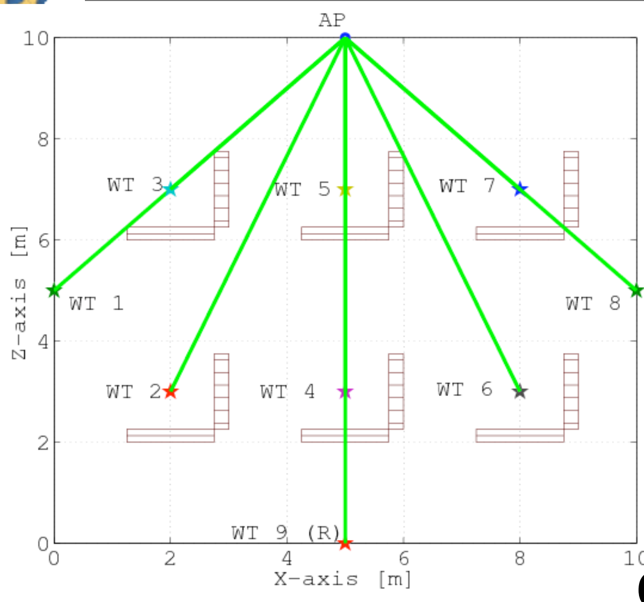
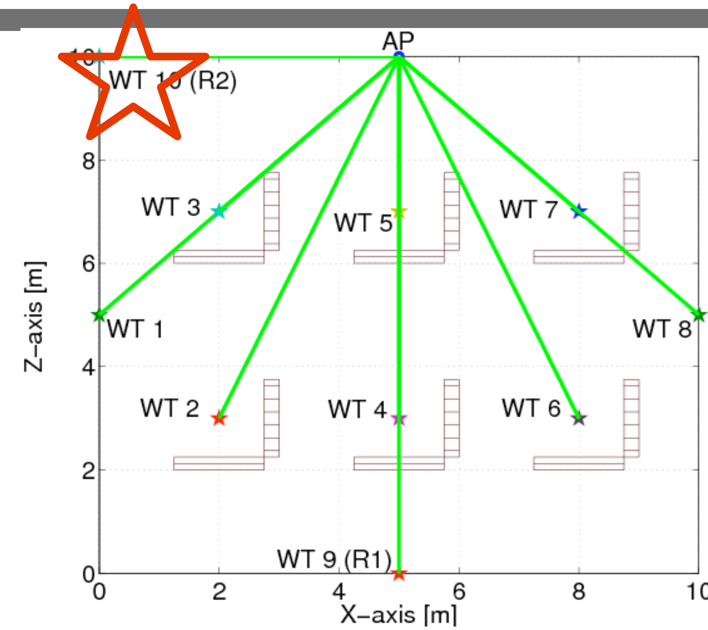
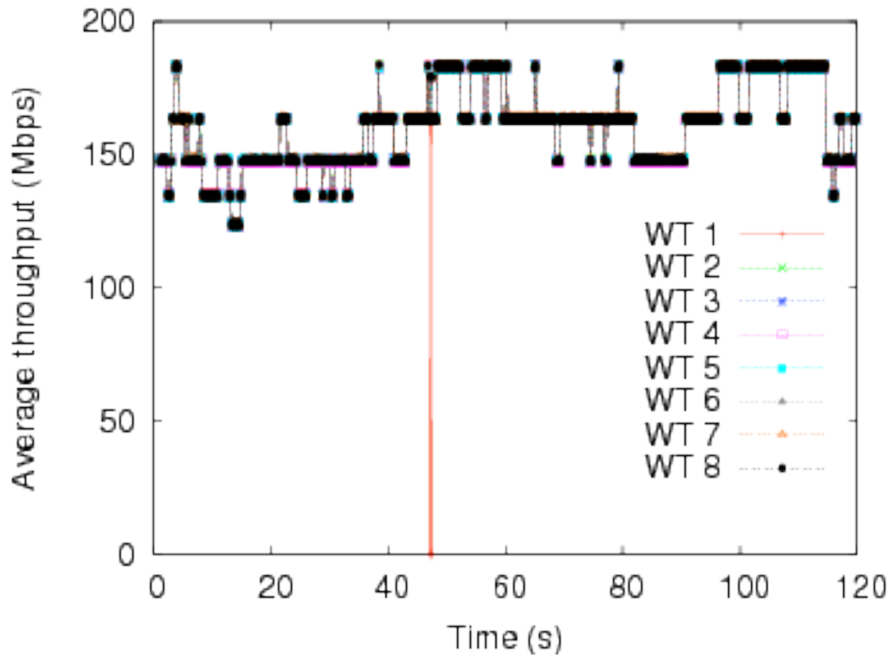
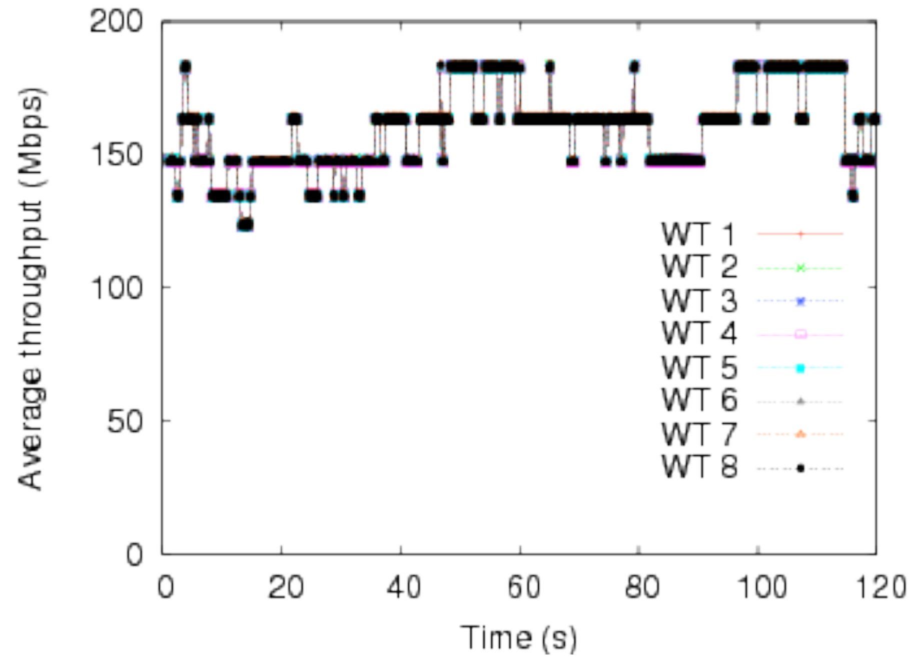


2nd Relay



Office Scenario



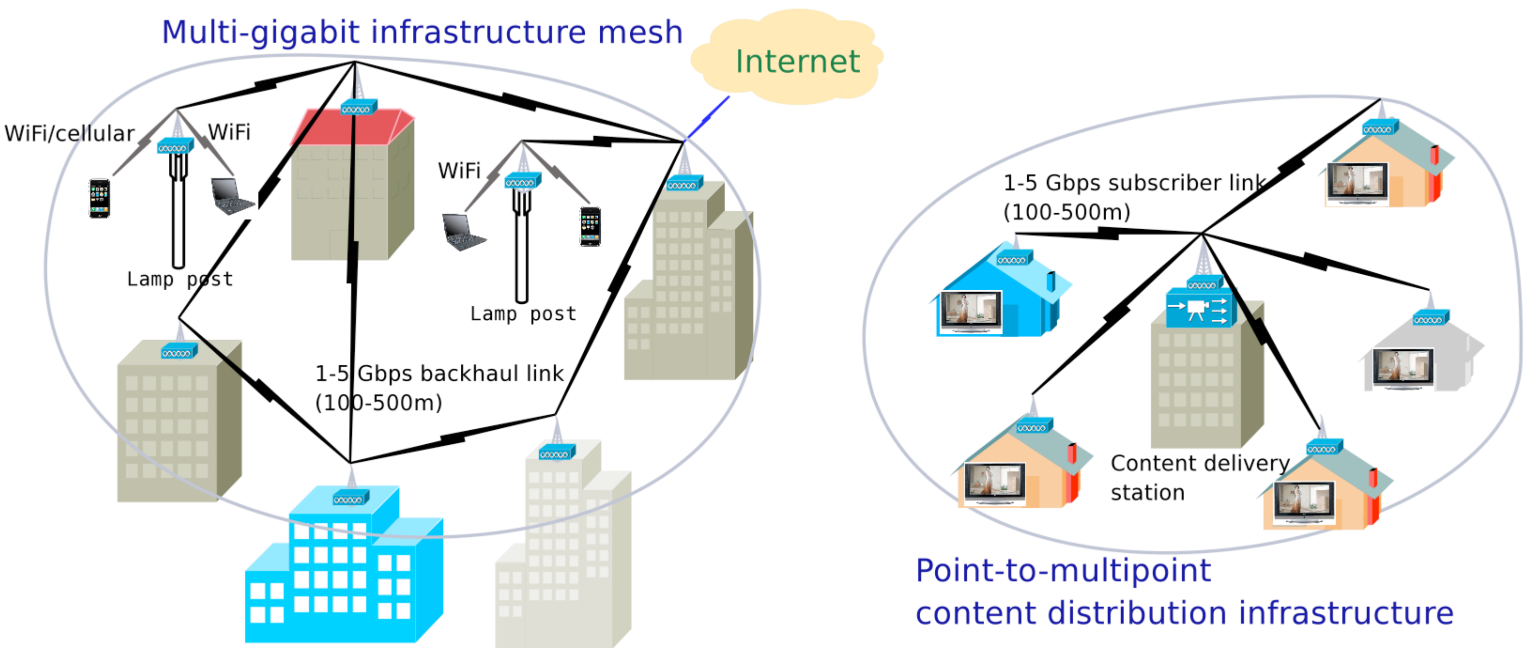


60GHz indoor networking summary

- Blockage is not a deal-breaker
  - Multihop with small number of relays works
  - Directional networking with centralized control is relatively simple
- Ray tracing and simple diffraction models enough for system level insights
- A huge amount of work remains
  - Cross-layer design taken to a new extreme: network topology hypersensitive to antenna placement and orientation
  - Quantify spatial interference patterns
  - Design protocols for reuse and coexistence (e.g., between WPAN, WLAN, wireless HD)
  - Discovery, topology update, MAC in decentralized directional networks

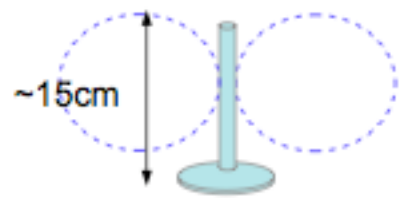
Outdoor Millimeter Wave Mesh Networks

Instant broadband infrastructure



Omni-coverage yet highly directional nodes

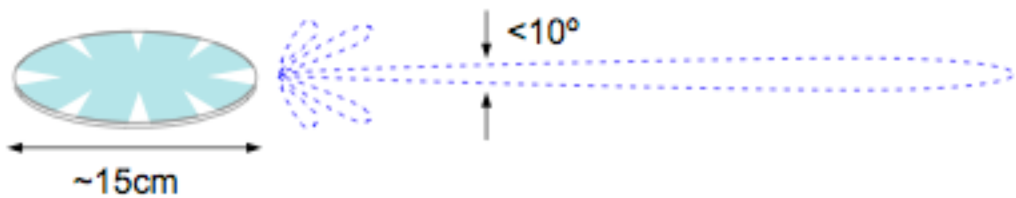
2.4 GHz
Wi-Fi antenna
D= 5dBi

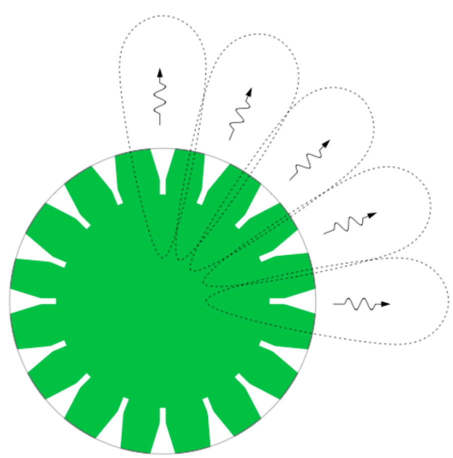


$$D \equiv \frac{\text{Max. power density}}{\text{Average power density}} = \frac{\pi}{\lambda^2} A_{eff} \propto f^2$$

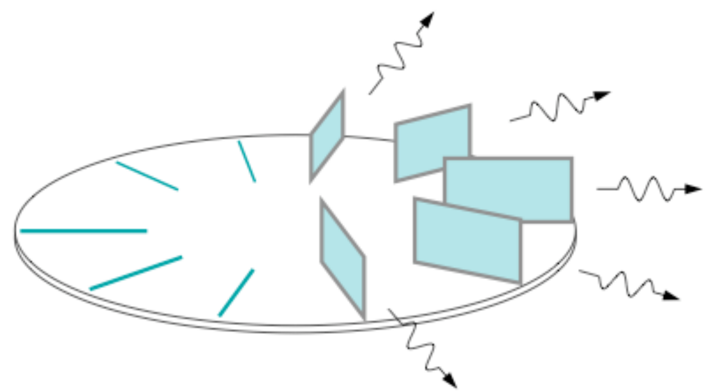
$$D \approx \frac{40{,}000}{\theta_{azimuth}\theta_{elevation}}$$

Circular array antenna
for a 60 GHz mesh network
D=30dBi



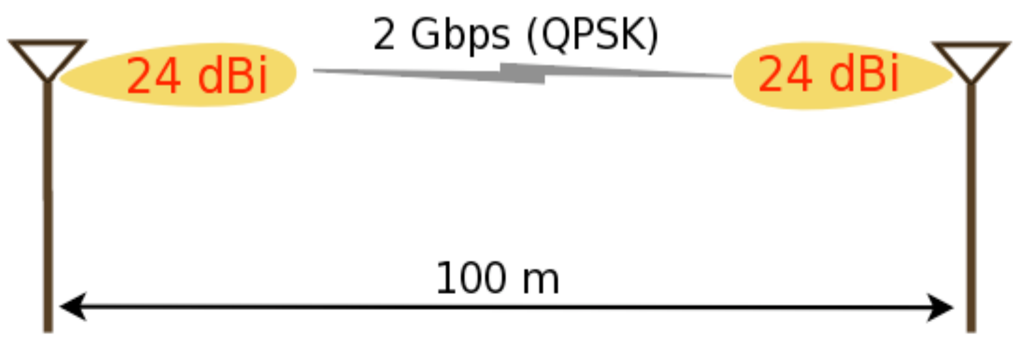


TOP VIEW



Reconfigurable circular array
Total 10 angular slots; 5 slots installed

Link budget



Tx power: 10dBm
Bandwidth: 1.5 GHz
SNR: 15 dB

Oxygen absorption: 15 dB/Km
Noise figure: 6 dB
Link margin: 10 dB

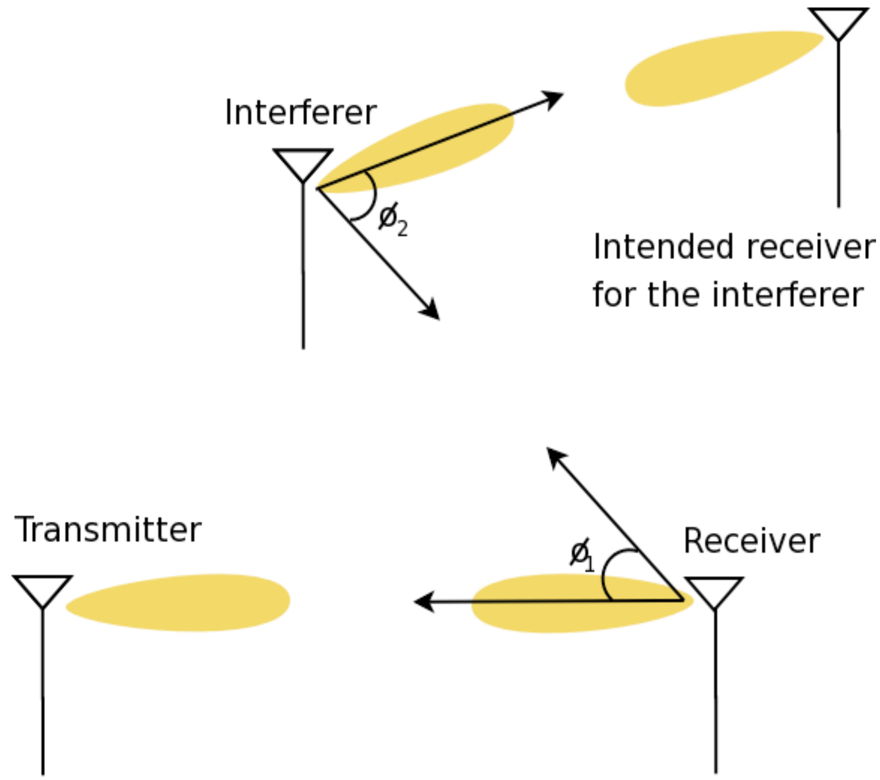
Caveat: can have significant fading due to ground and wall reflections
(need to explore diversity strategies)
Can get higher range and rate by using higher directivities
(need hardware architectures for steerable arrays with large number of elements)

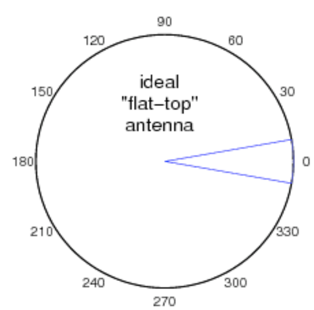
Key design issues

- No ``omnidirectional mode'' for MAC
  - Must use directionality to attain link budget
  - Directional only mode also simplifies PHY
- Are directional links like wires?
  - A qualified yes
- How do we exploit ``wire-like'' characteristics for MAC?
  - Carrier sense is out, but interference is much reduced
- Many other details
  - Network discovery
  - Synchronization maintenance (if used in MAC)
- Step 1: Understand spatial interference

Interference with highly directional antennas

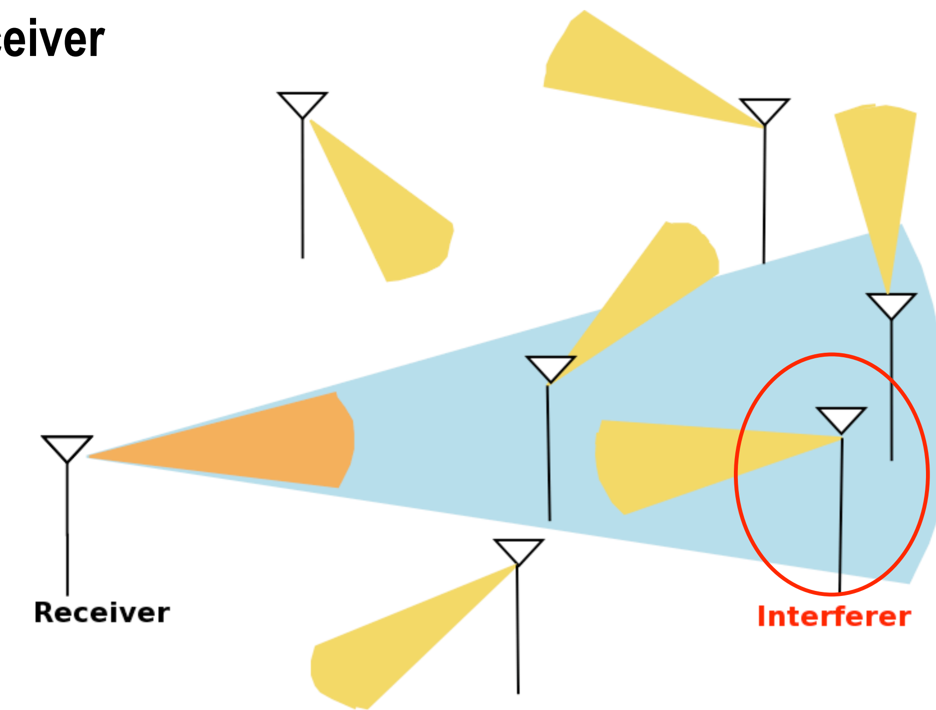
- Collision probability?
  - Dependence on beamwidth?
- Interference models?
  - Protocol model
  - Physical model
- Flat top antenna model
  - Constant gain within azimuthal angle Φ and zero outside





Interference under the protocol model

- Flat top antenna, randomly placed transmitters, random orientation wrt desired receiver
- Collision iff there exists at least one interferer
  - within the interference range
  - within the receiver beamwidth
  - pointing in the direction of the receiver



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Collision Probability $1-e^{-\lambda\beta A_c}$

$$A_c = \frac{(R_0\Delta\Phi)^2}{4\pi}e^{-\alpha(R_i - R_0)}$$

β : SINR threshold

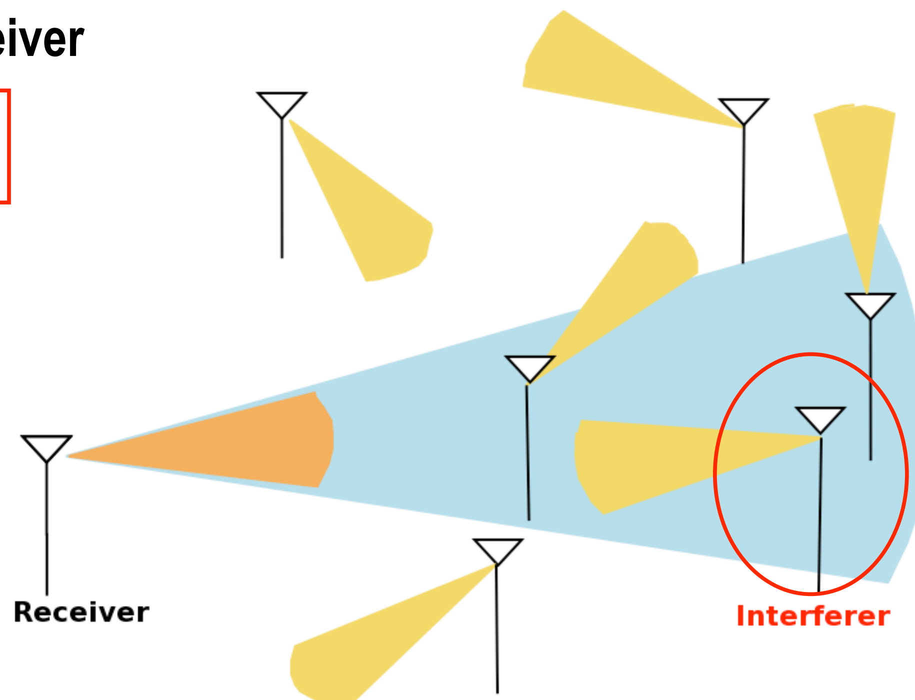
λ : density of transmitting nodes

ΔΦ: (azimuthal) beamwidth

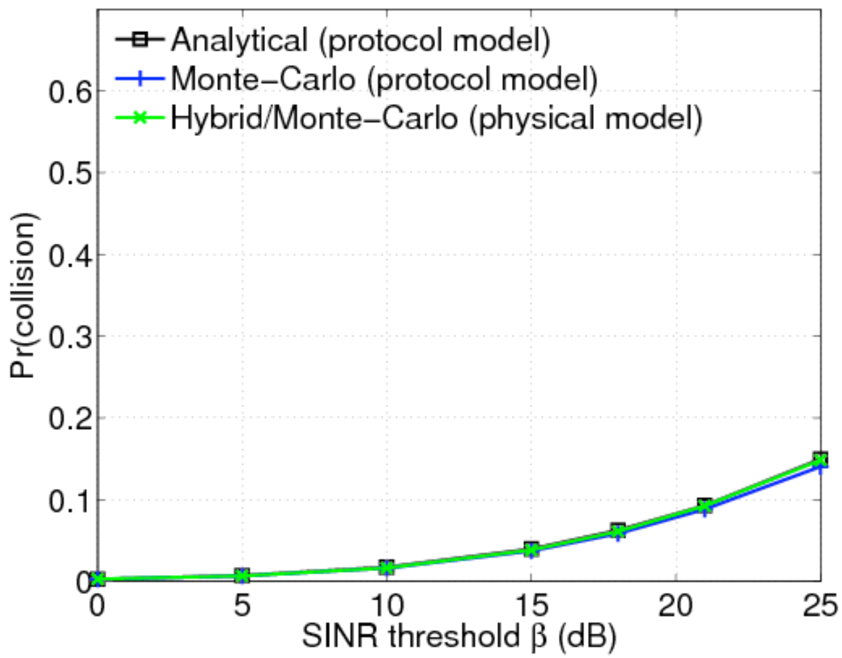
R_0 : nominal link range

R_i : interference range

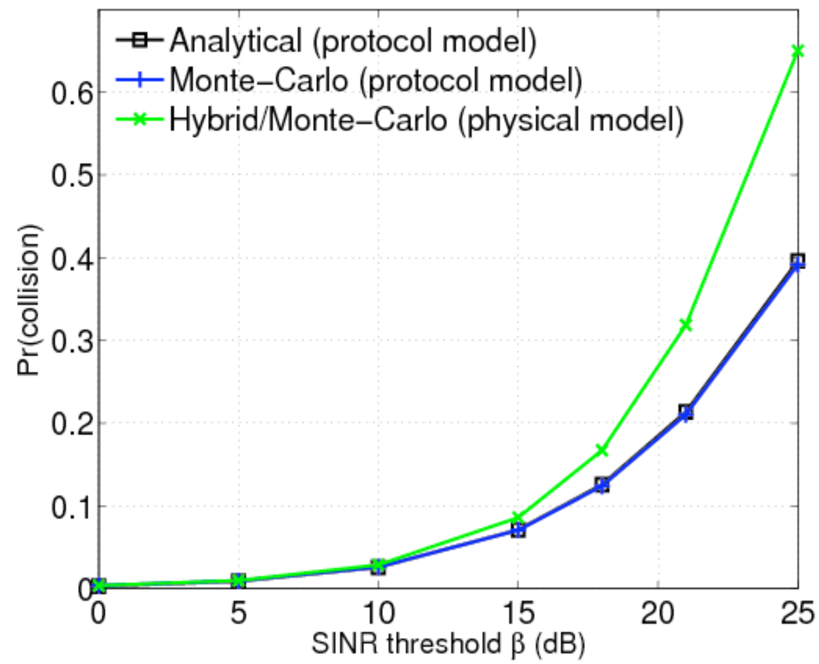
α : atmospheric absorption coefficient



Collision probabilities



Pr(collision) for flat-top antenna



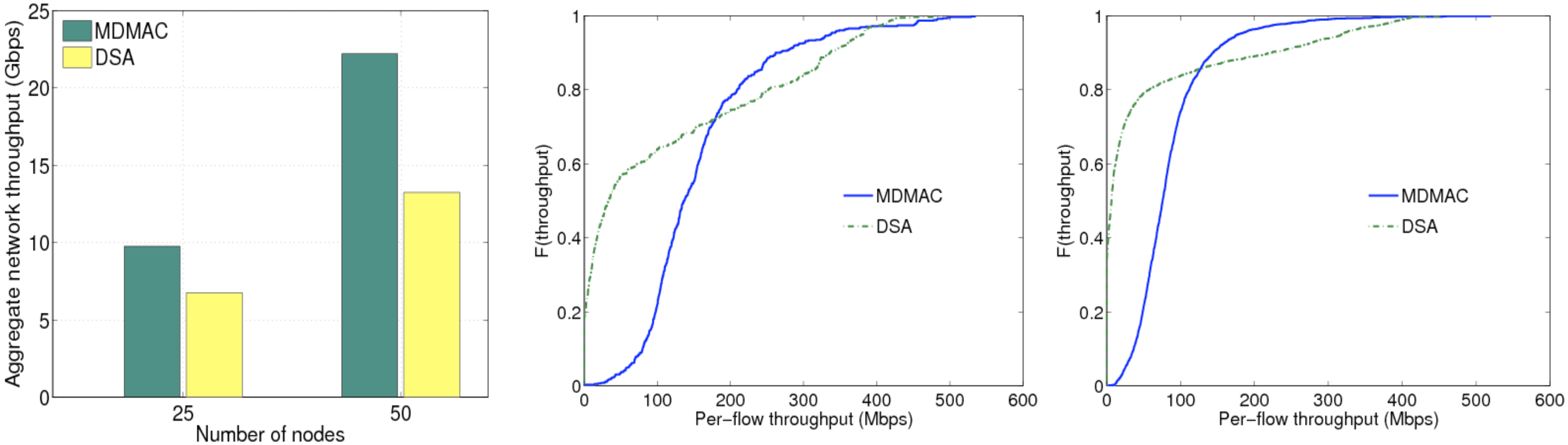
Pr(collision) for linear array

Sidelobes do matter, especially when desired SINR is higher
If antennas are directive enough and signaling constellations are small enough
--full spatial reuse possible
--protocol model is a good approximation
For lower directivity and/or larger constellations
--coordinate just enough and/or tune down transmit probabilities

MAC Design: Approach and Issues

- Different transmitters do not coordinate with each other
  - *Wire-like* links, *deaf* neighbors
- Transmitter tries to coordinate with intended receiver
  - Half-duplex constraint
  - Receiver can only receive successfully from one node at a time
- Benchmarks: slotted Aloha and TDM
- How to do better than slotted Aloha while staying simple?
- How to approach the performance of globally computed TDM schedules?
  - Use learning and memory (Singh, Mudumbai, Madhow, *Infocom 2010*)
- How to maintain slotting in lightweight fashion?

Saturated traffic throughput: Proposed MAC versus Directional Slotted Aloha



Aggregate network throughput

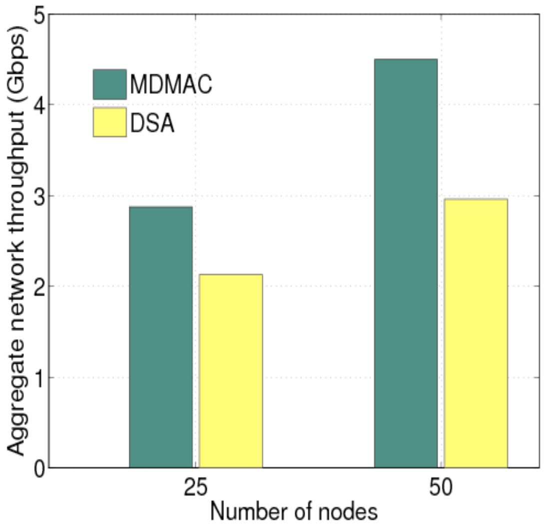
25 node random topologies

50 node random topologies

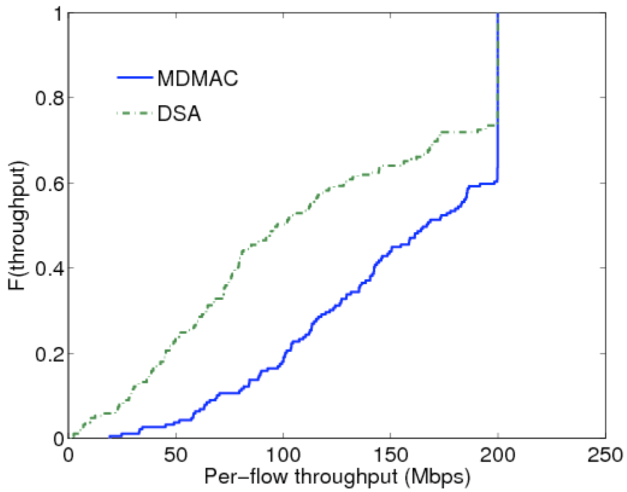
Saturated traffic model

- Proposed MAC has ~40% higher aggregate network throughput and fairer allocation
- Approaches more than 80% of maximal matching style benchmarks

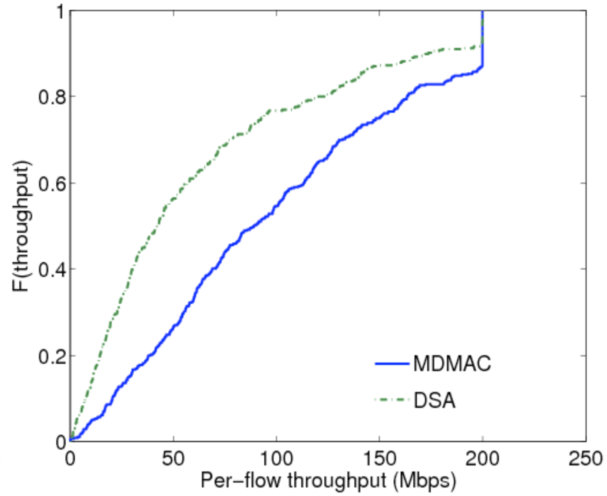
Mesh traffic with randomly chosen source-sink pairs



Aggregate network throughput



25 node random topologies



50 node random topologies

Mesh multihop traffic model

- Throughput and resource utilization gains extend to multihop mesh traffic

Outdoor mesh network summary

- Novel design approach needed
  - Pseudowired abstraction
  - MAC emphasis shifts from interference management/avoidance to scheduling
  - Promising preliminary results approaching TDM performance
- Omni-coverage yet highly directional nodes are an interesting hardware challenge
  - Interplay of form factor, antenna design, partitioning of RF/IF/baseband functionalities
  - May have significant cross-fertilization with emerging indoor WLAN efforts

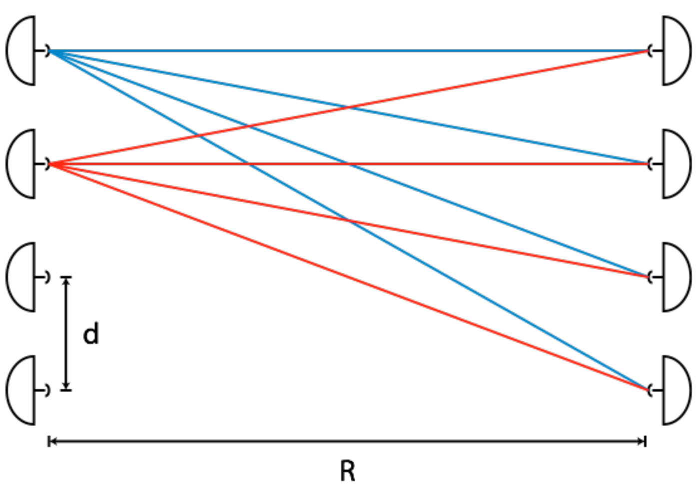
Millimeter Wave MIMO

Spatial Multiplexing at mm Wavelengths

- Spectral efficiency limited by hardware constraints
- How can we push data rates even further?
  - To keep up with wired specs (10.2 Gbps HDMI, 40 & 100 Gigabit Ethernet)
  - To meet future bandwidth demands
- Spatial domain remains an untapped resource at 60 GHz

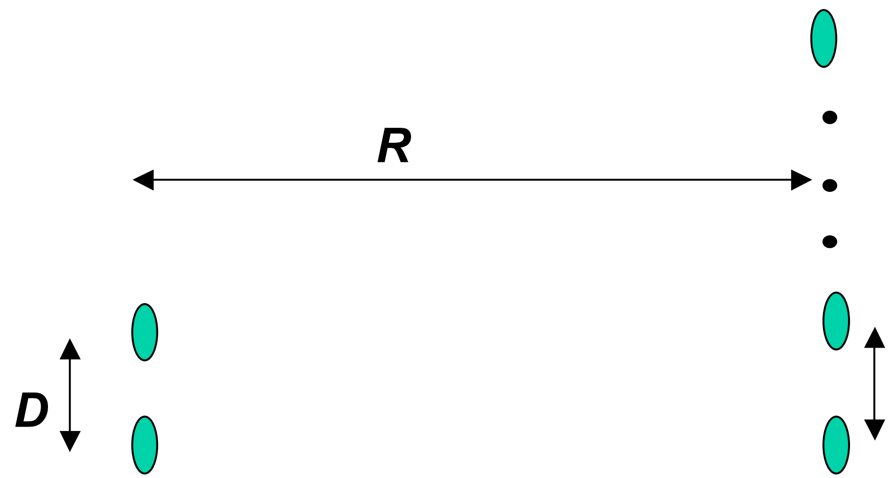
MIMO at mm Wavelengths

At lower frequencies, multipath relied on for uncorrelated channel.



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

Parallel spatial channels with zero cross-talk



Receive array responses

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

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

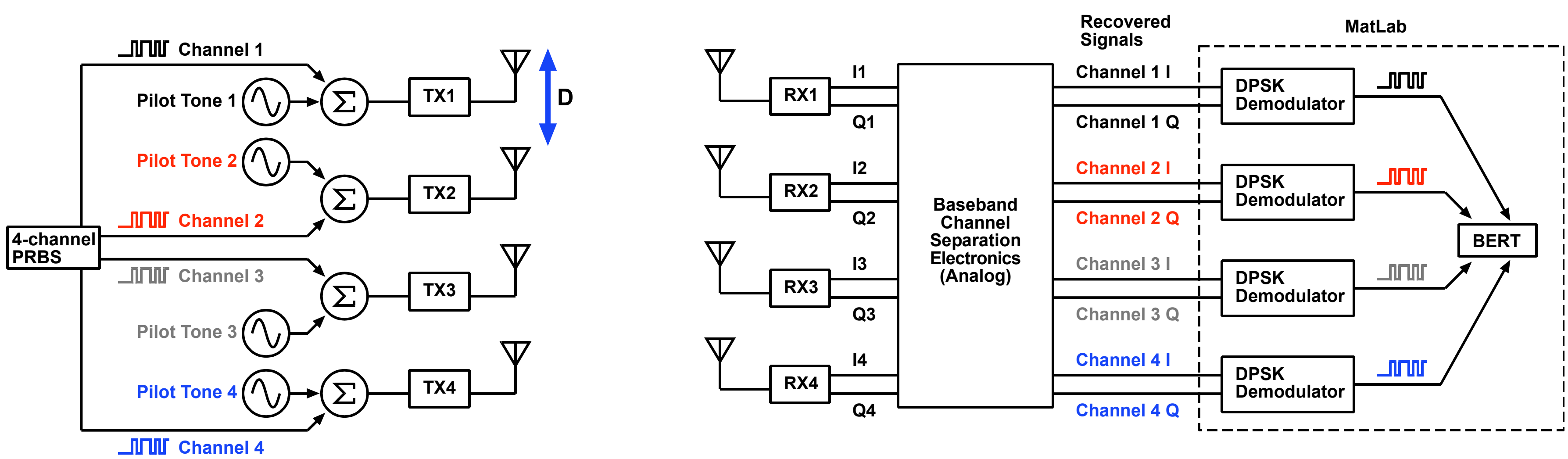
$$\phi = \frac{2\pi}{\lambda}\frac{D^2}{2R} = \frac{\pi D^2}{R\lambda}$$

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

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

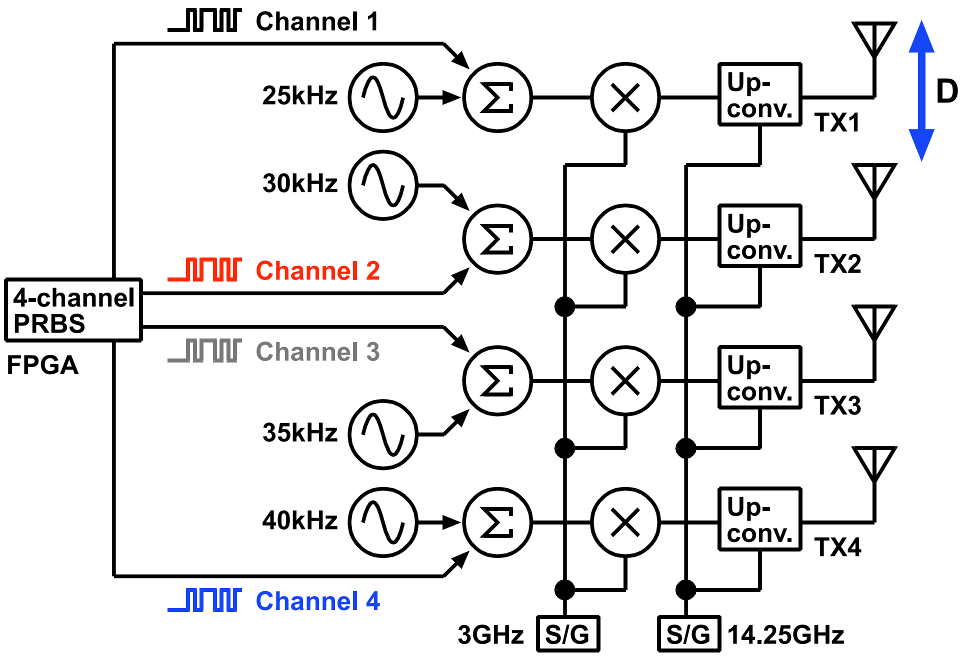
Example 1: 75 GHz, 1 km range, 4x4 system
Array dimension is about 3 meters
Example 2: 60 GHz, 10 m, 2 x 2 system
Array dimension about 16 cm

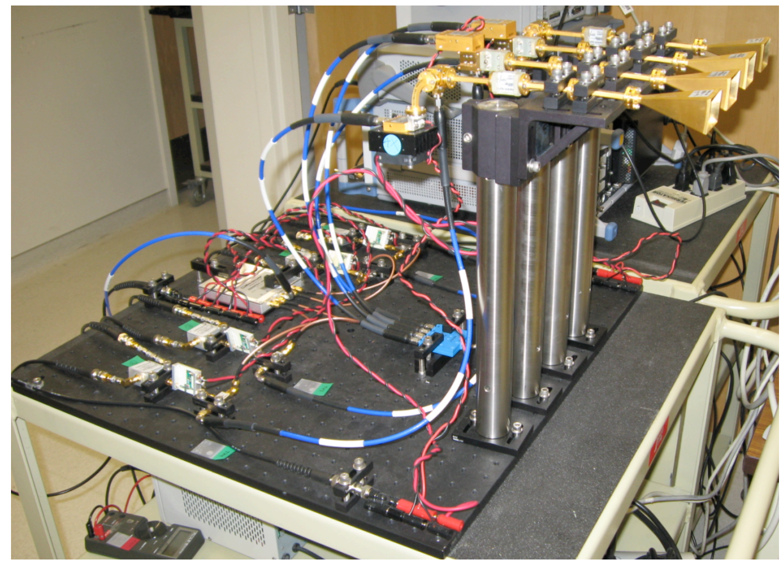
4x4 Prototype: System Architecture



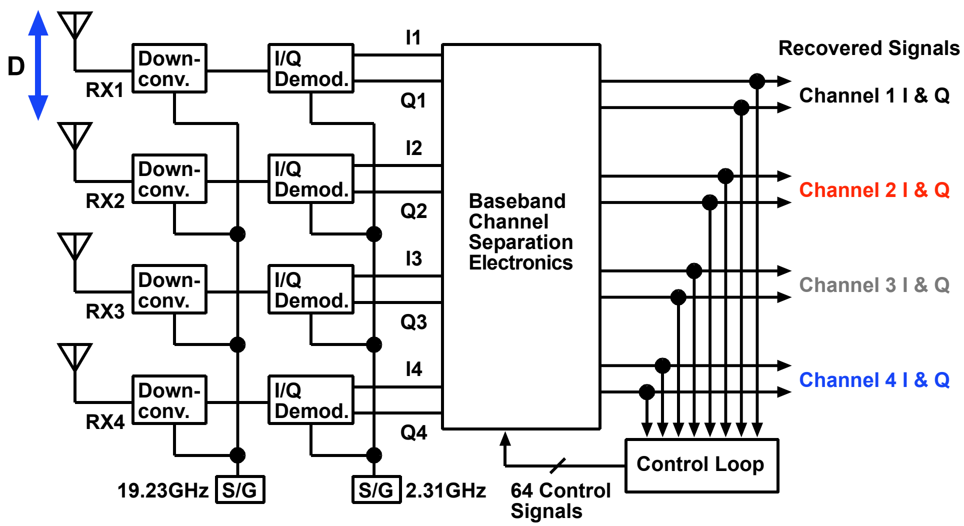
- Embedded pilot tones used to identify channels at the receiver
- Decouple receiver functions: channel separation and data demodulation
- Channel separation network implemented with baseband analog circuits

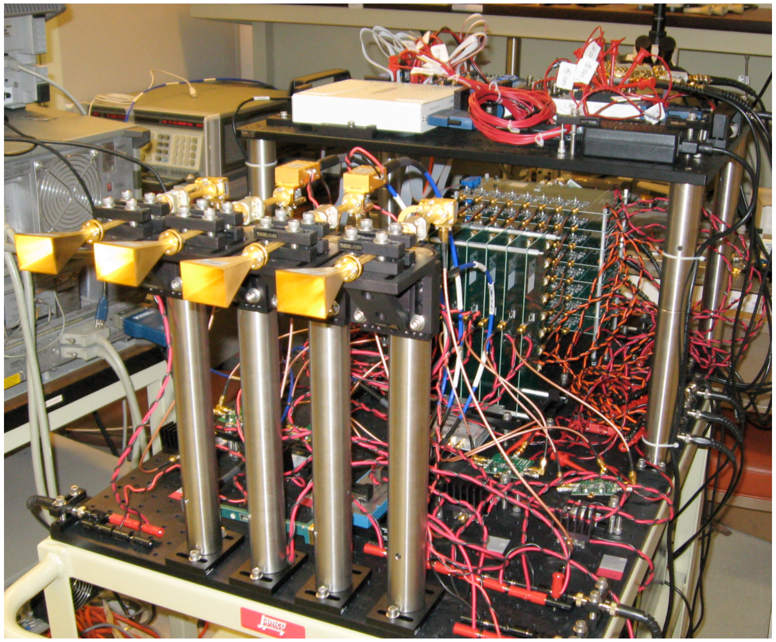
Transmitter Hardware Prototype



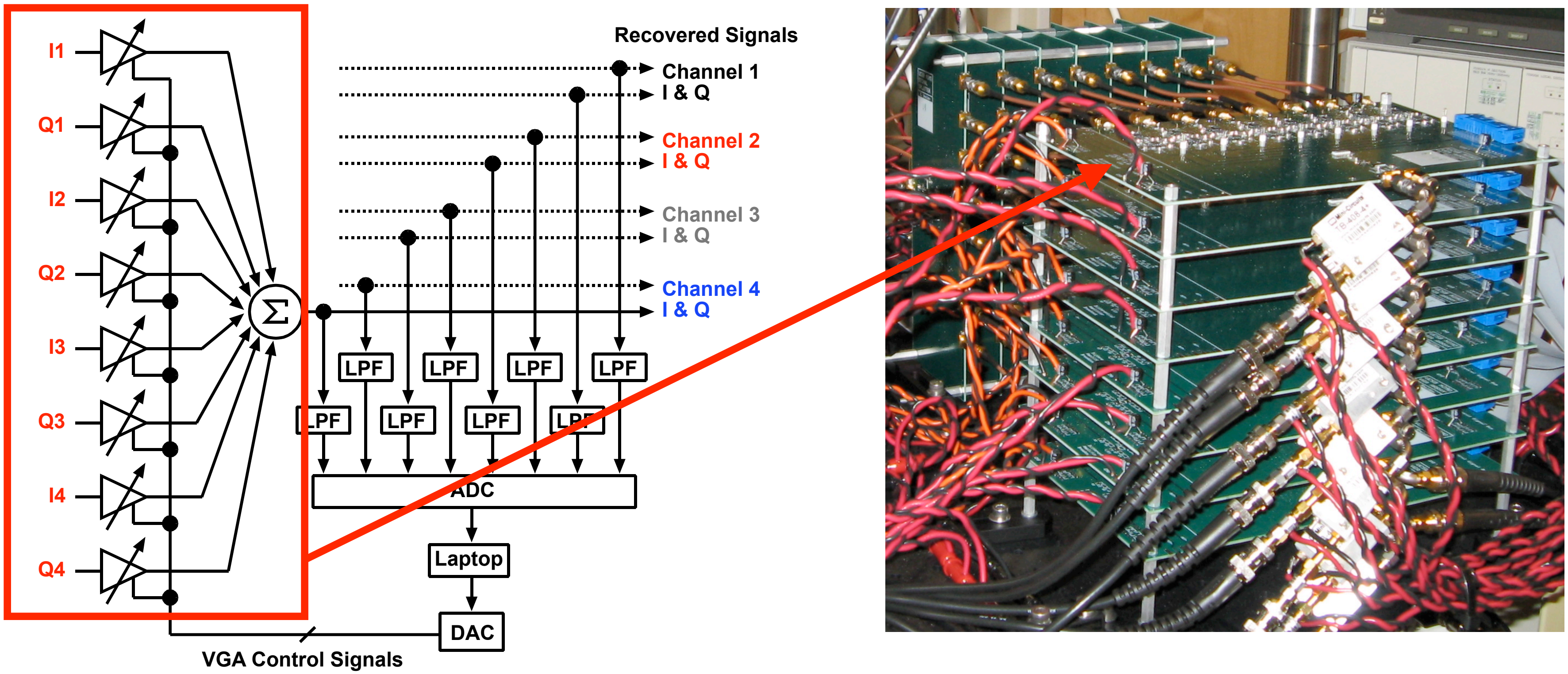


Receiver Hardware Prototype



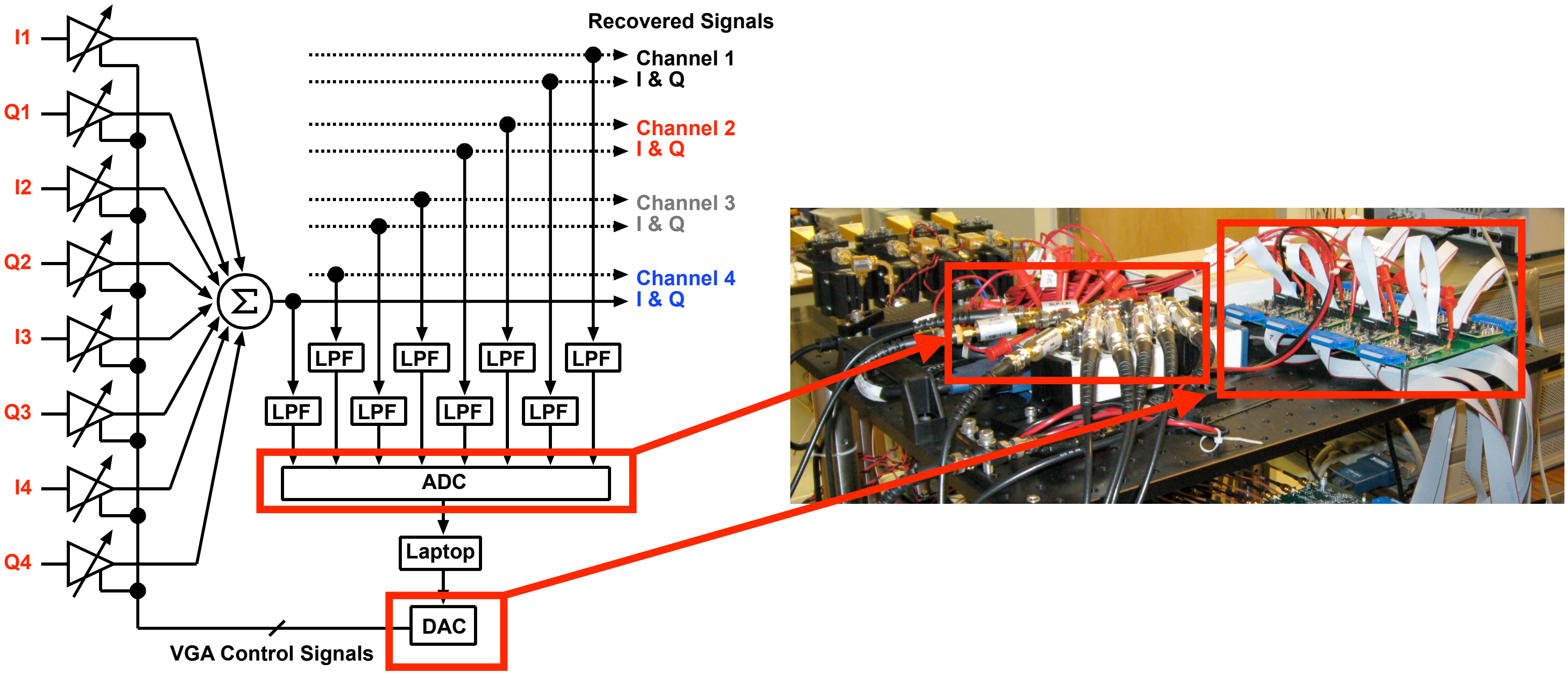


Channel Separation Prototype



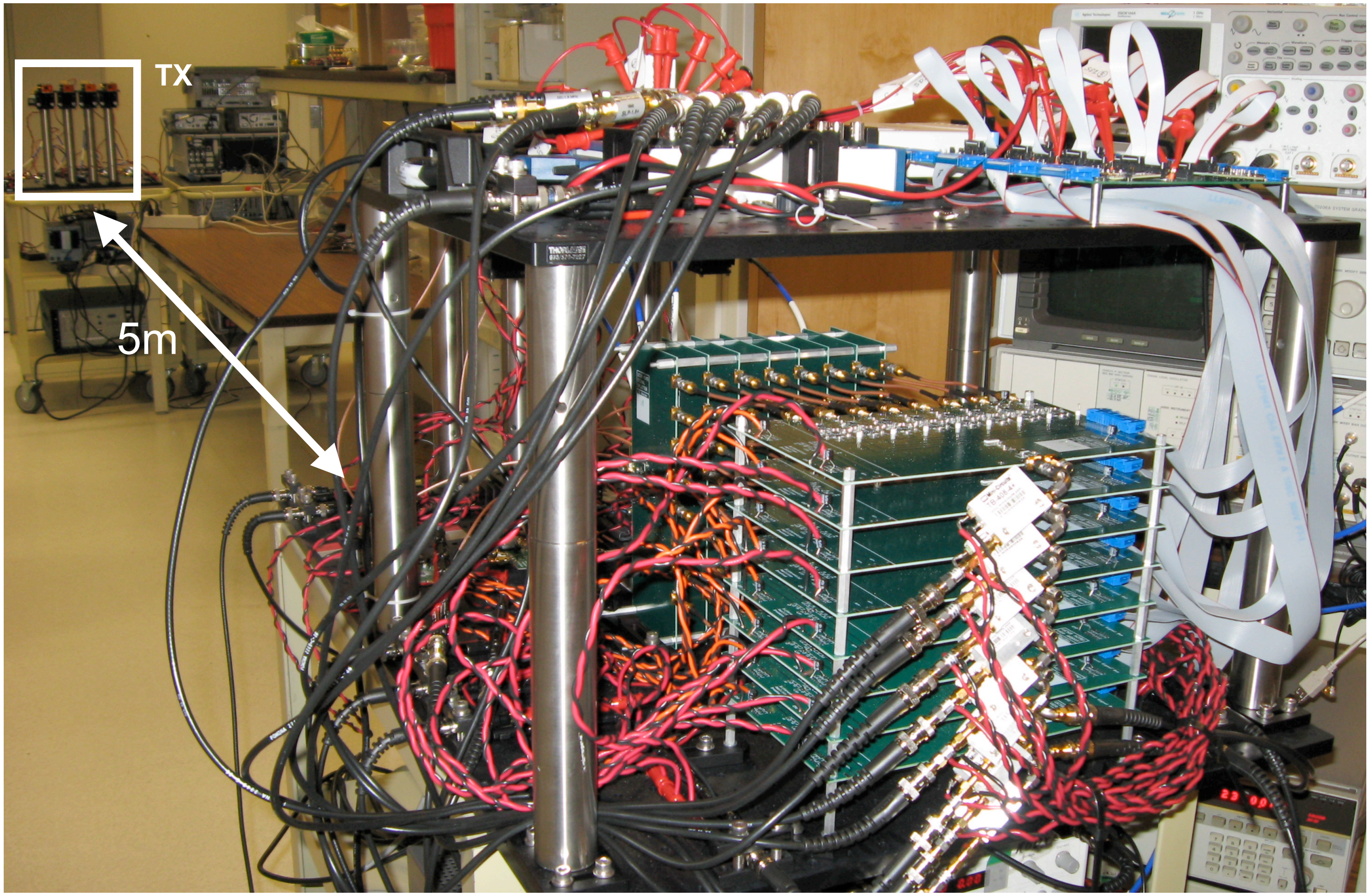
- VGAs are implemented as 4 quadrant analog multipliers using transistor array ICs
- Summation circuit consists of a resistor power combiner

Channel Identification and Control Loop



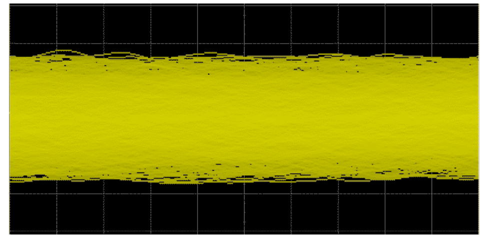
- Unique low frequency (25-40kHz) pilot tones added to each transmitter signal
- Control loop sets VGA control signals by maximizing desired pilot tone power
- Pilot tone signals from interfering transmitters are minimized

Indoor Radio Link Experiment



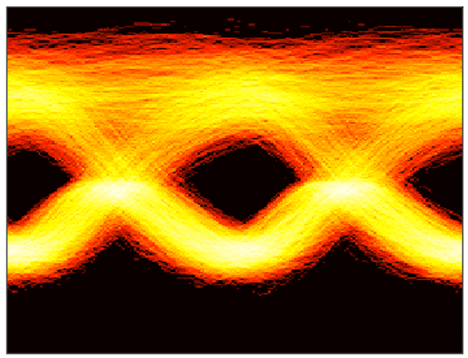
Time Domain Results

Before Channel Separation

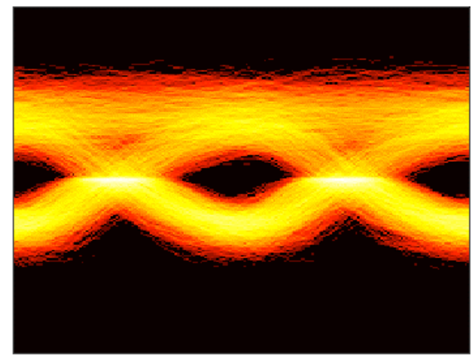


After Channel Separation

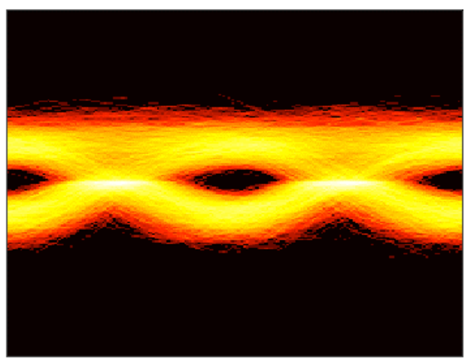
Channel 1



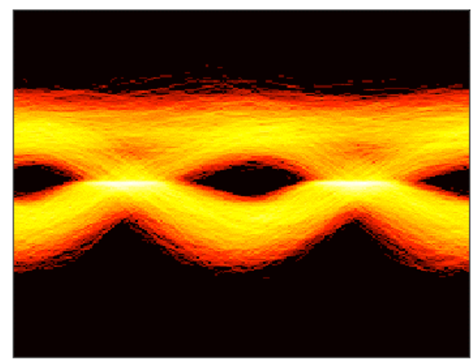
Channel 2



Channel 3

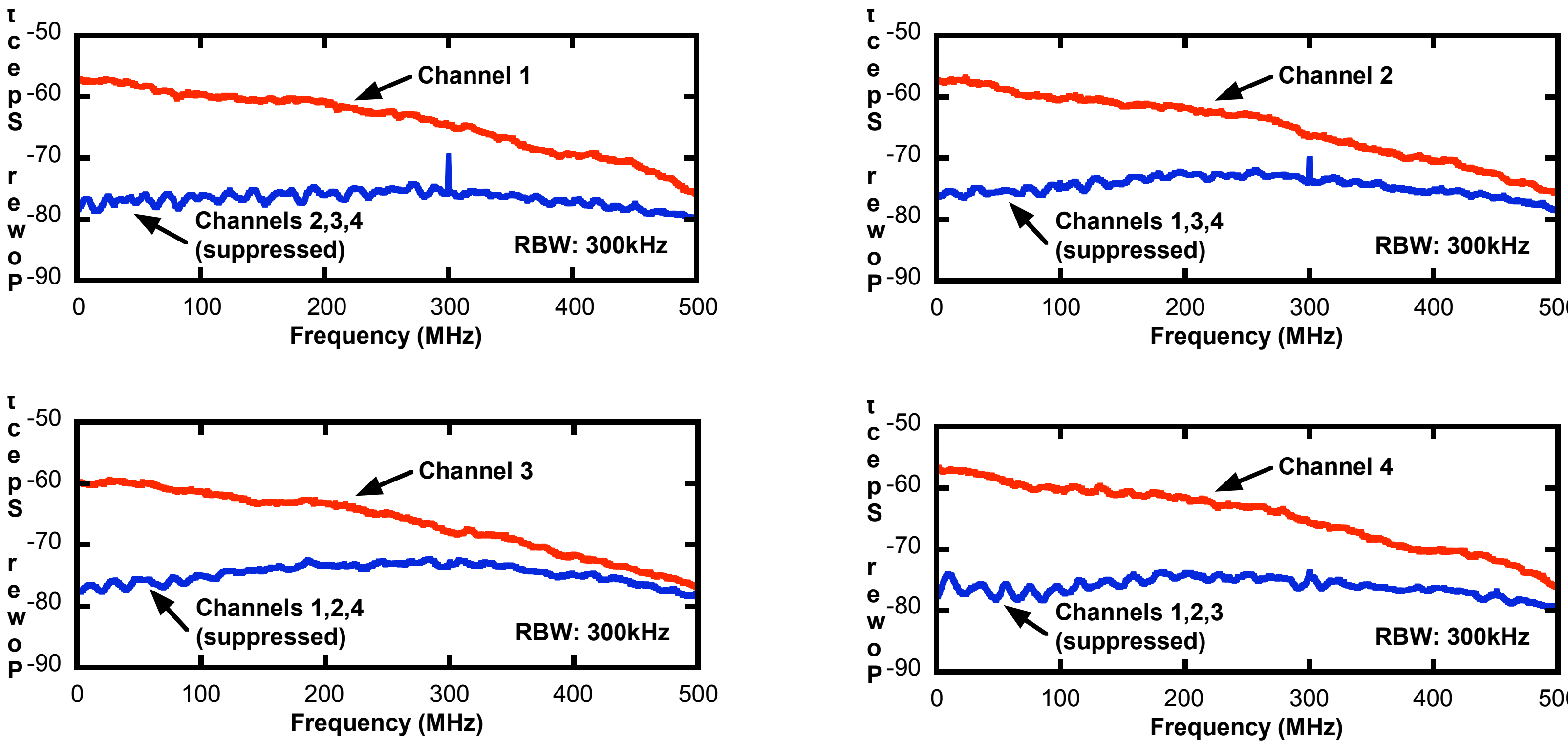


Channel 4



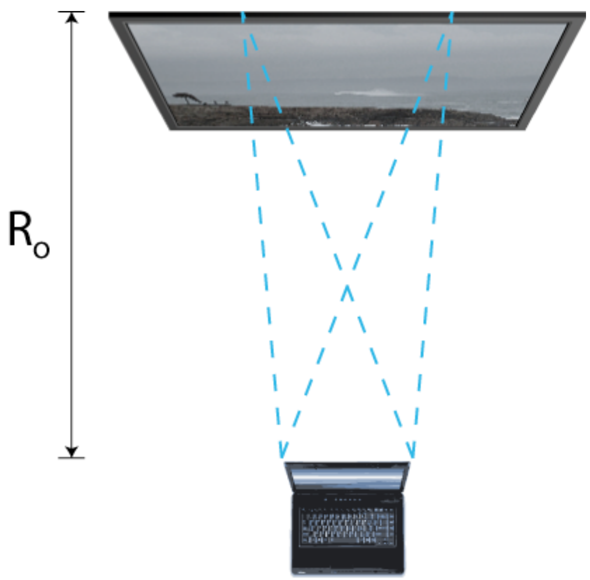
Differential data demodulation performed offline in software

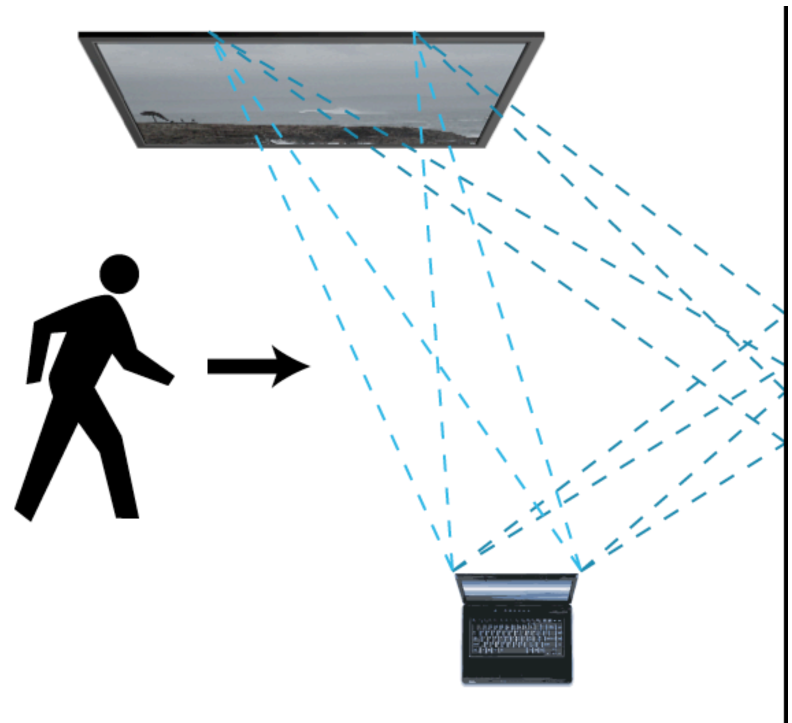
Frequency Domain Results



Recovered Channel	BER	Signal-to-Interference Ratio (dB)
1	$<10^{-6}$	15
2	$<10^{-6}$	12
3	1.2×10^{-5}	10
4	$<10^{-6}$	14

Mm-wave MIMO in Indoor Environments



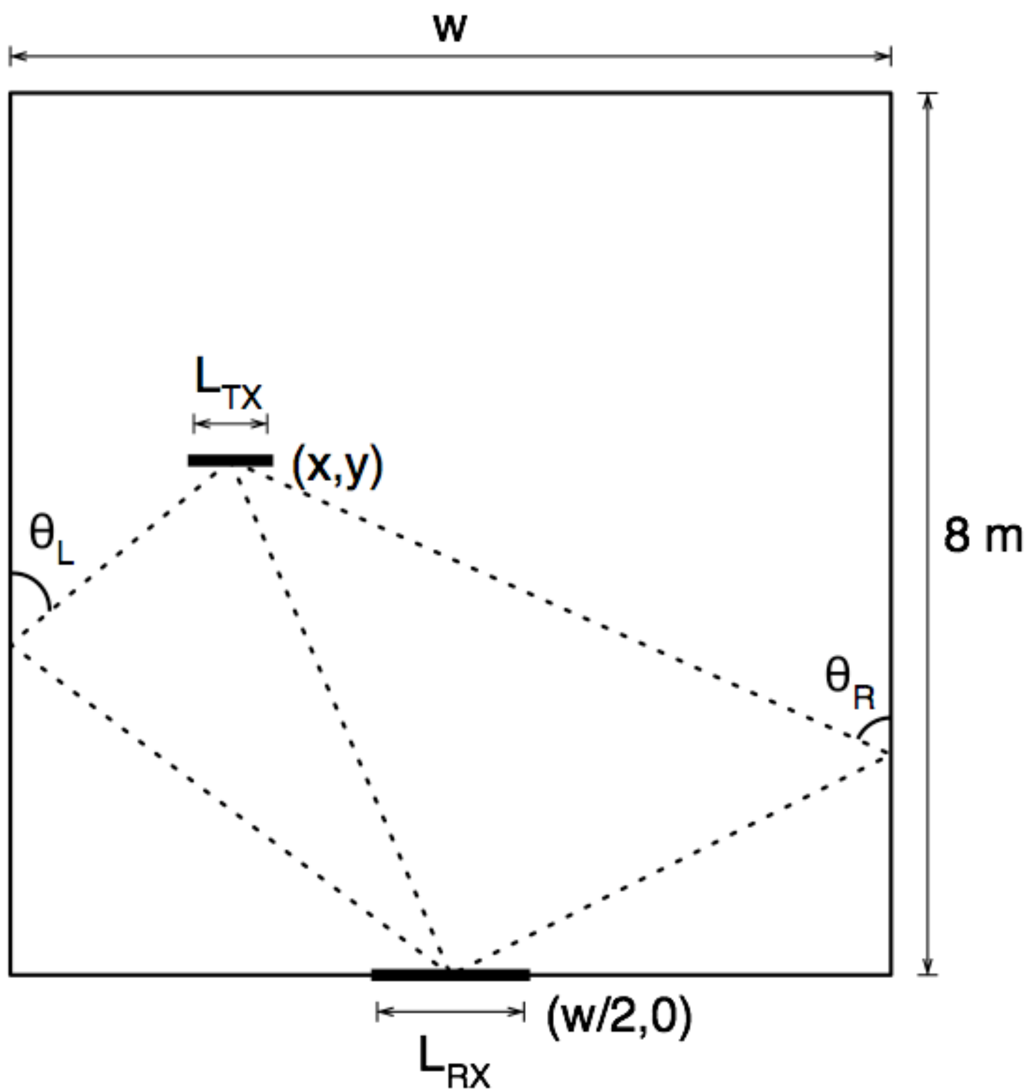


Ideal: Aligned at nominal range

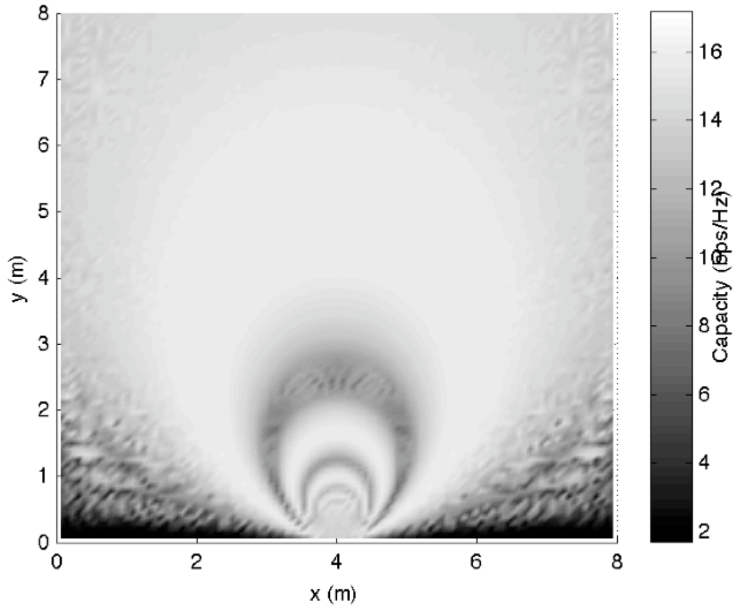
Reality: Misaligned; multipath; blockage

What about blockage and reflections?

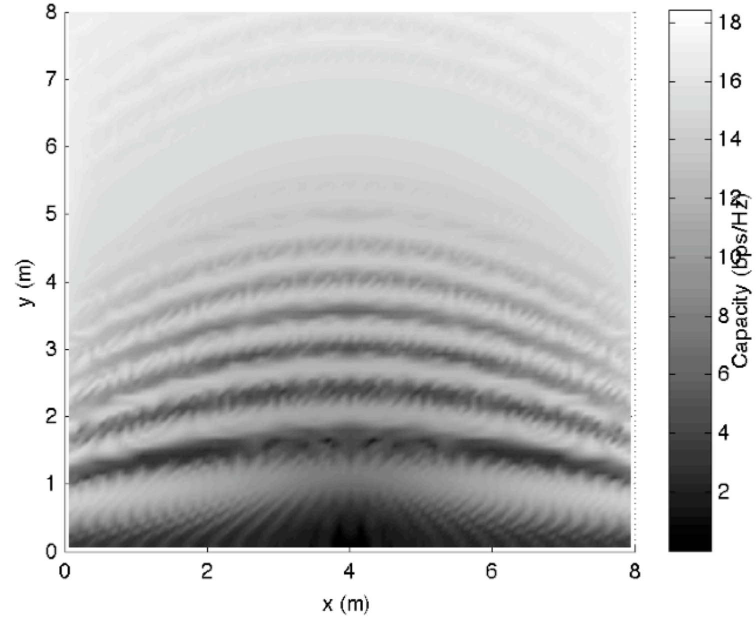
Ray tracing for a 2 x 2 MIMO system



Channel Capacity varies with Rx location



LoS path available



Los path blocked

Variations more drastic when LoS path blocked

Millimeter Wave MIMO Summary

- Successful brassboarding verifies LOS MIMO geometry
  - Novel signal processing architecture for multiGigabit speeds
  - Applies to both indoor and outdoor systems
- For indoor settings…
  - Upto 10 spatial eigenmodes with consumer electronic device form factors
  - Performance highly dependent on propagation geometry
  - Fluctuations can be reduced by adding Rx antennas
- Many interesting design challenges different from conventional MIMO
  - MIMO Processing for multiGigabit systems: beamsteering, spatial multiplexing, space-time coding
  - Alleviating sensitivity to propagation environment by cross-layer adaptation
  - Diversity/multiplexing tradeoffs for a new class of channels

Parting thoughts on 60 GHz networking

- Continues the wireless revolution well beyond 4G
  - Wireless catches up with wires
- Cross-layer system design
  - Networking/signal processing/hardware co-design
  - Coexistence and spatial reuse
- New channel models
  - Multiple antennas routinely available
  - MIMO geometry fundamentally changed by small wavelengths
  - Blockage
- Directional networking
  - Limited reliance on carrier sense
  - Coordination rather than interference is the bottleneck
- Challenges in multiGigabit baseband design
  - Addressing the ADC bottleneck