# The Road to MultiGigabit Wireless
# Challenges in Millimeter Wave Networking

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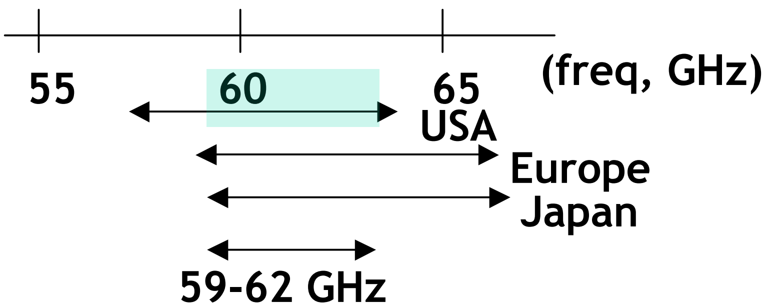
# The next phase of the wireless revolution?

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




Common unlicensed spectrum

*Oxygen absorption band*

*Ideal for short-haul multihop*

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

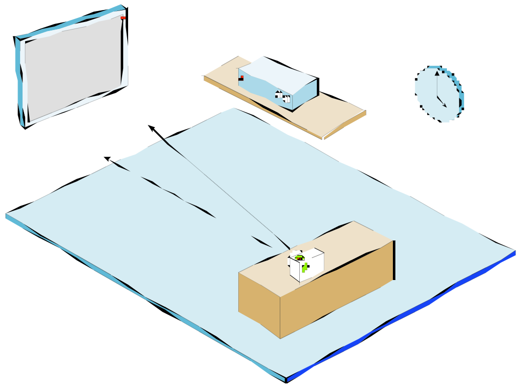
*Industry is getting serious about 60 GHz*

- *ECMA, Wireless HD, WiGig*

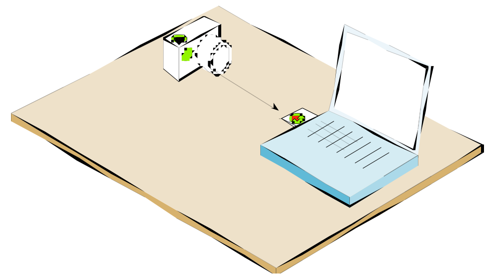
*Two major research challenges*

- *Hardware/signal proc. innovations for multiGigabit comm*
- *System-level innovations for directional networking*

# Indoor mm wave systems at 60 GHz



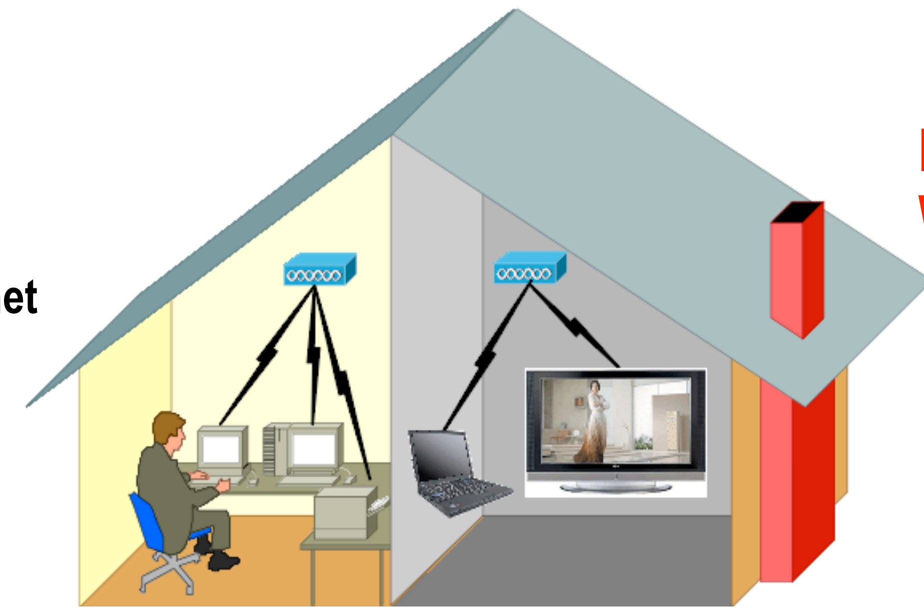
WirelessHD



Wireless USB/Sync and Go

IEEE 802.15.3c
WPAN

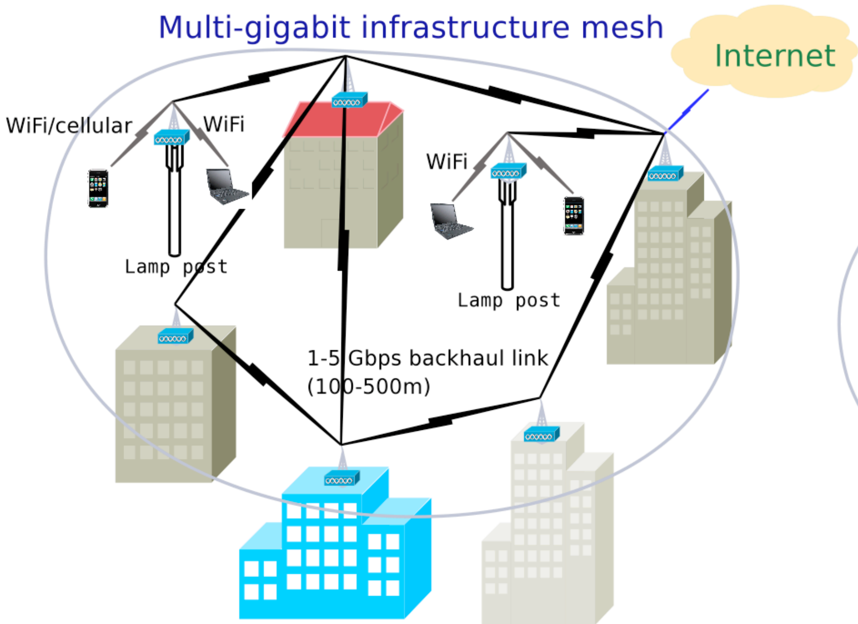
Wireless Gigabit Ethernet

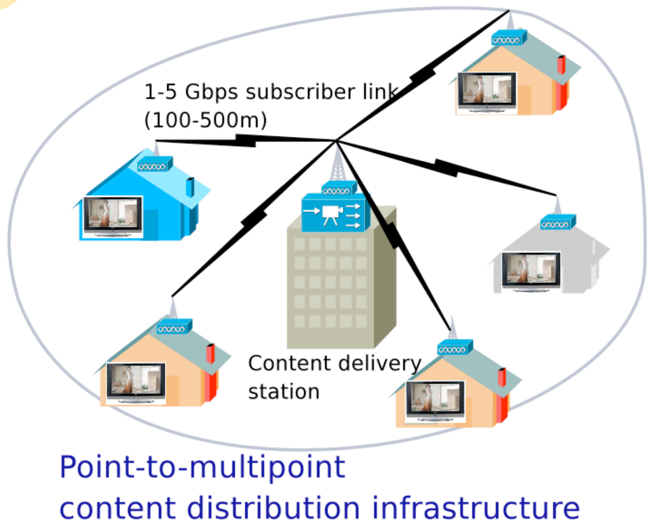


IEEE 802.11 VHT
WLAN

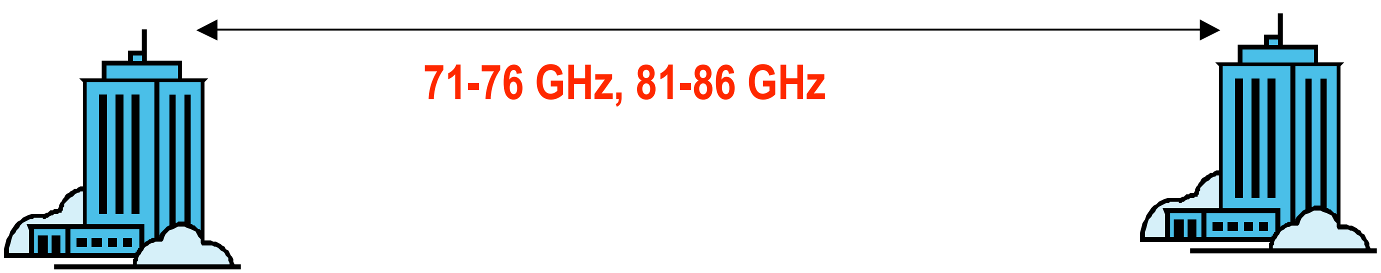
# Outdoor mm wave systems

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




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



# Research Directions

- Directional networking
  - When are wireless links like wires?
  - How to deal with deaf neighbors?
  - Blockage is routine: must steer around
- Transceiver architectures for multiGigabit comm
  - The ADC bottleneck
  - MIMO processing
- Channel modeling
  - Diversity/multiplexing with sparse multipath
- Hardware
  - Interaction of antenna geometry with form factor
  - Baseband/RF co-design

Today's talk

Main take-away: MM-Wave Design is XLayer to the Xtreme

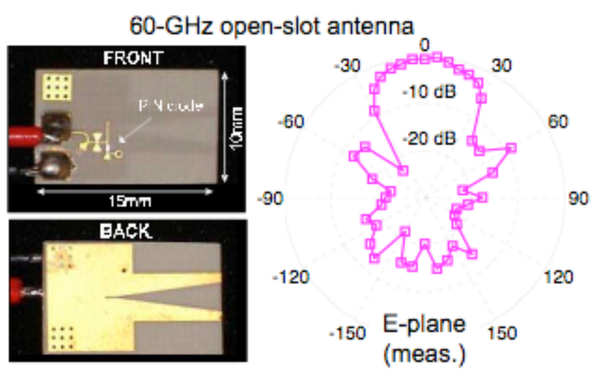
# Acknowledgements


- Millimeter wave MIMO hardware prototype
  - Dr. Colin Sheldon, Dr. Munkyo Seo, Eric Torkildson, Prof. Mark Rodwell
- Directional networking
  - Dr. Sumit Singh, Federico Zillioto, Prof. Raghu Mudumbai, Prof. Elizabeth Belding, Prof. Mark Rodwell
- Signal processing for multiGigabit comm
  - Dr. Jaspreet Singh, Sandeep Ponnuru, Feifei Sun, Stefan Krone, Prof. Onkar Dabeer
- Millimeter wave channel modeling
  - Eric Torkildson, Hong Zhang

# Directional Networking

# Mm wave links are inherently directional

- Omnidirectional links are a truly bad idea!
  - $\lambda^2$ 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 needed than 5 GHz
  - Circuit board antenna arrays can produce highly directive links
  - Electronic steerability usually essential, but need not be perfect



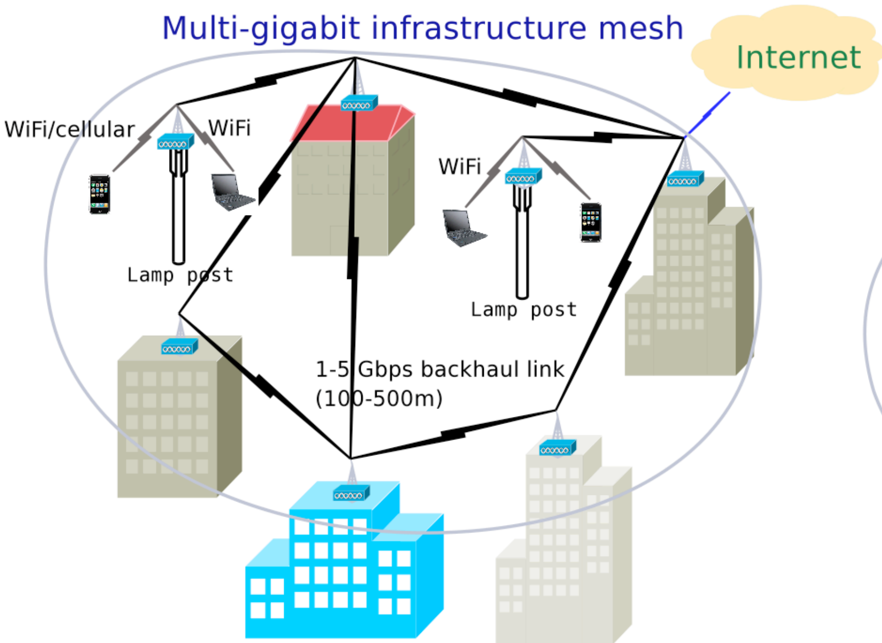

Slot antenna designed at UCSB for imaging sensor nets project

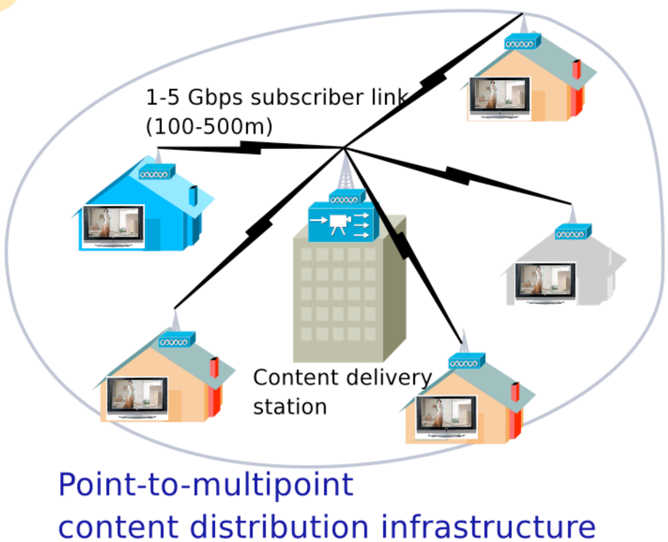
# MAC design considerations

- Deafness means we cannot count on carrier sense
  - Highly directional links make it hard to snoop on neighbors
- Can exploit reduced spatial interference to simplify MAC
- Blockage occurs routinely in indoor settings
- Today: Outdoor mesh networks
  - Step 1: Is a pseudowired model justified?
  - Step 2: How to do lightweight coordination despite deafness?

# MAC Design Example
# Outdoor Millimeter Wave Mesh Networks

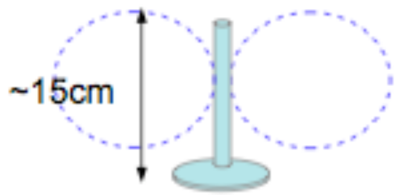
# Instant broadband infrastructure



# Omni-coverage yet highly directional nodes

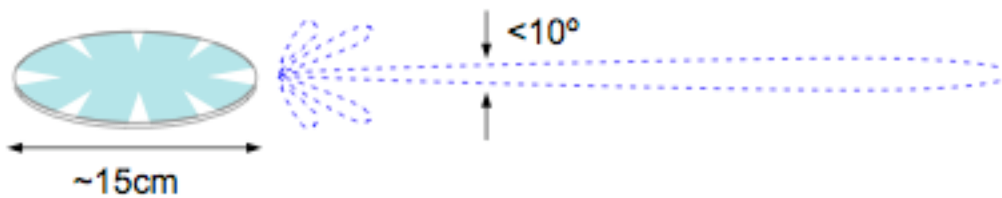
2.4 GHz
Wi-Fi antenna
D= 5dBi

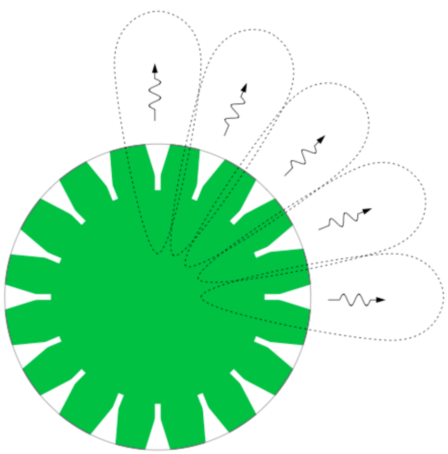



$$D \equiv \frac{\text{Max. power density}}{\text{Average power density}} = \frac{\pi}{\lambda^2} A_{eff} \propto f^2$$

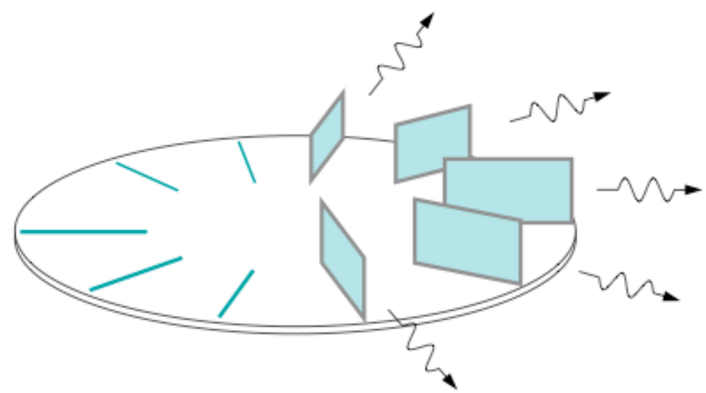
$$D \approx \frac{40{,}000}{\theta_{azimuth}\theta_{elevation}}$$

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



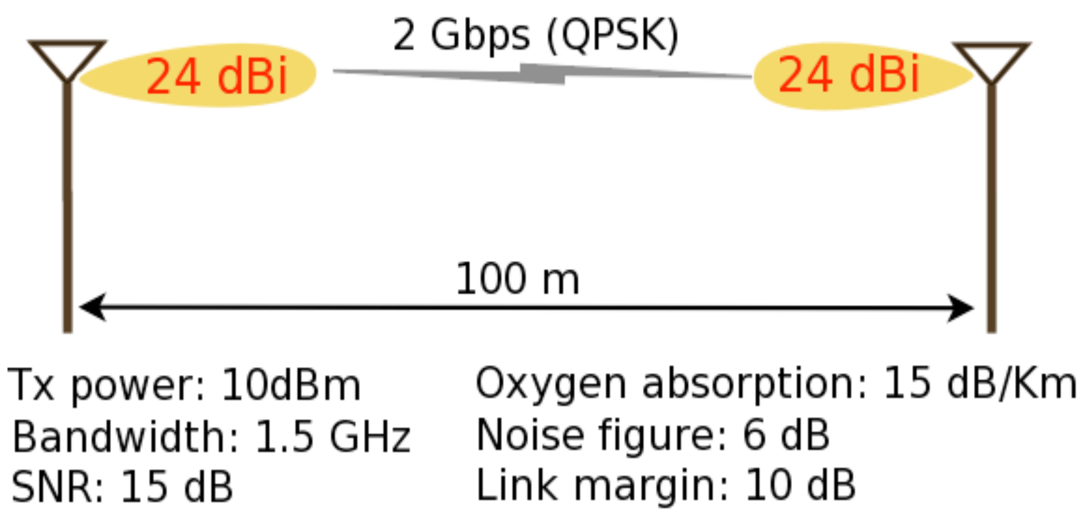



TOP VIEW



Reconfigurable circular array
Total 10 angular slots; 5 slots installed

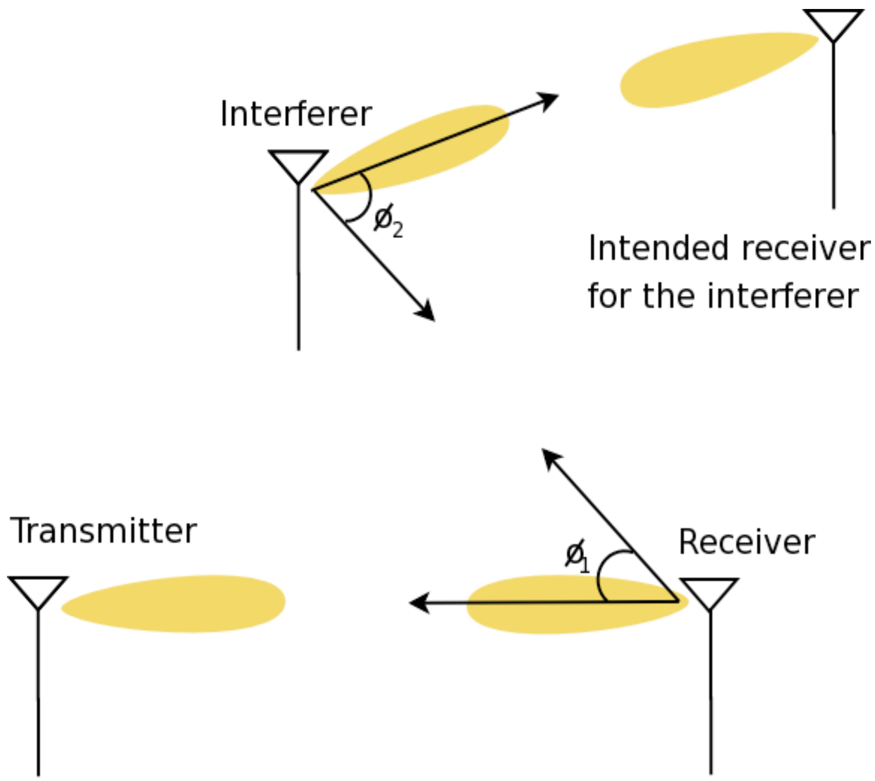
# Nominal Link



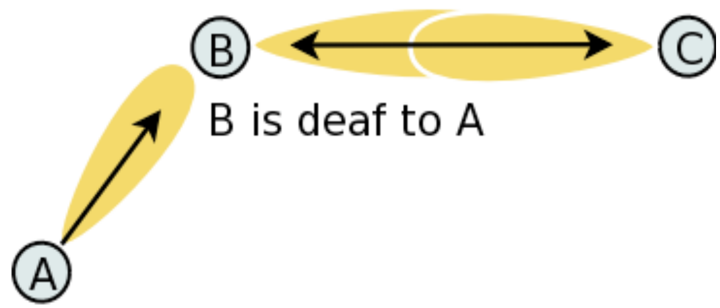

**Caveat: can have significant fading due to ground and wall reflections**
**(need to explore diversity strategies)**
**Can get higher range and rate by using higher directivities**
**(need hardware architectures for steerable arrays with large number of elements)**

# Interference and Deafness

### Interference with directional links




### Deafness

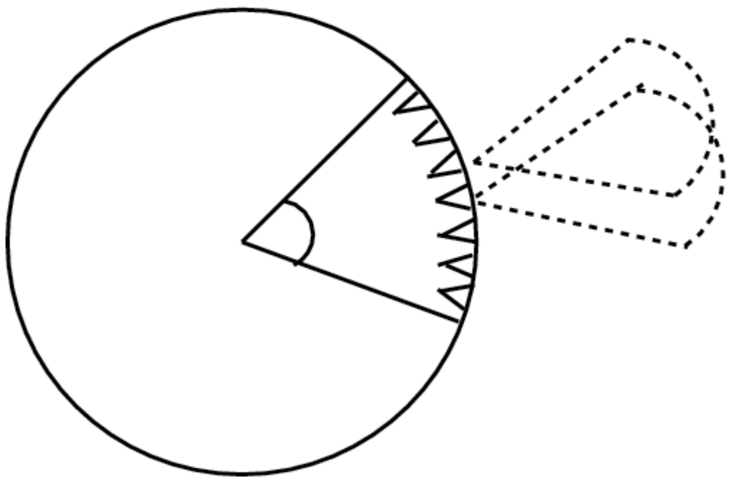


# Key design issues

- 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
- Step 1: Understand spatial interference

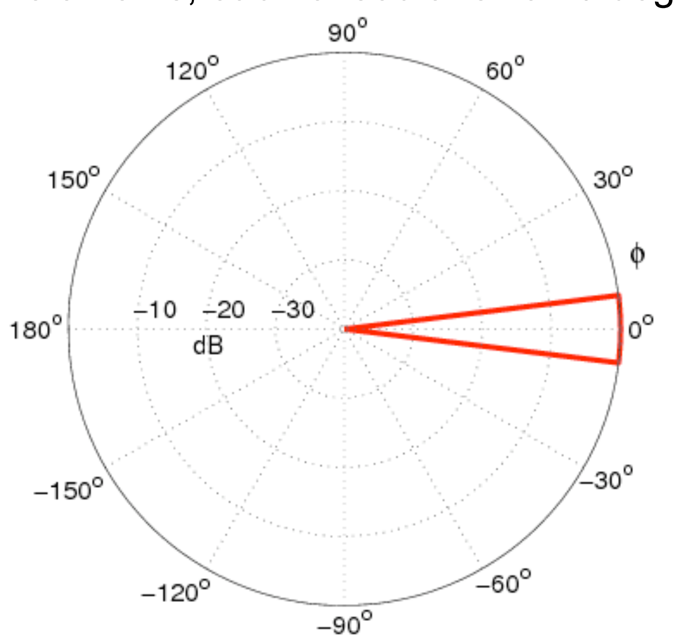
Mudumbai, Singh, Madhow: Infocom 2009

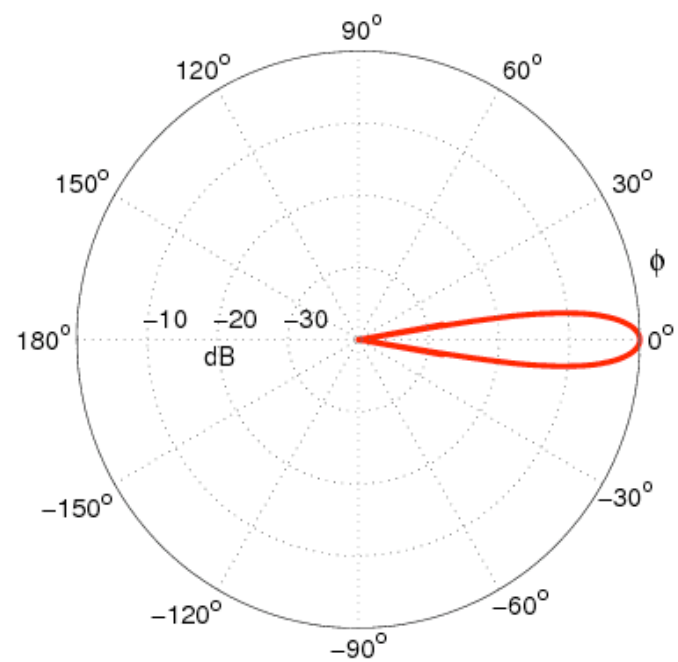
# Modeling beam patterns



Approximating a circular array of slot antennas as a uniform linear array of flat-top elements.

Gain pattern for a flat-top antenna (beam angle 14.4 degrees) and a 12 element linear array of flat-top elements, each of sector size 20 degrees. Antenna gain in both cases: 24 dBi



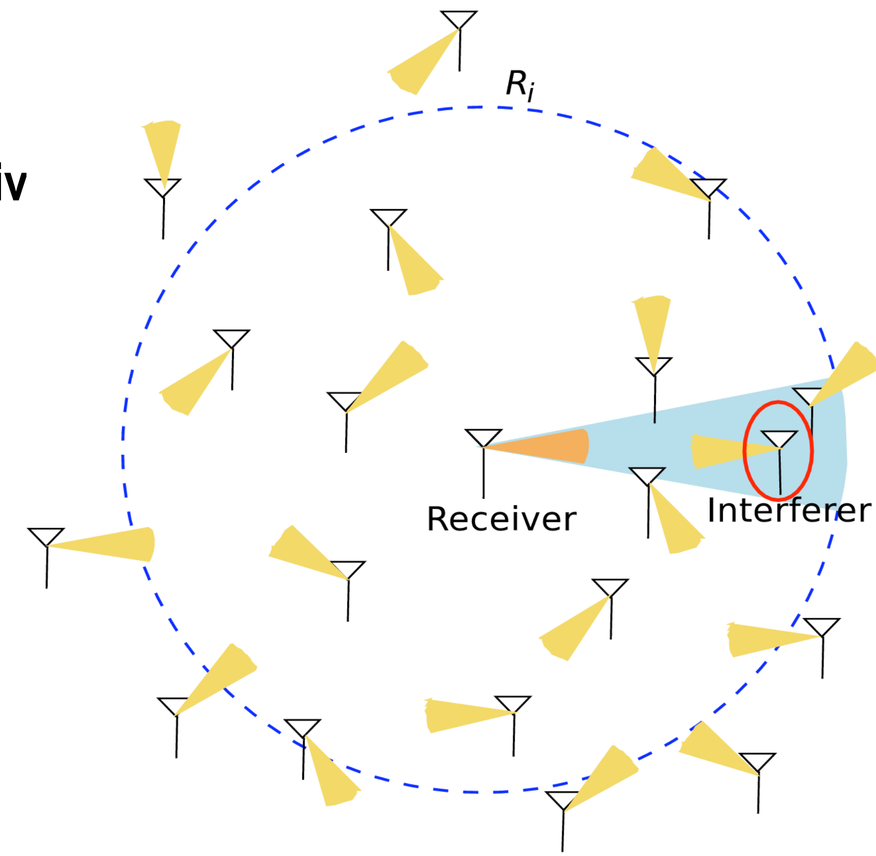



# Interference under the protocol model

- 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 receiv

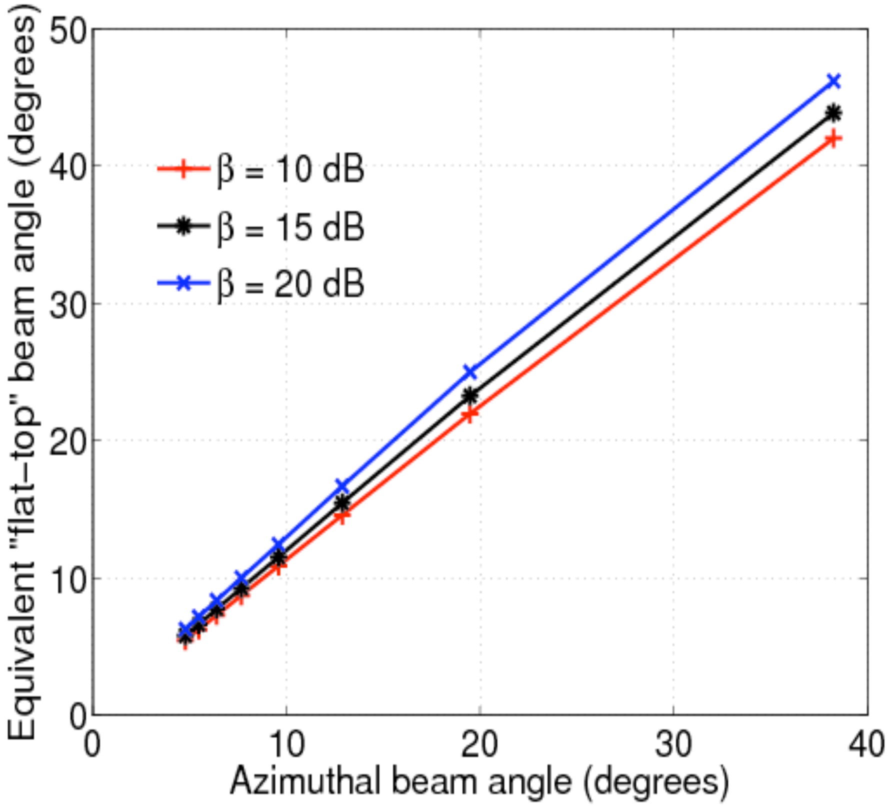
**Collision Probability** $$1 - e^{-\lambda \beta A_c}$$

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

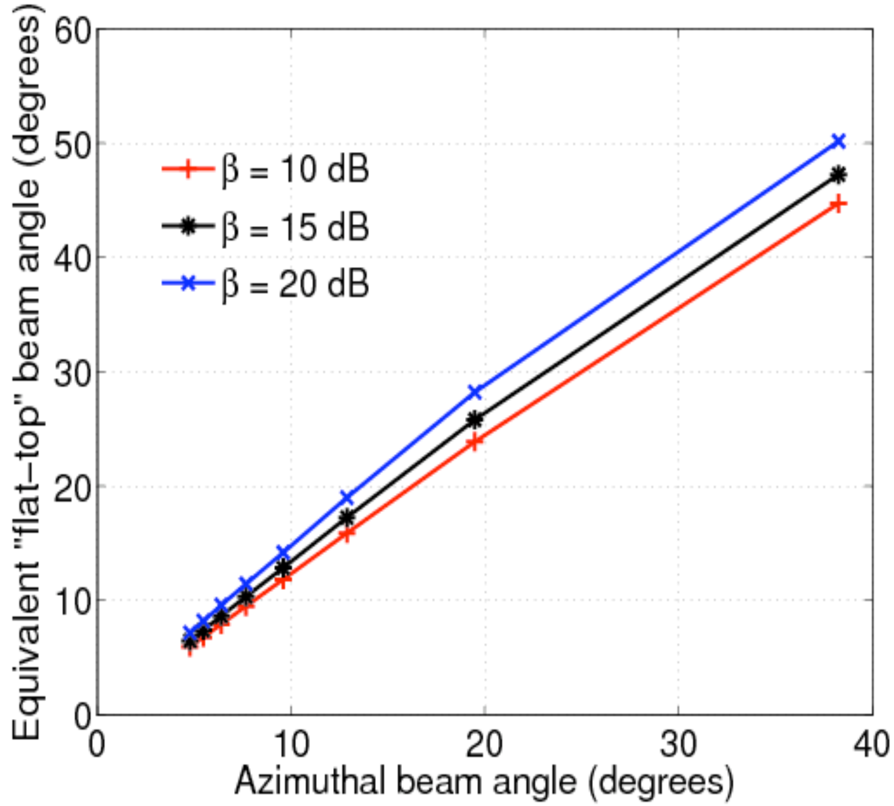



β : SINR threshold
λ : density of transmitting nodes
ΔΦ: (azimuthal) beamwidth
$R_0$ : nominal link range
$R_i$ : interference range
α : atmospheric absorption coefficient

# Generalizes to arbitrary antenna patterns




Nominal link 100m

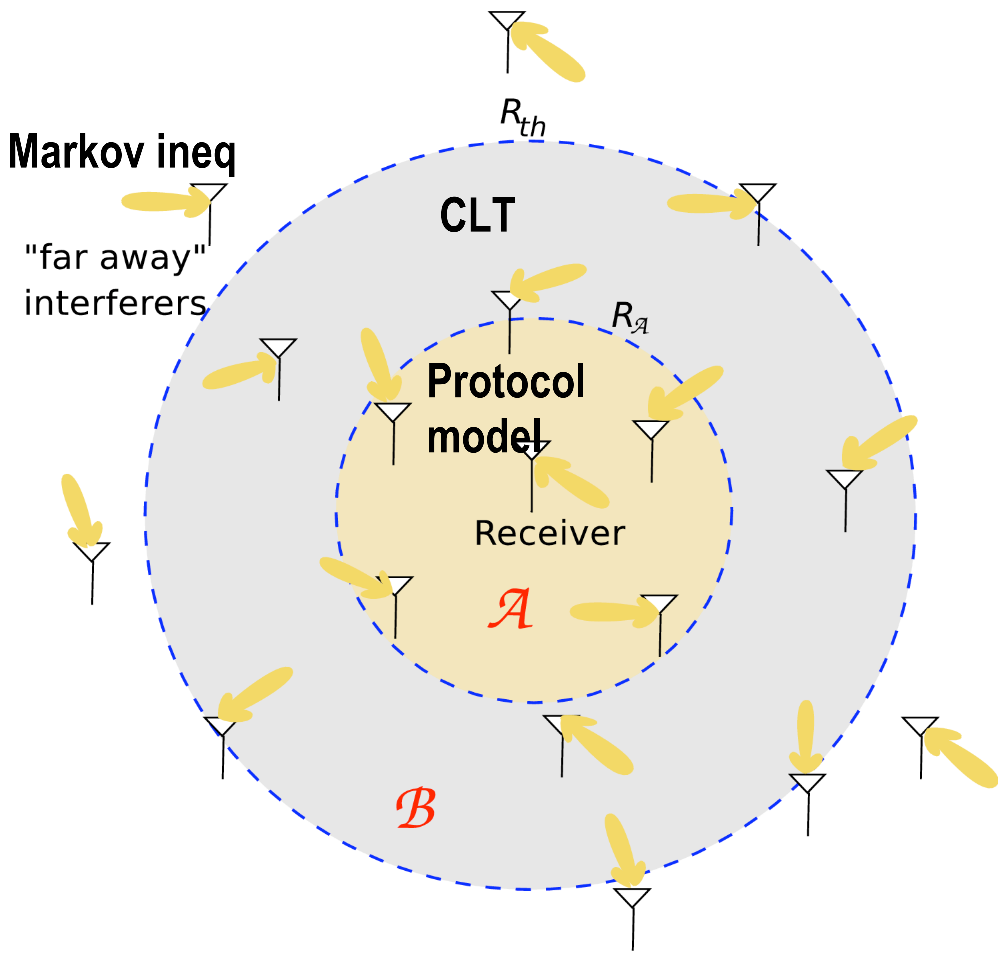



Nominal link 200m

General antenna patterns can be modeled using equivalent flat top beam angle

# Physical model

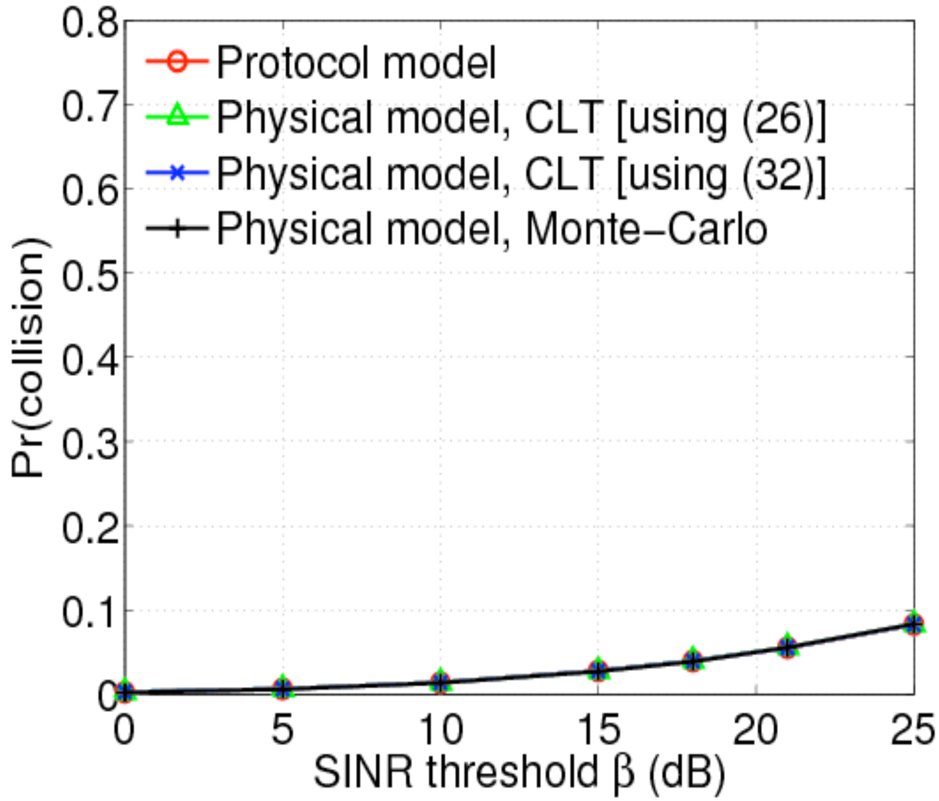
**Collision prob = P[sum interference exceeds threshold]**



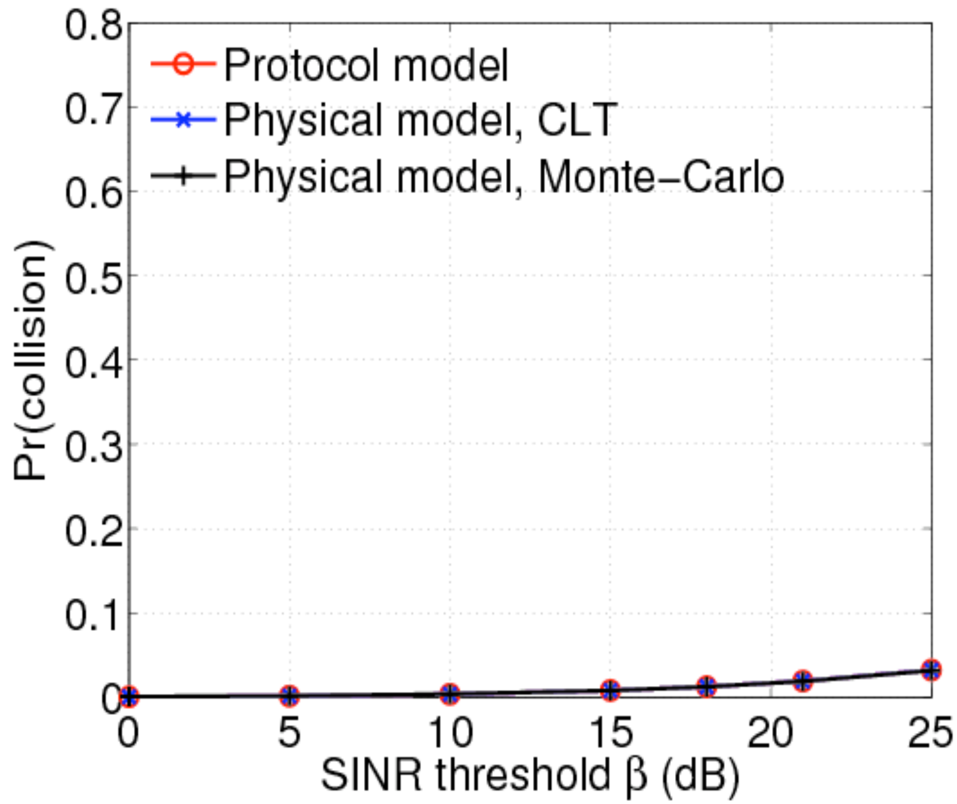

**Approach:**

1) Exploit oxygen absorption to bound effect of far-away interferers using Markov ineq
2) Use CLT or Chernoff bound plus protocol model for nearby interferers

# Collision probabilities (sparse network)



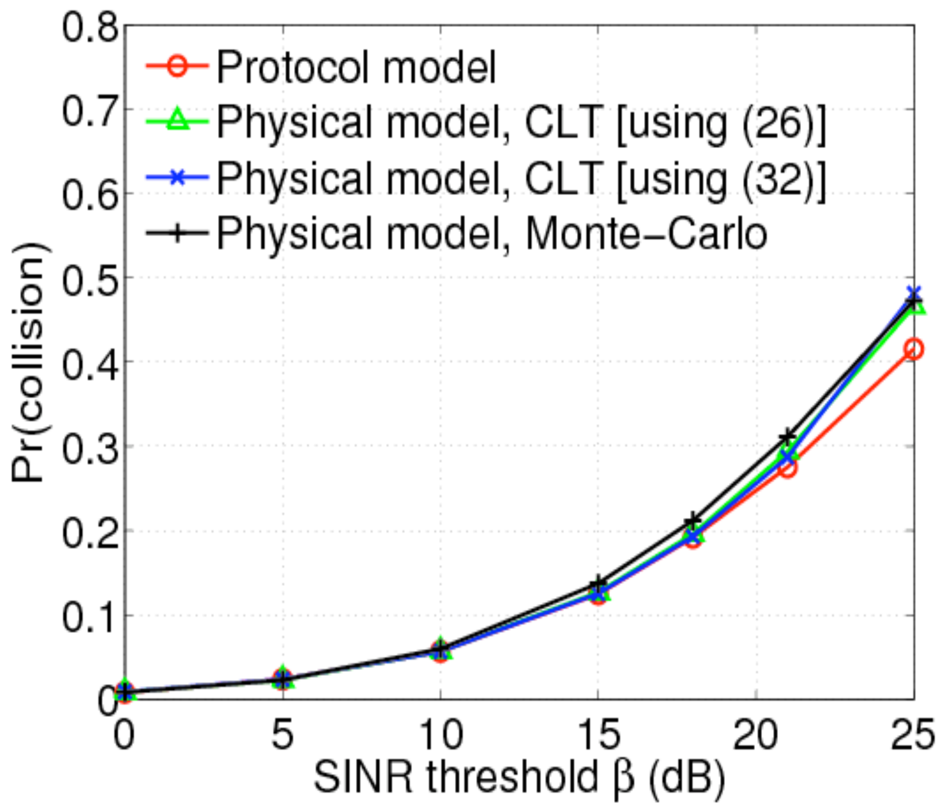

Flat-top antenna



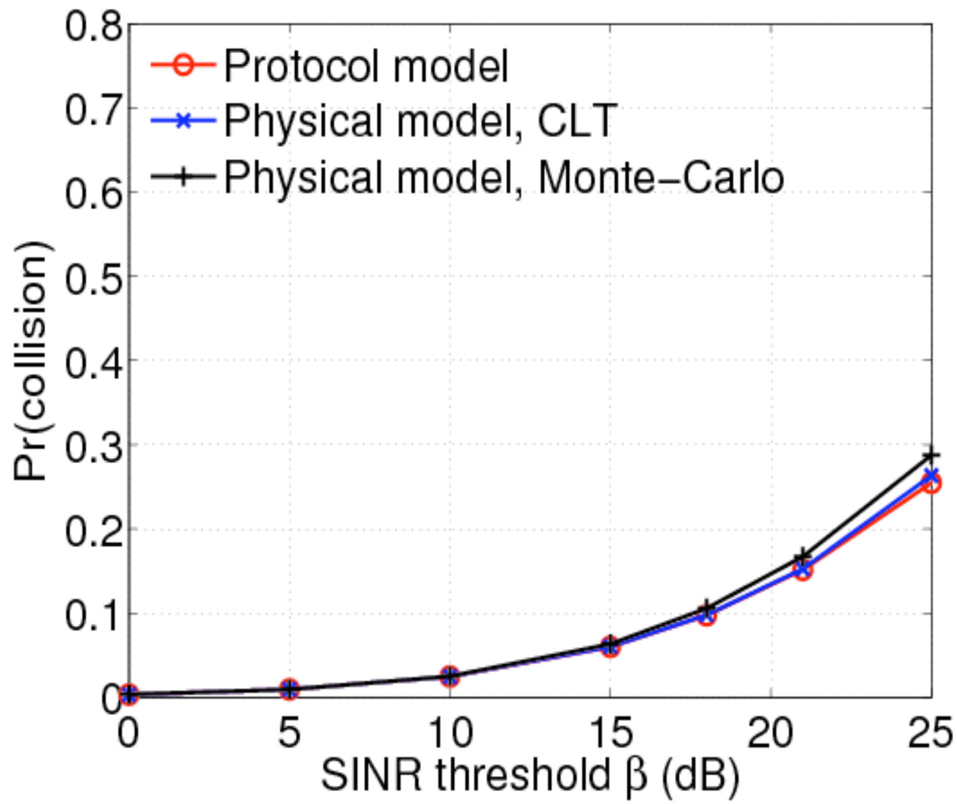

Linear array

Link range R =200m, $\pi\rho R^2=\pi$

# Collision probabilities (dense network)



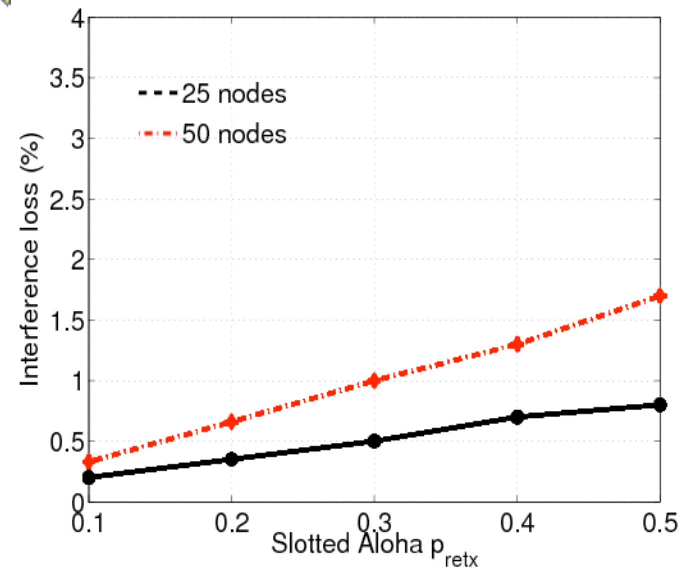

Flat-top antenna

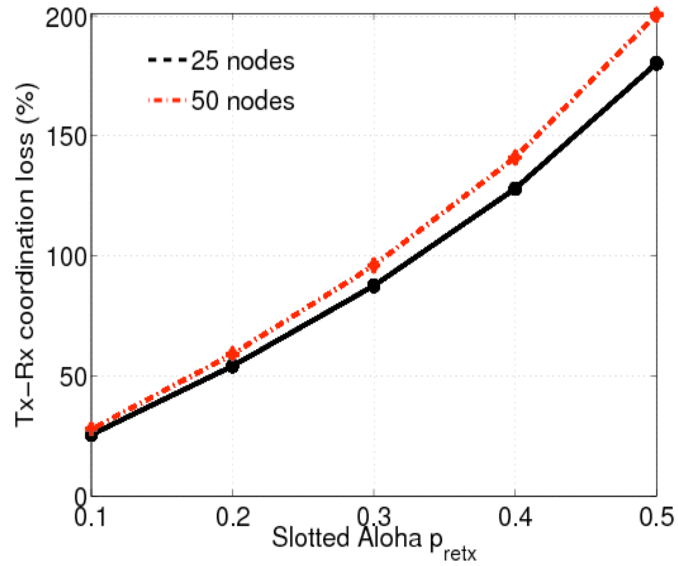



Linear array

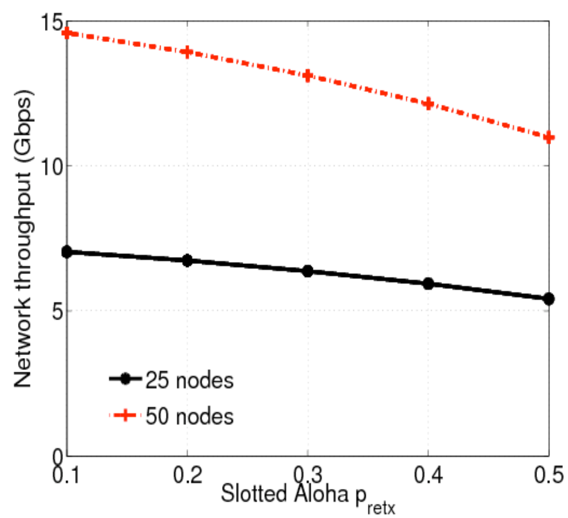
Link range R =100m, $\pi\rho R^2$=5.2 (Pr(connected network) = 0.99)

# Coordination is the bottleneck



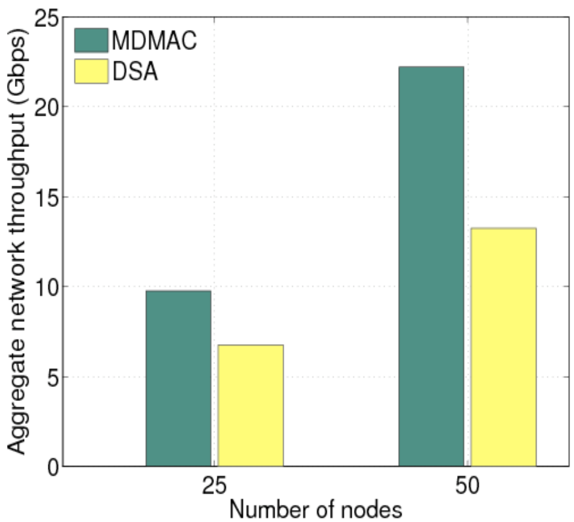

**Collision losses order of magnitude smaller than losses due to failed coordination**



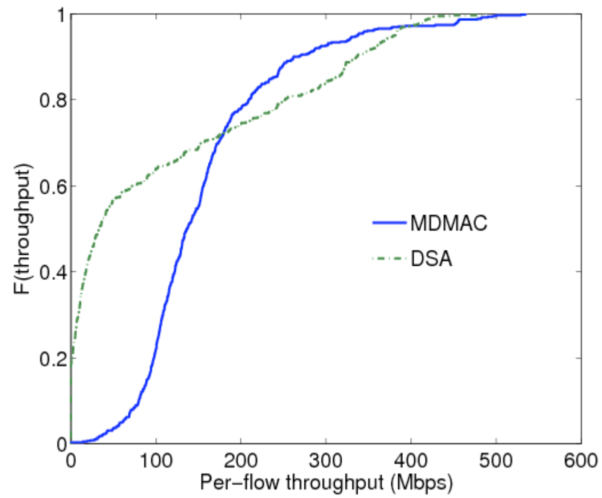
# Recap of MAC Design Criteria

- 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
- How to maintain slotting in lightweight fashion?
  - Work in progress

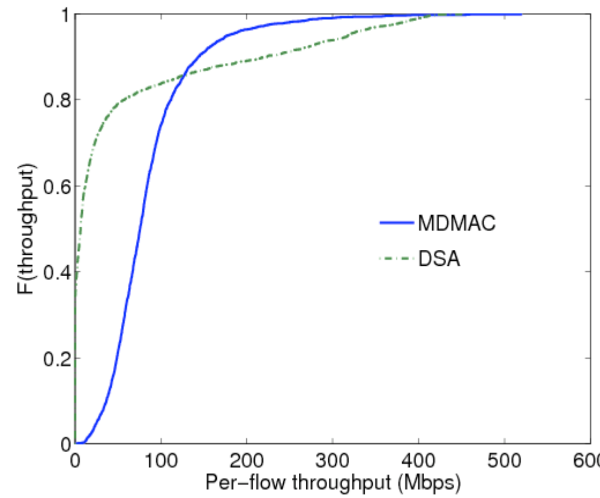
# Lightweight coordination using memory and learning




Aggregate network throughput




25 node random topologies



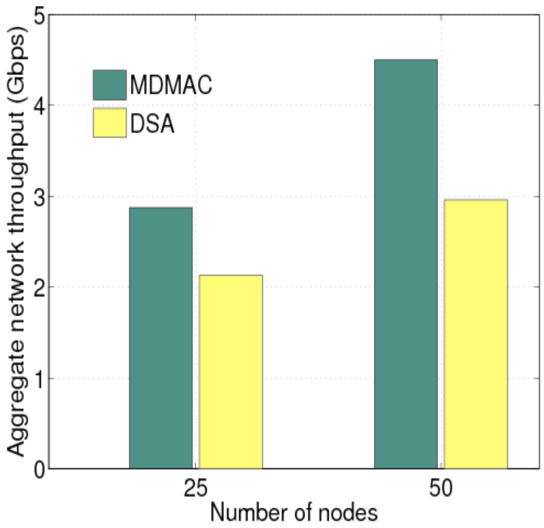

50 node random topologies

**Saturated traffic model**

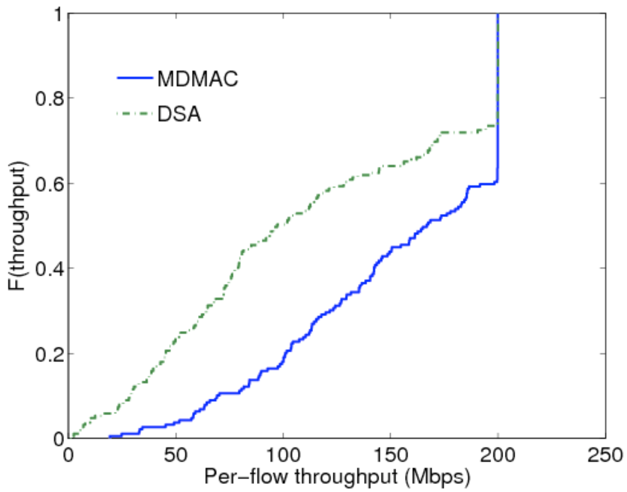
- Proposed MAC has ~40% higher aggregate network throughput and fairer allocation than slotted Aloha
- Approaches more than 80% of maximal matching style benchmarks

Singh, Mudumbai, Madhow, Infocom 2010

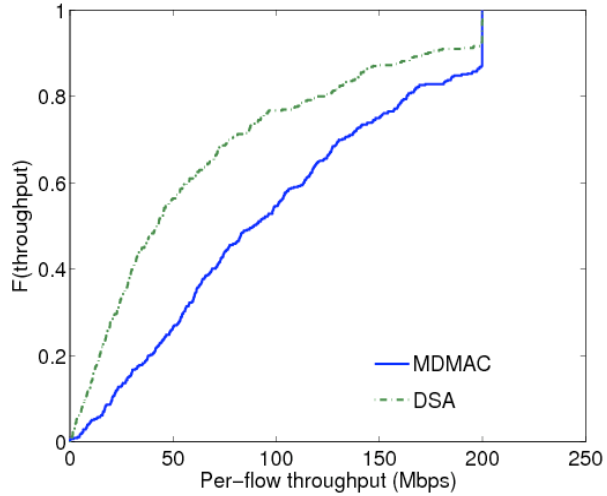
# Mesh traffic with randomly chosen source-sink pairs



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

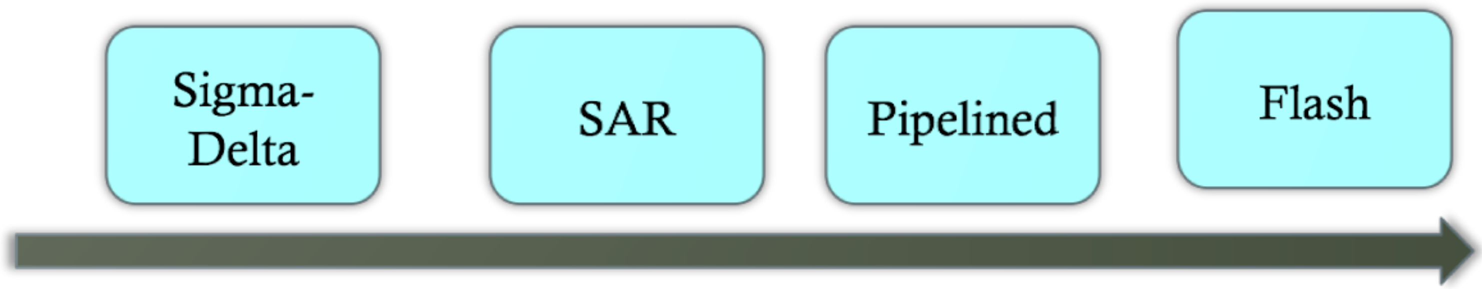
# Directional networking take-aways

- Physical layer modeling critical to determine design goals
  - When are antenna beamwidths small enough to warrant pseudowired model
- Novel design approach needed for pseudowired links
  - MAC emphasis shifts from interference management/avoidance to scheduling
  - Learning as a mechanism for lightweight implicit coordination
- Many interesting issues
  - Synchronization: lightweight maintenance of time slotting
  - Omni-coverage yet highly directional nodes are an interesting hardware challenge
  - Interplay of form factor, antenna design, partitioning of RF/IF/baseband functionalities
  - Cognitive operation: spatial reuse and co-existence with and without explicit coordination

# The ADC Bottleneck: Recent Results

# The importance of “mostly digital”

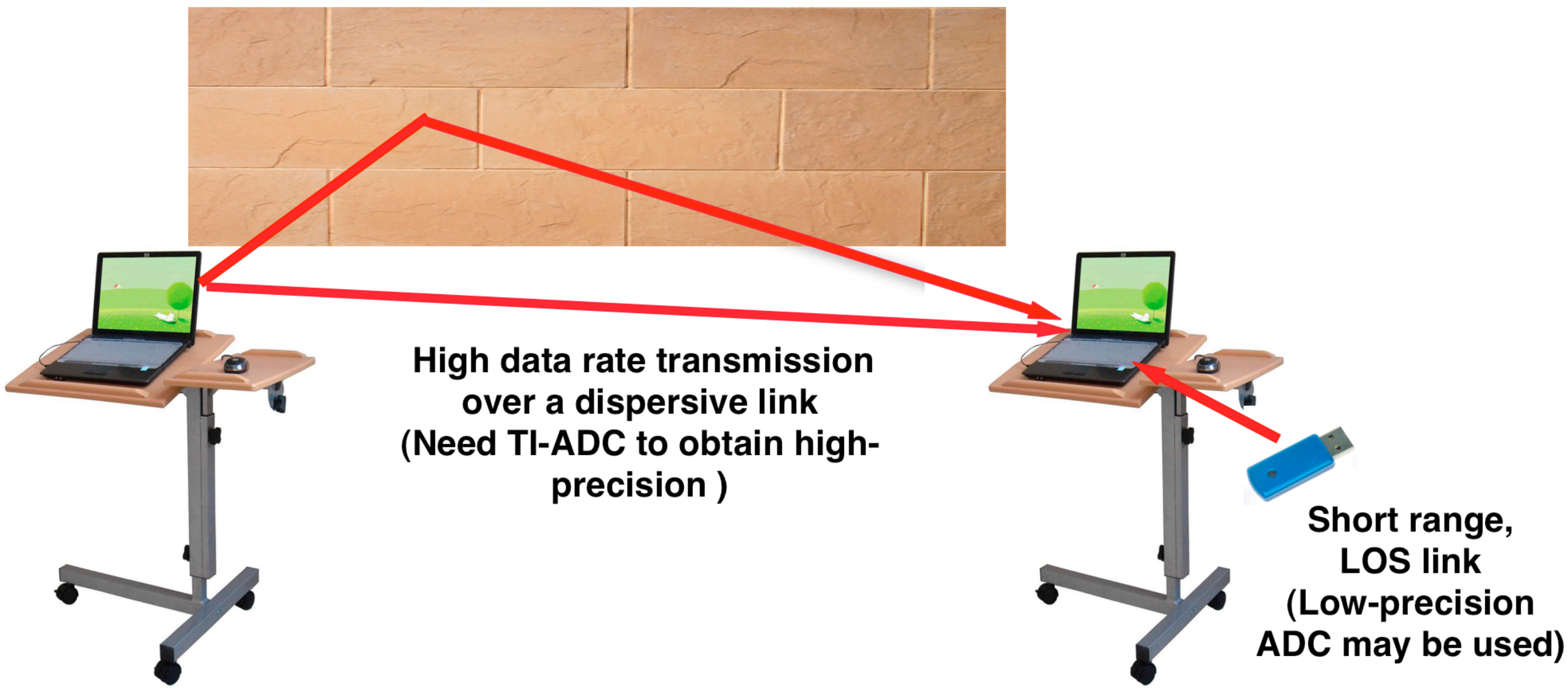
- Moore’s law has enabled cellular and WiFi revolution
- Can it continue to work its magic at multiGigabit speeds?
- The bottleneck is the ADC




| | | | | |
|---|---|---|---|---|
| Speed | 100 KHz | 10MHz | 100MHz | 1 GHz |
| Resolution | 24 bit | 18 bit | 15 bit | 8 bit |
| Power | 1-10mW | 10-100mW | 100mW-1W | 1-10W |

High-speed, high-precision ADCs are not available/too costly/too power-hungry

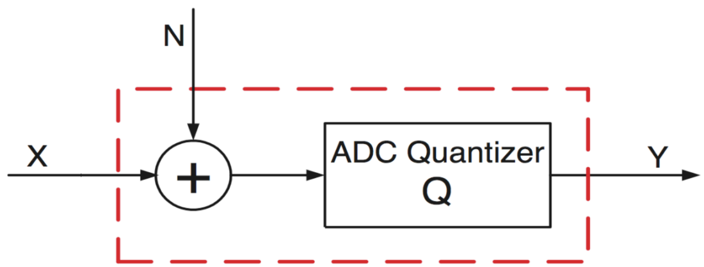
# Two complementary scenarios




Today: What can we do with low-precision ADC?

# Low-precision ADC: recap of earlier results

**Ideal Nyquist-sampled system**




J. Singh and Madhow, ISIT 2008, TCOM (to appear)

**Capacity achievable with discrete input**

**At most K+1 points for K quantization bins (K points appear to be enough)**

**Uniform PAM/ML decision boundaries near-optimal**

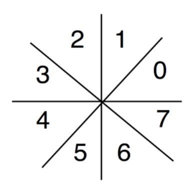
**10-15% reduction in spectral efficiency for moderate SNR**

**Joint carrier sync and data demodulation**

$$\boxed{Z_l = \mathrm{Q}(S_l e^{j\Phi} + N_l)}, \; l = 0, 1, \cdots, L-1$$

$$\mathrm{Q} : \mathbb{C} \rightarrow \mathcal{K} = \{0, 1, \cdots, K-1\}$$

$$\mathrm{Q}(c) \;=\; \lfloor \arg(c) | (\tfrac{2\pi}{K}) \rfloor$$




**Symmetry causes trouble**

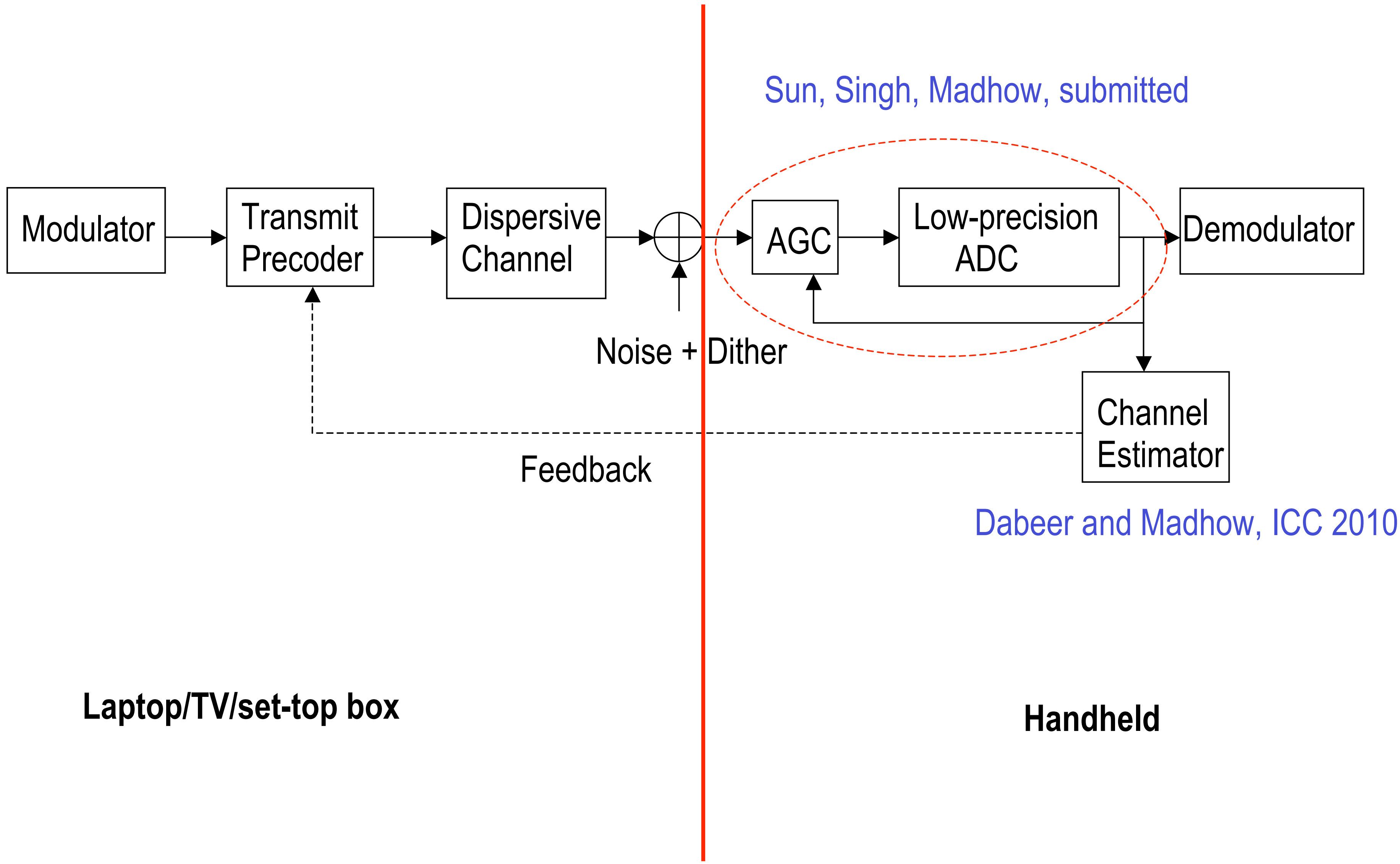
**Can break at Tx by dithering**

**Can break at Rx by asymmetric quantization**

**Can approach unquantized performance**

J. Singh and Madhow, ISIT 2009

# Low-precision ADC: possible transceiver architecture




**Asymmetric link with power-constrained receiver**

# AGC with low-precision ADC: set-up

**4-PAM**

**2-bit ADC with fixed thresholds**

**Analog LNA brings power within 10 dB range**

**Digital AGC matches signal levels to ADC thresholds**

**Use ADC output to estimate scaling required**

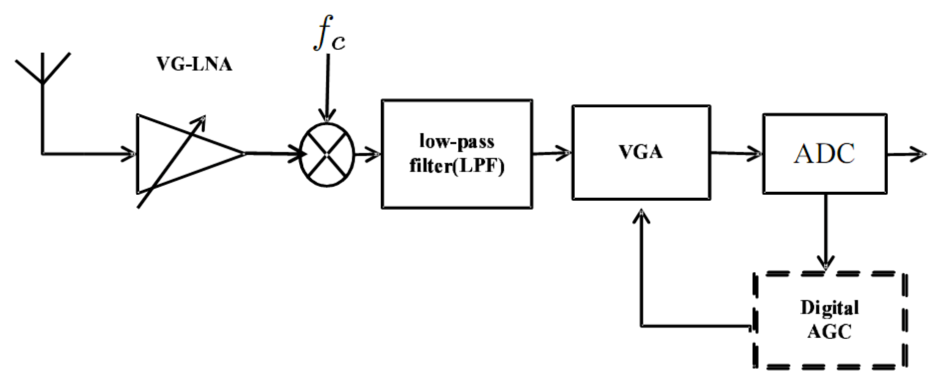
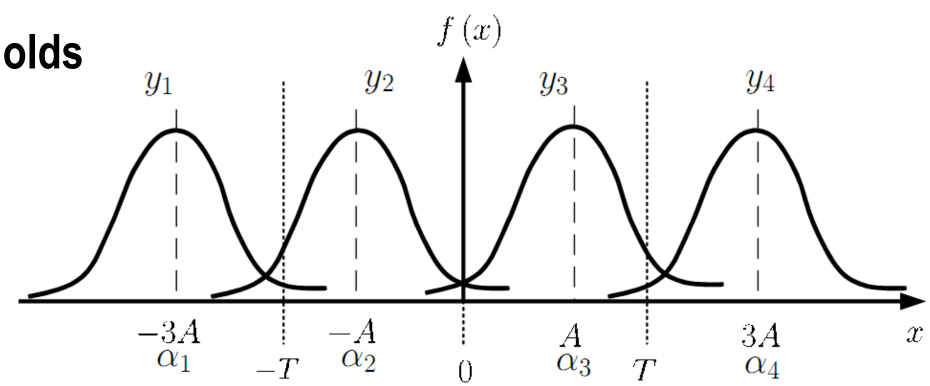



Fig. 1 A typical receiver front-end

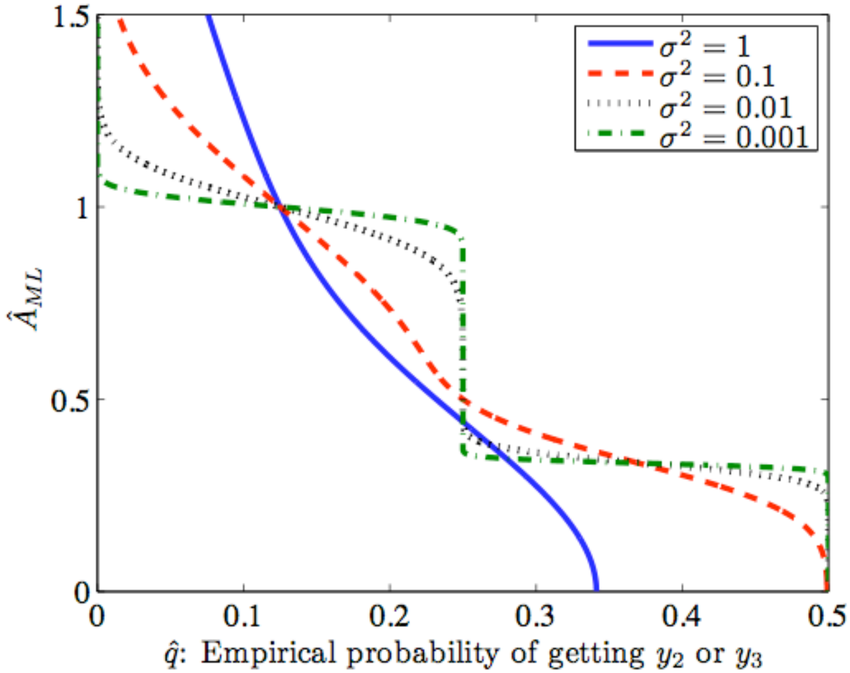



$$q_j(A) := \mathrm{P}(y_j \mid A) = \frac{1}{M}\sum_{i=0}^{M}\left(Q\left(\frac{t_{j-1}-\alpha_i(A)}{\sigma}\right) - Q\left(\frac{t_j-\alpha_i(A)}{\sigma}\right)\right)$$

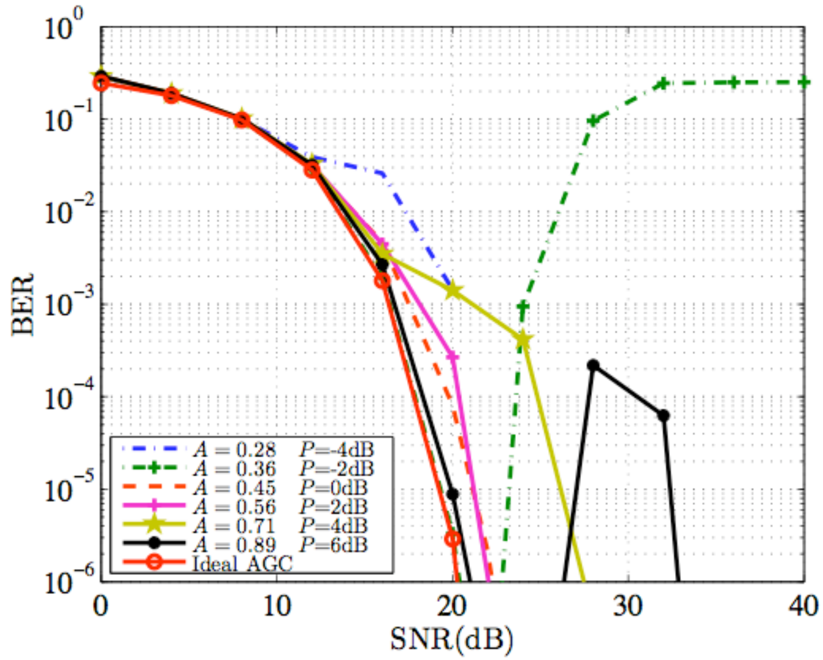
Fig. 2 Conditional probability density functions of 4-PAM and 2-bit quantizer.

# ML estimate bombs at high SNR

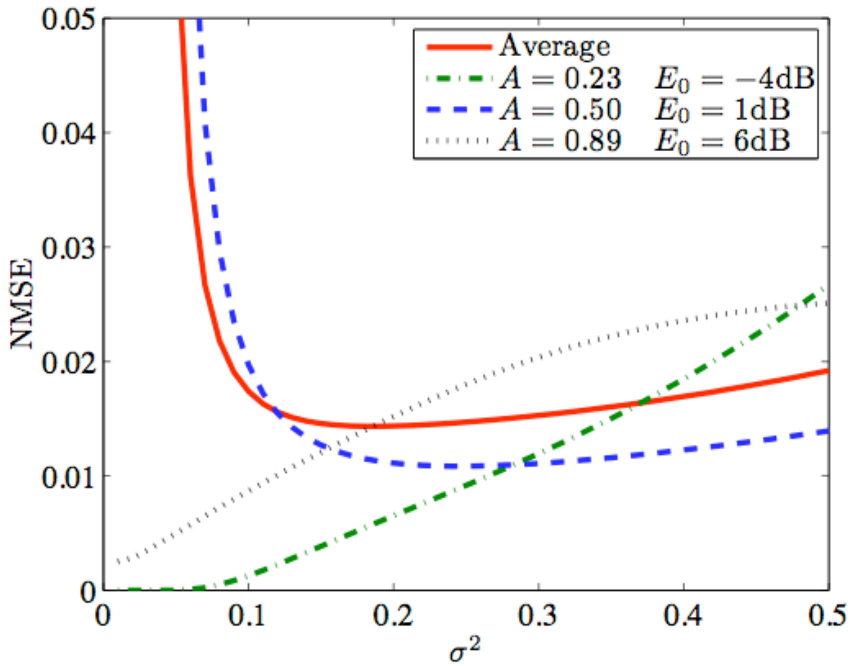
ML estimate as a fn of empirical probs

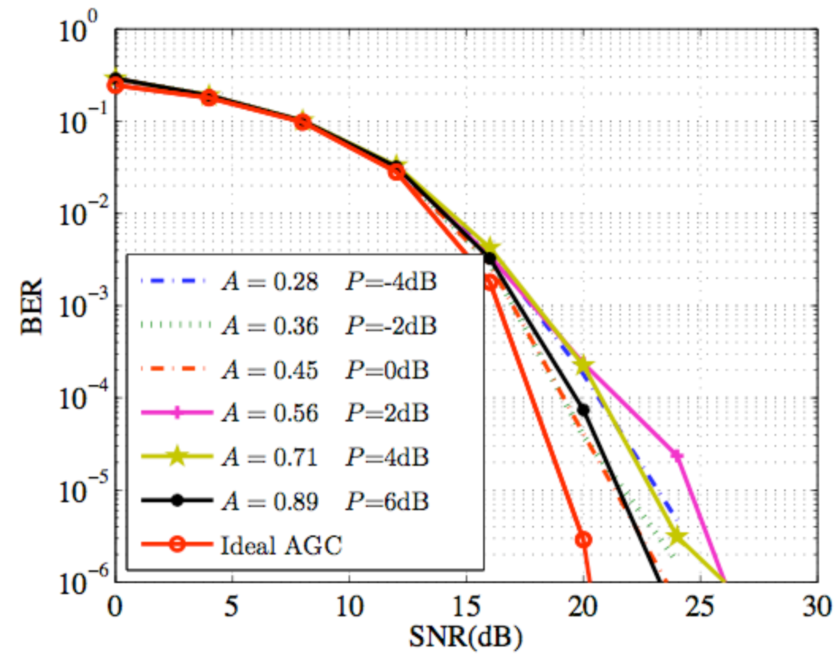



Horrible performance at high SNR



# Dither to achieve desired operating point




$$\mathrm{NMSE}(A) = \mathrm{E}\left[\left(\frac{\Delta A}{A}\right)^2\right] \approx \frac{\mathrm{E}\left[(\Delta q)\right]}{A^2}\left(\frac{\partial q}{\partial A}\bigg|_A\right)^2$$
$$= \frac{q(1-2q)}{2NA^2\left(\frac{\partial q}{\partial A}\big|_A\right)^2}.$$

**AGC based on dithered ML estimate works at high SNR**

# Take-aways on low-precision ADC

- May be interesting in near-LOS or asymmetric settings
- Dithering is crucial for most signal processing algorithms
  - At transmitter for block noncoherent model
  - At receiver for channel estimation and AGC
- Most theoretical and practical issues remain open
  - Algorithms for timing sync, carrier sync
  - Role of feedback and precoding
  - Shannon theory for models of increasing realism

# Conclusions

- 60 GHz is the next frontier in wireless research
  - Fundamental problems in communication theory and signal processing
  - Novel approaches to networking
  - New channel models and their consequences
  - Unavoidably cross-layer
- Needs engagement of a broad community of researchers
  - Comm, signal processing, hardware, network protocols


**Important dates**

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