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Cockrell School of Engineering

Millimeter Wave Cellular Channel Models for System Evaluation

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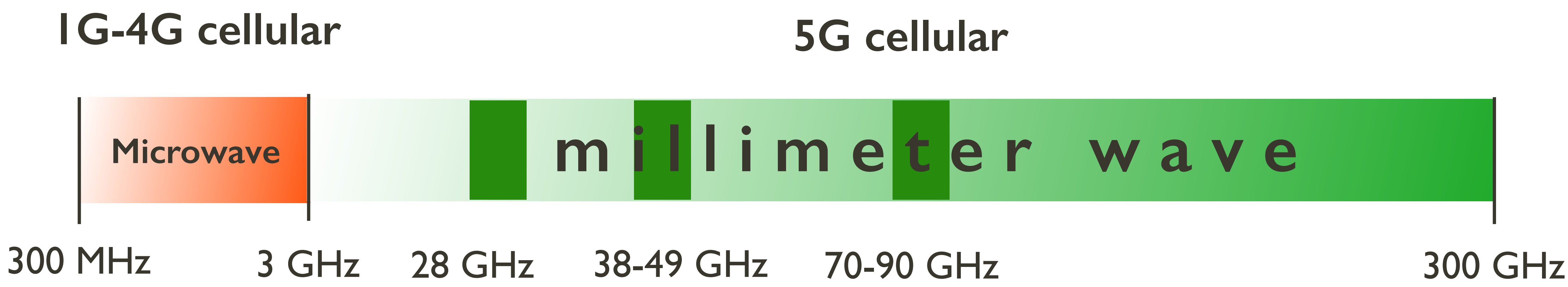
Why mmWave for Cellular?

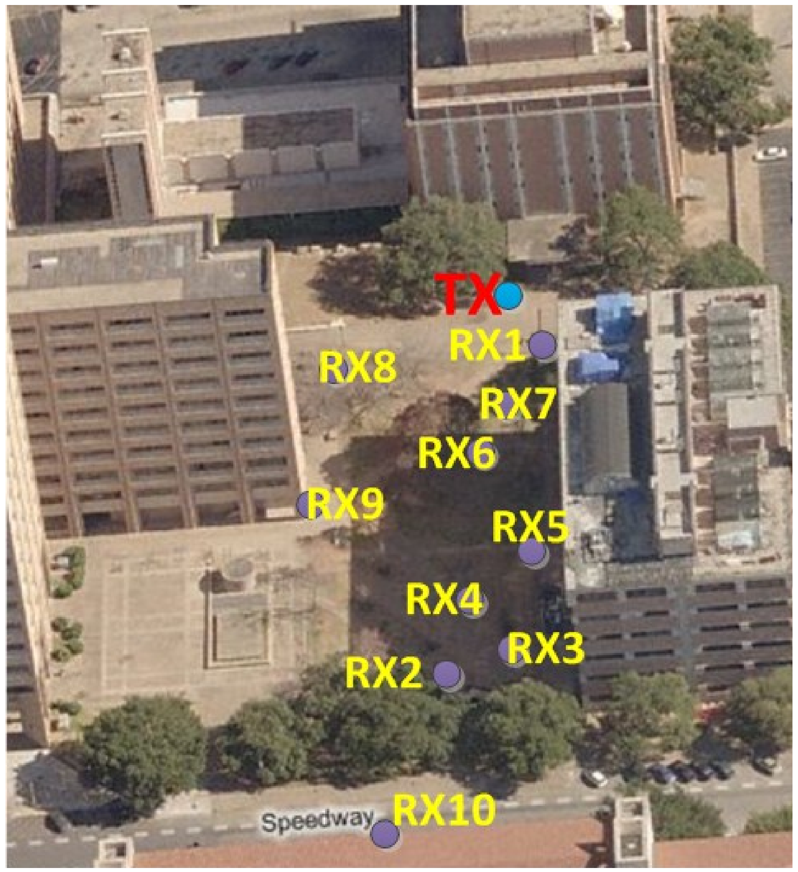


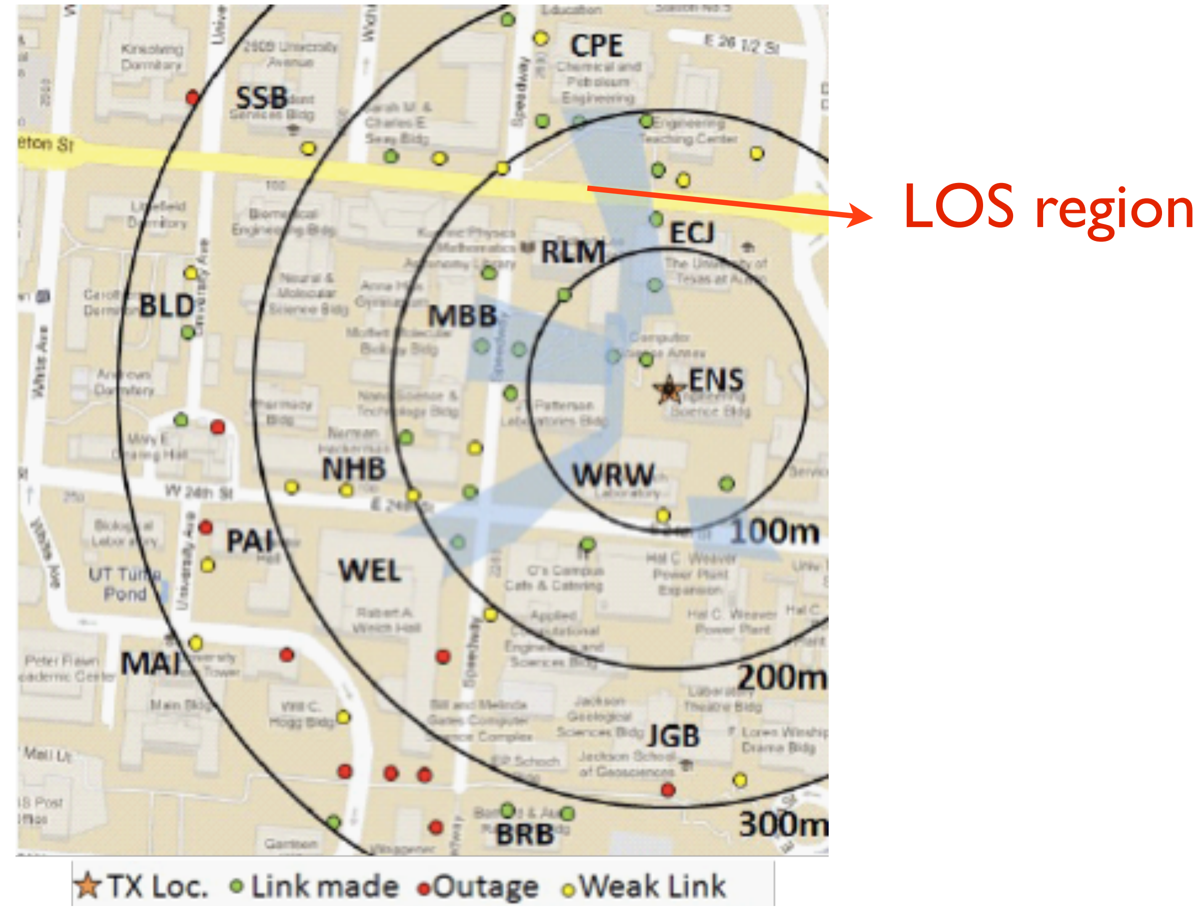
- Huge amount of spectrum available in mmWave bands*
  - Cellular systems live with limited microwave spectrum ~ 600MHz
  - 29GHz **possibly** available in 23GHz, LMDS, 38, 40, 46, 47, 49, and E-band
- Technology advances make mmWave possible
  - Silicon-based technology enables low-cost highly-packed mmWave RFIC**
  - Commercial products already available (or soon) for PAN and LAN
  - Already deployed for backhaul in commercial products

* Z. Pi and F. Khan. "An introduction to millimeter-wave mobile broadband systems." IEEE *Communications Magazine,* vol. 49, no. 6, pp. 101-107, Jun. 2011.
** T.S. Rappaport, J. N. Murdock, and F. Gutierrez. "State of the art in 60-GHz integrated circuits and systems for wireless communications." *Proceedings of the IEEE*, vol. 99, no. 8, pp:1390-1436, 2011

Characteristics of the MmWave Channel

Channel Measurements





mmWave cellular channel measurement at UT campus*

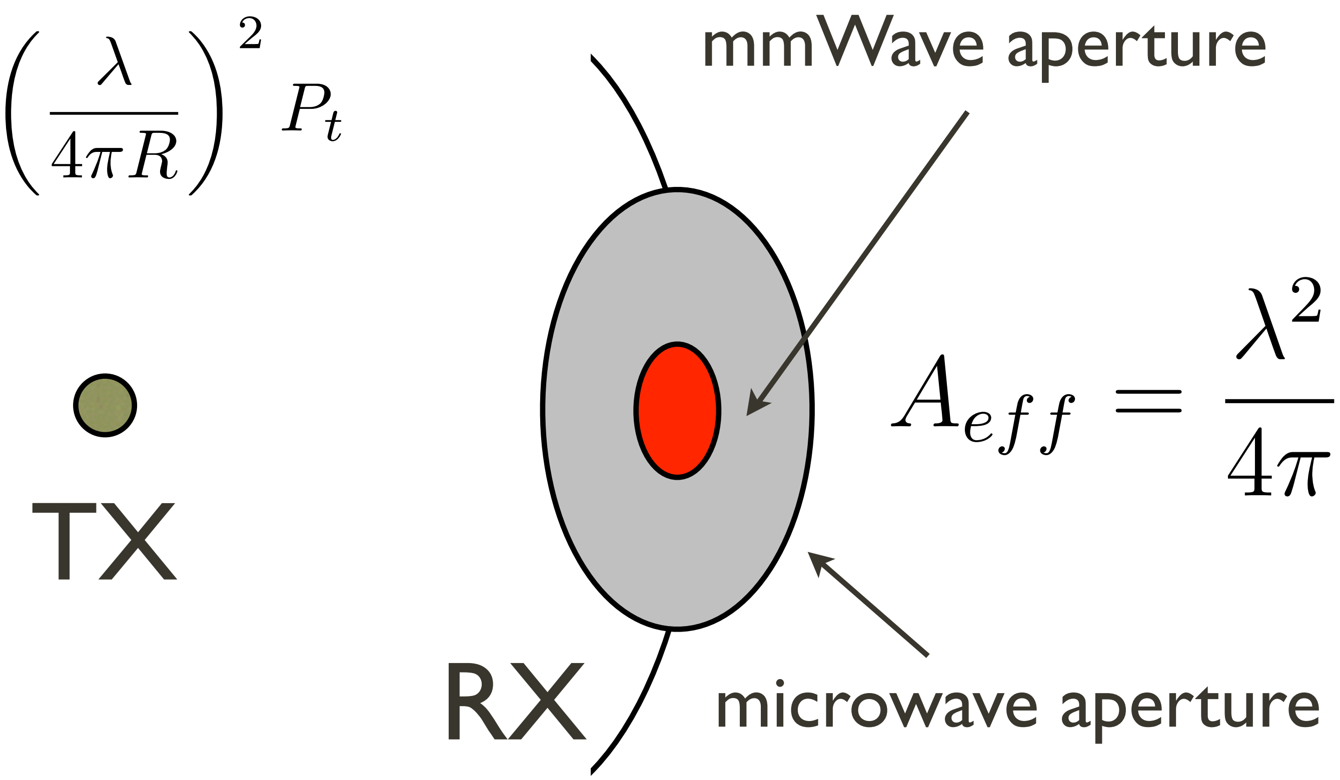
- MmWave cellular channel already measured in various environments
  - Measurement results validate the feasibility of mmWave cellular networks
  - MmWave channel appears more dependent on site-specific environments

Many channel characteristics for mmWave cellular are known

* T. S. Rappaport, E. Ben-Dor, J. Murdock, Y. Qiao, "38 GHz and 60 GHz angle dependent propagation for cellular & peer-to-peer wireless communications," In Proc. of International Conference on Communications (ICC), 2012.

Path Loss (1/2)

$$P_r = A_{\text{eff}} \frac{P_t}{4\pi R^2} = \left(\frac{\lambda}{4\pi R}\right)^2 P_t$$

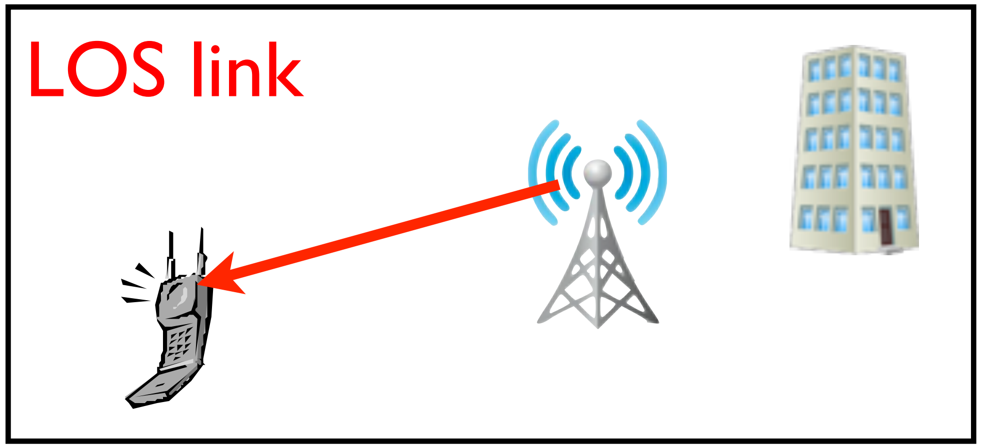


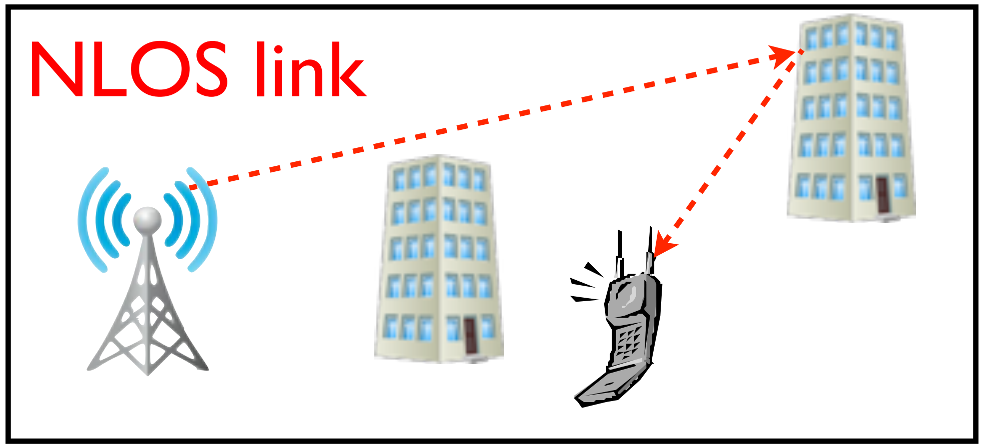
$$A_{eff} = \frac{\lambda^2}{4\pi}$$

- Path loss seems severe in mmWave bands
  - 3GHz->30GHz gives 20dB extra path loss due to aperture
- Additional losses require large margin in link budgets
  - Foliage loss limited the coverage in forests
  - Heavy rains may cause several dB loss in a 100 meter-link

mmWave will exploit large arrays to increase aperture

Path Loss (2/2)



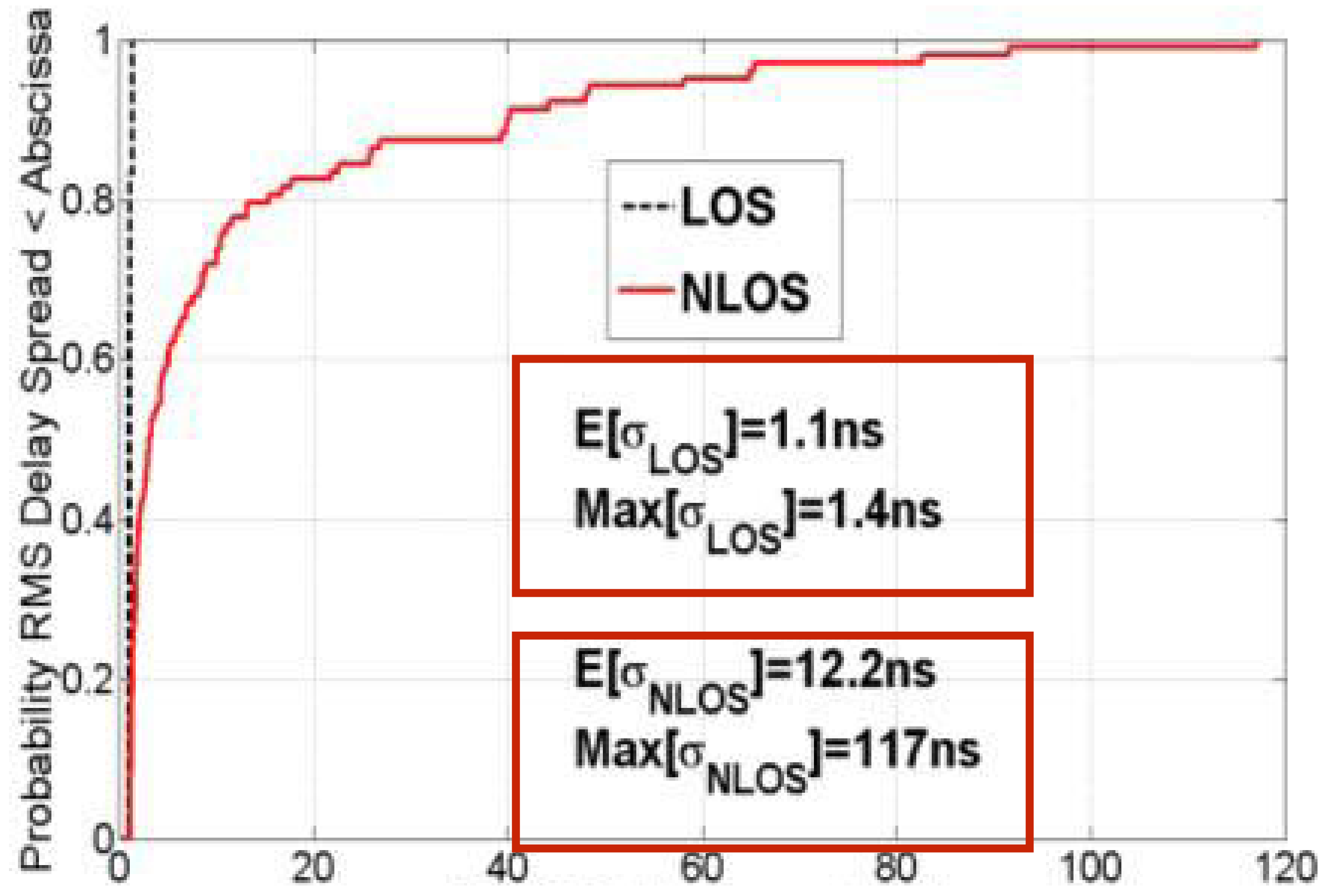


- MmWave signals more sensitive to blockages
  - Can not penetrate through some materials, e.g. brick walls
  - Isolation of indoor and outdoor networks
- Different path loss laws in LOS and NLOS paths
  - LOS transmits more like in free space: path loss exponent 2
  - NLOS signals much weaker and susceptible to environments

Need to incorporate blockage effects in channel model

Delay Spread

38 GHz measurements at UT Austin*



CDF of RMS delay in ns

- Delay spread is generally smaller than microwave
  - Delay spread depends much on scattering environment
  - Typical RMS delay is in the order of 10ns- 100ns
- Different characteristics between LOS and NLOS
  - With narrow-beam arrays, no delay spread in LOS links
  - Delay spread becomes higher in NLOS links, but varies with beam width

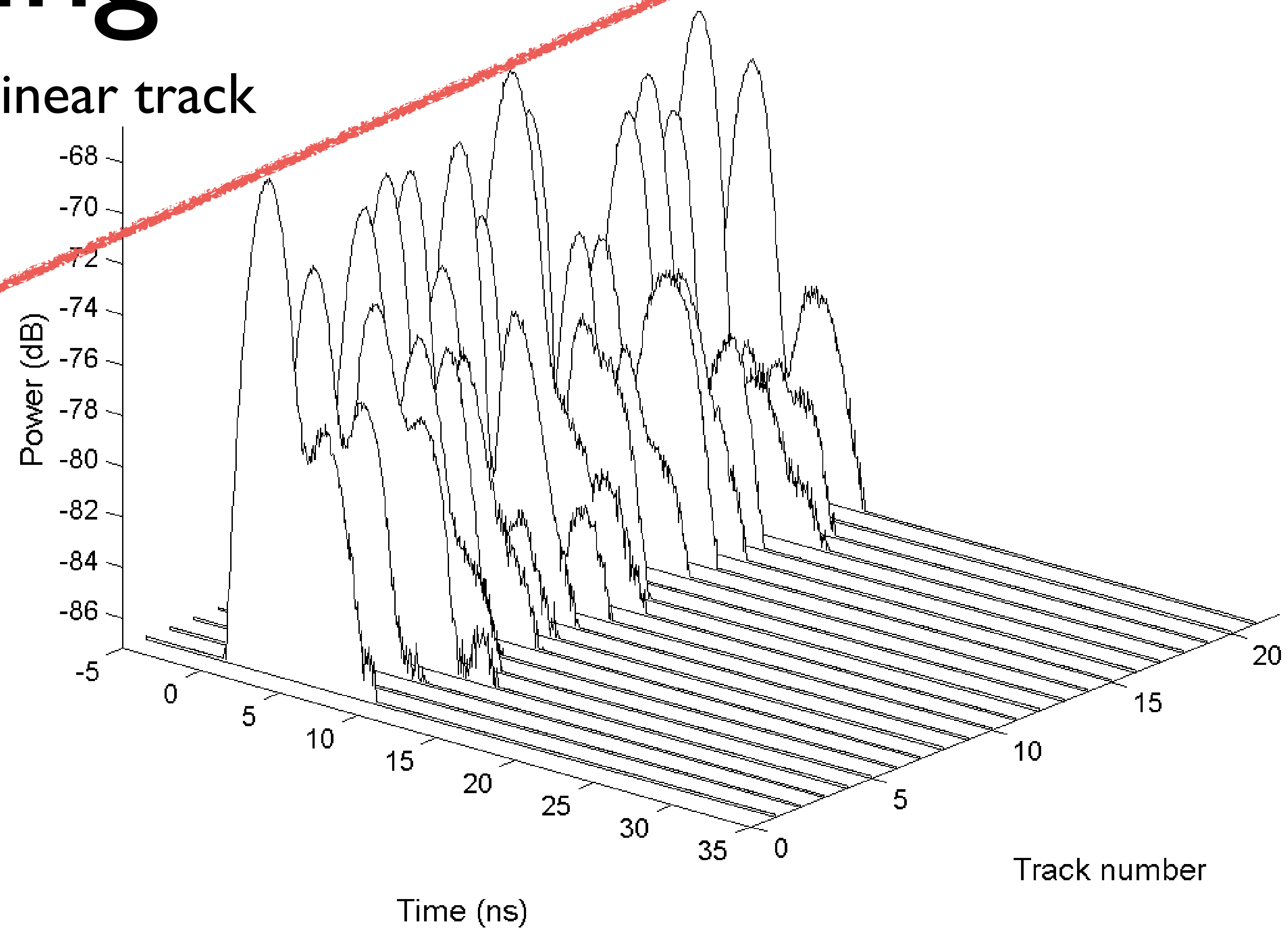
* T. S. Rappaport *et al,* "Millimeter wave Mobile Communications for 5G Cellular: it will work!", IEEE Access, Vol. 1, pp. 335-349, May. 2013.

Small-Scale Fading

Power delay profiles over a 10-wavelength linear track

Measured at 28 GHz in New York City*

A few dB difference in received power



- Small-scale fading is minor in mmWave cellular
  - One direct multi-path dominant in the LOS links
  - Number of multi-path is sparse even in NLOS links
  - Fading can be incorporated by a Nakagami random variable

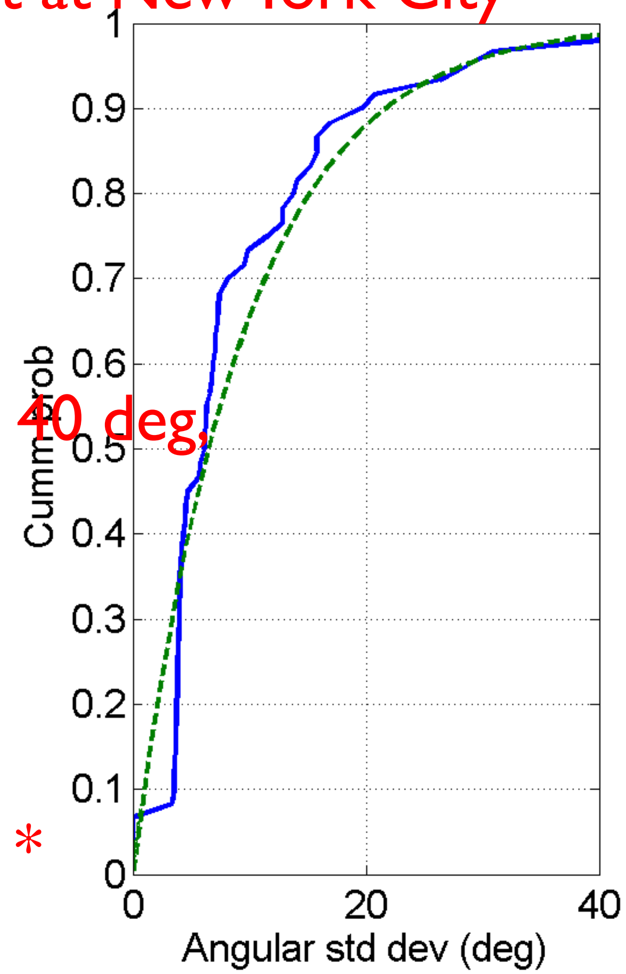
* T. S. Rappaport *et al,* "Millimeter wave Mobile Communications for 5G Cellular: it will work!", IEEE Access, Vol. 1, pp. 335-349, May. 2013.

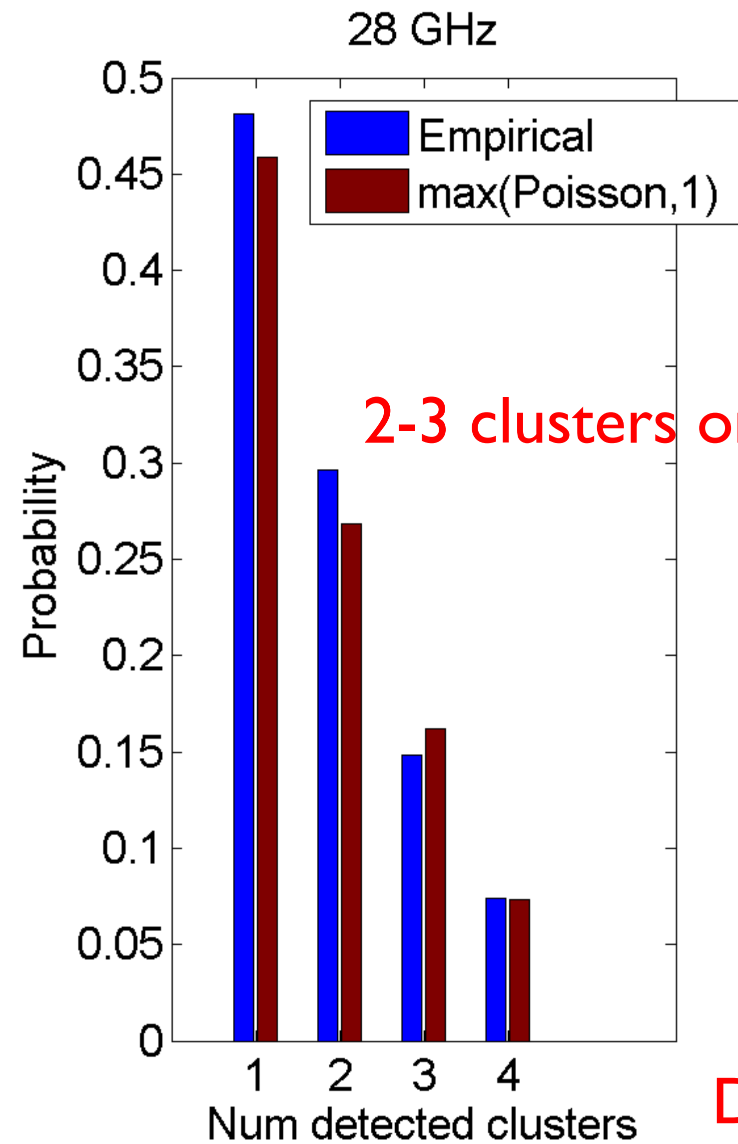
Angle Spread

28 GHz measurement at New York City*

Most angular offset < 40 deg

CDF of angle spread *





2-3 clusters on average

Distribution of cluster # *

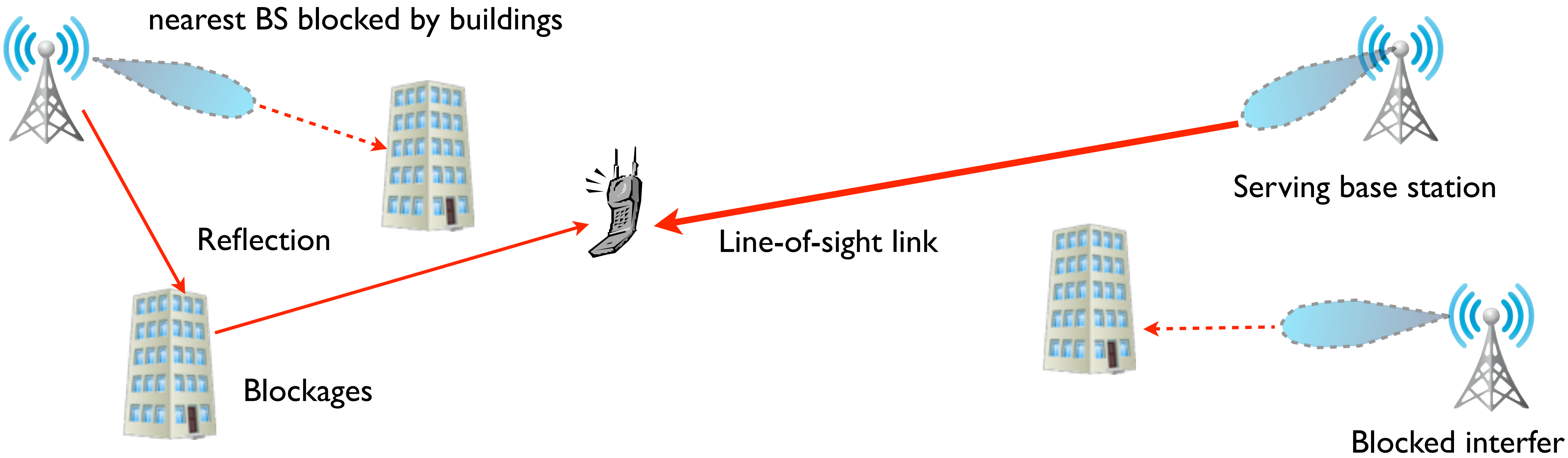
- Angle spread is relatively smaller in mmWave
  - Number of incoming rays is small, e.g. 2-3 on average
  - Generally concentrated around bore-sight directions
  - First statistics model seen in most recent work *

More measurements needed for a comprehensive model

* M. R. Akdeniz *et al*, "Millimeter wave channel modeling and cellular capacity evaluation", Dec. 2013. (http://arxiv.org/abs/1312/3921)

Stochastic Channel Model for Incorporating Blockage Effects

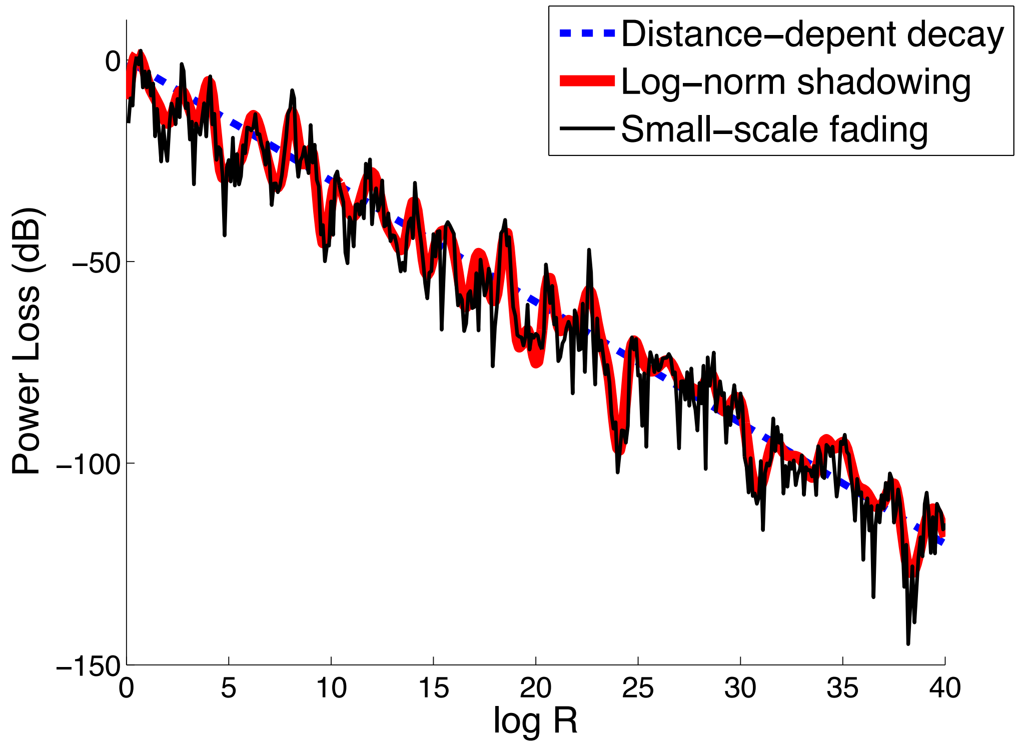
Impact of Blockage



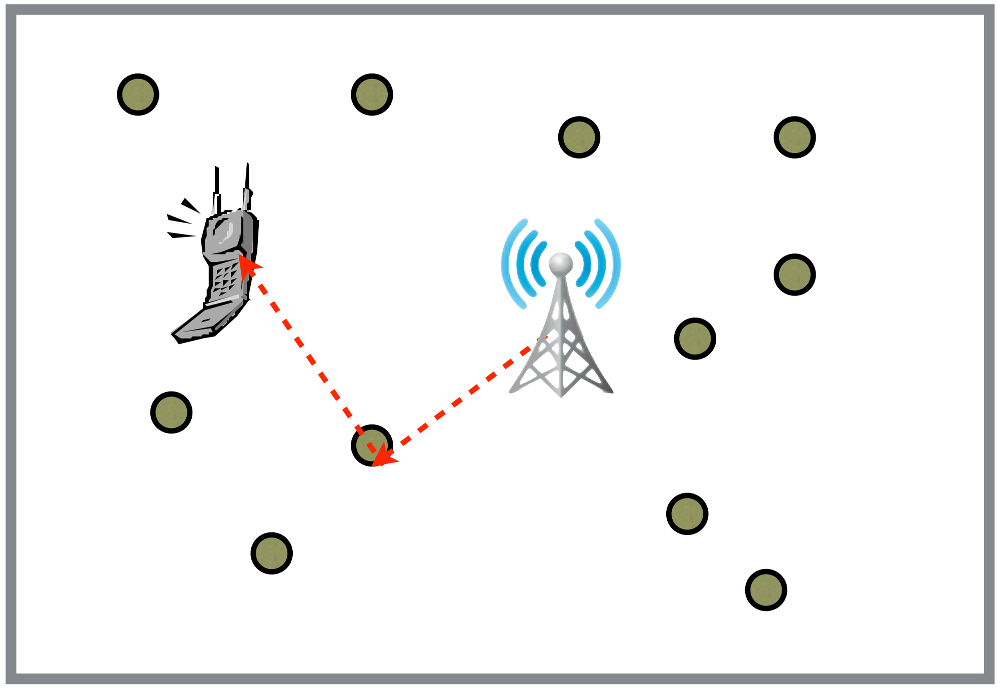
- Users may connect to a further unblocked base station
- Strong interferers may blocked
- Signal and interference may be either LOS or NLOS

How to model blockage in cellular networks?

Prior Blockage Model



Log-normal shadowing

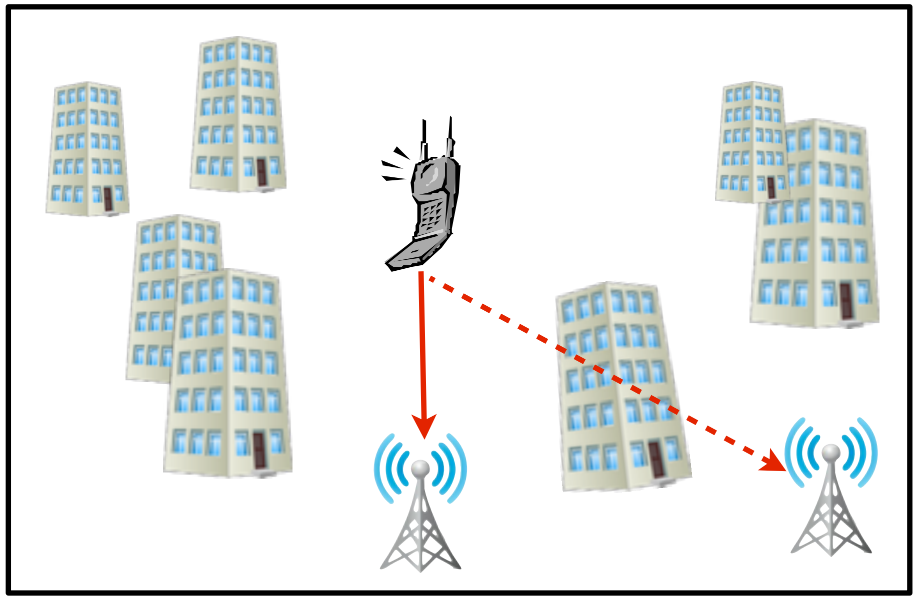


Model blockages as point process

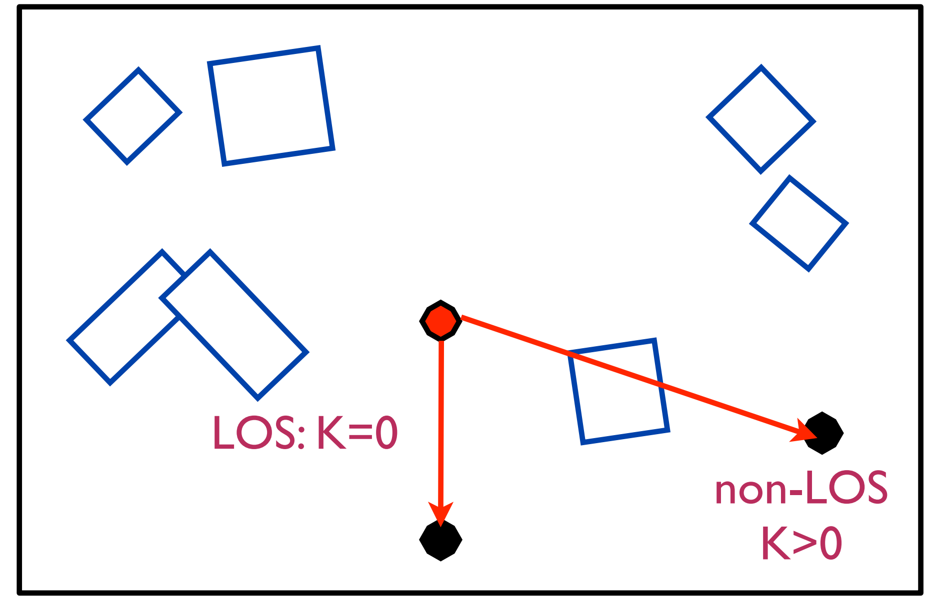
- Log-normal shadowing model
  - Assumes i.i.d. shadowing for all links
  - Does not capture the distance-dependent feature: longer link, more blockage
- Random walk model [Fra04]
  - Model blockages as random point process
  - Not characterize the size & shape of blockages

Propose to model blockages of random shape & size

Proposed Blockage Model



Randomly located buildings



Boolean scheme of rectangles
K: # of blockages on a link

- Use random shape theory to model buildings
  - Model random buildings as a rectangular Boolean scheme
  - Buildings distributed as PPP with independent sizes & orientations
- Compute the LOS probability based on the building model
  - # of blockages on a link is a Poisson random variable
  - The LOS probability that no blockage on a link of length R is $e^{-\beta R}$

Poisson point process (PPP)

Differentiate LOS and NLOS based on LOS probability

T. Bai and R. Vaze, and R. W. Heath, Jr., ``Analysis of Blockage Effects in Urban Cellular Networks,'' Submitted to IEEE. Trans. Wireless Commun., Aug. 2013

Proposed Path Loss Model

- Apply different path loss laws given a path is LOS/ NLOS

Indicator function

Bernoulli random variable with distance dependent parameter

$$\ell(R) = \mathbb{I}(p(R))\ell_{\mathrm{LOS}}(R) + \mathbb{I}(1-p(R))\ell_{\mathrm{NLOS}}(R)$$

LOS path loss law

NLOS path loss law

- Ignore correlations of shadowing between links
- Parameterize the channel model based on measurements
  - Line-of-sight with probability $\mathrm{e}^{-\beta R}$: average LOS range is $1/\beta$

The fraction of land covered by buildings

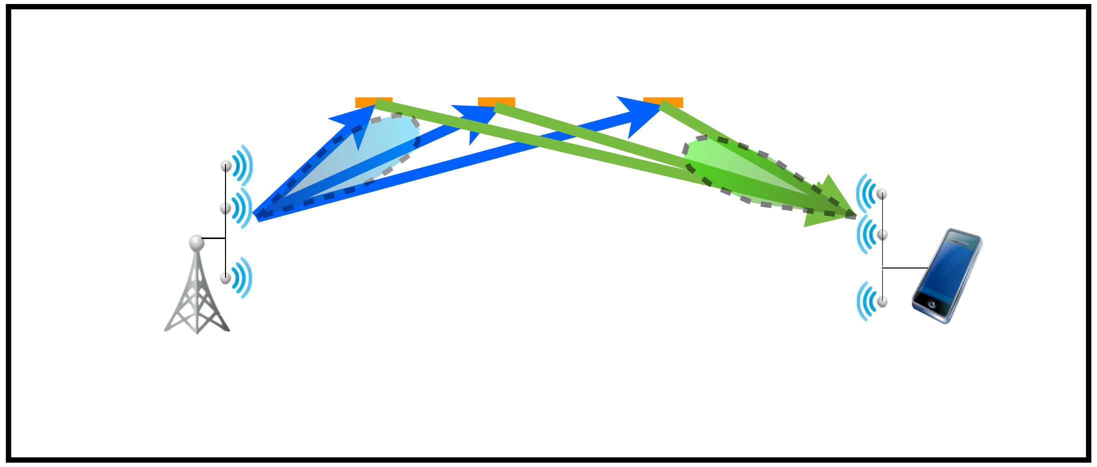
$$\beta = \frac{2\lambda(\mathbb{E}[L]+\mathbb{E}[W])}{\pi}$$

Average building length and width

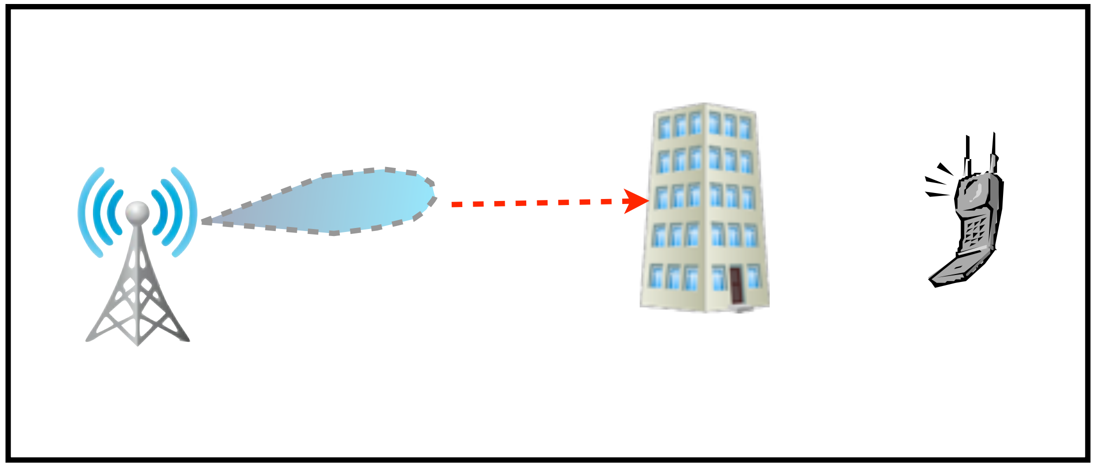
  - LOS path Loss in dB: $\mathrm{PL}_1 = C + 20\log R(\mathrm{m})$
  - NLOS path loss in dB: $\mathrm{PL}_2 = C + K + 40\log R(\mathrm{m})$

Using the Model to Evaluate System Performance

Incorporate mmWave Features



Directional Beamforming (BF)



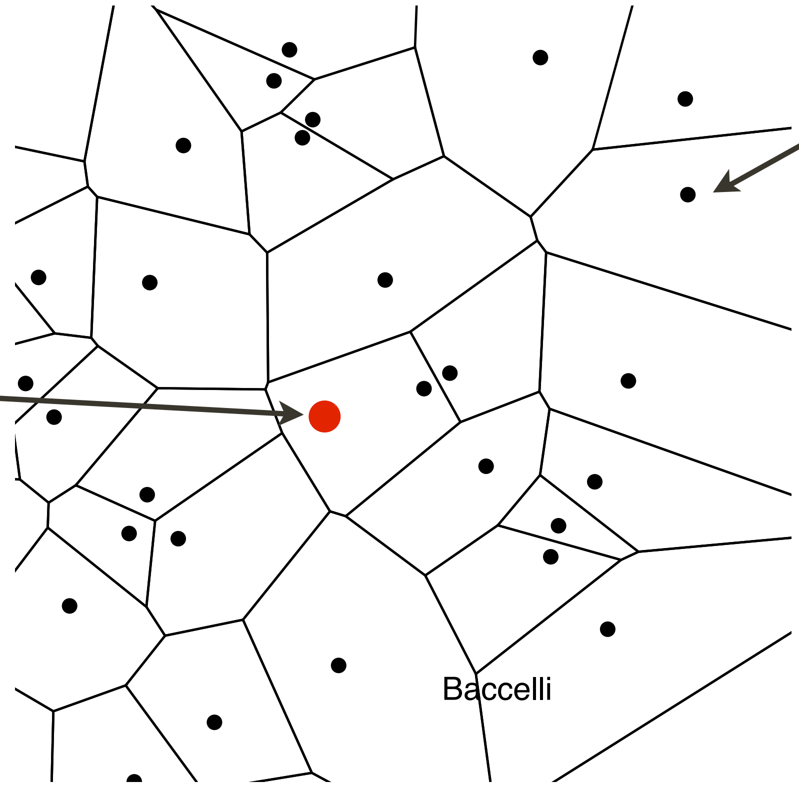
LOS & non-LOS links

- Need to incorporate directional beamforming
  - RX and TX communicate via main lobes to achieve array gain
  - Steering directions at interfering BSs are random
- Need to distinguish LOS and NLOS paths
  - Characterize LOS/ NLOS regions by modeling buildings explicitly
  - Apply different characteristics to LOS & NLOS channels

Need to include beamforming + blockages in the system model

Stochastic Geometry for Cellular

performance analyzed for a typical user



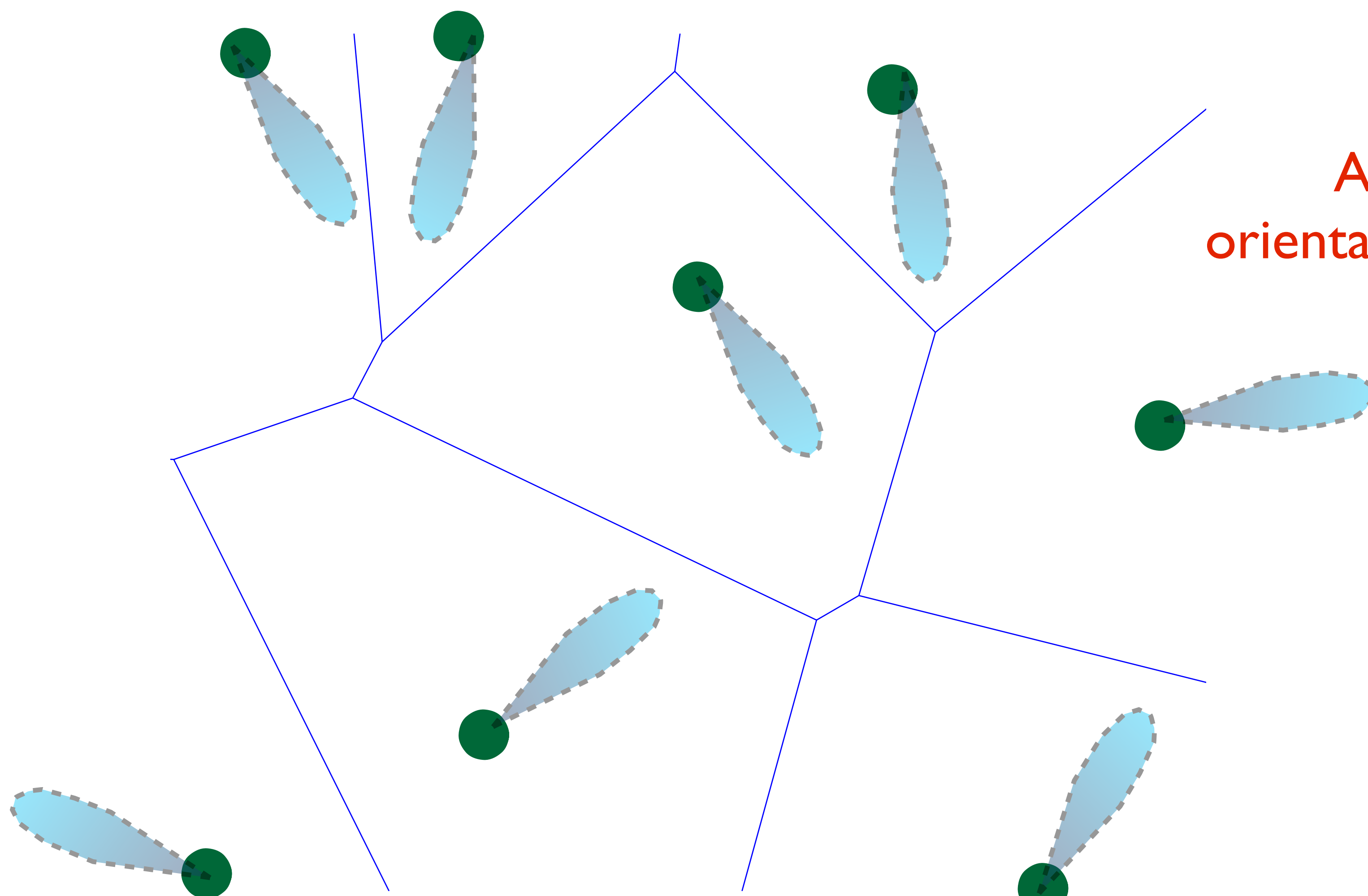
base station locations distributed (usually) as a Poisson point process (PPP)

- Stochastic geometry is a tool for analyzing microwave cellular
  - Better fit for less regular deployment in dense networks
  - Characterizes the performance of a typical user in the network
  - Provides a systemwide performance in large-scale networks

Need to add directional antennas and LOS/ NLOS links

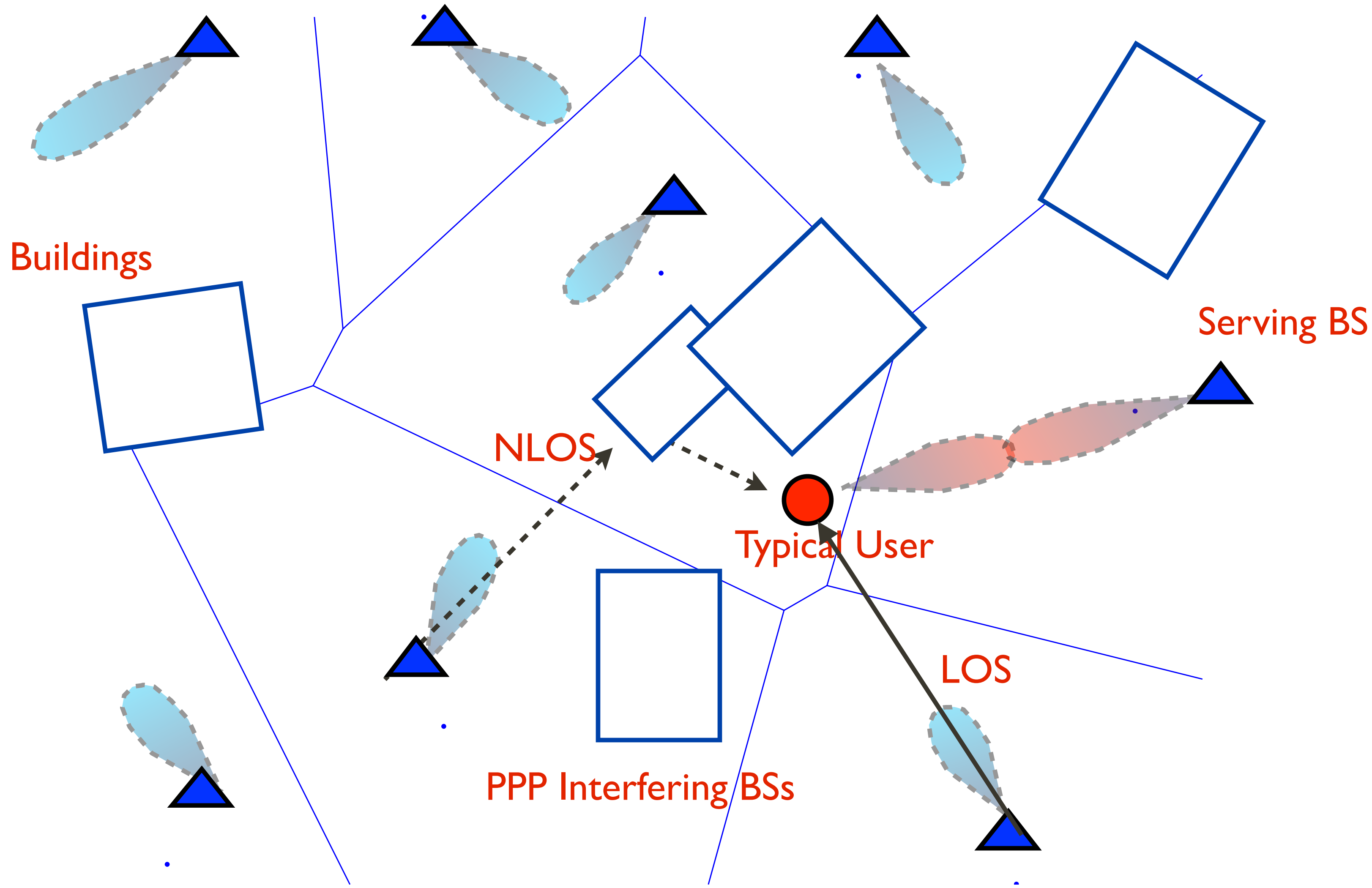
J. G. Andrews, F. Baccelli, and R. K. Ganti, "A Tractable Approach to Coverage and Rate in Cellular Networks", IEEE Transactions on Communications, November 2011.
T. X. Brown, "Cellular performance bounds via shotgun cellular systems," IEEE JSAC, vol.18, no.11, pp.2443,2455, Nov. 2000.

Poisson Point Processes



- Poisson point process (PPP): the simplest point process
  - # of points is a Poisson variable with mean λS
  - Given N points in certain area, locations independent
  - Assigning each point an i.i.d. random variable forms a marked PPP

Proposed System Model



- Distribute base stations as a PPP on the plane
- Model steering directions of arrays as marks of BS PPP
  - User and associated BS match directions to exploit maximum gain
  - Directions of interfering BSs are randomly distributed
- Apply proposed channel model to differentiate NLOS and LOS

Calculating SINR

$$\mathrm{SINR} = \frac{P_{\mathrm{t}} G(0,0) \ell(r_0)}{\underbrace{F\sigma^2}_{\text{Noise}} + \sum_{k>0} \underbrace{h_k}_{\text{Small-scale fading}} P_{\mathrm{t}} \underbrace{G(\theta_k, \psi_k)}_{\text{Directivity gain of k-th link}} \underbrace{\ell(r_k)}_{\text{Path loss of k-th link}}}$$

- Use proposed channel model to compute path loss $\ell(r)$
- Assume uniformly distributed angles θ_k and ψ_k in interf. links
- Incorporate TX and RX directional beamforming by $G(\cdot,\cdot)$
- Use Nakagami random variable h_k to model small-scale fading
- Associate the typical user with the BS with smallest path loss

Tianyang Bai and R.W. Heath, Jr., ``Coverage in Dense Millimeter Wave Cellular Networks ," to appear in the Proc. of the Asilomar Conf. on Signals, Systems, and Computers, Pacific Grove, CA, November 3-6, 2013.

Tianyang Bai and R.W. Heath, Jr., ``Coverage Analysis for Millimeter Wave Cellular Networks with Blockage Effects," to appear in the Proc. of the IEEE Global Signal and Information Processing Conference, Austin, TX, Dec. 3-5, 2013.

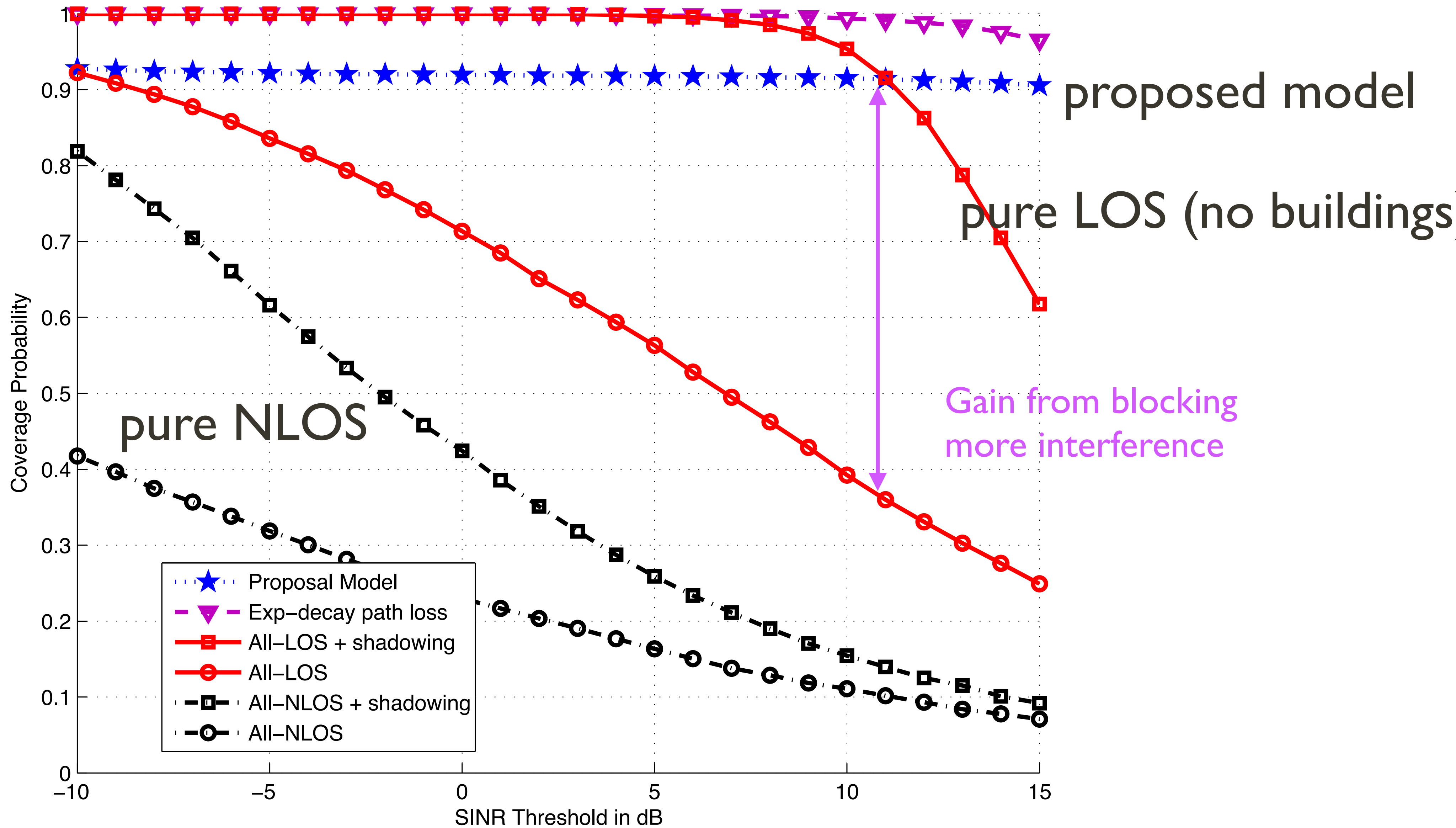
Simulation Results

Parameters for Simulation

- System parameters
  - Carrier frequency: 28 GHz
  - Transmitter power: 30 dBm
  - Signal bandwidth: 500 MHz
  - Noise power: -87 dBm, and noise Figure: 5 dB
  - Fading: Nakagami fading of parameter 3 in NLOS links
- Blockage parameters fitted to UT Austin campus
  - LOS range is approximately 150 meters
  - LOS path loss is 2, and NLOS path loss is 4
- Using ULA for directional beamforming at RX and TX
  - Half-wavelength spacing
- Network configurationHalf-wavelength spacing
  - BSs as a PPP with average cell radius Rc

Different Path Loss Model

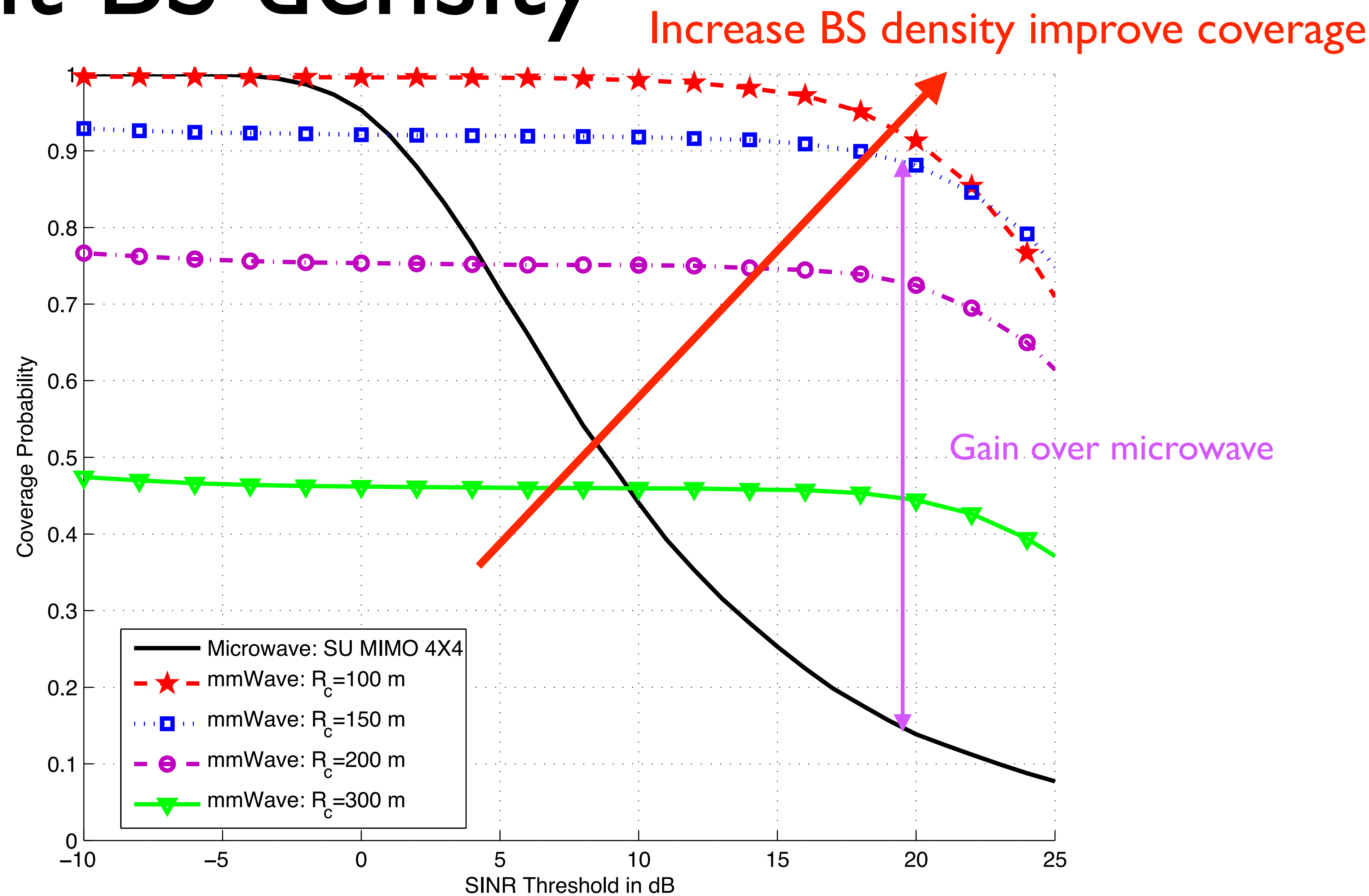
Tx BF: ULA 64 antennas
Tx beamwidth: 2 degree
Rx BF: ULA 8 antennas
Rx beamwidth: 13 degree
Rc=100 m
LOS range: $1/\beta$=150 m



- Coverage probability differs in LOS and non-LOS region
  - Need to incorporate blockage model & differentiate LOS and NLOS
  - NLOS coverage probability generally provides a lower bound
  - Buildings may improve coverage by blocking more interference

Different BS density

Tx BF: ULA 64 antennas
Tx beamwidth: 2 degree
Rx BF: ULA 8 antennas
Rx beamwidth: 13 degree



- Coverage probability depends on base station density
  - Dense network generally provides good coverage
  - Can achieve even better coverage than microwave networks

Data Rate Comparison

- Given coverage probability, the achievable rate is

clipped by 6 bps/Hz (64QAM)

$$C = \log_2(1 + \min(\mathbf{SINR}, 40\mathrm{dB}))$$

- Microwave network 4X4 SU MIMO with bandwidth 50MHz:
  - Spectrum efficiency is 4.48 bps/ Hz
  - Data rate is 224 Mbps (Rc=500 m)
- mmWave network with bandwidth 500MHz:

Tx BF: ULA with M antennas
Rx BF: ULA 8 antennas
Rx beamwidth: 13 degree
$1/\beta$=150 m

M \ R_c	100m	200m
64	2.74 Gbps	1.61 Gbps
100	2.91Gbps	1.88 Gbps

Average cell radius

# of antennas in TX arrays

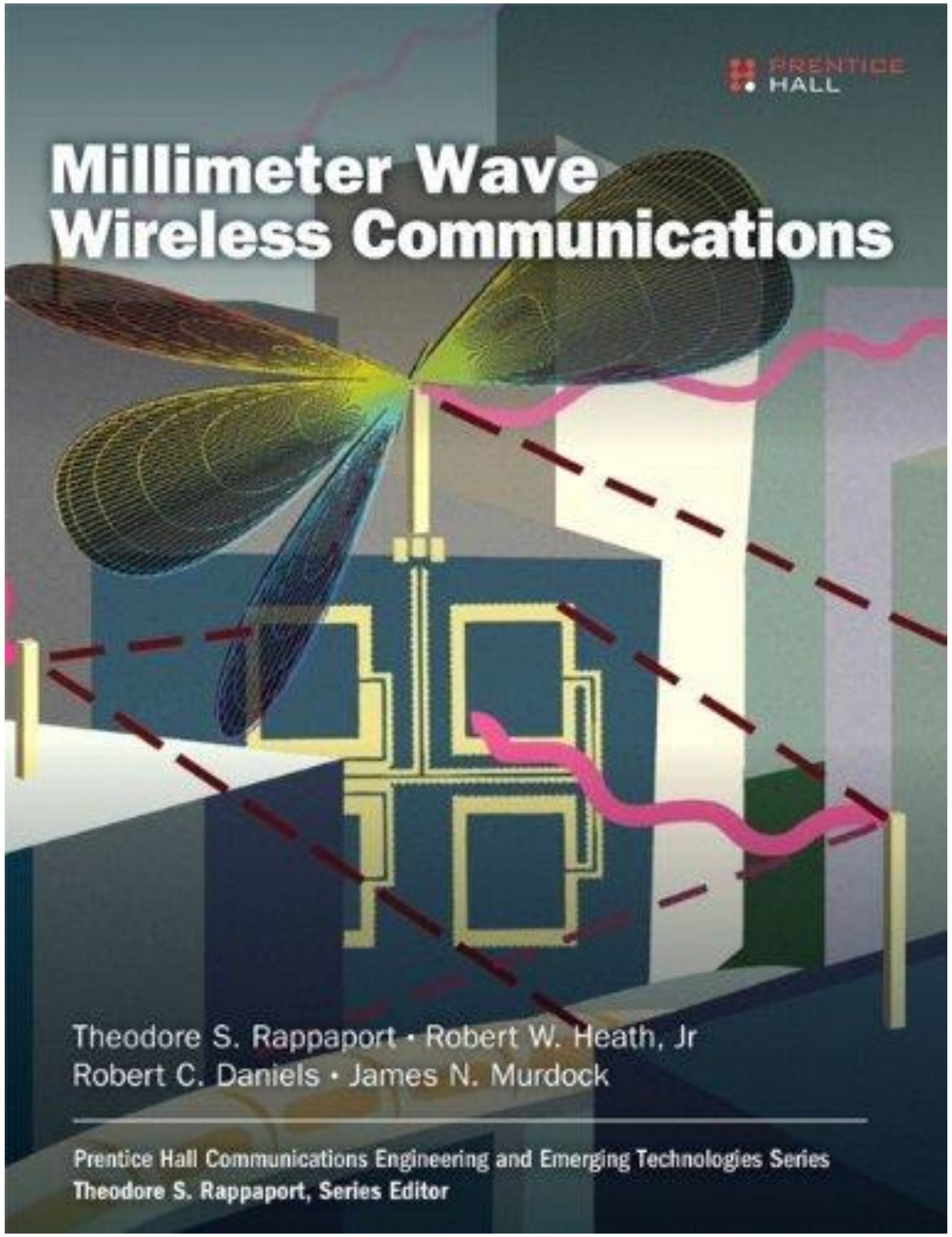
Average rate is a function of density

Conclusions

Going Forward with mmWave

- A mmWave path loss model proposed for system evaluation
  - Incorporate blockage effects by differentiating LOS and NLOS path loss
  - Interference is reduced by directional antennas and blockages
  - Good rates and coverage can be achieved when network is dense
- Theoretical challenges abound
  - Analog beamforming algorithms & hybrid beamforming
  - Channel estimation, exploiting sparsity, incorporating robustness
  - Multi-user beamforming algorithms and analysis
  - Microwave-overlaid mmWave system a.k.a. phantom cells
  - Going away from cells to a more ad hoc configuration

Questions?



Shipping in the end of April (sorry for gratuitous self promotion)