Accurately Accounting for Random Blockage in Device-to-Device mmWave Networks

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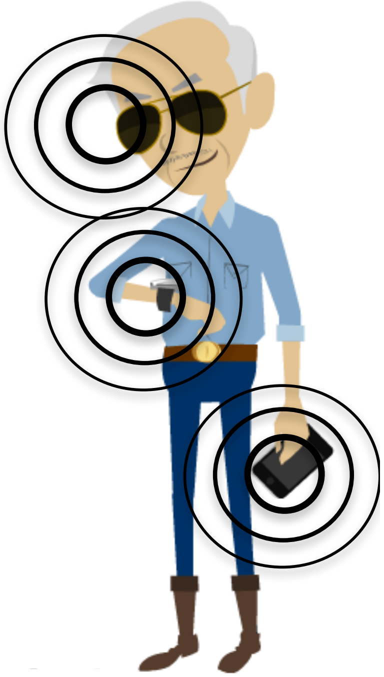
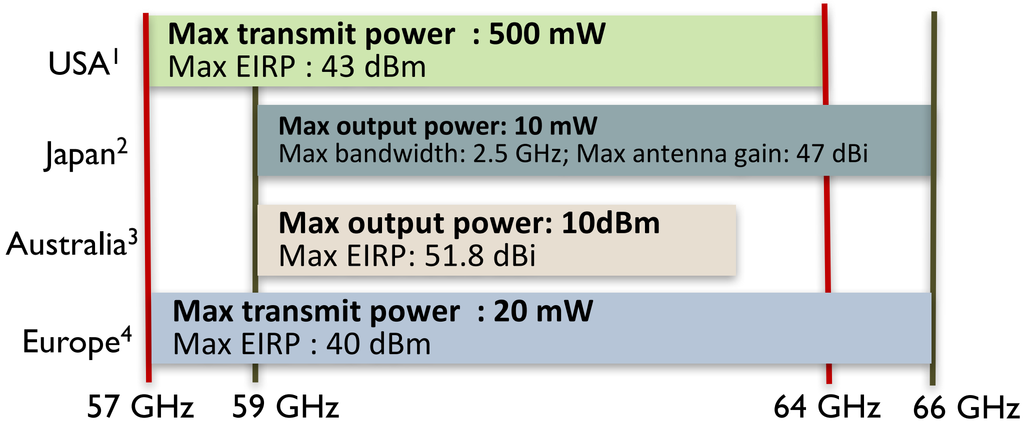
D2D, Wearables, and Virtual Reality



- The next frontier for wireless communications
  - Multiple devices in and around human body
  - Low-rate fitness monitors to high-rate virtual reality devices.
- Critical challenge
  - Supporting Gbps per user in dense environments
  - Effective operation in finite areas like VR rooms, trains, or buses

[1] Photo by David Paul Morris/Bloomberg via Getty Images
[2] "Smart wearable devices: Fitness, healthcare, entertainment & enterprise 2013-2018," Juniper Research, Oct. 2013.

MmWave as a Solution for Connected Devices



USA[1]
Max transmit power : 500 mW
Max EIRP : 43 dBm

Japan[2]
Max output power: 10 mW
Max bandwidth: 2.5 GHz; Max antenna gain: 47 dBi

Australia[3]
Max output power: 10dBm
Max EIRP: 51.8 dBi

Europe[4]
Max transmit power : 20 mW
Max EIRP : 40 dBm

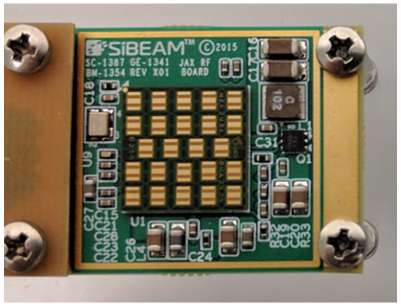
Several GHz of spectrum available for worldwide operation

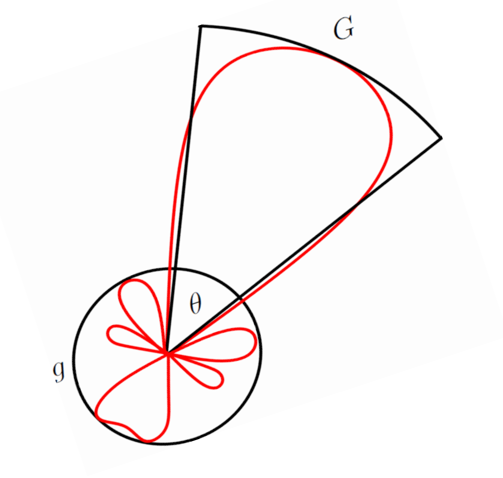
- High bandwidth and reasonable isolation
- Compact antenna arrays to provide array gains via beamforming
- Commercial products already available: IEEE 802.11ad, WirelessHD

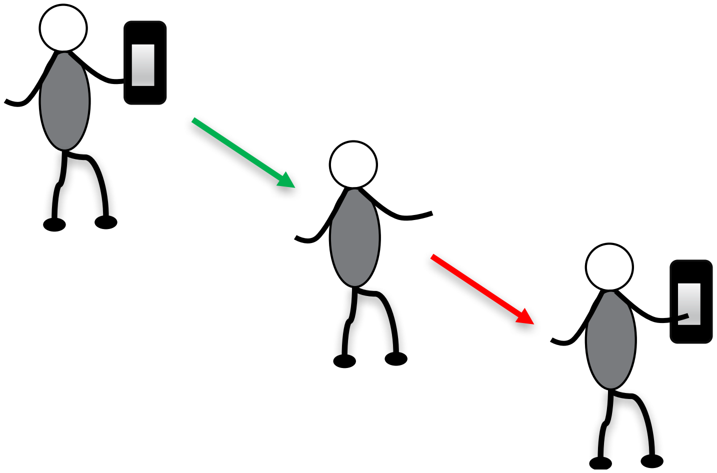
[1] 47 CFR 15.255; [2] ARIB STD-T69, ARIB STD-T74; [3] Radiocommunications Class License 2000; [4] CEPT : Official journal of the EU;

Challenges and Opportunities of mmWave for D2D

- Antenna Directivity
  - To compensate for path-loss, mmWave antennas are directional.
  - Can model as sectorized antenna.
  - Interference tends to be “pointy”.
- Blockage
  - mmWave subject to blocking.
  - Propagation primarily LOS.
  - In D2D, bodies are a main source of blockage.
  - Blockage isolates interference.

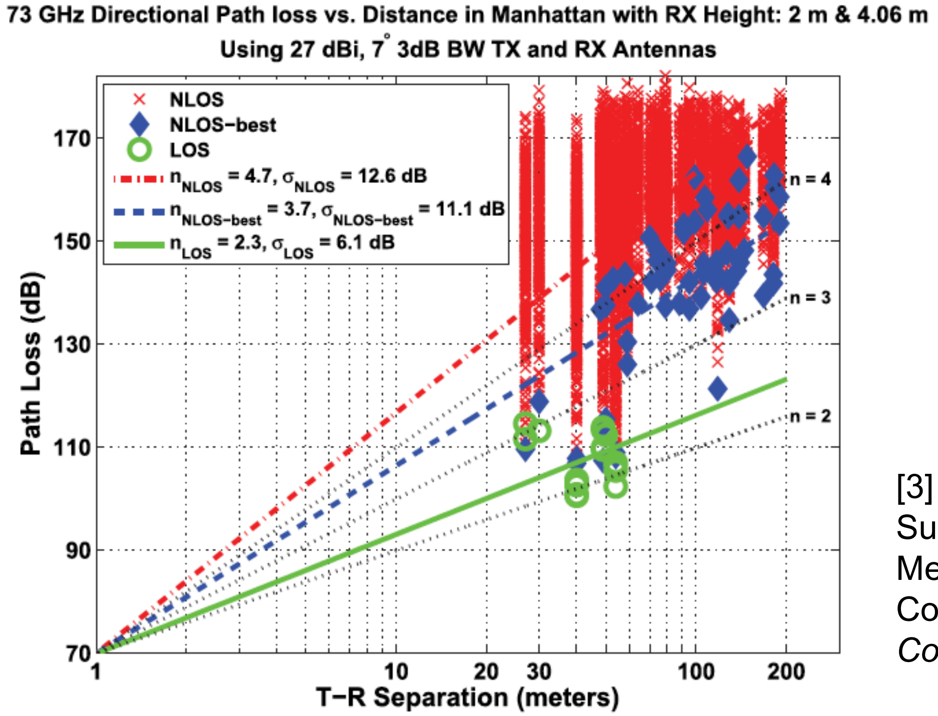






Blockage effect I: Change in Path Loss

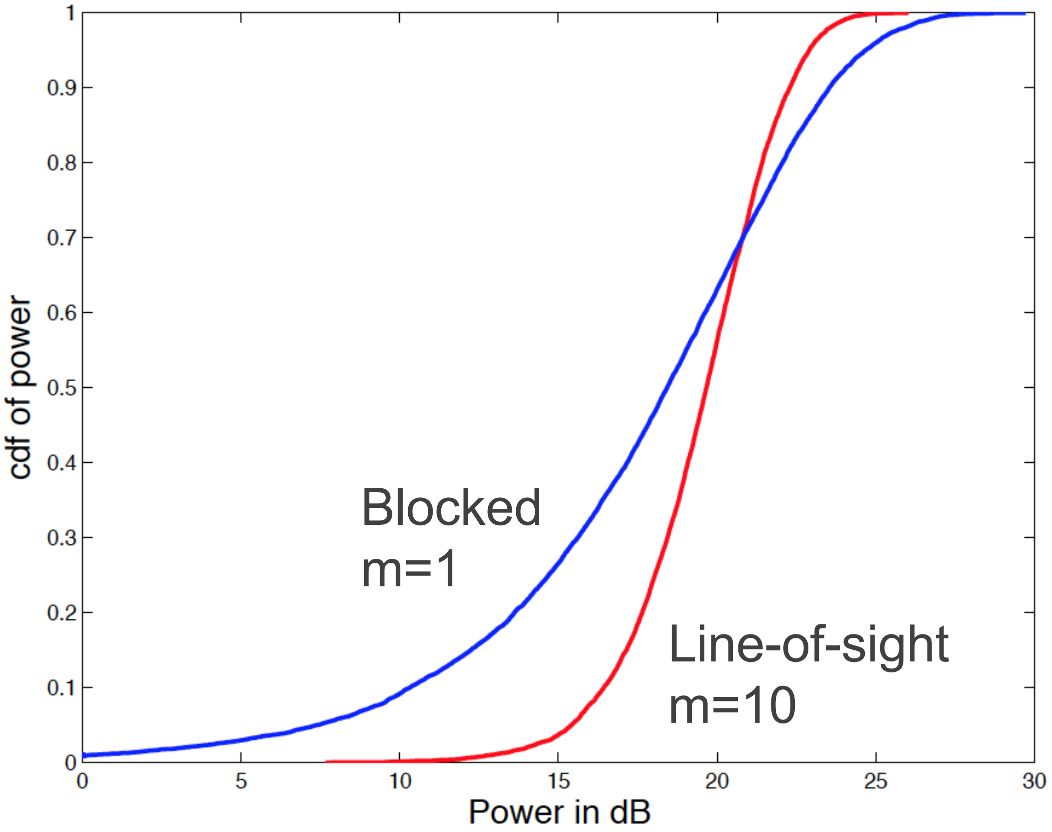
- Blocked signal has significantly higher path loss
  - **Path loss is proportional to d$^{\alpha}$**
  - **Modeled as a change in path loss exponent** α



[3] T. S. Rappaport, G. R. MacCartney, M. K. Samimi and S. Sun, "Wideband Millimeter-Wave Propagation Measurements and Channel Models for Future Wireless Communication System Design," in *IEEE Transactions on Communications*, vol. 63, no. 9, pp. 3029-3056, Sept. 2015.

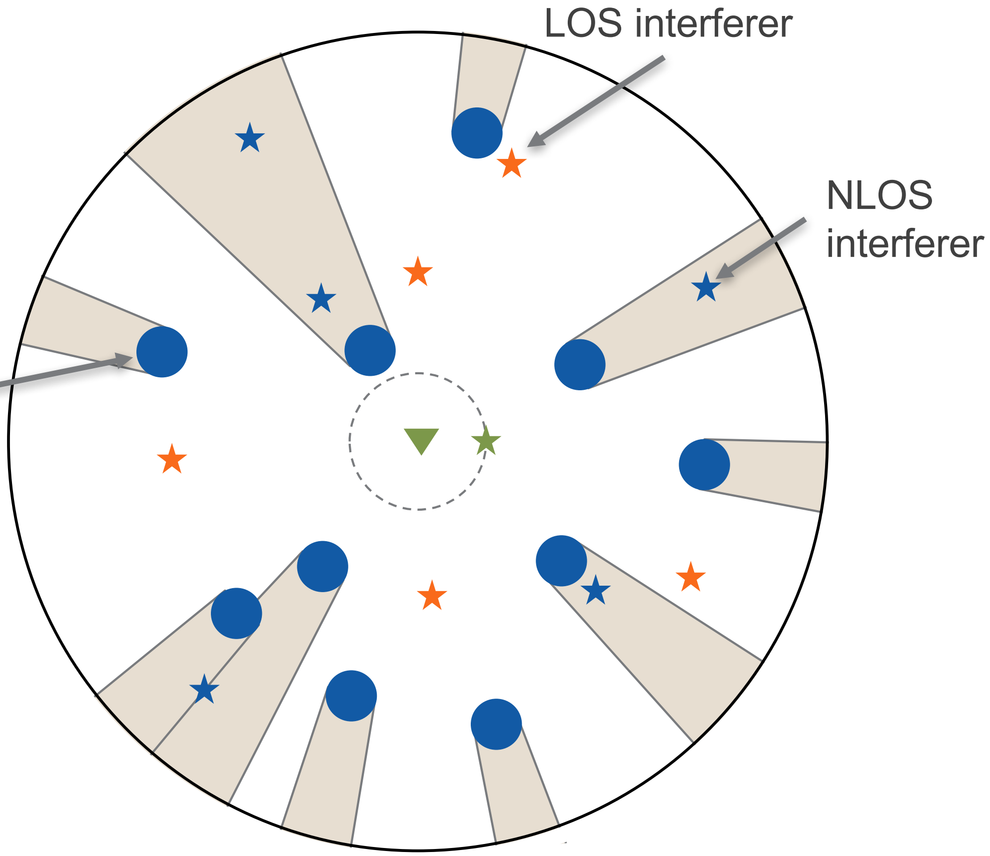
Blockage effect II: Impact on Fading Distribution

- Some energy of blocked signals still arrives, but via scattered and reflected paths.
  - Increases amount of fading – tends towards Rayleigh fading
- Direct paths are LOS-like, tends towards Nakagami fading
  - Variable "m" determines how direct the path is.



Modeling Blockage

- Blockage can be modeled as a point process.
  - Here, a binomial point process.
- Here, each source of blockage represented by a blue circle.
  - Constant width "W"
  - Its shadow is shown
- Transmitters are:
  - If in shadow = blocked/NLOS
  - Otherwise LOS



LOS interferer

NLOS interferer

▼ Reference receiver at origin

★ Reference transmitter

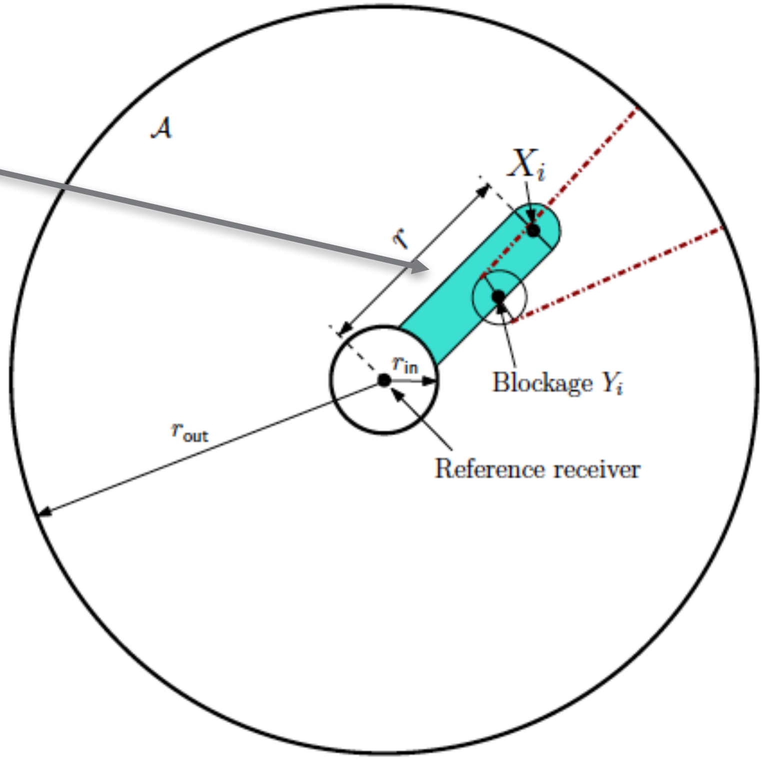
Computing Blockage Probability

- An interferer at distance r from the receiver will be blocked if a blocking object lies in its blocking zone.
- Probability that a given object lies in a given blocking zone can be found using geometric arguments:

$$p_z(r) = \frac{\text{Zone Area}}{\text{Network Area}}$$

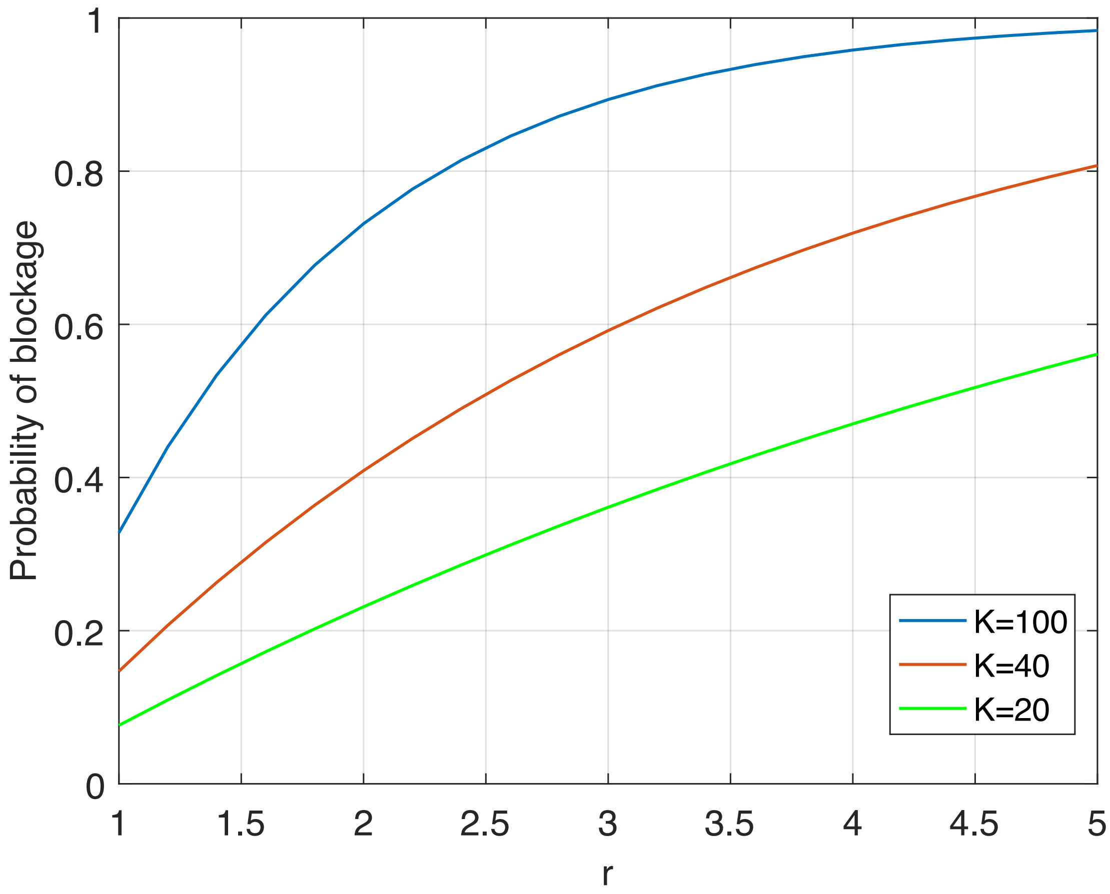
- If there are K objects in the network, then the interferer is blocked if any of them are in its blocking zone:

$$p_b(r) = 1 - (1 - p_z(r))^K$$



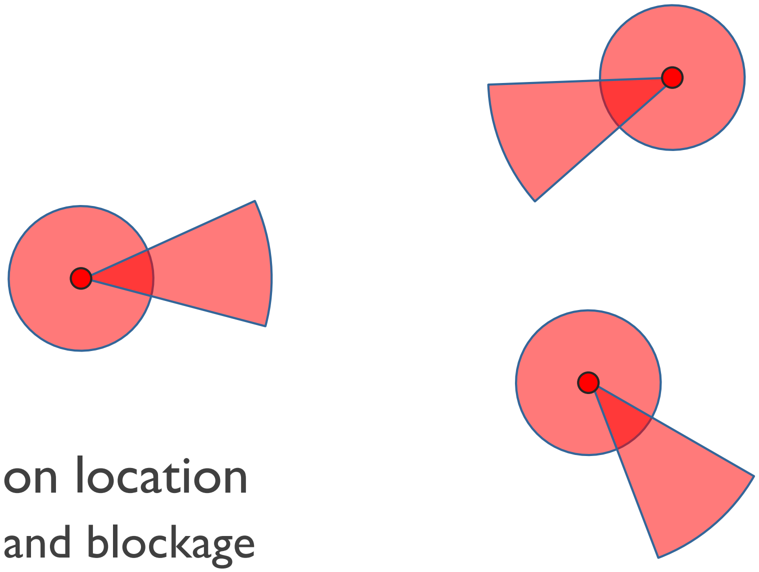
Example Blockage Probability

- Network topology
  - Disc
  - Radius $r_{in} = 6$
- Blockages
  - Circular: W=1
  - K objects



Analytical Challenges

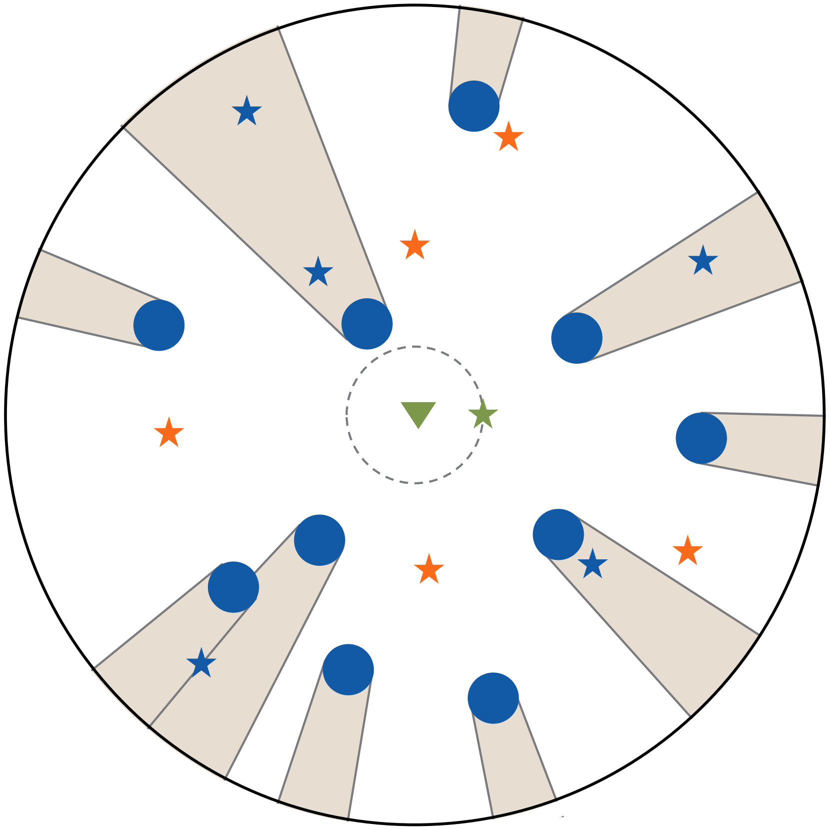
- We would like to quantify the outage or coverage probabilities.
- However, there are multiple interrelated sources of randomness:
  - Fading
  - Orientation of the antennas
  - Blockage
  - Location of the interferers
- These operate at different time scales
- Approach:
  - Determine SINR distribution conditioned on location
    - Averaged over fading, antenna orientation, and blockage
  - To handle random location, compute a meta-distribution of SINR's [1]
    - Or simply the spatial average



[4] N. Deng and M. Haenggi, "The meta distribution of the SINR in mm-Wave D2D Networks," GLOBECOM 2017.

LOS Ball Concept

- Even when conditioned on the interferer locations, computing outage probability is challenging.
  - The probability of blocking is distance dependent, and the fading factor depends on the blockage state.
- An approximation is to assume all interferers within distance r_{LOS} are LOS and those beyond are NLOS [5].
  - r_{LOS} can be found by matching areas.



[5] T. Bai and R. W. Heath, Jr., “Coverage and rate analysis for millimeter-wave cellular networks,” IEEE TWC, Feb. 2015.

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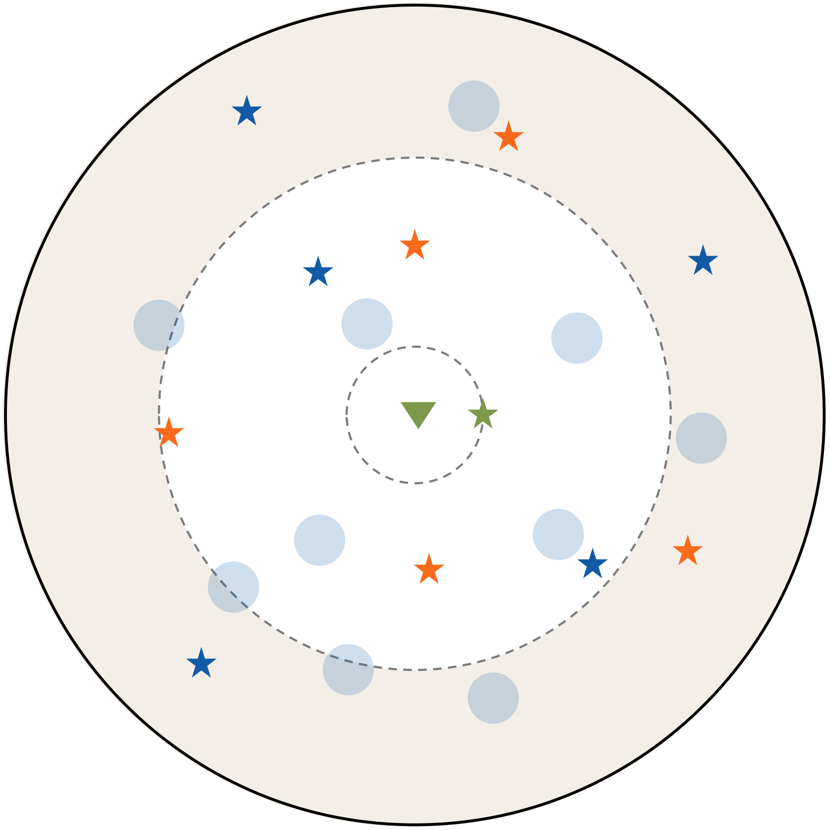


[5] T. Bai and R. W. Heath, Jr., “Coverage and rate analysis for millimeter-wave cellular networks,” IEEE TWC, Feb. 2015.

Framework for Computing Outage

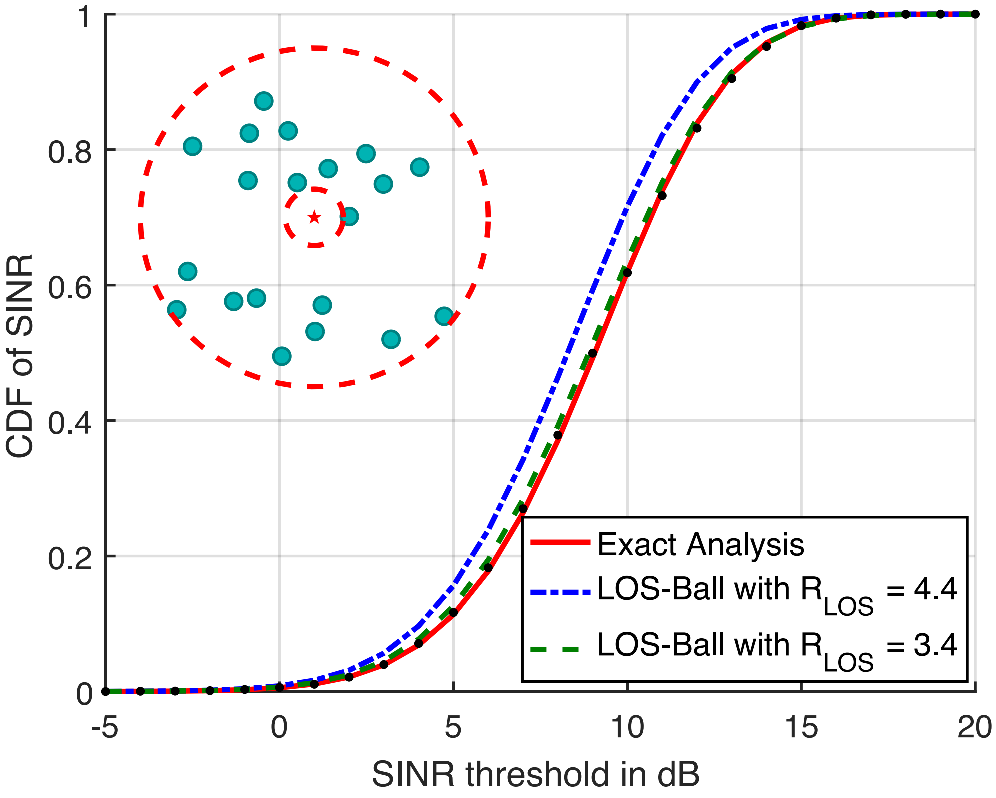
- Rather than using the LOS Ball approximation, our approach is to compute the outage probability exactly.
- The key is to define several interferer states, each with its own probability of occurrence:

State	Transmitting?	Pointing?	Blocked?	Probability
0	N	-	-	$1 - p_t$
1	Y	Y	Y	$p_b(R_i)\frac{\theta_t}{2\pi}p_t$
2	Y	Y	N	$(1 - p_b(R_i))\frac{\theta_t}{2\pi}p_t$
3	Y	N	Y	$p_b(R_i)(1 - \frac{\theta_t}{2\pi})p_t$
4	Y	N	N	$(1 - p_b(R_i))(1 - \frac{\theta_t}{2\pi})p_t$

- The (conditional) outage probability is the CDF of the SINR, where each interferer's distribution is itself randomly selected
  - Averaged over the fading and the interferer states
  - See paper for details of the derivation

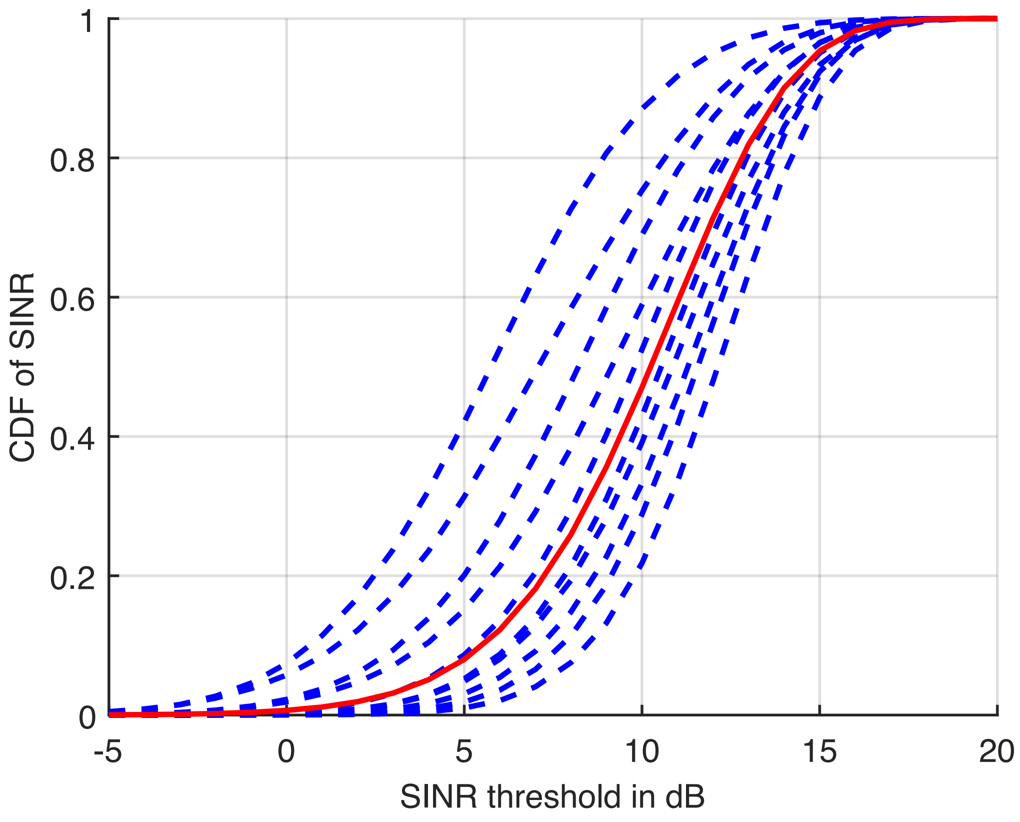
Results for Fixed Interferer Locations

- Outage probability for the pictured example network.
- Network features:
  - Disk w/ inner radius 1 and outer radius 6.
  - K=20 interferers and blockages.
  - Blockage width W=1.
- Channel parameters:
  - $m_{LOS} = 4$; $m_{NLOS} = 1$.
  - $\alpha_{LOS} = 2$; $\alpha_{NLOS} = 4$.
  - $p_t = 0.5$; SNR = 20 dB.
  - 4-element antenna arrays.
- Simulation shown by dots.



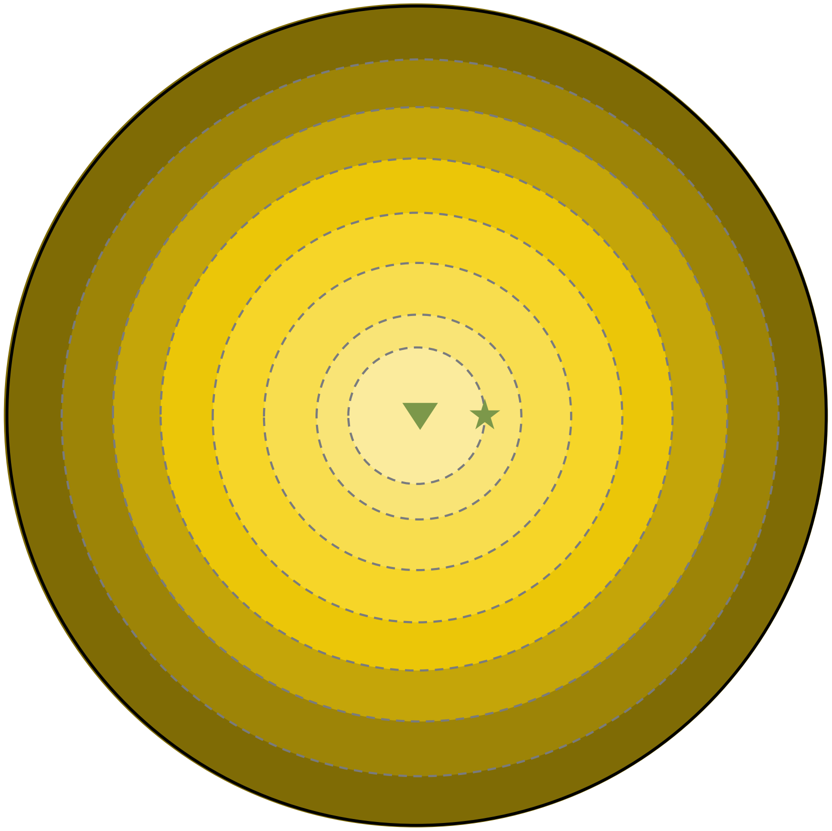
Results for Various Topologies

- Previous slide shows results for one network realization.
  - i.e., interferer locations.
- Drew 100 network realizations.
  - Red curve is average.
  - Dotted lines show outage for 10 realizations.
- Outage varies significantly with the location of the interferers.
- Analytical approach needed for characterizing the variability of the outage distribution.



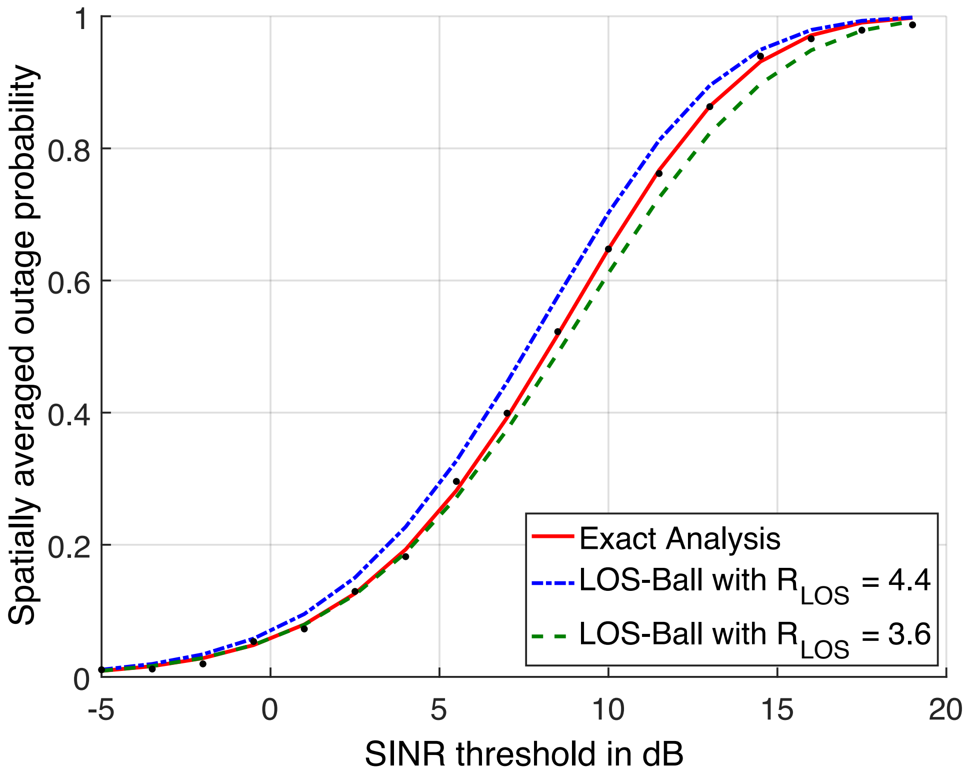
Spatial Averaging

- A first-order assessment of the effect of the variability in the outage distribution can be achieved by spatial averaging.
  - Assume interferers drawn from a binomial point process (BPP).
  - Spatial average: $E_X[F_s(s|X)]$
- The distance-dependent nature of blockage precludes the use of basic stochastic geometry.
- Our solution (the key):
  - Break network into L rings.
  - Blockage probability is constant within each ring.
  - Allow number of rings to get large.



Spatial Averaging Results

- Spatial model:
  - K=20 interferers.
  - Uniformly distributed on a disk.
- Same parameters as before:
  - $m_{LOS} = 4; m_{NLOS} = 1.$
  - $\alpha_{LOS} = 2; \alpha_{NLOS} = 2.$
  - $p_t = 0.5$; SNR = 20 dB.
  - 4-element antenna arrays
  - Radius: inner=1; outer=6.
  - Blockage width W=1.
- "Exact" analysis uses L=10 rings.
- Simulation shown by dots.



Concluding Remarks

- When the interferers are in fixed locations, the outage probability can be found in closed form, even in the presence of random blockage and randomly oriented directional antennas.
  - Key is to properly define a set of interferer states.
  - Each interferer's fading realization is drawn from a randomly chosen distribution.
- The spatial outage probability can be found in closed form over a disk.
  - Key is to break disk into rings.
  - Otherwise it can be found numerically [6].
- The approach is general and could be used for other applications where the power distribution of each interferer is drawn from a set of possibilities.
  - Frequency hopping systems.
  - More elaborate MAC protocols.
  - More accurate representation of the antenna pattern.
- Can extend from BPP to PPP by assuming the number of interferers is random, and that all signals beyond r_{out} are completely blocked.

[6] M.C. Valenti, D. Torrieri, and S. Talarico, "A direct approach to computing spatially averaged outage probability," IEEE Communications Letters, vol. 18, no. 7, pp. 1103-1106, July 2014.

QUESTIONS?