# 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**





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

<sup>1</sup>47 CFR 15.255; <sup>2</sup> ARIB STD-T69, ARIB STD-T74; <sup>3</sup> Radiocommunications Class License 2000; <sup>4</sup> 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 $\alpha$

73 GHz Directional Path loss vs. Distance in Manhattan with RX Height: 2 m & 4.06 m Using 27 dBi, 7<sup>°</sup> 3dB BW TX and RX Antennas



[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



#### **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**



### **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

### **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<sub>LOS</sub> are LOS and those beyond are NLOS [5].
  - r<sub>LOS</sub> 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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### **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	Ν	$(1 - p_b(R_i))\frac{\theta_t}{2\pi}p_t$
3	Y	Ν	Y	$p_b(R_i)(1-\frac{\theta_t}{2\pi})p_t$
4	Y	Ν	Ν	$(1 - p_b(R_i))(1 - \frac{\theta_t}{2\pi})p_t$

- 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 I and outer radius 6.
  - + K=20 interferers and blockages.
  - ✦ Blockage width W=I.
- Channel parameters:
  - +  $m_{LOS} = 4; m_{NLOS} = 1.$
  - +  $\alpha_{\text{LOS}} = 2; \alpha_{\text{NLOS}} = 4.$
  - +  $P_t = 0.5$ ; 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<sub>X</sub>[F<sub>s</sub>(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:

- +  $m_{LOS} = 4; m_{NLOS} = 1.$
- +  $\alpha_{\text{LOS}} = 2; \alpha_{\text{NLOS}} = 2.$
- +  $P_t = 0.5$ ; 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<sub>out</sub> 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?**