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
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**

<table>
<thead>
<tr>
<th>Region</th>
<th>Max transmit power</th>
<th>Max output power</th>
<th>Max EIRP</th>
<th>Bandwidth</th>
<th>Antenna gain</th>
</tr>
</thead>
<tbody>
<tr>
<td>USA</td>
<td>500 mW</td>
<td>10 mW</td>
<td>43 dBm</td>
<td>2.5 GHz</td>
<td>47 dBi</td>
</tr>
<tr>
<td>Japan</td>
<td>20 mW</td>
<td>10 dBm</td>
<td>40 dBm</td>
<td>2.5 GHz</td>
<td>51.8 dBi</td>
</tr>
<tr>
<td>Australia</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Europe</td>
<td>20 mW</td>
<td>51.8 dBm</td>
<td>51.8 dBm</td>
<td>6 GHz</td>
<td></td>
</tr>
</tbody>
</table>

Several GHz of spectrum available for worldwide operation

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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 $\alpha$

73 GHz Directional Path loss vs. Distance in Manhattan with RX Height: 2 m & 4.06 m

Using 27 dBi, 7° 3dB BW TX and RX Antennas

![Graph showing path loss vs. T-R separation with different scenarios marked with NLOS and LOS conditions.](image)

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

- 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

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 $r_{\text{LOS}}$ are LOS and those beyond are NLOS [5].
  - $r_{\text{LOS}}$ can be found by matching areas.

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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:

<table>
<thead>
<tr>
<th></th>
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</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>N</td>
<td>-</td>
<td>-</td>
<td>$1 - p_t$</td>
</tr>
<tr>
<td>1</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
<td>$p_b(R_i)\frac{\theta_x}{2\pi}p_t$</td>
</tr>
<tr>
<td>2</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
<td>$(1 - p_b(R_i))\frac{\theta_t}{2\pi}p_t$</td>
</tr>
<tr>
<td>3</td>
<td>Y</td>
<td>N</td>
<td>Y</td>
<td>$p_b(R_i)(1 - \frac{\theta_x}{2\pi})p_t$</td>
</tr>
<tr>
<td>4</td>
<td>Y</td>
<td>N</td>
<td>N</td>
<td>$(1 - p_b(R_i))(1 - \frac{\theta_x}{2\pi})p_t$</td>
</tr>
</tbody>
</table>

- 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:
  - $m_{LOS} = 4; m_{NLOS} = 1$.
  - $\alpha_{LOS} = 2; \alpha_{NLOS} = 4$.
  - $p_t = 0.5; \text{SNR} = 20 \text{ dB}$.
  - 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:
  - $m_{\text{LOS}} = 4; m_{\text{NLOS}} = 1$.
  - $\alpha_{\text{LOS}} = 2; \alpha_{\text{NLOS}} = 2$.
  - $p_t = 0.5; \text{SNR} = 20 \text{ dB}$.
  - 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.

QUESTIONS?