The Impact of Correlated Blocking on Millimeter-Wave Personal Networks

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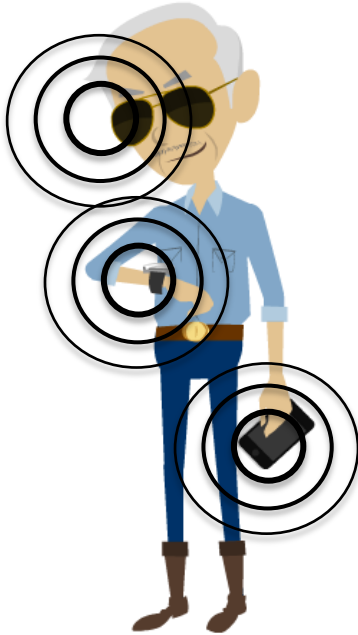
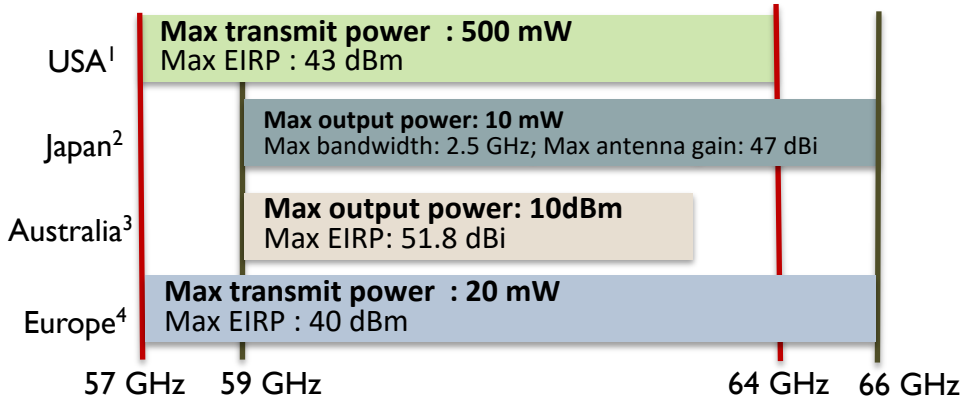
PANs, Wearables, and Virtual Reality



- Multiple devices in and around human body
  - Low-rate fitness monitors to high-rate virtual reality devices.
  - Such devices arranged into personal-area networks (PANs).
  - Military applications include training (VR) and situational awareness (AR).
- Critical challenge
  - Supporting Gbps per user in dense environments.
  - Effective operation in confined areas like VR rooms, ships, aircraft.

[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



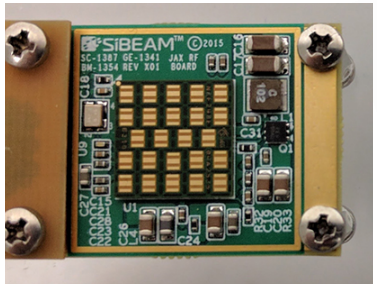
Several GHz of spectrum available for worldwide operation

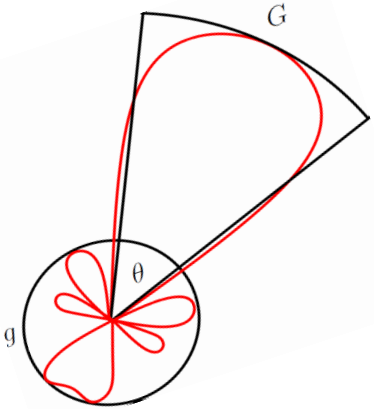
- High bandwidth and reasonable isolation
- Compact antenna arrays to provide array gains via beamforming
- Commercial products already available: IEEE 802.11ad, WirelessHD

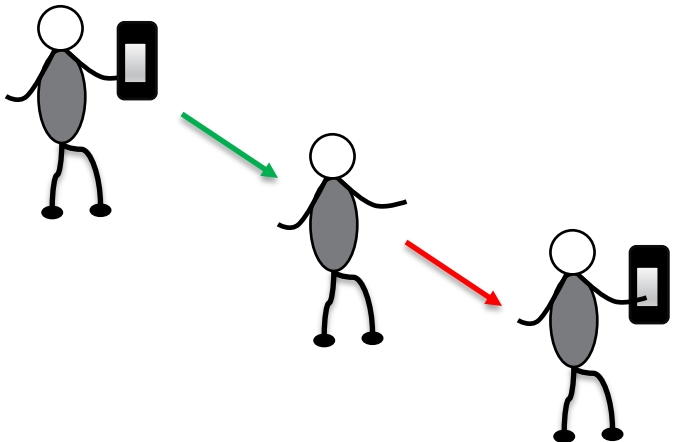
[1] 47 CFR 15.255; [2] ARIB STD-T69, ARIB STD-T74; [3] Radiocommunications Class License 2000; [4] CEPT : Official journal of the EU;

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.
  - At mmwave, human bodies are a main source of blockage.
  - Blockage isolates interference.

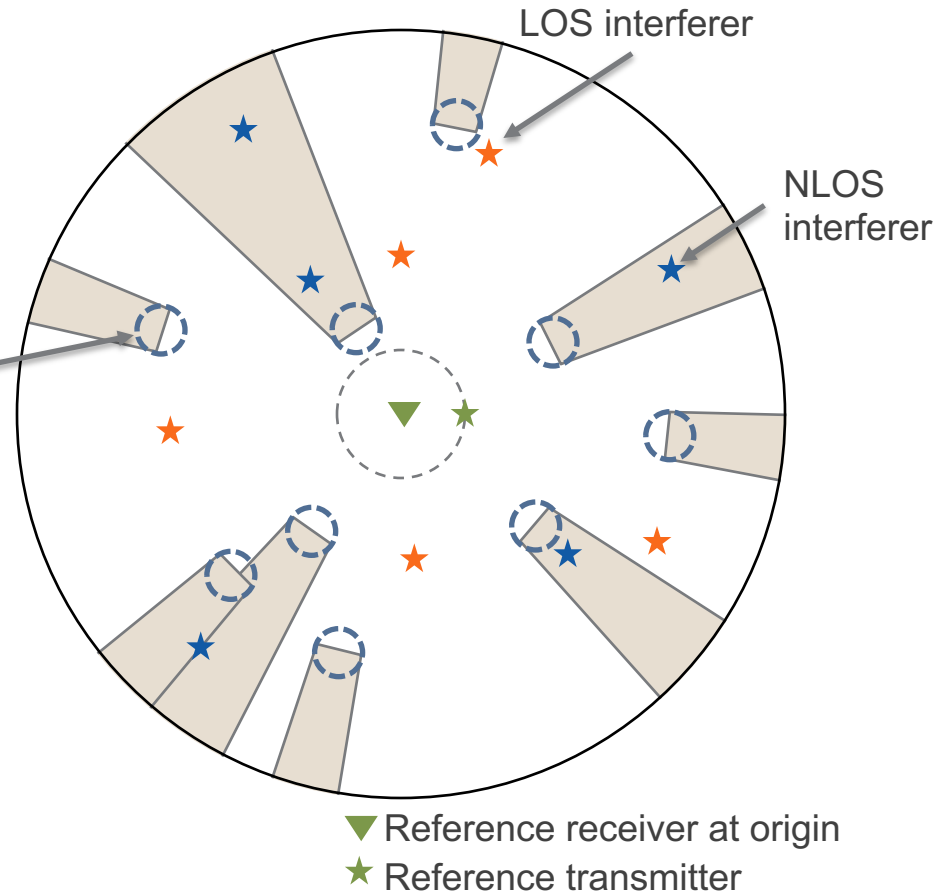






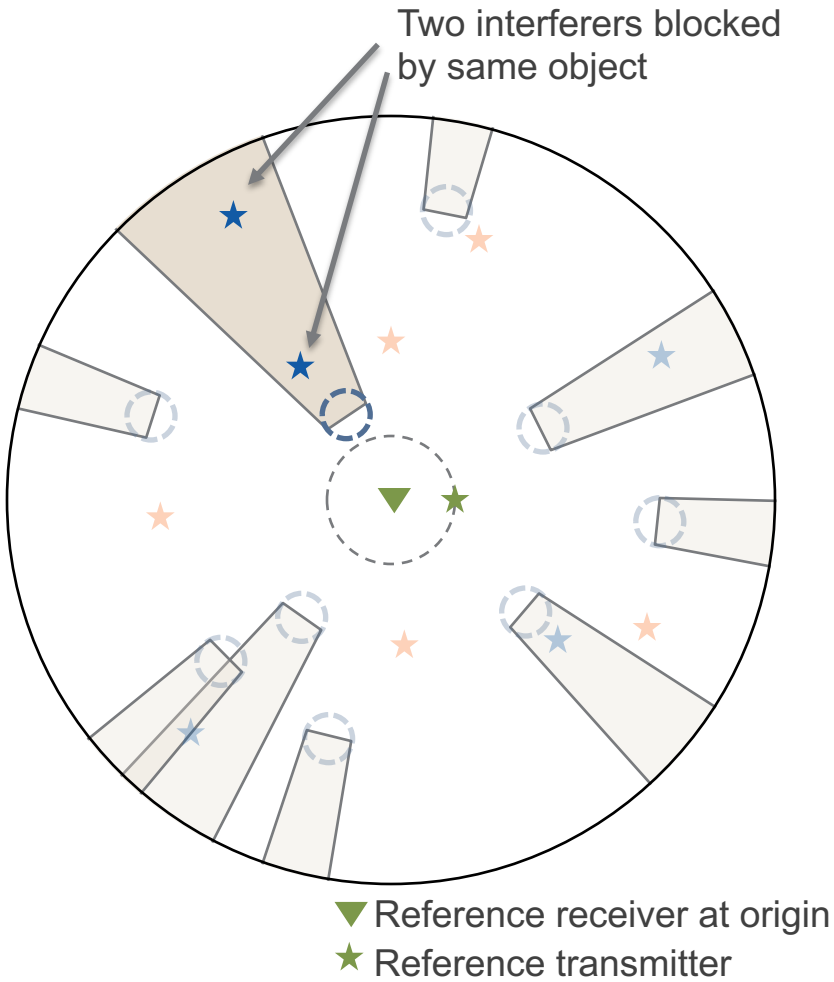
Modeling Blockage

- 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



Correlated Blockage

- Previous work has assumed that blocking is independent.
- However, blocking can be correlated.
  - One object could block more than one interferer
  - Correlation arises even if the blockage process is independent
- Goal of this paper is to characterize the impact of corelated blocking.



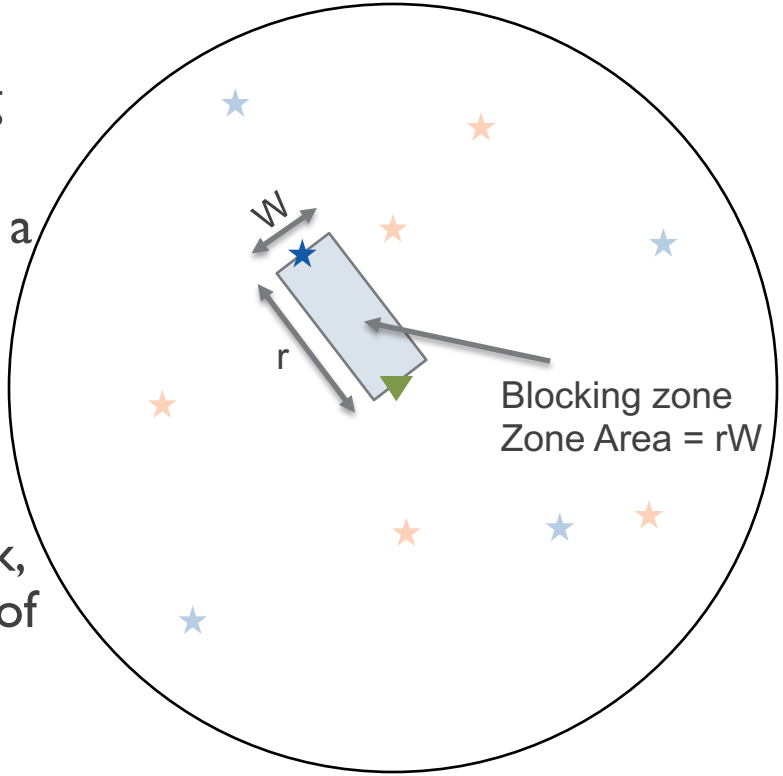
Computing Blockage Probability

- 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:

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

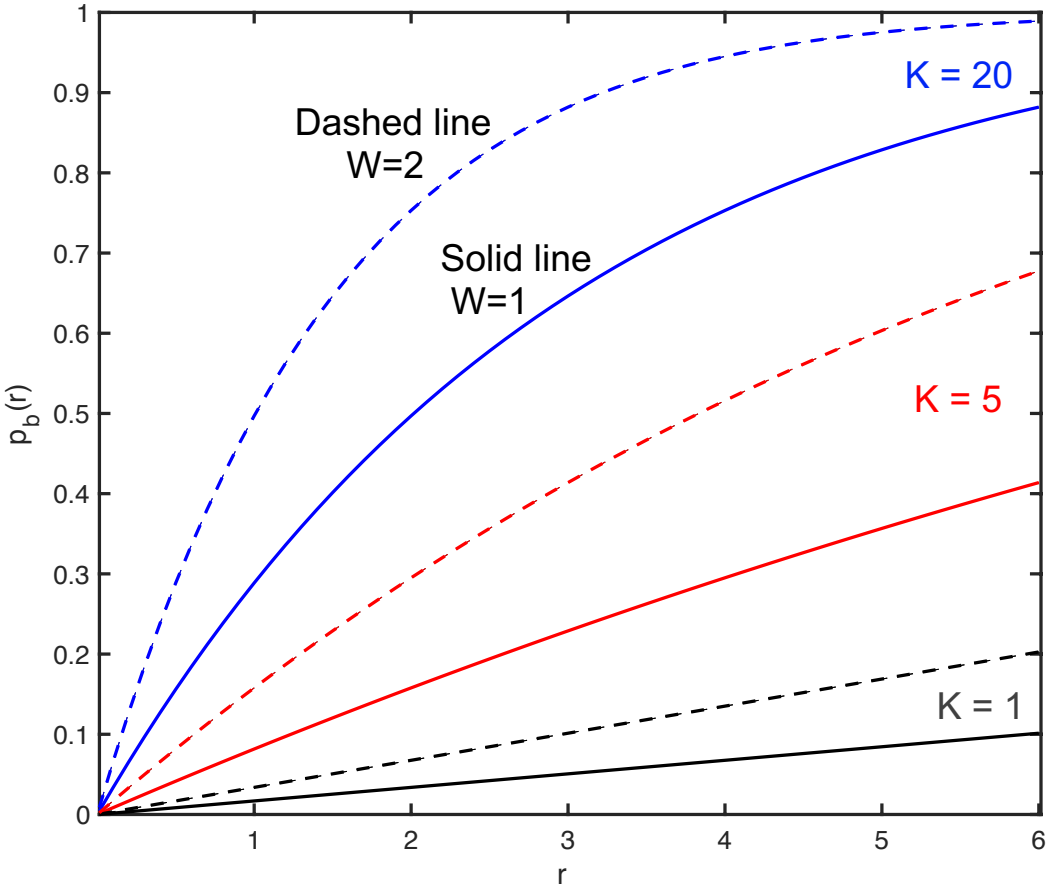
- If there are K objects in the network, then the interferer is blocked if any of them are in its blocking zone:

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



Blockage Probability (An Example)

- Network topology
  - Radius-6 disc
  - $A=6^2\pi$
- Blockages
  - W = 1 or 2
  - K = 1, 5, or 20



Outage Probability

- Assuming that LOS paths are AWGN and NLOS paths are completely attenuated, the SINR at the receiver is:

$$\mathrm{SINR} = \frac{1}{\mathrm{SNR}^{-1} + \sum_{i=1}^{2}(1 - B_i)\left(\frac{R_i}{R_o}\right)^{-\alpha}}$$

R_0 distance to source transmitter.
R_i distance to i^{th} interferer, $i = \{1, 2\}$.
$B_i = 1$ when the ith interferer is blocked.
$B_i = 0$ when the ith interferer is not blocked.

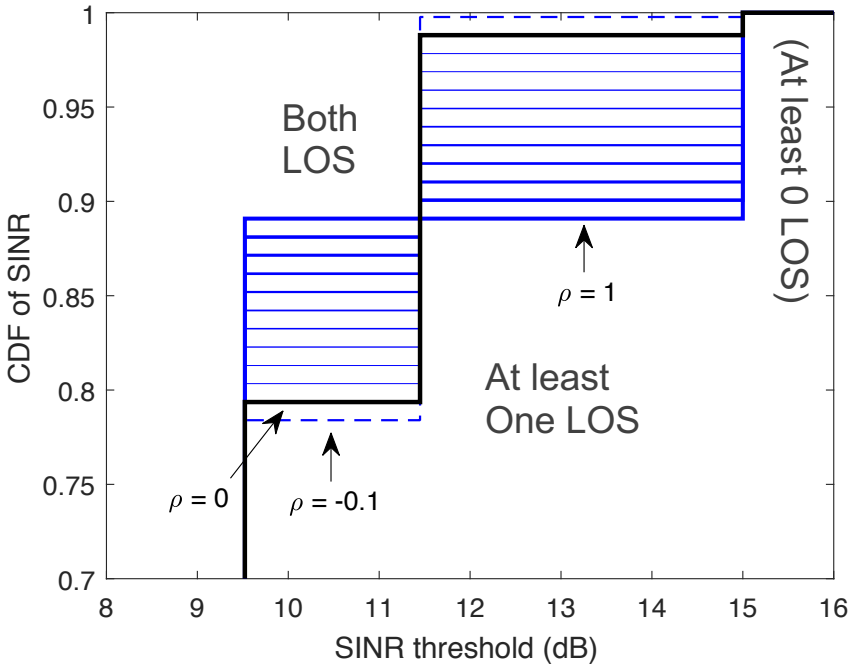
- An outage occurs whenever SINR < β
- The outage probability is the CDF of the SINR:

$$F_{\mathrm{SINR}}(\beta) \quad = \quad P\left[\mathrm{SINR} \leq \beta\right]$$

- The CDF depends on the statistics of (B_1, B_2), which is a pair of correlated Bernoulli random variables with correlation coefficient ρ.

How Blocking Correlation Impacts Outage

- Example:
  - 2 interferers at same distance
    - $R_1 = R_2 = 5$
  - $p_b(r) = 0.6$, corresponding to $W=1$, $K = 20$, $A=6^2\pi$, $r = 5$.
  - SNR = 15 dB and $\alpha = 2$.
- Variable correlation coefficient ρ
  - ρ varies in increments of 0.1
- SINR values:
  - 9.5 dB = both interferers LOS
  - 11.4 dB = one LOS (one blocked)
  - 15 dB = zero LOS (both blocked)



Computing the Blockage Correlation Coefficient

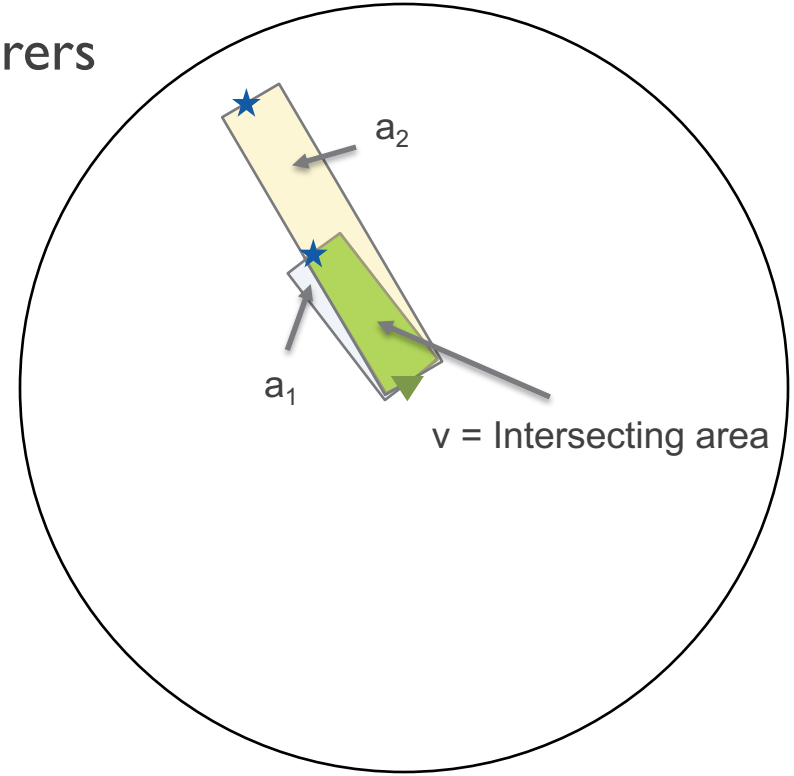
- The probability that both interferers are LOS (not blocked) is:

$$p_{B_1,B_2}(0,0) = \left(1 - \frac{a_1 + a_2 - v}{A}\right)^K$$

- The correlation coefficient is:

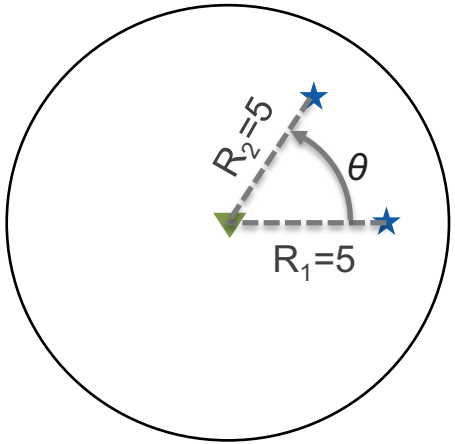
$$\rho = \frac{p_{B_1,B_2}(0,0) - q_1 q_2}{\sqrt{p_1 p_2 q_1 q_2}}$$

$$\boxed{\begin{aligned} q_i &= 1 - p_i \\ p_i &= p_b(R_i) \\ i &= \{1,2\} \end{aligned}}$$

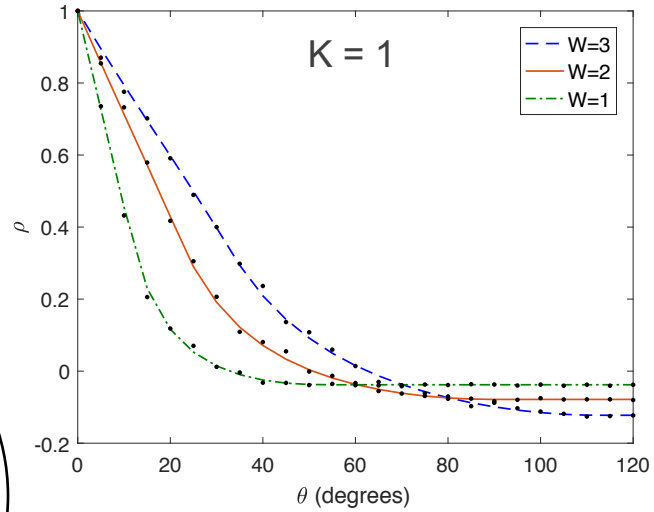


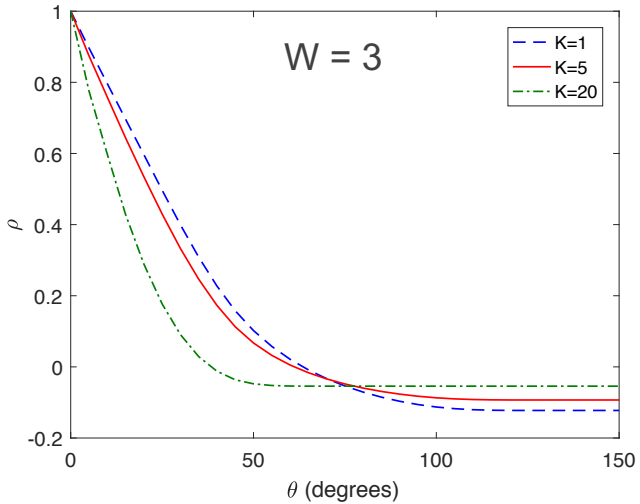
The Correlation Coefficient

- ρ depends on the angular separation θ between the interferers.
- Example network:
  - $R_1 = R_2 = 5$
  - $A=6^2\pi$



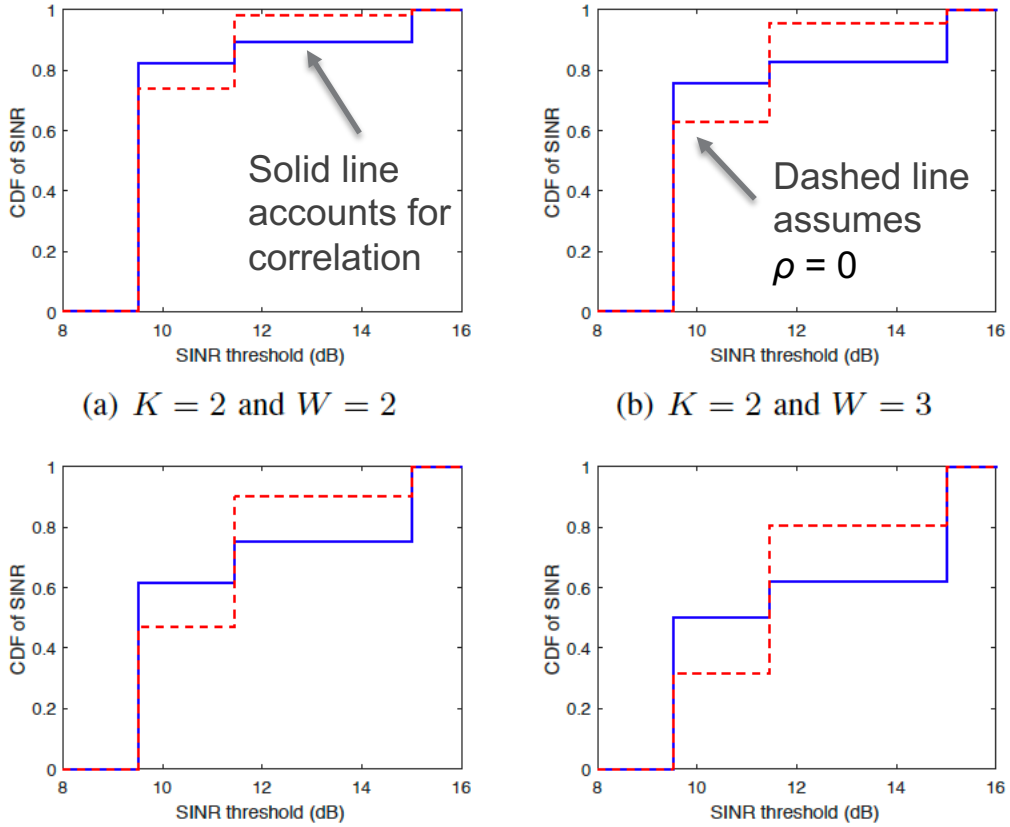
- Variable blockage width W
- Variable number of interferers K.
- Simulation shown by dots.





Outage vs. β

- CDF of the SINR
- Network:
  - $R_1 = R_2 = 5$
  - $\theta = 25°$
  - $A=6^2\pi$
  - SNR = 15 dB and $\alpha = 2$
  - Variable K & W
- Comparison:
  - Considering the correlation (solid blue line)
  - Ignoring the correlation (dashed red line)
  - Gap = ρpq

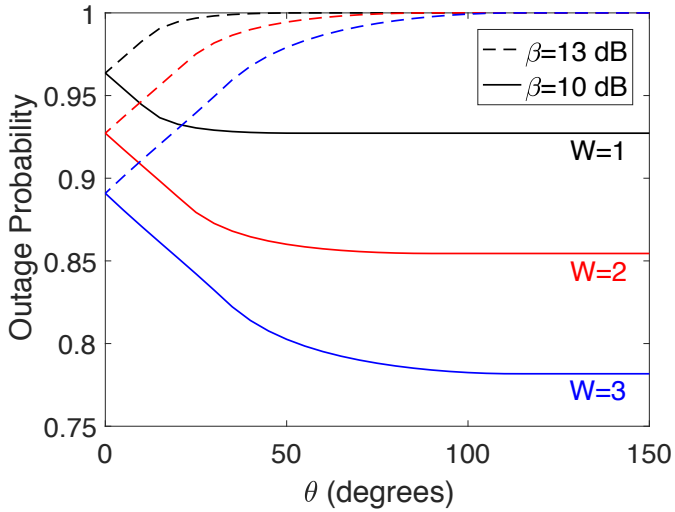


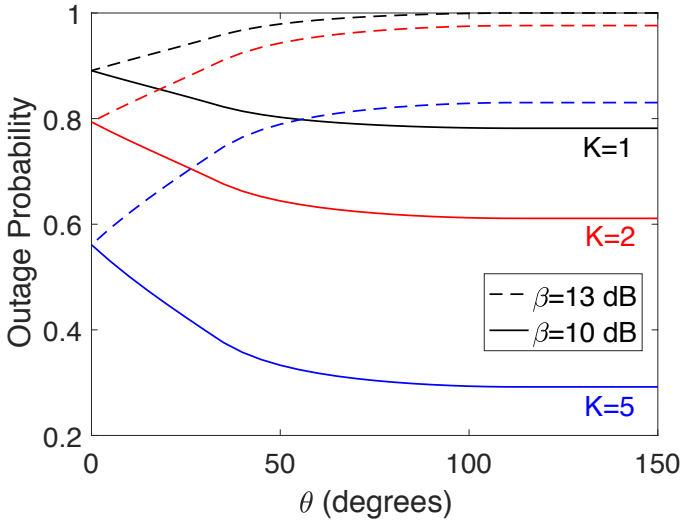
(a) $K = 2$ and $W = 2$ (b) $K = 2$ and $W = 3$

(c) $K = 5$ and $W = 2$ (d) $K = 5$ and $W = 3$

Outage vs. θ

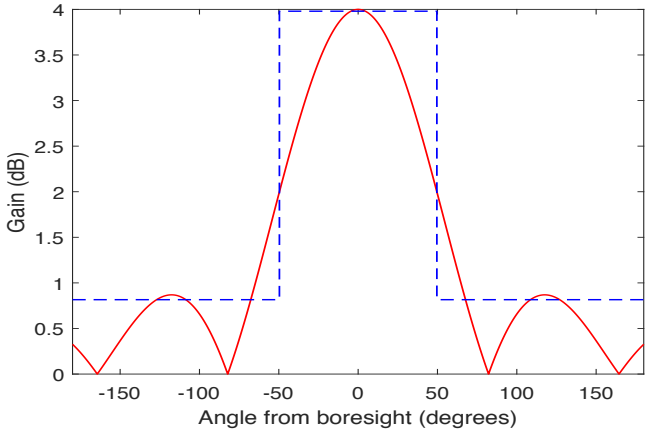
- Outage vs. angular separation
- Network:
  - $R_1 = R_2 = 5$
  - Variable θ
  - $A=6^2\pi$
  - SNR = 15 dB and $\alpha = 2$
  - Variable K & W
- Outage at two thresholds:
  - β = 10 dB (both LOS)
  - β = 13 dB (at least one LOS)
- Curves account for correlation

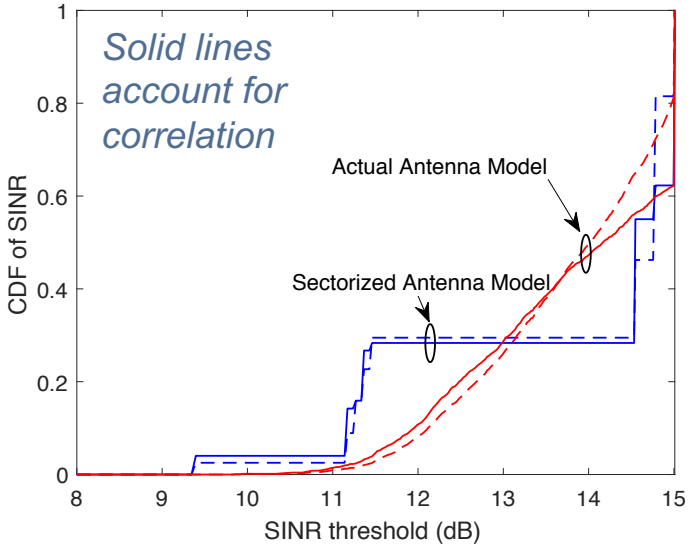




Antenna Directivity

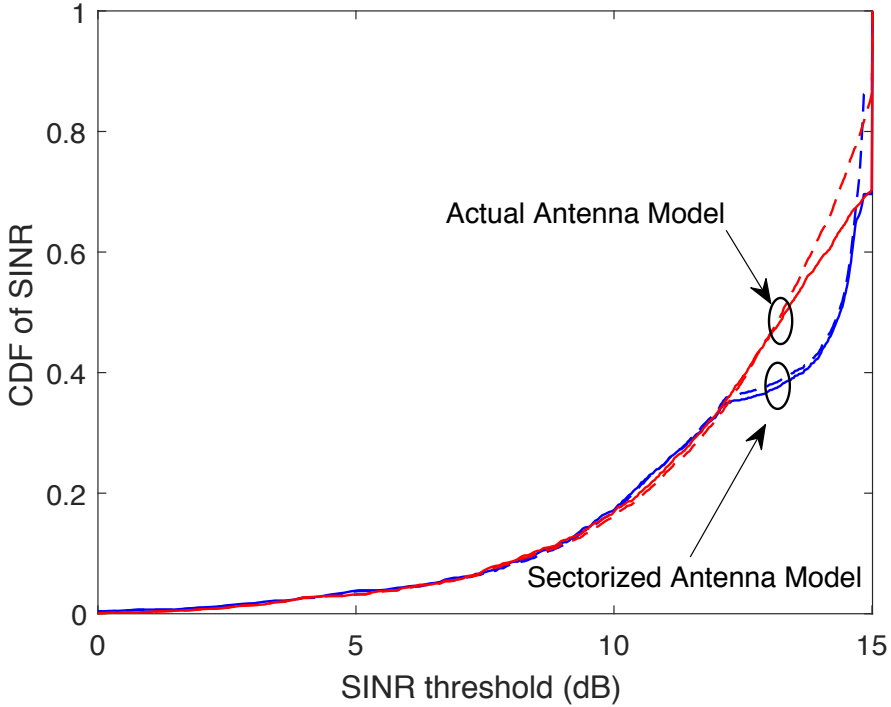
- Previous results assumed the use of omnidirectional antennas.
  - mmWave systems typically employ directional antennas to overcome path loss
- Here, we consider a 4-element antenna
  - Each interferer points in random direction
  - Both actual and sectorized approximation considered.
- Key parameters:
  - K=5, W=2
  - $R_1 = 4, R_2 = 5, \theta = 25°$





Randomly Located Interferers

- In previous slides, interferers are in fixed locations.
- Here, we vary their location by drawing them from a BPP
  - Binomial point process
  - Independently and uniformly placed on the radius-6 circle
- Assumes 4-element antenna array
- Spatial averaging done via MC simulation.
  - Each trial corresponds to one network realization
  - 1000 trials



Concluding Remarks

- Blocking may be correlated, even when the blockages themselves are independently placed.
  - Correlation more pronounced when there are only a few blockages or when the blockages are large.
  - The outage probability is more accurately computed if it accounts for blockage correlation.
- Outage also depends on antenna directivity.
  - Antenna patterns need to be taken into account.
- Future work:
  - Considering more than 2 interferers.
  - More sophisticated channel models: Fading, reflection, variable path loss.
  - Analytical approach to handling randomly located interferers.

QUESTIONS?