Driven by Capacity or Blockage? A Millimeter Wave Blockage Analysis

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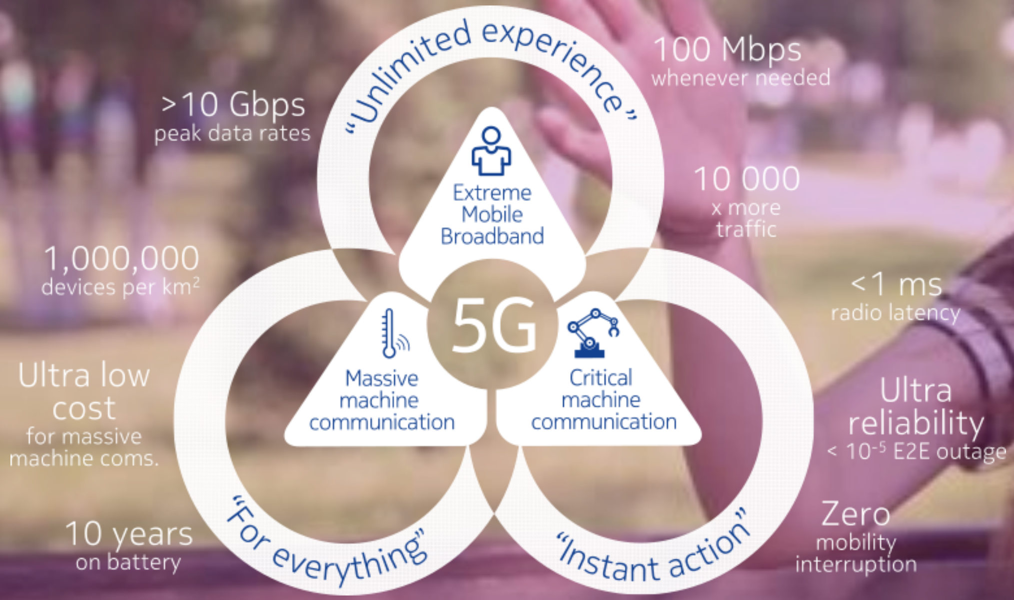
QoS Requirements



Source: Nokia, VR/AR in the 5G Era
NEM Summit November 23, 2016

AR/VR requirements

Data Rates	**100Mbps-1Gbps**
Interruptions	0.1/min
Video stall (pause)	<10 ms

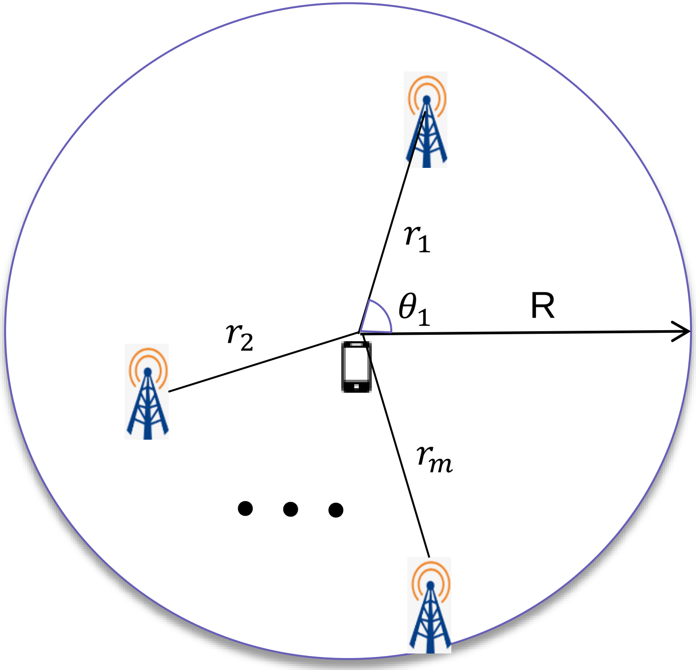
(otherwise causes nausea or sickness)

Base station Model

- A typical user at Origin
- Consider the coverage range R m
- Density of BS λ_T BS/m^2
- Number of BS $m_T \sim \text{Poission}(\lambda_T \pi R^2)$
- Location of BS (r_i, θ_i) – Uniform in disc B(o,R)
- BS height h_T m. User's height h_R m

m ~ Poisson($\lambda_T \pi R^2$)

Given m,
BS location ~ Uniform

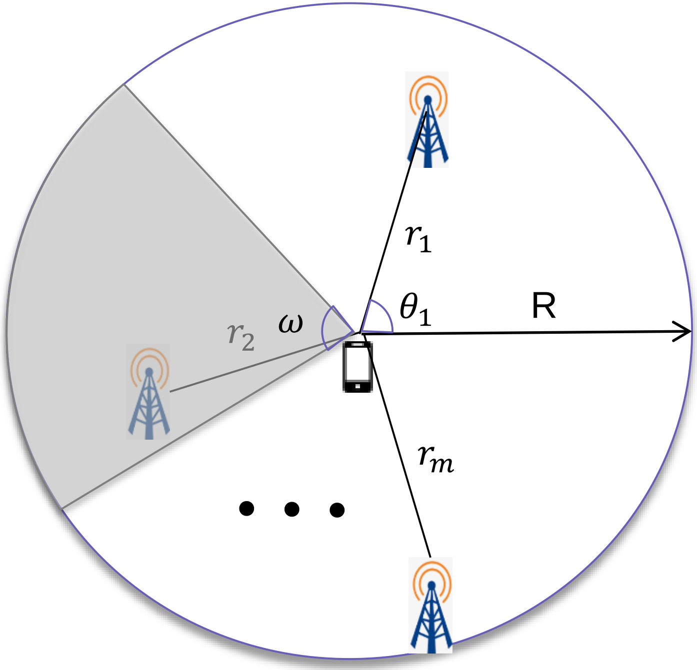


Self-blockage Model

- Self-blockage zone: a sector of angle ω
- All BSs in self-blockage zone are blocked
- Number of BS N outside this zone follow

$$P_N(n) = \frac{[p\lambda_T \pi R^2]^n}{n!} e^{-p\lambda_T \pi R^2}$$

- Where $p = 1 - \frac{\omega}{2\pi}$
- Coverage event $\mathcal{C}$:
  - At least one BS not blocked by user's body
- Probability of coverage: $P(\mathcal{C}) = 1 - e^{-p\lambda_T \pi R^2}$



Dynamic Blockage Model

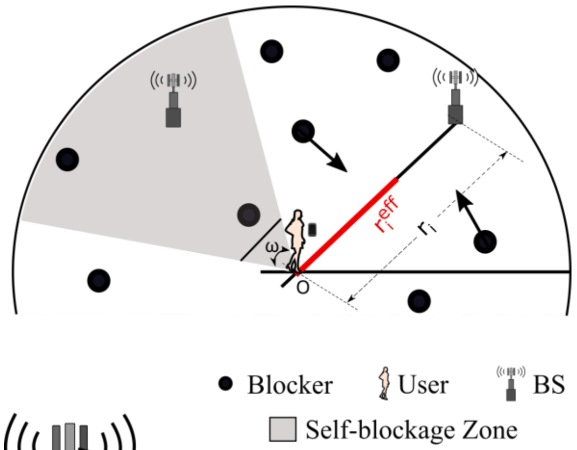
- Moving people and vehicles (mobile blockers)
- Blocker density λ_B bl/m^2, height h_B m, velocity V m/s
- Effective blockage zone distance r_i^{eff}

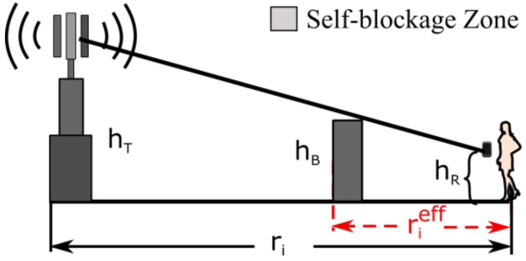
$$r_i^{eff} = \frac{(h_B - h_R)}{(h_T - h_R)} r_i$$

- Blocker Arrival Rate ~ Poisson(α_i)

$$\alpha_i = \underbrace{\frac{2}{\pi}\lambda_B V \frac{(h_B - h_R)}{(h_T - h_R)}}_{C \text{ (proportional to } \lambda_B)} r_i = C r_i$$

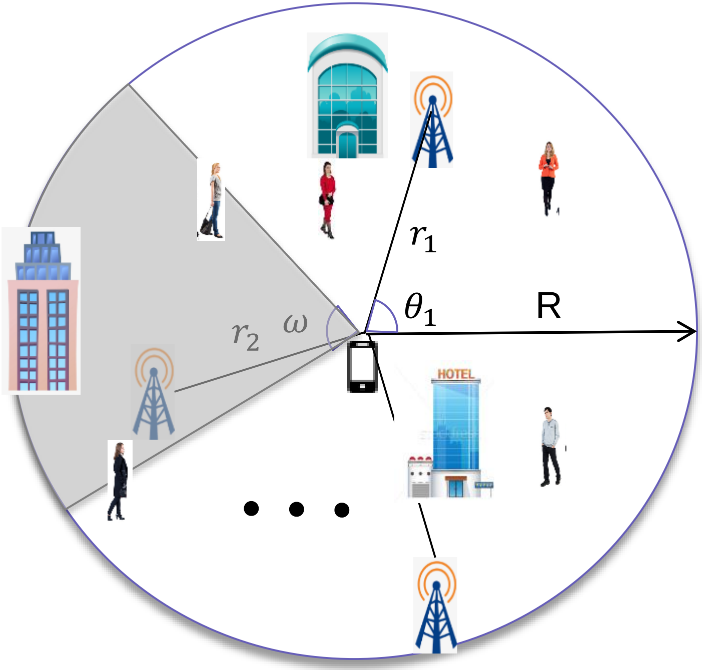
- Blockage duration ~ Exponential(μ)





Blockage scenarios

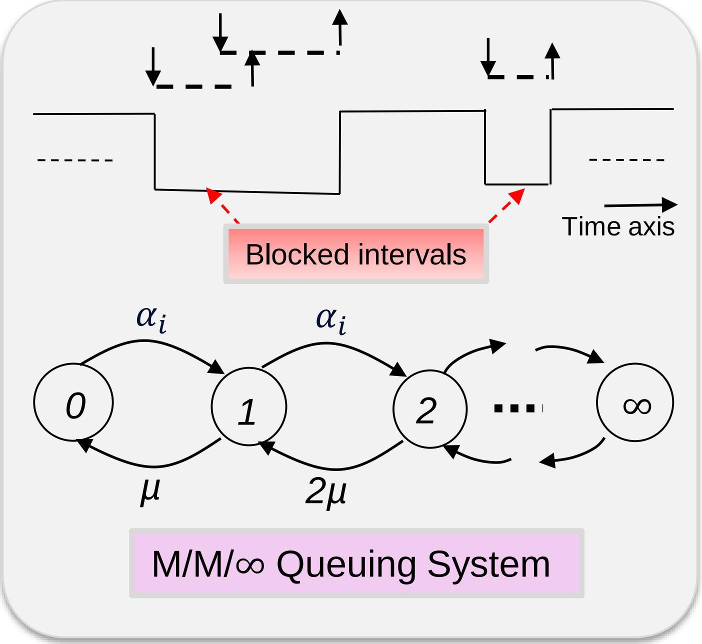
- **Open park scenario:** Focus of this paper
  - LOS analysis
  - Dynamic and self-blockage
- **Urban scenario:** Extension of this paper available on ArXiv*
  - Buildings may cause static blockage
  - LOS as well as NLOS paths

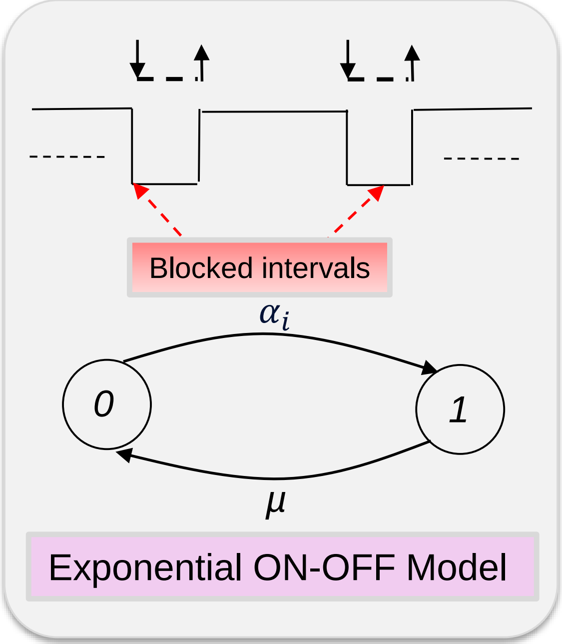


*Jain IK, Kumar R, Panwar S. Can Millimeter Wave Cellular Systems provide High Reliability and Low Latency? An analysis of the impact of Mobile Blockers. arXiv preprint arXiv:1807.04388. 2018 Jul 12.

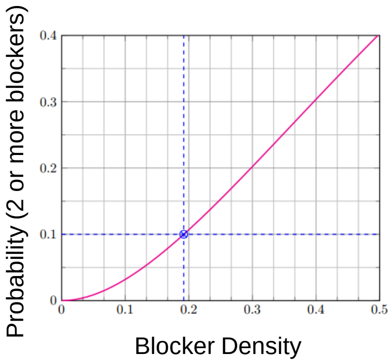
Generalized Blockage Model: an approximation

- Approximation: No more than one blocker at a time blocking the LOS link





Explaination:
For λ_B < 0.2 bl/m^2 the Probability of having 2 or more blockers < 0.1

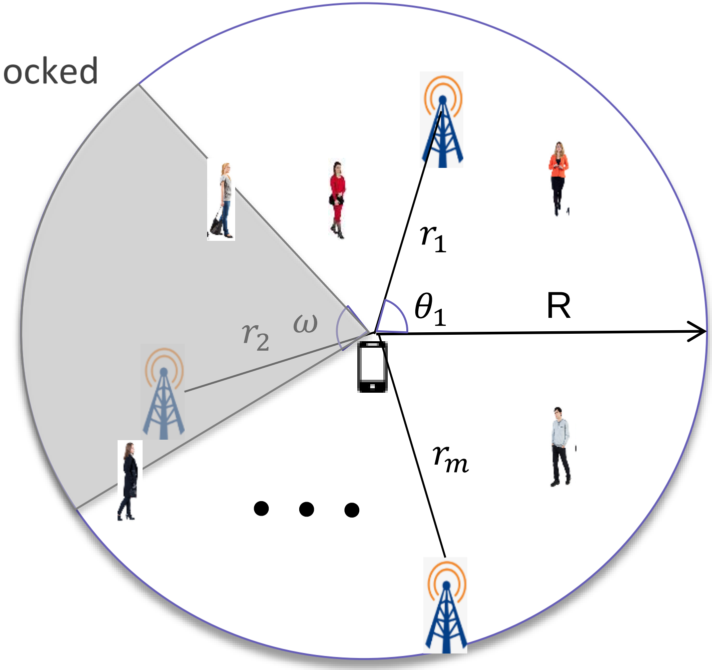


Simultaneous Blockage

- Blockage is defined when all BSs are simultaneously blocked
- Consider r.v. B indicating blockage of all n links

$$P(B|N,\{R_i\}) = \prod_{i=1}^{n} \frac{\alpha_i/\mu}{1+\alpha_i/\mu} = \prod_{i=1}^{n} \frac{(C/\mu)r_i}{1+(C/\mu)r_i}.$$

- Integrate over distributions of N and R_i



Macro-Diversity

UE can quickly switch between BSs in case of blockage events.

Blockage Probability

- Unconditional/Marginal Blockage Probability

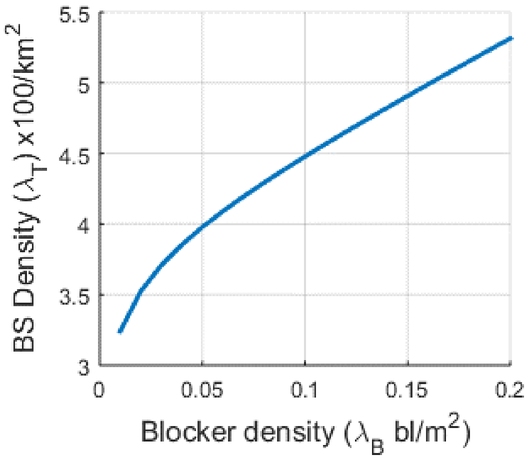
$$P_B = e^{-ap\lambda_T \pi R^2}$$

where, $a = \frac{2\mu}{RC} - \frac{2\mu^2}{R^2C^2}\log\left(1 + \frac{RC}{\mu}\right)$

$$a \approx 1 - \frac{2RC}{3\mu},\ p = 1 - \frac{\omega}{2\pi}$$

- We know that C is proportional to blocker density
- Blockage ↑ when λ_B ↑ or λ_T ↓ or R ↓ or μ ↓
- Pure blockage (given Coverage) $P(B|\mathcal{C})$

$$P(B|\mathcal{C}) = \frac{e^{-ap\lambda_T \pi R^2} - e^{-p\lambda_T \pi R^2}}{1 - e^{-p\lambda_T \pi R^2}}$$



BS Density scales linearly with blocker density

Blockage Frequency

- Consider r.v. ζ_B indicating blockage of all BSs-UE link

$$\zeta_B = n\mu P(B|N, \{R_i\}) = n\mu \prod_{i=1}^{n} \frac{(C/\mu)r_i}{1 + (C/\mu)r_i}$$

- Expected blockage frequency given the coverage

$$\mathbb{E}\left[\zeta_B|\mathcal{C}\right] = \frac{\mu(1-a)p\lambda_T\pi R^2 e^{-ap\lambda_T\pi R^2}}{1 - e^{-p\lambda_T\pi R^2}}$$

Blockage Duration

- Consider r.v. T_B indicating blockage of all BSs-UE link

$$\mathbb{E}[T_B|N] = \frac{1}{n\mu}$$

- Expected blockage duration given coverage

$$\mathbb{E}\left[T_B|\mathcal{C}\right] = \frac{e^{-p\lambda_T\pi R^2}}{\mu\left(1 - e^{-p\lambda_T\pi R^2}\right)} Ei\left[p\lambda_T\pi R^2\right].$$

$$Ei\left[p\lambda_T\pi R^2\right] = \sum_{n=1}^{\infty} \frac{[p\lambda_T\pi R^2]^n}{nn!}.$$

Simulation setup

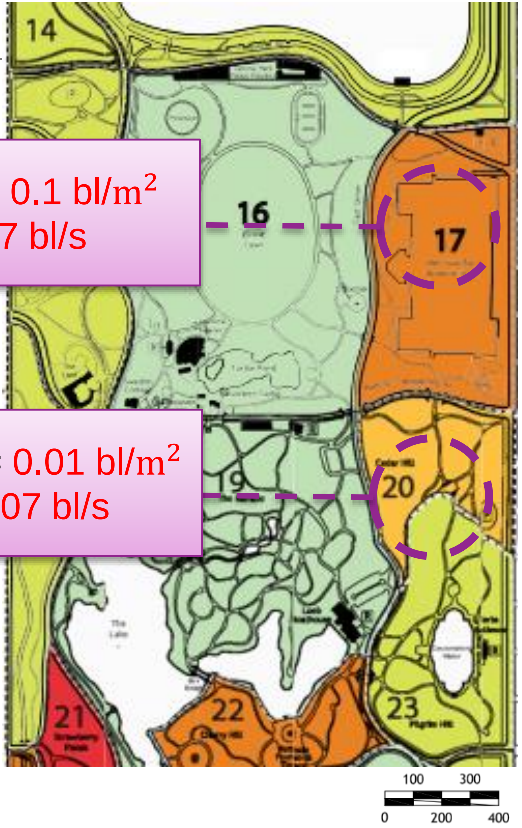
- MATLAB Simulations
- Random way-point mobility model (blockers)

Parameters	Values
Radius R	100 m
Velocity of blockers V	1 m/s
Height of Blockers h_B	1.8 m
Height of UE h_R	1.4 m
Height of APs h_T	6 m
Expected blockage duration $1/\mu$	1/2 s

Table I: Simulation parameters

Blocker Density= 0.1 bl/m^2
Blocking rate= 0.7 bl/s

Blocker Density= 0.01 bl/m^2
Blocking rate= 0.07 bl/s



Results: Blockage Probability

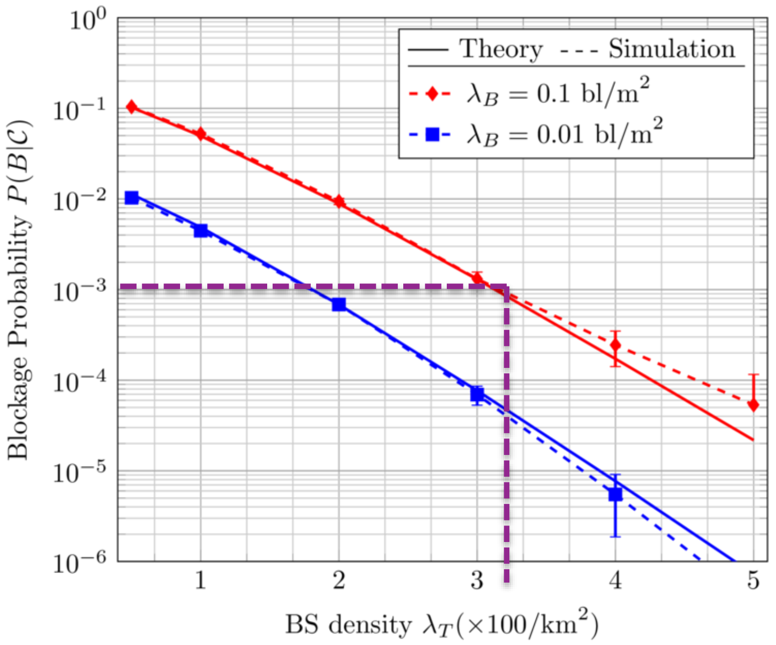
For blockage probability =1e-3, and blocker density 0.1bl/m^2, we need around >300 BS/km^2 (cell radius ~33m).

Capacity requirements can be satisfied with BS density of around 100 BS/km^2.

mmWave wireless networks may be *blockage limited* instead of *capacity limited.*

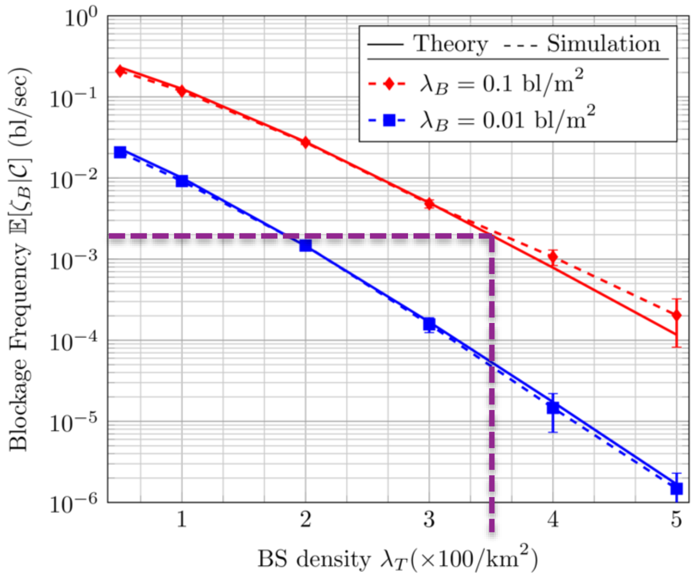
A potential solution can be fallback to LTE or Local WiFi networks.

- Conditional Blockage Probability (given coverage)



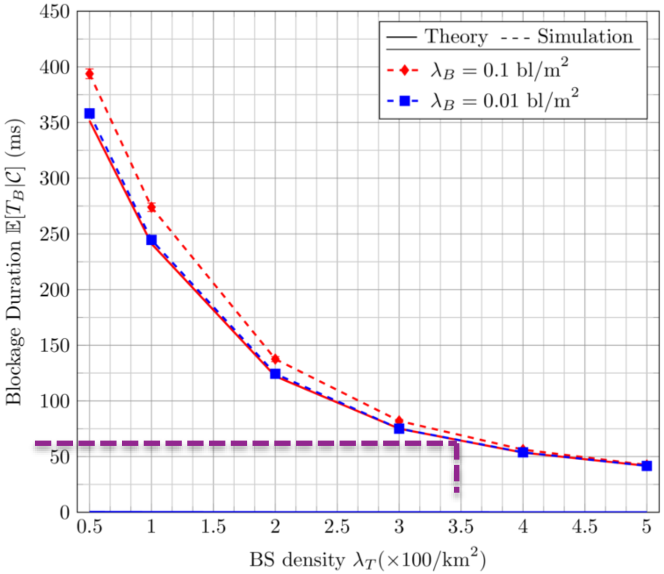
Blockage Frequency

For blockage frequency ~0.1 interruptions per min, we need even higher BS density.



Blockage Duration

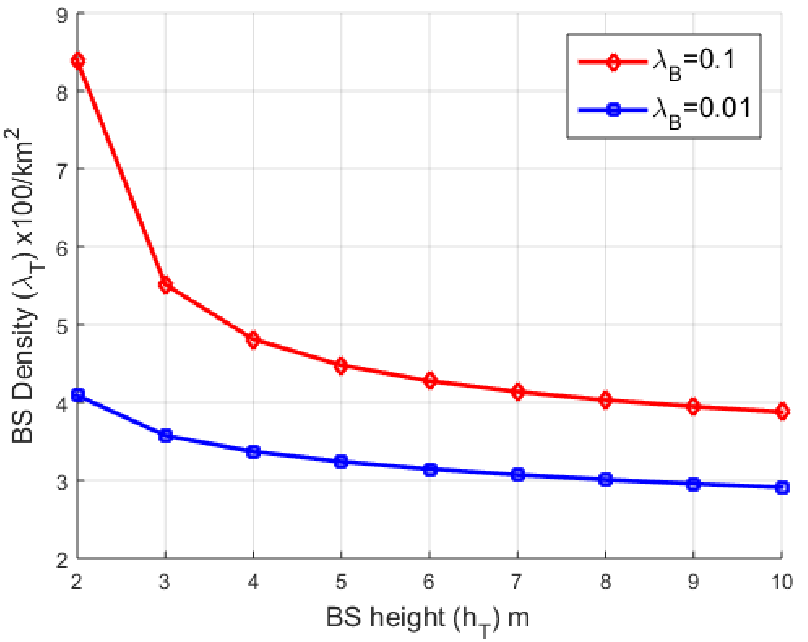
Even at high BS density, the blockage duration is ~ 50 ms.



BS density-height trade-off

Increasing BS height from 4 m to 8 m can reduce the BS density by only 20%.

Optimal BS density-height trade-off can also be obtained through closed-form expression of blockage probability.



Related Work

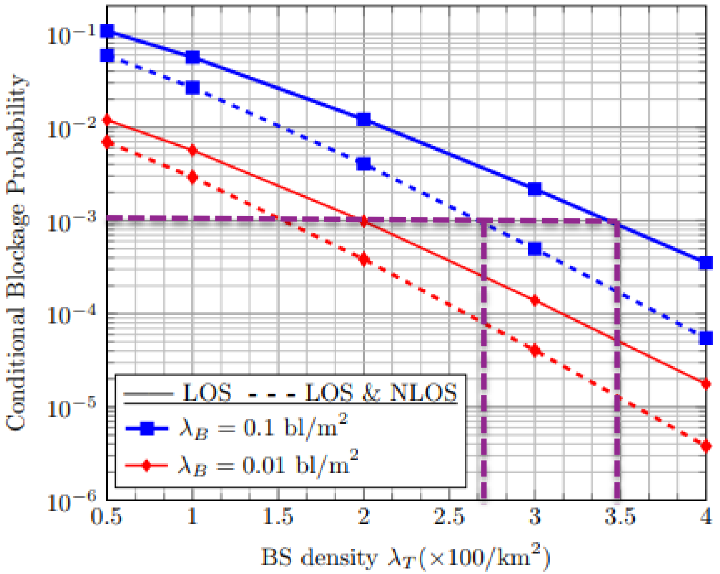
- Robert Heath *et al*. (UT Austin) [1,2,3]
  - Random shape theory: Static blockage due to buildings and permanent structures
  - Coverage and rate analysis (no reliability study)
  - Macrodiversity with correlated *static* blockages [3]
- MacCartney *et al.* (NYU Wireless) [4,5]
  - Model based on experimental measurements or ray tracing data
  - Markov model without temporal correlation
- Intel and TUT Finland group [6,7]
  - Dynamic blockage model based on M/G/∞ arrival process of blockers
  - Macrodiversity is not considered due to model complexity
- Qualcomm [8]
  - Analysed self-blockage for different portrait and landscape modes of handheld devices

Related Work (References)

1. Bai, Tianyang, and Robert W. Heath. "Coverage and rate analysis for millimeter-wave cellular networks." *IEEE Transactions on Wireless Communications* 14.2 (2015): 1100-1114.
2. Bai, Tianyang, Rahul Vaze, and Robert W. Heath. "Using random shape theory to model blockage in random cellular networks." *Signal Processing and Communications (SPCOM), 2012 International Conference on*. IEEE, 2012.
3. Gupta, Abhishek K., Jeffrey G. Andrews, and Robert W. Heath. "Macrodiversity in cellular networks with random blockages." *IEEE Transactions on Wireless Communications* 17.2 (2018): 996-1010.
4. Akdeniz, Mustafa Riza, et al. "Millimeter wave channel modeling and cellular capacity evaluation." *IEEE journal on selected areas in communications* 32.6 (2014): 1164-1179.
5. MacCartney, George R., Theodore S. Rappaport, and Sundeep Rangan. "Rapid fading due to human blockage in pedestrian crowds at 5g millimeter-wave frequencies." *GLOBECOM 2017-2017 IEEE Global Communications Conference*. IEEE, 2017.
6. Gapeyenko, Margarita, et al. "On the temporal effects of mobile blockers in urban millimeter-wave cellular scenarios." *IEEE Transactions on Vehicular Technology* (2017).
7. Petrov, Vitaly, et al. "Dynamic multi-connectivity performance in ultra-dense urban mmWave deployments." IEEE Journal on Selected Areas in Communications 35.9 (2017): 2038-2055.
8. Raghavan, Vasanthan, et al. "Statistical blockage modeling and robustness of beamforming in millimeter wave systems." *arXiv preprint arXiv:1801.03346* (2018).

Summary and Extended Results (avl. on arxiv*)

- For open area: Deterministic Network (with Hexagonal Cells) require significantly lower density of BS to meet reliability requirements.
- For urban scenario:
  - Static blockage: For blockage probability 1e-3 a high BS density (350 BS/km^2) is required.
  - NLOS paths: Reduces the BS density to 270 BS/km^2 but, still the requirement is very high.



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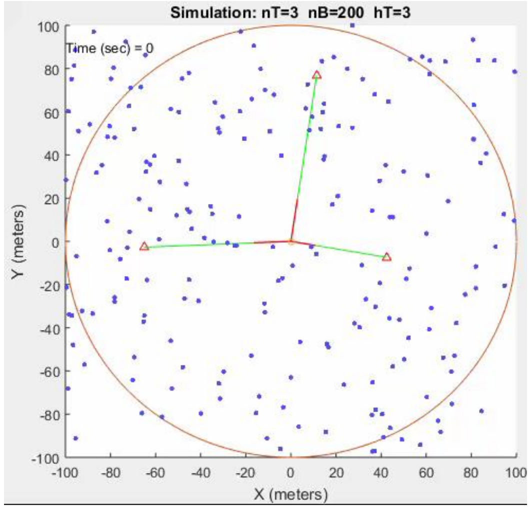
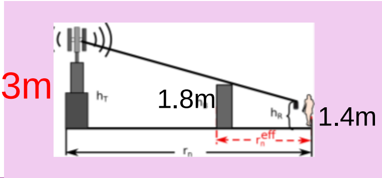
Thank You

Questions?

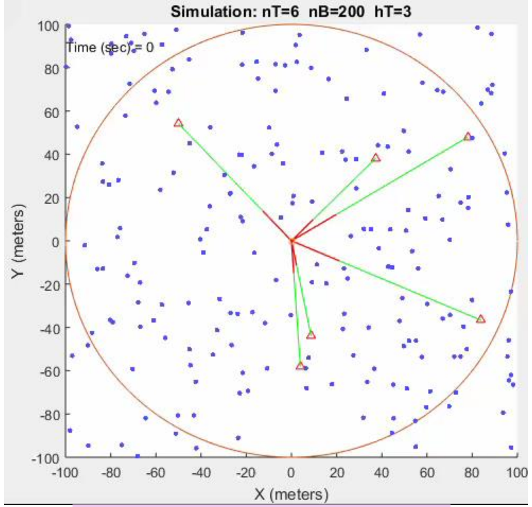
Simulation: Random Way Point Mobility

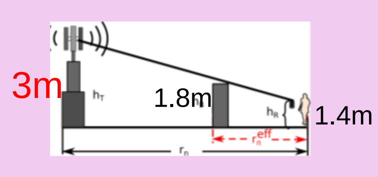
BS Density: 1 (x100/km^2)



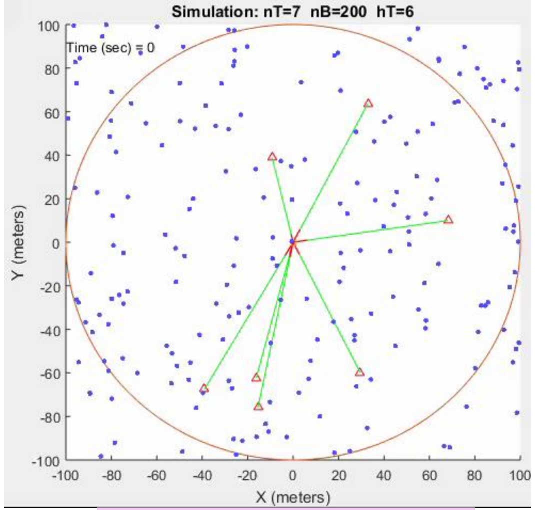


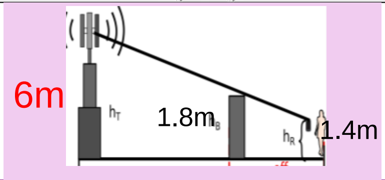
BS Density: 2 (x100/km^2)





BS Density: 2 (x100/km^2)





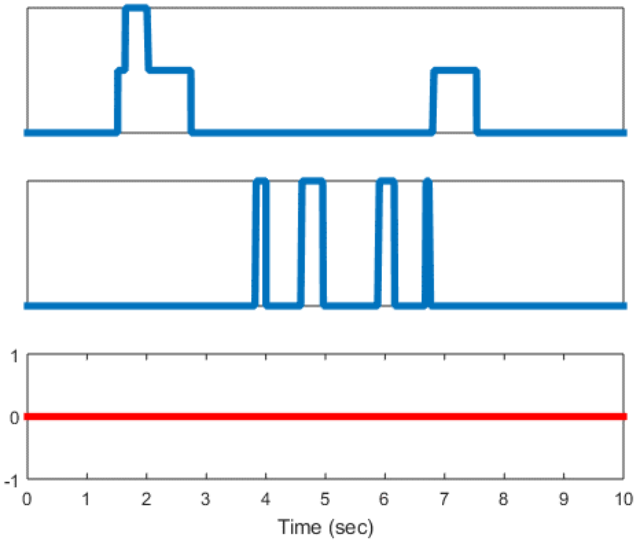
Simulation: Time Series

BS-1 blockage

BS-2 blockage

Both BS-1,2 blockage

Blocker Density= 0.01 bl/m^2



Blocker Density= 0.1 bl/m^2