Application of Stochastic Geometry in Modeling Future LTE-A and 5G Wireless Networks

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SAMSUNG

Samsung Research America, Dallas

- **Wireless Communications & Connectivity (~ 40 researchers)**
  - Create wireless communications solutions for a better connected world through research, prototyping and standardization

Innovate and Incubate → Prototype and Demo → Global Standards

Samsung 5G mmWave mobile communication

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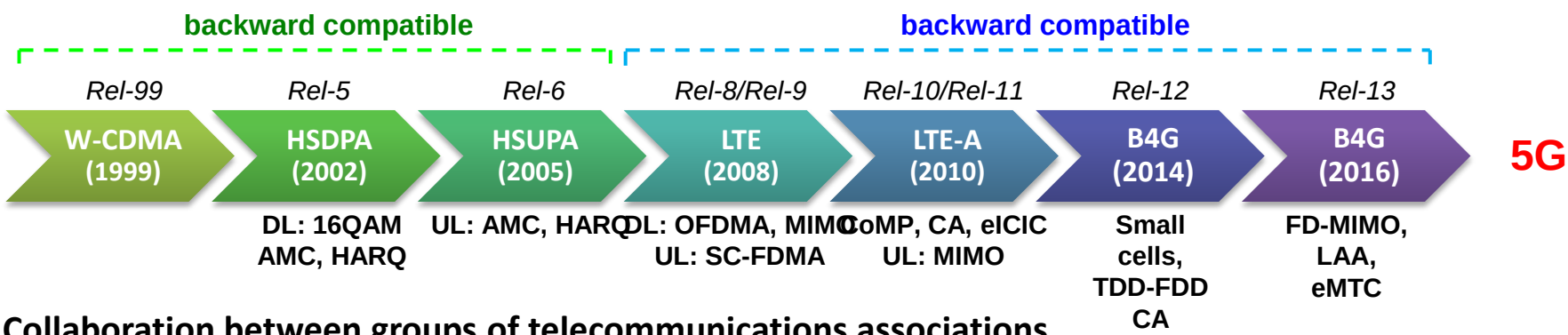
3rd Generation Partnership (3GPP) Project

- **Initiated in December, 1998 for development of wireless communication standards**



- **Collaboration between groups of telecommunications associations**
  - China: CCSA (China Communications Standards Association)
  - Europe: ETSI (European Telecommunications Standards Institute)
  - Japan: ARIB (Association of Radio Industries and Businesses), TTC (Telecommunication Technology Committee)
  - Korea: TTA (Telecommunications Technology Association)
  - USA: ATIS (Alliance for Telecommunications Industry Solutions)
  - India: TSDSI (Telecommunications Standards Development Society of India)

- **Specification work done in Technical Specification Groups**
  - GERAN (GSM/EDGE Radio Access Network): GERAN specifies GSM radio technology, including GPRS and EDGE
  - RAN (Radio Access Network): RAN specifies the UTRAN and the E-UTRAN
  - SA (Service and System Aspects): SA specifies service requirements and overall architecture of 3GPP system
  - CT (Core Network and Terminals): CT specifies the core network and terminal parts of 3GPP

Industry Participation in 3GPP

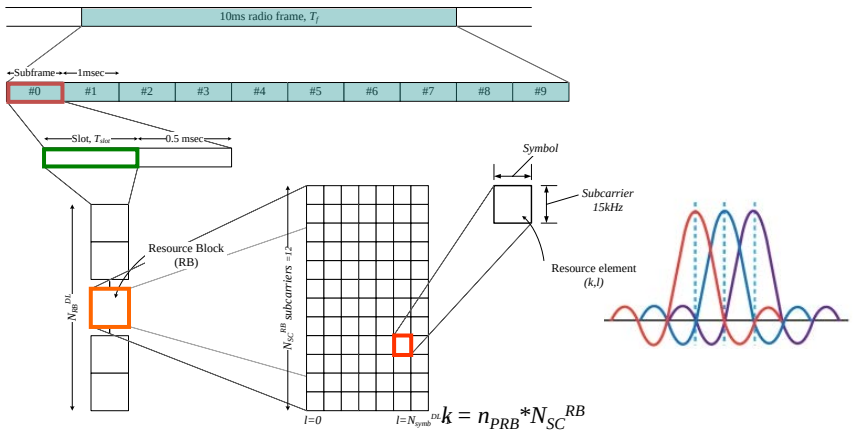
- **Over 100 companies involved in LTE specification development**
  - **Mobile Vendors**: Samsung, Nokia, Blackberry, LGE, ZTE, Pantech, Motorola, HTC, Apple, …
  - **System Vendors**: Ericsson, Huawei, Alcatel Lucent, Nokia Network, …
  - **Chipset Vendors**: Qualcomm, Intel, MediaTek, Broadcom, NVIDIA, …
  - **Service Operators**: CMCC, Vodafone, Orange, Verizon, AT&T, Sprint, DT, DOCOMO, KDDI, Telecom Italia, LG U$^+$, KT, SKT, …
  - **Measurement Instrument Vendors**: Agilent Technology, NI, Rhode & Schwarz, …
  - **Terminal Location Providers:** TruePosition, Polaris Wireless, NextNav..
  - **Research Firms/Organizations**: InterDigital, ETRI, ITRI, III, …

In 2011 over
48,000
delegate days
were contributed
to 3GPP meetings

LTE Release 8: First LTE Specification

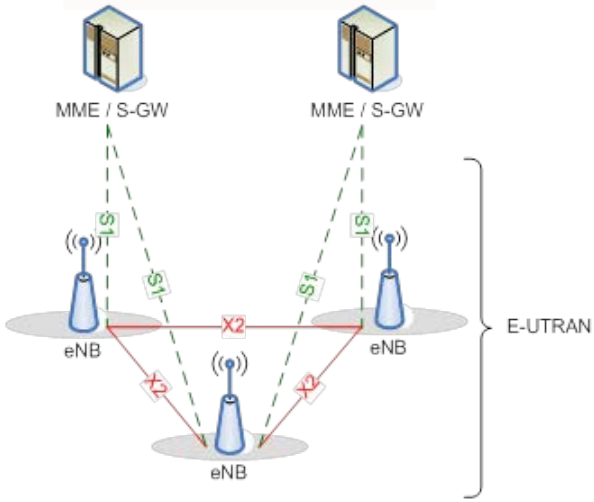
Key technologies

OFDMA / SC-FDMA: 1.4MHz – 20MHz

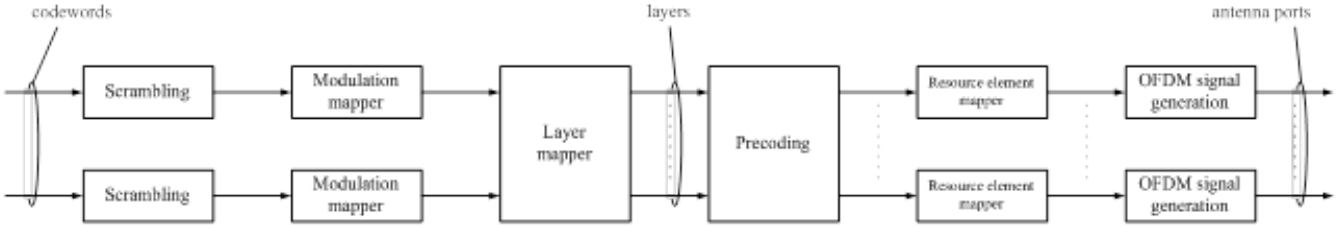


$$k = n_{PRB} * N_{SC}^{RB}$$

Flat RAN architecture



4x4 DL MIMO

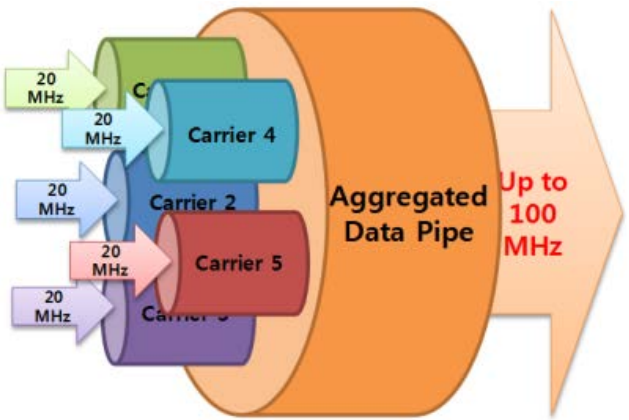


Requirements	Target
Peak transmission rate (Mbps)	>100 (DL), >50 (UL)
Peak spectral efficiency (bps/Hz)	>5 (DL), >2.5 (UL)
Average cell spectral efficiency (bps/Hz/cell)	>1.6–2.1 (DL), >0.66–1.0 (UL)
Cell edge spectral efficiency (bps/Hz/user)	>0.04–0.06 (DL), >0.02 –0.03 (UL)
User plane latency / Control plane latency (ms)	< 10 / <100

LTE-Release 10: LTE Advanced (LTE-A)

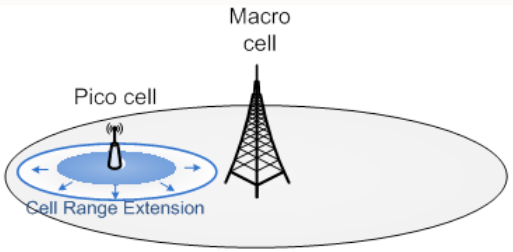
Key technologies

Carrier Aggregation

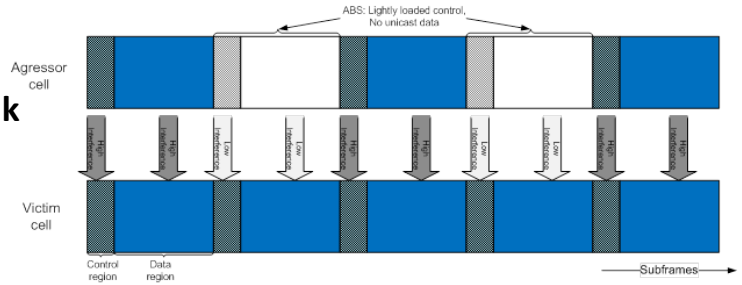


Time-domain Inter-cell Interference Coordination

Cell range expansion

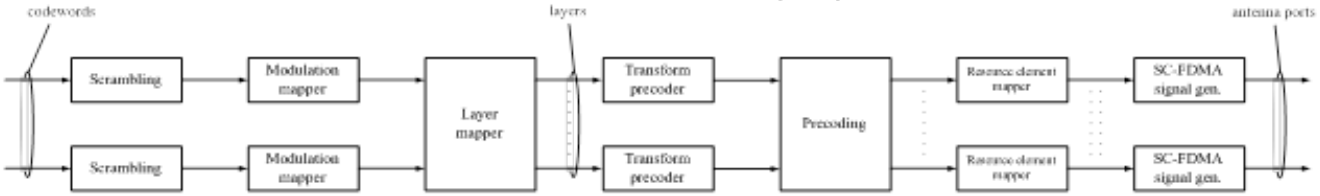


Almost Blank Subframe



4x4 UL MIMO

8x8 DL MIMO



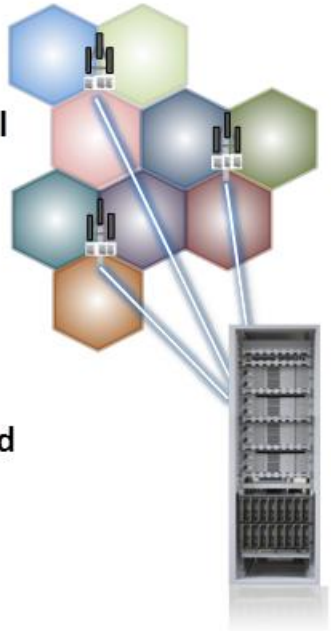
Requirement	Target
Peak transmission rate (Mbps)	1000 (DL), 500 (UL)
Peak spectral efficiency (bps/Hz)	30 (DL), 15 (UL)
Average cell spectral efficiency (bps/Hz/cell)	2.4–3.7 (DL), 1.2–2.0 (UL)
Cell edge spectral efficiency (bps/Hz/user)	0.07–0.12 (DL), 0.04 –0.07 (UL)

LTE-Release 11: Network Coordination for LTE

- **Key Technology: CoMP (Coordinated Multi-Point Transmission and Reception)**
  - Allows network to coordinate wireless resources (time, frequency, transmission power, etc)
  - Significant improvement in system performance (Average: 20~30%, Edge: 30~40%)
  - Well suited for C-RAN (Centralized Radio Access Network)

Traditional Multi-Cell System

Each RRH site is a cell

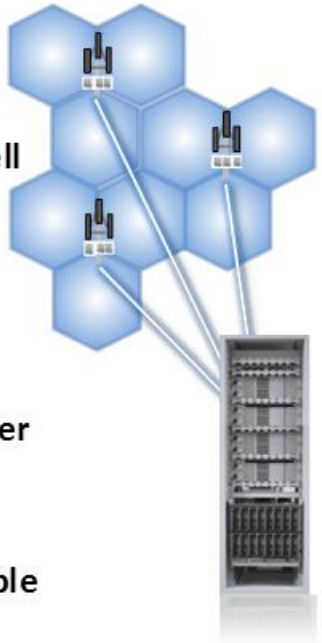


- Handover required between RRHs

RRH: Remote Radio Head

'One Cell' System

Each RRH site is a configurable virtual cell

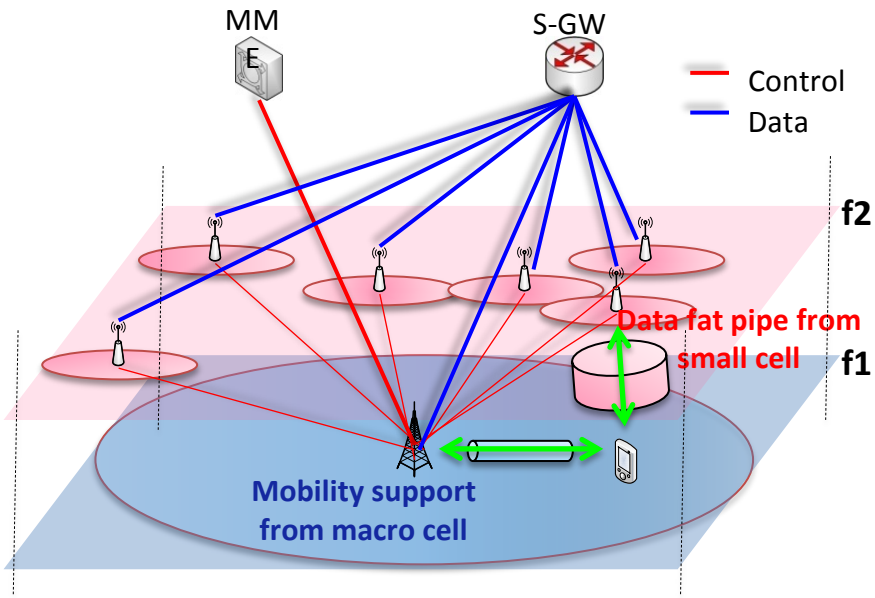


- No need for handover between RRHs
- Flexible cell virtualization possible

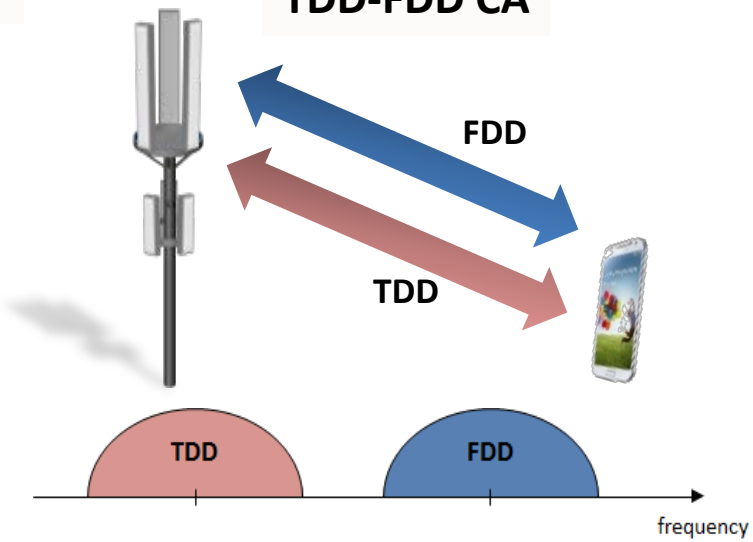
LTE-Release 12: Small Cells and D2D

Key technologies

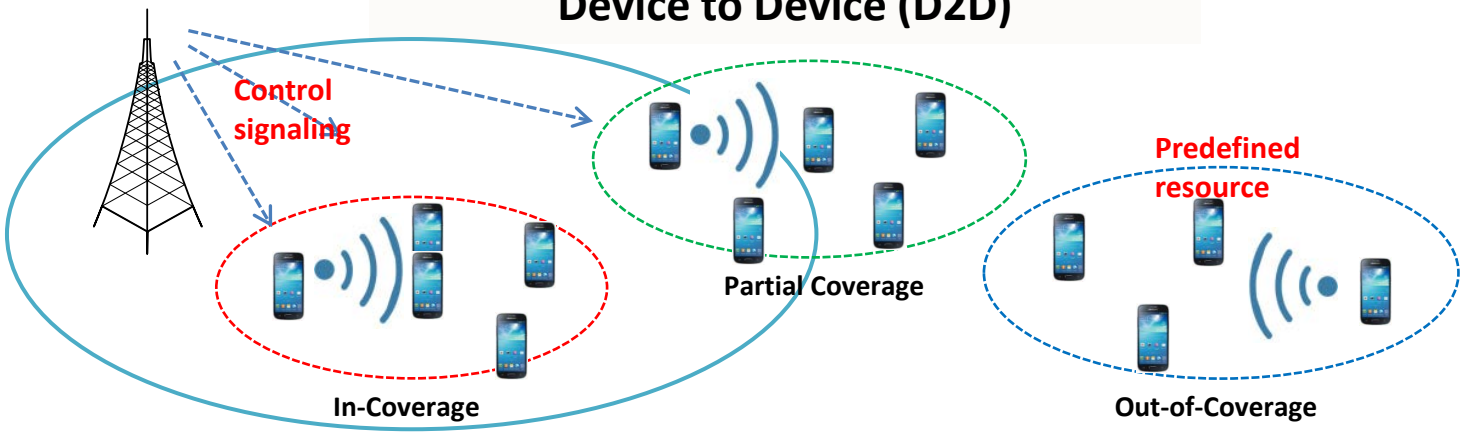
Small Cell Enhancement (w/ dual connectivity)



TDD-FDD CA



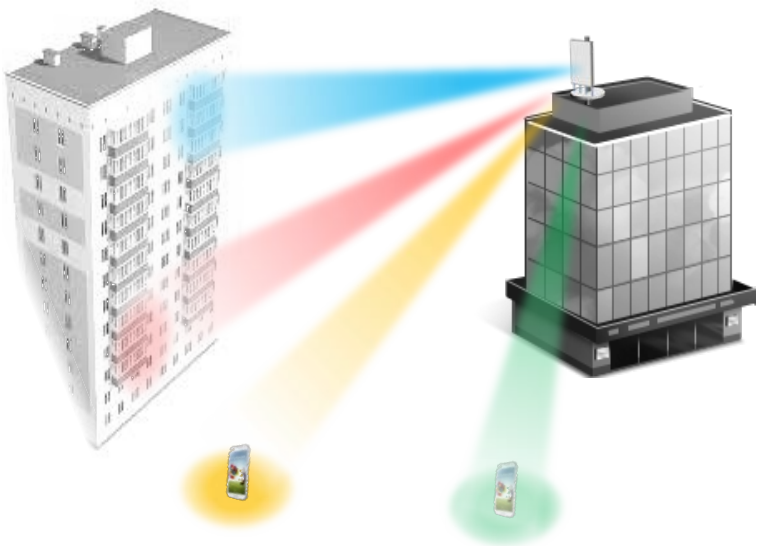
Device to Device (D2D)



LTE-Release 13: FD-MIMO, eMTC, and LAA

Key technologies

FD-MIMO

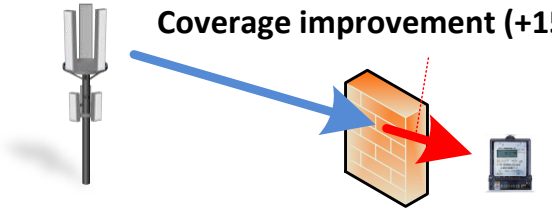


eMTC

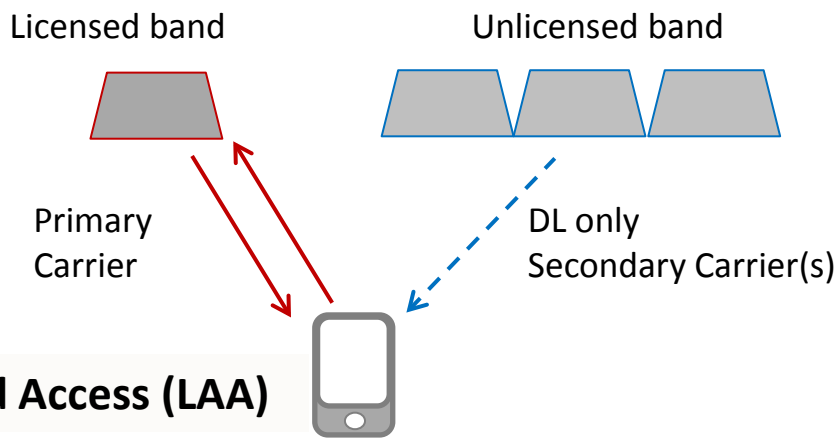
Normal LTE UE

Low cost MTC UE

Coverage improvement (+15dB)



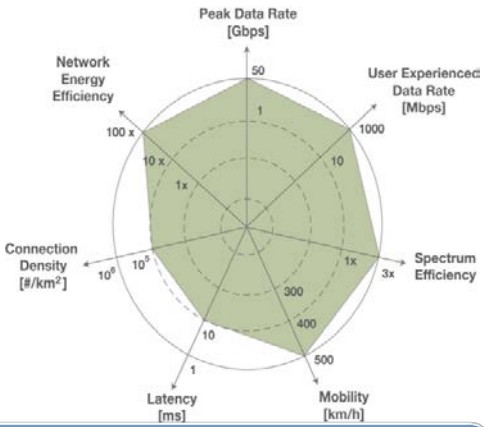
Reduced MTC UE power consumption



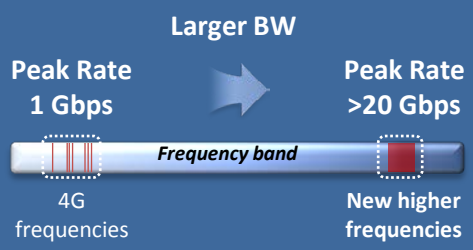
Licensed Assisted Access (LAA)

Enhanced Mobile Broadband

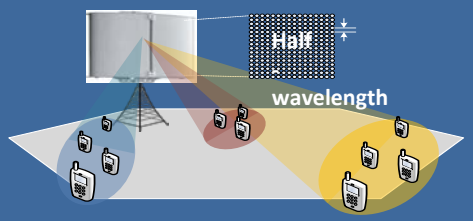
- **Frequency band above 6GHz** needs to be strongly considered to support high peak rate up to 50Gbps
- Beamforming, small cell, and inter-RAT aggregation are major techniques to meet eMBB requirement



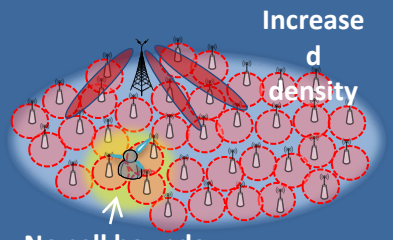
mmWave Frequency



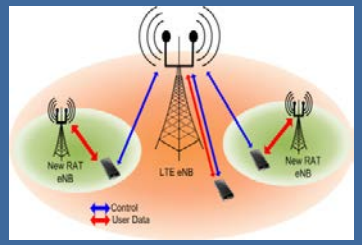
Advanced MIMO & Beamforming



Advanced Small Cell

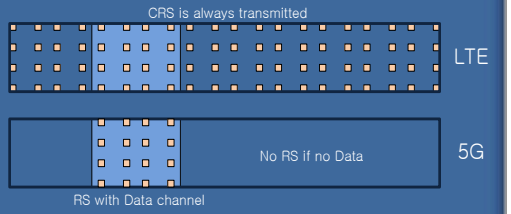


4G-5G Aggregation



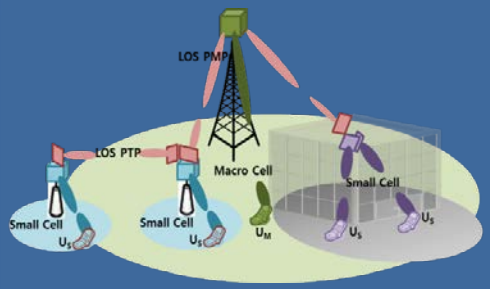
LTE for coverage layer, 5G for capacity layer

Forward Compatible Design



Minimal design for forward compatibility

Wireless Backhaul

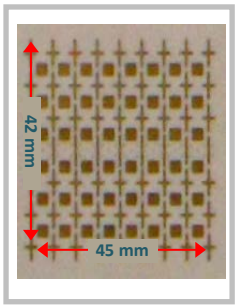


mmWave Testbed - Overview

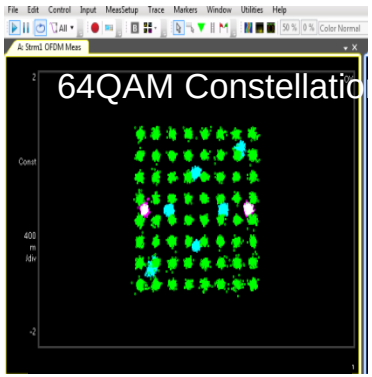
World's First 5G mmWave Mobile Technology (May, 2013)

Adaptive array transceiver technology operating in mmWave frequency bands for outdoor cellular

Base Station



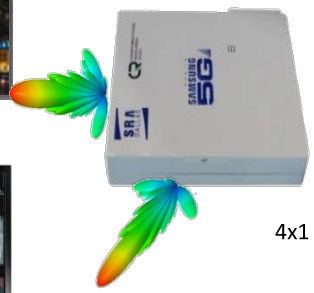
8x6 (=48) Antenna Elements

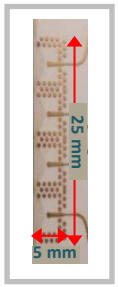


RF + Array Antenna

	BS	MS
Carrier Frequency	27.925 GHz	
Bandwidth	800 MHz	
Beamwidth (Half Power)	10°	20°(AZ) /140°(EL)

Mobile Station





4x1 (=4) Antenna Elements

Baseband Modem

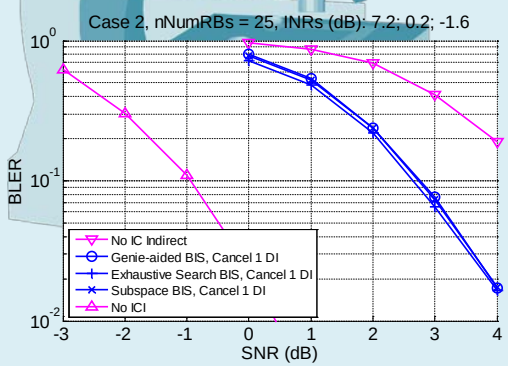
3GPP Evaluation Methodology

3GPP Evaluation Methodology

- **For every new technology or enhanced feature, performance needs to be evaluated and validated (hopefully by multiple sources)**
- **Two major toolkits:**

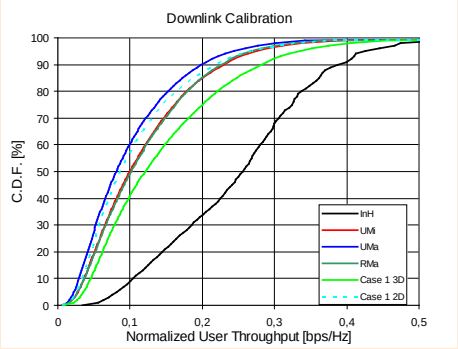
Link-level Simulation (LLS)

- **Focus on single-link performance**
- **Explicit bit-level packet transmission/reception**
- **Abstract scheduling and sweep over a range of SNR/INR values**
- **Key metric: block-level error rate (BLER) or "waterfall" curves**



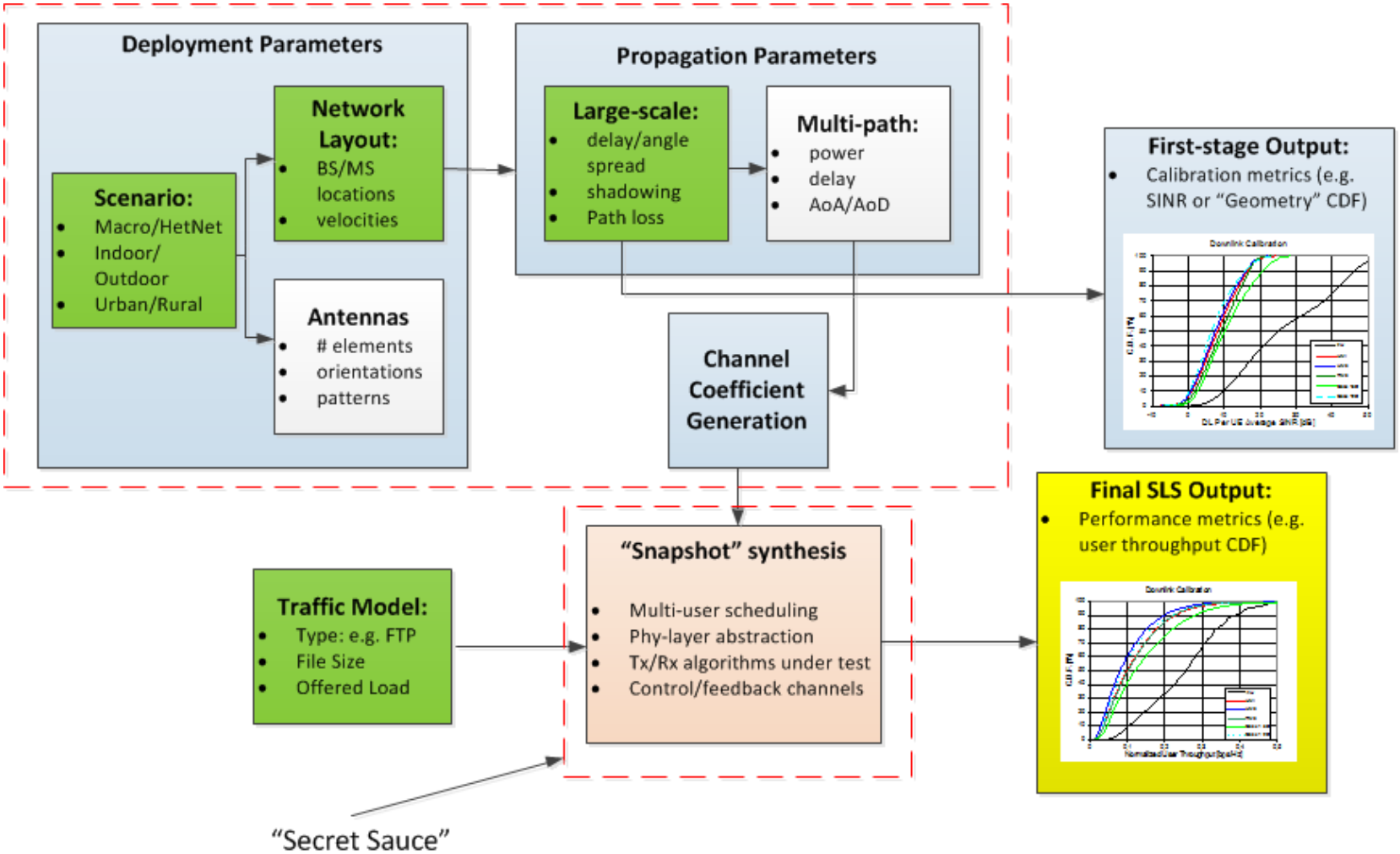
System-level Simulation (SLS)

- **Focus on aggregate network performance**
- **Explicit multi-cell scheduling and interference modeling**
- **Abstract control channel and PHY-layer coding/decoding**
- **Key metric: user throughput CDF**



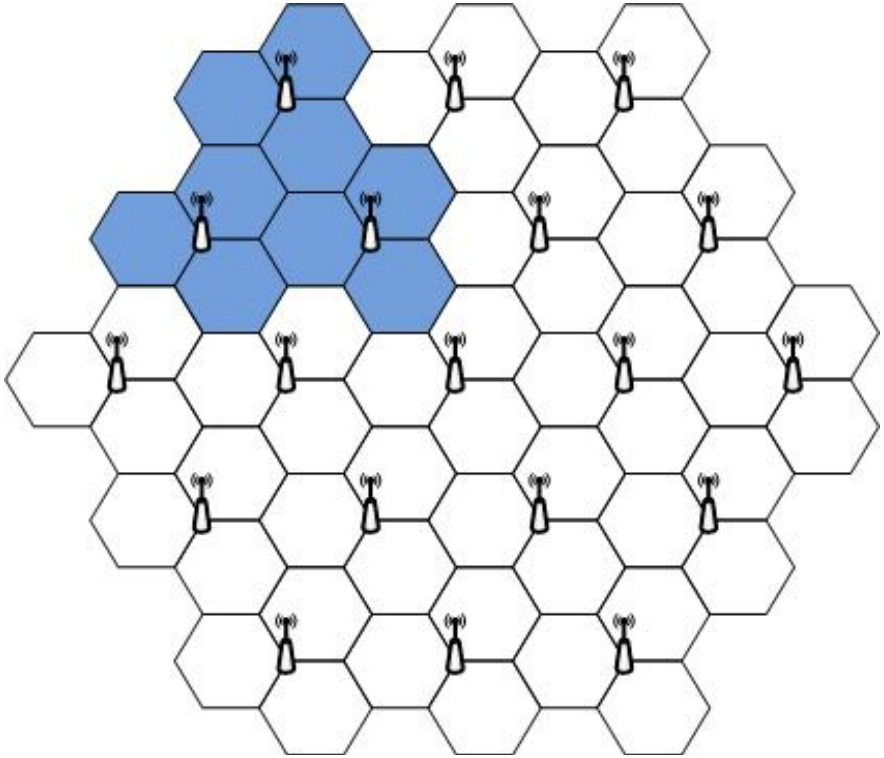
SLS Methodology

- **Uses "drop" or "snapshot" concept to achieve statistically representative results**
- **Random properties of the channel remain constant except for the fast fading**
- **Lots of fine tuning required…**



Macro Deployment Scenarios

- Coverage-oriented, including high-mobility users
- 7 or 19 site layout, 3 co-located sectors (cells) per site
- Wrap-around to avoid edge effects
- 20m-30m sectored antenna heights with downtilt (~12degrees)
- Inter-site distance (ISD): 200m (dense urban), 500m (urban), 1732m (suburban)
- Tx power: 37-47dBm
- 10-20 active UEs per sector
- Typically assume 80% indoor users

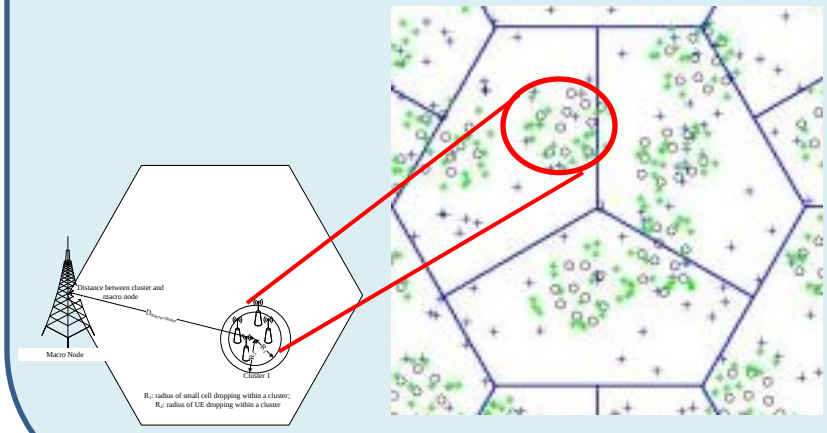


Small Cell Deployment Scenarios

- Capacity hotspot-oriented, typically low-mobility users
- 6-10m antenna heights, omni-directional pattern
- Tx power: 17-30dBm
- 40-60 active UEs per sector, 2/3 users dropped within hotspots

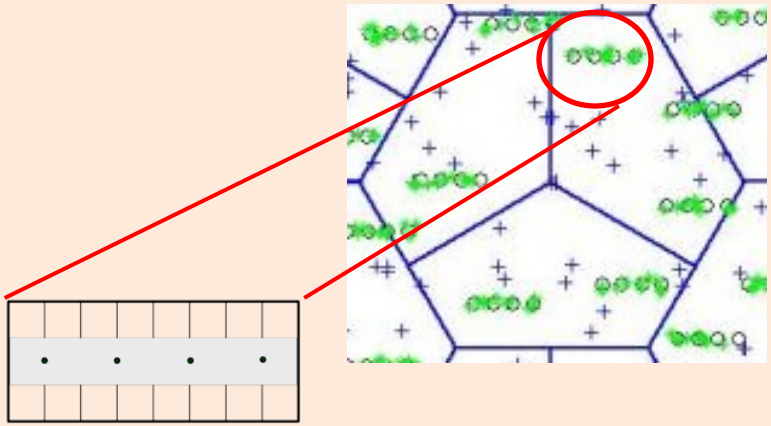
Outdoor

- **1-2 small cell clusters uniformly random within each macro sector**
- **4-10 small cells dropped uniformly random within cluster area**
- **Up to 12dB SINR bias for macro-layer offloading**



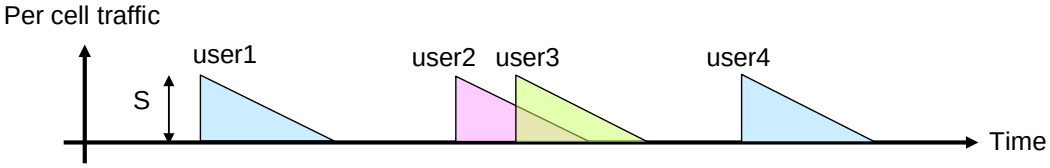
Indoor

- **The outdoor clusters are replaced by 120mx50m indoor hotspots**
- **ISD between small cells within the same floor is 30m**
- **1-2 floors, 4 small cells per floor**

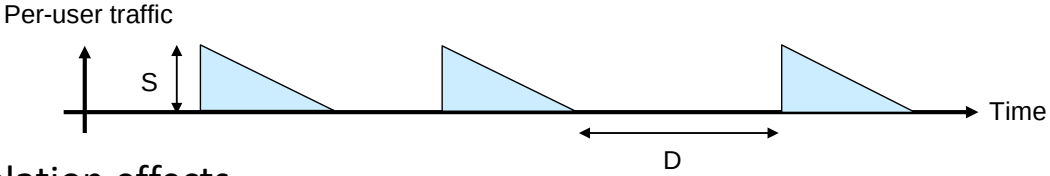


Hybrid Traffic Models

- **Full-buffer traffic models are rarely used except for calibration purposes**
- **Characterize traffic types based on file size and inter-arrival times:**
- **FTP model 1: Per-cell traffic**
  - Poisson arrivals overlap
  - Scales well at high loads



- **FTP model 2: Per-user traffic**
  - Reading time, D is exponentially distributed: $f_D = \lambda e^{-\lambda D}, D \geq 0$
  - Captures packet congestion correlation effects

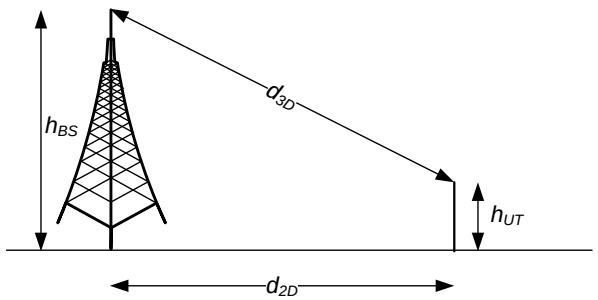


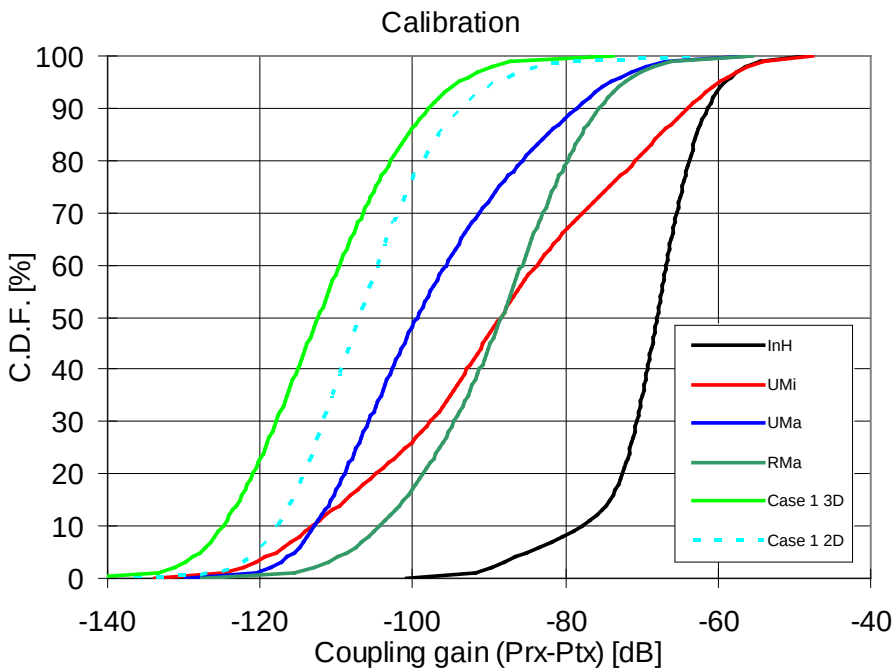
- **Can be tuned to capture a range of realistic traffic types:**

Traffic type	File Size	Inter-arrival time (sec)
Skype	40 Byte	.02
Web Browsing	.01 MB	.1-1 sec
You Tube	.05-.1 MB	.02
FTP	.5-2 MB	> 1 sec

Path loss models

- **Path loss models for the various propagation scenarios have been developed based on measurement results as well as results from the literature**
- **The main models listed below can be applied in the frequency range of 2 – 6 GHz**
  - Urban macro (UMa), Urban micro (UMi), Rural macro (RMa), Indoor hotspot (InH)
- **Log-normal, correlated shadowing as a function of distance**
- **2D vs. 3D distance:**



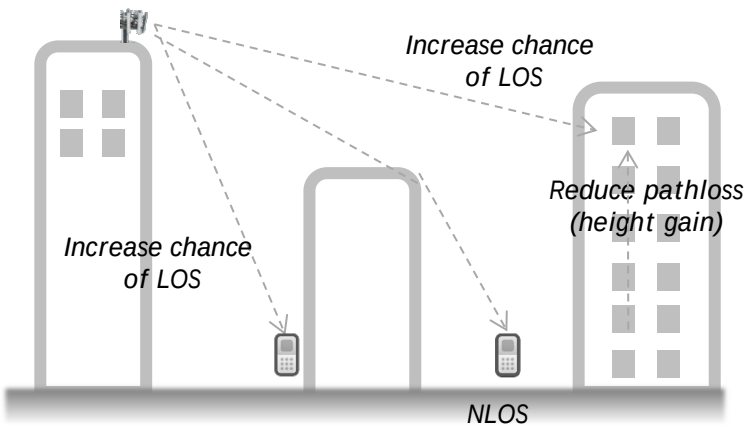


- **Typically assumes mix of 80% indoor, 20% outdoor users**
- **NLOS/LOS probability is a function of distance, with explicit wall modelling for indoor users**

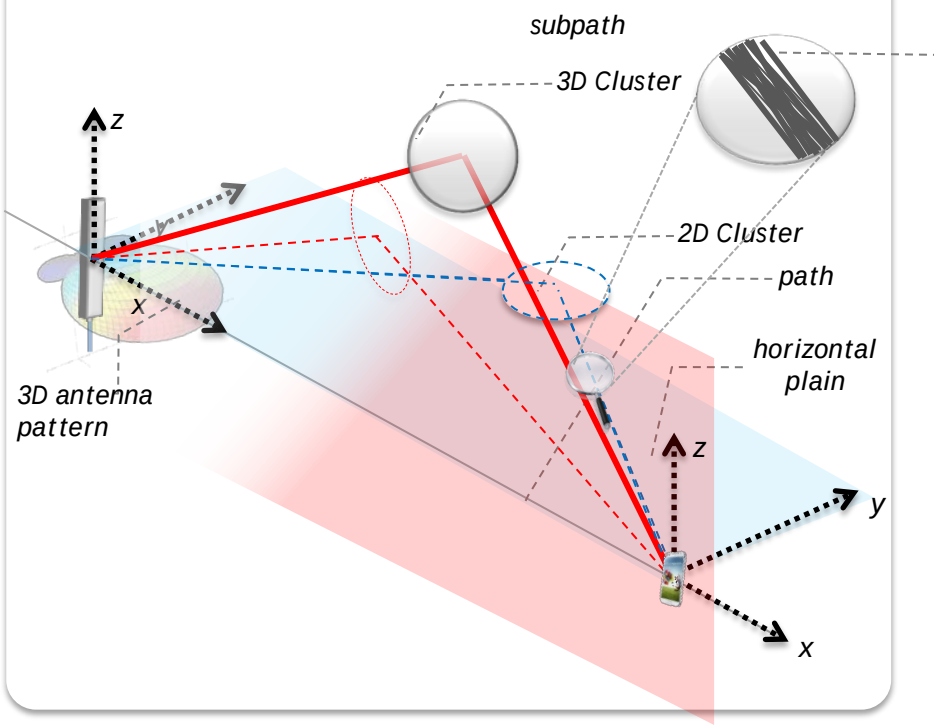
3D Channel Model

- **3D extension of channel model**
  - **Long-term channel characteristics of UE height (e.g LOS probability of UE and pathloss)**
  - **Short-term channel characteristics of vertical domain and UE height (e.g. Zenith angle spread in departure as well as arrival)**

Long-term channel extension



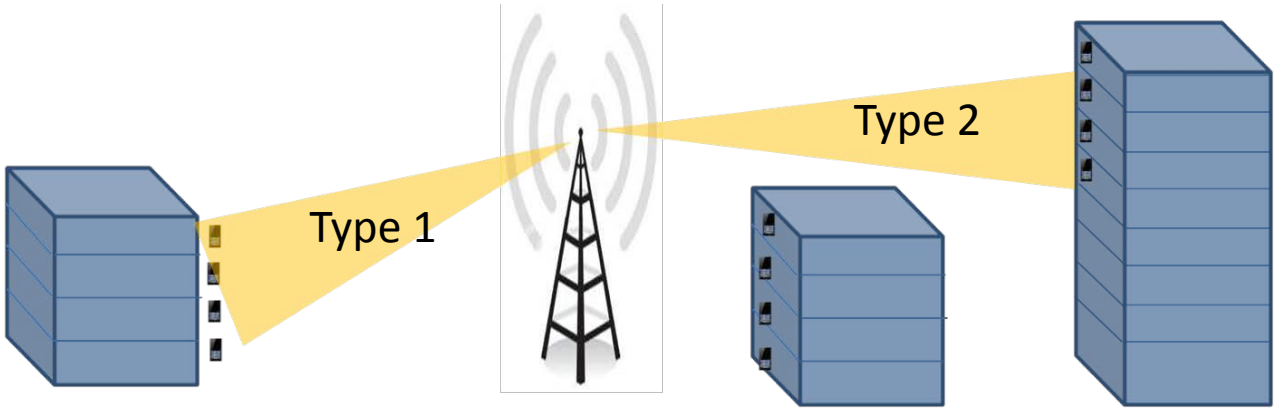
Short-term channel extension



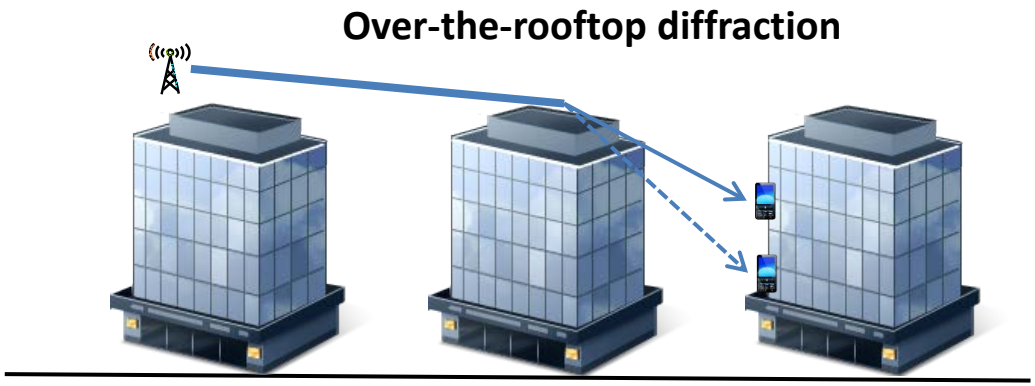
LOS Probability and Pathloss for 3D

- LOS probability is **height** dependent as well as distance dependent
  - UEs on the higher floors are more likely to be LOS

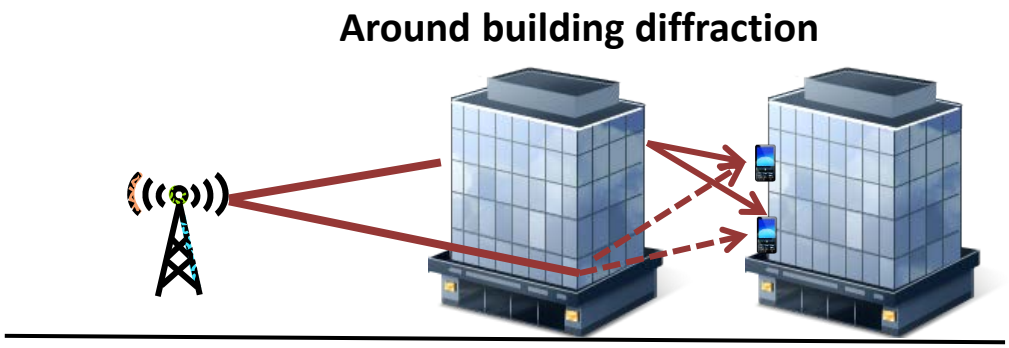
- Environmental height and BP distance characterization for LOS pathloss
  - One of two LOS types is determined for LOS UEs on high floors
  - LOS type 1: LOS over street (same as 2D)
  - LOS type 2: LOS over building (environmental height is building height)
  - BP distance of LOS type 2 is shorter than LOS type 1.



NLOS Pathloss in 3D Channel Model



Urban Macro



Urban Micro

- **Height gain: NLOS pathloss gets smaller as UE height gets higher**

$$PL_{\text{3D-UMa-NLOS}}(d, h_{\text{UT}}) = PL_{\text{2D-UMa-NLOS}}(d) - 0.6(h_{UT} - 1.5)$$

$$PL_{\text{3D-UMi-NLOS}}(d, h_{\text{UT}}) = PL_{\text{2D-UMi-NLOS}}(d) - 0.3(h_{UT} - 1.5)$$

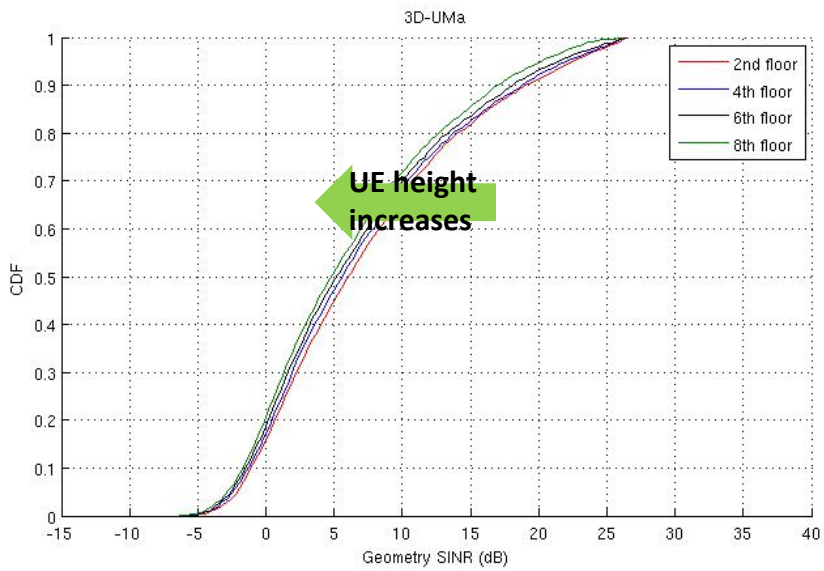
Height-Dependent Geometry SINR

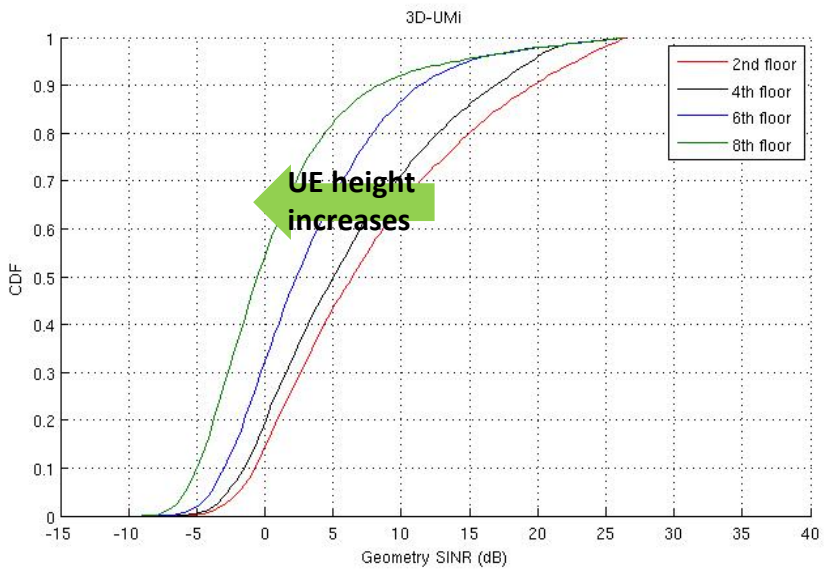
- ***Higher floor UEs*** **tend to have more LOS state, and smaller pathloss**

➔ **both signal and interference power goes up**

➔ **More likely to be interference limited than ground UEs**

➔ ***Worse SINR than ground UEs***

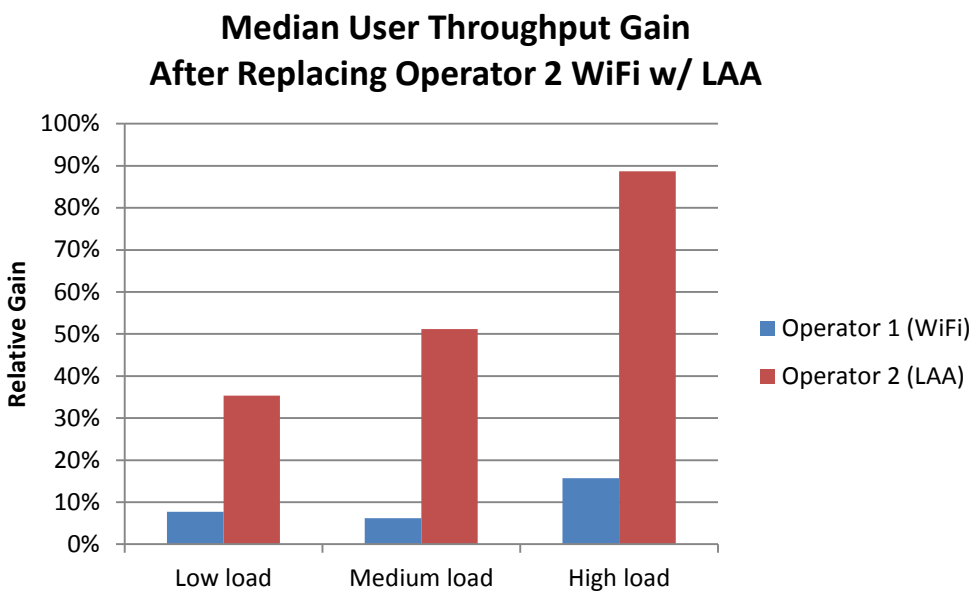


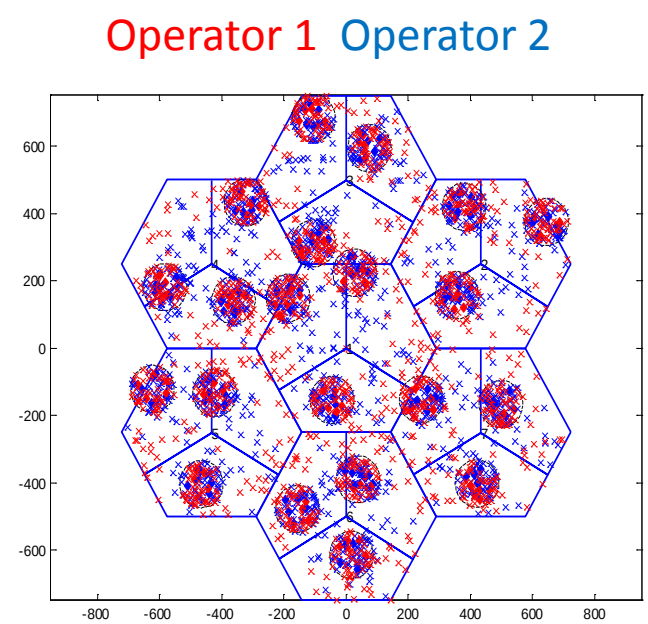


More details on 3D channel model in 3GPP TR 36.873

Example: LTE-WiFi SLS Integration

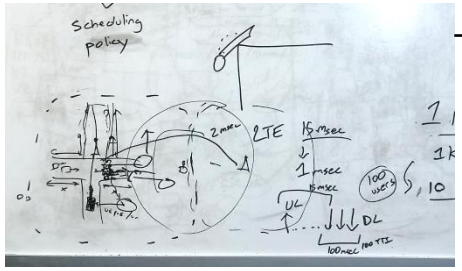
- **Recently LTE operation on unlicensed spectrum has been proposed:**
  - LTE-U: Verizon Forum (Verizon, Qualcomm, Ericsson, ALU, Samsung)
  - Licensed-Assisted Access (LAA): 3GPP
- **FCC, ETSI, IEEE, are asking for coexistence studies with WiFi to ensure fairness**
- **Performance of the small cell deployments of two different operators are compared**
  - One using WiFi, the other licensed assisted access for LTE (LAA-LTE)
  - Key metrics of throughput and buffer occupancy (over-the-air congestion)
  - Requires running both a WiFi SLS and LAA SLS and exchanging states in real time!



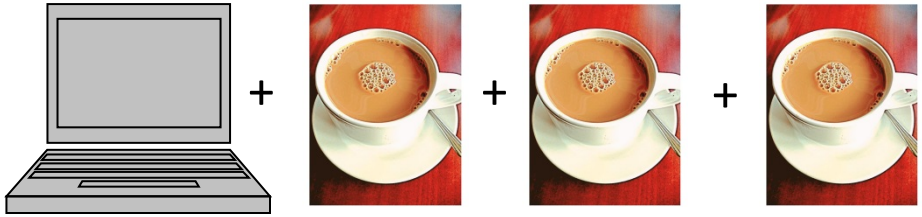


Life of a 3GPP simulation expert

Inspiration strikes!



Weeks writing/debugging code:



There's a reason the server is called "grumpy":

```
[t.novlan@grumpy ~]$ bhosts
HOST_NAME          STATUS       JL/U    MAX  NJOBS
grumpy             unavail        -      1      0
mpisrv01dal        ok             -     24      5
mpisrv02dal        unavail        -      1      0
mpisrv03dal        ok             -     20     14
mpisrv04dal        ok             -     24     18
mpisrv05dal        ok             -     20      0
```

Come back after waiting this long:

seconds!

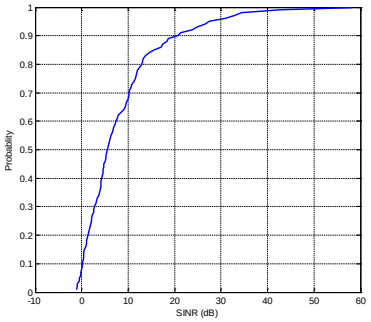
```
runTime =

   1.4498e+05
```

Hope you don't find this:

```
Segmentation violation detected------
R8 = 000000002c81d6f5   R9 = 00002ac
_interpreter.so+02245206[  7] 0x0000
xa64/libmwm_interpreter.so+01923475[
13a/bin/glnxa64/libmwm_dispatcher.so
[ 36] 0x00002ac2133eeb88 /opt/HW/app
```

All for a few numbers and a MATLAB plot:

```
Buffer Occupancy
    Operator 1 (laa): 0.560
    Operator 2 (wifi): 0.607
UE Throughput (Mbps)
    Operator 1 (laa): 10.804
    Operator 2 (wifi): 8.708
Packet Latency (s)
    Operator 1 (laa): 0.606
    Operator 2 (wifi): 0.702
```



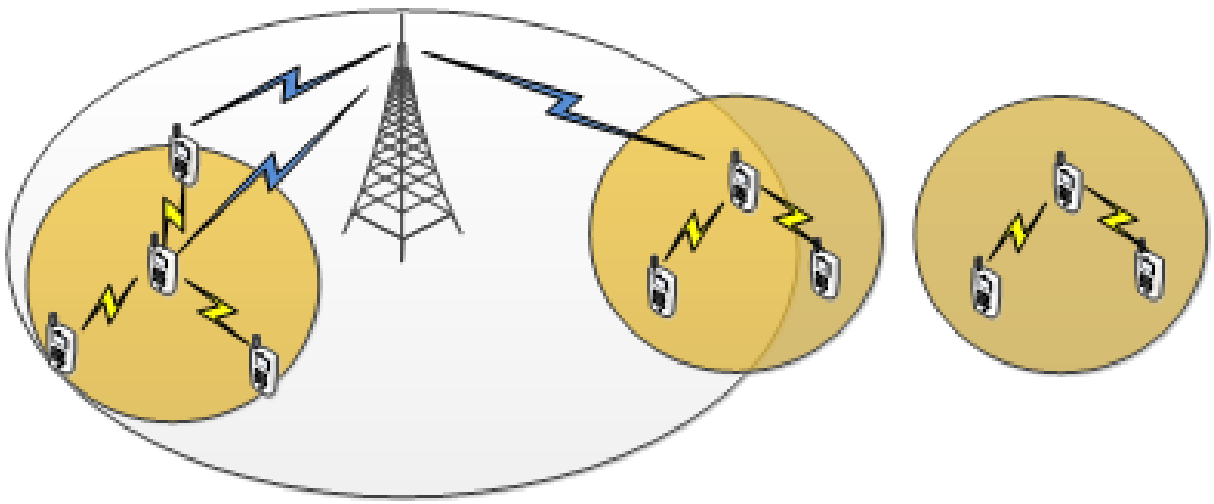
Spectrum Sensing for Device-to-Device Communication in Cellular Networks

In collaboration with:

KU INFORMATION & TELECOMMUNICATION TECHNOLOGY CENTER
The University of Kansas

LTE-D2D Deployment Scenarios

- In-coverage, partial-coverage, and out-of-coverage scenarios
- 10-20 active UEs per sector (communication), 150-200 active UEs (discovery)
- UE Tx power: 23dBm (commerical UE), 30dBm (public safety UE)
- Minimum RSRP to establish D2D link = -107 dBm
- 40-320msec communication periods, 1-10sec discovery periods
- Utilize *uplink* resources for D2D transmissions



Spectrum Sensing

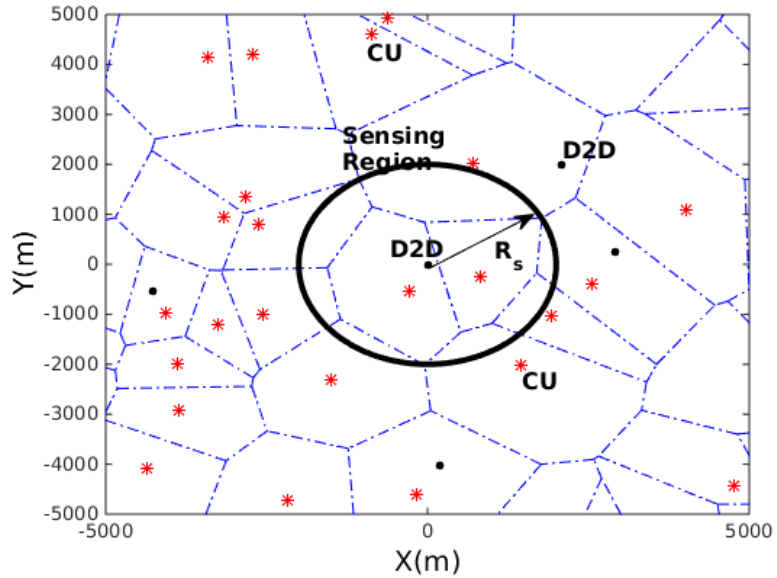
- **Conventional spectrum sensing focuses on *temporal* holes**
- **Spatial spectrum sensing focuses on *spatial* holes**
- **Benefits of spatial spectrum sensing:**

  1) Reduce interference; 2) reduce control overhead.

- **Goal: detect whether there are cellular user(s) within a distance of R_S to the D2D user.**

Mathematical Formulation

- Cellular users (CUs) form a Poisson point process $\Phi_{c,a}$ with density λ_b
- Sensing region A_S is the disc area centered at the D2D user with radius R_S



D2D users conduct spatial spectrum sensing simultaneously and periodically.

$$H_0 : y[n] = \sum_{i \in \Phi_{c,a} \cap A_s^c} x_i[n] + w[n]$$

There is no CU

$$H_1 : y[n] = \sum_{\substack{i \in \Phi_{c,a} \cap A_s \\ \Phi_{c,a} \cap A_s \neq \varnothing}} x_i[n] + \sum_{i \in \Phi_{c,a} \cap A_s^c} x_i[n] + w[n]$$

At least one CU

Energy Detection

The test statistic is:

$$\Gamma = \frac{1}{N}\sum_{n=0}^{N-1}|y[n]|^2$$

Using the central limit theorem,

- **If H_0 is true**

$$E(\Gamma) = I_0 + \sigma_n^2, \qquad \mathrm{Var}\,(\Gamma) = \frac{2(I_0 + \sigma_n^2)^2}{N}$$

- **If H_1 is true**

$$E(\Gamma) = I_1 + \sigma_n^2, \qquad \mathrm{Var}(\Gamma) = \frac{2(I_1 + \sigma_n^2)^2}{N}$$

where $I_0(I_1)$ is the interference power received when H_0 (H_1) is true.

Performance Analysis

Probability of spatial false alarm

$$\overline{P_f} = \int_0^\infty \mathrm{P}_f(x)\, f_{I_0}(x)\, \mathrm{d}\, x$$

$$\mathrm{P}_f(x) = \mathrm{P}(\Gamma > \varepsilon \,|\, H_0, I_0 = x)$$

Probability density function of I_0

Probability of spatial detection

$$\overline{P_d} = \int_0^\infty \mathrm{P}_d(x)\, f_{I_1}(x)\, \mathrm{d}\, x$$

$$\mathrm{P}_d(x) = \mathrm{P}(\Gamma > \varepsilon \,|\, H_1, I_1 = x)$$

Probability density function of I_1

The distribution of I_0 can be approximated by Log-normal

$$f_{I_0}(x) \approx \frac{1}{\sigma x \sqrt{2\pi}} \exp\left(\frac{-(\log(x/m))^2}{2\sigma^2} \right)$$

σ and m can be decided by the Laplace transform of I_0.

Main Results

Theorem1: ***In cellular networks with D2D communication of our interest, when the path loss exponent α= 4, the probability of spatial false alarm and spatial detection can be expressed as***

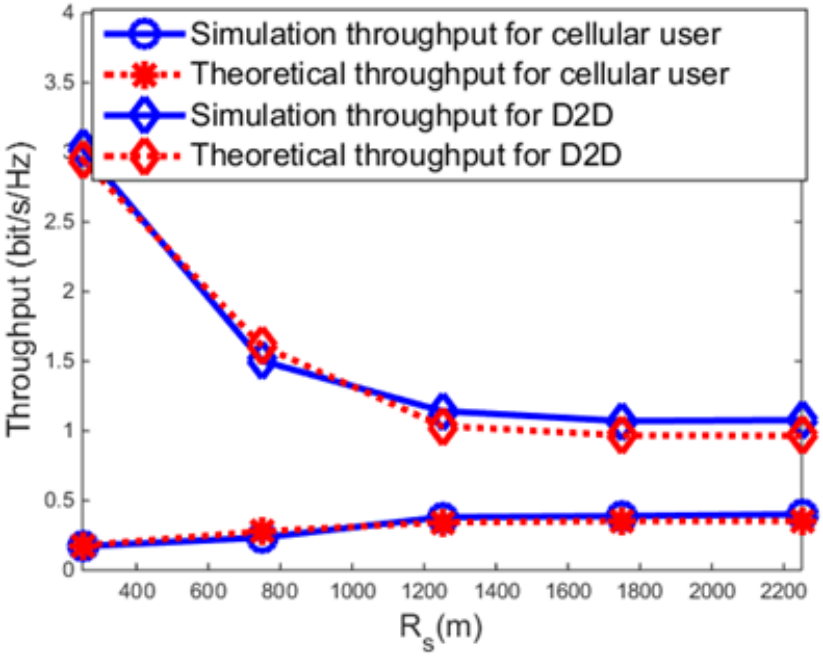
$$\overline{P_f} = \int_0^\infty Q\left(\frac{\varepsilon - x - \sigma_n^2}{\sqrt{2(x+\sigma_n^2)^2/N}}\right)\frac{1}{\sigma x\sqrt{2\pi}}\exp\left(\frac{-(\log(x/m))^2}{2\sigma^2}\right)\mathrm{d}\,x$$

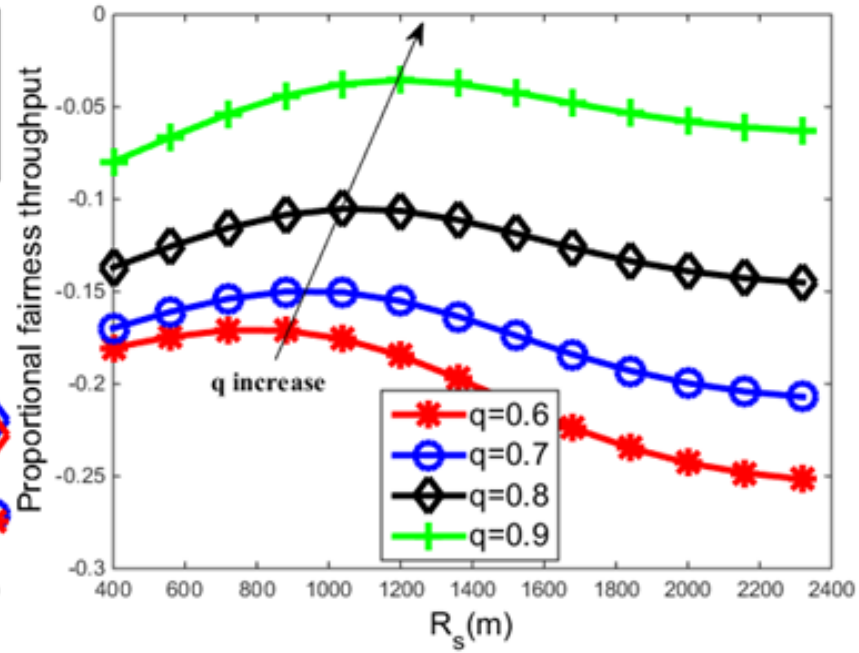
$$\overline{P_d} = \int_0^\infty Q\left(\frac{\varepsilon - x - \sigma_n^2}{\sqrt{2(x+\sigma_n^2)^2/N}}\right)\frac{\exp(-\frac{\pi^4\lambda_b^2 P_c}{16x})\lambda_b\sqrt{P_c}\pi^{3/2}}{4(1-\exp(-\lambda_b\pi R_s^2))x^{3/2}}\mathrm{d}\,x - \frac{\exp(-\lambda_b\pi R_s^2)}{1-\exp(-\lambda_b\pi R_s^2)}\overline{P_f}$$

Corollary 1: ***In the interference limited regime, when Neyman-Pearson detector is employed, the spatial spectrum sensing threshold and probability of spatial detection can be expressed as***

$$\varepsilon = \frac{P_c\exp\left(Q^{-1}\left(\overline{P_f}^*\right)\sqrt{\log\left(2R_b^2/3R_s^2+1\right)}\right)}{R_s R_b^2\sqrt{2R_b^2/3+R_s^2}} \qquad \overline{P_d} = \frac{\mathrm{erf}\left(\frac{\pi^2\lambda_b}{4\sqrt{\varepsilon/P_c}}\right)}{1-\exp(-\lambda_b\pi R_s^2)} - \frac{\exp(-\lambda_b\pi R_s^2)}{1-\exp(-\lambda_b\pi R_s^2)}\overline{P_f}^*$$

Simulation/Analytical Results





Tradeoff between D2D users and cellular users

- **Increasing the sensing radius will create a bigger guard zone, while reducing the access probability of D2D users.**
- **Optimal sensing radius will balance the performance of D2D users and cellular users.**

Conclusion: Spatial spectrum sensing has advantages over conventional spec trum sensing, especially in dense networks

H. Chen, L. Liu, T. Novlan, B. Ng, and J. Zhang, "Spatial Spectrum Sensing for Device-to-Device Communication in Cellular Networks", submitted to IEEE GLOBECOM 2015.

Conclusions

- **The wireless communications industry is rapidly evolving**
  - 5G will include many diverse technologies: HetNets, FD-MIMO, mmW cellular, D2D, and more…
- **System models have been critical for simulation and analysis of performance trends leading to the development of new algorithms.**
- **It is challenging to accurately incorporate many of the complexities of real-world deployments.**
  - Need for flexible techniques such as stochastic geometry
- **Application of stochastic geometry for sensing-based spectrum sharing D2D networks:**
  - Optimal sensing radius to maximize the proportional throughput of the system