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

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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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- 3GPP Standardization Overview
- 3GPP Evaluation Methodology
- Spatial Spectrum Sensing for D2D communication in cellular networks
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**

- **4x4 DL MIMO**

**Flat RAN architecture**

**Requirements**

<table>
<thead>
<tr>
<th>Requirement</th>
<th>Target</th>
</tr>
</thead>
<tbody>
<tr>
<td>Peak transmission rate (Mbps)</td>
<td>&gt;100 (DL), &gt;50 (UL)</td>
</tr>
<tr>
<td>Peak spectral efficiency (bps/Hz)</td>
<td>&gt;5 (DL), &gt;2.5 (UL)</td>
</tr>
<tr>
<td>Average cell spectral efficiency (bps/Hz/cell)</td>
<td>&gt;1.6–2.1 (DL), &gt;0.66–1.0 (UL)</td>
</tr>
<tr>
<td>Cell edge spectral efficiency (bps/Hz/user)</td>
<td>&gt;0.04–0.06 (DL), &gt;0.02–0.03 (UL)</td>
</tr>
<tr>
<td>User plane latency / Control plane latency (ms)</td>
<td>&lt; 10 / &lt;100</td>
</tr>
</tbody>
</table>
LTE-Release 10: LTE Advanced (LTE-A)

Key technologies

- **Carrier Aggregation**
  - Up to 100 MHz

- **Time-domain Inter-cell Interference Coordination**
  - Cell range expansion
  - Almost Blank Subframe

**4x4 UL MIMO**

**8x8 DL MIMO**

### Requirement Target

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

'One Cell' System

- Each RRH site is a configurable virtual cell
- No need for handover between RRHs
- Flexible cell virtualization possible

RRH: Remote Radio Head
LTE-Release 12: Small Cells and D2D

Key technologies

Small Cell Enhancement (w/ dual connectivity)

- MM
- S-GW

- Control
- Data

- Data fat pipe from small cell

- Mobility support from macro cell

TDD-FDD CA

- FDD
- TDD

Device to Device (D2D)

- Control signaling
- Partial Coverage
- Predefined resource
- In-Coverage
- Out-of-Coverage
Key technologies

FD-MIMO

eMTC

Licensed Assisted Access (LAA)

Licensed band

Unlicensed band

Primary Carrier

DL only

Secondary Carrier(s)

Coverage improvement (+15dB)

Reduced MTC UE power consumption

Normal LTE UE

Low cost MTC UE

LTE-Release 13: FD-MIMO, eMTC, and 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**
  - Larger BW
  - Peak Rate 1 Gbps vs Peak Rate >20 Gbps
  - 4G frequencies vs New higher frequencies

- **Advanced MIMO & Beamforming**
  - Half-wavelength

- **Advanced Small Cell**
  - Increase density
  - No cell boundary

- **4G-5G Aggregation**
  - LTE for coverage layer, 5G for capacity layer

- **Forward Compatible Design**
  - CRS is always transmitted
  - No RS if no Data

- **Wireless Backhaul**
  - Minimal design for forward compatibility
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
- 64QAM Constellation
- RF + Array Antenna

### Mobile Station

- 4x1 (=4) Antenna Elements
- Baseband Modem

<table>
<thead>
<tr>
<th>Parameter</th>
<th>BS</th>
<th>MS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Carrier Frequency</td>
<td>27.925 GHz</td>
<td></td>
</tr>
<tr>
<td>Bandwidth</td>
<td>800 MHz</td>
<td></td>
</tr>
<tr>
<td>Beamwidth (Half Power)</td>
<td>10°</td>
<td>20°(AZ) / 140°(EL)</td>
</tr>
</tbody>
</table>
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

![Link-level Simulation Graph](image)

![System-level Simulation Graph](image)
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 (~12 degrees)
- 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

---

\[ R_1: \text{radius of small cell dropping within a cluster} \]
\[ R_2: \text{radius of UE dropping within a cluster} \]
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:

<table>
<thead>
<tr>
<th>Traffic type</th>
<th>File Size</th>
<th>Inter-arrival time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Skype</td>
<td>40 Byte</td>
<td>.02</td>
</tr>
<tr>
<td>Web Browsing</td>
<td>.01 MB</td>
<td>.1-1 sec</td>
</tr>
<tr>
<td>You Tube</td>
<td>.05-.1 MB</td>
<td>.02</td>
</tr>
<tr>
<td>FTP</td>
<td>.5-2 MB</td>
<td>&gt; 1 sec</td>
</tr>
</tbody>
</table>
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

![Diagram showing coupling gain (Prx-Ptx) vs. C.D.F. [%]]

- InH
- UMi
- UMa
- RMa
- Case 1 3D
- Case 1 2D

Calibration

Coupling gain (Prx-Pbx) [dB]

C.D.F. [%]

0 10 20 30 40 50 60 70 80 90 100

-140 -120 -100 -80 -60 -40
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

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• 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

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

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

\[ PL_{3D-UMi-NLOS}(d, h_{UT}) = PL_{2D-UMi-NLOS}(d) - 0.3(h_{UT} - 1.5) \]
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
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!

Example: LTE-WiFi SLS Integration

### Median User Throughput Gain
After Replacing Operator 2 WiFi w/ LAA

<table>
<thead>
<tr>
<th>Load Level</th>
<th>Operator 1 (WiFi)</th>
<th>Operator 2 (LAA)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low</td>
<td>10%</td>
<td>50%</td>
</tr>
<tr>
<td>Medium</td>
<td>30%</td>
<td>60%</td>
</tr>
<tr>
<td>High</td>
<td>80%</td>
<td>90%</td>
</tr>
</tbody>
</table>

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Life of a 3GPP simulation expert

Inspiration strikes!

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

<table>
<thead>
<tr>
<th>HOST_NAME</th>
<th>STATUS</th>
<th>JOB</th>
<th>MAX</th>
<th>JOBS</th>
</tr>
</thead>
<tbody>
<tr>
<td>grumpy</td>
<td>unavail</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
<tr>
<td>pisrv01dal</td>
<td>ok</td>
<td>24</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>pisrv02dal</td>
<td>unavail</td>
<td>1</td>
<td>0</td>
<td></td>
</tr>
<tr>
<td>pisrv03dal</td>
<td>ok</td>
<td>20</td>
<td>14</td>
<td></td>
</tr>
<tr>
<td>pisrv04dal</td>
<td>ok</td>
<td>24</td>
<td>18</td>
<td></td>
</tr>
<tr>
<td>pisrv05dal</td>
<td>ok</td>
<td>20</td>
<td>0</td>
<td></td>
</tr>
</tbody>
</table>

Come back after waiting this long:

runTime = 1.4498e+05

Hope you don't find this:

Segmentation violation detected-----
R8 = 00000000002c81d6f5 R9 = 00002ac:_interpreter.so+02245206[ 7] 0x0000:xa64/libmwm_interpreter.so+01923475[13a/bin/glnta64/libmwm_dispatcher.so [36] 0x00002ac2133eeb88 /opt/Hw/app:

All for a few numbers and a MATLAB plot:

Buffer Occupancy
- Operator 1 (1aa): 0.560
- Operator 2 (wifi): 0.607

UE Throughput (Mbps)
- Operator 1 (1aa): 10.804
- Operator 2 (wifi): 8.708

Packet Latency (s)
- Operator 1 (1aa): 0.606
- Operator 2 (wifi): 0.702
Spectrum Sensing for Device-to-Device Communication in Cellular Networks

In collaboration with:
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 (commercial 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 \( \lambda_b \)
- 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

\[
H_1 : y[n] = \sum_{i \in \Phi_{c,a} \cap A_S} x_i[n] + \sum_{i \in \Phi_{c,a} \cap A_S^c} x_i[n] + w[n]
\]

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**
  
  $$E(\Gamma) = I_0 + \sigma_n^2, \quad \text{Var}(\Gamma) = \frac{2(I_0 + \sigma_n^2)^2}{N}$$

- **If** $H_1$ **is true**
  
  $$E(\Gamma) = I_1 + \sigma_n^2, \quad \text{Var}(\Gamma) = \frac{2(I_1 + \sigma_n^2)^2}{N}$$

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

Probability of spatial false alarm

\[
\bar{P}_f = \int_0^{\infty} P_f(x) f_{I_0}(x) \, dx \quad \Rightarrow \quad P_f(x) = P(\Gamma > \varepsilon \mid H_0, I_0 = x)
\]

Probability density function of \( I_0 \)

Probability of spatial detection

\[
\bar{P}_d = \int_0^{\infty} P_d(x) f_{I_1}(x) \, dx \quad \Rightarrow \quad P_d(x) = P(\Gamma > \varepsilon \mid H_1, I_1 = x)
\]

Probability density function of \( I_1 \)

The distribution of \( I_0 \) can be approximated by Log-normal

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

\( \sigma \) and \( m \) can be decided by the Laplace transform of \( I_0 \).
Main Results

Theorem 1: In cellular networks with D2D communication of our interest, when the path loss exponent $\alpha = 4$, the probability of spatial false alarm and spatial detection can be expressed as:

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

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

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:

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

$$
\overline{P_d} = \frac{\exp\left(\frac{\pi^2 \lambda_b}{4\sqrt{\varepsilon / P_c}}\right)}{1 - \exp(-\lambda_b \pi R_s^2)} - \frac{\exp(-\lambda_b \pi R_s^2)}{1 - \exp(-\lambda_b \pi R_s^2)} \overline{P_f}^*
$$
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 spectrum sensing, especially in dense networks.

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