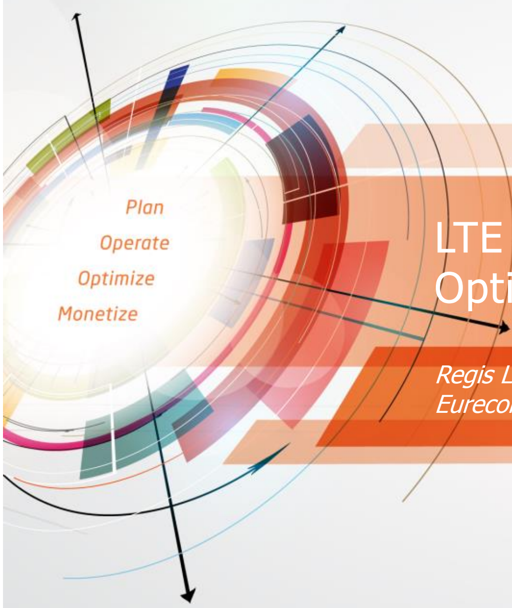


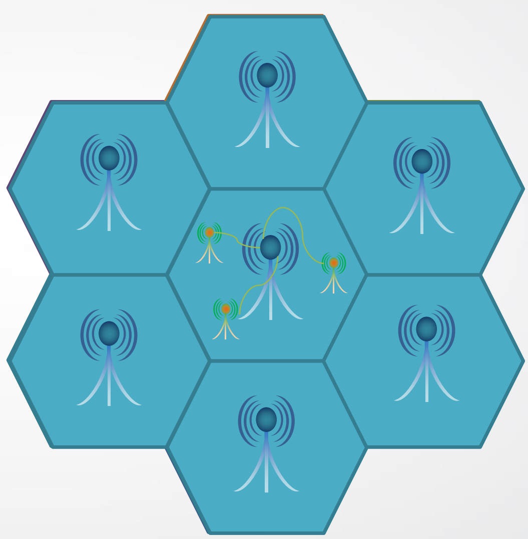
InfoVista
Orchestrating network performance

LTE Network Planning & Optimization

Regis Lerbour
Eurecom – May 26th 2015

Introduction

- What is a cellular network?
- What is a cell?
  - Macro, Micro, Pico, Femto…
- What is cellular antenna?
  - Directive (but not too) or omnidirectional
  - Size depends on frequency



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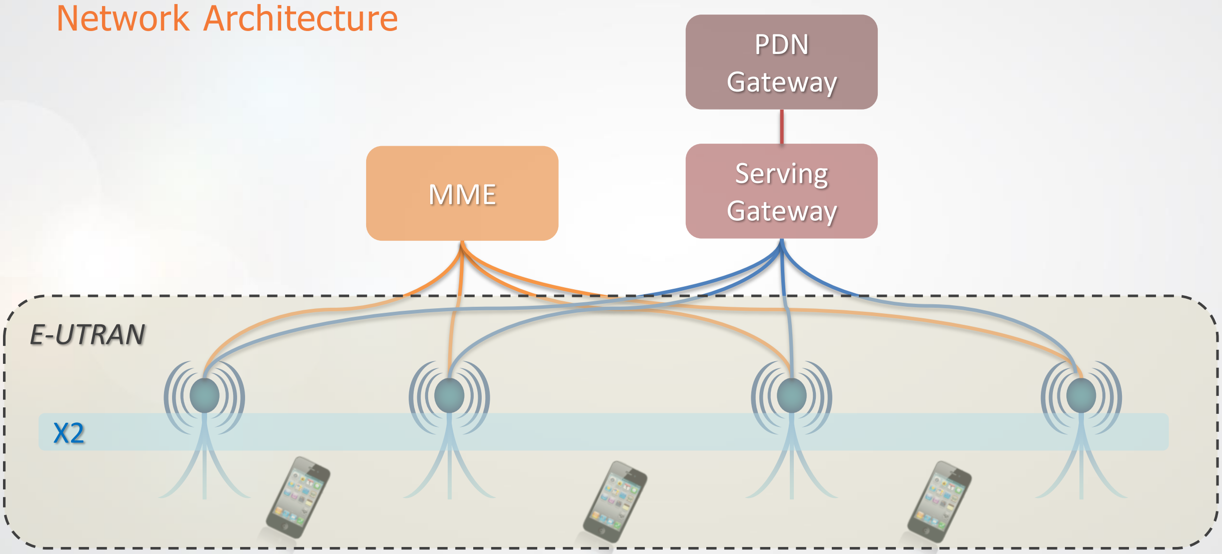
Outline

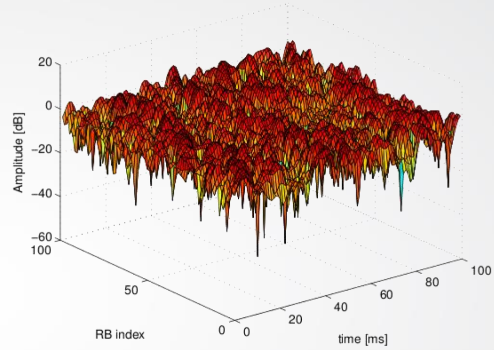
- Fundamentals of LTE
- LTE Network Planning
  - Frequency Planning
  - Synchronization Signal, Reference Signal, Random Access, Tracking Areas…
- Network Planning & Optimization In Practice
  - Propagation Models and Model Tuning
  - Traffic
  - Coverage maps
  - Monte-Carlo simulations
  - Optimization
  - Heterogeneous Networks
  - MBSFN

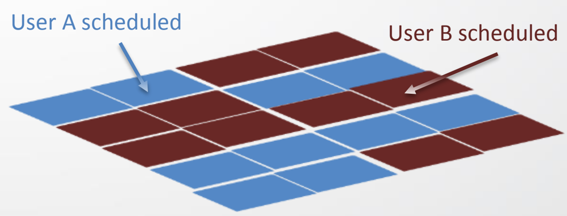
Network Architecture



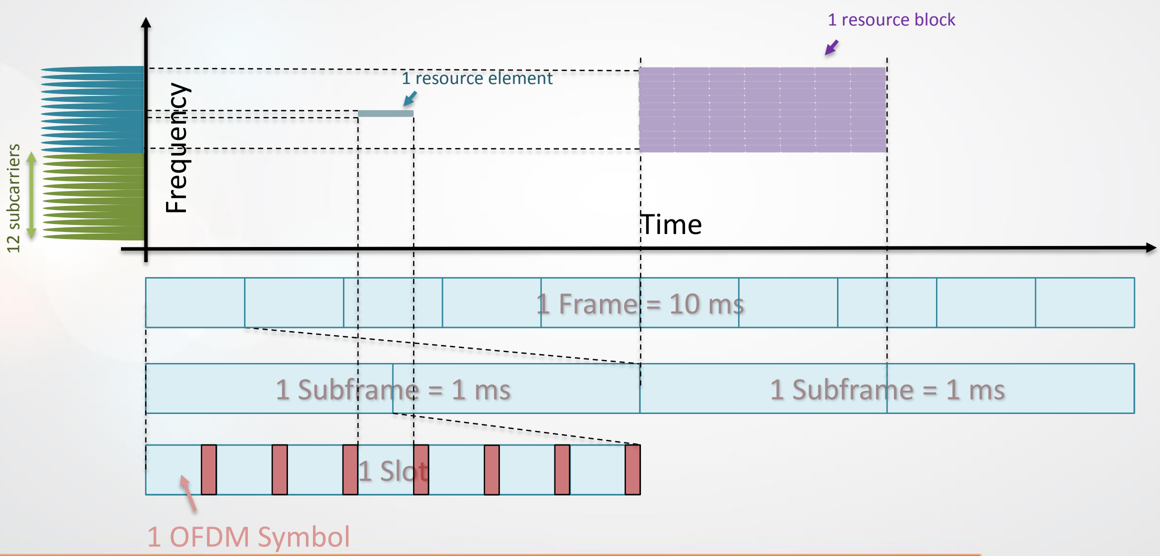
OFDM & OFDMA / SC-FDMA

- Single high data rate stream broken into multiple parallel lower data rate streams which are modulated individually over narrowband orthogonal carriers
  - Larger symbol duration for less inter-symbol interference (larger than channel delay spread)
  - Simple receiver equalization
  - Flexible Resource Scheduling
  - Less sensible to frequency offsets (Doppler)
  - High PAPR
    - SC-FDMA in the Uplink





Time & Frequency Structure

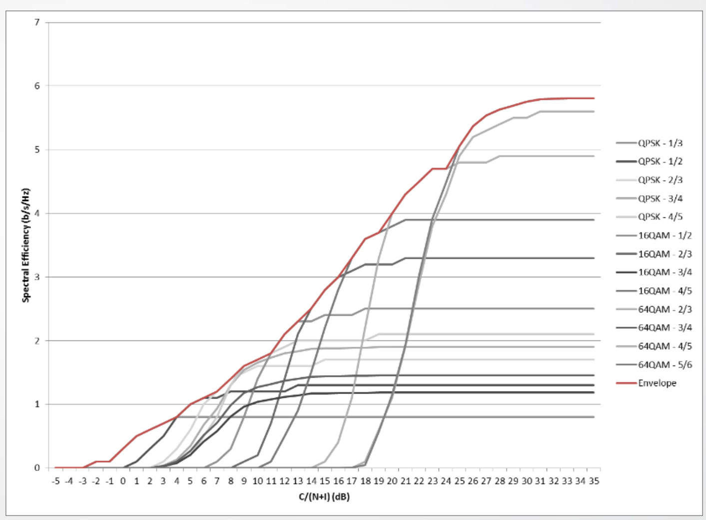


Physical Channels and Signals

- Downlink signals and channels
  - Reference Signal (Cell-Specific or UE/DM)
  - Synchronization Signal
  - PBCH
  - PDCCH, PCFICH, PHICH
  - PDSCH
- Uplink signals and channels
  - PRACH
  - PUCCH
  - PUSCH

Modulations and Coding Schemes

- MCS: combination of a modulation and a coding scheme
  - CINR Requirement (as per simulation or measurement study)
  - Spectral efficiency
- Consequence of CQI Reporting



Multiple Antennas

- 3 main categories
  - Transmit diversity
  - Spatial multiplexing
  - Beamforming

LTE Downlink Transmission Modes

Transmission Mode	Application	Release
1	Single Antenna	8
2	Transmit Diversity	
3	Spatial Multiplexing (open loop)	
4	Spatial Multiplexing (closed loop)	
5	Multi-user MIMO	
6	Single-layer closed loop Spatial Multiplexing	
7	Non Codebook-based precoding (1 layer) - Beamforming	
8	Non Codebook-based precoding (up to 2 layers)	9
9	Non Codebook-based precoding (up to 8 layers)	10

Codebook-based Precoding

Non Codebook-based Precoding

Fallback to Transmit Diversity

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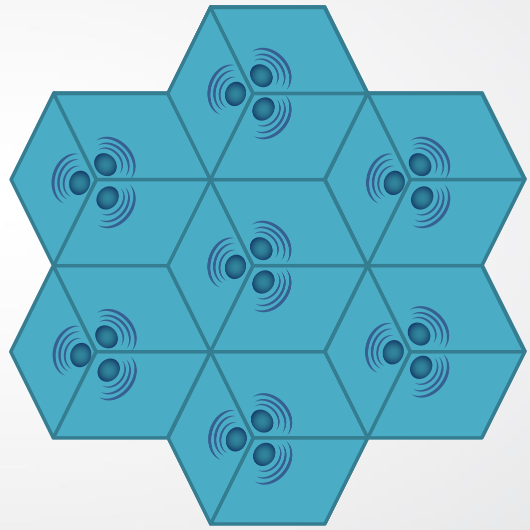
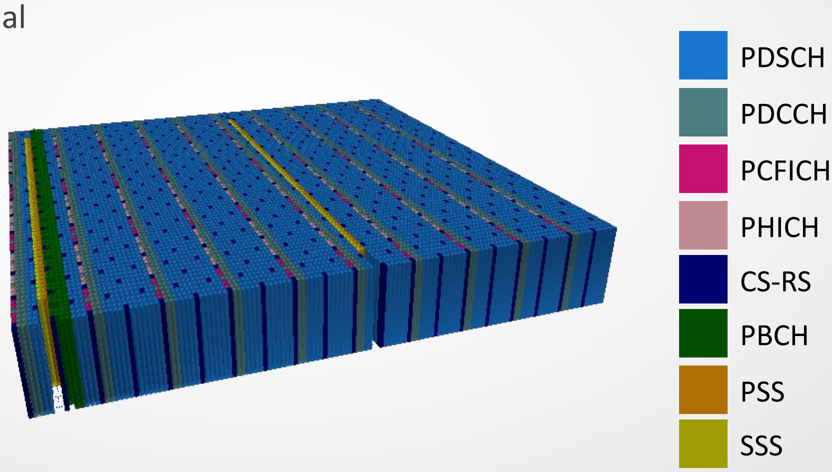
Frequency Planning

- In LTE, the frequency reuse is typically 1
- No frequency planning ☺



Downlink Synchronization Signal

- Initial downlink synchronization relies of the primary and secondary synchronization signal

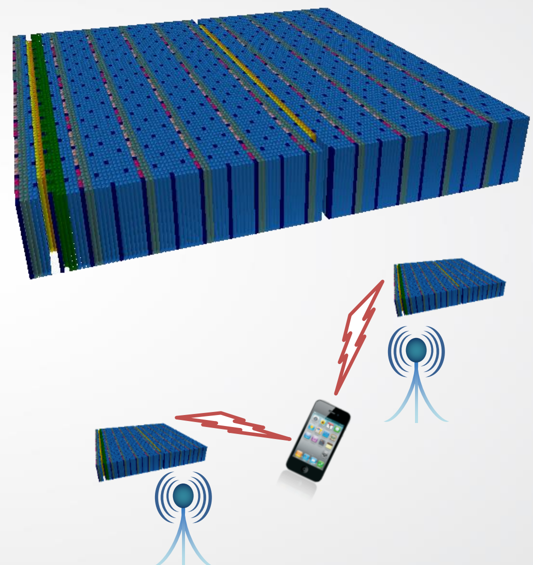


Downlink Synchronization Signal

P-SCH Acquisition → Half-frame synchronization (5ms), Cell Identity (0, 1, 2)

S-SCH Acquisition → Frame synchronization, Cell Identity Group (0...168)

Physical Cell ID (0...503)



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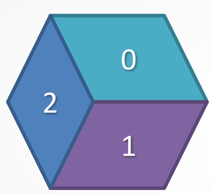
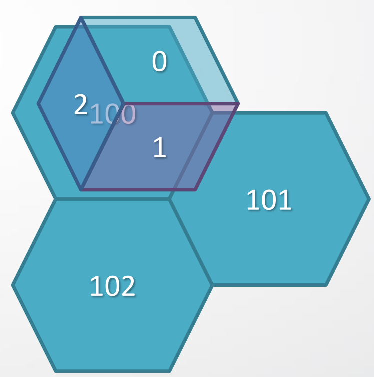
Downlink Synchronization Signal

- Network planning should ensure that adjacent cells use different P-SCH sequences



- Network planning should ensure that overlapping cells use different S-SCH sequences



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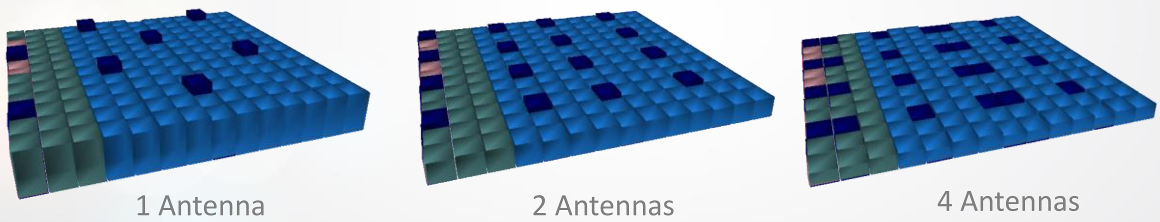
Downlink Cell-Specific Reference Signal

- Downlink cell-specific reference signal is critical for channel estimation and coherent demodulation

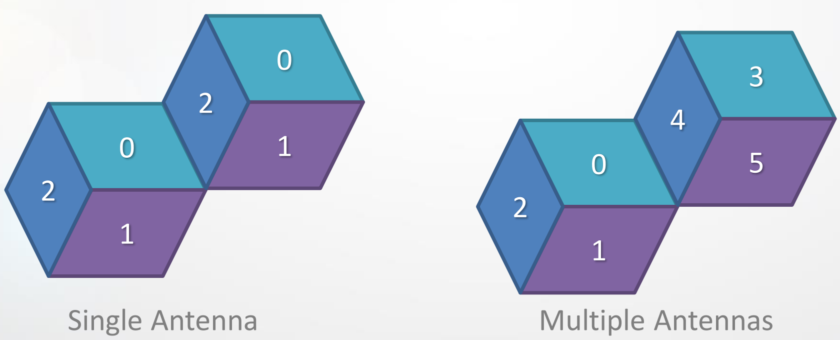
PCID =



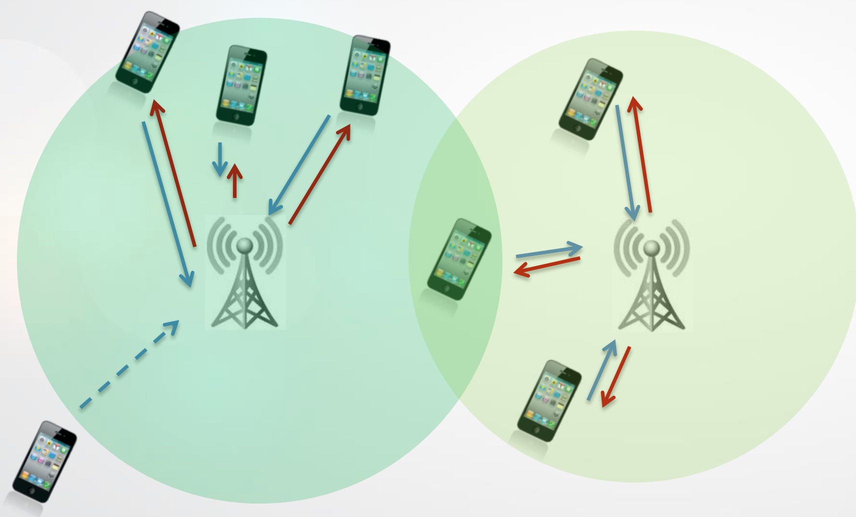
PDSCH PDCCH PCFICH PHICH CS-RS

Downlink Cell-Specific Reference Signal

- Network planning should ensure that adjacent and neighbouring cells use different resource elements for CS-RS
- The planning should consider the number of antennas of each cells



Random Access Procedure



1. eNodeBs broadcasts (PBCH)
   - Set of 64 preamble sequences
   - PRACH possible resource allocations (6RBs)

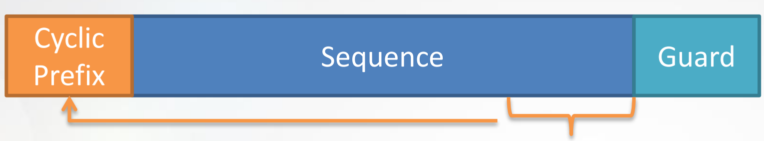
2. UE sends random access request to selected eNodeB (PRACH)
   - UE randomly selects one preamble sequence (signature)
   - UE sends RA preamble on resources allocated by eNodeB

3a. eNodeB response (PDCCH) with timing instructions and temporary identifier

3b. Or, the network tries to resolve the contention…

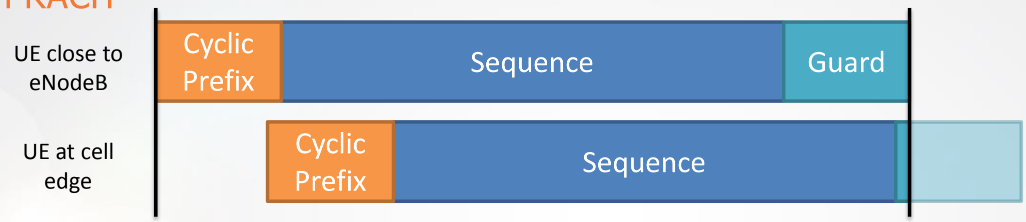
4. etc…

PRACH



- Just like any other OFDM symbol, the PRACH symbol includes a cyclic prefix to cancel inter-symbol interference
- The sequence contains the random access preamble
- A PRACH sequence is built from cyclic shifts of a root «Zadoff-Chu» sequence
  - No correlation between different cyclic shifts of the same root sequence
  - Low and constant correlation between root sequences
  - Good spectral characteristics (flat frequency spectrum)
- Each cell offers 64 different preamble sequences, if possible all generated from the same root sequence

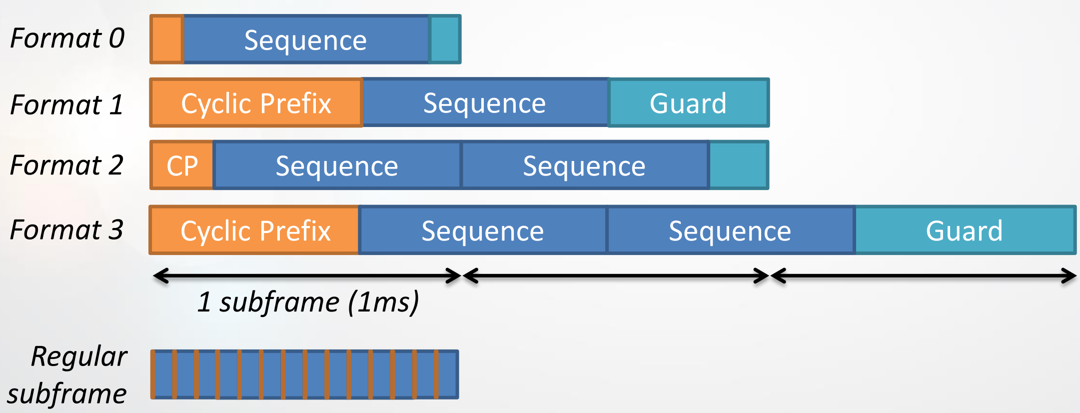
PRACH



- Because the timing advance is unknown, a guard interval (unused portion of time) is included
  - UE aligns its PRACH transmission assuming a timing advance of zero
  - A important guard interval is necessary for large cells to compensate for the propagation delay and avoid interference to the next subframe
  - A lower guard interval is sufficient for regular cells
- Additionally, the guard interval is designed in such a way that PRACH consumes an integer number of subframes and is hence aligned with the other uplink subframes

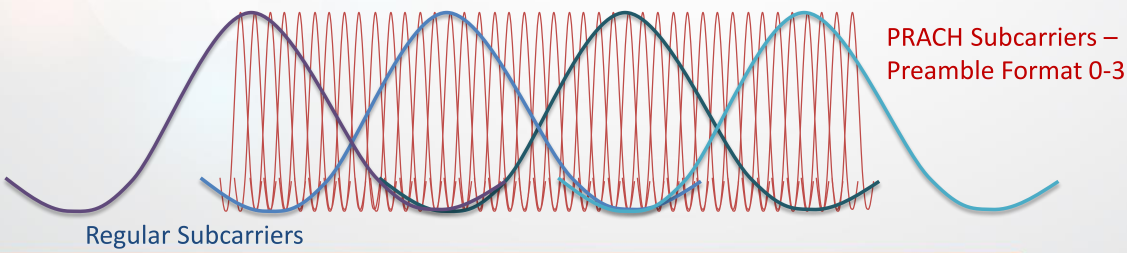
PRACH Preamble

- Cyclic prefix, sequence and guard interval length depend on the preamble format used by the cell:



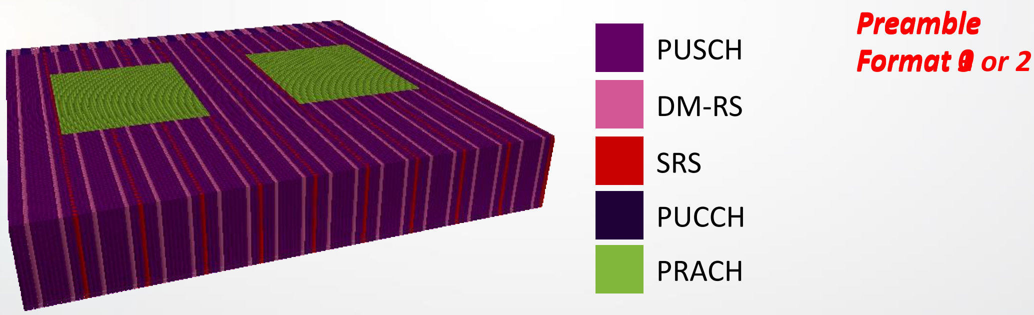
PRACH

- Symbol duration is much longer
  - Sequence duration is 800µs as opposed to 66.7µs for regular symbols (PUSCH for example)
  - A single symbol occupies the entire subframe, as opposed to 14 symbols for a regular subframe (with PUSCH, PUCCH…etc.)
- As a consequence, the subcarrier spacing is much smaller
  - 1.25kHz for PRACH subcarriers as opposed to 15kHz for regular subcarriers
  - 864 subcarriers in 6 RBs (only 839 are used -> 839 symbols in preamble sequence)
- PRACH subcarrier spacing is a submultiple of the regular subcarrier spacing
  - Orthogonality is preserved, but interference from/to other channels cannot be avoided



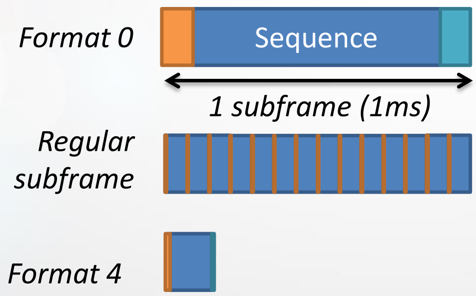
PRACH Resources

- Each cell is configured to contain one or several PRACH resource depending on the RACH load
- The start of a random access resource is aligned with the start of an uplink subframe
- The length of the PRACH resource depends on the preamble format (1, 2 or 3 subframes)
- There is a maximum of one PRACH resource (6 RBs) per subframe



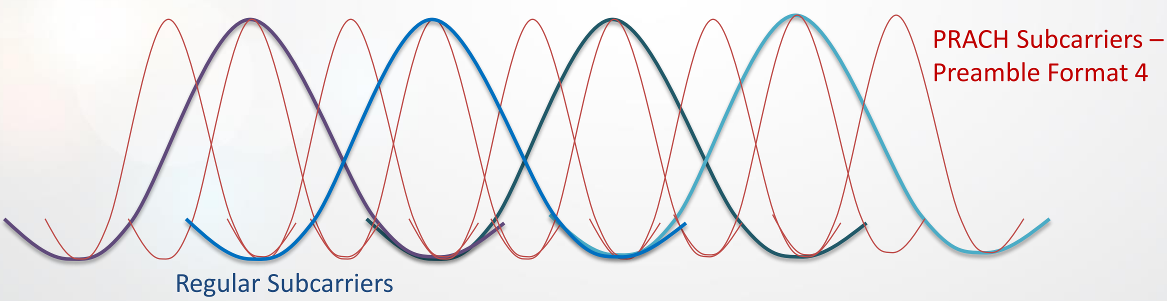
PRACH in LTE TDD

- Additional preamble format is available to LTE TDD cells: Format 4
  - PRACH is carried by UpPTS (uplink part of the special subframe)
  - Only available for special subframe configurations 5, 6, 7 and 8 (as well as special subframe configuration 4 in case of extended cyclic prefix
- PRACH is carried by uplink subframe for preamble format 0-3, just like in LTE FDD



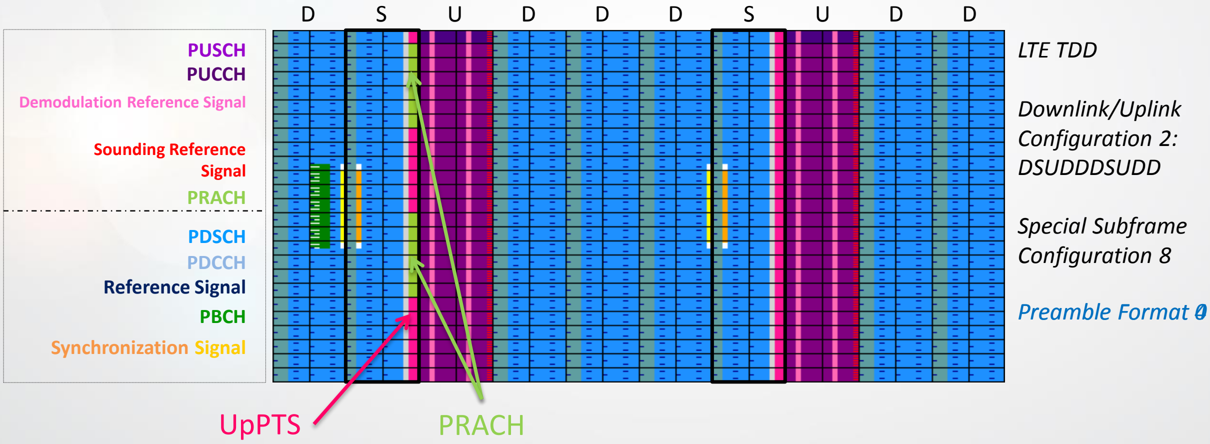
PRACH in LTE TDD

- OFDM Sequence is much smaller (133µs vs. 800µs for Preamble Format 0-3), hence larger subcarrier spacing (7.5kHz)
- Only 144 subcarriers in 6 resource blocks (only 139 are used -> 139 symbols in preamble sequence)



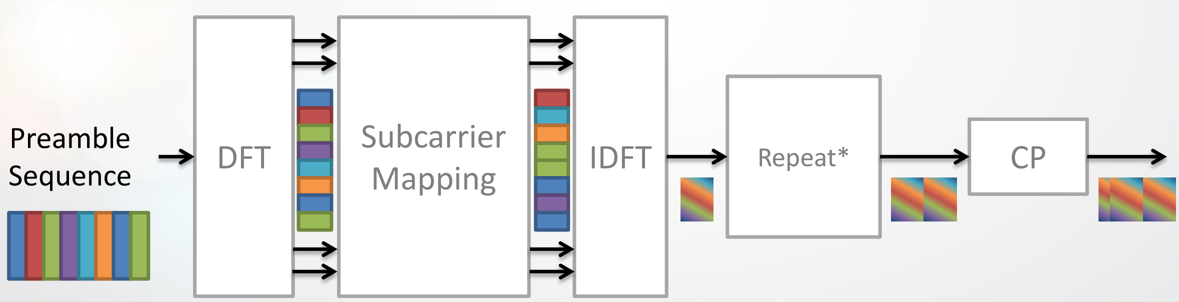
PRACH in LTE TDD

- As opposed to LTE FDD, there can be multiple PRACH resources per uplink subframe (or UpPTS for preamble format 4).



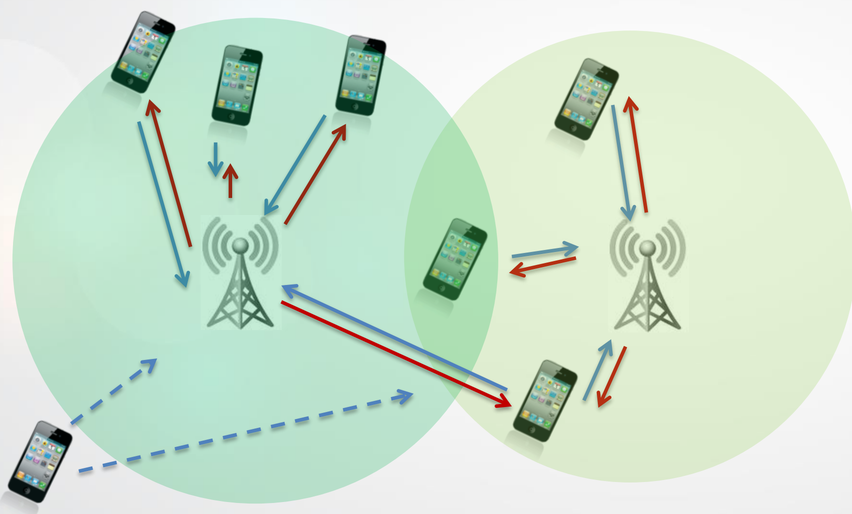
PRACH Signal Generation

- Uplink LTE uses SC-FDMA (or DFT-Spread) signal to reduce PAPR
- The ZC Sequence is generated in the time domain
- Then converted to frequency domain through DFT
- After subcarrier mapping, converted back to time domain through IDFT



** Only for Preamble Format 2 and 3*

PRACH Planning – Why?



- What happens if PRACH is not properly planned?
- With a reuse distance, cells must have a unique set of preamble sequences
- If root sequences of neighboring cells overlap, the UE preamble is detected by multiple cells that will reply and allocate unnecessary resources for these UEs

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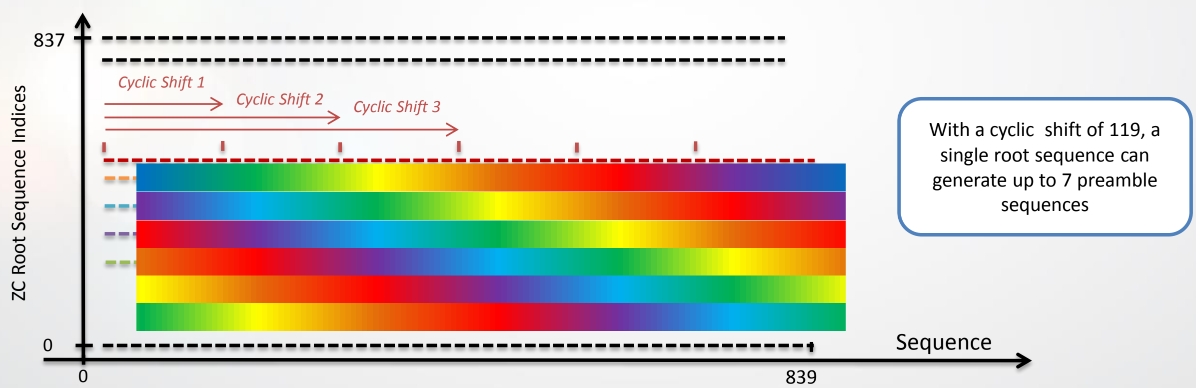
PRACH Planning – Zadoff-Chu Root Sequences

- There are a total of 838 ZC root sequences (only 138 ZC root sequences for preamble format 4 in LTE TDD)
- Each root sequence can be used to generate a number of preamble sequences, through cyclic shifts
- Each cell must be allocated 64 consecutive preamble sequences



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Root Sequence Dimensioning

- PRACH dimensioning consists in determining the most appropriate preamble format of each cell, based on the cell size
  - Format 1 and Format 3 include a large guard interval for the support of large cells
  - Format 2 and Format 3 include a repetition of the preamble sequence, which means a higher received energy and hence a better detection at low CINR levels, but also a larger overhead.

Preamble Format	Use
0	Small and medium cells
1	Large cells
2	Medium cells with link budget issues
3	Very large cells (with link budget issues)

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Root Sequence Dimensioning

- From a single ZC root sequence, different numbers of preamble sequences can be generated, depending on the length of the cyclic shift

Cell Cyclic Shift Configuration	Cyclic Shift Length *(Unrestricted Set)*	Number of Preamble Sequences per Root Sequence	Number of Required Root Sequences per Cell
0	0	1	64
1	13	64	1
2	15	55	2
3	18	46	2
…	…	…	…
15	419	2	32

As defined by 3GPP

The length of a sequence is 839

Each cell requires 64 preamble sequences

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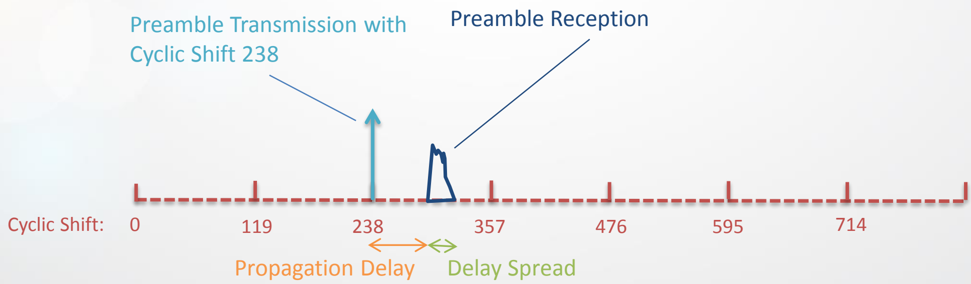
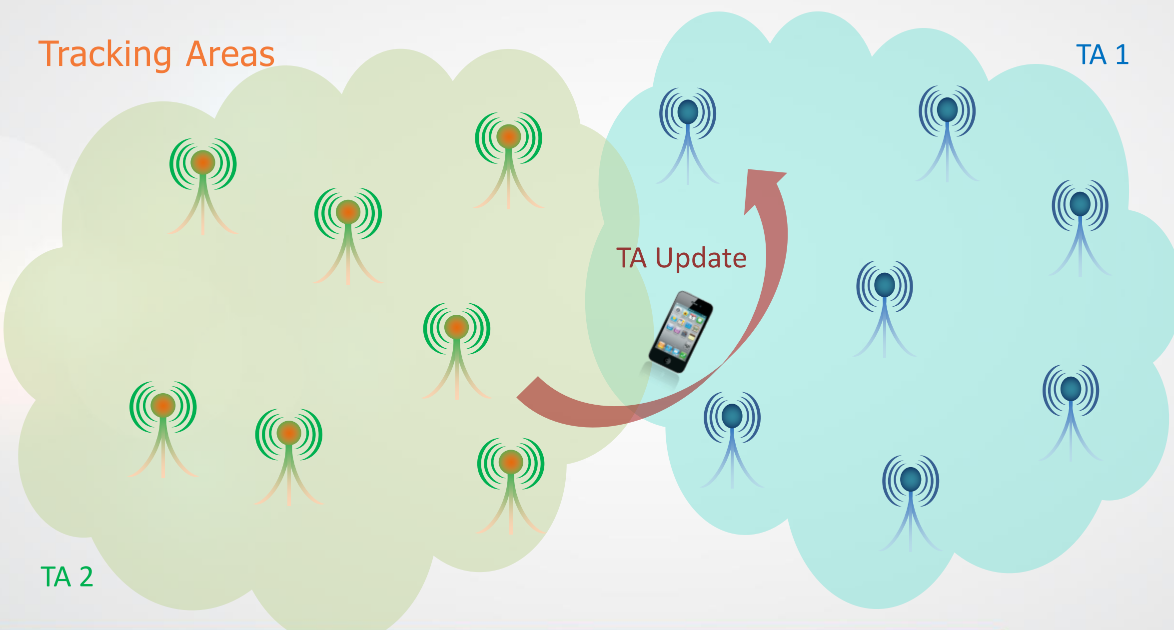
Root Sequence Dimensioning

- PRACH dimensioning also consists in determining the most appropriate cyclic shift configuration of each cell.
  - With a high cyclic shift length, many root sequences are necessary which makes the PRACH planning more difficult and results in a higher root sequence re-use.
  - On the other hand, one needs to ensure that the cyclic shift duration covers the maximum delay spread and time uncertainty of an uplink non-synchronized UE.



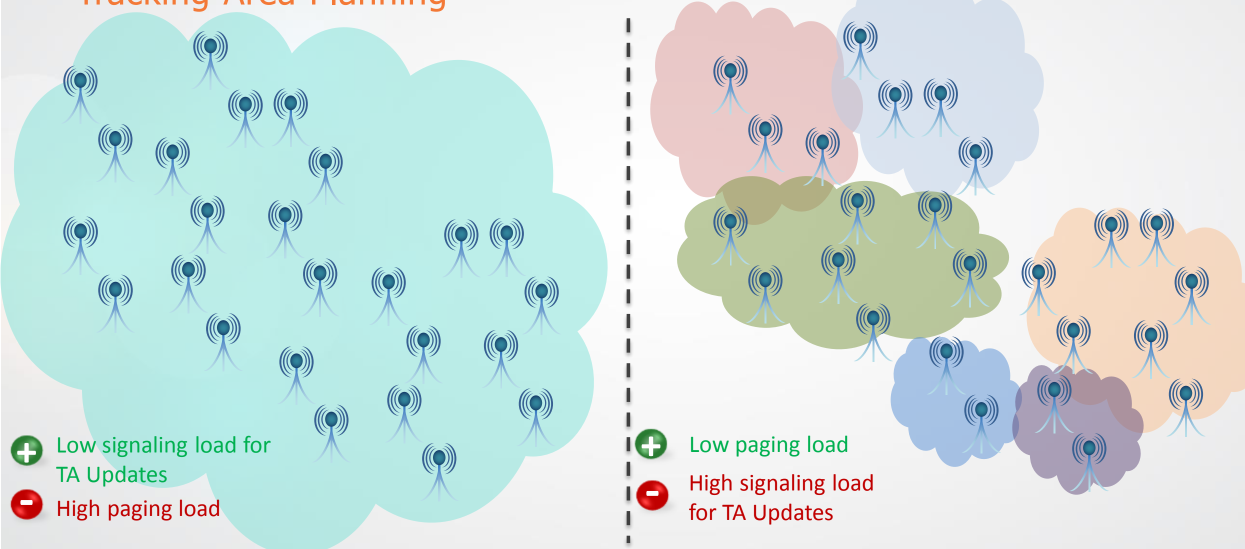
Tracking Areas



Tracking Area Planning

- Tracking Area (TA) Planning aims to plan tracking areas in a manner that strikes a balance between
  - The network paging load
  - The tracking area update (TAU) signaling load.
- Increasing the size of a tracking area by assigning a large number of cells per TAC reduces the network TAU signaling load but will increase the paging load within the TA
- Conversely, reducing the size of a tracking area by assigning a lower number of cells per TAC increases the TAU load, creating unnecessarily high amount of signaling.

Tracking Area Planning



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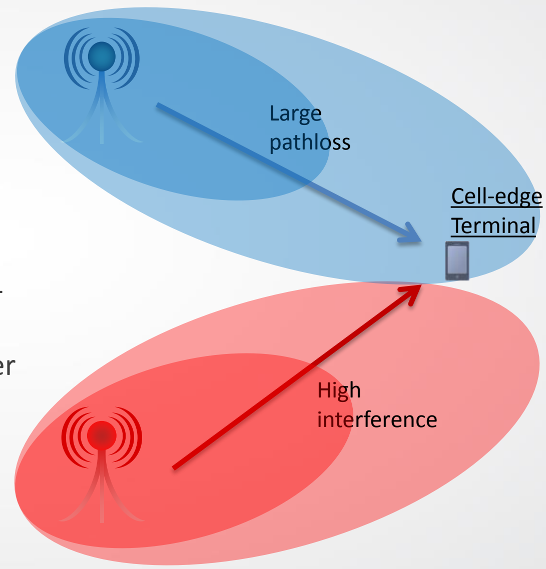
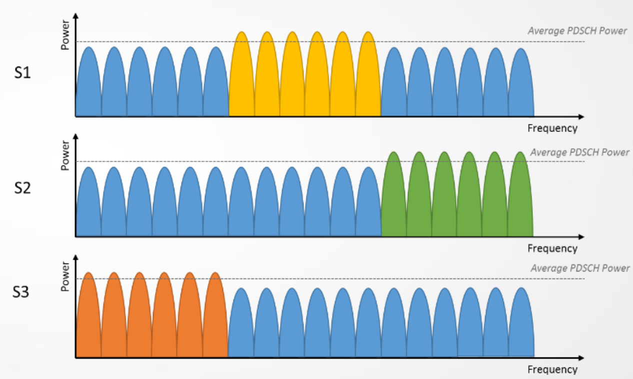
Interference Coordination (ICIC)

- The objective is to protect the data transmissions of cell-edge users from interference
  - Inter-cell coordination of resource allocations and transmit power
  - In the outer cell portion of the cell (cell-edge users), only a portion of the resources can be allocated, with a higher transmit power
  - In the inner portion of the cell, a large reuse is allowed, and a lower transmit power is acceptable



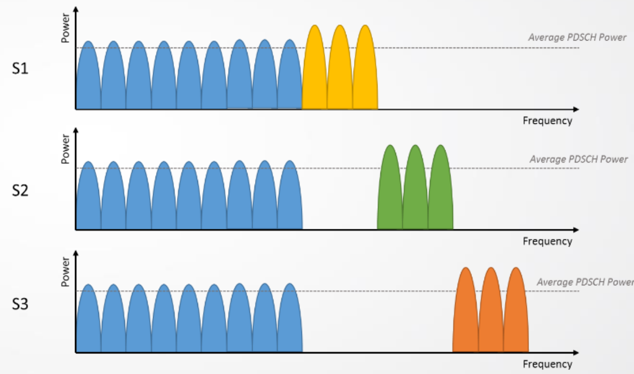
Interference Coordination (ICIC)

- Soft Frequency Reuse (SFR)
  - Terminals located in the inner cell can use 2/3 of the resources
  - Terminals located in the outer cell use the remaining 1/3 of the resources
- Outer cell resource blocks can be transmitted at a greater power, which limits the power transmitted to inner cell terminals



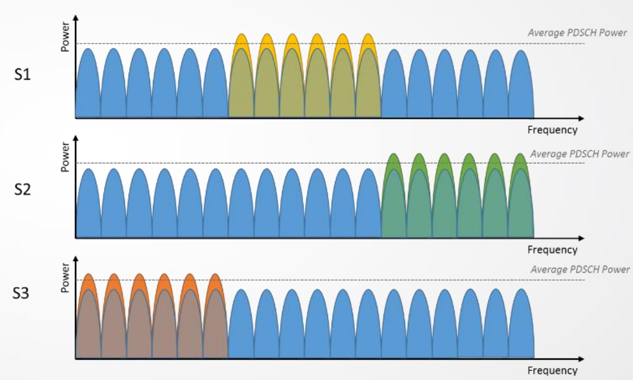
Interference Coordination (ICIC)

- Partial Frequency Reuse (PFR)
  - Terminals located in the inner cell can use a pre-defined portion of the resources
  - Terminals located in the outer cell use 1/3 of the remaining resources
- Outer cell resource blocks can be transmitted at a greater power, which limits the power transmitted to inner cell terminals.



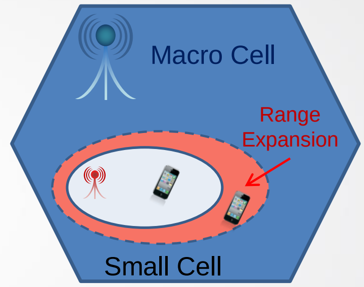
Interference Coordination (ICIC)

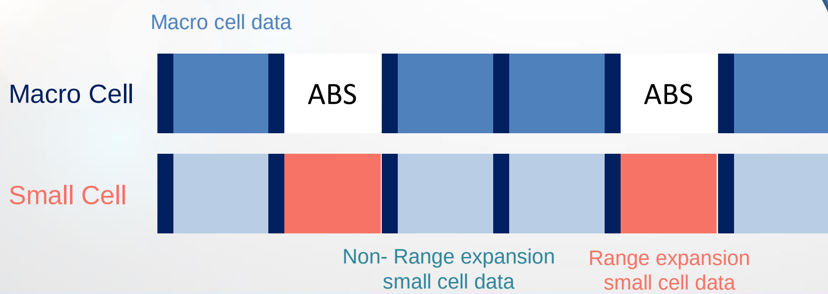
- Fractional Frequency Reuse (FFR)
  - Terminals located in the inner cell can use all resources
  - Terminals located in the outer cell are limited to 1/3 of the resources
- Some resources can be used by both inner cell and outer cell users
- 2 types of subframes in inner cell and outer cell



Enhanced Interference Coordination (eICIC)

- Small cells are often located in areas of strong downlink interference
- With ABS, the macro cell blanks part of its radio frame to reduce the interference on the pico cell edge (range expansion) users.
- Small cell schedules “Range Expansion” users during Almost blank subframes





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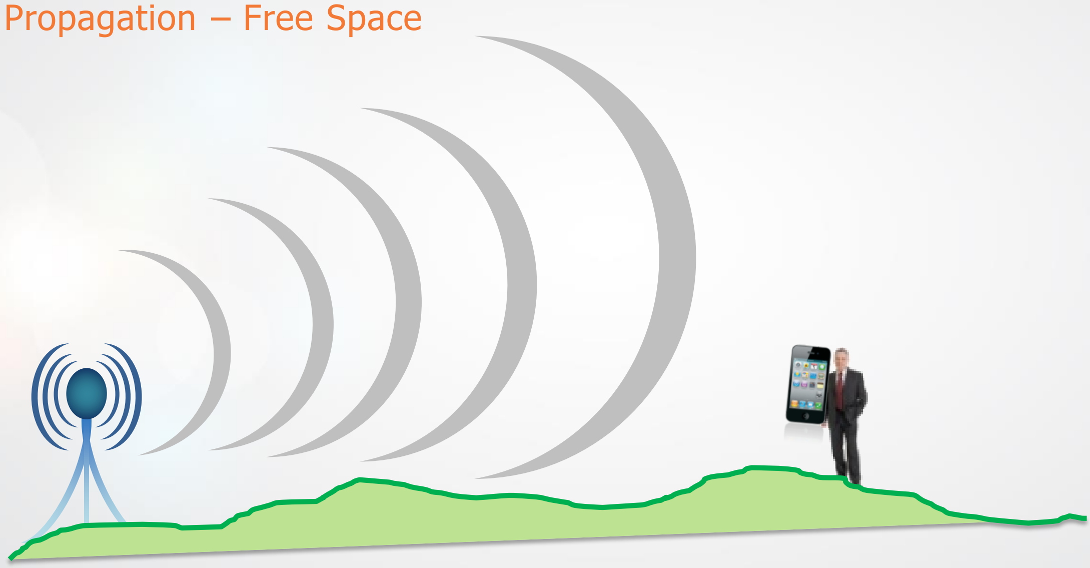
Propagation

- Maxwell Equations have been known since 1873
- It would be great if we had
  - Perfect information about the terrain and clutter
  - Lots of time and very powerful machines
- But we have to deal with
  - Incomplete and always obsolete environment data
  - Approximate propagation models that need to be calibrated thanks to measurements

Propagation – Free Space



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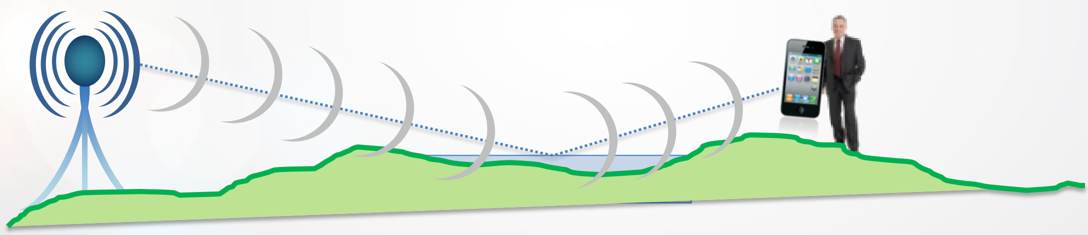
Propagation – Reflection



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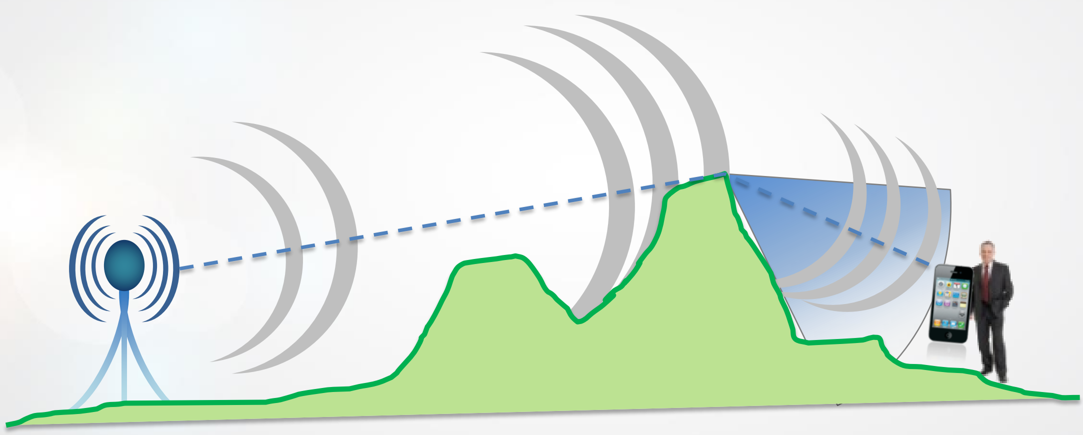
Propagation – Diffraction



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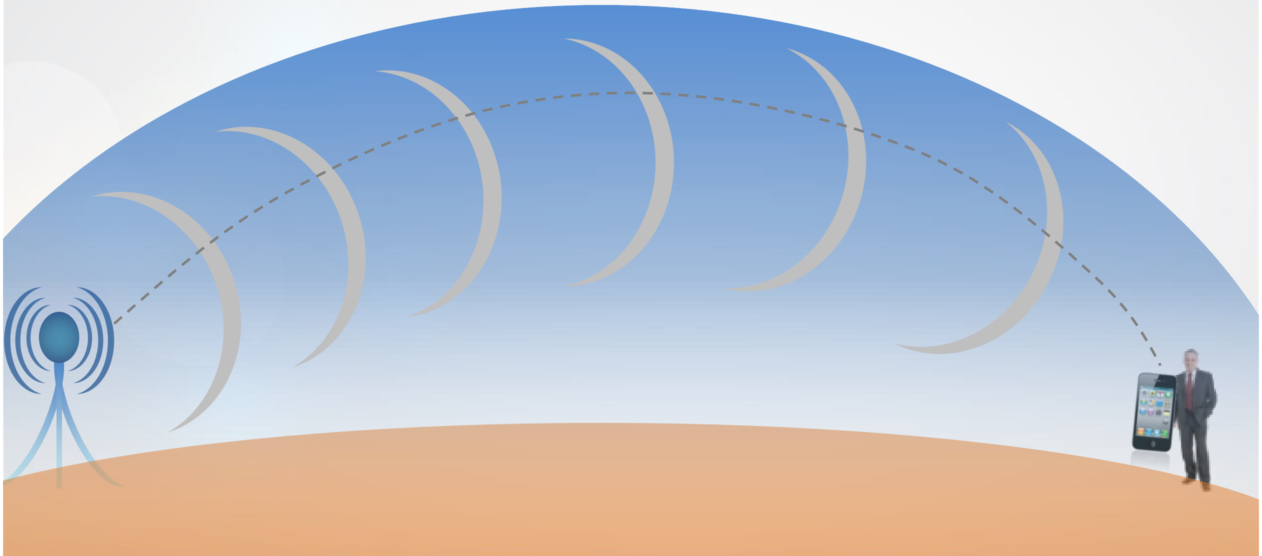
Propagation – Refraction



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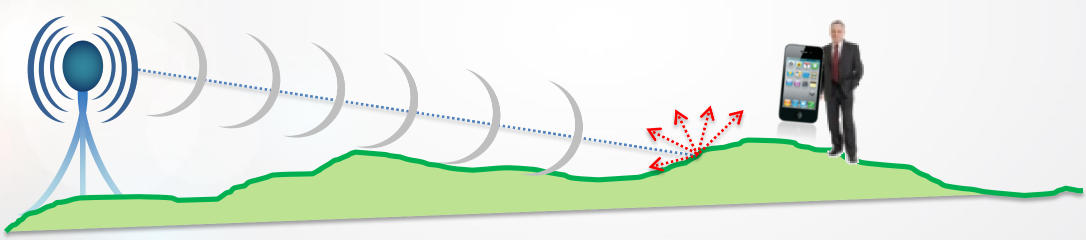
Scattering



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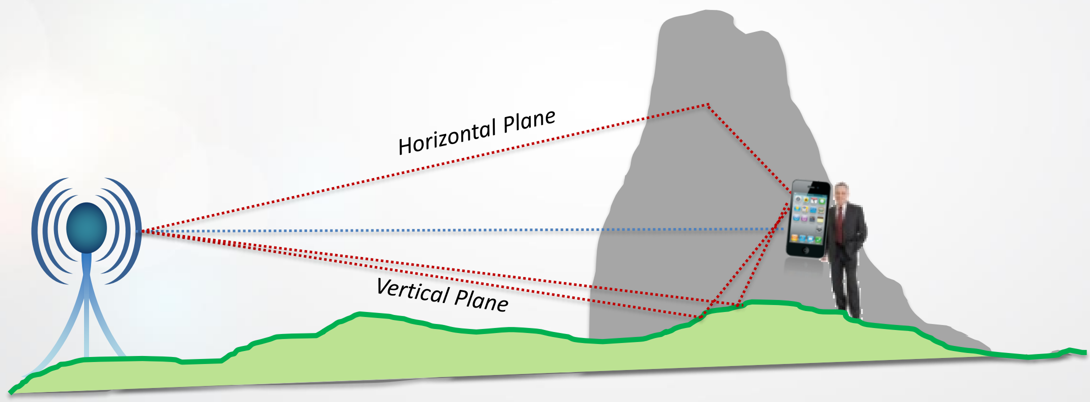
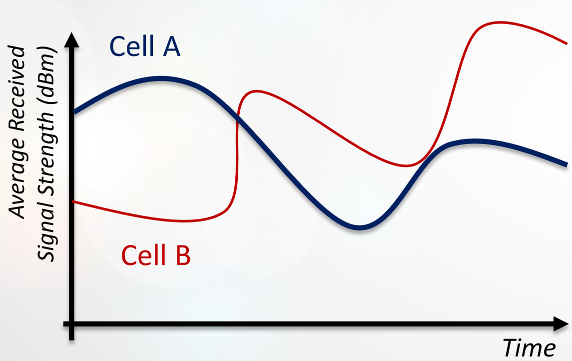
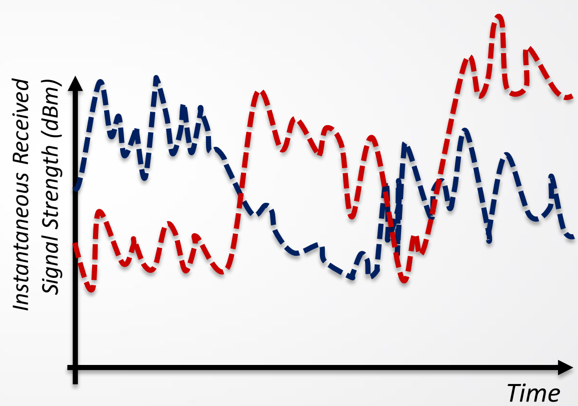
Multipath



Fast Fading





Propagation Models

- Propagation models aim at predicting the path loss between a transmitting and receiving antenna
  - Allows modeling of RF environment in network
  - Critical to all tasks performed by a planning tool, from initial design to ongoing network management
- Network planning tools are using propagation models in specific ways
  - The models are performing large scale predictions, where the received signal is averaged over several meters
  - The models are performing far field predictions only (i.e. several wavelengths from the transmitter) and consider the primary propagation mechanisms (free space, refraction, reflection, diffraction, scattering…)
- Network planning tools are "binning" the result of the predictions at a given resolution
  - In general that resolution is the same as the underlying geodata used

Model Types

- Empirical models
  - Result from experimental measurements of path loss
  - Very fast, non tunable and of poor accuracy
- Slope-based models with diffraction algorithms
  - Result from experimental measurements and mathematical modeling expressions
  - Very fast, very tunable and of good accuracy
  - Require tuning and little re-use possible
- Deterministic models
  - Result from development of propagation science
  - Slow, reasonably tunable and good accuracy
  - Highly re-usable
- Hybrid models
  - They use several algorithms & techniques to achieve optimum accuracy
  - Highly accurate and tunable with reasonable performance
  - Highly re-usable

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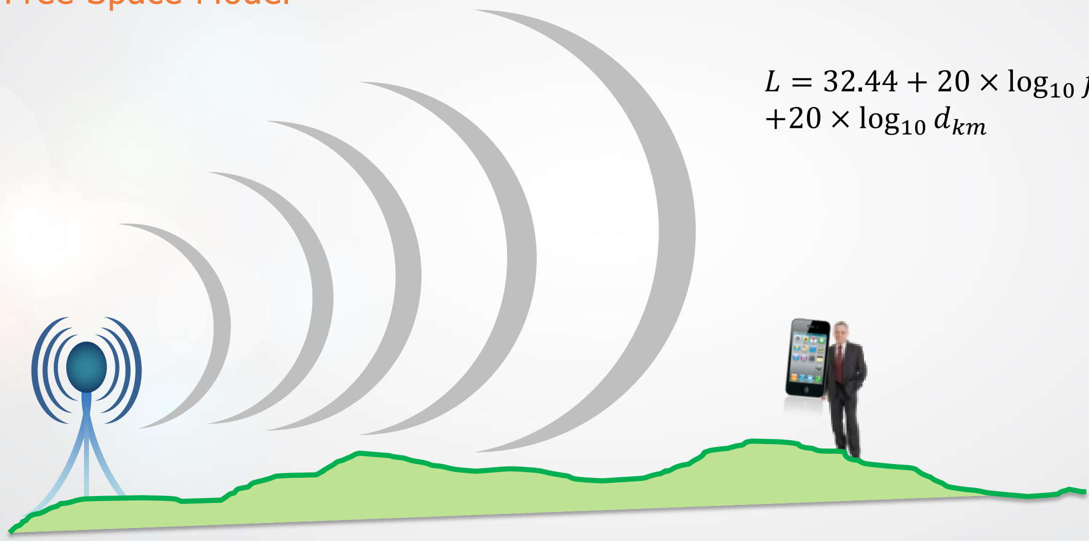
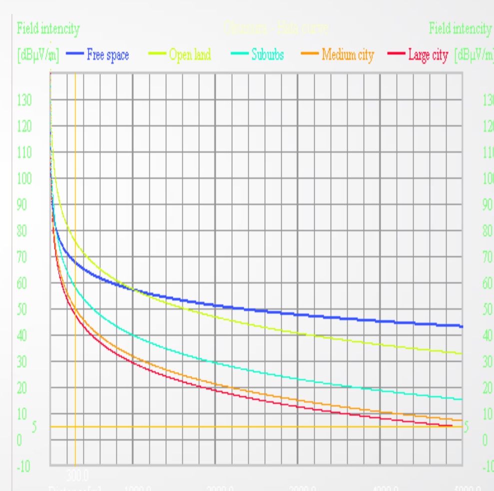
Free Space Model



$$L = 32.44 + 20 \times \log_{10} f_{MHz} + 20 \times \log_{10} d_{km}$$

Okumura-Hata

- Slope-based empirical model
- Applicability:
  - Frequency range: 150 to 1500 MHz
  - Propagation Distance: 1 to 20 km
  - Base station antenna height: 30 to 200m
  - Receiver antenna height: 1 to 10m



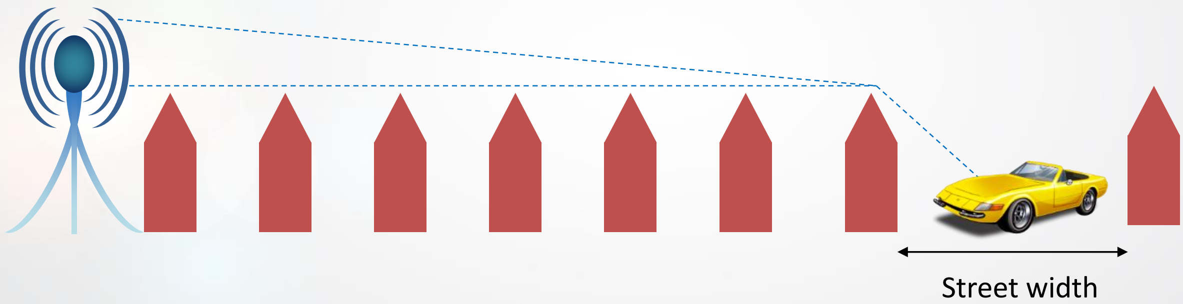
$$L = A + B \times \log d - a(h) + C$$

$$A = 69.55 + 26.16 \times \log f - 13.82 \times \log H$$

$$B = 44.9 - 6.55 \times \log H$$

Cost 231 Walfisch-Ikegami Model

- Propagation over uniformly-spaced rooftops



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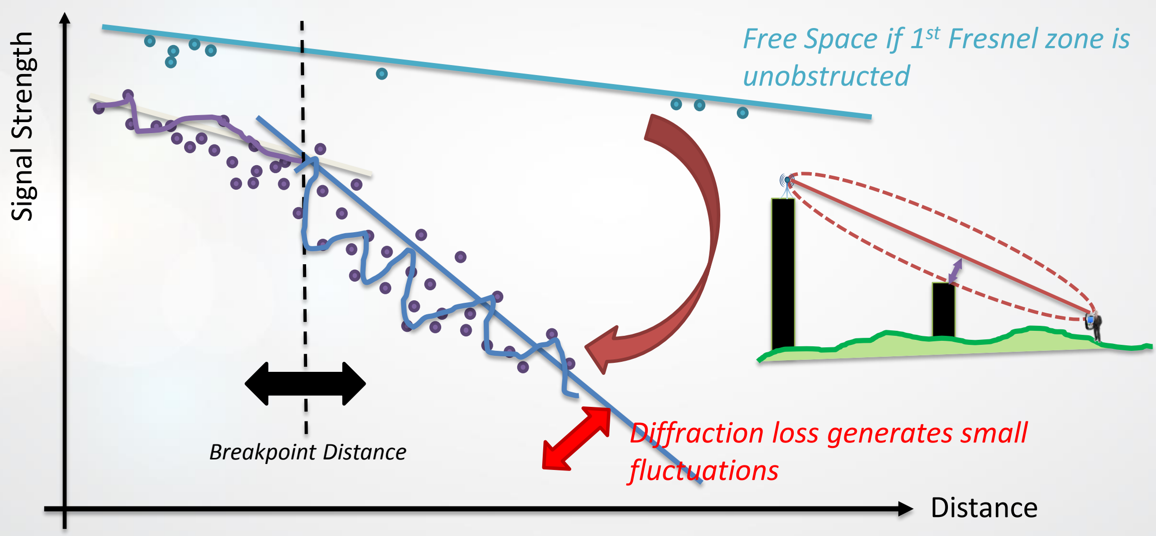
Slope-based Models



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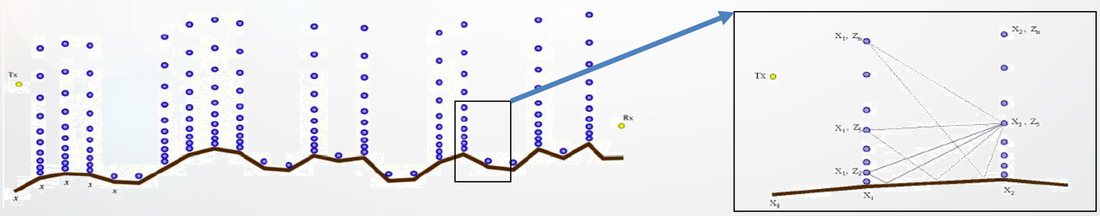
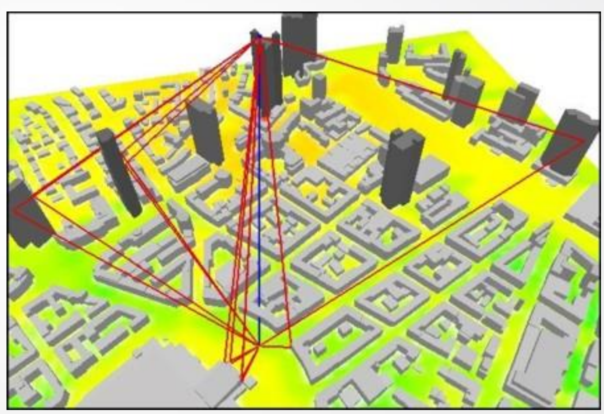
Predict

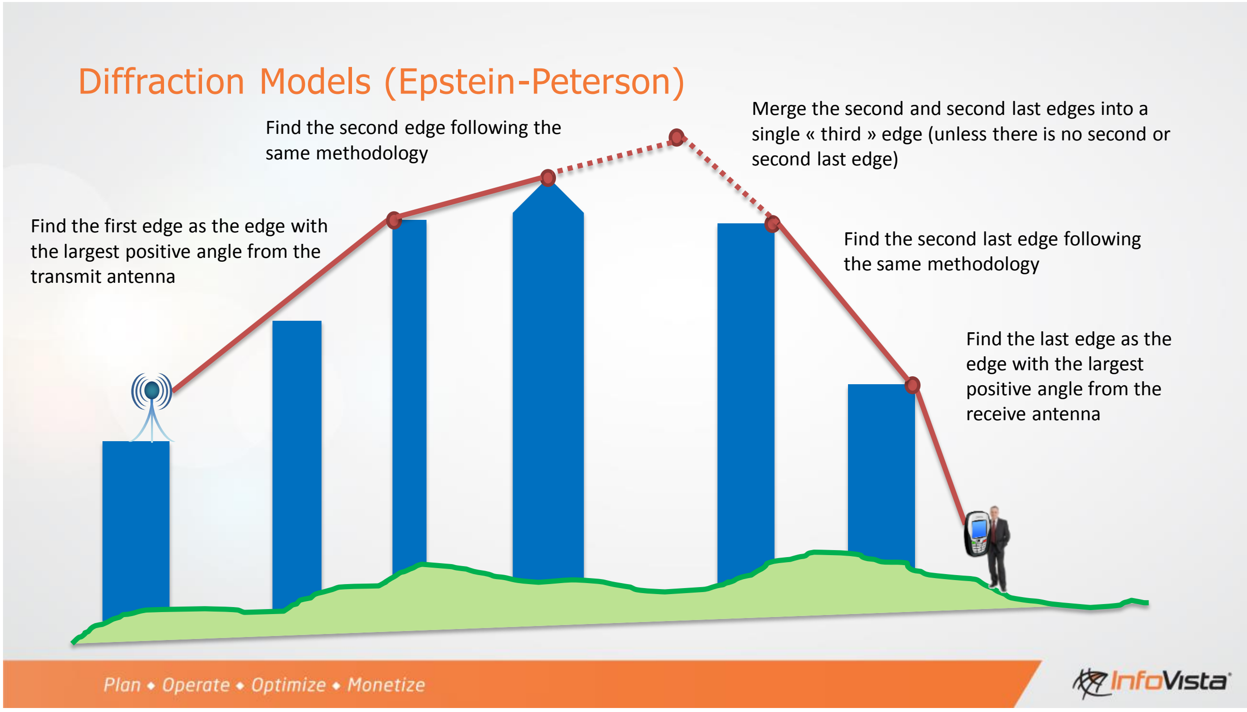
- Deterministic model based on physical optics (Fresnel-Kirchhoff theory), which is expressed in terms of the Huygens' principle of optics
- Used when accurate terrain and clutter data are available (20 – 30m resolution)
- Good accuracy in macro-cellular environment
- Highly re-usable and particularly good in green field environments or where clutter height is known



Ray Tracing Models

- Assume that the wave can be modeled as a number of narrow beams through an optical approximation
- Quite accurate but computationally intensive
- The number of reflected and diffracted components must be limited for computation time reasons




Diffraction Models (Epstein-Peterson)
Find the second edge following the same methodology
Merge the second and second last edges into a single « third » edge (unless there is no second or second last edge)
Find the first edge as the edge with the largest positive angle from the transmit antenna
Find the second last edge following the same methodology
Find the last edge as the edge with the largest positive angle from the receive antenna
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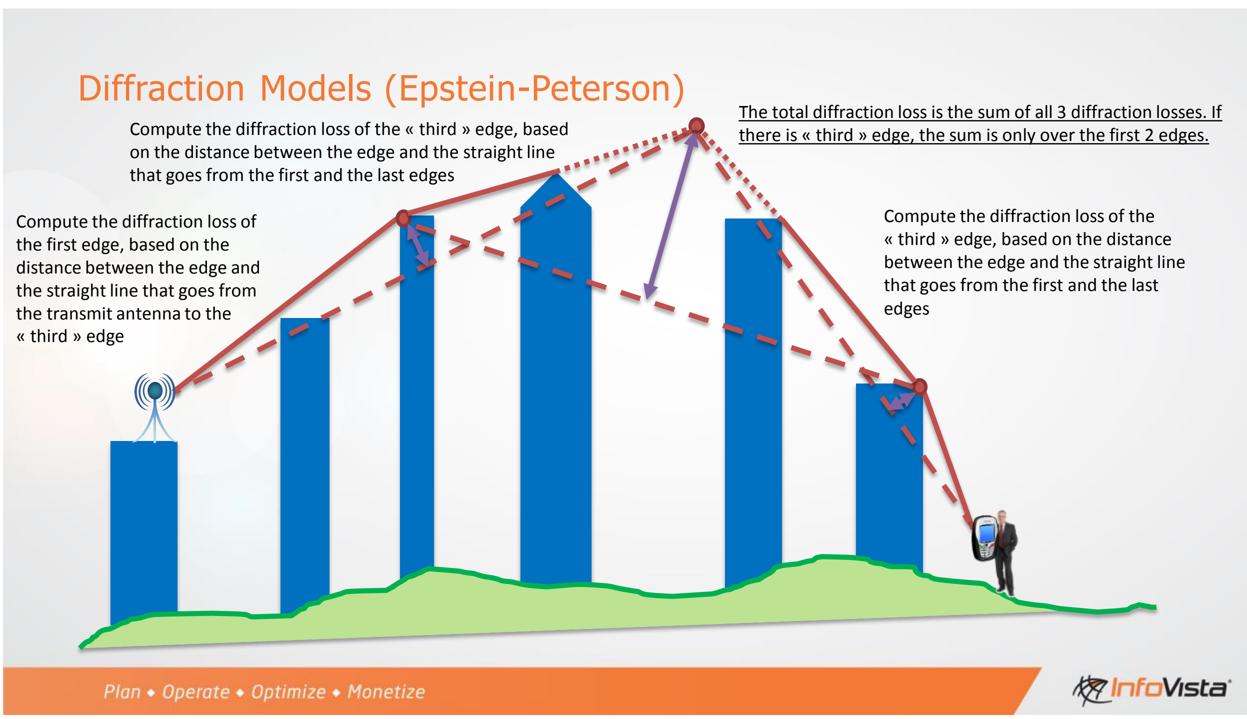
Diffraction Models (Epstein-Peterson)
Compute the diffraction loss of the « third » edge, based on the distance between the edge and the straight line that goes from the first and the last edges
The total diffraction loss is the sum of all 3 diffraction losses. If there is « third » edge, the sum is only over the first 2 edges.
Compute the diffraction loss of the first edge, based on the distance between the edge and the straight line that goes from the transmit antenna to the « third » edge
Compute the diffraction loss of the « third » edge, based on the distance between the edge and the straight line that goes from the first and the last edges
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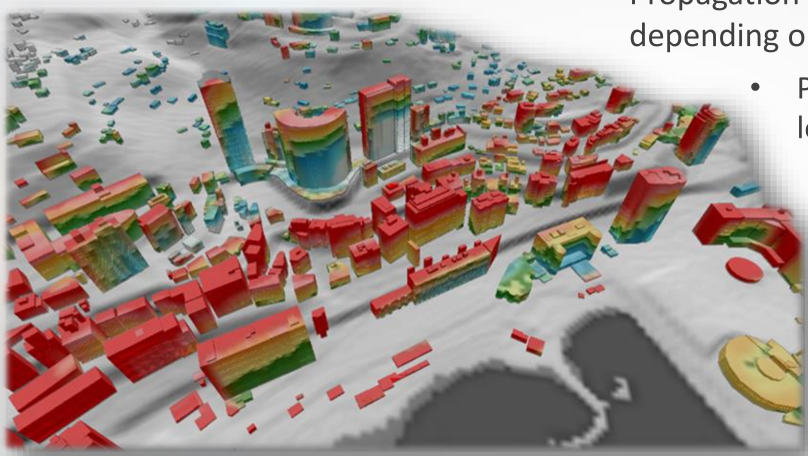
3D and Prediction Heights



- Propagation conditions largely vary depending on the receiver height
  - Pathloss prediction at street level are not sufficient
    - Predictions are computed at several heights, within buildings only

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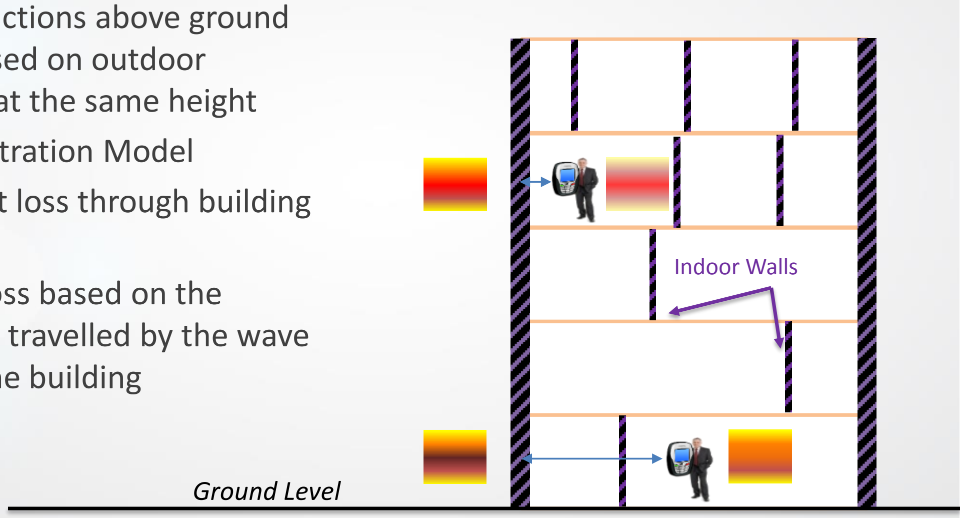
Indoor Penetration

- Indoor predictions above ground level are based on outdoor predictions at the same height
- Indoor Penetration Model
  - Constant loss through building wall
  - Linear loss based on the distance travelled by the wave inside the building



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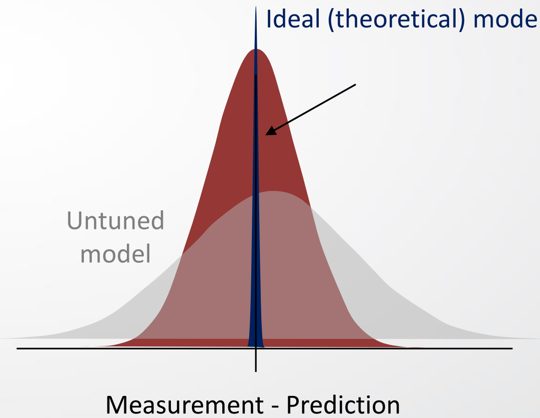
Model Tuning

- Propagation predictions can be improved with the use of measurements by adapting the parameters of a propagation algorithm
  - Entirely automated process
  - Operators can use different strategies on how to tune models
  - Each model type has its own unique parameters and hence, unique tuner
- Model tuning improves the accuracy of RF tool simulations, analyses and optimizations, and is necessary when
  - Model accuracy is questionable
  - Frequency band changes
  - Terrain changes
  - Coverage expansion is required



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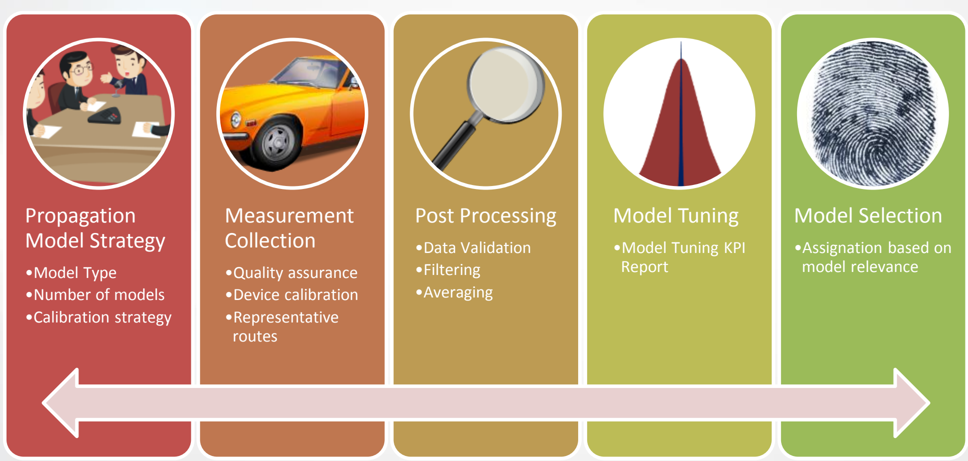
Model Tuning Process



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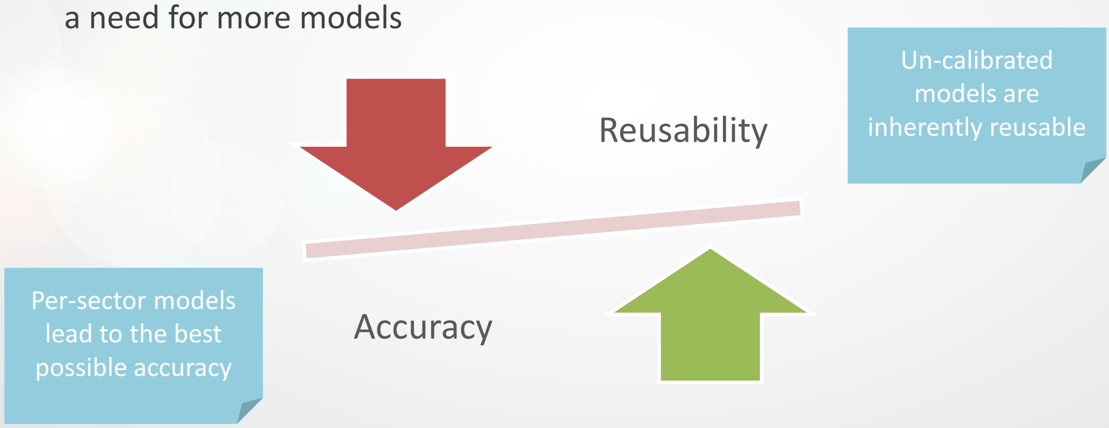
Model Tuning

- The more you tune a model for a specific environment, the better the model for that environment but the less re-usable it gets, hence leading to a need for more models



Propagation Model KPIs

- Comparison of predictions with measurements provides a mean to evaluate the accuracy of predictions

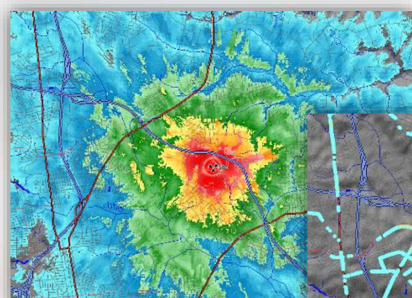
Metric (dB)	**Meaning**
Mean Error (Offset)	Always close to zero due to the tuning process and hence, truly only relevant in “blind” tests.
RMS	A metric that combines the standard deviation and the mean. This means that the RMS of the various test sites is the most important parameter.
Correlation	Indicates the robustness of the model and its ability to properly model the radio phenomena. A key parameter in the assessment of the quality of the drive test.
Error vs. Distance	A parameter that is used to ensure the model does not have fundamental error bias when close or far from transmitter

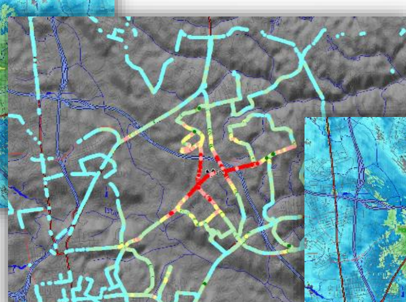
Propagation Model KPIs

- The accuracy level to target highly depends on the type of model and environment

	RMS	Correlation	Offset
Exceptional	< 6 dB	> 0.90	< 2 dB
Very good	6 dB – 7.5 dB	0.85 – 0.90	2 dB - 3 dB
Good	7.5 – 8.5 dB	0.80 – 0.85	3 dB – 5 dB
Fair	8.5 – 10 dB	0.70 – 0.80	5 dB – 7 dB
Poor	> 10 dB	< 0.70	> 7 dB

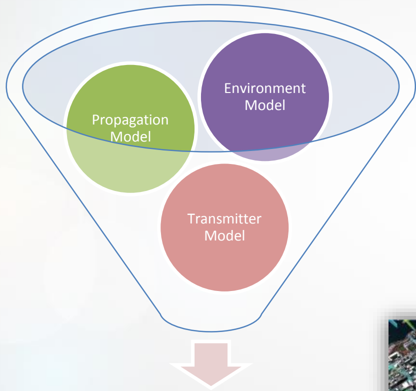
Model Merging


Predictions

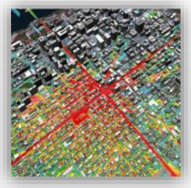

Measurements

Merged Predictions


Propagation Models



Propagation Prediction



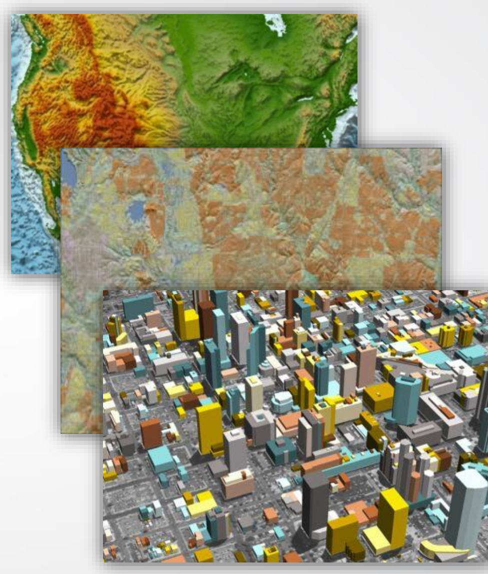
Geographical Data

Transmitter Location and Antenna Configuration

Model Type and Parameters

Geographical Data

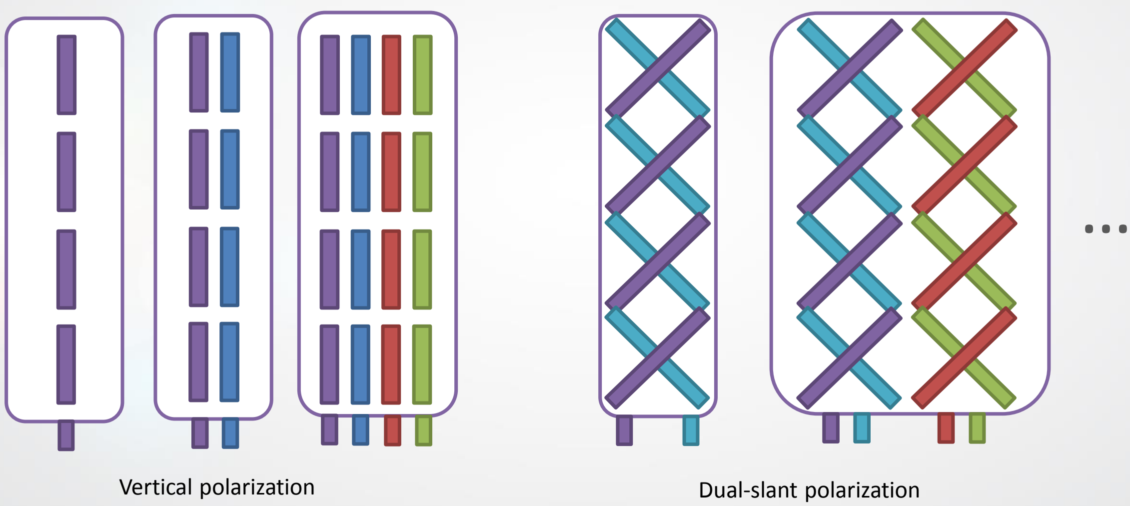
- Digital **Elevation** Models (DEMs) are grids representing the height of the terrain above sea level.
- Land-use information, or "**Clutter**" grids are a classified representation of the type of terrain (i.e. vegetation, trees, man-made structures…etc.).
- **Building** and vegetation heights can be represented by grids or by high-resolution vectors and specify the mean height above ground of e.g. the building. This information is particularly useful in urban areas.



Antennas

- The influence of the antenna model is typically computed separately from the path loss
- It depends on:
  - The antenna model
  - The frequency band
  - The antenna installation (location, height, azimuth and tilt)
  - The antenna configuration (electrical parameters)

Cellular Antennas



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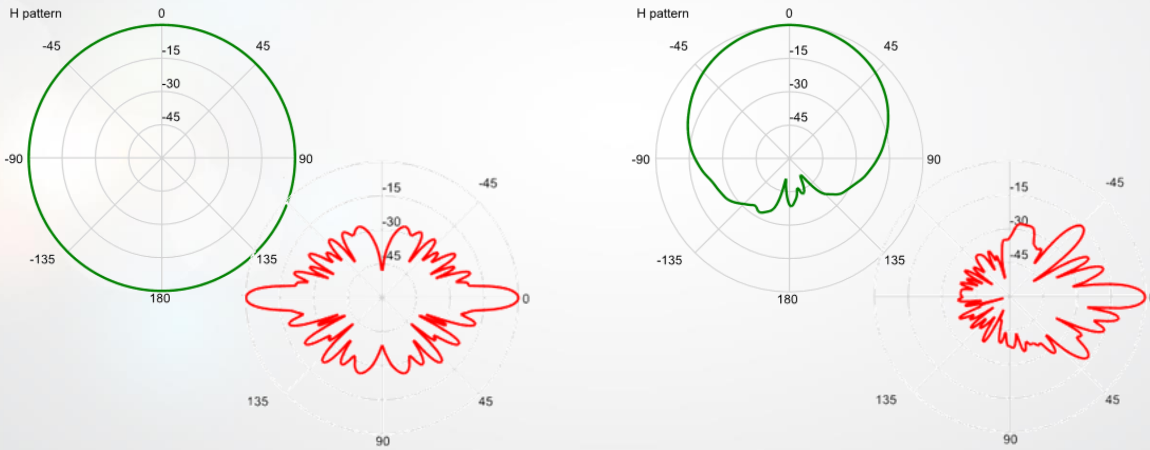
Cellular Antennas

- Omni-directional vs. sectorized antennas



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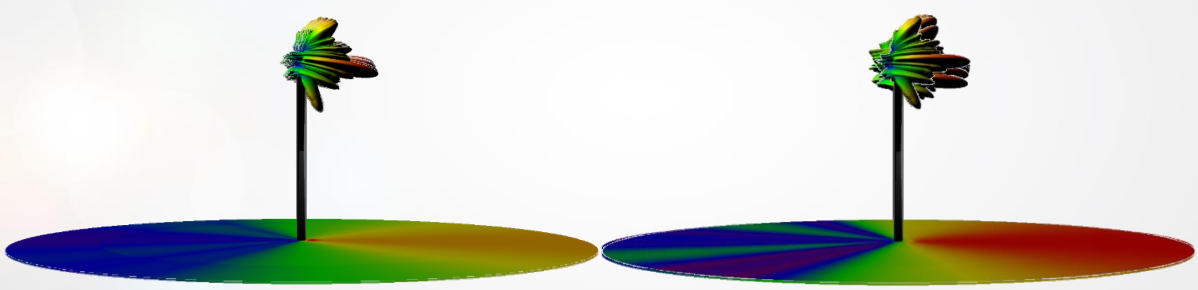
Cellular Antennas

- Electrical tilt vs. Mechanical tilt



Mechanical Tilt: 80°

Electrical Tilt: 80°

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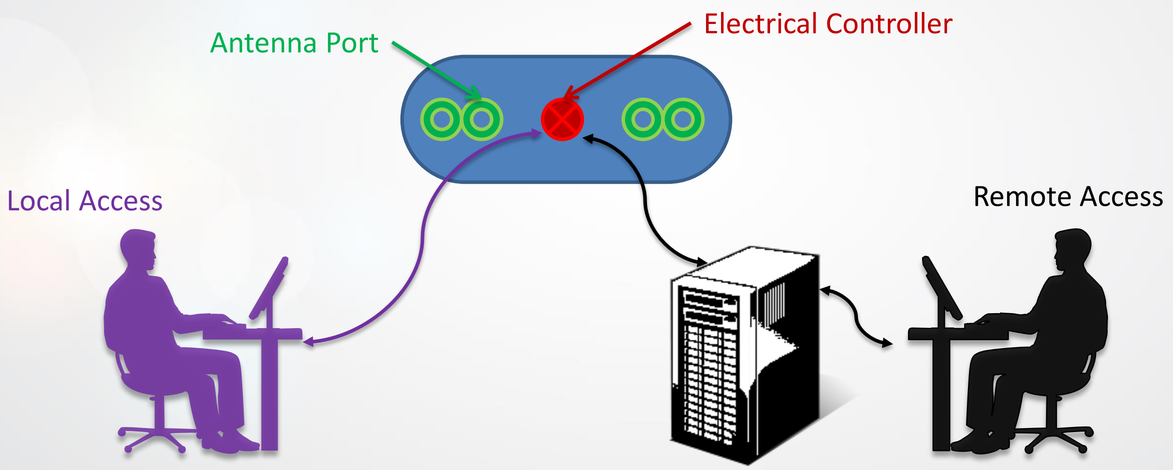
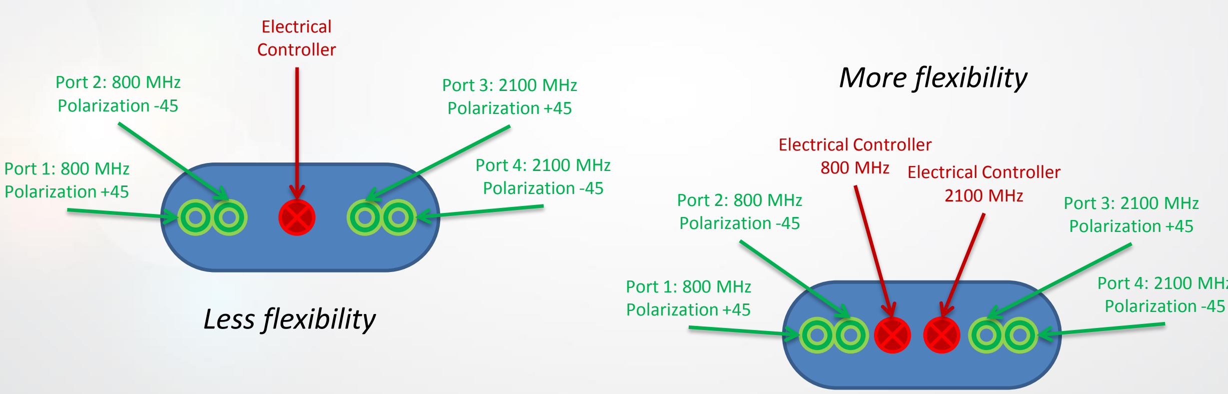
Cellular Antennas – (Remote) Electrical Tilts

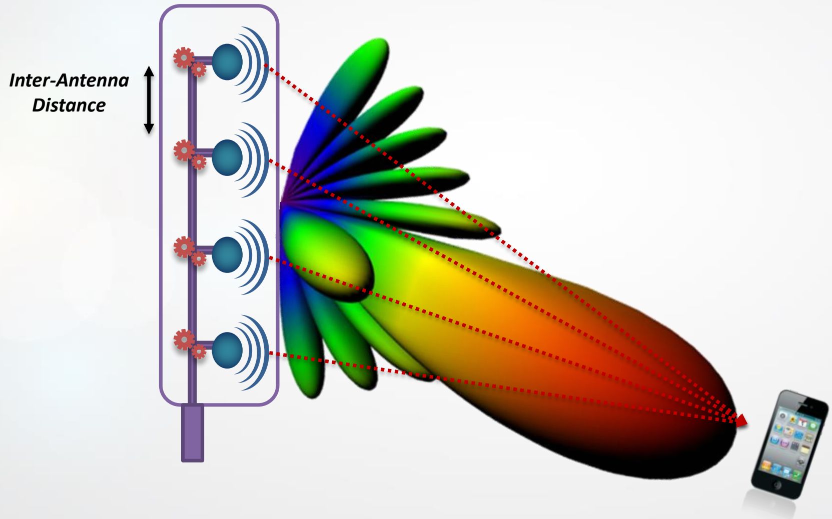


Cellular Antennas – (Remote) Electrical Tilts

- Multi-band antennas … and electrical tilts



Antenna Arrays



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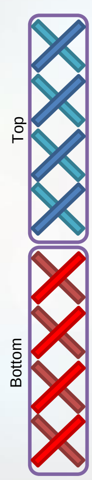
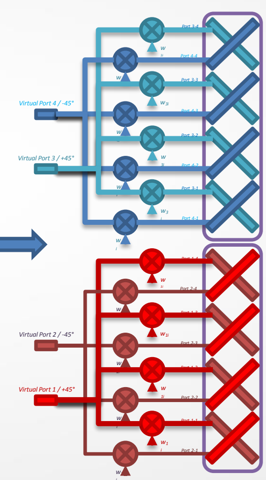
Multi-Stream Beamforming



4 Stream Beamforming

- 2 columns
- 4 cross-polarized antennas per column



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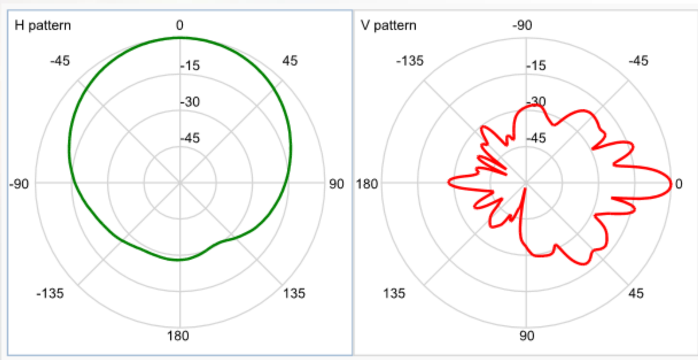
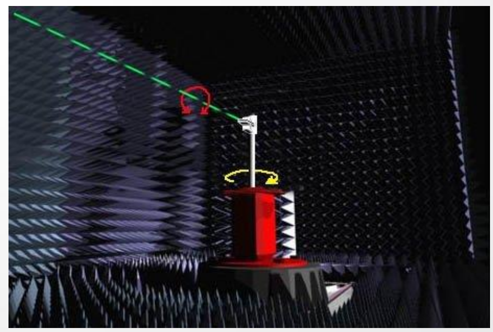
Antenna Diagrams

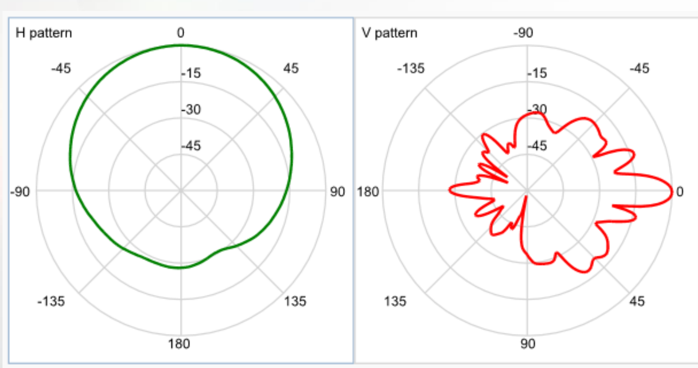
- In planning tools, antennas are represented by 2D diagrams, or antenna patterns
  - Measured in anechoic chambers
  - Typically, only the vertical and horizontal cuts are provided

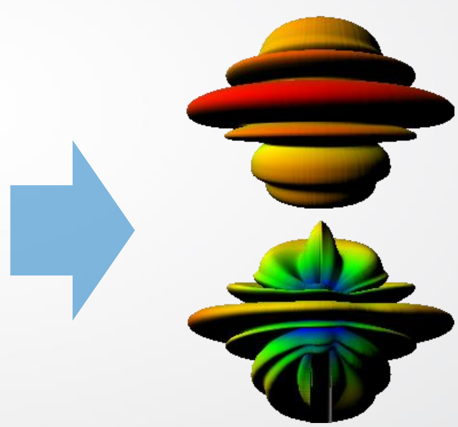




Antenna Masking

- The process of antenna masking consists of converting the H/V patterns into a 3D representation of the antenna

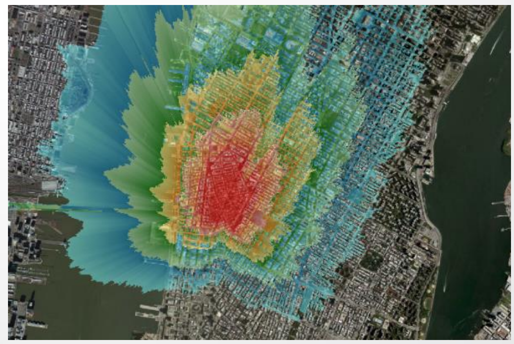




Antenna Masking

- After antenna masking, the signal strength can be computed

$$(Signal\ Strength)_{dBm} = (Tx\ Power)_{dBm} + (Antenna\ Gain)_{dB} - (Path\ Loss)_{dB}$$



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Traffic Modeling

- Model mix of traffic in a network
  - All services do not have the same requirements (data rates, activity factors, DL vs. UL, delay…)
- Model quantity and distribution of traffic in a network
  - Critical to estimate network (cell) loads
  - Site placement
  - Site selection
  - Antenna optimization (load balancing)
  - Indoor planning

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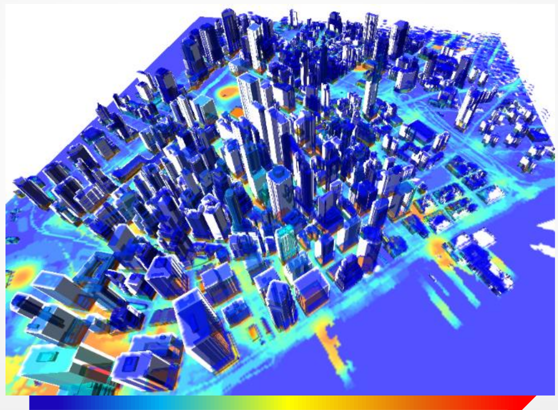
Traffic Spreading

Cell	Traffic (kbps)
Cell1	13561
Cell2	14561
Cell3	16448
Cell4	54189
Cell5	16546
Cell6	56464
Cell7	18949
Cell8	54194
Cell9	48949



Traffic density

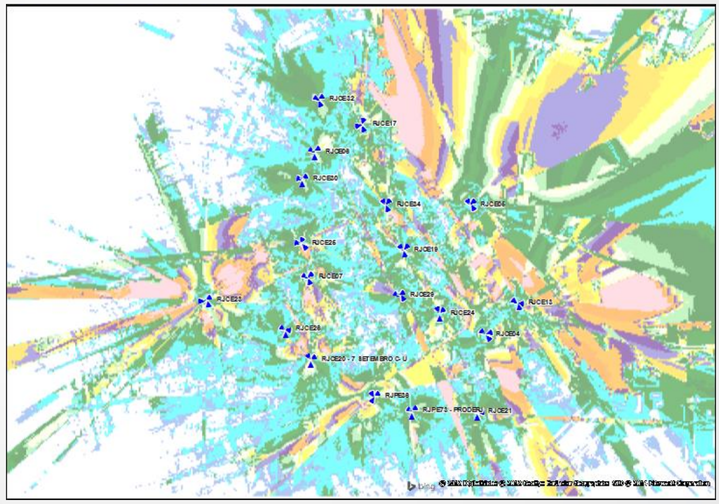
Coverage Areas
Coverage Probabilities
Geodata
Buildings
External Source
3D

Outline

- Fundamentals of LTE
- LTE Network Planning
  - Frequency Planning
  - Synchronization Signal, Reference Signal, Random Access, Tracking Areas…
- Network Planning & Optimization In Practice
  - Propagation Models and Model Tuning
  - Traffic
  - Coverage maps
  - Monte-Carlo simulations
  - Optimization
  - Heterogeneous Networks
  - MBSFN

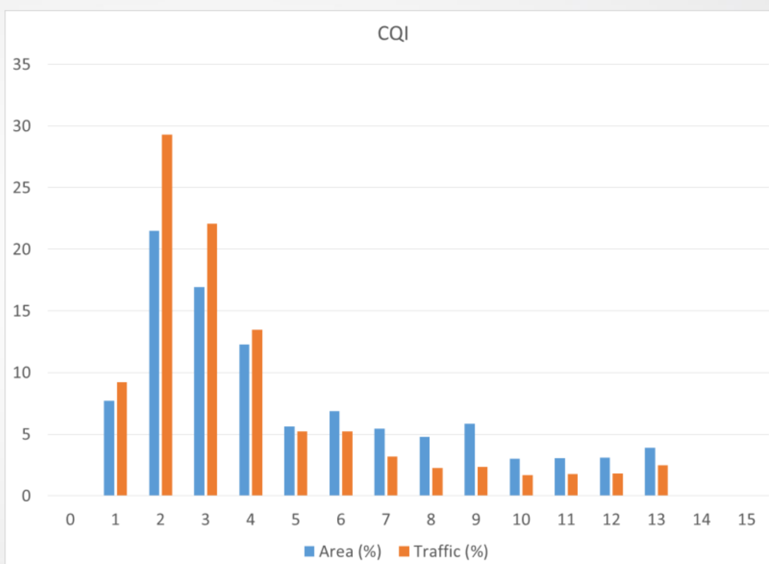
Coverage Maps

- Best Server
- RSRP
- RSRQ
- Signal to Noise and Interference Ratios
  - SCH
  - PBCH
  - PDCCH
  - PDSCH
  - PUCCH
  - PUSCH
- CQI
- Data Rates



Statistics

- Coverage Levels
  - Area
  - Traffic
  - By type of terrain
- Classifications
  - CQI
  - Modulation and Coding Schemes
  - Spectral Efficiency
  - Data Rates



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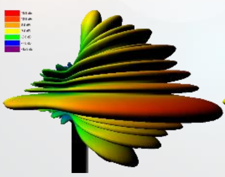
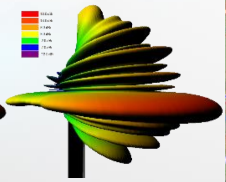
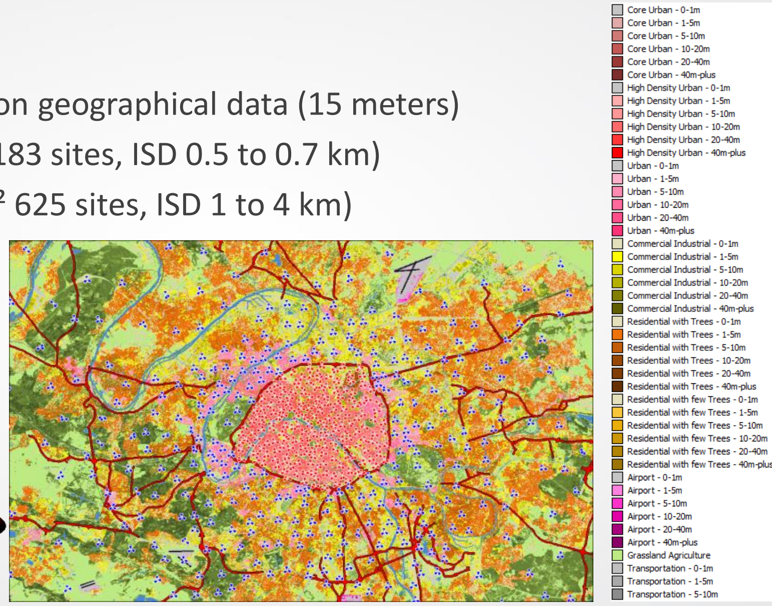
Example

- Paris with high-definition geographical data (15 meters)
- Downtown (84.9 km², 183 sites, ISD 0.5 to 0.7 km)
- Greater area (1688 km² 625 sites, ISD 1 to 4 km)

- LTE TDD
- 20 MHz
- <u>Antenna Comparison</u>







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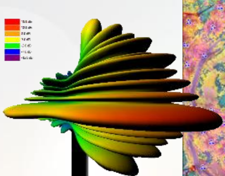
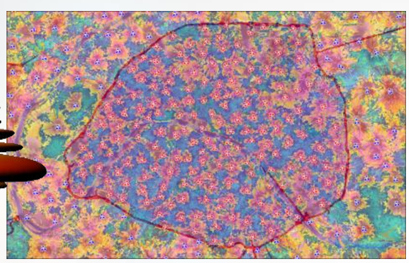
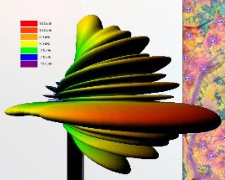
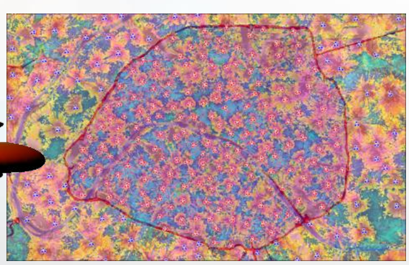
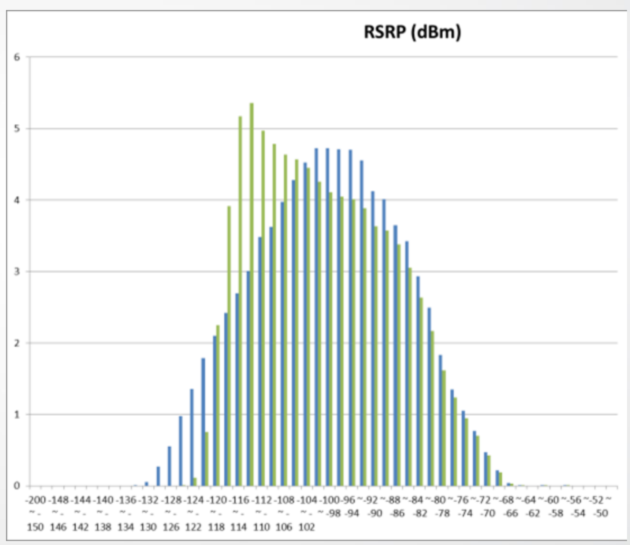
RSRP











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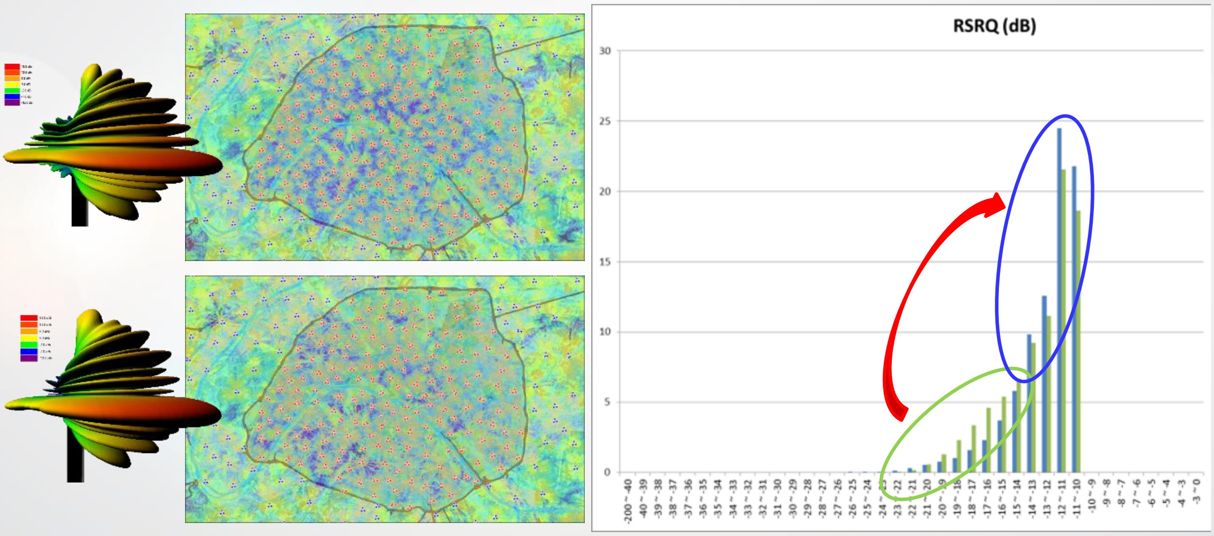
RSRQ



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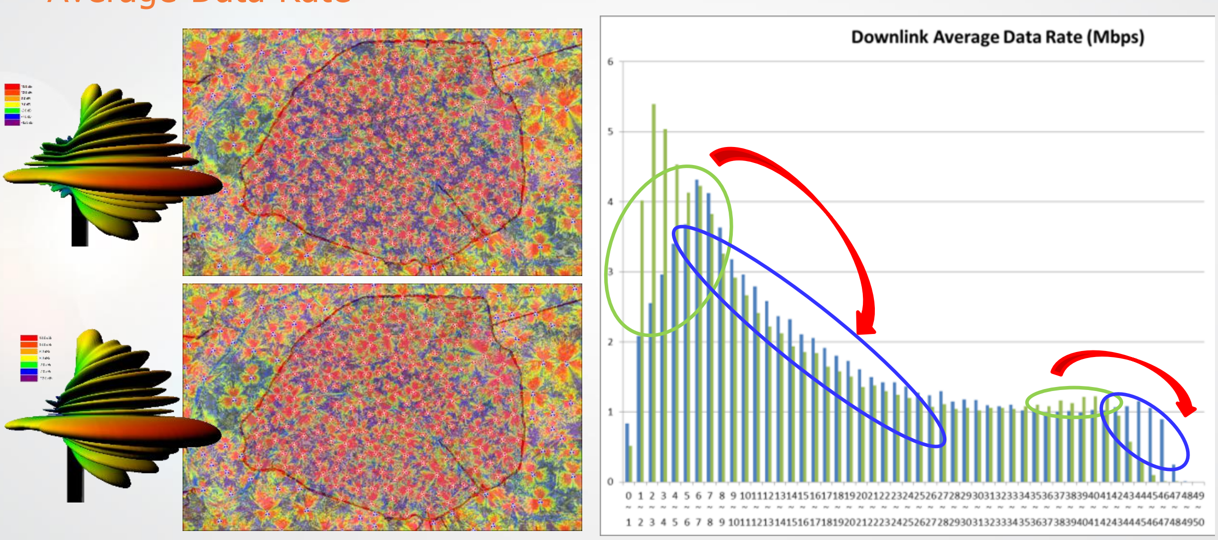
Average Data Rate



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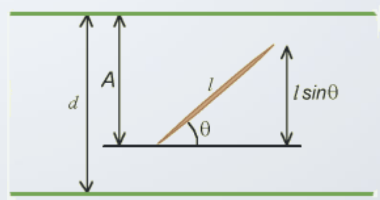
Monte-Carlo Simulations - Principles

- Approximate solution of a quantitative problem through stochastic techniques
  - Uses in economics, finance, nuclear physics, traffic regulation…
- A large system is sampled into a number of random configurations that represent the system as a whole

Determination of π

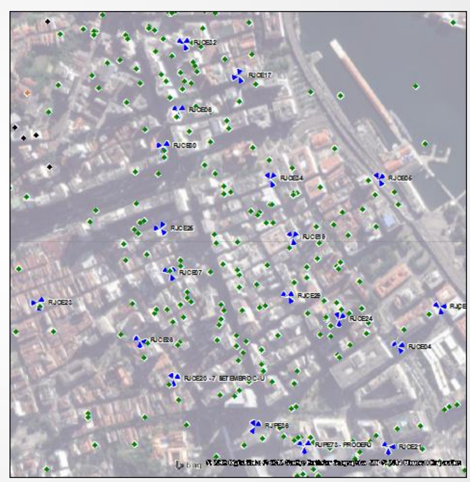
If a needle of length l is dropped at random on the middle of a horizontal surface ruled with parallel lines a distance d > l apart, what is the probability that the needle will cross one of the lines?

$$P = \frac{2l}{d\pi} \longrightarrow \pi = \frac{n}{M} \times \frac{2l}{d\pi}$$



Monte-Carlo Simulations - Principles

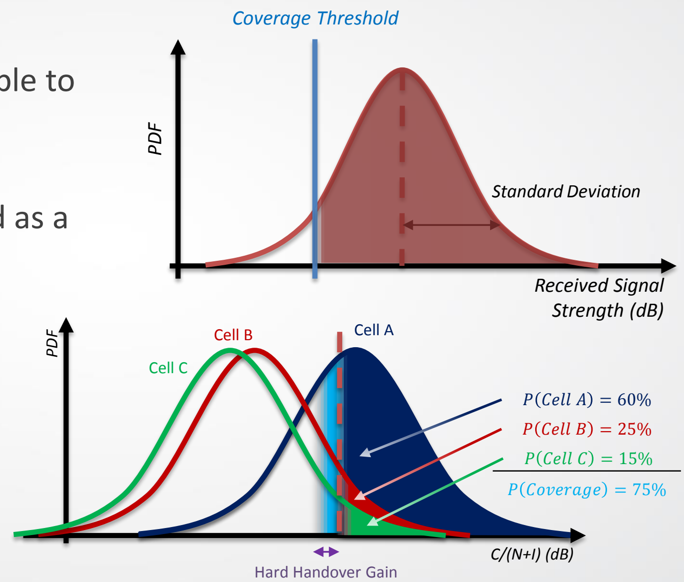
- The network is analyzed for each snapshot
  - Subscribers are served or blocked
  - Resources are allocated by eNodeBs
  - Services meet their requirements or not
- Final reports average the results of all snapshots to represent the network
  - Cell by cell analysis
  - Blocked/Dropped call analysis
  - QoS analysis



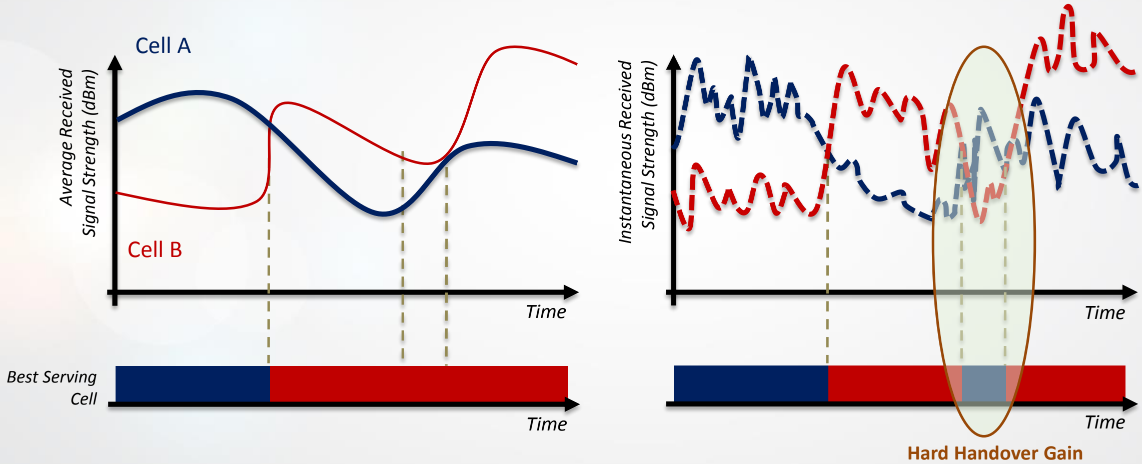
Monte-Carlo Snapshots

Coverage Probability

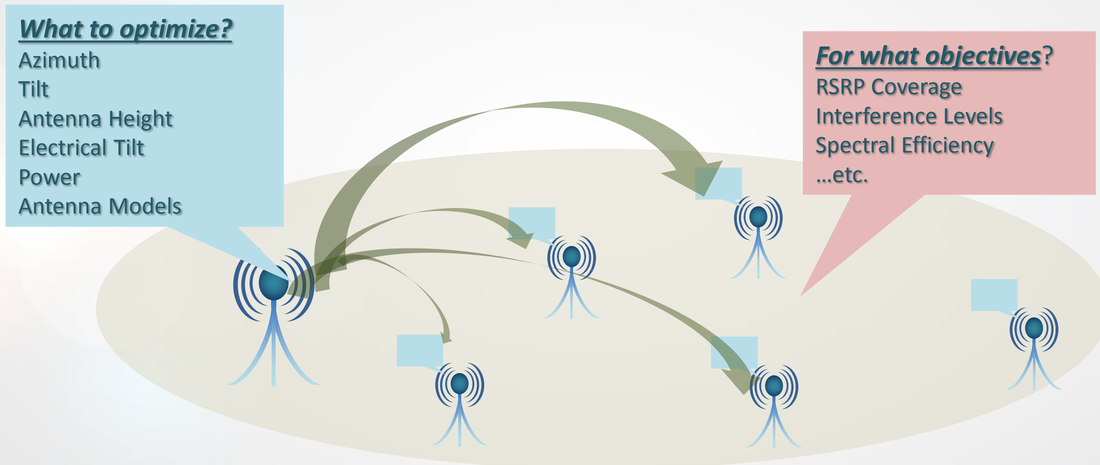
- Propagation prediction are unable to account for fading
  - Mean pathloss is reported
- Coverage can only be presented as a probability
- At the cell edge, multiple cells are involved



Coverage Probability



Cell Optimization



Cell Optimization

- Number of network configurations is massive
  - Azimuth/Tilt optimization, resolution 5°/1°, range of 60°/10° -> 120 possibilities per antenna
  - 10000 cells -> 120^{10000} combinations
- Optimization algorithms rely on non-linear optimization techniques
  - Gradient, Hill-climbing algorithms
  - Genetic algorithms
  - Simulated Annealing
- Cost function depends on the area/traffic when the optimization target is not achieved

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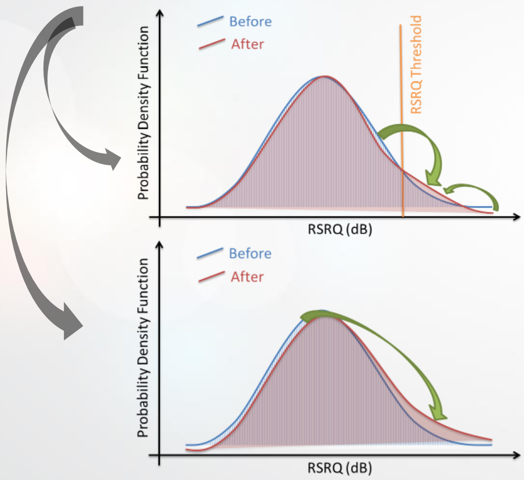
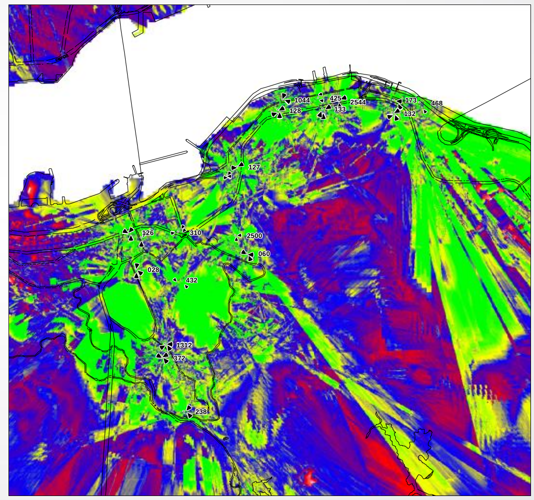
Cell Optimization

The choice of optimization targets is critical



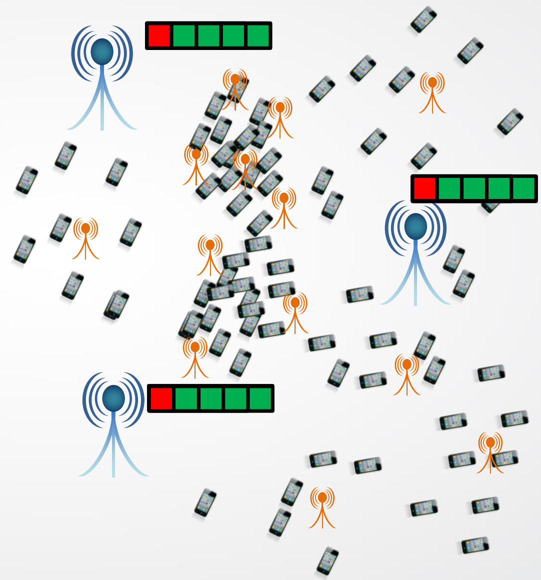


Cell Optimization & Selection

- The question is not only to choose which sites to activate but also in which order they should get activated
- In addition, traffic is a key consideration
- The time dimension is not to be excluded
  - What is the best order to be deployed today
  - What is the best order to be deployed in 6 months
  - What is the best compromise?

Heterogeneous Networks

- Concept of small cells
  - Coverage holes
  - Data offloading
- Impact on network planning
  - Propagation
  - Cell Selection Offsets
  - Interference Coordination
  - Optimization



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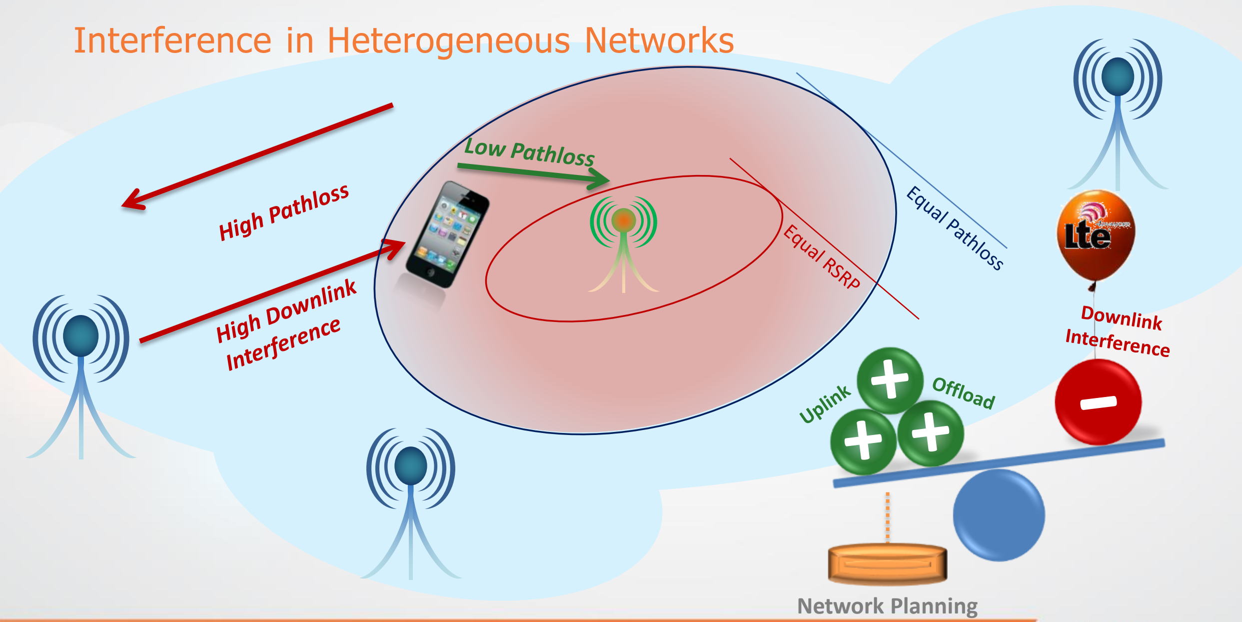
Interference in Heterogeneous Networks



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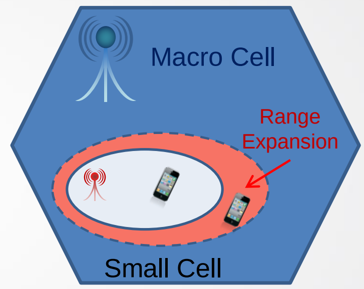
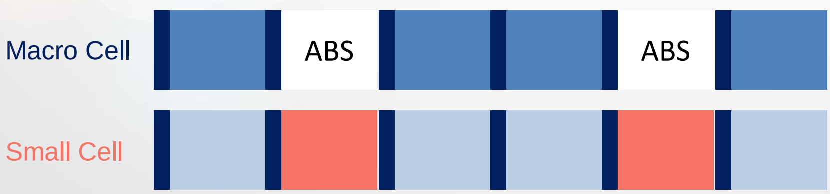
eICIC Optimization

- What eICIC parameters need optimization?
  - The small cell “Cell Selection Offset” (CSO) which defines the expansion area of the small cell.
  - The “Almost Black Subframe” pattern used by the Macro cells, which consists of:
    - The amount of subframes that are blanked per frame
    - The location of the of these blanked subframes



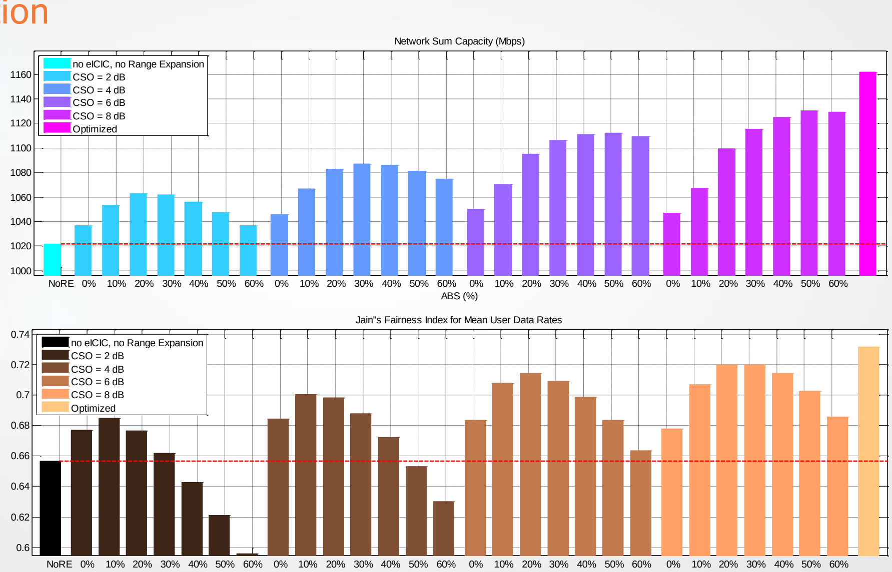


eICIC Optimization

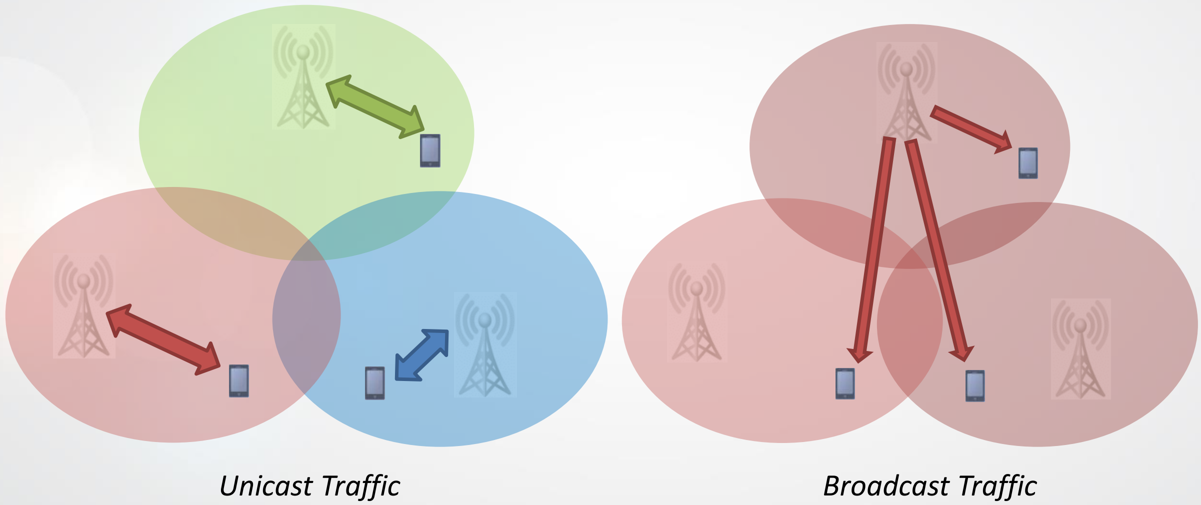
Simulation:

- 21 macro cells
- 42 small cells
- 30 users per macro cell
- 2/3 of the users within 40 meters of small cell

- 29 different eICIC configurations
- 2 evaluations criteria



MBSFN



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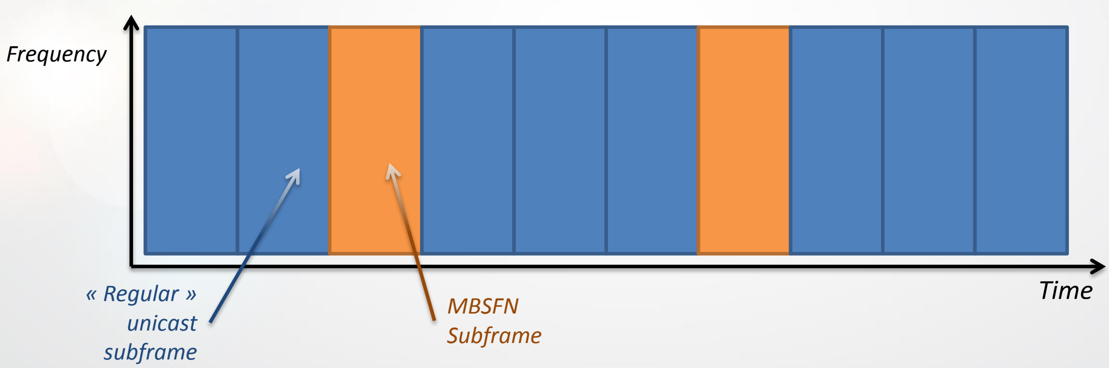
MBSFN

- Unicast and Broadcast traffic are separated in the time domain
- The broadcast traffic transmitted only during MBSFN subframes



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MBSFN

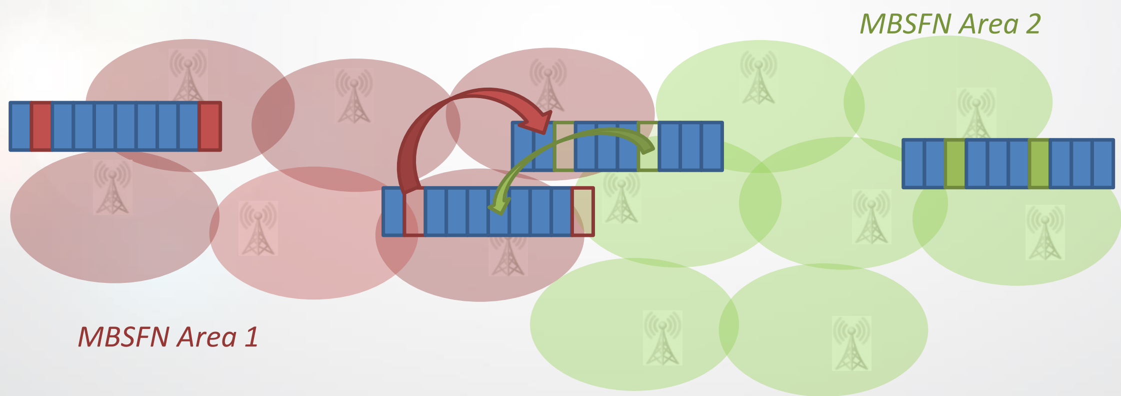
- All cells within the same MBSFN area transmit the same content, one or several of MBMS service(s)
- As a consequence, they all use the same time resources (subframes) to transmit that content.

MBSFN

- Some cells may belong to multiple MBSFN areas in order to transmit the content of all MBSFN areas

MBSFN

- At the border between MBSFN areas, interference could occur between MBSFN and unicast transmissions
- Border cells may be configured as « reserved cells » in order to not transmit any data and hence avoid interference from and to MBSFN subframes



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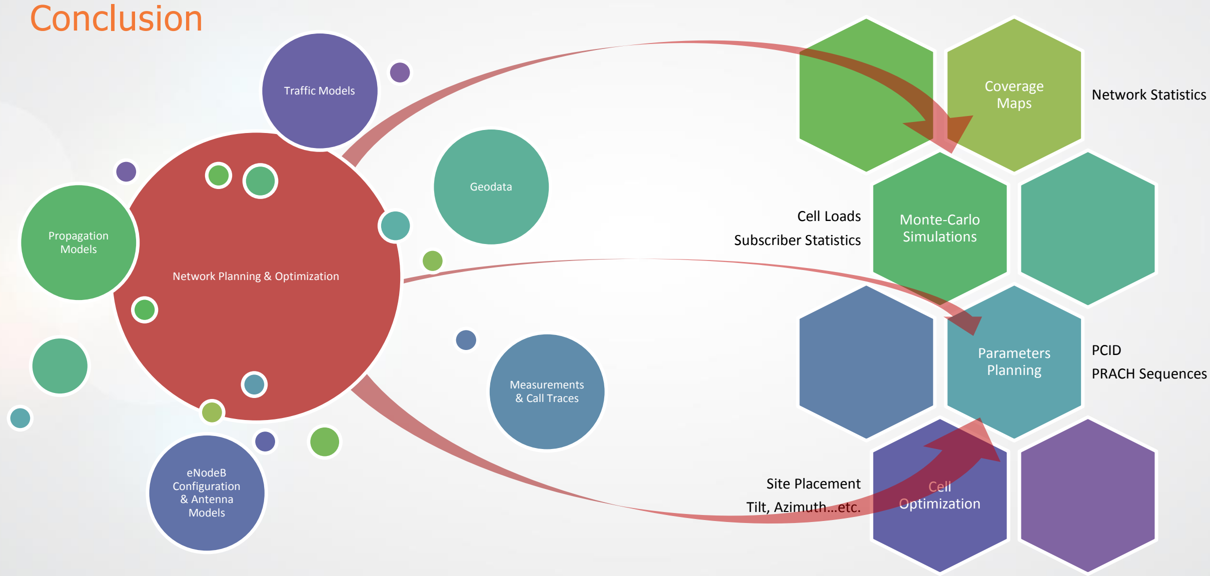
Conclusion



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Network Planning Directions

- Leveraging all sources of information
  - Network counters
  - Call traces
  - Social data..etc.
- Move to 3D network planning
  - Traffic collection
  - Simulations, coverage maps
  - Optimizations
- Self-optimized and Self-organized networks (SON)
  - Embedding network planning algorithms in to SON

- Regis Lerbour
- rlerbour@infovista.com
- 01 64 86 85 73

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