# Mobility Management for Femtocells in LTE-Advanced: Key Aspects and Survey of Handover Decision Algorithms

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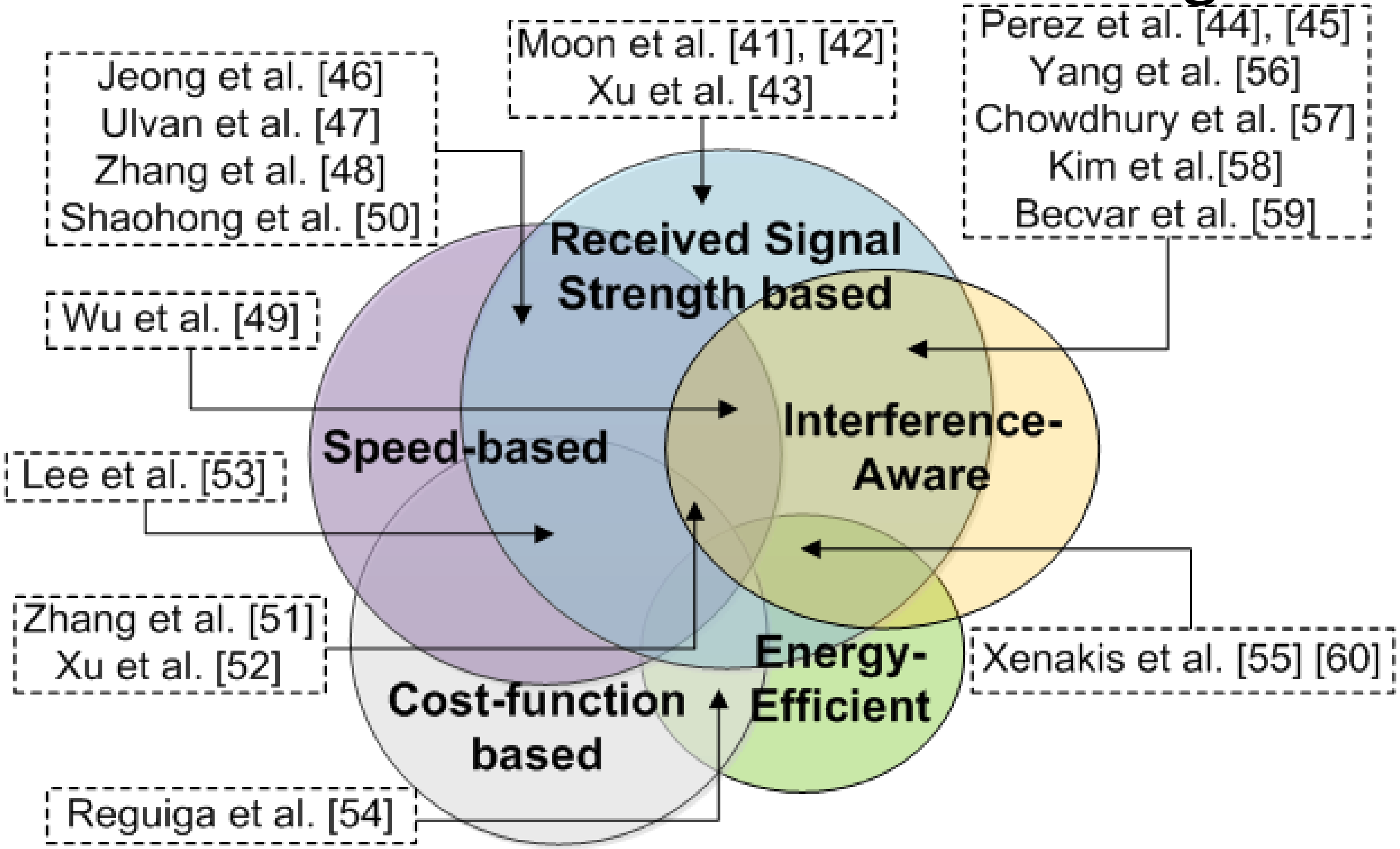
# Part II: Handover Decision for femtocells in LTE-Advanced

- **Overview of Part II**
  - **Handover Decision Criteria and Context**
  - **Classification of Handover Decision Algorithms**
  - Survey of Handover Decision Algorithms
  - Performance Evaluation and Modeling Issues
  - Comparative Summary
  - Future Research Directions

# Part II: Handover Decision for femtocells in LTE-Advanced

- Classification of Handover Decision Algorithms



# Part II: Handover Decision for femtocells in LTE-Advanced

- Survey of Handover Decision Algorithms
  - Three representative HO algorithms per class
    - Overview key features and give algorithmic flowchart
    - Summarize the main advantages / disadvantages
    - Adapt the presentation to the LTE-A system and use a common notation

| **Parameter** | **Notation** |
|---|---|
| Serving cell | $s$ |
| Candidate cell | $c$ |
| Set of candidate cells | $\boldsymbol{L}$ |
| Reference Signal Received Power (RSRP) of a tagged cell $c$ | $RSRP(c)$ |
| Minimum RSRP threshold for sustaining service continuity | $RSRP_{th}$ |
| Reference Signal Received Quality (RSRQ) of a tagged cell $c$ | $RSRQ(c)$ |
| Minimum RSRQ threshold for sustaining service continuity | $RSRQ_{th}$ |
| Received Interference Power in a tagged cell $c$ | $I(c)$ |
| Downlink Reference Signal Transmit Power of a tagged cell $c$ | $P_{RS}(c)$ |
| Signal to Interference plus Noise Ratio (SINR) for cell $s$ | $SINR(s)$ |
| Handover Hysteresis Margin (HHM) for a tagged cell $c$ | $HHM(c)$ |
| Time to Trigger | $TTT$ |
| UE speed | $V$ |
| UE speed threshold | $V_{th}$ |

# Part II: Handover Decision for femtocells in LTE-Advanced

- Performance Evaluation and Modeling Issues
  - The performance of existing algorithms is evaluated either based on simulations [45]-[47], [50], [52]-[53], [55]-[60] or on analytical modeling [41]-[43] [48]
  - Recent trends for performance evaluation and modeling
    - System-level simulations using the Small Cell Forum evaluation methodology [110]
    - Performance Analysis using Stochastic Geometry [111]

# Part II: Handover Decision for femtocells in LTE-Advanced

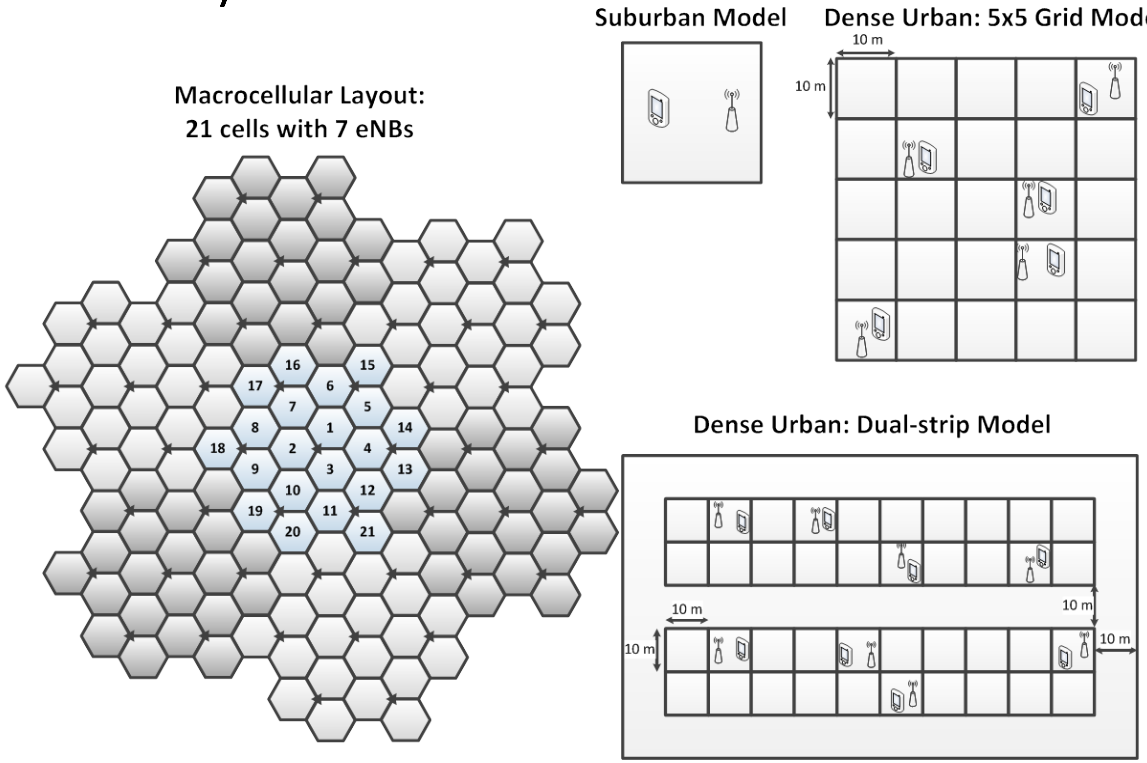
- Performance Evaluation and Modeling Issues
  - Small Cell Forum evaluation methodology for system-level simulation model
    - Main cluster area consists of 7/19 eNBs
      - Each cell has 3 sectors
    - 7 clusters using the wrap-around technique
    - **Femtoblocks:** set of blocks of apartments
      - Models for suburban, urban and dense urban environment
    - **Femtocell deployment ratio** $r_{fc}$
      - Percentage of apartments with a femtocell installed
    - **Femtocell activation ratio a**
      - Percentage of time where the femtocell is on
  - An additional parameter can be used
    - **Femtoblock deployment density** $d_{FB}$
      - Percentage of the main cluster area covered with femtoblocks

# Part II: Handover Decision for femtocells in LTE-Advanced

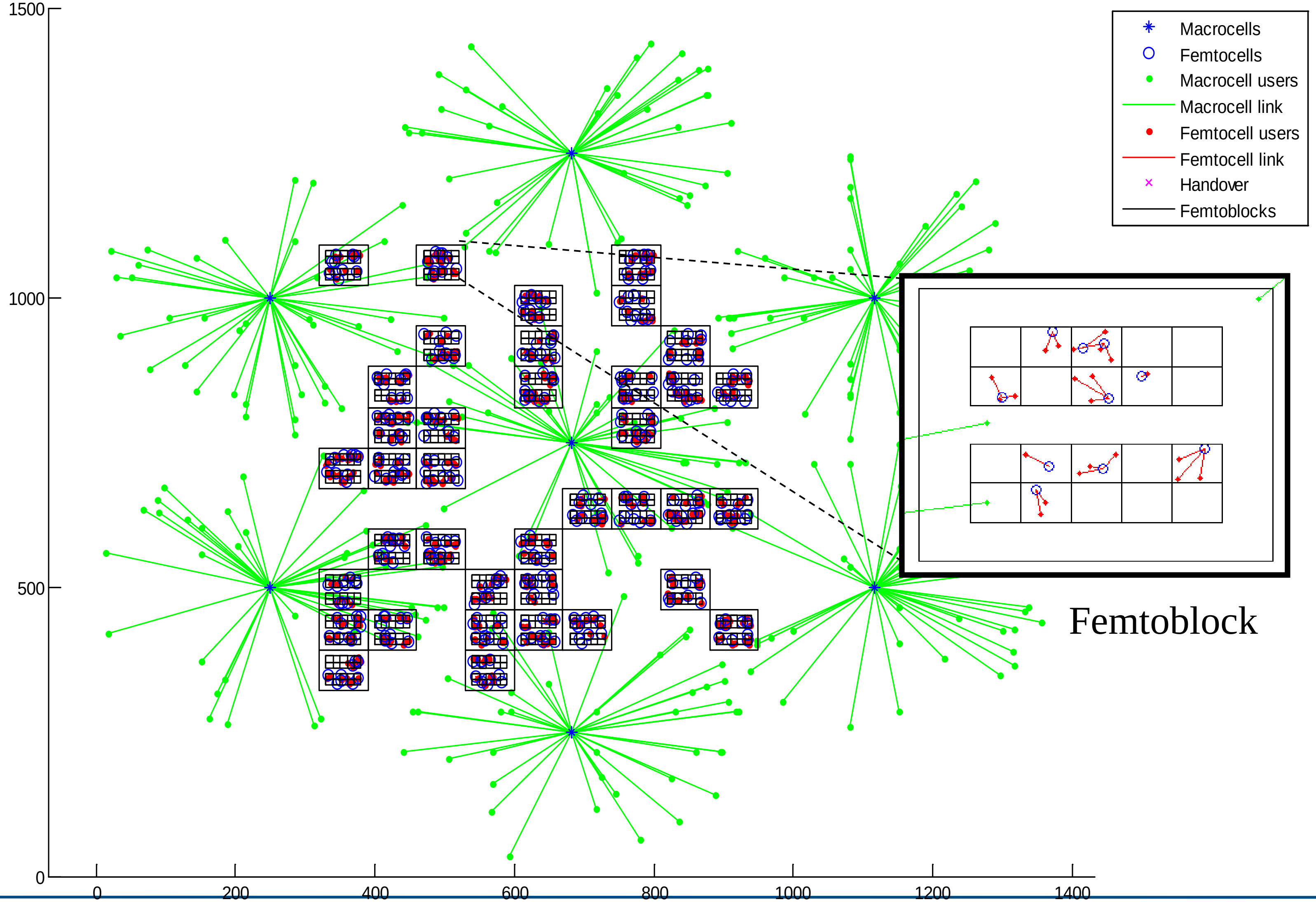
- Performance Evaluation and Modeling Issues
  - Small Cell Forum evaluation methodology for system-level simulation model
    - Macrocell users uniformly dropped in the sectors
    - Femtocell stations uniformly dropped inside the apartments
    - Femtocell users uniformly dropped inside the apartments (a minimum separation is provisioned)
    - CSG or hybrid cells
    - Provision for various network and femtoblock layouts
    - Path loss models adapted depending on the femtoblock layout
      - Depend on the serving cell type and the user location
    - Monte-Carlo sampling

# Part II: Handover Decision for femtocells in LTE-Advanced

- Performance Evaluation and Modeling Issues
  - Small Cell Forum evaluation methodology for system-level simulation model
    - Network layout and femtoblock models



# Part II: Handover Decision for femtocells in LTE-Advanced




Femtoblock

# Part II: Handover Decision for femtocells in LTE-Advanced

- Performance Evaluation and Modeling Issues
  - Small Cell Forum evaluation methodology for system-level simulation model: Mobility and Path Loss models

| Parameter | Value | | |
|---|---|---|---|
| Mobility model [12] | User speed at time t | | $v_t = N(\overline{v}, s_u)$ (m/s) |
| | User direction at time t | | $\varphi_t = N\left(\varphi_{t-1}, 2\pi - \varphi_{t-1}\tan\left(\frac{\sqrt{v_t}}{2}\right)\Delta t\right)$, where $\overline{v}$ is the mean user speed, $s_u$ the user speed standard deviation, $\Delta t$ the time period between two consecutive updates of the model and $N(a, b)$ indicates a Gaussian distribution of mean $a$ and standard deviation $b$ |
| Path loss Model [22] | UE to Macrocell | UE outdoors | $PL(dB) = 15.3 + 37.6log_{10}d$ |
| | | UE indoors | $PL(dB) = 15.3 + 37.6log_{10}d + L_{ow}$ |
| | UE to Femtocell | UE in the same apartment stripe | $PL(dB) = 38.46 + 20log_{10}d + 0.7d_{indoor} + w \cdot L_{iw}$ |
| | | UE outside the apartment stripe | $PL(dB) = \max(15.3 + 37.6log_{10}d, 38.46 + 20log_{10}d) + 0.7d_{indoor} + w \cdot L_{iw} + L_{ow}$ |
| | | UE inside a different apartment stripe | $PL(dB) = \max(15.3 + 37.6log_{10}d, 38.46 + 20log_{10}d) + 0.7d_{indoor} + w \cdot L_{iw} + 2 \cdot L_{ow}$ |

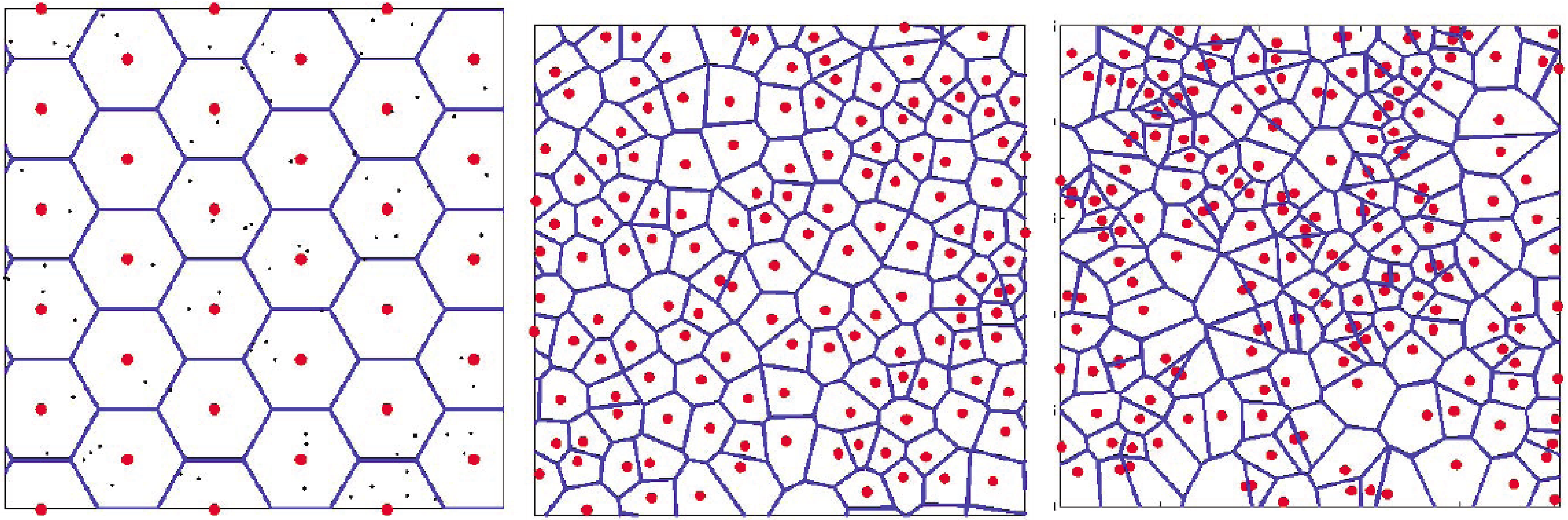
# Part II: Handover Decision for femtocells in LTE-Advanced

- Performance Evaluation and Modeling Issues
  - Analytical modeling using Stochastic Geometry
    - Growing literature for modeling large-scale wireless networks using SG
    - Calculates spatial averages that capture the key dependencies of the network performance as a function of a relatively small number of system parameters
      - Interference, outage probability, transmission capacity
    - SG models basic network properties by averaging over all potential geometrical patterns
    - Main SG study object: Point Processes (PP)
      - *Simple or not:* multiplicity of a point is at most one
      - *Stationary or not*: the law of the PP invariant to translation
      - *Isotropic or not*: the law of the PP invariant to rotation
      - *Marked or not*: marks assign labels to the points of the PP, which are typically independent of the PP and i.i.d.

# Part II: Handover Decision for femtocells in LTE-Advanced

- Performance Evaluation and Modeling Issues
  - Analytical modeling using Stochastic Geometry
  - Poisson PP (PPP) is the most commonly used PP
    - Offers the highest level of analytical tractability
    - Key properties
      - *Superposition*: the superposition of two or more independent PPP is again a PPP
      - *Independent thinning:* the PP obtained by randomly and independently removing a point from the initial PPP is still a PPP
      - *Displacement theorem:* the PP obtained by displacing a point independently of everything else, according to some Markov kernel that defines the distribution of the displaced position of the point, yields another PPP

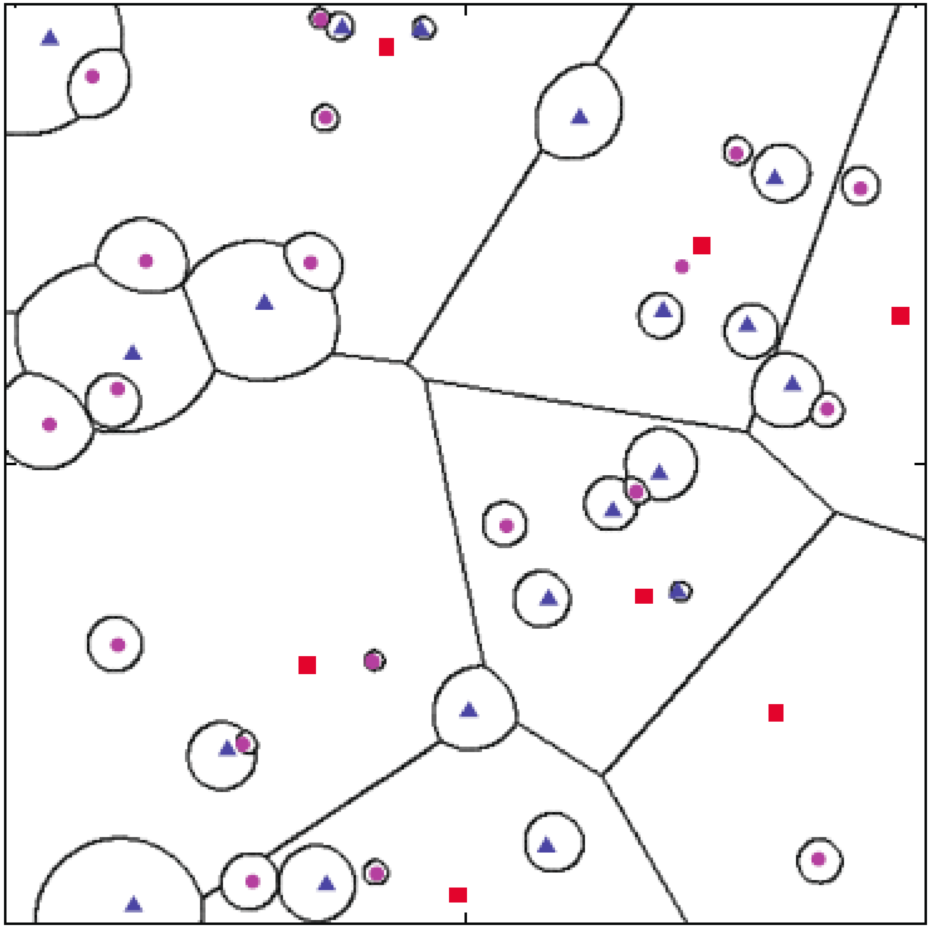
# Part II: Handover Decision for femtocells in LTE-Advanced



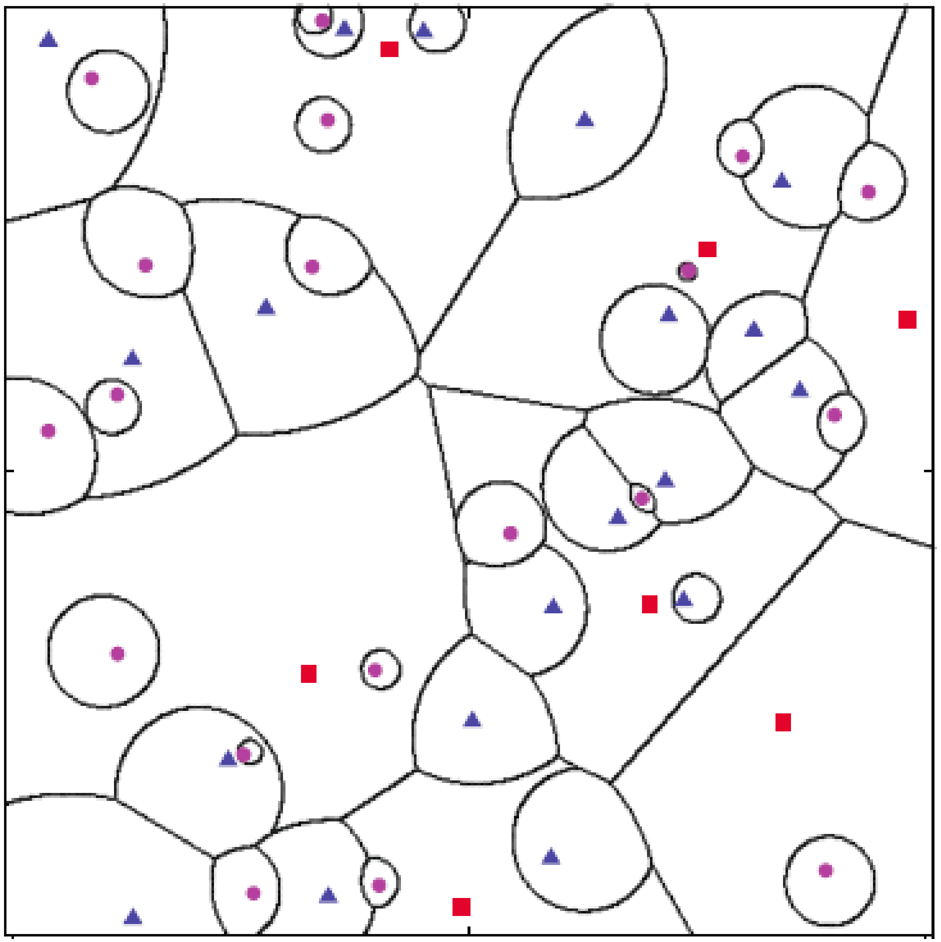
Traditional grid model | Actual 4G macrocells today | Completely random BSs

- Network layout
  - Maximum SINR connectivity

# Part II: Handover Decision for femtocells in LTE-Advanced



Unbiased Cell Association in a 3-tier Heterogenous Network



Biased Cell Association in a 3-tier Heterogenous Network. Picos and femtos have a 10 dB bias.

# Part II: Handover Decision for femtocells in LTE-Advanced

- Performance Evaluation and Modeling Issues
  - Analytical modeling using Stochastic Geometry
  - Existing results using SG
    - Interference, outage probability, transmission capacity, and spectral efficiency of distributed wireless networks [112]-[114]
    - SG has been used to evaluate the performance of multi-tier cellular networks [65], [115]-[117]
  - Beyond State of the Art for HO decision and SG
    - Capture the impact of user mobility [118]
      - Most of the existing works assume static network topologies
    - Allow for varying cell and UE transmit power [116]
      - Most of the existing works assume fixed transmit power
    - Performance analysis with regards to the HO probability

# Part II: Handover Decision for femtocells in LTE-Advanced

- Comparative Summary
  - Existing HO decision algorithms
    - Divergent system models and assumptions, simulation setups, and performance measures
      - Difficult to readily compare them
  - Comparison based on
    - The HO decision parameters
    - The HO decision scenario under consideration
    - The performance evaluation methodology
    - Their key features

# Part II: Handover Decision for femtocells in LTE-Advanced

| HO decision parameters \ Algorithms | RSS-based | | | | Speed-based | | | | Cost-function based | | | | Interference-Aware | | | | | E. E. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | Moon et. al [41], [42] | Xu et al. [43] | Perez et al. [44], [45] | Jeong et al. [46] | Ulvan et al. [47] | Zhang et al. [48] | Wu et al. [49] | Shaohong et al. [50] | Zhang et al. [51] | Xu et al. [52] | Lee et al. [53] | Reguiga et al. [54] | Xenakis et al. [55] | Yang et al. [56] | Chowdhury et al. [57] | Kim et al. [58] | Becvar et al. [59] | Xenakis et al. [60] |
| **RSS related** | | | | | | | | | | | | | | | | | | |
| RSS | v | v | v | v | v | v | v | v | v | | v | | v | v | v | v | | v |
| Minimum required RSS for service continuation | v | | | | v | | | v | | | | | | | | | | |
| Path loss | | v | | | | | | | | | | | v | | | | v | |
| RS transmit power | | v | | | | | | | | | | | v | | | | | v |
| Window function on the RSS | v | v | | | | | | | | | | | | | | | | |
| **Handover Hysteresis Margin related** | | | | | | | | | | | | | | | | | | |
| HHM | v | v | | | | v | | | v | | v | | v | | | | v | |
| **Interference related** | | | | | | | | | | | | | | | | | | |
| RSQ | | | | | | | | | v | v | | | | v | v | v | v | |
| Minimum required RSQ for service continuation | | | | | | | | | | | | | | | | | | |
| Received interference power at the cell sites | | | | | | | | | | | | | v | | | | | v |
| Interference constraints on the target cell(s) | | | | | | | v | | | | | | | | | | | v |
| **Speed related** | | | | | | | | | | | | | | | | | | |
| UE speed | | | | v | v | v | v | v | v | v | v | | | | | | | |
| UE residence time in the cell | | | | v | | | | | | | | | | | | | | |
| UE mobility pattern | | | | v | | | | | | | | | | | | | | |
| **Bandwidth related** | | | | | | | | | | | | | | | | | | |
| Available bandwidth / Cell load | | | | | | | v | | v | | v | v | | v | v | v | | v |
| Cell capacity | | | | | | | | | v | | | | | | | | | |
| Number of camped UEs on the target cell | | | | | | | | | v | | | | | | | | | |
| Number of UE connections per traffic-type | | | | | | | | | | | v | | | | | | | |
| Cell type | | | | | | | | | v | | | | | | | | | |
| **Traffic related** | | | | | | | | | | | | | | | | | | |
| Traffic-type | | | | | v | | v | | | v | v | | | | | | | |
| Mean SINR target of the UE | | | | | | | | | | | | | v | | | | | v |
| Bit Error Rate (BER) | | | | | | | | | | | | v | | | | | | |
| Current SINR at the serving cell | | | v | | | | | | | | | | | | | | | |
| **Energy-efficiency related** | | | | | | | | | | | | | | | | | | |
| UE power class | | | | | | | | | | | | | | | | | | v |
| UE battery power | | | | | | | | | | | | v | | | | | | |
| Mean UE transmit power | | | | | | | | | | | | | v | | | | | v |
| **Other** | | | | | | | | | | | | | | | | | | |
| UE membership status | | | | | | | v | | | | | v | | | | v | | v |
| UE priorities | | | | | | | | | | | | v | | | | | | |

# Part II: Handover Decision for femtocells in LTE-Advanced

- Comparative Summary
  - HO decision parameters
    - RSS is a common basis for HO decision making
    - RSQ is typically used as an SINR estimate
    - UE speed broadly used to anticipate the negative impact of user mobility
    - Available bandwidth utilized to lower the HO failure probability due to the lack of resources
    - Traffic-type is used to avoid frequent service interruption for delay-sensitive services

# Part II: Handover Decision for femtocells in LTE-Advanced

| Points of Comparison / Algorithms | RSS-based | | | | Speed-based | | | | Cost-function based | | | | Interference-Aware | | | | | E. E. |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
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| **HO DECISION SCENARIO** | | | | | | | | | | | | | | | | | | |
| Single-macrocell single-femtocell for inbound HO to femtocell | | v | | v | | | | | v | v | | | | v | v | v | v | |
| Single-macrocell single-femtocell | v | | | | | v | v | | | | | v | | | | | | |
| Single-macrocell multiple-femtocell | | | v | | | | | v | | | | | | | | | | |
| Multiple-macrocell multiple-femtocell | | | | | v | | | | | | v | | v | | | | | v |
| **PERFORMANCE EVALUATION RESULTS** | | | | | | | | | | | | | | | | | | |
| **Analytical (A) / Simulation (S) results** | A | A | S | S | S | A | x | S | x | S | S | x | S | S | S | S | S | S |
| HO probability | v | v | | | | v | | v | | | | | v | | | | v | v |
| HO failure probability | | | v | | | | | | | | v | | | | | | | |
| Assignment probability to femtocell | v | v | | | | | | | | | | | | | | | | |
| Assignment probability to macrocell | v | v | | | | | | | | | | | | | | | | |
| Number of HOs | v | v | v | | v | | | | | v | | | | v | v | v | | |
| Number of unnecessary HOs | | | | v | | | | | | | | | | v | | | | |
| Unnecessary HO probability | | | | | | | | | | | | | | | v | v | | |
| Impact of the HHM | | | v | | | | | | | | | | v | | | | v | v |
| Throughput | | | v | | | | | v | | | | | | | | | v | |
| Signaling overhead | | | | | | v | | | | | | | | | | | | |
| Transmit power | | | | | | | | | | | | | v | | | | | v |
| Received interference power | | | | | | | | | | | | | v | | | | | v |
| Energy consumption per bit | | | | | | | | | | | | | | | | | | v |
| Power consumption | | | | | | | | | | | | | | | | | | v |
| **Uses the evaluation methodology in [110]** | | | | | | | | | | | | | v | | | | v | v |
| **Includes a comparison with other algorithms** | v | v | | v | | v | | v | | | | | v | v | v | v | | v |

# Part II: Handover Decision for femtocells in LTE-Advanced

| Points of Comparison \ Algorithms | RSS-based | | | | Speed-based | | | | Cost-function based | | | | Interference-Aware | | | | | E. E. |
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| **KEY FEATURES** | | | | | | | | | | | | | | | | | | |
| Accounts for the uneven RS transmit powers | v | v | | | | | | v | | | | | v | | | | v | v |
| Accounts for the impact of interference by using the RSRQ/SINR status | | | v | | | | | | v | v | | v | | v | v | v | v | |
| Accounts for the impact of interference by using the RIP at the cell sites | | | | | | | | | | | | | v | | | | | v |
| Accounts for potential IF limitations at the cells | | | | | | | v | | | | | | | | | | | v |
| Jointly performs interference mitigation and HO | | | v | | | | v | | | | | | v | | | | | v |
| Performs preliminary admission control | | | | | | | v | | v | | | v | | v | v | v | | v |
| Enables load balancing | | | | | | | | | v | | v | v | | | | | | |
| Uses a HHM to lower the HO probability and minimize the ping-pong effect | v | v | v | | | | v | | v | | v | | v | | | | v | v |
| Requires the assessment of the UE speed | | | | | v | v | v | v | v | v | v | v | | | | | | |
| Uses mobility prediction for HO mitigation | | | | v | v | | | | | | | | | | | | | |
| Accounts for the UE service requirements/ characteristics | | | v | | v | | v | | v | v | v | v | v | | | | | v |
| Requires interventions to the standard network functionality or architecture | | | v | v | | | | | | | | | | | | | | |
| Requires increased signaling/processing overhead | | v | v | v | | | v | | v | | v | | v | | | | | v |
| The signaling procedure for supporting the algorithm is described, e.g., parameter acquisition | | | | | | | | | | | | | | | | | | v |
| Algorithm-related parameters are fully specified | v | v | | v | | | | | | | | v | v | | | | | v |
| Accounts for the UE energy-efficiency | | | | | | | | | | | | v | v | | | | | v |

# Part II: Handover Decision for femtocells in LTE-Advanced

- Comparative Summary
  - RSS-based algorithms
    - Strong Aspects
      - Low-complexity and easier to validate through performance analysis
      - Require minimum network interventions unless more sophisticated capabilities are deployed
        - » Interference mitigation [44]-[45] or mobility prediction [46]
    - Weak Aspects
      - They do not account for the impact of interference on the SINR, throughput and energy consumption performance
      - Interference-agnostic

# Part II: Handover Decision for femtocells in LTE-Advanced

- Comparative Summary
  - Speed-based algorithms
    - Strong Aspects
      - Reduce the HO probability for medium to high speed users
      - Reduce the number of unnecessary HOs in the system
    - Weak Aspects
      - Arbitrary selection of the UE speed thresholds
      - Typically do not incorporate the monetary, signaling or energy consumption overhead for assessing the UE speed
      - The impact of the algorithms on the interference and throughput performance is not assessed

# Part II: Handover Decision for femtocells in LTE-Advanced

- Comparative Summary
  - Cost-function based algorithms
    - Strong Aspects
      - Incorporate a wide set of parameters to reach a HO decision
      - Perform preliminary admission control or load balancing by incorporating bandwidth-related parameters
    - Weak Aspects
      - Do not provide a detailed methodology for calculating the optimal weights or adjustment factors of the cost-function
      - The performance of the algorithms is typically evaluated by fixing the weights and adjustment factors of the cost-function

# Part II: Handover Decision for femtocells in LTE-Advanced

- Comparative Summary
  - Interference-aware algorithms
    - Strong Aspects
      - Improve the SINR performance in the system
      - Allow for interference handling at a macroscopic level
    - Weak Aspects
      - RSQ based algorithms: Need to incorporate a HHM to lower the HO probability and reduce the ping-pong effect
        - » RSQ can be subject to fast variations
      - RIP based algorithms: Need to deploy more complicated signaling procedures
        - » Commute the cell RIP of the target cells to the serving cell

# Part II: Handover Decision for femtocells in LTE-Advanced

- Comparative Summary
  - Energy-efficient algorithms
    - Strong Aspects
      - Reduce the energy expenditure per bit
      - Improve the SINR performance in the system
      - Enhance the QoE of the users
    - Weak Aspects
      - Increase the signaling and processing overhead to keep track or estimate the energy-efficiency at the network nodes

# Part II: Handover Decision for femtocells in LTE-Advanced

- Comparative Summary
  - Future Research Directions
    - Need for HO decision algorithms that apply to the multiple-macrocell multiple-femtocell scenario
      - The number of femtocells is expected to surpass that of macrocells by up to six times before 2016 [119]
      - Existing algorithms typically apply to the inbound mobility scenario to femtocell with single-macrocell single-femtocell
    - Attain backwards compatibility with the cellular standard
      - Specify the additional network functionality and the required network signaling procedures
    - Use of a HHM during the RSS / RSQ comparison
      - Anticipate with the fast variations of the wireless medium
      - Mitigate the ping-pong effect
      - Combined with speed-based criteria, the HHM reduces the HO probability for medium to high speed users
      - The HHM selection should be optimized

# Part II: Handover Decision for femtocells in LTE-Advanced

- Comparative Summary
  - Future Research Directions
    - Integrate bandwidth-based HO decision criteria
      - Increase the spectrum availability for the UEs
      - Perform preliminary admission control and load-balancing
      - Reduce the HO failure probability due to lack of resources
    - Account for the ongoing connections' characteristics
      - Prescribed mean SINR target [55] [60] or traffic-type of the user connections [43] [49] [52]
      - Enhance the QoE

# Part II: Handover Decision for femtocells in LTE-Advanced

- Comparative Summary
  - Future Research Directions
    - Validate the performance of the proposed algorithms by using realistic system assumptions or simulation setups
      - Existing algorithms accompanied with performance analysis focus on simple network layouts
      - Only a few works conduct system-level simulations based on the evaluation methodology of the Small Cell Forum
      - Compare the performance of the algorithms against other competing ones
      - Focus on performance measures closely related to the femtocell operation
        - » Interference, Energy Consumption, Throughput

# Part II: Handover Decision for femtocells in LTE-Advanced

- Conclusions
  - The smooth integration of femtocells dictates architectural and procedural enhancements that go beyond the standard cellular operation
  - Open Issues for MM in the presence of femtocells
    - Cell Identification
      - Develop more sophisticated procedures to uniquely and swiftly identify the femtocell infrastructure
      - Propose distributed PCI selection algorithms for copying with the random yet dense femtocell deployment
    - Cell Search
      - Design UE-based autonomous cell search algorithms
        - » Use of cognition, context-awareness and cooperation
      - Develop femtocell-specific DRX and packet scheduling algorithms
        - » Utilize the exciting new IMT-Advanced capabilities

# Part II: Handover Decision for femtocells in LTE-Advanced

- Conclusions
  - Open Issues for MM in the presence of femtocells
    - Cell Selection/Reselection
      - Design femtocell-specific selection / reselection strategies
        - » Use of cognition, context-awareness and cooperation
      - Optimize the formation of tracking areas
    - HO Decision
      - Focus on the multiple-macrocell multiple-femtocell case
      - Specify the additional network functionality and the required network signaling procedures
      - Utilize a HHM during the RSS/RSQ comparison
        - » Optimized selection is required
      - Be based on the recent trends for femtocell-specific performance evaluation
    - HO Execution
      - Develop novel signaling methods and protocols to smoothly integrate femtocell-specific processes

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***Thanks for your kind attention!***

# ***Questions?***

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# Component and System-Level Energy Saving for femtocells in Future Mobile Heterogeneous Networks

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# Table of Contents

# References

- This presentation is based on the following references

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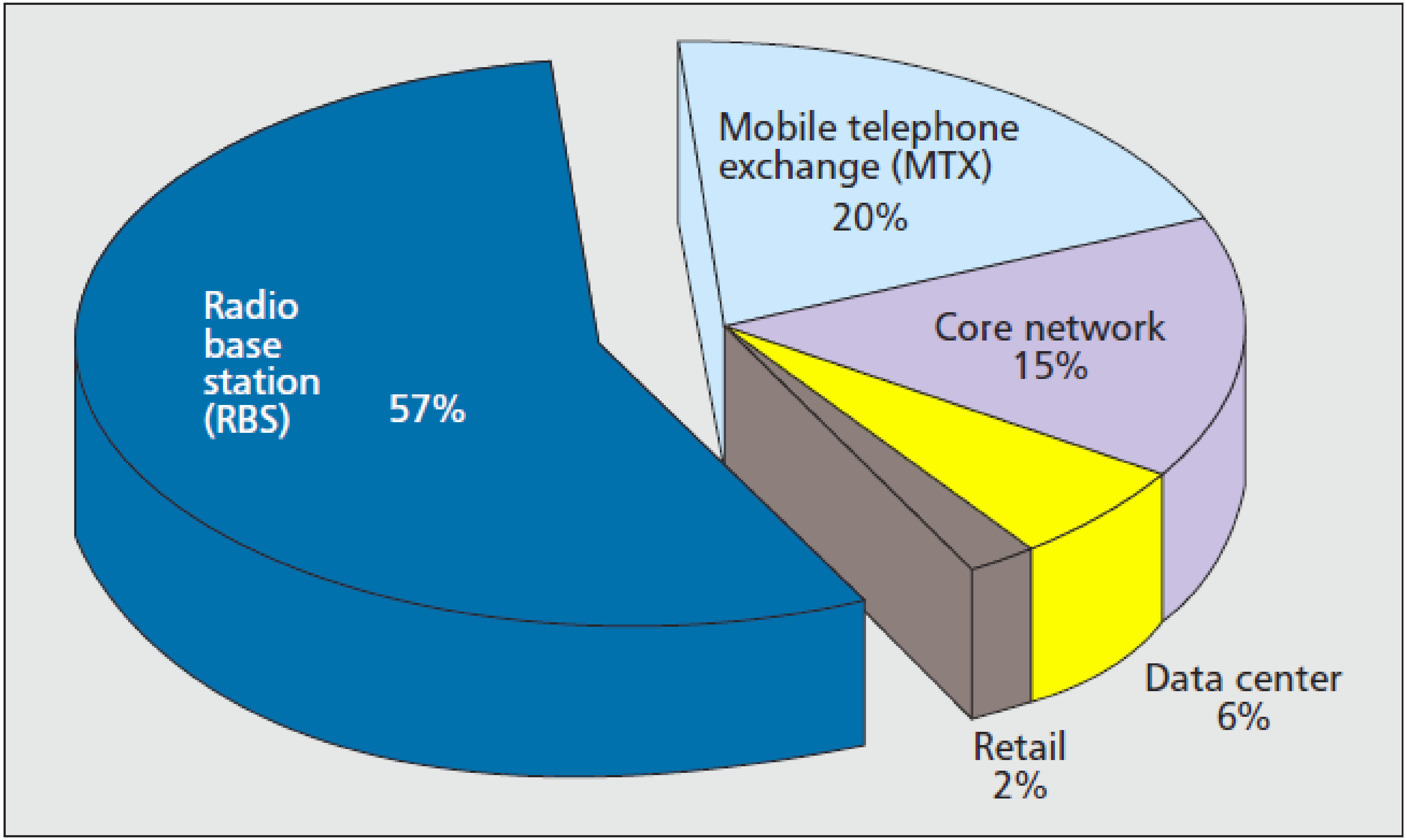
# Introduction

- Mobile industry faces a critical energy consumption challenge
  - More wireless infrastructure has to be deployed
    - Smart-phones will exceed 1.82 billion units by 2013
    - Network load increases 10-fold every five years
      - Energy consumption increase of 16-20%
  - Mobile communications contribute 15-20% of the entire ICT energy footprint
    - 0.3-0.4 % of global $CO_2$ emissions
  - Need for energy-efficient wireless networking

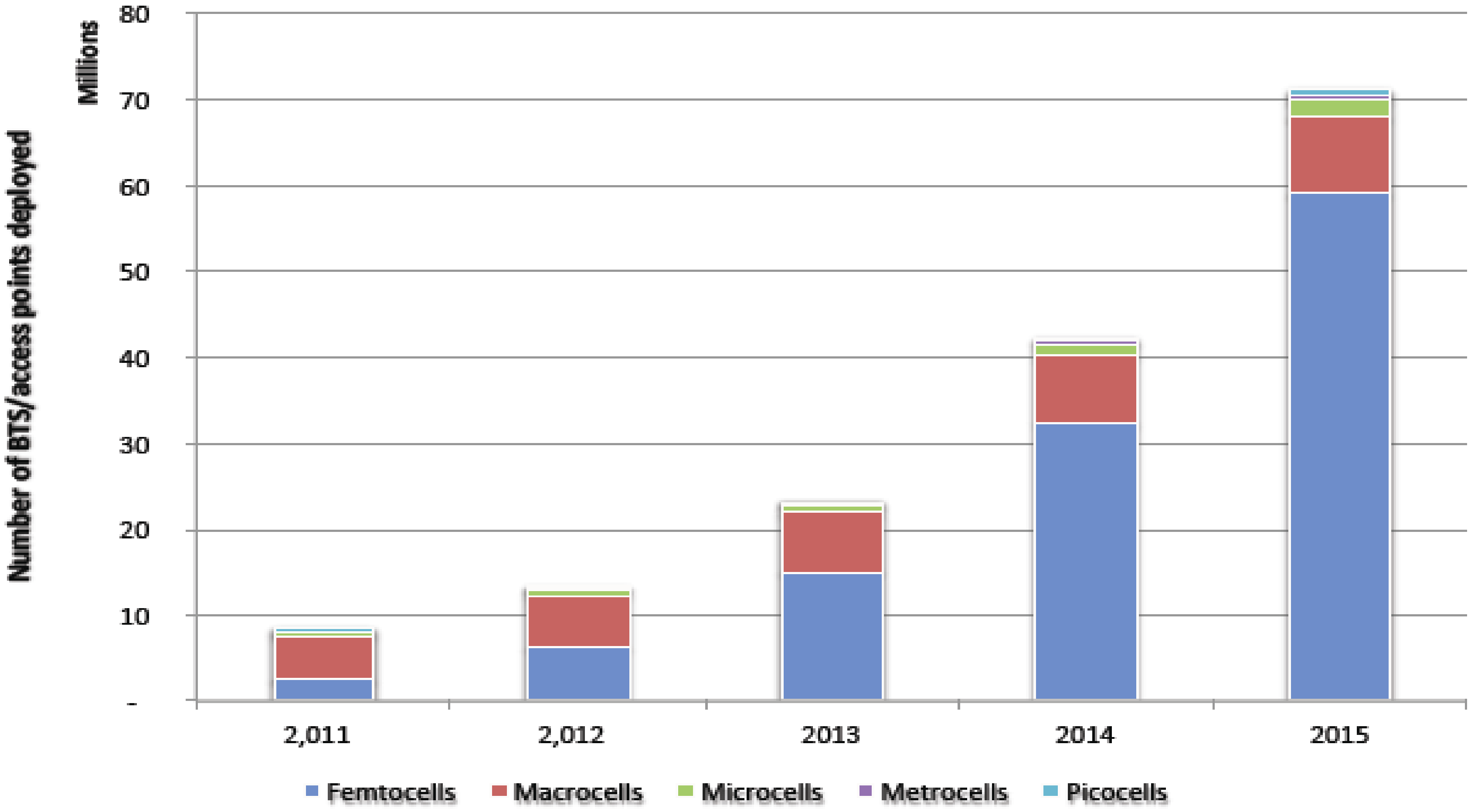
# *Energy consumption composition of a mobile operator*



# Radio Access Network

- Radio Access Network: The key energy contributor for a mobile operator
- Motivation for focusing on ES for the RAN
  - Wireless standards traditionally focus on maximizing the user throughput
    - Performance trade-offs: Energy Efficiency (EE) vs Throughput
  - Mobile users urgently ask for enhanced EE
    - Enjoy better mobile services and improve their Quality of Experience (QoE)
  - Provides a big energy saving pool
- Key issues
  - How will the cellular RAN evolve?
  - How to model the EE of a RBS?

# How will the cellular RAN evolve?

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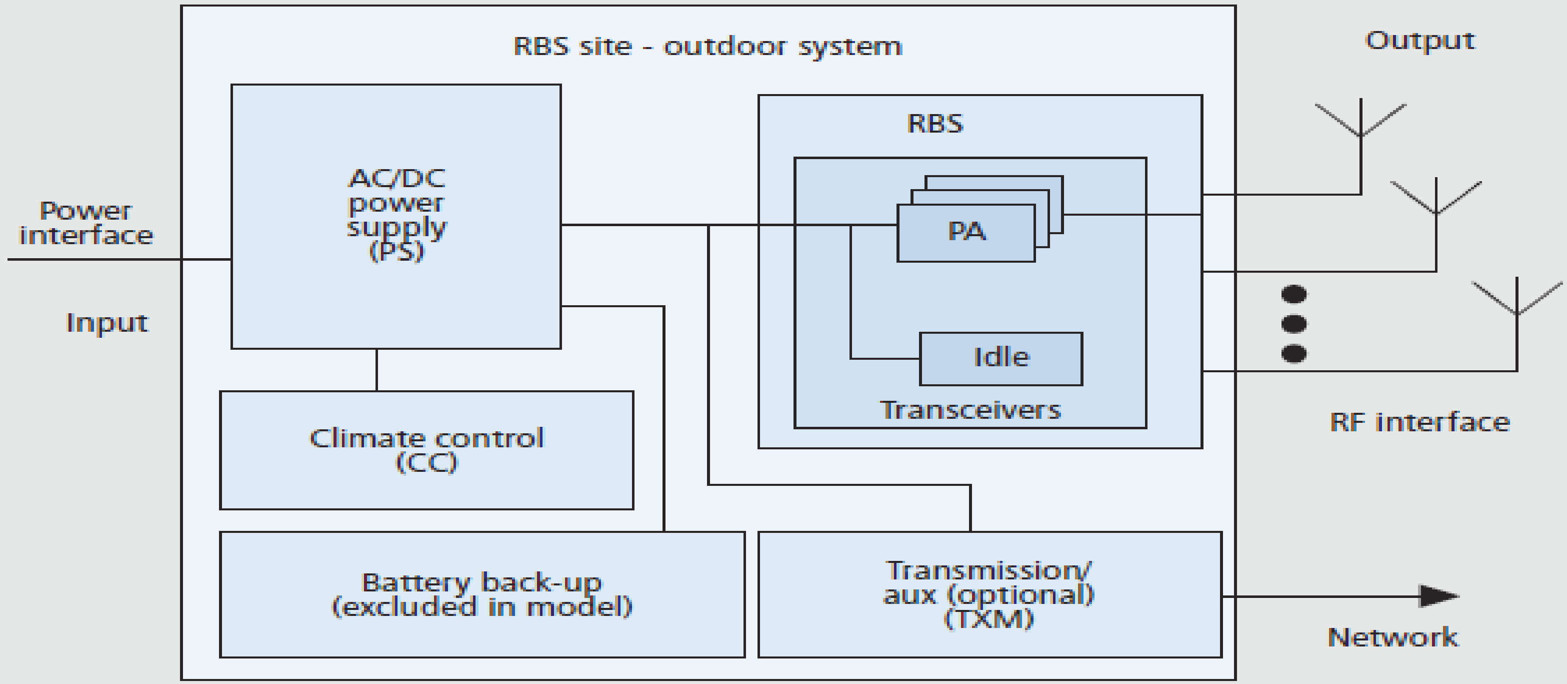
# Forecasts for cellular deployment

- Femtocell Market Status
  - 10-fold increase in the number of deployed femtocells from 2012 to 2015
  - The number of deployed femtocells will surpass that of deployed macrocells by six times
- ES for femtocells is challenging
  - Femtocells are deployed and managed by the consumer
  - Unplanned deployment
  - Dense and overlapping deployment
  - Plug and play operation – self-x operation

# *How to model the EE of a RBS?*

- ETSI EE model for outdoor RBS
  - RBS equipment
    - Serves one or more interfaces to the mobile device
    - Radio transceivers: Responsible for transmission and reception of radio signals, include RF Power Amplifiers (PA)
      - The PA amplifies the signal for transmission via antenna
      - In case of no traffic load, the RBS equipment could enter the idle mode (ES)
  - Support systems for the RBS
    - Power Supply (PS)
      - Connects to the AC power line or battery, and offers electrical energy to the equipment
    - Climate Control
      - Maintains the operating climate of the equipment within a defined range
    - Transmission Module (TXM)
      - Connects the RBS to the core network
    - Battery backup
      - Supplies energy to the RBS when the AC power line is down

# *ETSI EE model for an outdoor RBS*




Examples of power consumption values of RBS (unit: watt)

| | Input | PS | TXM | RBS* | CC | Output | EE |
|---|---|---|---|---|---|---|---|
| GSM | 3802 | 602 | 300 | 2400 | 500 | 120 | 3.1% |
| 3G | 300 | 20 | 110 | 150 | 20 | 60 | 20% |

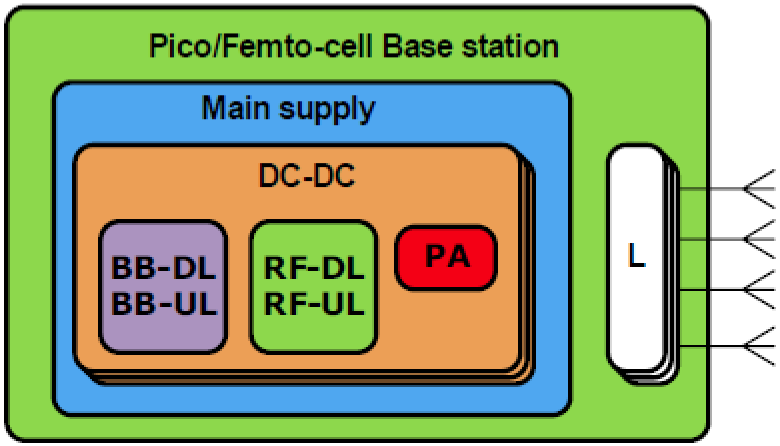
*PA of RBS in GSM consumes 1320 watt power

- EE is defined as the ratio of the radiated to the feeding power

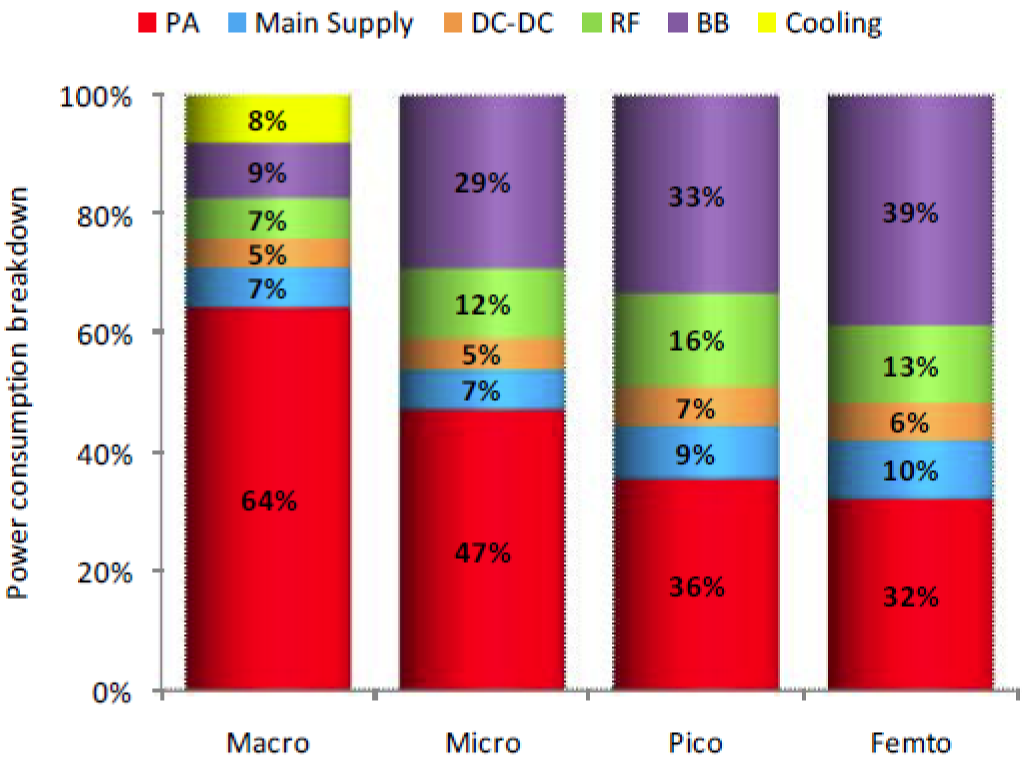
# RAN Energy Saving Approaches

- Radio Access Network
  - Energy Saving approaches for femtocells
    - Component-level energy saving
      - Optimize the performance of the various (hardware) components of the femtocell
        - » Digital Baseband Engine, Power Amplifier, Analog RF transmitter, matching network
    - System-level energy saving
      - Modify some of the fundamental network parameters to save energy
        - » Cell bandwidth, number of carriers, number of antennas, Number/density of cellular stations in the network

# Component-Level Energy Saving for femtocells




Simplified block diagram of a pico/femto-cell base-station

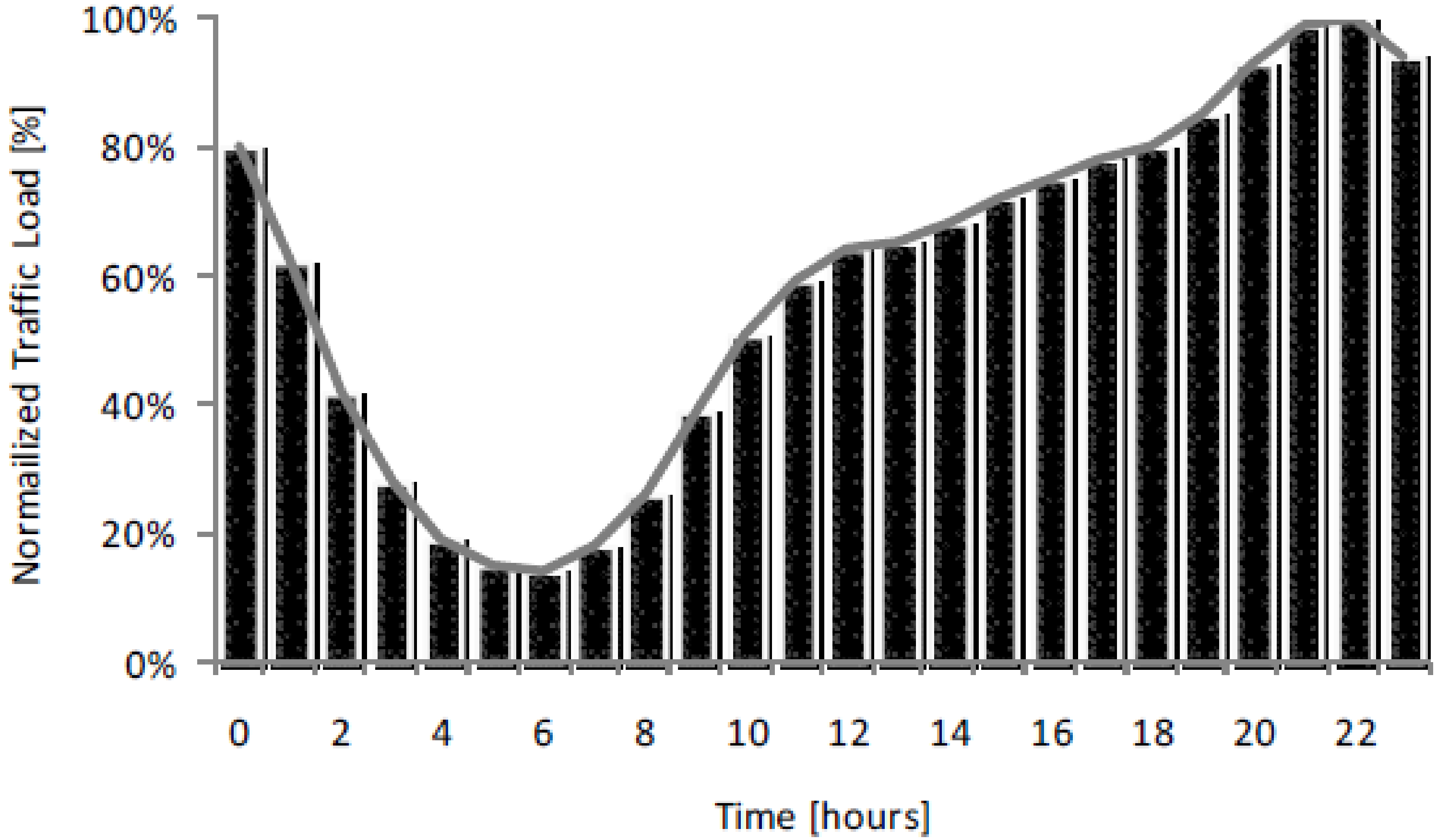



RBS power consumption breakdown for different cell-sizes

# Component-Level Energy Saving Opportunities

- Base-stations are designed for serving high traffic load and achieve their maximum performance
- The daily data traffic profile for cellular systems in a dense urban environment shows high variations
  - The highest utilization is observed between 18.00 and 24.00

# *Daily (24h) data traffic profile for cellular systems (Dense urban)*

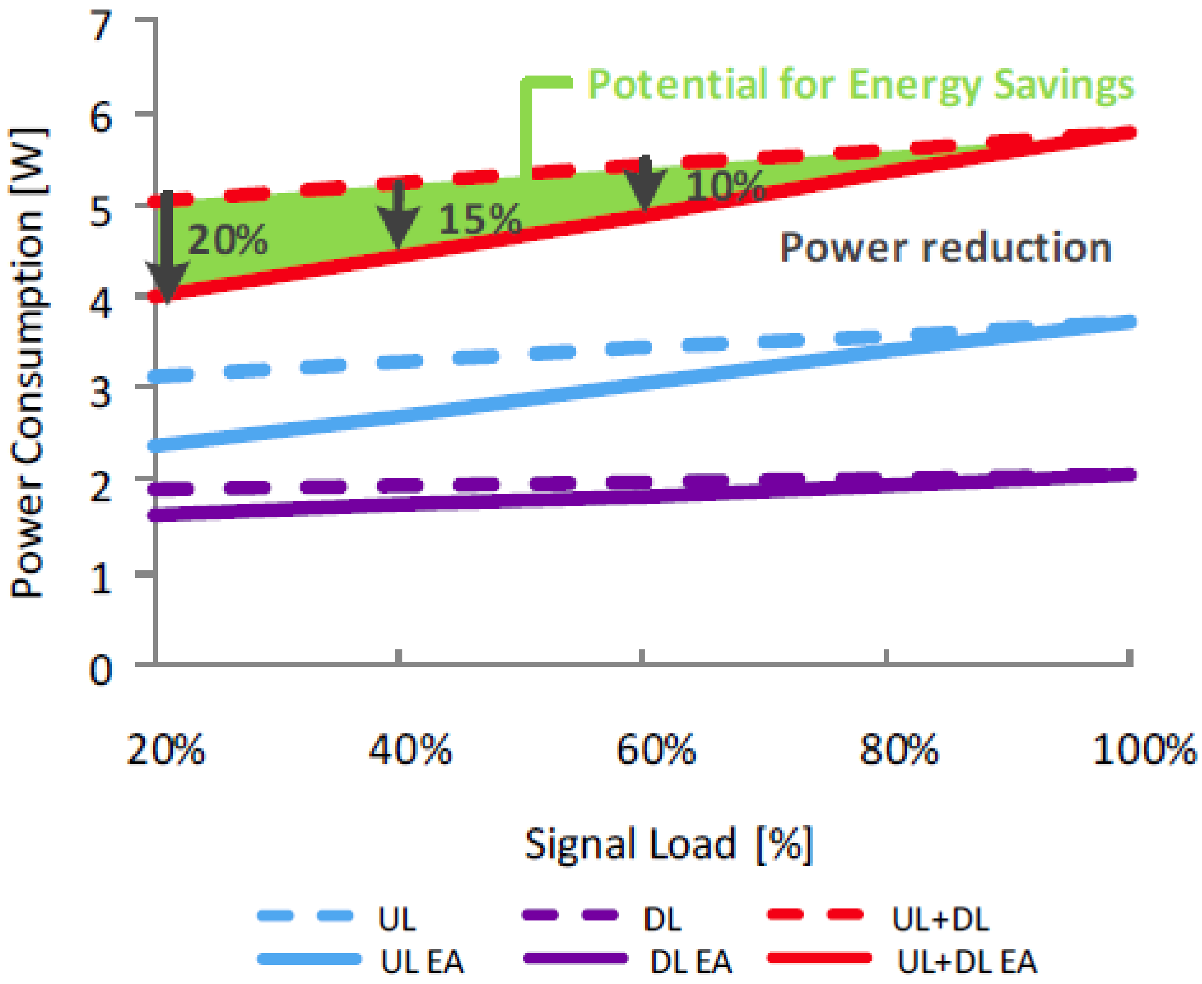



Key idea: Adapt the operation of the various femtocell components with respect to the traffic load

# Component-Level Energy Saving: Digital Baseband Engine (DBE)

- DBE functionality
  - Frequency-domain processing for modulation/ demodulation or equalization, channel coding/decoding, pre-distortion, platform control and backbone network serial link
- The energy consumption of the DBE is becoming more and more dominant
  - Due to the shrinking cell size and the rapidly growing signal processing complexity
- Enable energy scalability depending on the signal load
  - Bandwidth, modulation, coding rate, number of antennas, duty-cycling in time or frequency

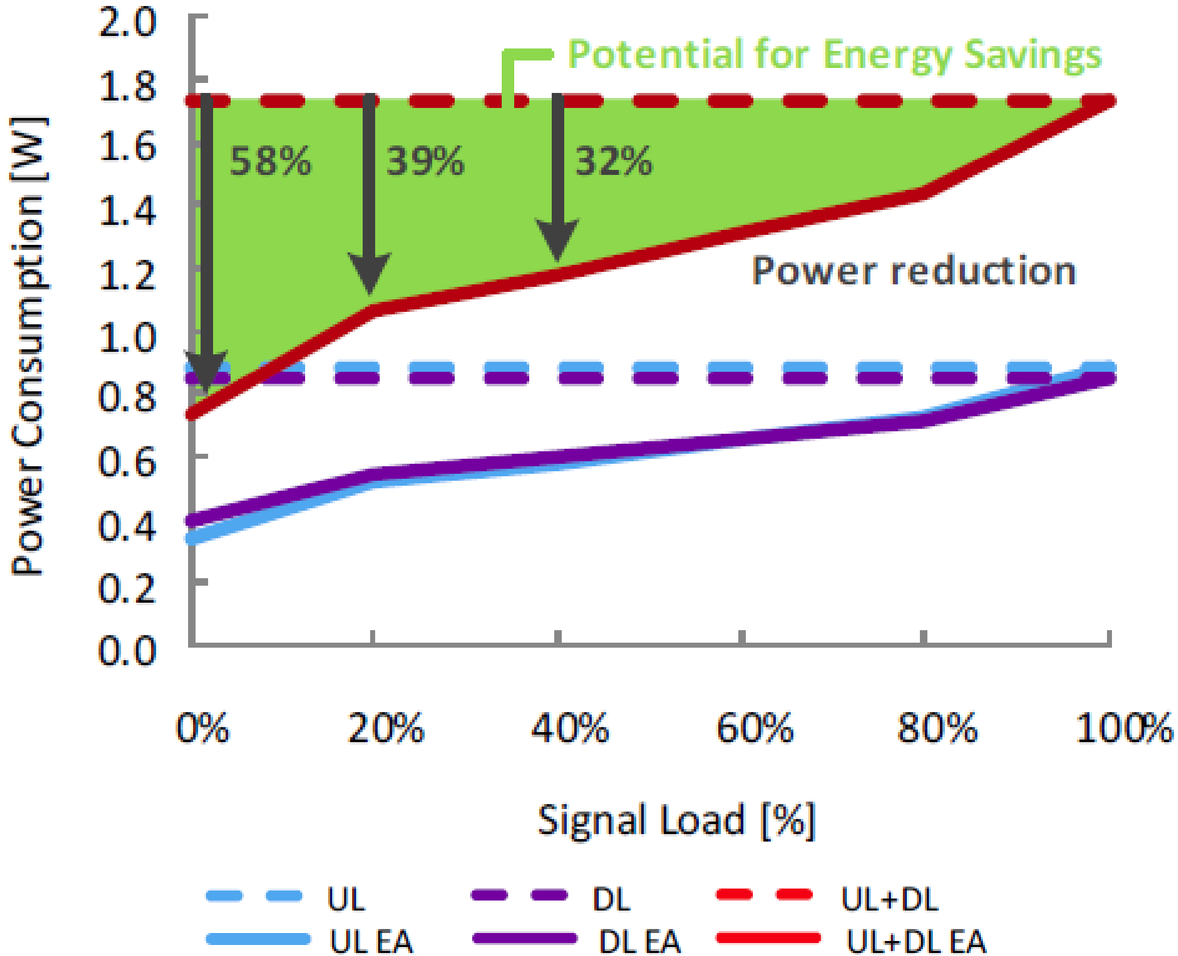
# Component-Level Energy Saving: Digital Baseband Engine



# Component-Level Energy Saving: RF Transceiver

- The RF transceiver of traditional base-stations, targets to achieve the best SiNAD performance independent of the signal load
  - **Signal-to-noise and distortion ratio** (**SiNAD**) is a measure of the quality of a signal from a communications device
- Scale the transceiver to provide a ‘just good enough’ SiNAD performance depending on the current signal load (SDR technology)

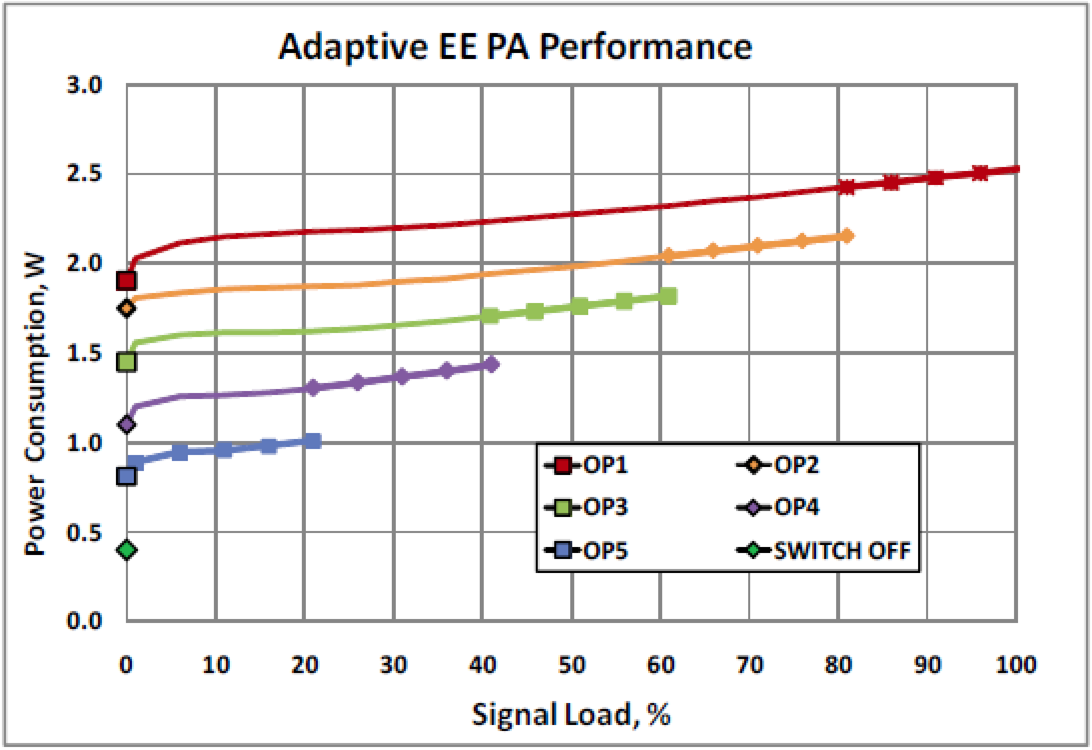
# Component-Level Energy Saving: RF Transceiver



# Component-Level Energy Saving: Power Amplifier

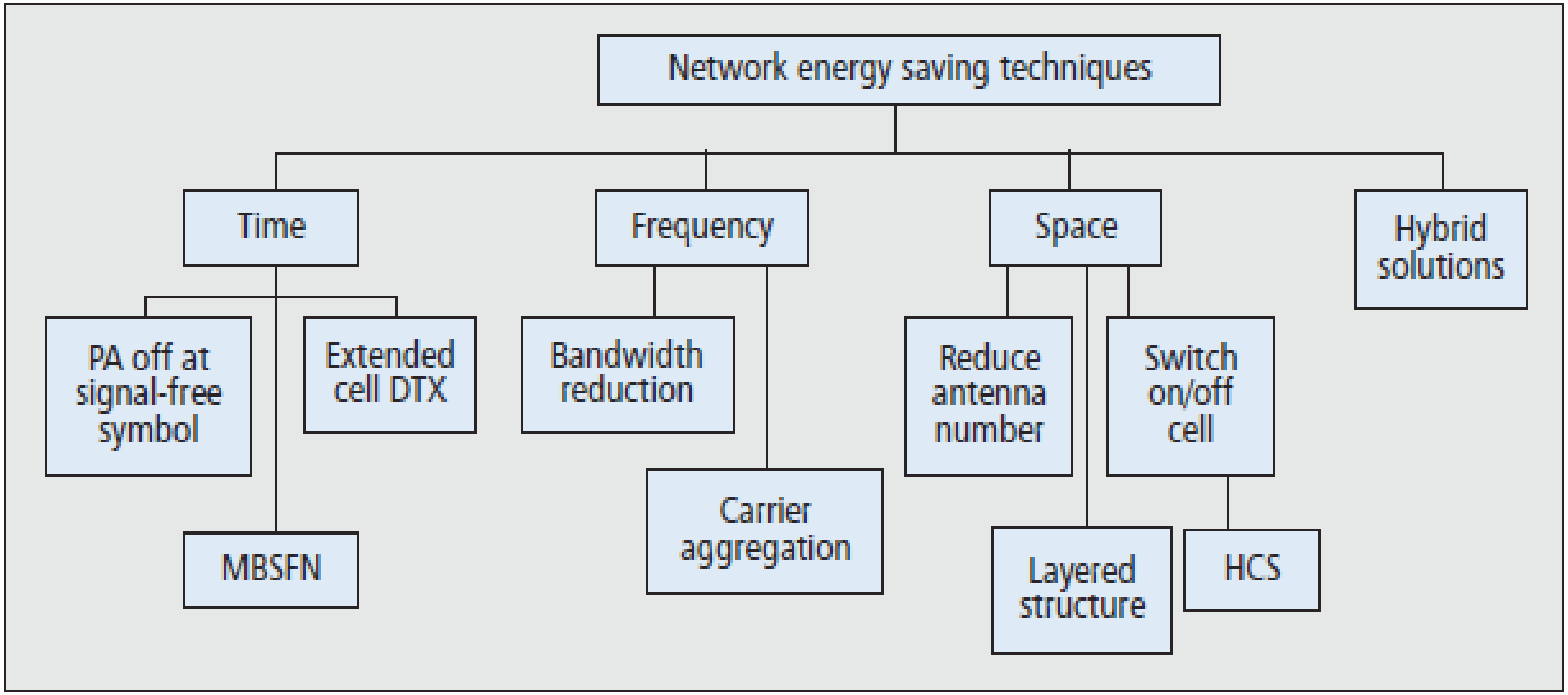
- The PA is not the major energy consumption contributor in femtocells
- Adaptive Energy Efficient Power Amplifier
  - Adjust the PA Operating Point
    - The PA operating point can be optimized according to the required RF output power level (traffic load), while fulfilling the spectral mask and PAPR specifications
  - Enable fast switching on/off of the RF power transistor
    - Minimum consumption when no RF output power is required

# Component-Level Energy Saving: Power Amplifier




- OP5: <20% load, OP4:20%-40% load, OP3: 40%-60% load, OP2: 60%-80% load, OP1: 80%-100% load

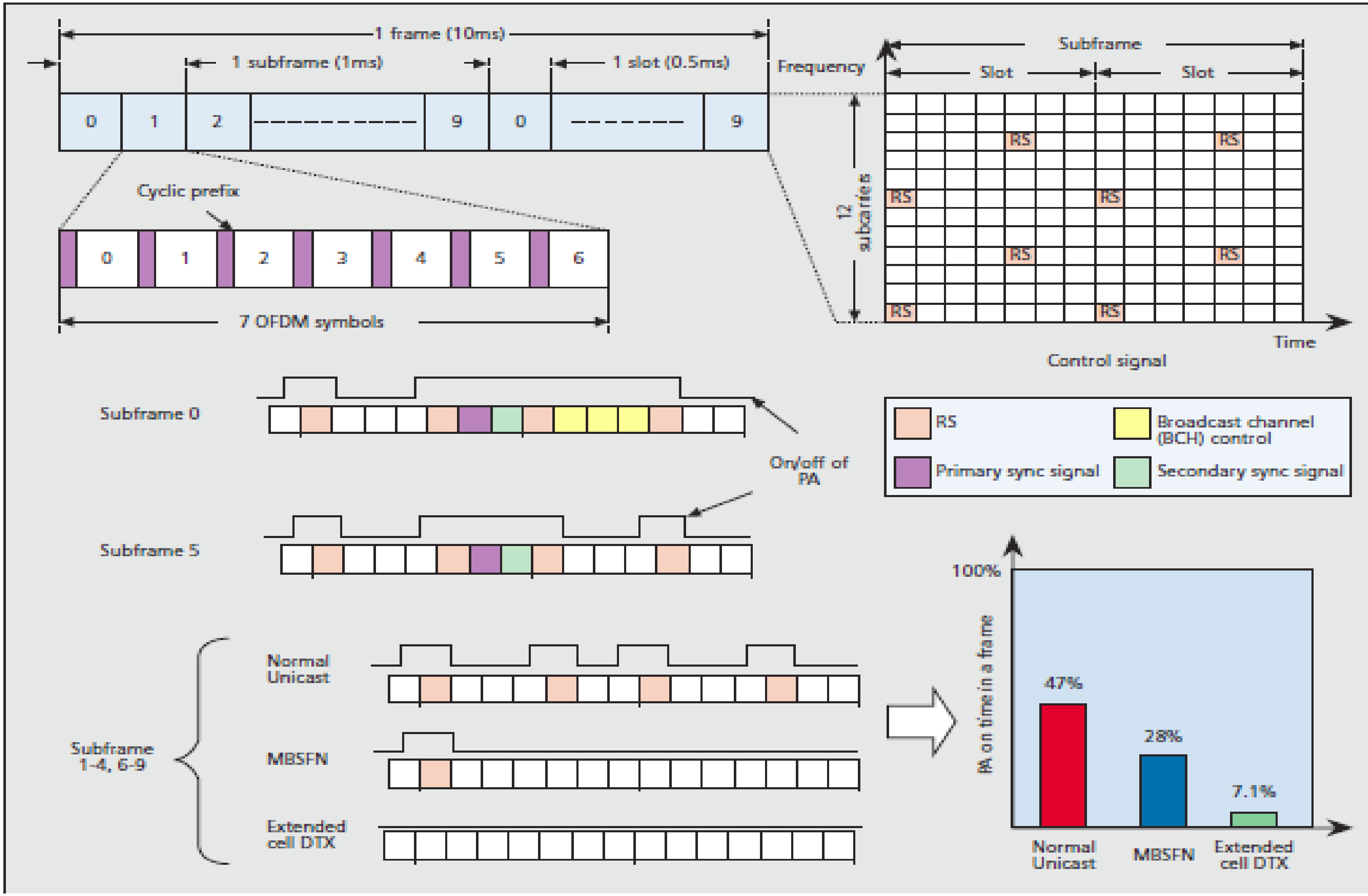
# *System-Level Energy Saving*



# *System-Level Energy Saving: Time domain*

- Time domain solutions temporally shut down PAs in a RBS when there is no data traffic in the downlink
  - Tightly related to the frame structure of the cellular system
  - Three basic ways to temporally shut down PAs
    - Turning off a PA in signal-free symbols
    - Using a multicast broadcast single frequency network (MBSFN) subframe to reduce RSs
    - Use the extended cell discontinuous transmission (DTX) to further reduce the number of RSs

# System-Level Energy Saving: Time domain



# System-Level Energy Saving: Time domain

- PA Off at Signal-Free Symbol
  - Turn off PAs in time periods of a slot where downlink symbols are signal-free
  - Signal-free periods do not include DL RSs and control signals
  - Assuming it takes half of a symbol time to turn on a PA but the PA can be immediately turned off: The PA is only required to be on for at least 47% of the time in a frame

# System-Level Energy Saving: Time domain

- Utilize the MBSFN frame structure
  - MBSFN is proposed to deliver services such as mobile TV using the LTE infrastructure
  - In an MBSFN frame, the symbols for RS in subframes 1–4 and 6–9 are reduced to 1
  - Use the MBSFN structure to further reduce the number of RSs
    - The PA operating time during a frame is then reduced to 28 percent

# System-Level Energy Saving: Time domain

- Utilize the Extended Cell DTX mode (3GPP)
  - The extended cell DTX allows to further reduce RSs compared to the MBSFN approach
  - If there is no downlink traffic, in the extended cell DTX mode there is no need to have any transmission in subframes 1–4 and 6–9 of a frame
  - The PA operating time in a frame is further reduced to 7.1 percent

# System-Level Energy Saving: Time domain

- Advantages
  - Significantly reduce the PA operation time when a cell is idle (apply better in rural areas)
  - Need for joint time-frequency domain scheduling to make them effective in urban areas as well, and only under low traffic conditions
- Disadvantages
  - Without enough RSs, some UEs may experience unpredictable problems synchronizing with an RBS or decoding control signals
  - Reducing RSs may also prevent UE from entering into terminal DTX mode and thus shorten its battery life

# System-Level Energy Saving: Frequency domain

- Bandwidth Reduction
  - Existing cellular systems allow for scalable bandwidth utilization
  - Adapt the cell bandwidth depending on the downlink traffic load
    - Lower the overall transmit power and reduce the number of DL RSs
  - This approach is suitable only for low traffic
  - Marginal gains given that the PA is still active

# System-Level Energy Saving: Frequency domain

- Carrier Aggregation
  - Shut down the associated PAs when the corresponding aggregated carriers are not scheduled for the downlink traffic
  - Applicable to an RBS that has aggregated carriers and separate PAs attached to each group of carriers

# System-Level Energy Saving: Frequency domain

- Advantages
  - Frequency domain approaches are backwards compatible and easy to implement at the RBS
- Disadvantages
  - Can only be deployed for low traffic
  - Result in marginal EE gains

# System-Level Energy Saving: Spatial domain

- Time and frequency domain approaches are employed in a single RBS
- Spatial domain the solutions can be extended to heterogeneous networks, and are therefore more flexible
  - Reduce the Antenna Number
  - Switch On/Off Cells
  - Layered Structure (Heterogeneous Networking)

# System-Level Energy Saving: Spatial domain

- Reducing the antenna number
  - The most commonly used energy saving technique in the spatial domain
  - Can be used when the traffic load of a cell is low
  - Advantages
    - Decreases the total output power and shrinks the cell size
    - For example, if the branches of antennas are reduced from 4 to 1, energy consumption of transceivers is reduced to 1/4, as the PAs associated with those branches can be switched off
  - Disadvantages
    - Need to boost the power of RSs and control signals so as to maintain the cell size
    - May lead to service degradation or interruption as the antenna reconfiguration is needed
    - The change of the antenna number should notify UEs properly

# System-Level Energy Saving: Spatial domain

- Switch On/Off Cell
  - A system-level approach that works in an area covered by multiple (and overlapping) cells
    - When the traffic load in a given area is low, some cells can be shut down, and the served UE units are handed over to the remaining cells
    - Those inactive cells can be turned on during the busy time autonomously or based on signals by active neighbor cells or from the core network (OAM module)
  - Advantages
    - Attains maximum energy saving
    - No need to modify the low-layer components in the RBS
    - Provides a good balance between network performance and energy saving
  - Limitations
    - Frequent switching on/off cells affects the UE services
    - Reduce the battery life of the served UEs as they have to connect with other cells far away (Reduced network density)
    - If there is no overlapping between cells, the remaining active cells need to increase their power to cover this area, (perhaps) neutralizing the energy saving gain

# System-Level Energy Saving: Spatial domain

- Layered Structure
  - Applies to heterogeneous multi-tier networks
    - Prioritized access to low-power nodes
      - E.g., prioritized access to the femtocell station
  - Advantages
    - Provides energy saving opportunities for the RBS of higher layers
      - More energy consuming in general
    - Prolongs the UE battery lifetime
      - Lower tiers are typically characterized by low-power operation and short cell radii
  - Disadvantages
    - Requires for more sophisticated admission control and mobility management algorithms
      - Lower tiers are characterized by random deployment and short cell radii

# System-Level Energy Saving: Hybrid Solutions

- Hybrid solutions
  - Combine solutions in different domains to adapt energy consumption of an RBS in different traffic conditions
  - Achieve the highest ES gain
  - Ask for increased processing/interruption time and signaling for system reconfiguration
  - Need to anticipate their impact on the UE performance

# System-Level Energy Saving: Research Directions

- Account for the total energy consumed in the life-cycle of the system
  - Include the energy consumed in the use phase of a system and the energy used to manufacture telecom equipment
- Investigate the impact of introducing any new architecture and device to the overall EE improvement
  - The optimization of EE at one point of the system may lead to suboptimal results at other points
- Attain a good trade-off between optimizing the QoS performance and achieving high energy saving gains
  - The improvement of EE should not compromise the supported QoS

# System-Level Energy Saving: Research Directions

- Propose comprehensive energy consumption models
  - Capture the key variables of a system regarding energy consumption while providing sufficient abstraction
- Use appropriate metrics to evaluate the performance of the proposed ES technique
  - The EE metric is normally defined as a performance per unit of energy, and the performance typically refers to throughput
  - Capture the provided QoS by accounting QoS measures other than the end throughput
- Optimize the functionality of the system under a EE perspective
  - The EE problem at the system level can be modeled as a joint optimization problem which takes into account resource allocation in time, frequency and spatial domain

***Thanks for your kind attention!***

# *Questions?*

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