

# Energy Efficient Cellular Networks

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Hermes Partnership Workshop on Future Networks  
May 18-19, 2011

# Outline

- Energy efficiency of ICT & mobile communications
- Sustainable mobile networks solutions
  - Holistic approach for future energy efficient cellular networks
  - Energy Efficient metrics
  - Green Radios
  - Green Networks
- Green RRM in LTE-like systems
- EE RRM for two-tier cellular networks: Ghost femto-cells
- Conclusions

# The Issue (1/2)

- **Currently, 3 % of the world-wide energy is consumed by the Information and Communication (ICT) infrastructure**
  - which causes about 2 % of the world-wide CO2 emissions
  - comparable to the world-wide CO2 emissions by airplanes or 1/4 of the world-wide CO2 emissions by cars
- **Power consumption of ICT is currently rising at 16-20% / year**
- **The transmitted data volume increases approximately by a factor of 10 every 5 years**



# The Issue (2/2)

- **Undesired Consequence:** growth of wireless network's energy consumption
  - increase of the global carbon dioxide (CO<sub>2</sub>) emissions
  - impose more and more challenging operational cost for operators
- Communication energy efficiency represents indeed an alarming bottleneck in the telecommunication growth paradigm.

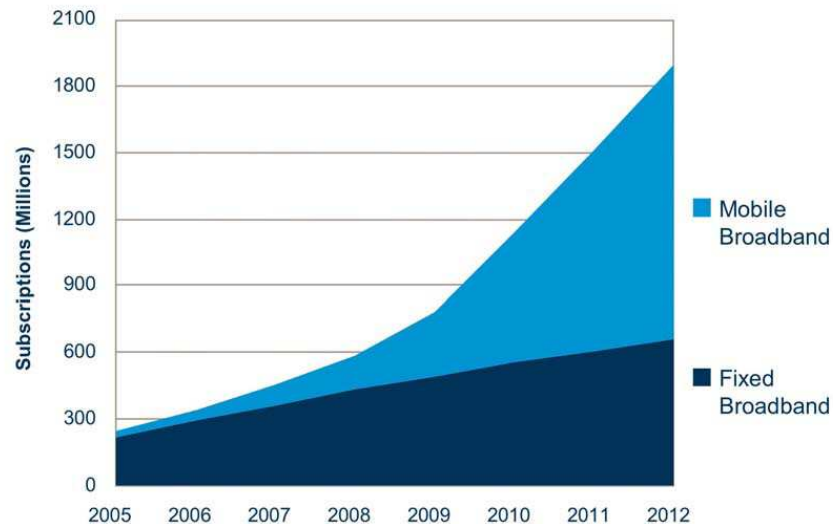
# EE & Mobile networks (1/3)

- So far, mobile networks design rules have ignored EE
  - Cellular networks have been optimized in terms of spectral efficiency, capacity or throughput, not really in terms of Energy Efficiency!
  - EE consideration mainly for UE (battery issues)
  - EE considered only for high load scenarios
- Long-term vision: sustainable energy powered micro/femto base stations
  - ➔ Green challenges



# EE & Mobile networks (2/3)

- **Mobile operators are already today among the top energy consumers**
  - Telecom Italia (fixed & mobile) is the 2nd largest energy consumer in Italy
- **Energy consumption of Mobile Networks is growing much faster than ICT on the whole**
  - Rapid traffic growth and build-up of broadband coverage
  - Mobile replacing fixed in many areas
  - Enabling ICT services for energy saving in other sectors (teleconferencing,...) further increases mobile networks growth



Annual growth rate of internet traffic is 85%.

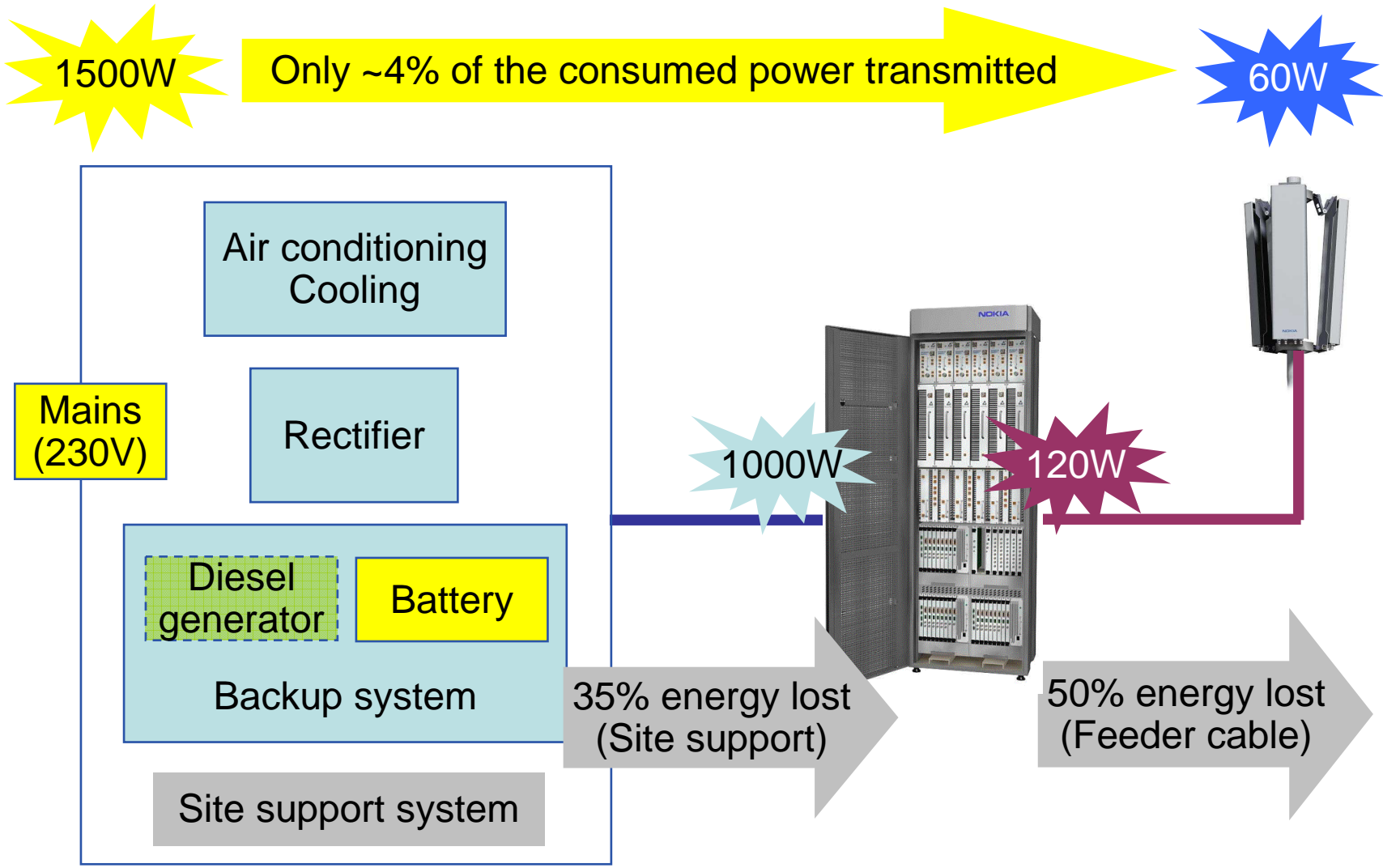
Source: OVUM, Strategy Analytics & Internal Ericsson

# EE & Mobile networks (3/3)

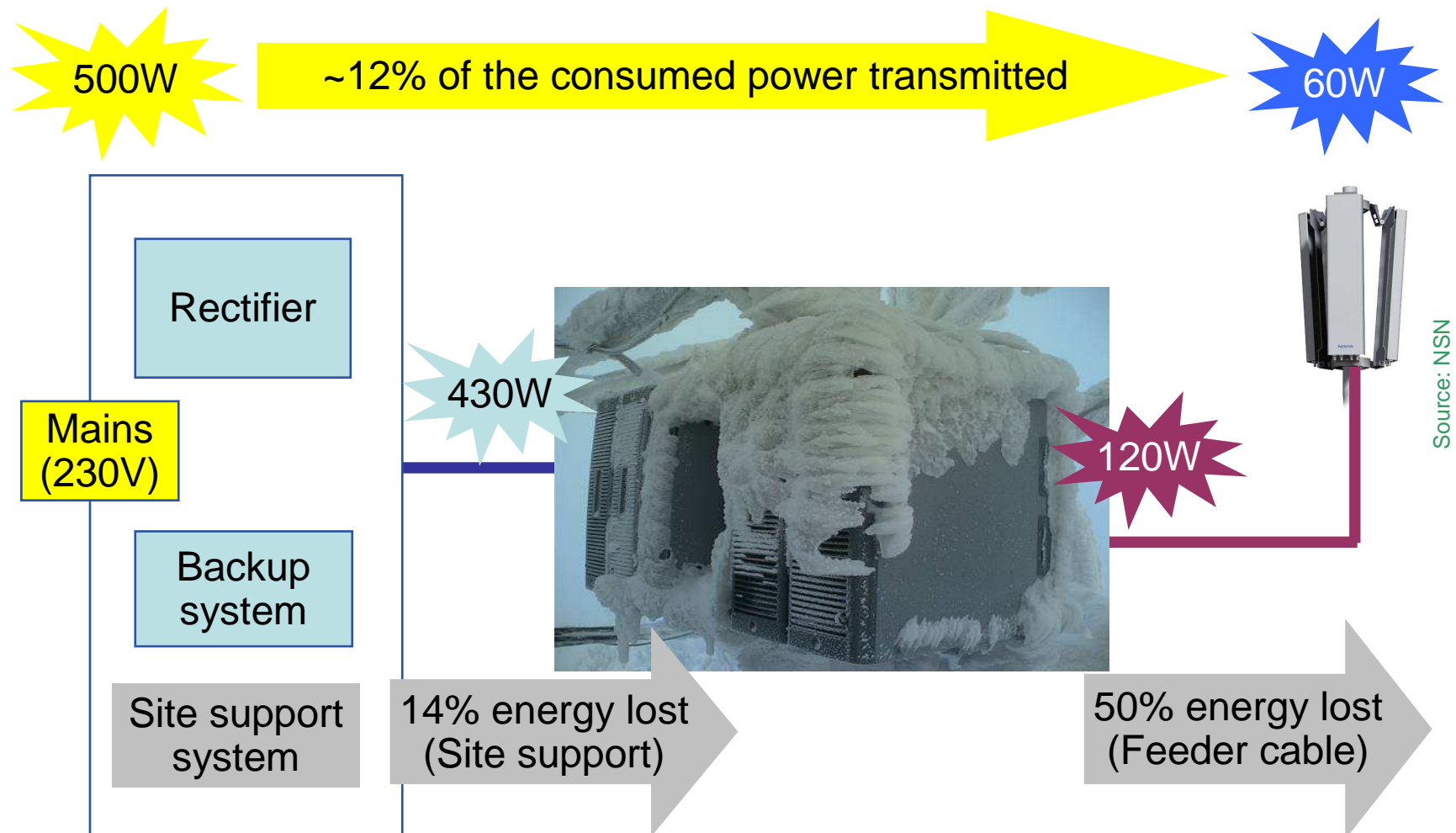
- **Energy savings should be considered primarily at the network level**
  - NTT DOCOMO has calculated that, for their 52 million subscribers in 2006, the energy consumption of their network per mobile user per day was **120 times greater** than the daily energy consumption of a typical user's mobile phone.
  
- **Large savings potential not only for quiet hours.**  
**Network load is not evenly distributed**
  - Typically 10% of the sites carry 50% of all traffic.
  - 50% of sites are lightly loaded, carrying only 5% of the traffic.



# Power consumption of a traditional cellular site



# Power consumption of a modern cellular site



## Objectives: sustainable mobile networks solutions

- **Make ICT ecologically and economically sustainable for all sectors of society.**
  - by investigating and proposing effective mechanisms to **drastically reduce energy wastage & improve energy efficiency** of existing and future communication systems
  - in particular in **low-load conditions** (which are most commonly experienced in most base stations) these savings could be even considerably higher.
  - without compromising users' perceived “quality” of service

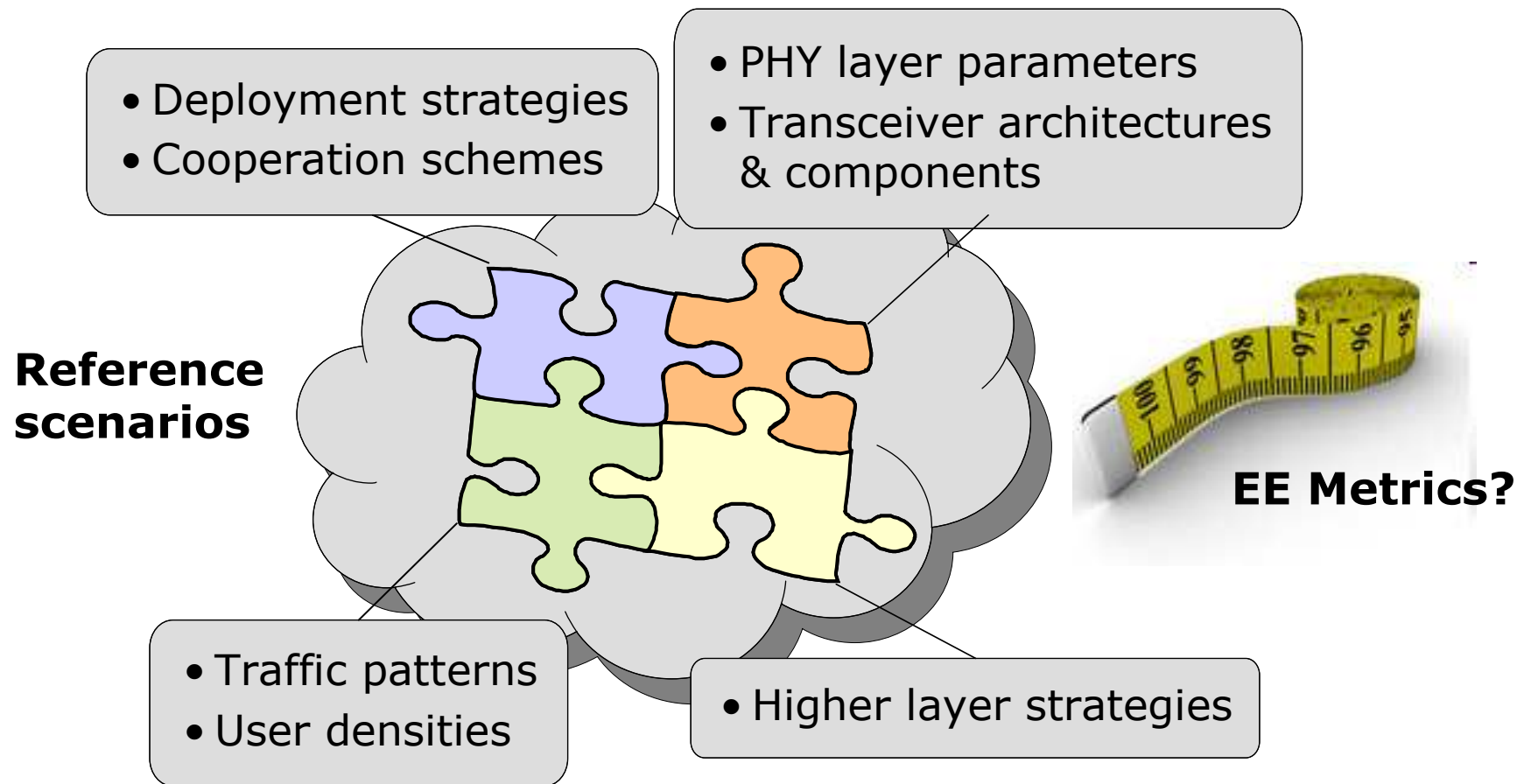
# Methodology

## Holistic approach

- ❖ Energy efficient network topologies, architectures & protocols
- ❖ Network management
- ❖ Radio devices
- ❖ Radio transmission

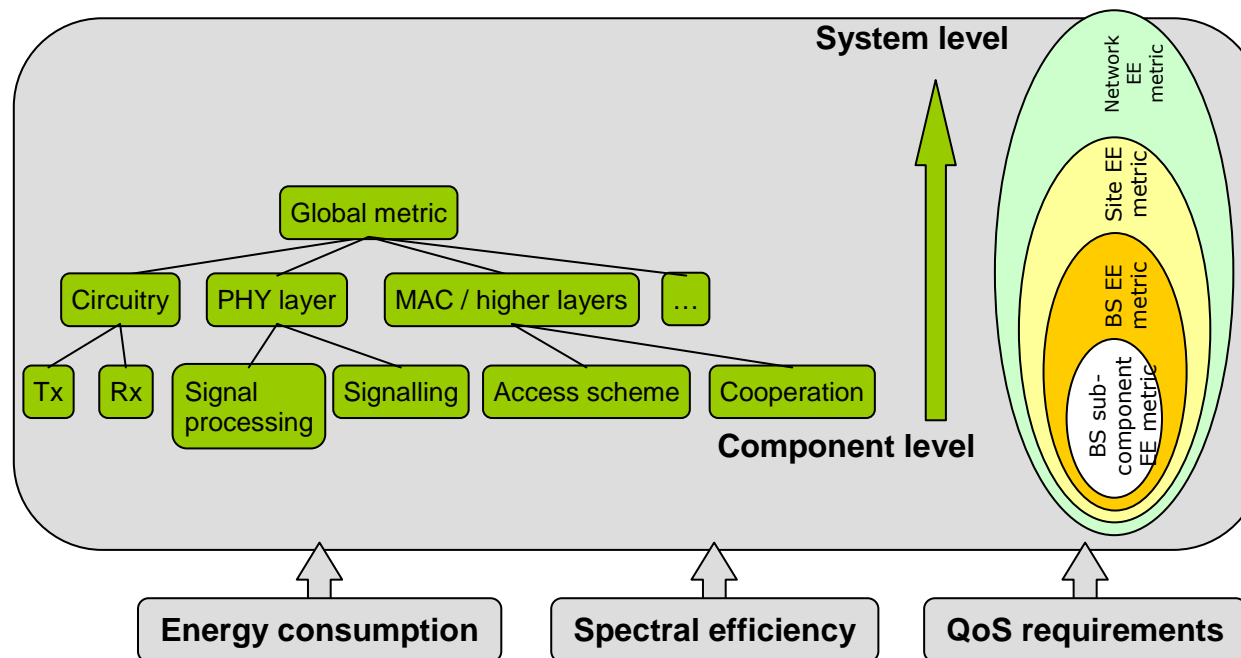
# EE mobile networks require an holistic approach

Innovation should range from semiconductor technology to radios and networks



# EE metrics (1/2)

- Metrics should be defined to measure energy consumption (in e.g. Joule) on component, node and system/network levels, in relation to delivered QoS and system spectral efficiency



# EE Metrics (2/2)

## Fundamental Role:

- To benchmark EE improvement of specific solutions
- To cross-benchmark improvements/losses introduced in the whole network by novel solutions

## Type of EE metrics:

- **Energy consumption metrics:**
  - KPI for BTS Energy Efficiency for coverage: Power / Area in [W/m<sup>2</sup>]
  - KPI for BTS Energy Efficiency for capacity: Energy / Information = Power / Rate in [J/bit] = [W/bps]
- **Combined energy consumption metrics:**
  - Energy / Information / Area = Power / Rate / Area in [J/bit/m<sup>2</sup>] = [W/bps/m<sup>2</sup>]
- **EE index**

# How to smartly waste?

- **Analysis of fundamental tradeoffs:**
  - **Spectrum efficiency versus energy efficiency**
    - Ex. AMC scaling, repetition coding, cooperation,...
  - **Bandwidth versus power**
    - Cognitive, ghost femto cells, ...
  - **Service delay versus power**
    - Power-delay aware scheduling, ...

# Towards Green Radios

## EE Technologies and Components

Power scalable transceivers

Power control on component, front-end and system level

Adaptable matching networks



## EE Enabling Radio Interface Techniques

**Integrated optimisation considering component, radio and interface to network-level**

- Base station power adaptation
- Sleep mode and associated signalling
- Transmission mode adaptation
- Dynamic load adaptation
- Cross layer optimisation

## EE Application of Innovative Radio Transmission Techniques

- MIMO
- Adaptive antennas
- Coordinated multi-points
- Advanced retransmission



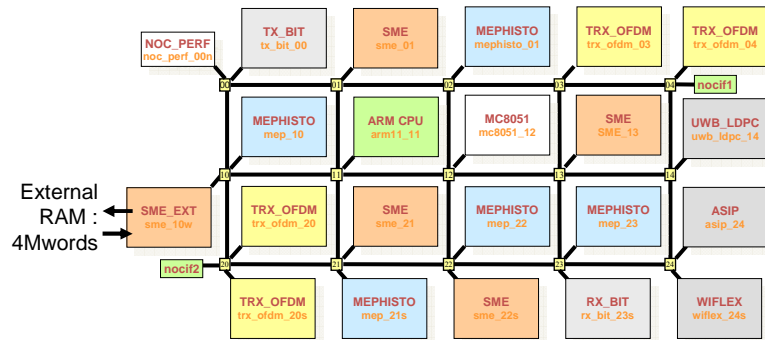
# Innovations in RF front-end architectures

- Design flexible architectures with new components
  - ➔ MEMS to have better perf. (filtering) with lower consumption
  
- Tune performances at run time to the required flexibility & reconfigurability
  
- Co-design of PAs and LNAs
  - Better performance (BW-gain) for a given current
  - Lower current for given performance
  
- Avoid losses in the chain
  - Best matching between amplifiers and the antenna (impedance adaptation)
  - Use of PA in their non linear domain + predistorsion techniques & digital compensation

# Innovations in digital BB architectures

- **NoC architecture: flexibility / processing / consumption**

- ➔ Complex & dense digital partitioned NoC (network on chip / multi-cores)
- ➔ Use of DFVS in GALS systems, i.e. tuning of local power supply units & clock generators



- **LETI's ALPIN chip - Main features:**

- 5 supply modes ( $V_{low}$ ,  $V_{high}$ , VDD hopping, Idle, Cut-off)
- 9 power domains / 6 clock domains
- 65nm CMOS STM technology / chip area: 12 mm<sup>2</sup>
- A global microcontroller is in charge of the global power budgeting of the chip using DVFS technique

- **Run full frequency only when required**

- **Master leakages**

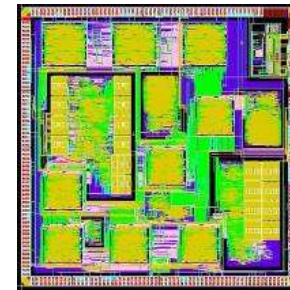
- Leakage currents represent up to 25% of the power consumption with submicron technos

- **LETI's Magali chip - Main features:**

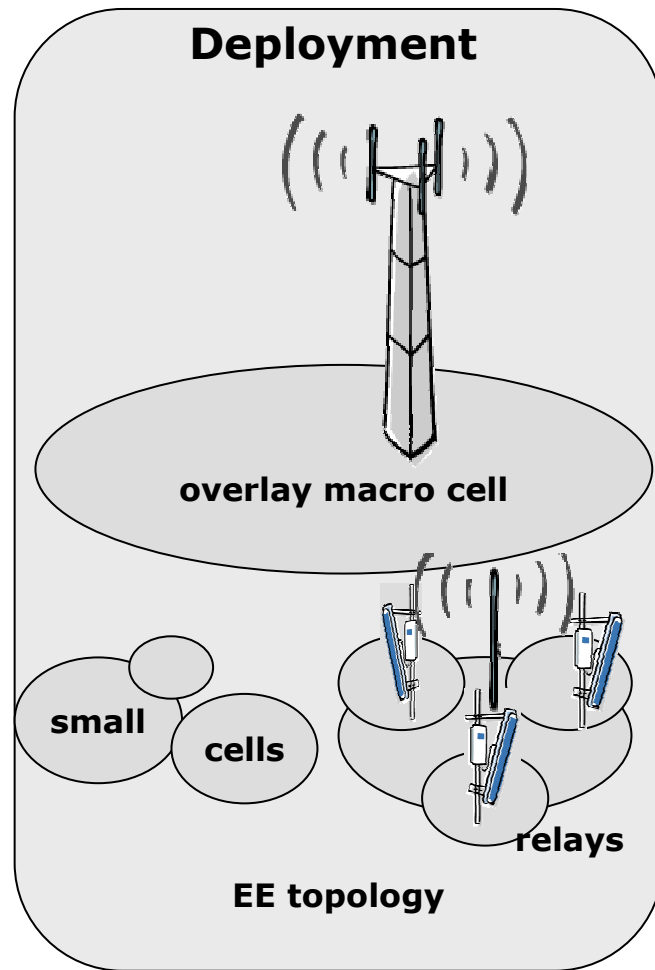
- 37 GOPS available
- 65nm CMOS STM techno, 30mm<sup>2</sup>
- Asynchronous Network-on-Chip (NoC) for communications: 15 nodes – 88Gbps aggregated throughput
- 10  $\mu$ s reconfiguration time

- **Power advanced features:**

- **Local clock generator**
- Run-time frequency management
- 500 mW (MIMO RX)



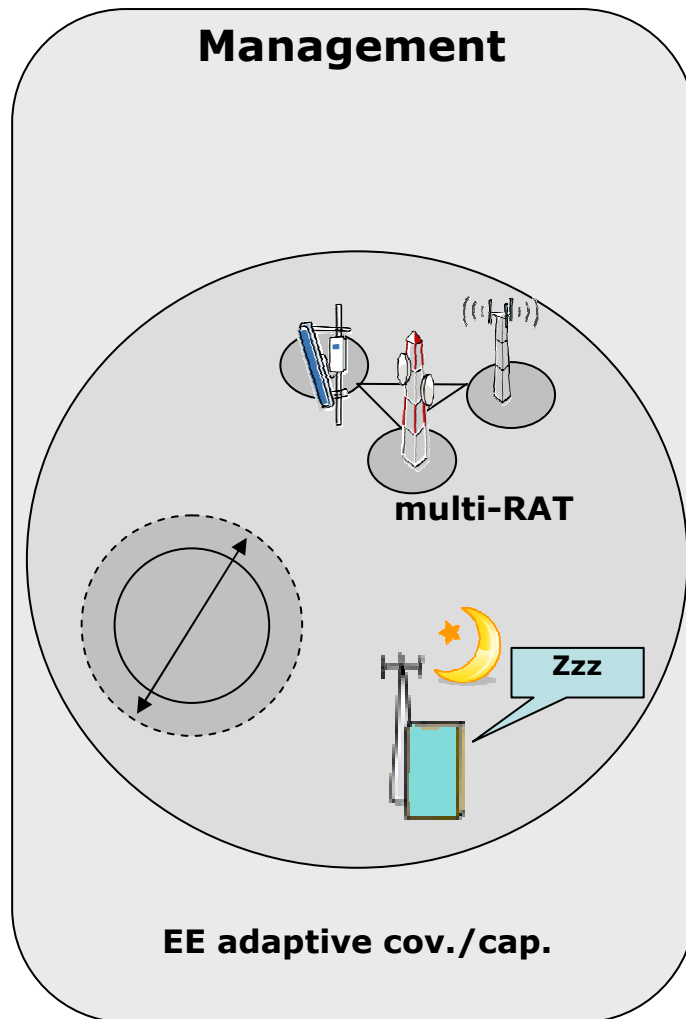
# Towards Green Networks (1/4)



Design of green networks for efficient operation **not only at high load** but **low and medium** load conditions

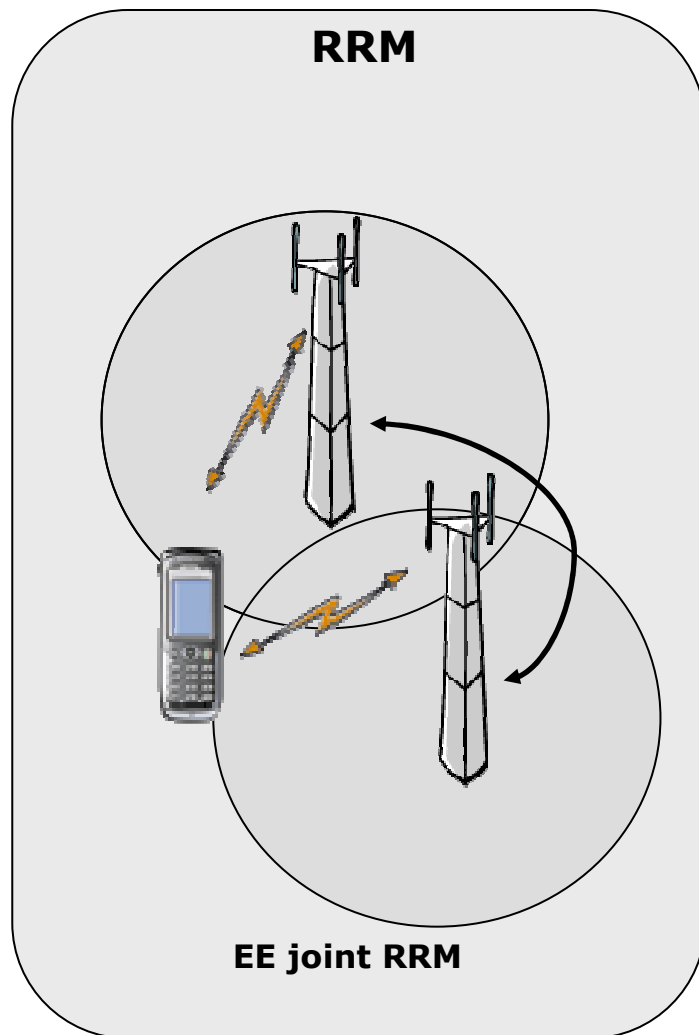
- **Deployment scenarios:**
  - optimum cell sizes
  - mix of cell sizes (HetNets)
  - hierarchical deployments
  - multi-RAT deployments
  - relays & repeaters
  - Femto cells

# Towards Green Networks (2/4)



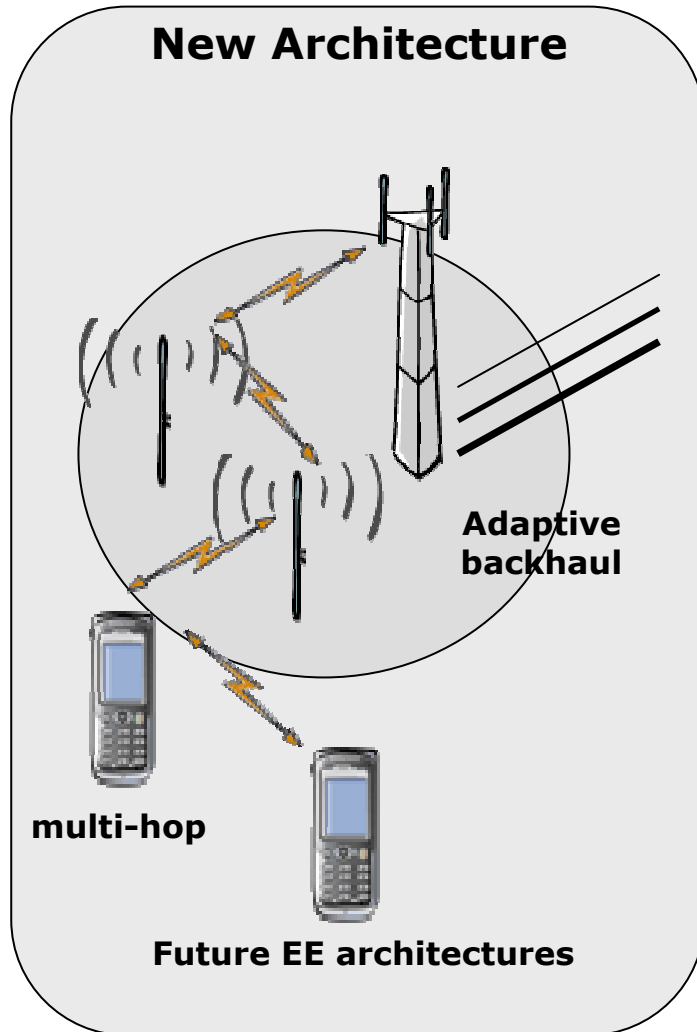
- **Management algorithms:**
  - coverage adjustment
  - capacity management
  - multi-RAT coordination
  - base station sleep mode
  - protocol design

# Towards Green Networks (3/4)



- **Objectives:**
  - Adapt energy consumption to time and space varying communication conditions (interference, traffic load, transmission scenario, local density of users, type of service, etc.)
- **RRM algorithms:**
  - EE transmission mode adaptation
  - Cooperative inter-cell scheduling & dynamic load optimization
  - Inter-cell interference coordination
  - Joint power allocation and resource allocation
  - Dynamic network planning and cognitive coordination between **Femto** cells and macro cells
- **Tradeoffs for optimization rules:**
  - EE vs. spectral efficiency
  - EE vs Band
  - EE vs QoS

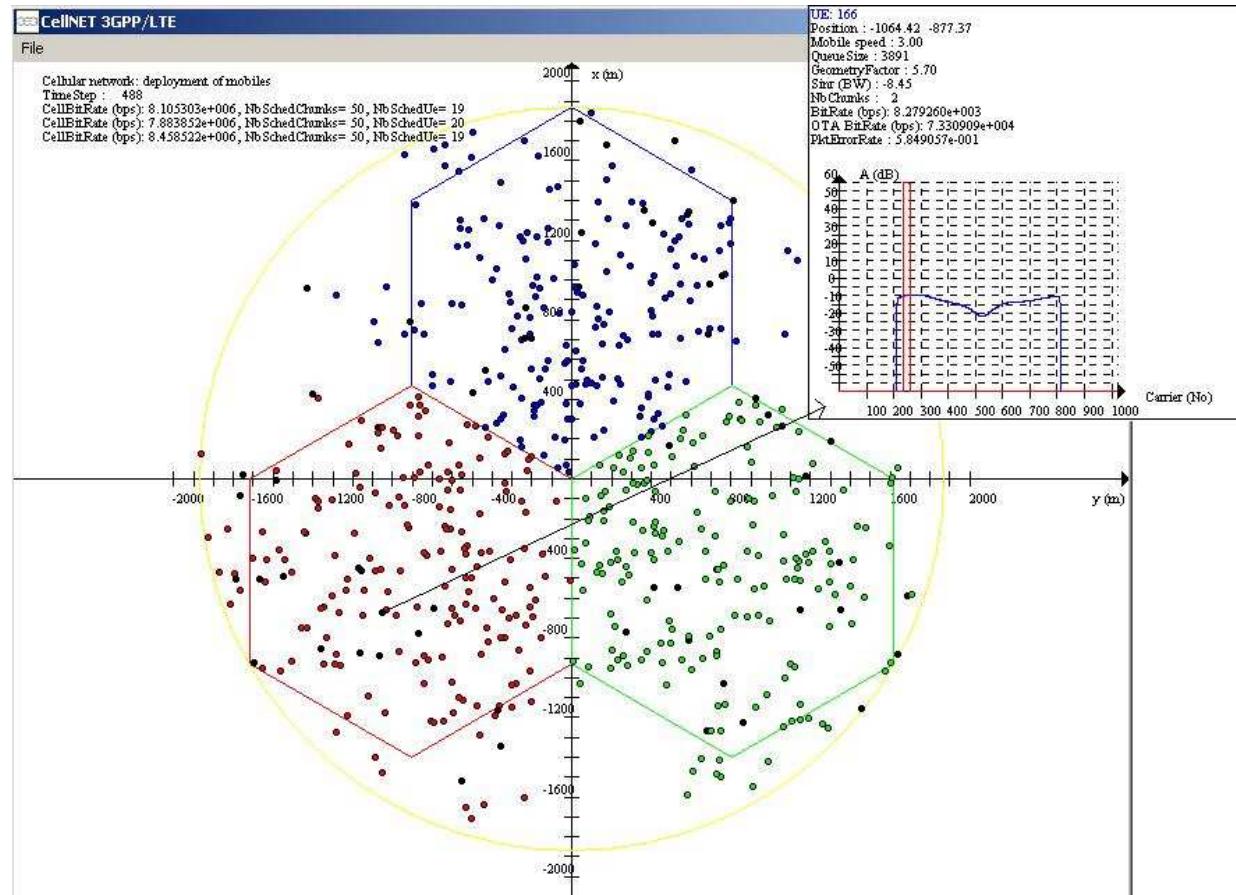
# Towards Green Networks (4/4)



## ■ Disruptive approaches:

- multi-hop transmission
- ad-hoc networks
- terminal-terminal transmission
- cooperative multipoint arch.
- EE adaptive backhauling
- cognitive/opportunistic radios & networks
- geographical coexistence of heterogeneous BS on same spectrum (Macro, femtos, relays, repeaters)

# System level Evaluation tool



- Green metrics and QoS monitoring
- Evaluation of green algorithms & protocols



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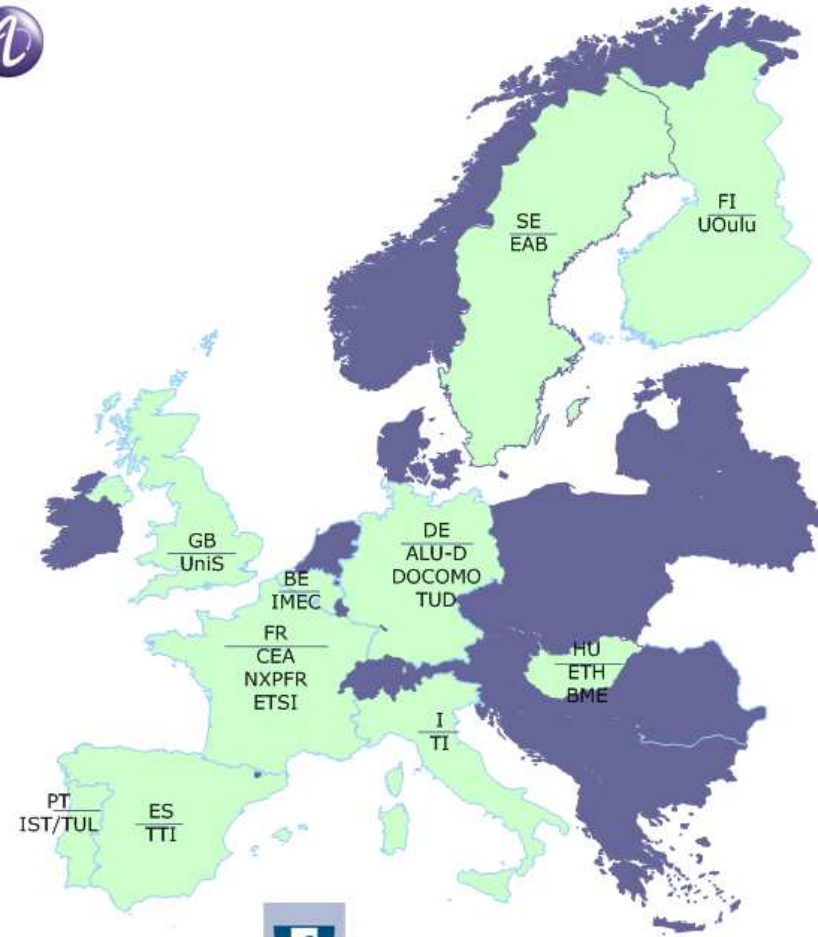
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# Green RRM in LTE-like systems: Green Allocation Scheduler

# Specific Challenges of EE RRM for DL OFDMA

- Improve the EE of RRM according to **short term** dynamics in the cell while meeting the target QoS.
- Track dynamic variation on cell load
- Track and exploit dynamic variation of traffic composition:
  - VoIP, NRTV, HTTP, FTP, ...

## Problem to be solved

- Base station **power** downlink consumption can be **optimized**
- Users do not need at the same time T/F resource with the same urgency  
*or ... same energy effort*

## Goals :

1. Meet QoS constraints: a challenging task with heterogeneous services (VoIP, NRTV, HTTP, ...)
2. Limit power consumption of BS (*green issue*)

# SoTA Scheduling Algorithms in OFDMA

## Classical approach:

- Resources are allocated to users which are identified as '*priors*': best channel, earliest deadline, etc...
- Adaptive Modulation and Coding (AMC) optimizes transmission **spectral efficiency** to improve overall system capacity and reduce average packet delivery delay.
- The highest modulation and coding scheme (MCS) which permits to achieve the desired target QoS (classically a target PER) is selected for transmission:  
**however such MCS is high energy demanding!**
- Target: maximum data transmitted in a chunk and reliable communications

→ Traditional packet scheduling algorithms are designed to increase the maximum system capacity, subject to QoS constraints and fairness.

## Observations

- With SoTA priority scheduling algorithms, the exploitation of available time and frequency resources is typically not optimized from an energy perspective.
- Most of the time, wireless systems are only moderately loaded.

**Scope:** design an energy efficient scheduling algorithms which meets the QoS constraint of an heterogeneous population of UEs

# Proposal: Green Adaptive Scheduler

***Idea: don't rush = don't waste!***

***first deal with urgencies : allocate high power for transmission  
then minimize the transmission power***

- **Step 1 [Classify Users]:**  
    **Rushing:** packets which are close to expire their QoS (according to a predefined threshold  $Th_{rush}$ )  
    **Non-rushing:** otherwise
- **Step 2 [Deal with Urgency]:**  
    Assign resources only to entities that are 'rushing' regardless to their momentary link quality and their potential to save energy.
- **Step 3 [Schedule 'Best Users']:**  
    Allocate unscheduled chunk resources (if any) to 'best users' which maximize spectral efficiency, regardless to any QoS constraints
- **Step 4 [AMC Scaling]:**  
    Perform energy efficient link adaptation to save downlink energy. We trade throughput (lowering the transmission spectral efficiency and allocating a larger number of chunks to UEs) with downlink power by limiting the power budget on each chunk

# System Model (LTE-like)

Network	
Parameter	Value
Carrier frequency	2.0 GHz
Bandwidth	10 MHz
Inter-site distance	500 m
Minimum distance	35 m
TTI duration	1 ms
Cell layout	Hexagonal grid, 19 three-sectored cells
Link to System interface	EESM
Traffic model	VoIP, NRTV
Nb of antennas (Tx, Rx)	(1,1)
Access Technique	OFDMA
Total Number of Sub-carriers	600
Nb of Sub-carriers per PRB	12
Total Nb of Chunks (PRB)	50
Propagation Channel	
Parameter	Value
Fast fading	Typical urban 6-tap model, 3 km/h
Interference	White
UE	
Parameter	Value
Channel estimation	ideal
CQI reporting	ideal or partial
Turbo decoder	max Log-MAP (8 iterations)
Dynamic Resource Allocation	
Parameter	Value
Nb of MCS	12 (from QPSK 1/3 to 64-QAM 3/4)
AMC $PER_{target}$	10 %
CQI report	Each TTI, with 2ms delay
Packet Scheduling	EDF, MCI
Sub-carriers Allocation Strategy	Chunk based allocation
Number of control channels per TTI	16
HARQ	
Parameter	Value
Stop and Wait	synchronous adaptive
Number of processes	6
Retransmission Interval	6 ms
Maximum Nb of retransmissions	up to 3
Combining technique	Chase

Based on the 3GPP/LTE downlink specifications

MCS mode	Modulation	Coding Rate	Spectral efficiency
1	QPSK	1/3	2/3
2	QPSK	1/2	1
3	QPSK	2/3	4/3
4	16-QAM	1/3	4/3
5	QPSK	3/4	3/2
6	16-QAM	1/2	2
7	64-QAM	1/3	2
8	16-QAM	2/3	8/3
9	16-QAM	3/4	3
10	64-QAM	1/2	3
11	64-QAM	2/3	4
12	64-QAM	3/4	9/2

TABLE I  
MODULATION AND CODING SCHEMES IN LTE.

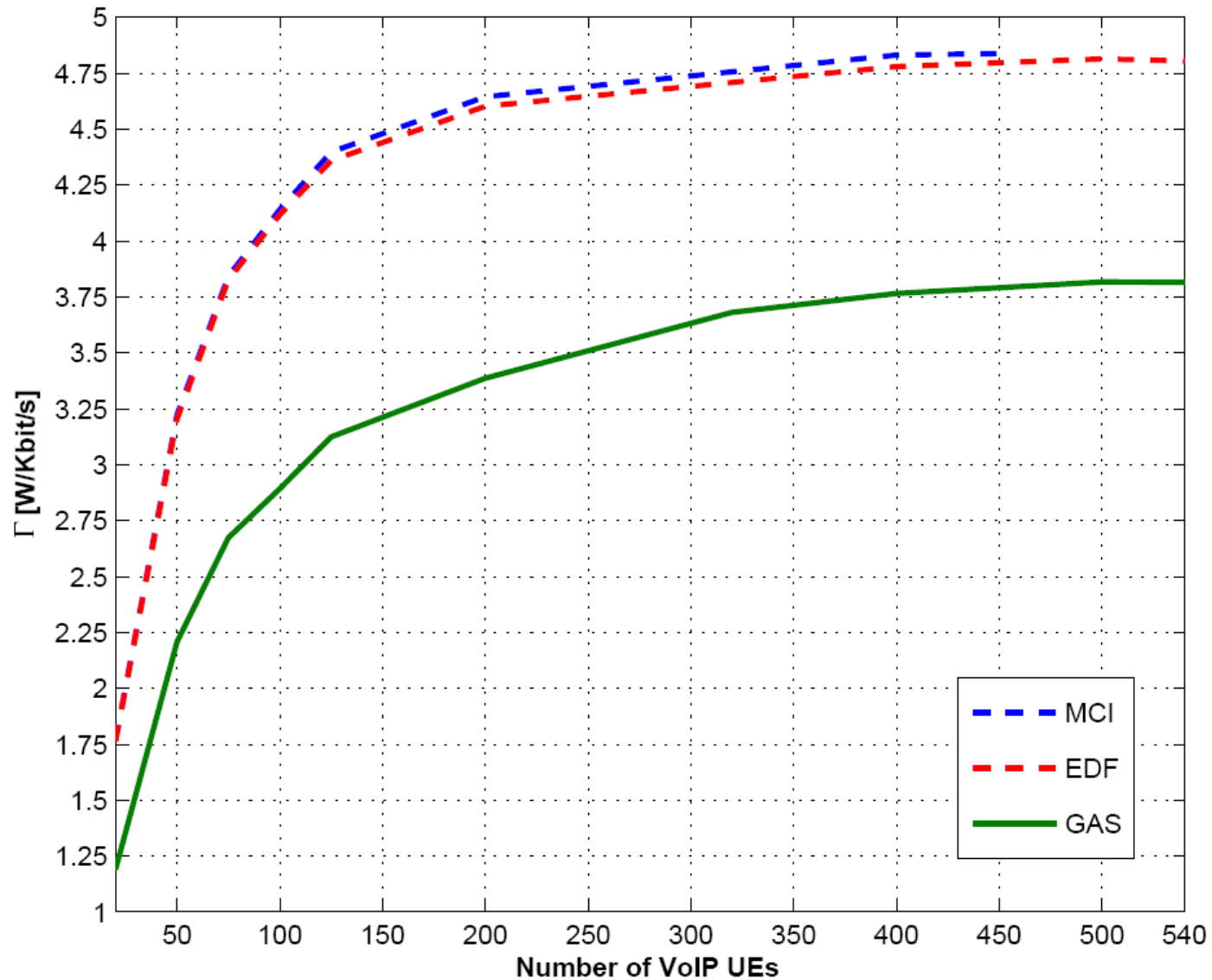
# Adopted EE Metric for Downlink OFDMA

- Power efficiency metric:

$$\Gamma_i = \sum_{j=1}^{K_i^{UE}} \frac{Nb_{i,j}^{chk} \cdot Pow_{i,j}^{dl}}{\rho_{i,j}}$$

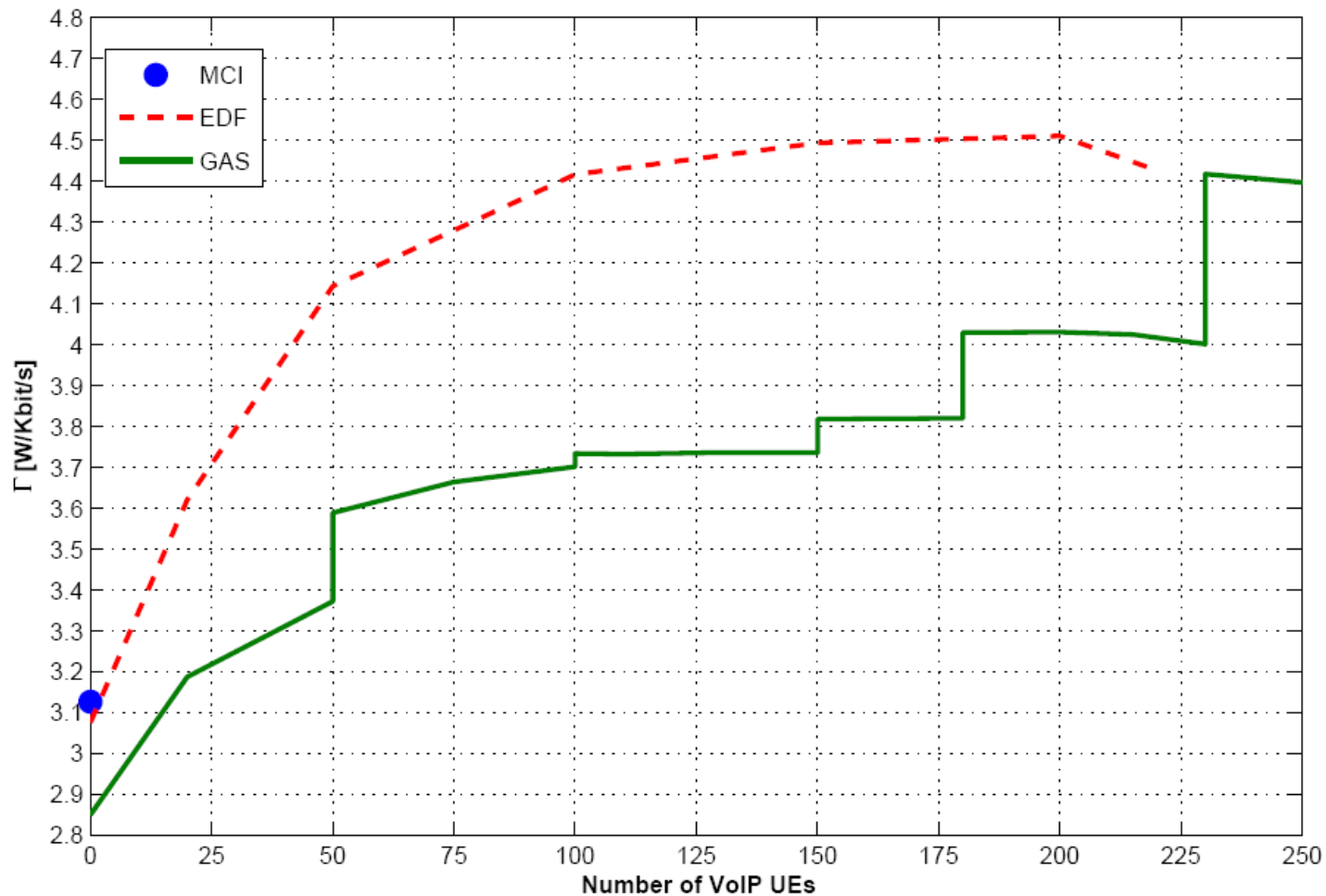
Where at TTI  $i$ ,  $K_i^{UE}$ ,  $Nb_{i,j}^{chk}$ ,  $Pow_{i,j}^{dl}$  and  $\rho_{i,j}$  are respectively the number of active UEs, the number of chunks allocated to user  $j$ , the downlink power for transmission on each chunk and the throughput of user  $j$

# Simulation Results: *single traffic scenario (VoIP)*

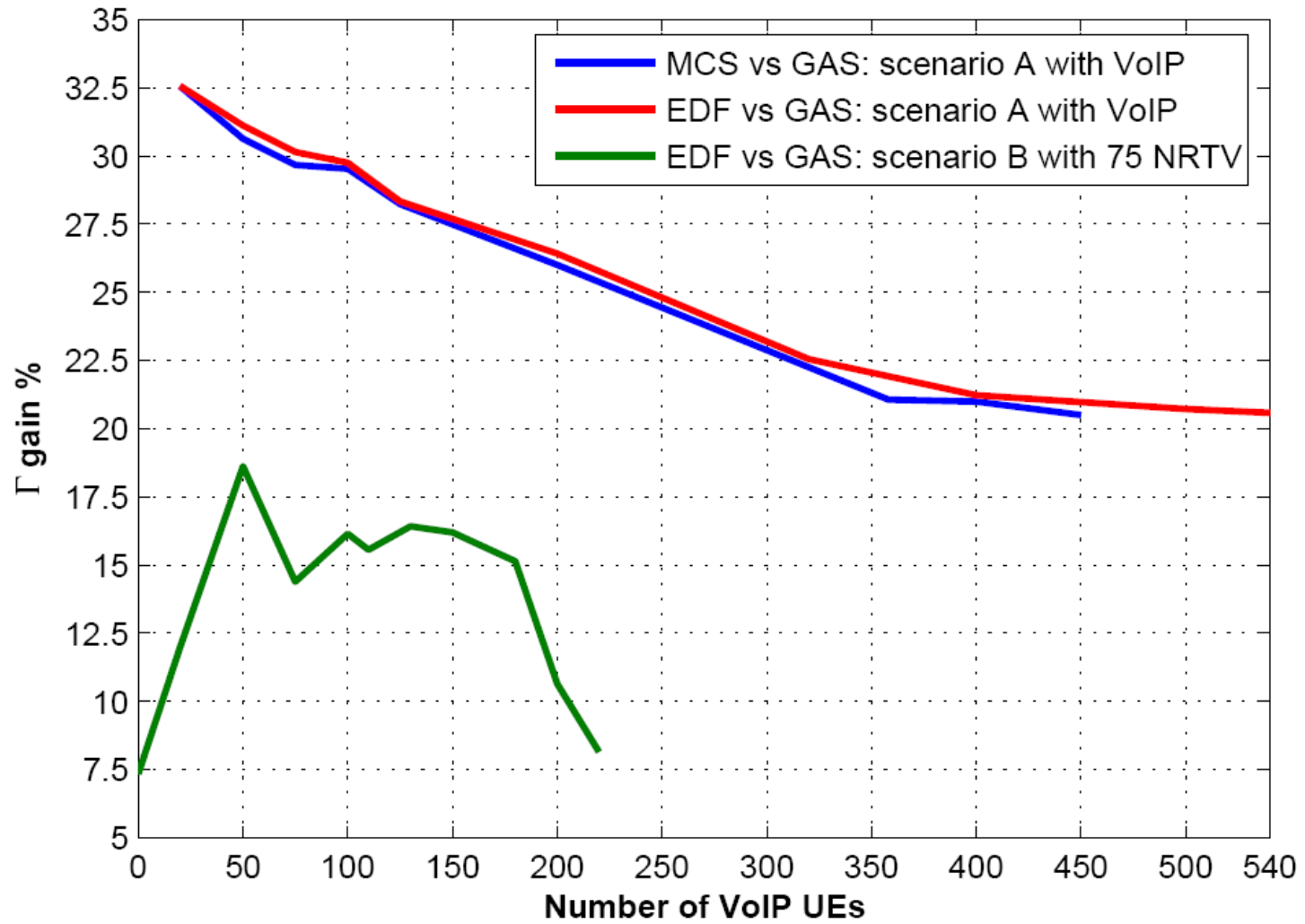


# Simulation Results: *Mixed traffic scenario (VoIP + NRTV)*

- Coexistence of VoIP and NRTV traffic in the same cell. NRTV users are fixed to 75 while VoIP users range from 0 to 220.



# A Flavor of the Energy Saving



# Conclusions on GAS algorithm

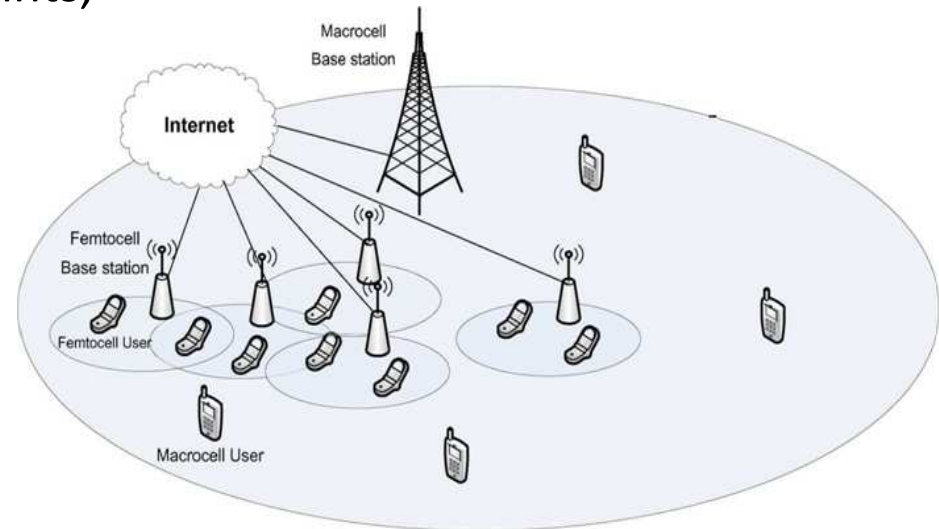
- SoTA RRM:
  - EDF never trades delay with EE
    - EDF never targets to trade delay with energy efficiency even in low load scenarios for which transmission of packets can be delayed or slowed down to save energy.
  - MCI never trades SE with EE
    - MCI never targets to trade spectral efficiency with energy efficiency even in low load scenarios for which system throughput does not need to be maximized to meet QoS of active UEs.
- GAS: *don't rush = don't waste!*
  - Classify packets: rushing/not rushing
  - Serve Rushing without EE
  - Serve Not Rushing with EE approach:
    - Packet transmission can be done at lower MCS than classically suggested by AMC:
      - lower spectral efficiency **but**
      - **lower transmission power too !!** → lower interference and lower power consumption
  - *Waste chunks to save Energy*: more chunks can be allocated for the transmission of the same packet for non urgent users.

**Result: up to 30% of energy saving**

# EE RRM for two-tier cellular networks: Ghost femto-cells

# Application context: Femtocell networks

□ Femtocell access points (FAPs) are **low-power** ( $\approx 20\text{mW}$ ) radio access points, providing wireless services to customers ( $\leq 5$ ) primarily in the **home environment**.



□ By using femtocells the aggregate **network capacity** could be greatly **increased** at a **fraction** of the macro-cellular **cost**.

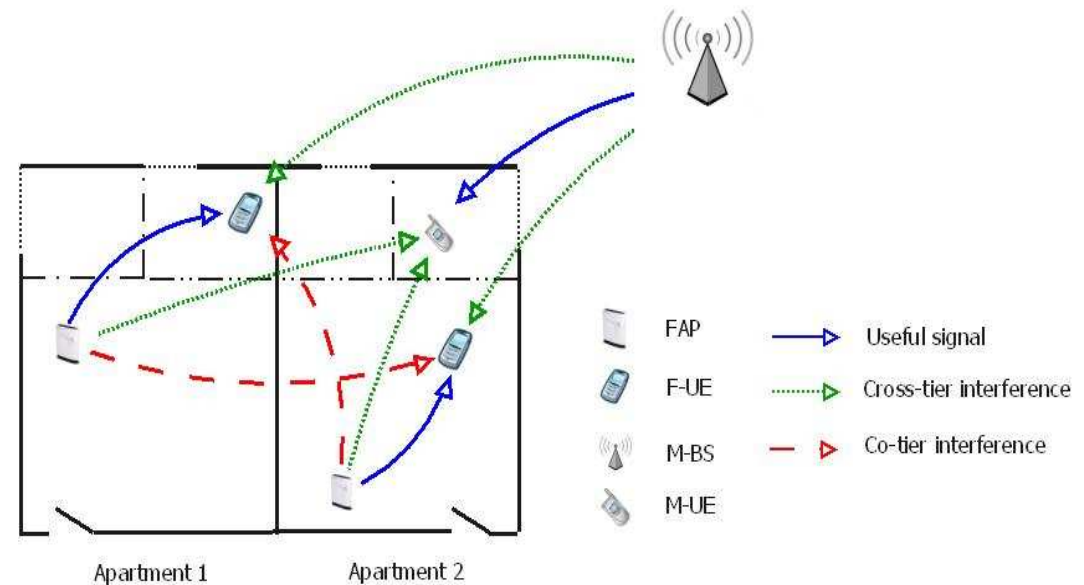
□ The management of radio **interferences** is a **key** concept to achieve this goal.

# Challenges of the femtocell networks deployment

Femtocells and macrocells will likely share the **same spectrum** in a given geographic area.

- **Cross-tier interference** may harmful **affect** both macro and femto **transmissions**
- Furthermore, **neighbour femtocells** may **interfere** with each other (**co-tier interference**)

• Finally, the aggregate wireless network **energy consumption** might be drastically increased by the **massive roll out of femtocells**



The downlink interference scenario in co-tier networks

# Ghost Femtocell: a new RRM paradigm

Three main considerations drive our investigation towards a **novel approach**:

- Femto-UEs can experience **high quality signal** due to the short range of communications
- **Few UEs** locally compete for a **large** amount of transmission (frequency /power) resources
- **Interference** is strongly mitigated by wall losses

## Profit from

- the **low ratio** between **required frequency/power** resources per femto user and the global **available** resources
- and **Cognitive underlay** techniques



## To make Femtocells

## Invisible

- Our Ghost Femtocells **limit interference** generated outside their coverage area by **reducing** the **transmission power** in each Resource Block.
- This scheme achieves **effective spectral reuse** between macro and femto cells, while **guaranteeing** end-users' QoS.

# Ghost Femtocell: the algorithm (1/2)

- Each femtocell overhears transmissions of neighbors cells and estimates which interferers may impact their transmission reliability
  - This information is provided to a local controller that manages the resources and decides on frequency reuse between neighbor cells
  - Our algorithm exploits techniques based on modulation and coding scaling to trade off transmission power and frequency resource.
- 
- It reduces the downlink transmission power
  - It meets target Rate constraints
  - It decreases the overall generated interference

# Ghost Femtocell: the algorithm (2/2)

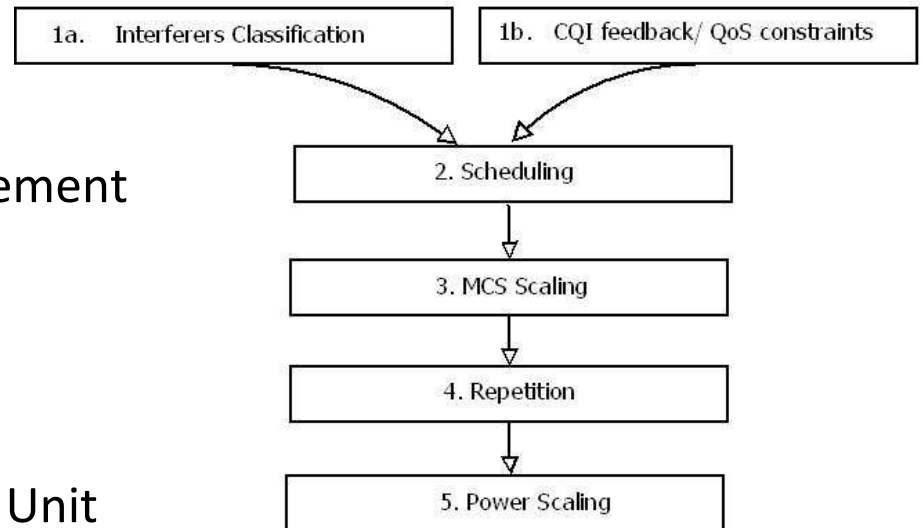
- Each femtocell estimates strong interferers FAPs

(Step 1a.)

- Users feedback to their FAP CQI measurement and QoS constraints (Step 1b.)

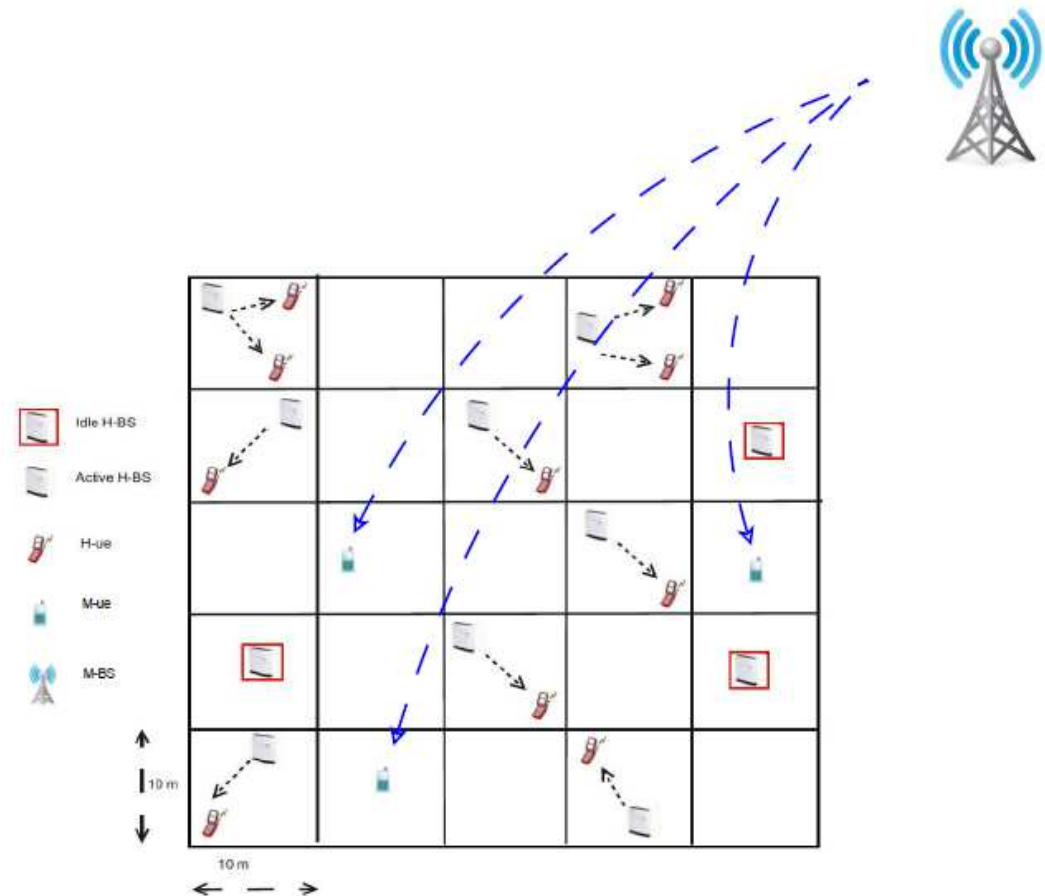
- This information is reported to a Central Unit that manages the access of neighbor femto-UEs and decide the spectrum reuse between femtocells (Step2)

- We apply techniques based on MCS scaling to tradeoff transmission energy for frequency resource (Step 3, 4, and 5 )

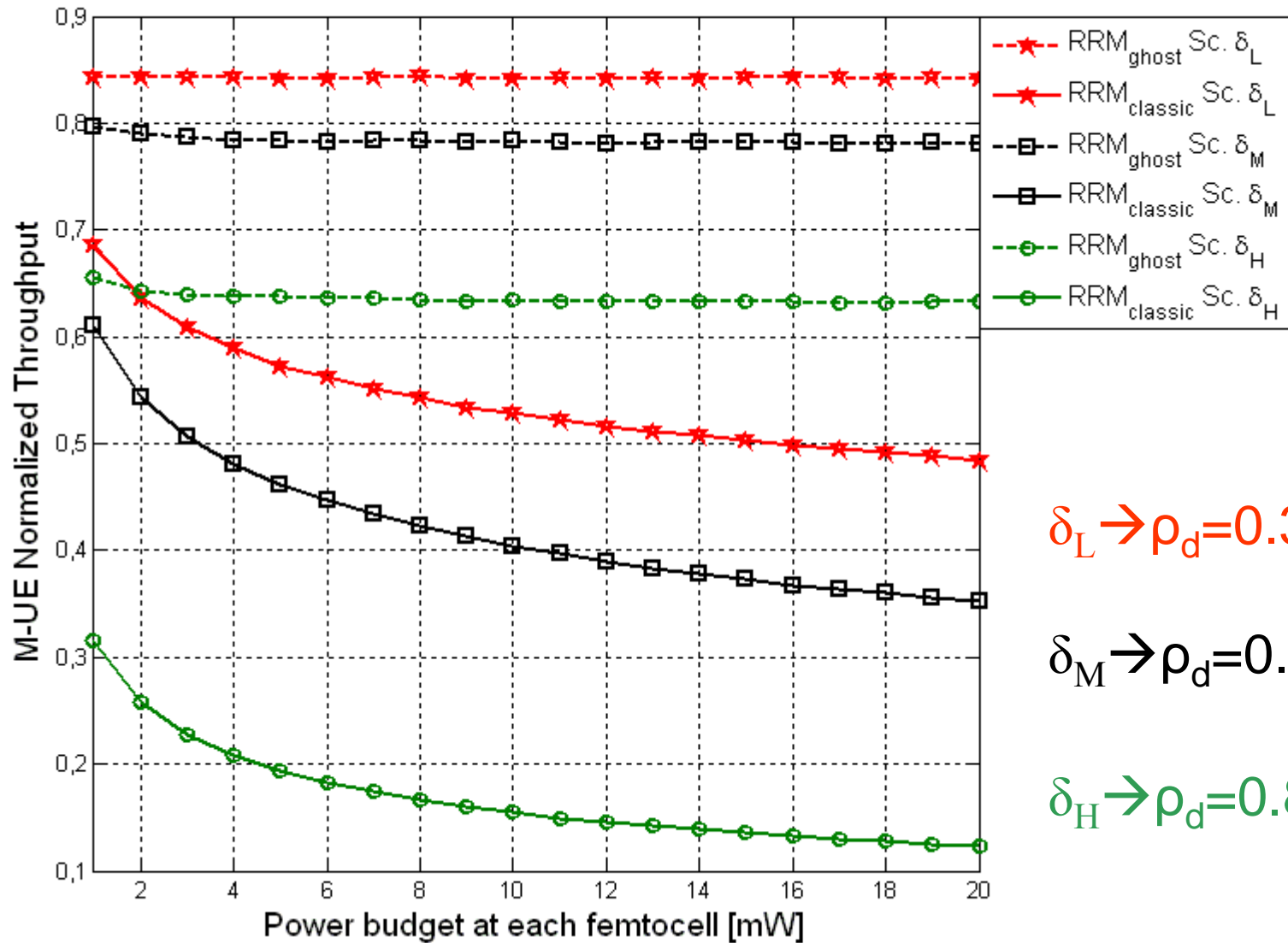


# The 3GPP Femtocells grid urban deployment model

- 10 m x 10 m apartments are placed into a 5x5 grid
- Deployment ratio  $\rho_d$
- Activation ratio  $\rho_a$
- X users/ femto
- Outdoor wall attenuation (20 dB)
- 5 dB of loss due to walls within the grid of apartments
- Loss to walls inside each apartment are modelled as a loglinear value equal to 0.7 dB/m



# Simulation Results: M-UE throughput

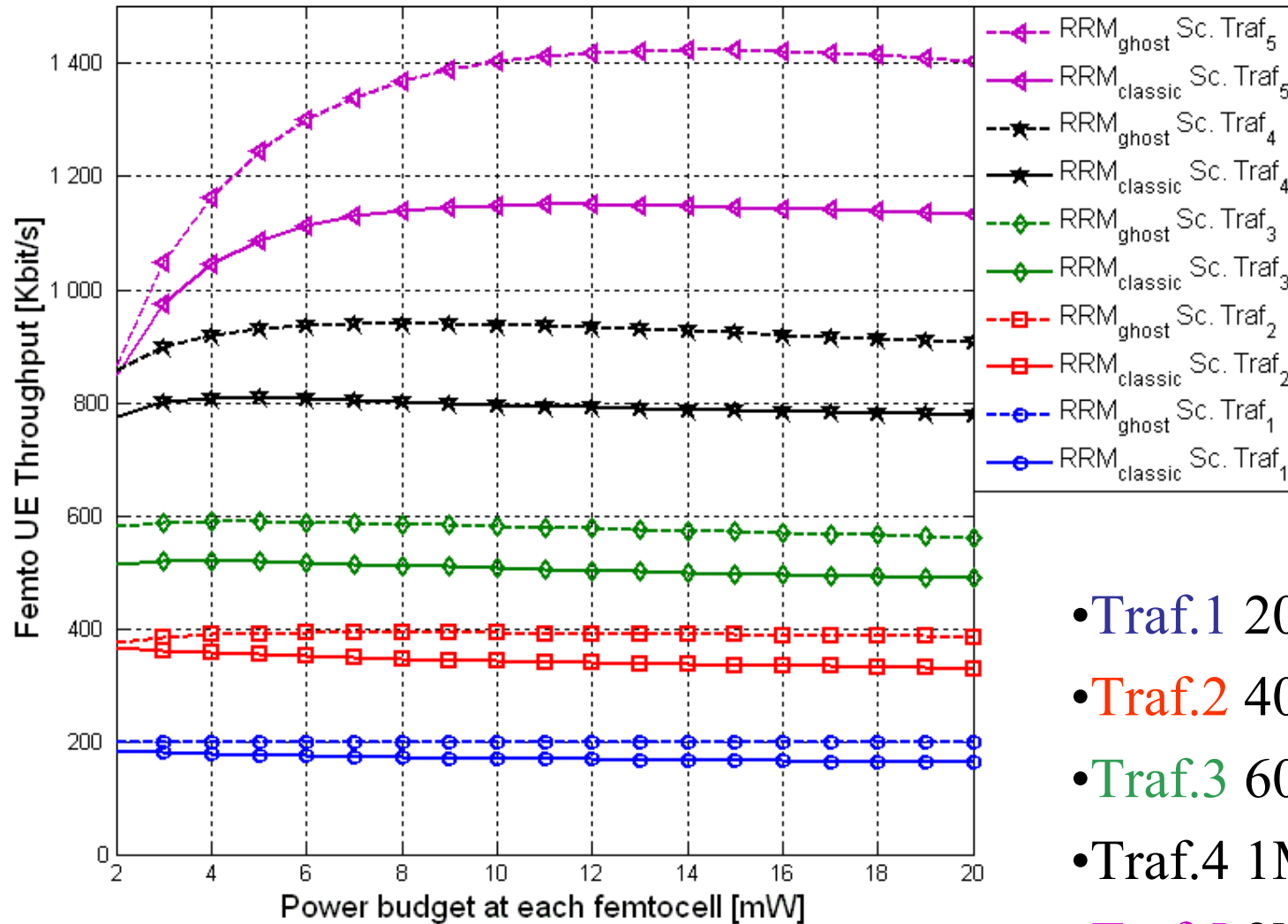


$\delta_L \rightarrow \rho_d = 0.3$

$\delta_M \rightarrow \rho_d = 0.5$

$\delta_H \rightarrow \rho_d = 0.8$

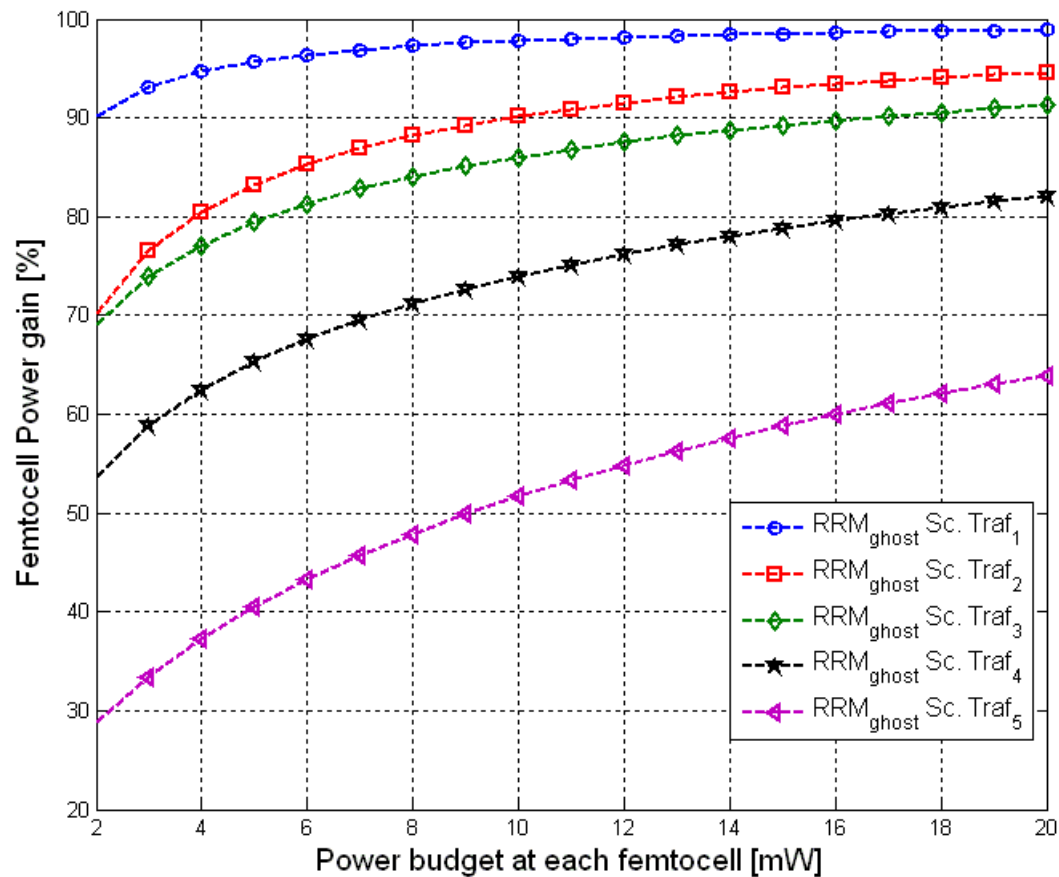
# Simulation Results: F-UE throughput



- Traf.1 200Kbit/s
- Traf.2 400Kbit/s
- Traf.3 600Kbit/s
- Traf.4 1Mbit/s
- Traf.5 2Mbit/s

# Simulation Results: H-UE power gain

$$P_{\text{Gain}} = (P_T - P_{\text{Ghost}}) / P_T$$



- Traf.1 200Kbit/s
- Traf.2 400Kbit/s
- Traf.3 600Kbit/s
- Traf.4 1Mbit/s
- Traf.5 2Mbit/s

# Conclusion on ghost femto cells

- Simulation results show how the proposed scheme:
  - Limits the undesired effect of **interference**
- And profiting of channel and interference diversity
  - Improves the femto cells **Effective Spectral Efficiency**
  - Enhances the femto cells **coverage**
  - To optimize the **allocated power** in order to optimally meet QoS target while reducing interference and **improving the system energy consumption**

# Conclusion and outlook

- Significant energy savings in cellular networks can be expected by:
  - Defining and standardizing EE metrics;
  - Combining energy aware flexible radios and networks;
  - Exploiting time, spatial and load variation of communication context;
  - Limit interference
  
- EE mobile networks are a key component for a sustainable growth

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# Thanks for your attention



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