Holistic Approach for Future Energy Efficient Cellular Networks

Dr. Emilio Calvanese Strinati

CEA-LETI, France

Assistant Director, Strategic Telecommunications Program

emilio.calvanese-strinati@cea.fr

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 CO_2 emissions
  - comparable to the world-wide CO_2 emissions by airplanes or ¼ of the world-wide CO_2 emissions by cars

- **The transmitted data volume increases approximately by a factor of 10 every 5 years**

The Issue (2/3)

- **ICT: 10% of electrical energy in industrialized nations**
  - 900 Bill.. kWh / year = Central and South Americas
- **Power consumption of ICT is currently rising at 16-20% / year**
- **Wireless communications are used extensively to save energy in other industrial sectors.**

The Issue (2/2)

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

EE & Mobile networks

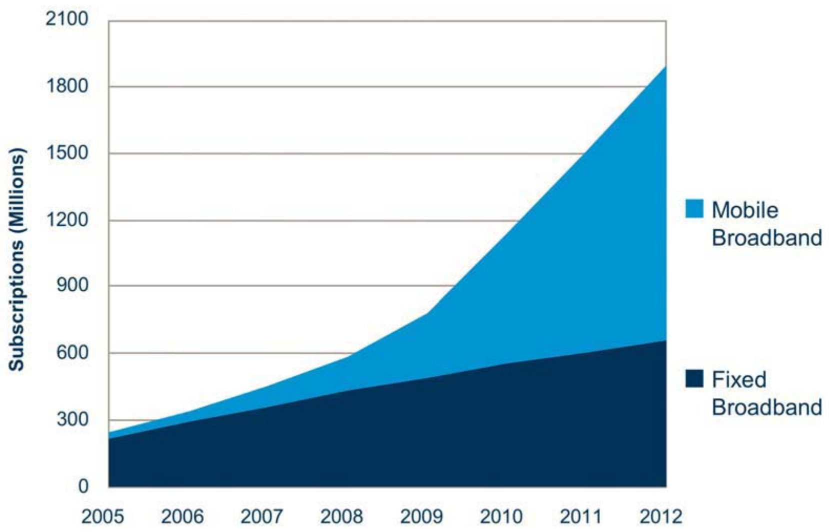
- **So far, mobile networks design rules have ignored EE**
  - Cellular networks have been optimized in terms of spectral efficiency, capacity or throughput, not really in terms of Energy Efficiency!
  - EE consideration mainly for UE (battery issues)
  - EE considered only for high load scenarios
-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

➔ **Green challenges**

EE & Mobile networks

- **Mobile operators are already today among the top energy consumers**
  - Telecom Italia (fixed & mobile) is the 2nd largest energy consumer in Italy

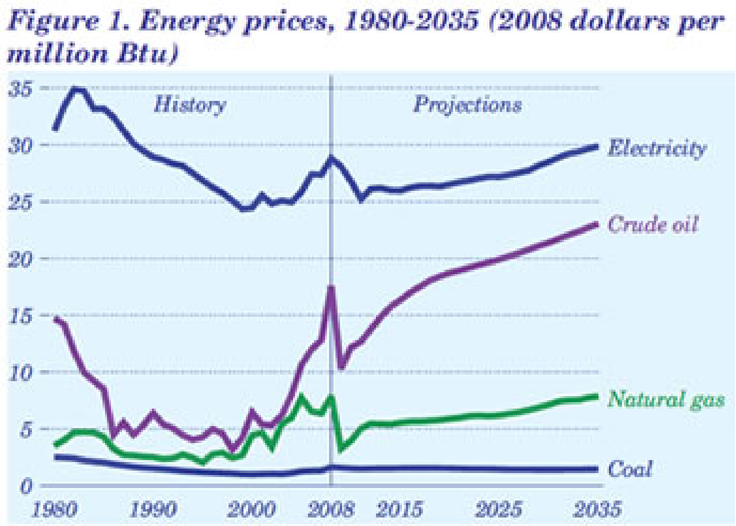
- **Energy consumption of Mobile Networks is growing much faster than ICT on the whole**
  - Rapid traffic growth and build-up of broadband coverage
  - Mobile replacing fixed in many areas
  - Enabling ICT services for energy saving in other sectors (teleconferencing,...) further increases mobile networks growth

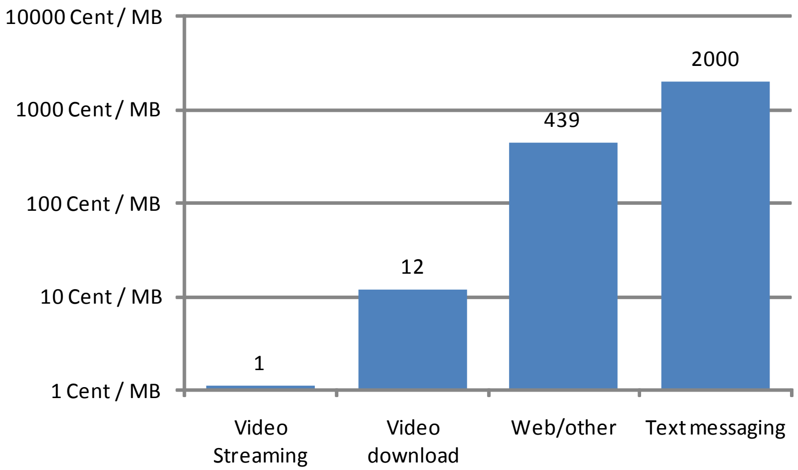


Source: OVUM, Strategy Analytics & Internal Ericsson

Annual growth rate of internet traffic is 85%.

Economic Impact for Providers

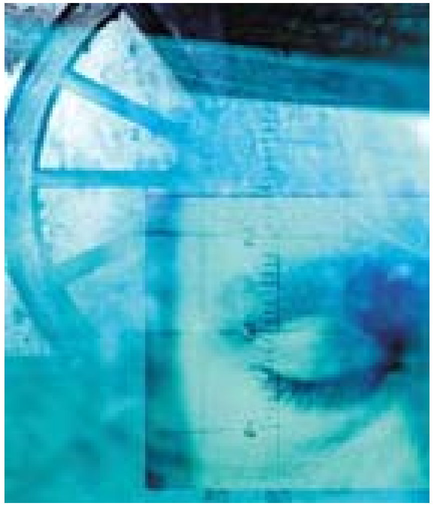




- Energy price forecast (US DoE EIA, 2009)
- Steady growth is projected worldwide
- Energy OPEX problems for mobile providers are becoming even more pressing! (especially for off-grid sites)
- data traffic volume is growing, but...
- revenue varies with service type

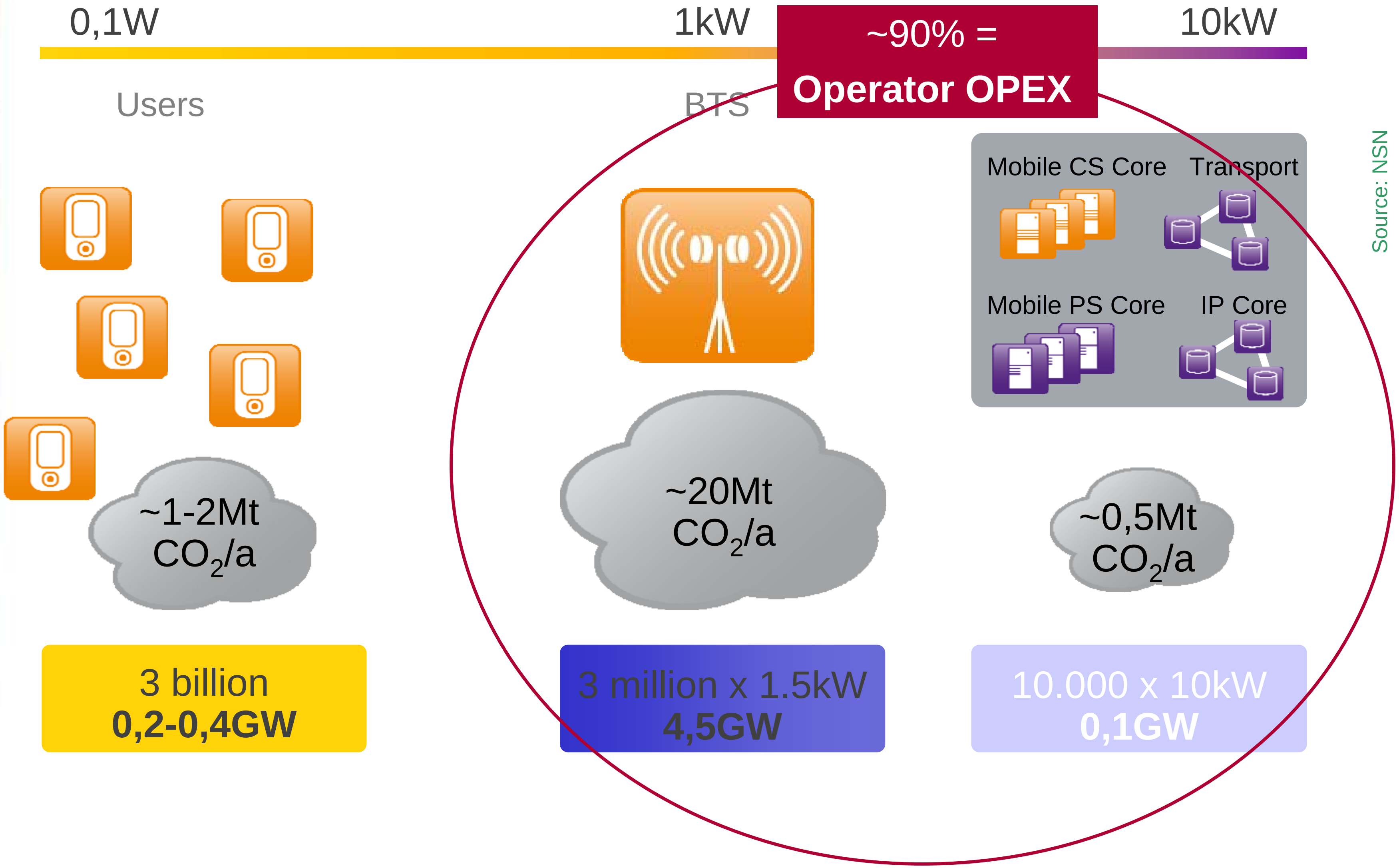
Mobile networks

- **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.



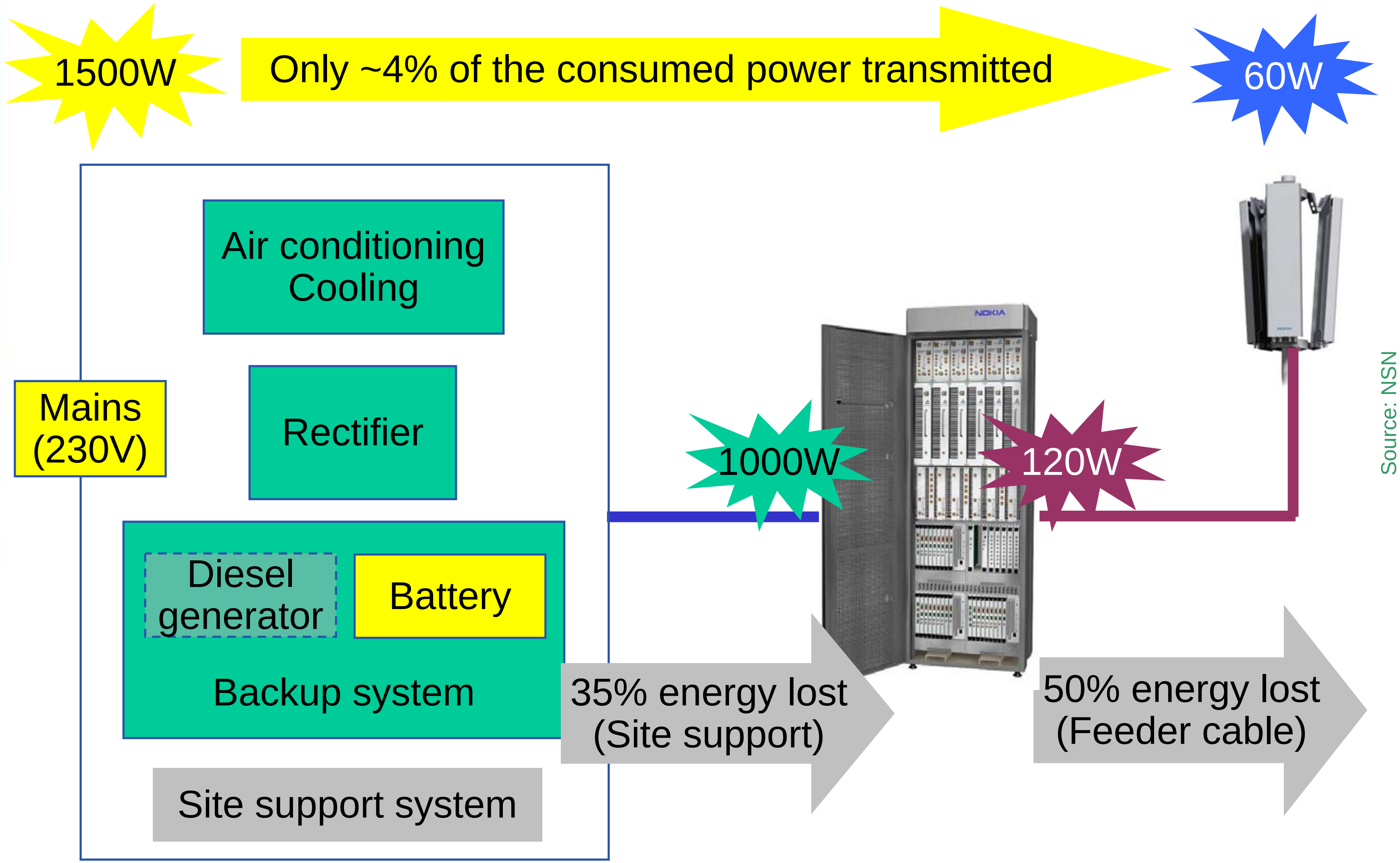
- **Energy savings should be considered primarily at the network level**
  - NTT DOCOMO have calculated that, for their 52 million subscribers in 2006, the energy consumption of their network per mobile user per day was **120 times greater** than the daily energy consumption of a typical user's mobile phone.

Power consumption of cellular networks



Source: NSN

Power consumption of a traditional cellular site



Power consumption of a modern cellular site

500W

~12% of the consumed power transmitted

60W

Mains (230V)

Rectifier

Backup system

Site support system

430W

120W

14% energy lost (Site support)

50% energy lost (Feeder cable)

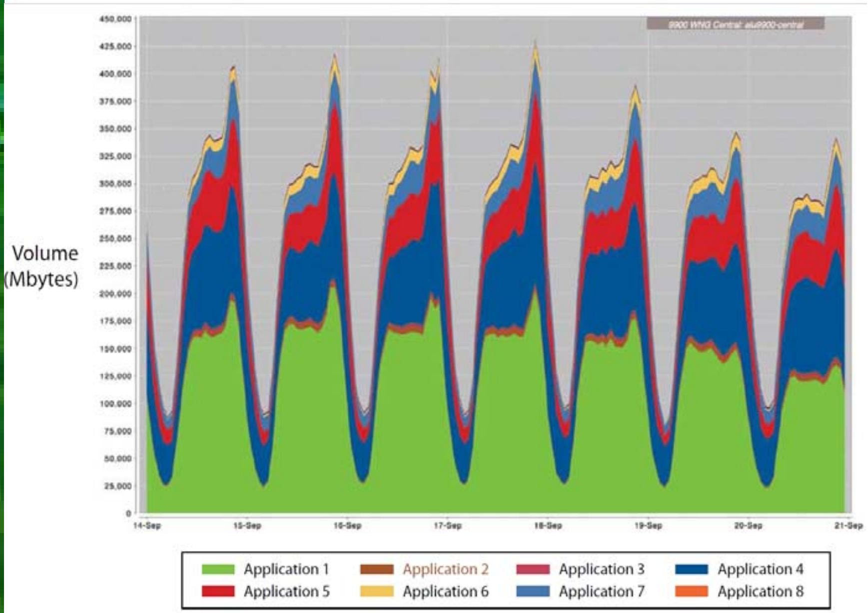
Objectives

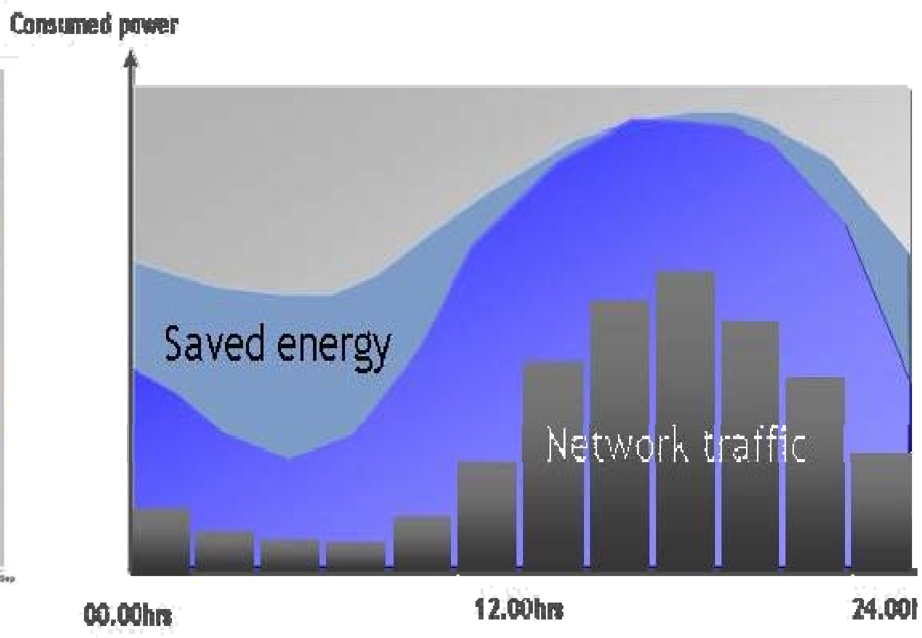
Make ICT ecologically and economically sustainable for all sectors of society.

- 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

Energy saving

- **Reducing base power consumption to make energy consumption proportional to traffic load**
  - dynamically according to traffic demand at specific cell site
  - during night and in low-load conditions (which are most commonly experienced in most base stations)





Source: Alcatel-Lucent 9900 Wireless Network Guardian, Technology White Paper, 2008

Methodology

Holistic approach

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

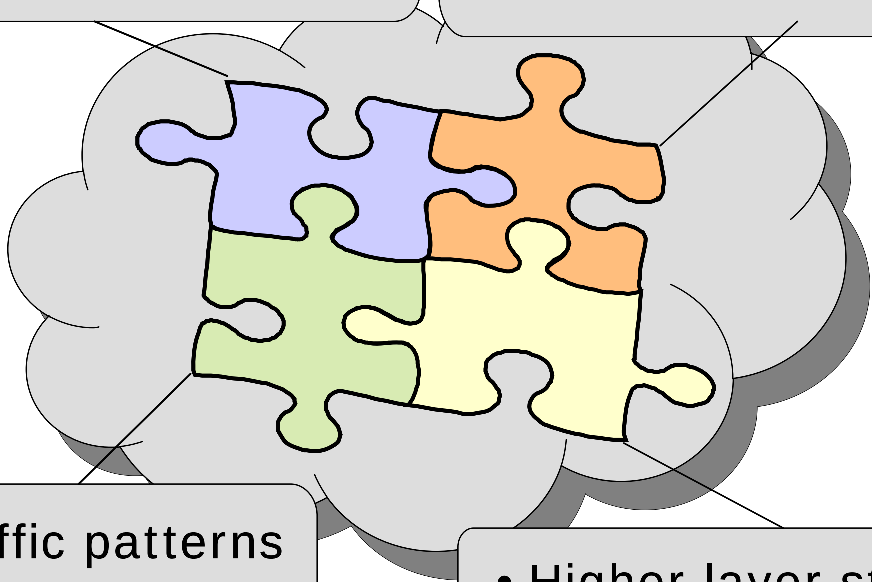
EE mobile networks require an holistic approach

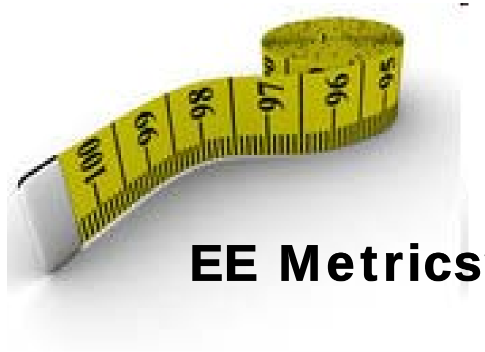
Innovation should range from semiconductor technology to radios and networks

- Deployment strategies
- Cooperation schemes

- PHY layer parameters
- Transceiver architectures & components

Reference scenarios





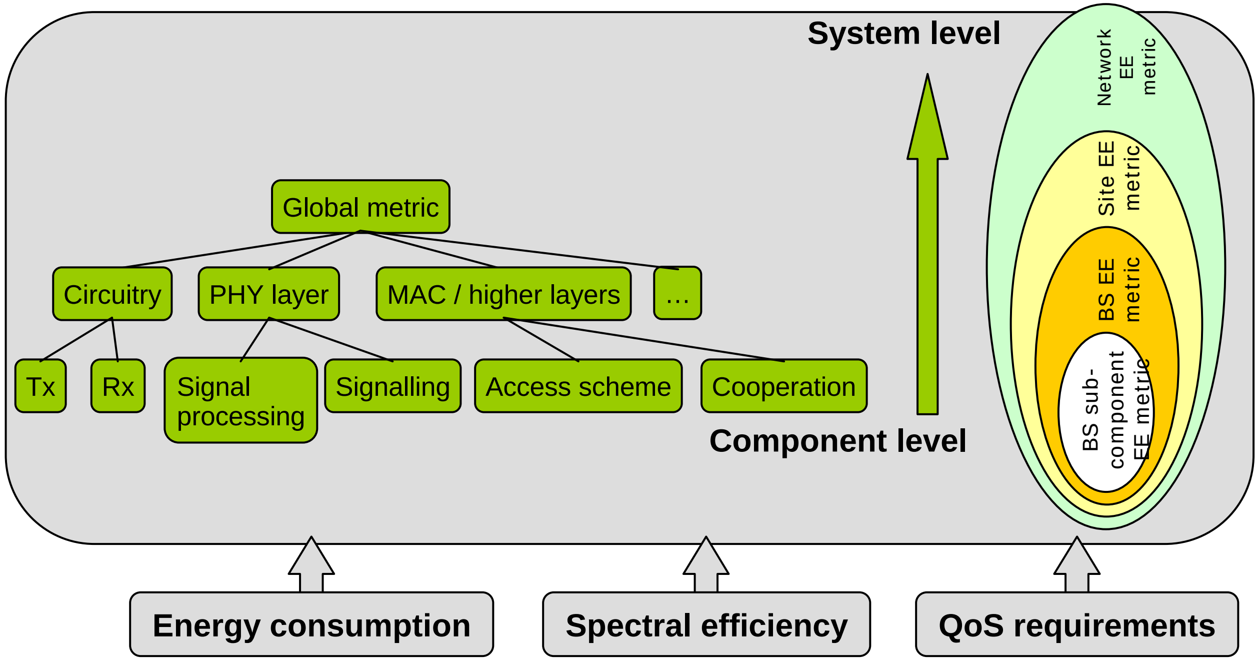
EE Metrics?

- Traffic patterns
- User densities

- Higher layer strategies

EE Metrics

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



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. with lower consumption

- Tune performances at run time to the required flexibility & reconfigurability

- Avoid losses in the chain

  ➔ best match between amplifiers and the antenna

RF requirements of high end terminals: **against an energy consumption decrease**

- Support multiple-standards
  - Various bandwidths / data rates / frequency bands
    - ➔ High reconfigurability is necessary
- Keep a high level of performance
  - Interference management in a crowded spectrum
  - Complexity of the front-end
    - ➔ use of bank of filters to select the bands
    - ➔ over-specifications to fit with multiple standards

One solution lies in more digital process

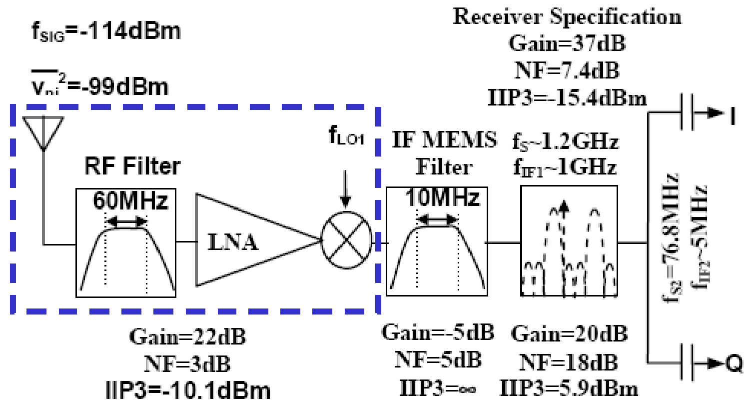
Innovations in RF front-end architectures

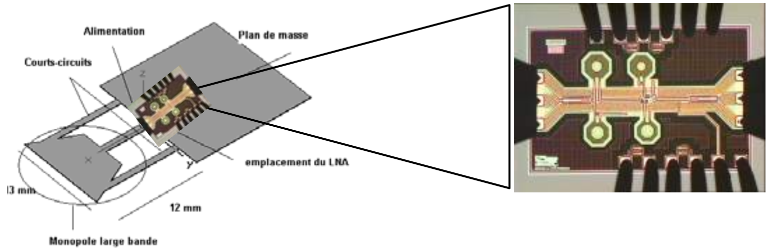
- **Design flexible architectures with new components**
  - ➔MEMS to have better perf. (filtering) with lower consumption

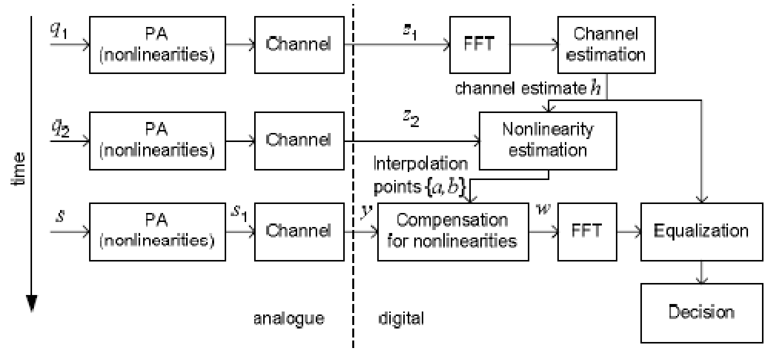
- **Tune performances at run time to the required flexibility & reconfigurability**

- **Co-design of PAs and LNAs**
  - Better performance (BW a gain) for a given current
  - Lower current for given performance

- **Avoid losses in the chain**
  - ➔ Best matching between amplifiers and the antenna
  - ➔ Use of PA in their non linear domain + predistorsion techniques & digital compensation (Tx or **Rx**)







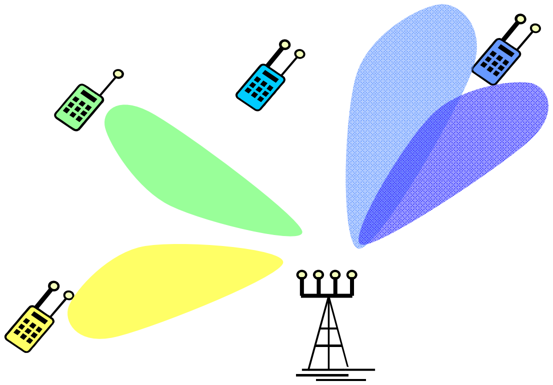
Innovations in digital BB architectures

- **Multi-User MIMO**

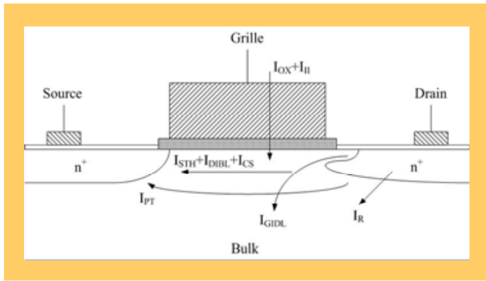
- **Manage multiple standards in the terminal**
  - ➔ Complex & dense digital partitioned NoC (network on chip / multi-cores)
  - ➔ Use of DFVS in GALS systems, i.e. Tuning of local power supply units & clock generators

- **Run full frequency only when required**

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



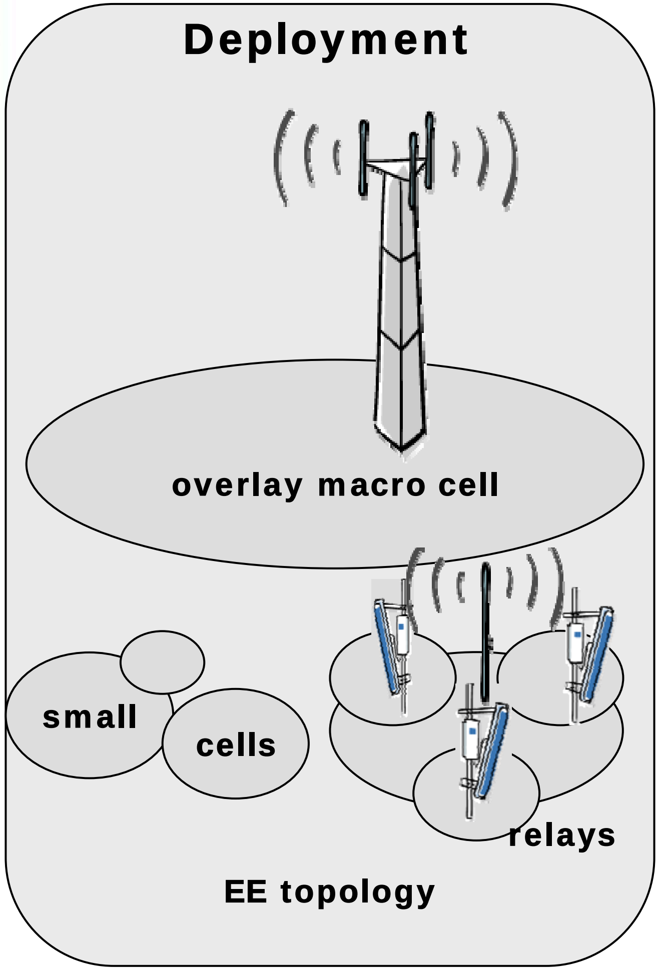
- Spatial dimensions assigned to **several** users.
- Separation of users by TDMA, FDMA **and** SDMA.



Innovations in digital BB architectures

- Multi-User MIMO
- Manage multiple standards in the transceivers
  - ➔ complex & dense digital partitioned NoC (network on chip)
- Run full frequency only when required
- Master leakages

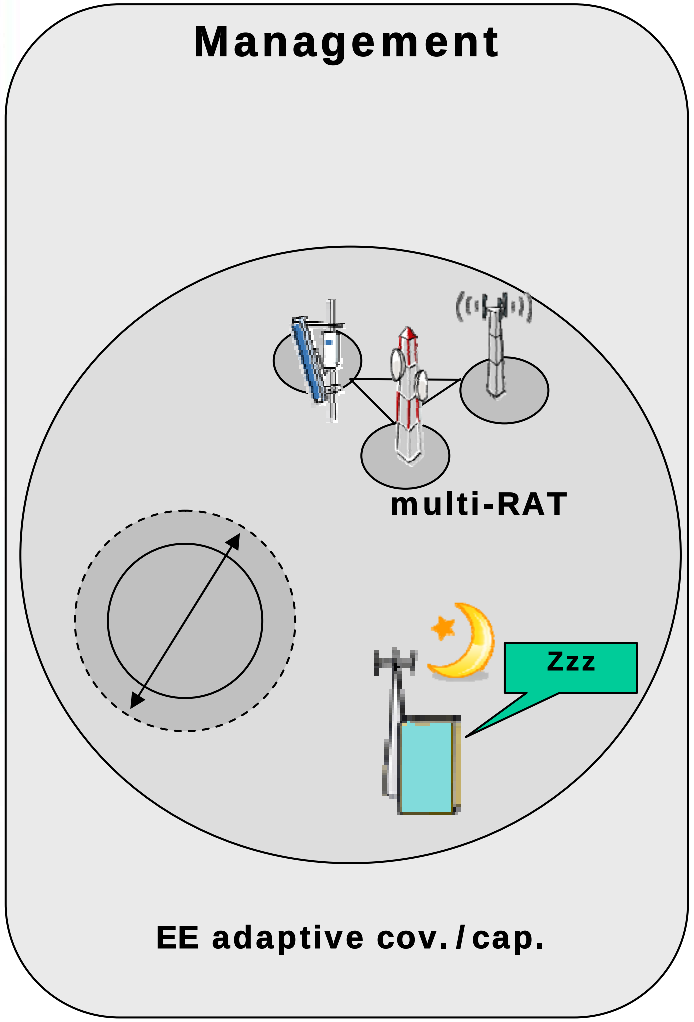
Towards Green Networks (1/4)



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
  - hierarchical deployments
  - multi-RAT deployments
  - relays & repeaters

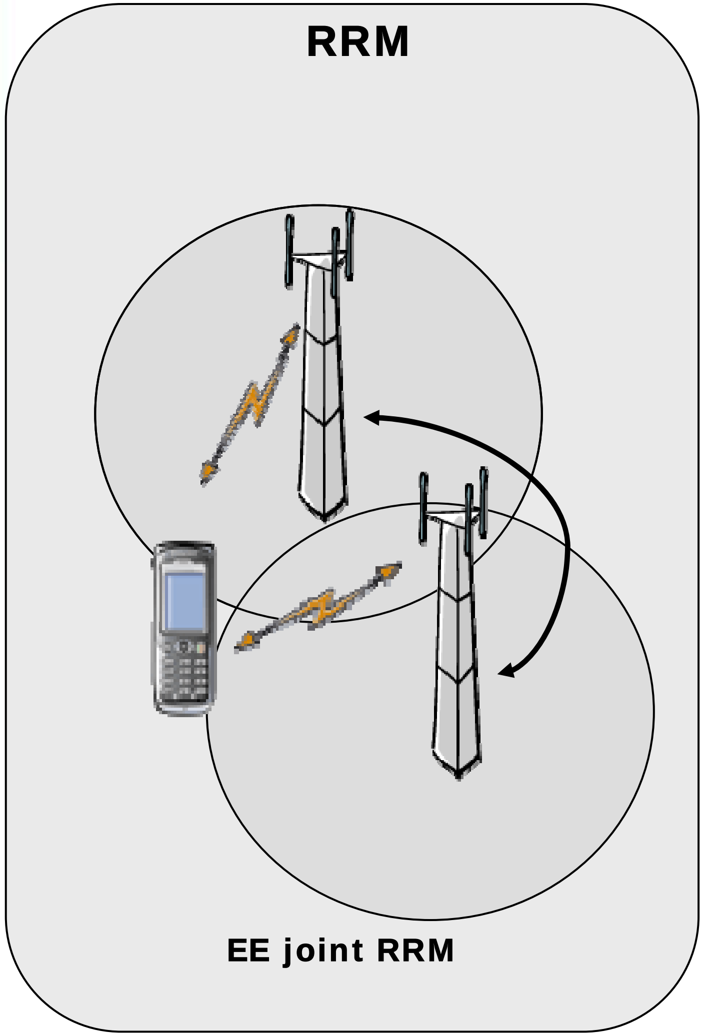
Towards Green Networks (2/4)



■ Management algorithms:

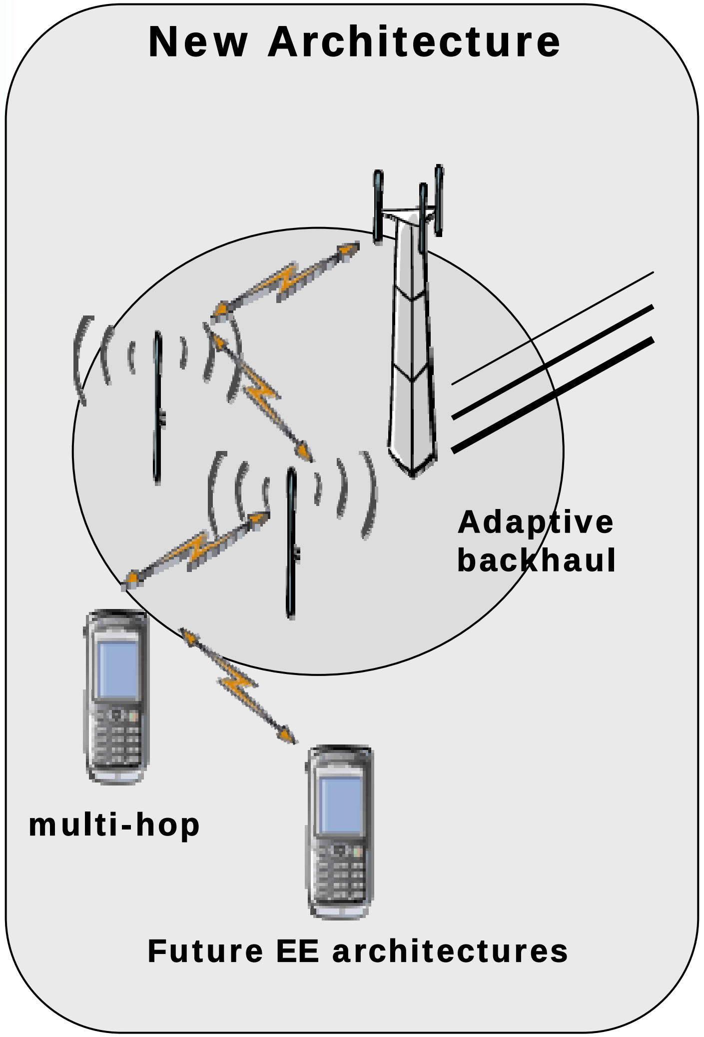
- coverage adjustment
- capacity management
- multi-RAT coordination
- base station sleep mode
- protocol design

Towards Green Networks (3/4)



- **RRM algorithms:**
  - cooperative scheduling
  - interference coordination
  - joint power allocation and resource allocation
  - EE vs. spectral efficiency

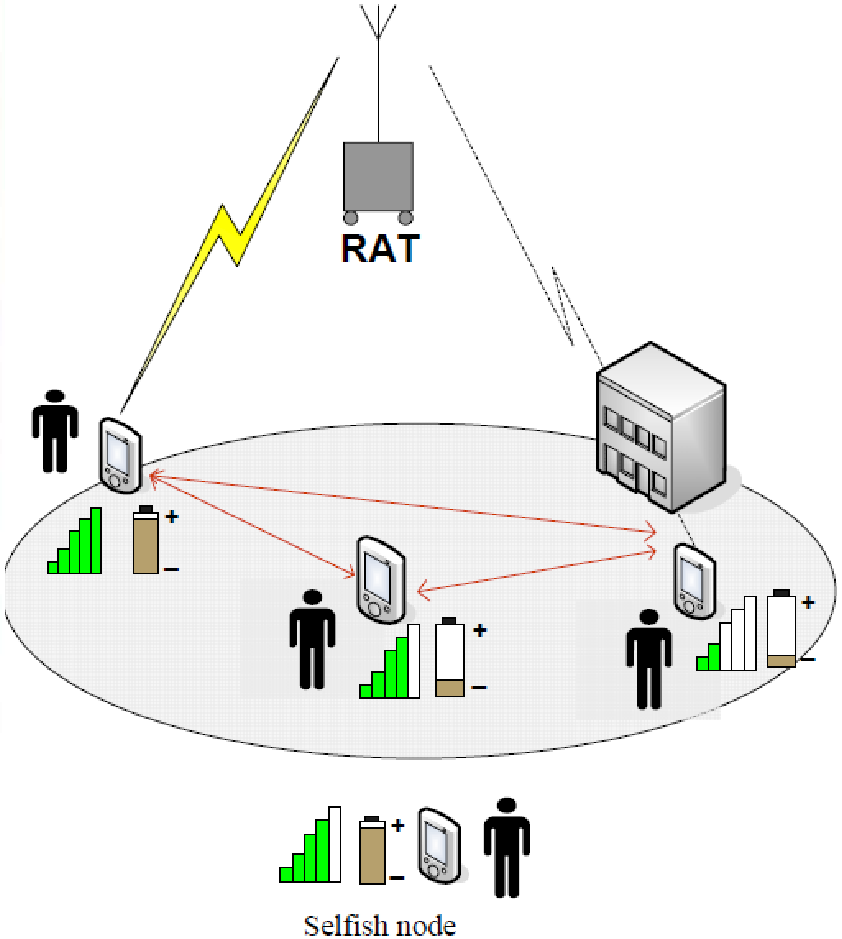
Towards Green Networks (4/4)



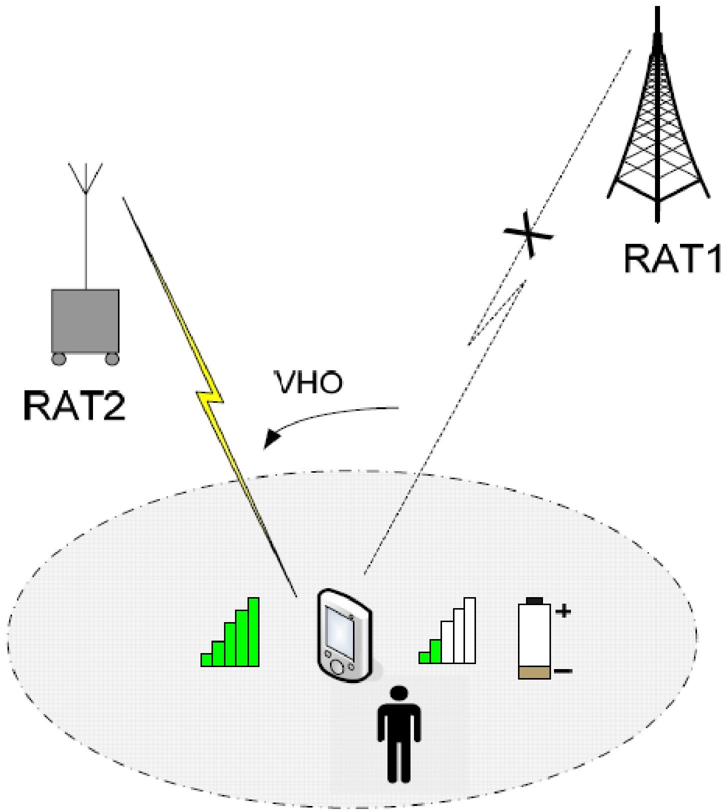
- **Disruptive approaches:**
  - multi-hop transmission
  - ad-hoc networks
  - terminal-terminal-transmission
  - cooperative multipoint arch.
  - EE adaptive backhauling
  - cognitive/opportunistic radios & networks

Some disruptive power saving strategies

- Use of cognitive radios and networks

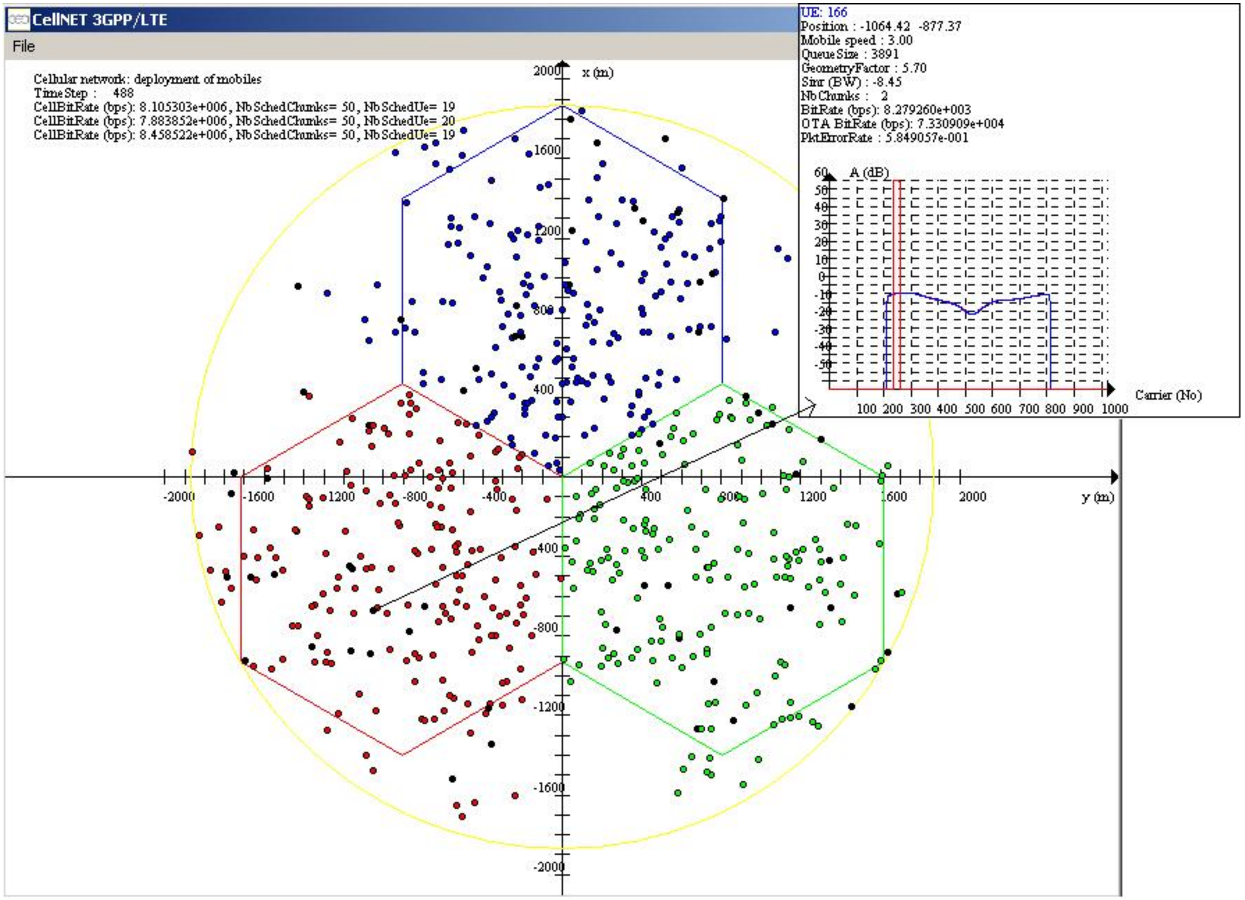


short range cooperative clusters in homogeneous networks



exploiting heterogeneous RATs

System level simulations



- Green metrics
- Evaluation of green algorithms & protocols

EARTH Project

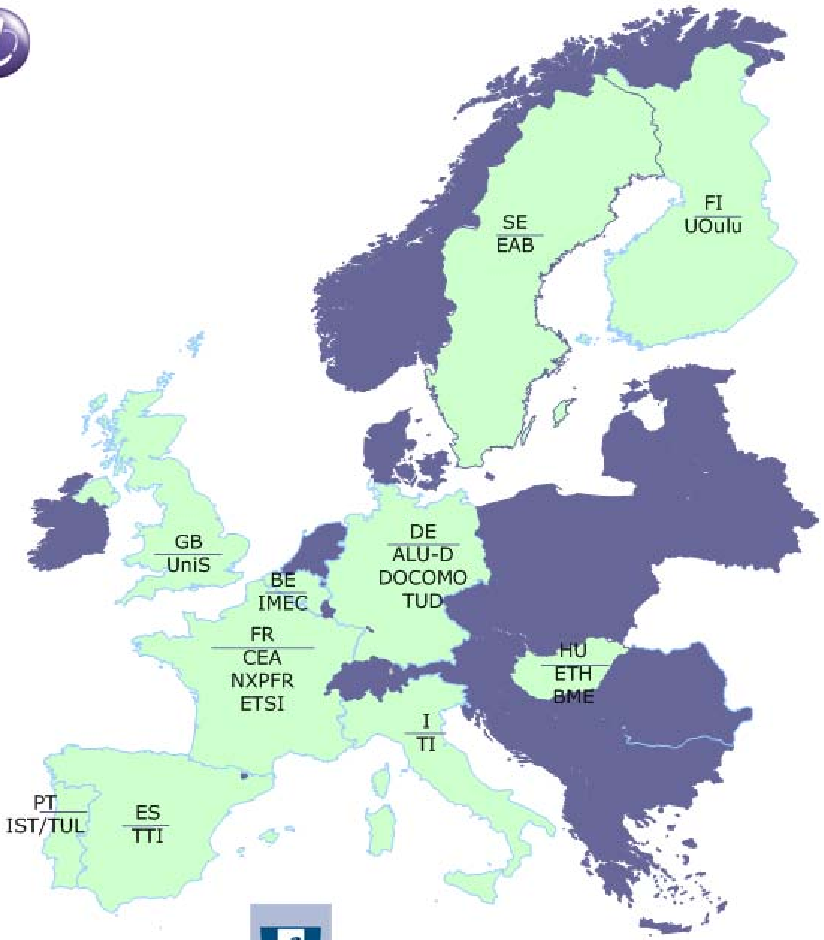
- **A structuring European initiative has started in 2010**

earth

Energy Aware Radio and neTwork tecHnologies

- **Web site:** **https://www.ict-earth.eu/**

EARTH Consortium



Industrials, Operators
ALUD, EAB, DOCOMO, TI, NXPFR,ETH

Research centre
CEA, IMEC

Higher education
UNIS, TUD, UOulu, BME, IST/TUL

SME
TTI

Other
ETSI

What's about Green RRM in OFDMA Systems?

Specific Challenges of RRM for DL OFDMA

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

SoTA Scheduling Algorithms in OFDMA

- We have investigated EE performance of two commonly adopted packet schedulers: Maximum Carrier over Interference (MCI) and Earliest Deadline First (EDF):
- **MCI**: Its goal is to maximize the instantaneous system throughput regardless to any traffic QoS constraints. Even if maximum system throughput can be achieved with MCI, users whose momentary channels are not good for a relatively long period may starve and consequently release their connections. MCI is indeed inadequate for real-time traffic. Moreover, **MCI never targets to trade spectral efficiency with energy efficiency even in low load scenarios for which system throughput do not need to be maximized to meet QoS of active UEs**.

- **EDF**: It allocates resources first to packets with smaller remaining TTLs. With OFDMA based transmission, allocation is decoupled: each packet is prioritized according to its remaining TTL (RTTL) and then chunks are allocated to the ordered packets in order to maximize spectral efficiency. The drawback of this scheduler is that multiuser diversity is not exploited since any momentary channel state information is taken into account in the scheduling rule. **EDF never targets to trade spectral efficiency with energy efficiency even in low load scenarios for which transmission of packets can be delayed or slowed down to save energy.**

System Model (LTE-like)

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.

Parameter	Value
Network	
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	
Fast fading	Typical urban 6-tap model, 3 km/h
Interference	White
UE	
Channel estimation	ideal
CQI reporting	ideal or partial
Turbo decoder	max Log-MAP (8 iterations)
Dynamic Resource Allocation	
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	
Stop and Wait	synchronous adaptive
Number of processes	6
Retransmission Interval	6 ms
Maximum Nb of retransmissions	up to 3
Combining technique	Chase

EE Metric for Downlink OFDMA

- Future wireless 4G cellular networks like LTE have chosen OFDMA as their downlink air interface

- **Observation**: In OFDMA, at each time slot (TTI), downlink power allocated to each chunk can be different (even on/off if only part of chunks are used at a given TTI).

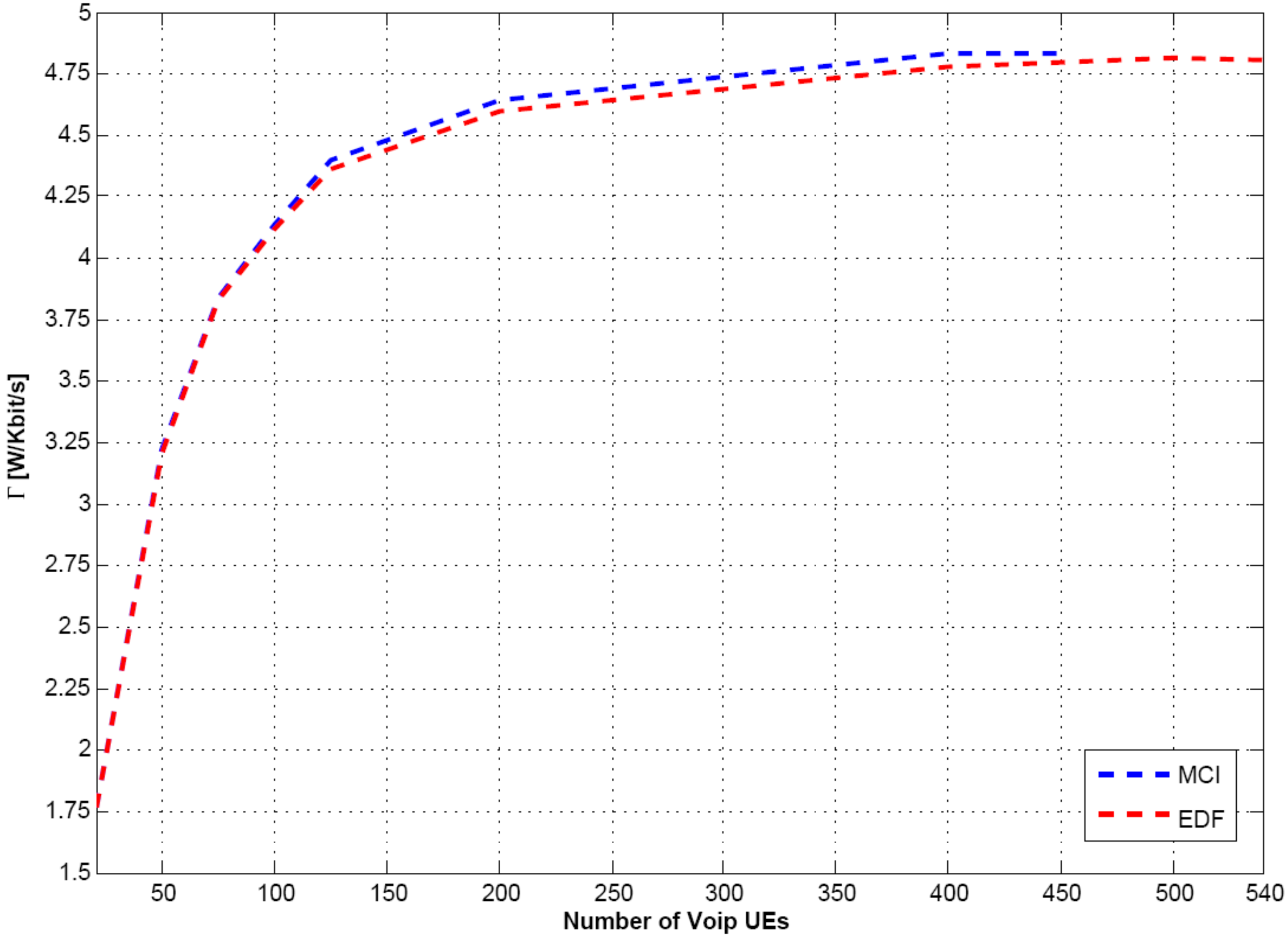
Adopted EE Metric for Downlink OFDMA

- Adopted power efficiency metric:

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

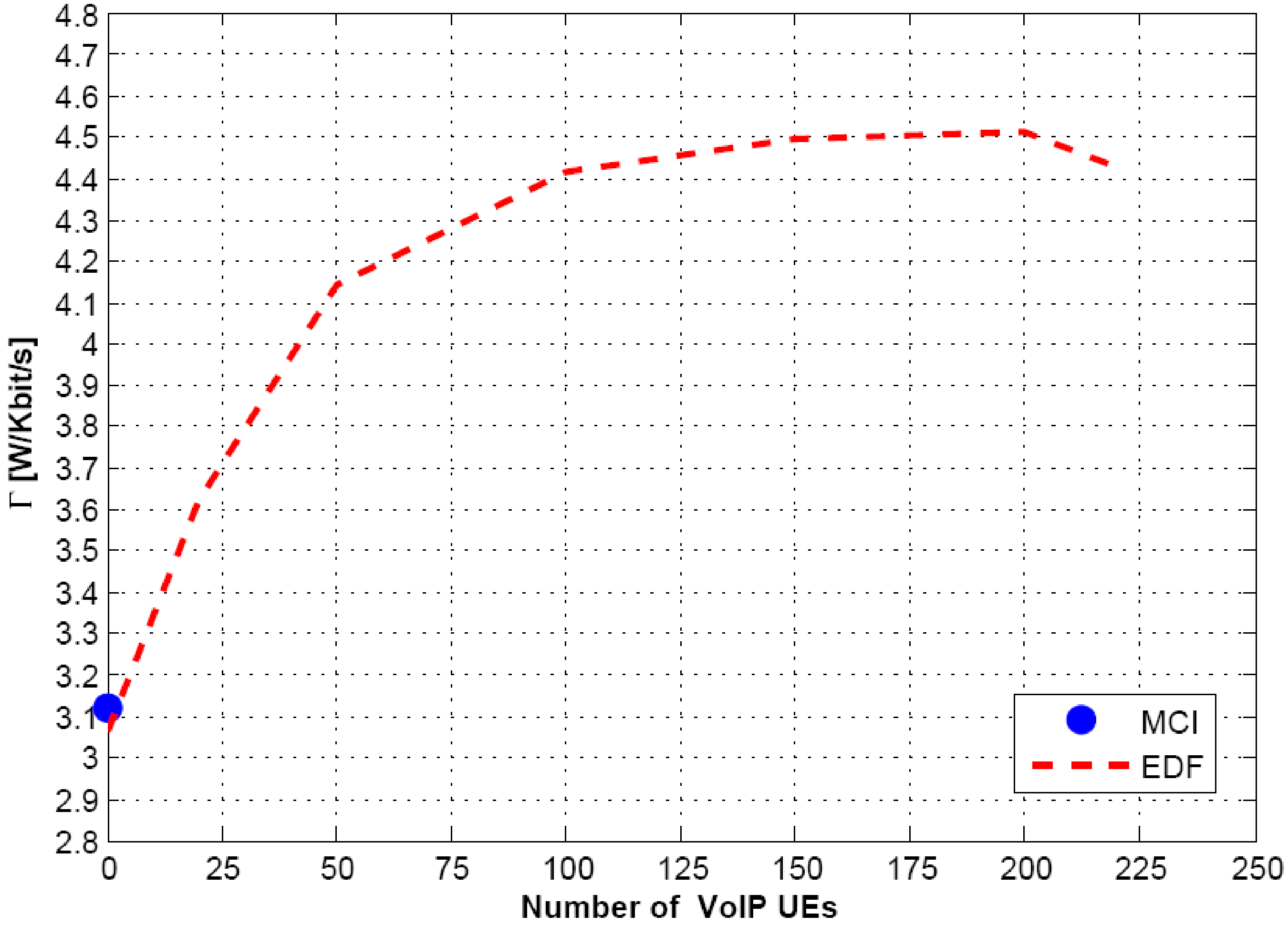
Where at TTI i, K_i^{UE}, $Nb_{i,j}^{chk}$, $Pow_{i,j}^{dl}$ and $\rho_{i,j}$ are respectively the number of active UEs, number of chunk allocated to user *j*, the downlink power for transmission on each chunk and the throughput of user *j*

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



Simulation Results: ***Mixed traffic*** scenario

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



Remarks on SoTA Scheduling

- Traditional packet scheduling algorithms are designed to increase the maximum system capacity, subject to QoS constraints and fairness.
- Nevertheless, most of the time, wireless systems are only moderately loaded.
- With SoTA priority scheduling algorithms, the exploitation of available time and frequency resources is typically not optimized from an energy perspective.

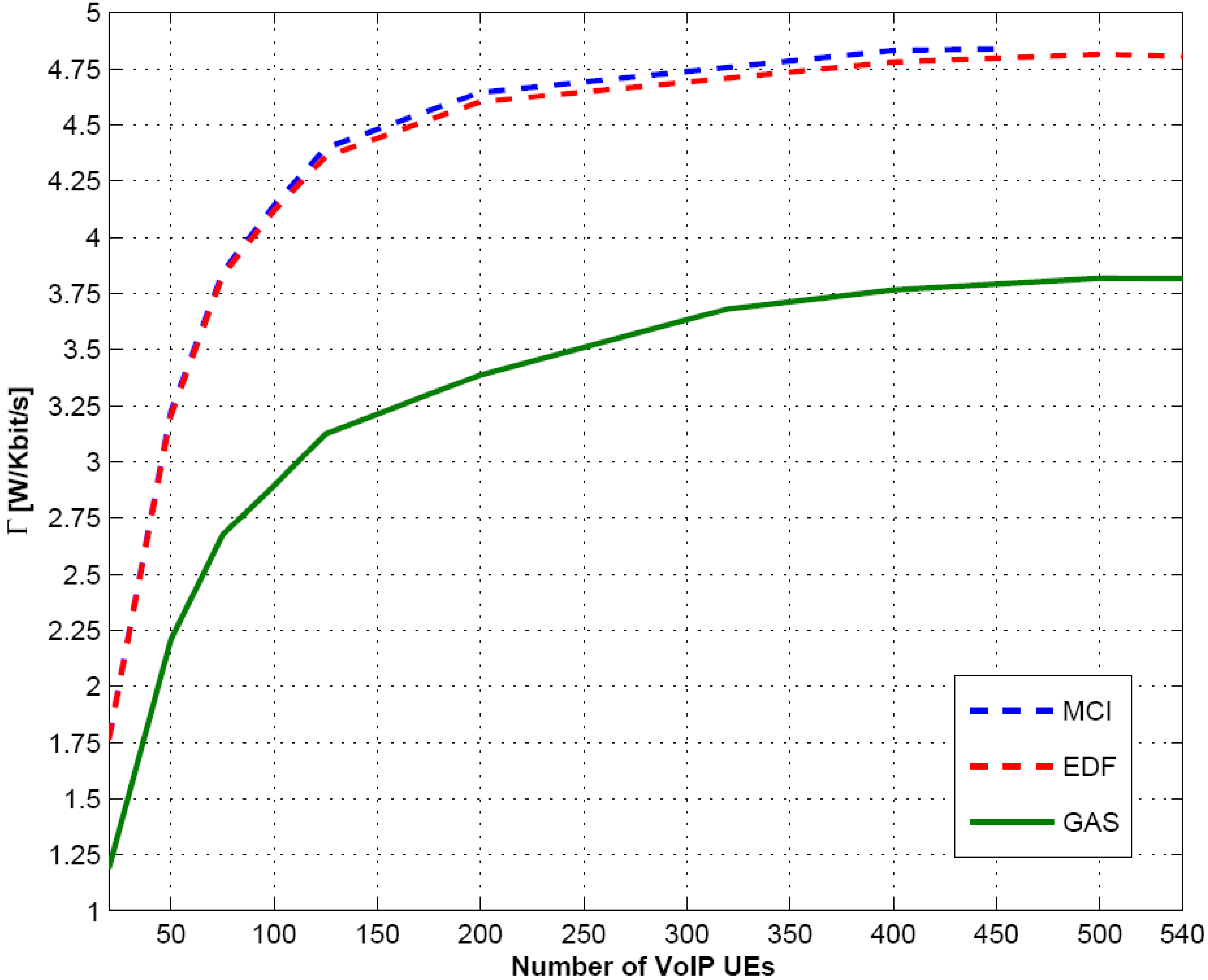
- **EDF-like** schedulers do not profit much from time diversity as much as they should do.
- **MCI-like** schedulers aim at maximizing the cell throughput regardless of the user QoS and the actual system load, and consequently they are totally insensitive to any time constraints of the data traffic.

Green Allocation Scheduler (**G**AS)

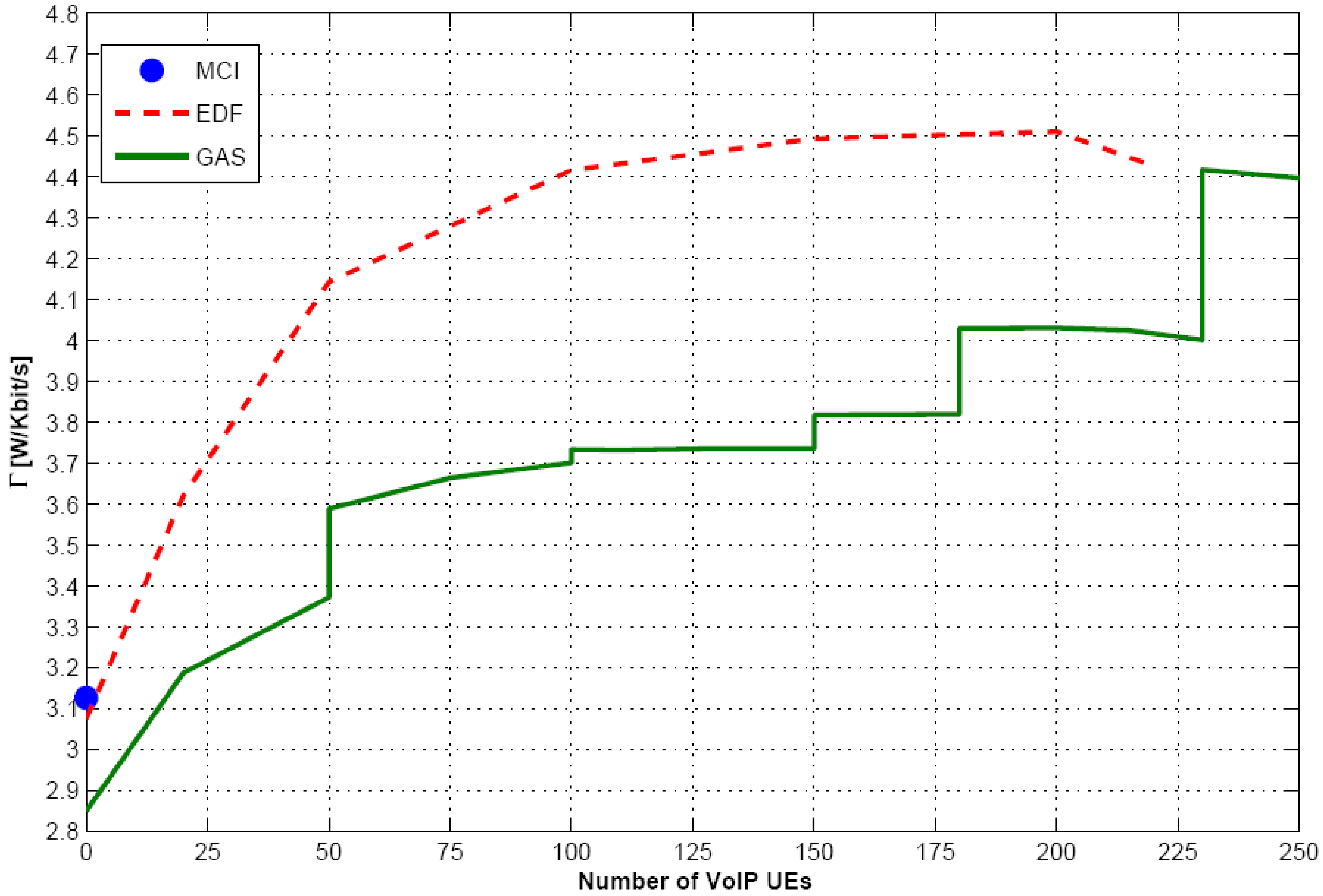
Scope: design an energy efficient scheduling algorithms which meets the QoS constraint of an heterogeneous population of UEs

Observation: In not saturated system load scenarios, the exploitation of available time and frequency resources is typically not optimized from a energy perspective.

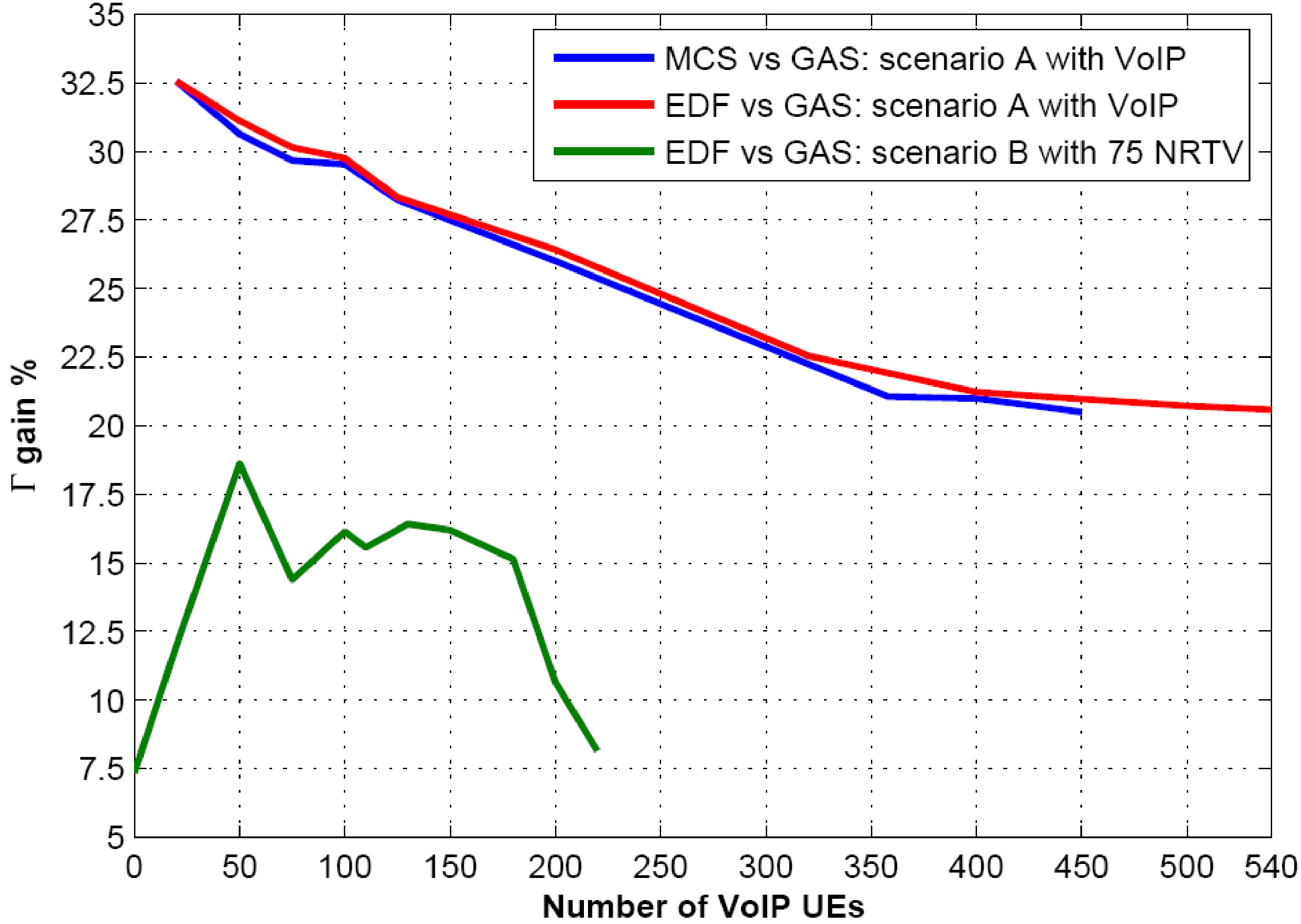
Simulation Results: ***single traffic*** scenario (VoIP)



Simulation Results: ***Mixed traffic*** scenario



A Flavor of the Energy Saving

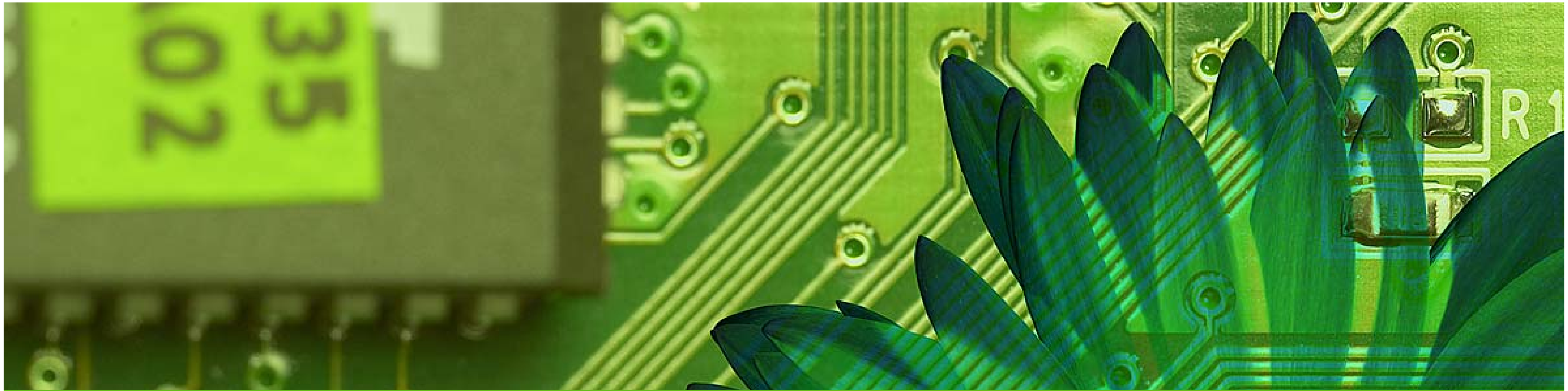


Conclusions

- **Significant energy savings in mobile networks can be expected**
  - by defining and standardizing EE metrics, and
  - combining energy aware flexible radios and networks

- SoTA RRM:
  - EDF does not profit from multi-user diversity
  - MCI targets at maximizing the cell throughput regardless of the user's QoS constraints even in low load scenarios for which spectral efficiency can be trade with energy efficiency

- Proposal: **G**AS
  - It splits the resource allocation process in several steps, reducing the downlink power when the system is not fully loaded
  - it improves the scheduling energy efficiency in OFDMA based wireless cellular networks
  - it is a highly flexible and effective scheduler for a variety of traffic scenarios and it drives to notable energy cost reductions while meeting the QoS of UEs active admitted in the system.



Thank you

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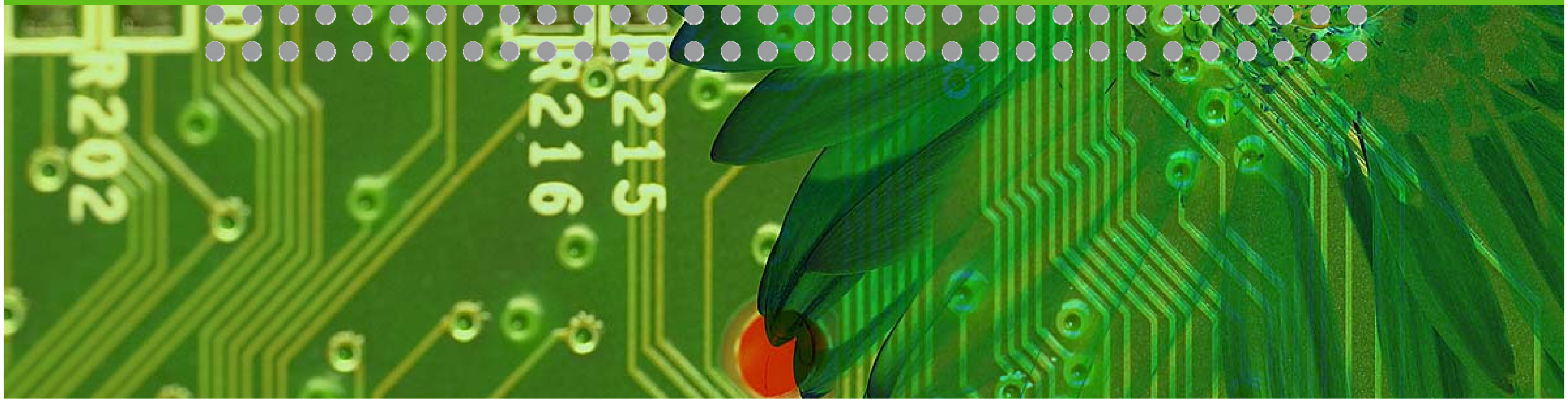

Motivation

- Up to now innovation has targeted to improve wireless networks coverage and capacity while meeting the QoS for users admitted in the system
- Nowadays, the number of mobile subscribers equals more than half the global population
- Forecast of increase of subscrivers and consequent roll out of additional base stations for next generation mobile networks

Motivation

- Undesired Consequence: growth of wireless network's energy consumption
  - increase of the global carbon dioxide ($CO2$) emissions
  - impose more and more challenging operational cost for operators
- Communication energy efficiency represent indeed an alarming bottleneck in the telecommunication growth paradigm.

Holistic Approach

- EE enhancement in wireless communication can be achieved only if improvements are experienced in the whole communication chain for different operational load scenarios.