Spectrum and Energy Efficient Heterogeneous Wireless Networks

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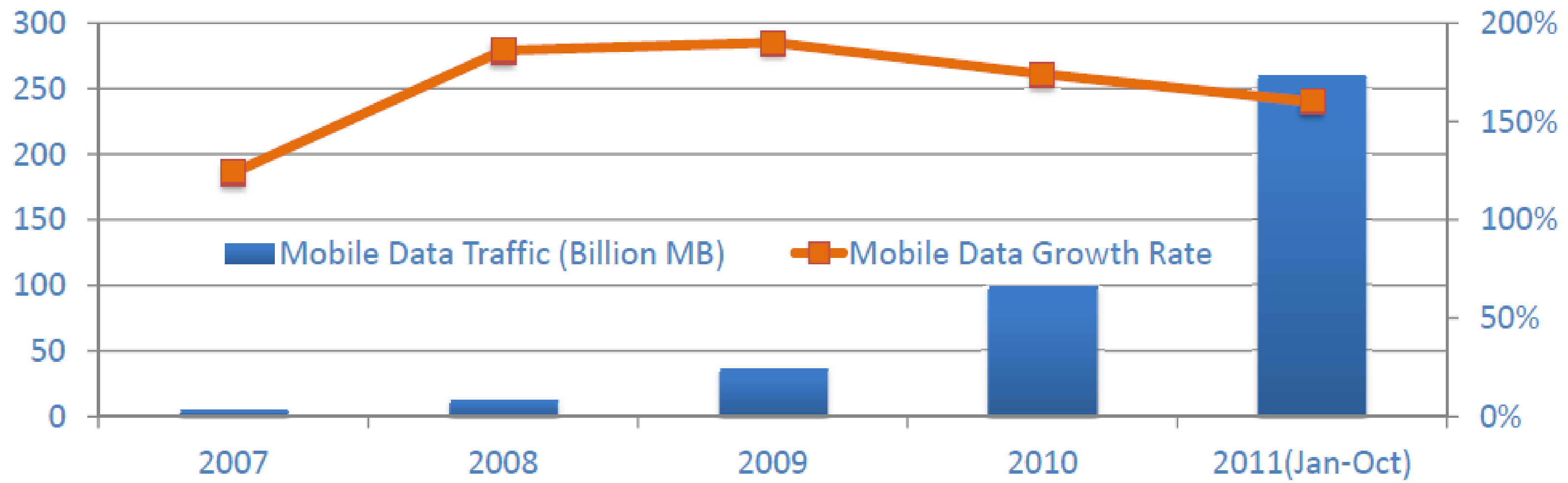
Outline

- Introduction and Background Review
- Spectrum Efficiency in HetNets
- Energy Efficiency in HetNets
- Technical Challenges in HetNets
- HetNet in LTE Rel 12
- Conclusion

Introduction and Background Review

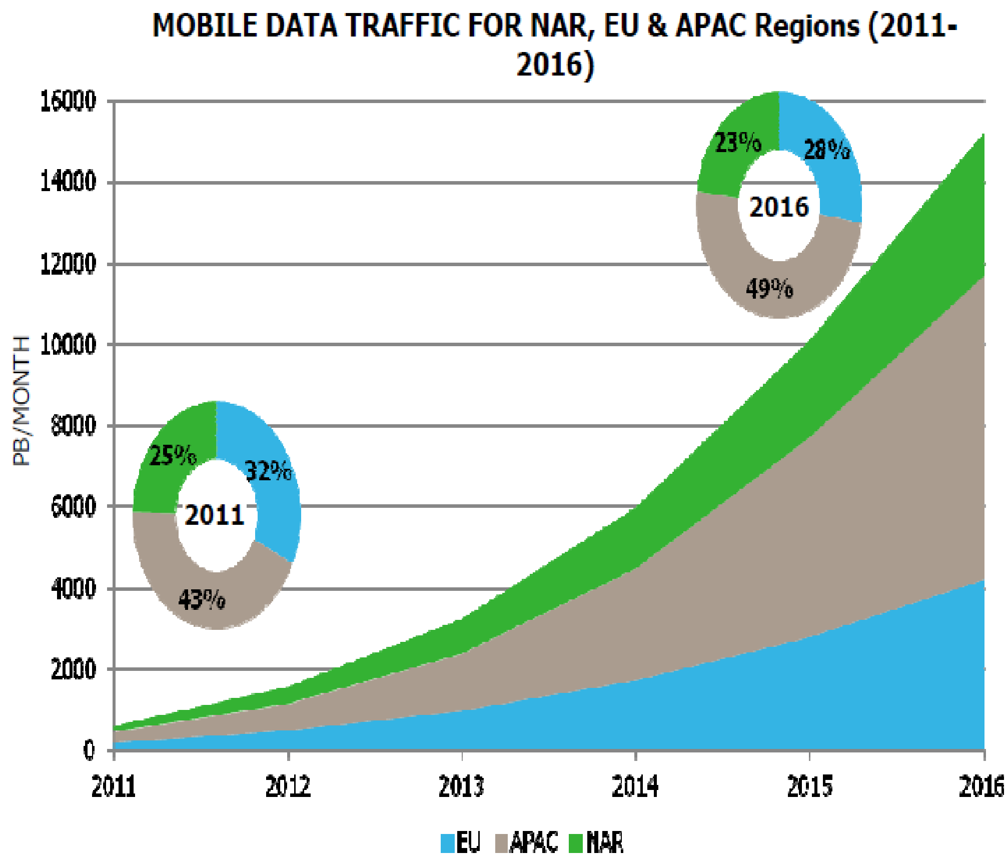
Mobile Data Traffic Grows Explosively

- Explosive growth of mobile data traffic:
  Increasing Smartphone & Mobile-broadband penetration
  - Global mobile broadband subscribers grew 45% CAGR in the past 4 years
  - Smartphone has been becoming a key driver (Penetration: Global 10%, China 8%)
  - Global mobile data traffic grew 2.3-fold in 2011, higher than anticipated
  - China: over 10% of global mobile data traffic in 2016 (5% in 2011, estimated by Cisco)
  - **CMCC's Mobile data traffic increased 60 times in the past 5 years**



RWS-120029, "Views on LTE Rel-12 & Beyond", by China Mobile Communications Corporation

Mobile broadband data is exploding



Source: Traffic Index, 2012 - Bell Labs Modeling

TODAY

DATA is 90% of traffic

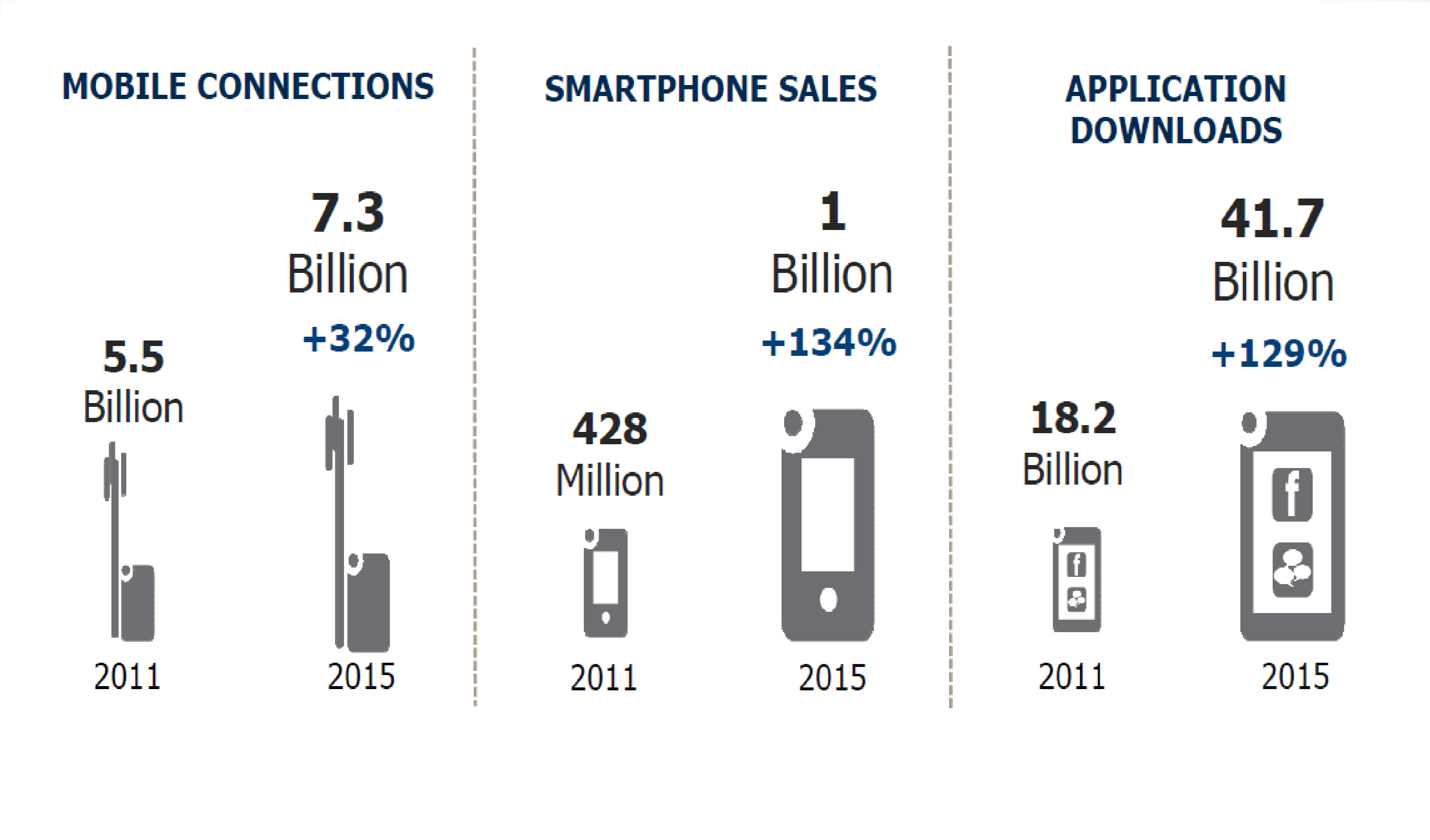
BY 2016

MOBILE DATA TRAFFIC WILL GROW >25 TIMES

Mobile broadband data is driving the need for network capacity

RWS-120014, "Towards LTE Ran Evolution", ALU

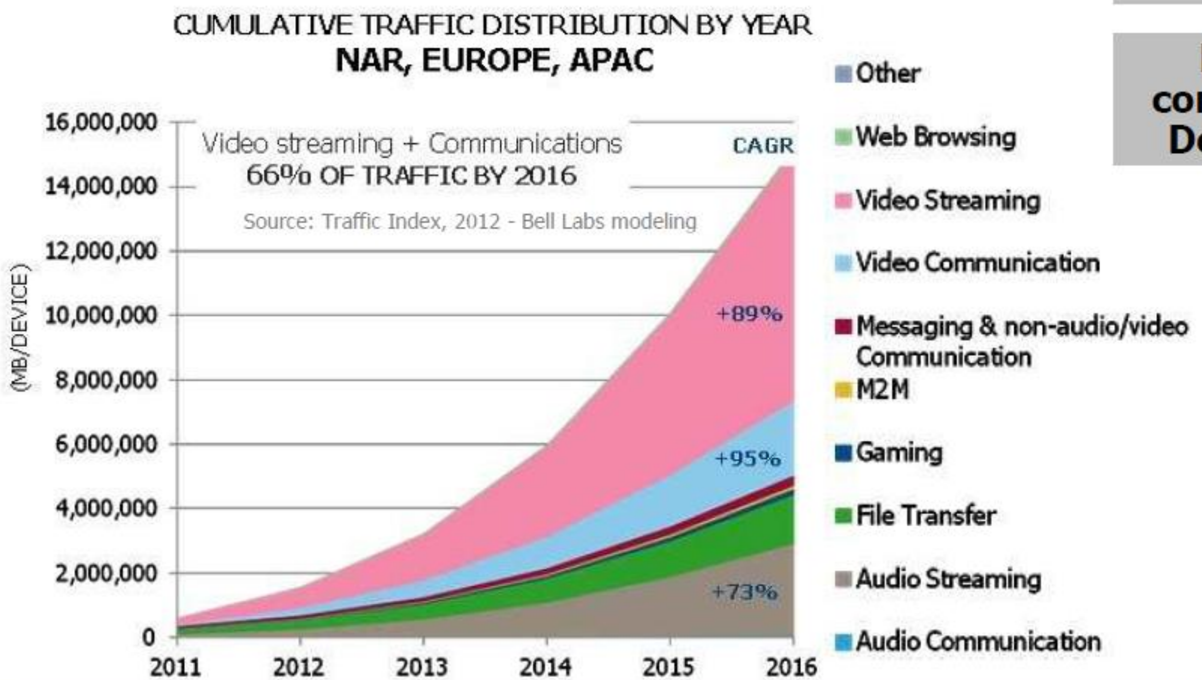
Industry Trend



RWS-120014, “Towards LTE Ran Evolution”, ALU

Data traffic is changing

- Smartphones predominating
- Wider range of applications
- New revenue streams for operators



VIDEO

43% of data today
66% by 2016

Most operators considering Content Delivery Networks

Mobile broadband is no longer just downloading: Engaging not just informing

RWS-120014, "Towards LTE Ran Evolution", ALU

Green Trend

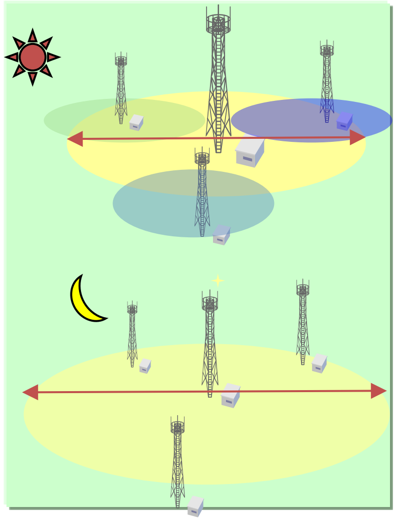
Consumer

Long Battery Life

Energy Saving Products

Network

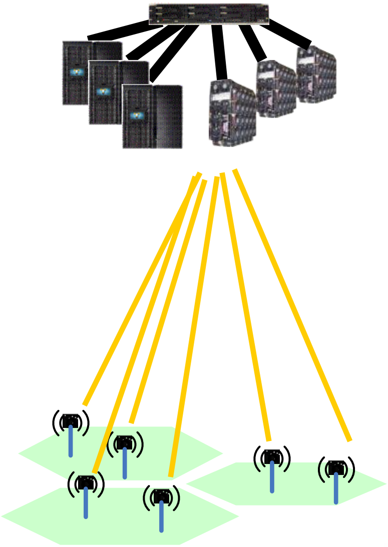
Reduced OPEX, Govt. Regulations



Protocols

Environmental

Low CO2 & Radiation



Architectures

Challenges in Wireless Communication Networks

Imbalance between galloping mobile data traffic growth and lagging network capacity

- Global mobile data traffic is increases much faster than the network capacity.

Green communication in reducing carbon footprint and improving energy efficiency

- ICT represents around 2% of total carbon emissions of which mobile networks represents about 0.2%, and this is expected to increase every year

Ever-increasing demand on high-quality user experience and low-cost services

- Widespread application of smart phones and machine type devices, and users desire of staying connected at anytime, anywhere and through any media including instant messages, emails, voice and video.

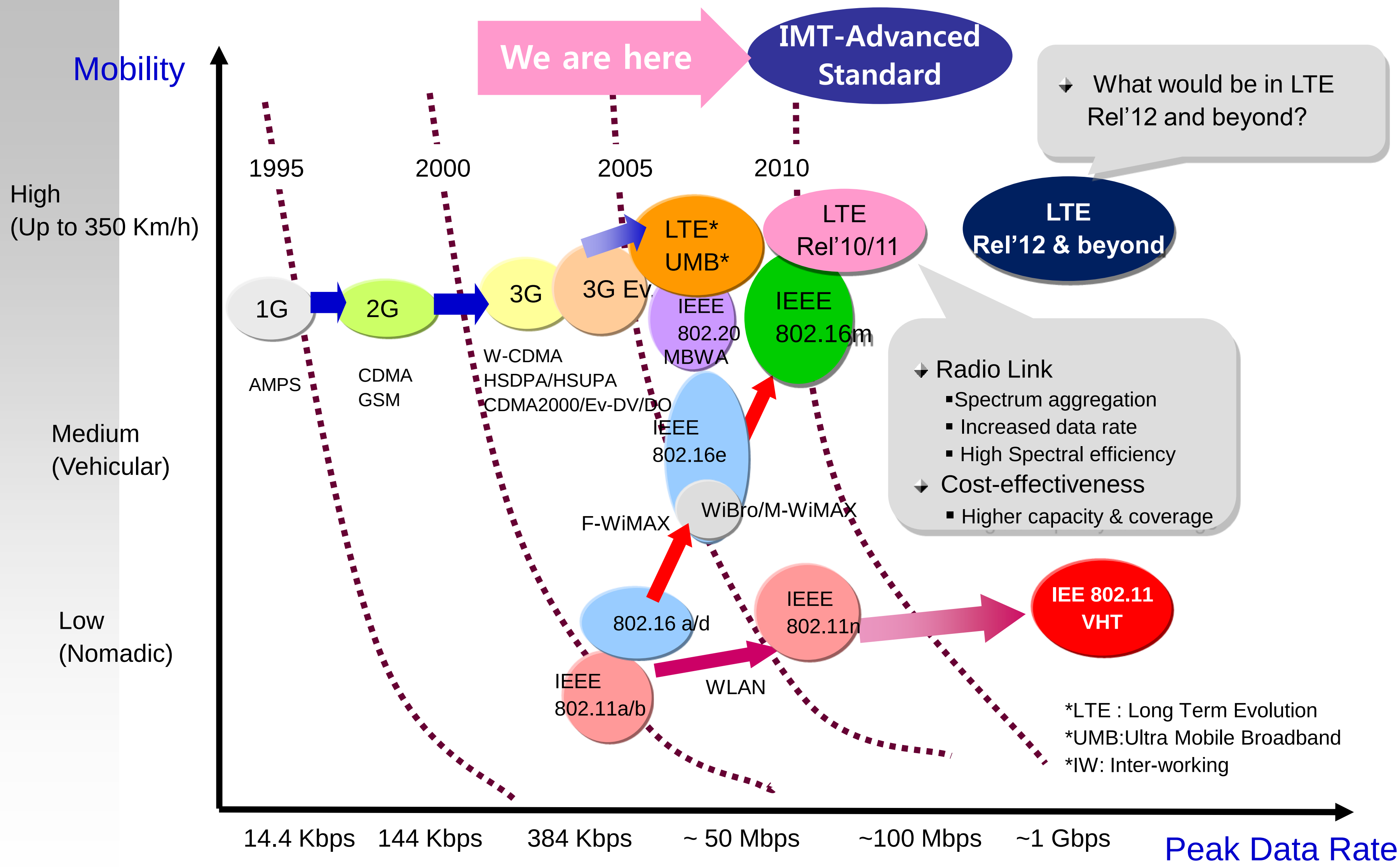
Sustainable growth of Information and Communication Technology and Ecosystem

- May need network sharing among operators in the long run

Requirements to embrace the challenges

- High-capacity energy-efficient broadband communication
  - Improved spectrum efficiency/usage
  - Improved energy efficiency/usage
  - Proper cooperation and coordination among network entities
- Enhanced network deployment
  - Support of diverse user equipment, applications, and services
  - Seemless inter-working among multiple RATs
  - Efficient support of hop spots and in-door environments
  - Traffic offloading from licensed spectrum to unlicensed spectrum
  - High capacity wired/wireless backhaul
  - Energy-efficient network deployment
  - Capability in self-healing and self-optimization

Communication Standard Evolution

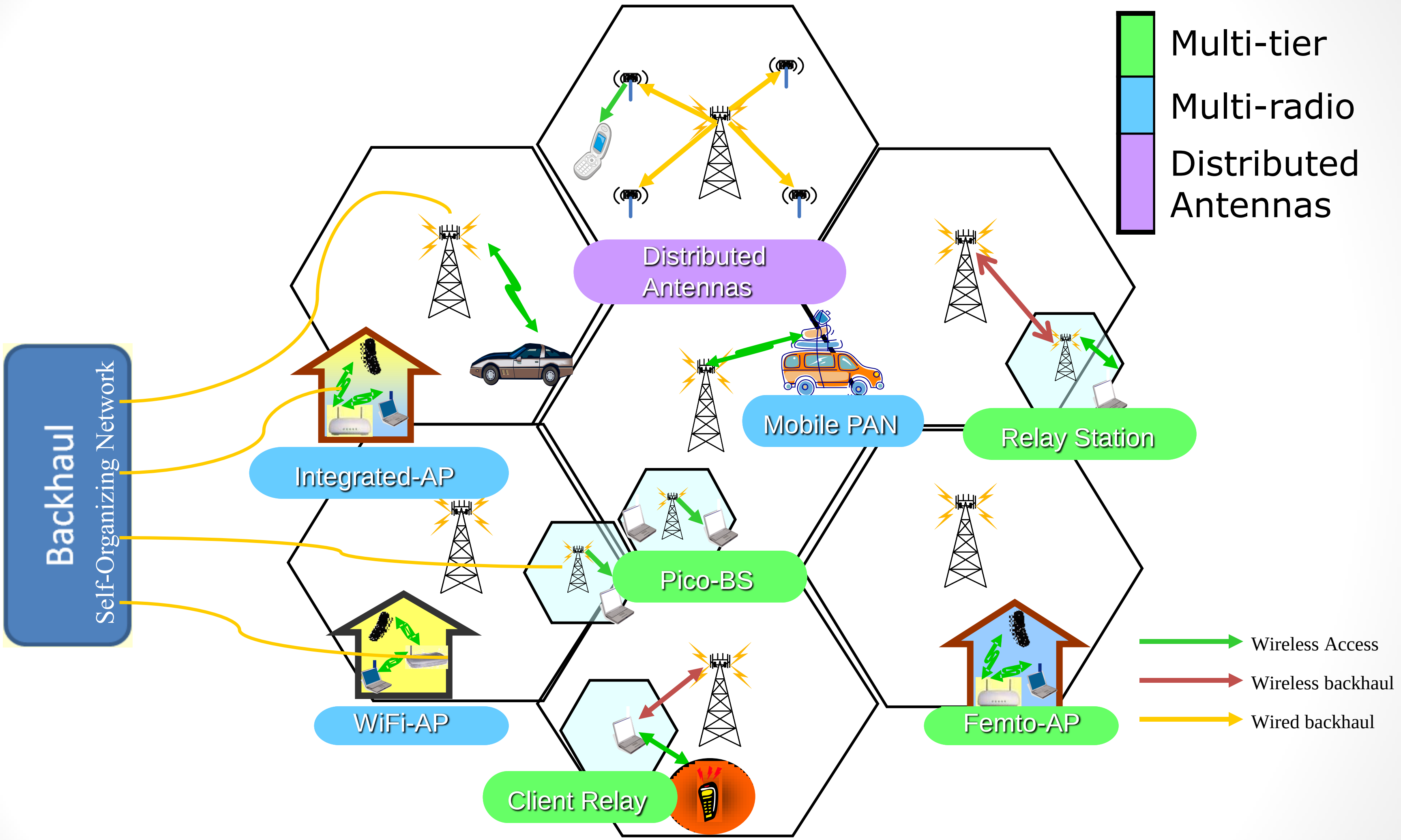


Key technologies under development

- Co-located/distributed large-scale antenna system
- Small-cells and heterogeneous networks
- Coordinated multi-point (CoMP) transmission
- 3D MIMO/beamforming
- Carrier-aggregation
- Cognitive Radio
- Device-to-device (D2D) communication
- Inter-RAT Coordination
- Self organizing networks (SON) and minimization of drive testing (MDT)

We will focus on heterogeneous networks

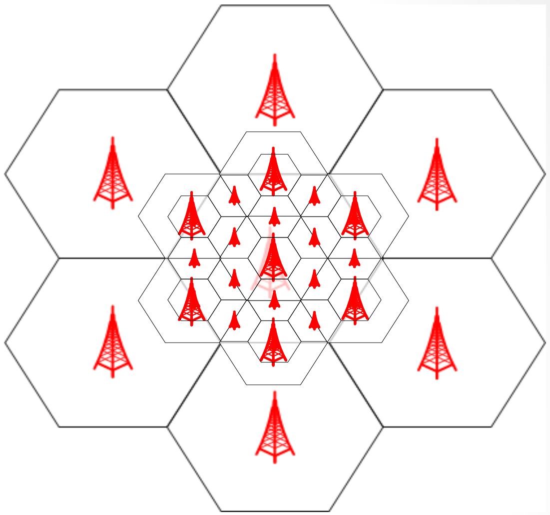
What is HetNet?



Heterogeneous Network (HetNet): A network that consists of a mix of macro cells and low-power nodes, e.g. Pico, Femto, Relay Node (RN) and Remote Radio Head (RRH)

Topology Elements/Nodes

- Overlay low power low cost network devices in the same coverage area as macro-cell
  - Single radio (shared spectrum, aggregation)
  - Multi-Radio (leverage unlicensed spectrum)
- Large macro-cells provide mobility, while small cells boost coverage and capacity
- Devices are deployed opportunistically, where needed
  - Coverage holes, range extension
  - Capacity demanding hotspots
  - Indoor coverage
- Capacity gain from spatial reuse and improved link reliability as serving device is brought closer
- Heterogeneous nodes interface to a self-organizing network, that manages communication between small cells, and macro cells.

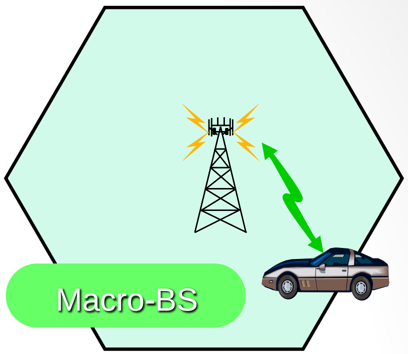


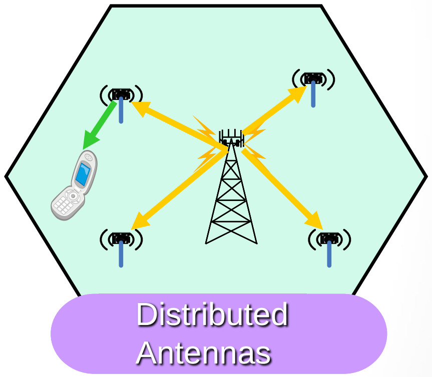
Hierarchical Cells

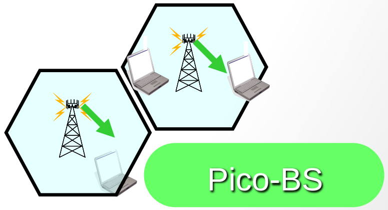
New Network Elements

Tiers - by footprint

- Macro/micro cells
  - Provide wide-area cellular coverage
  - Typically > 500m inter-site distance
  - Support high mobility users, minimizing handover frequency
- Distributed Antennas
  - Create small virtual cells by distributing antennas of macro BS across entire cell
  - Each antenna typically has LOS to user, hence improved coverage & link reliability
  - Antennas are connected to a common processing unit via fiber
- Pico cells
  - Provide hotspot coverage in malls, airports, stadiums, high user rates
  - Typically, 100 - 300m inter-site distance
  - Access is open to all cellular users
  - Operator deployed and managed (small BS)

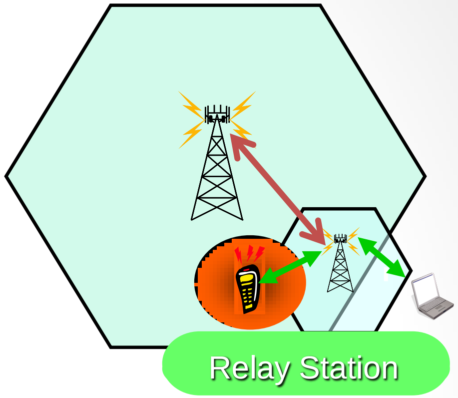


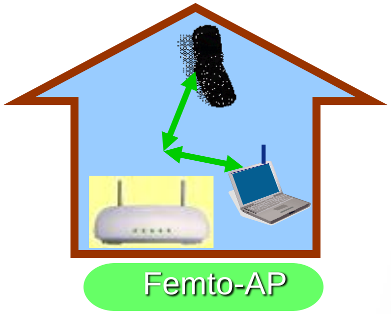


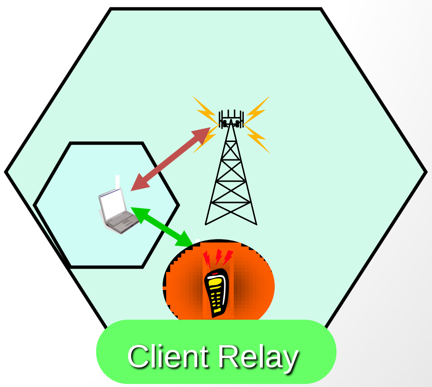


Tiers - by footprint (2)

- Relays
  - Provide coverage enhancement, range extension
  - Similar footprint as Pico cells
  - Backhaul is wireless, using operator's spectrum
  - Better flexibility in deployment, but lowers access bandwidth
- Femtocells
  - Provide in-building coverage
  - Typically serve < 100m radius, similar to WiFi
  - Access can be closed for residential users
  - Utilize subscriber backhaul, install
- Client Relays
  - Improve coverage & short-range link quality
  - Smallest tier, typically < 30m
  - Better flexibility in deployment, but lowers access bandwidth

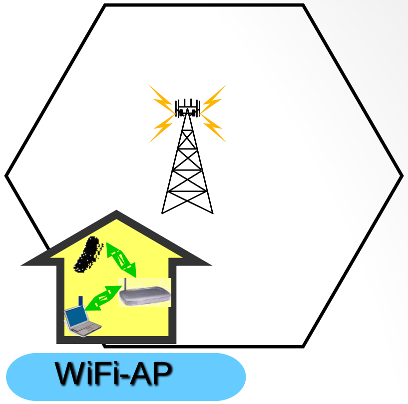




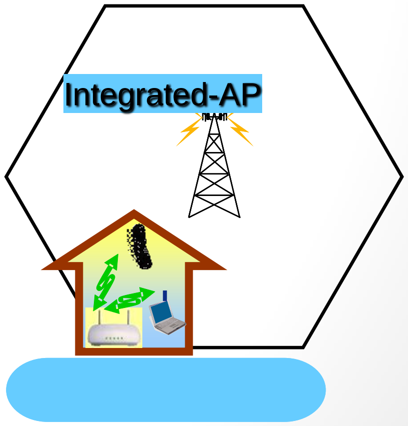


Tiers - by footprint (Multi-RAT)

- WiFi Access Points
  - Offload traffic from macro-cells in fixed, hotspot settings
  - Similar footprint as femtocells, unlicensed bands



- Integrated Access Points
  - Synergistic use of licensed and unlicensed spectrum in single device
  - Improve network capacity by carrier aggregation (WiFi is virtual carrier)
  - Improve user QoS by dynamic switching between RAT’s



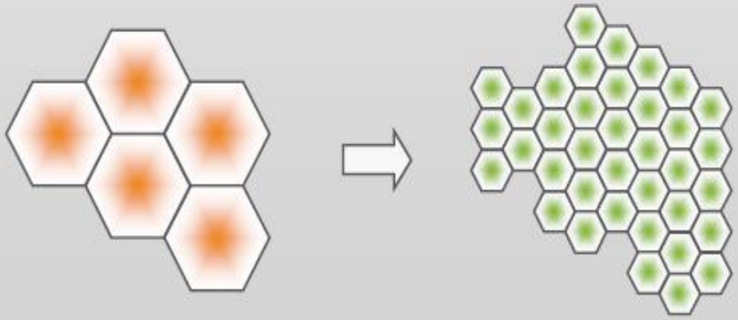
Promising benefits of HetNet

- HetNet greatly improves network capacity
  - Traffic offloading
  - Better serve of hotspot and indoor areas
- HetNet expands the coverage of wireless networks
  - Better serve for cell-edge users
- HetNet improves network energy efficiency
  - HetNets offer opportunity to lower transmission power, saving energy at BS and battery life at clients
- Inter/intra-cell CoMP in HetNet further improves spectrum and energy efficiency
  - Macro and micro BSs cooperate in transmission/reception further bring gains in diversity, capacity and energy reduction
- Low deployment cost
  - $60,000 /year/macrocell vs. $200 /year/femtocell

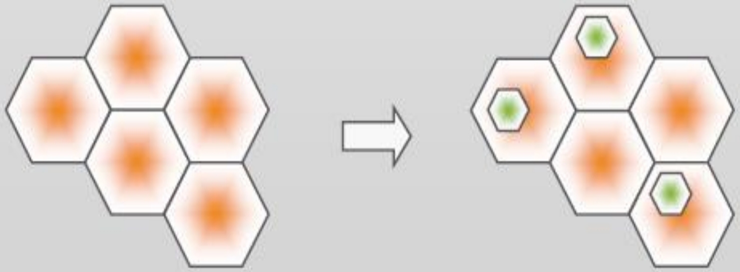
Why HetNet

- Higher data rates ➧ need denser infrastructure
  - …but user distribution and traffic density is often non-uniform

- Alt 1 – Denser "macro cells"
  - Not cost efficient (in case of non-uniform traffic)
  - Issues with rapidly moving users – frequent handovers



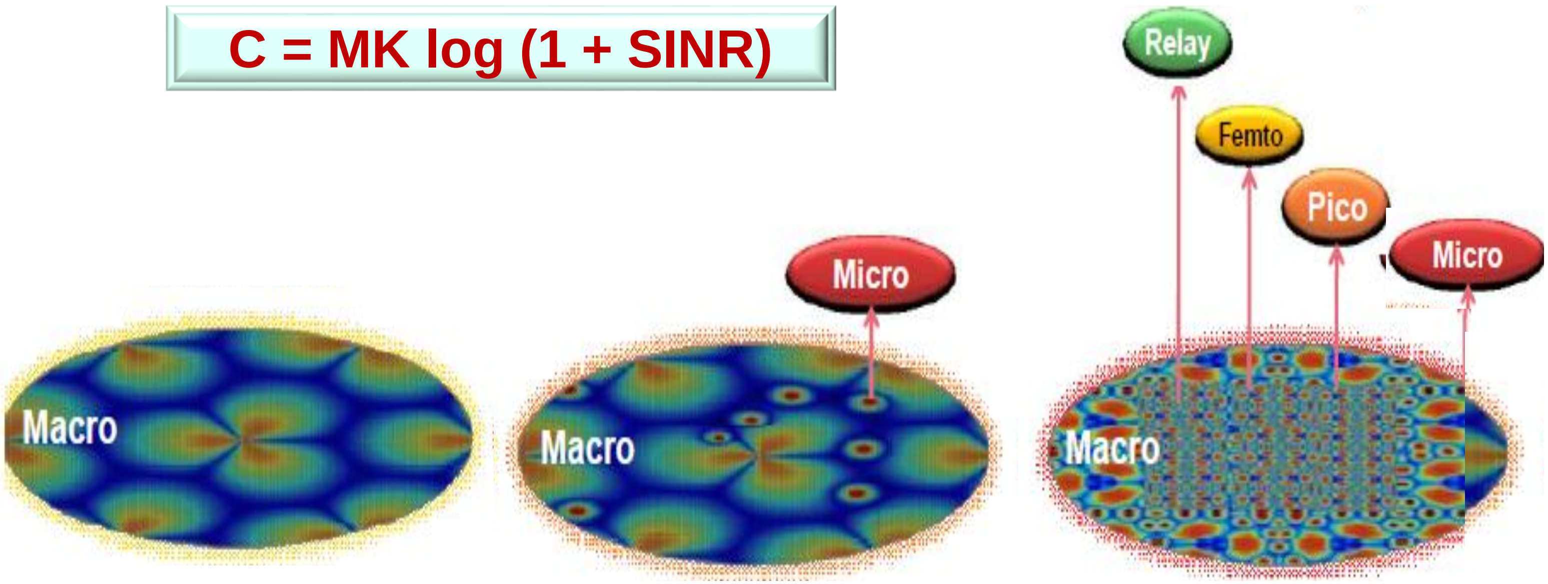
- Alt 2 – Heterogeneous Networks
  - Macro for coverage, pico for capacity
  - Semi-static, or dynamic, sharing of resources across macro - pico layers



Why HetNets: Capacity

- Heterogeneous Networks Capacity: scales with number of lower tier cells

$$C = MK \log (1 + SINR)$$

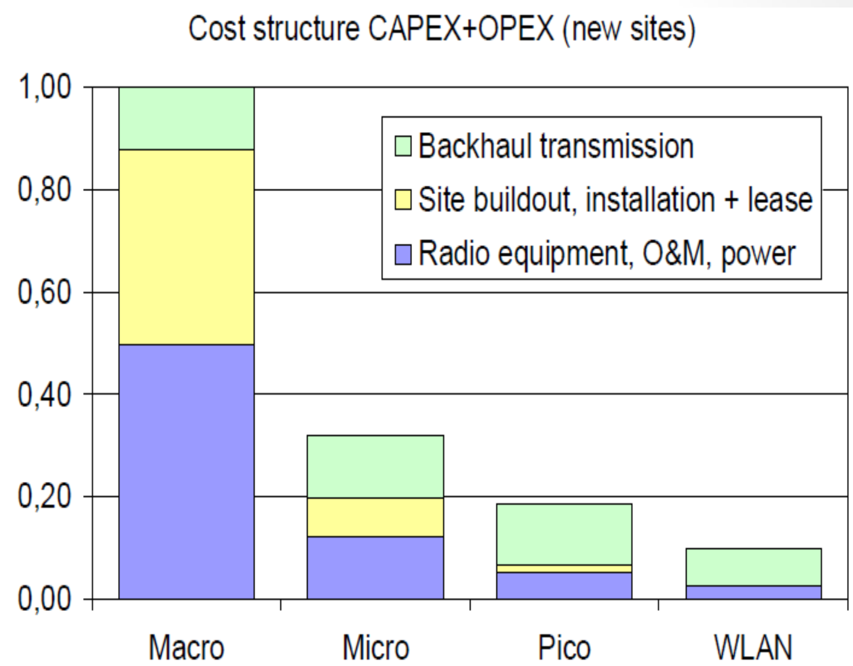


- M = number of antennas, ~ 4 to 8 maximum
- K = number of small cells, can be >> 100
- Capacity is limited by interference

Why HetNets: Cost

Cost structure of smaller cells (pico and femto) is more favorable

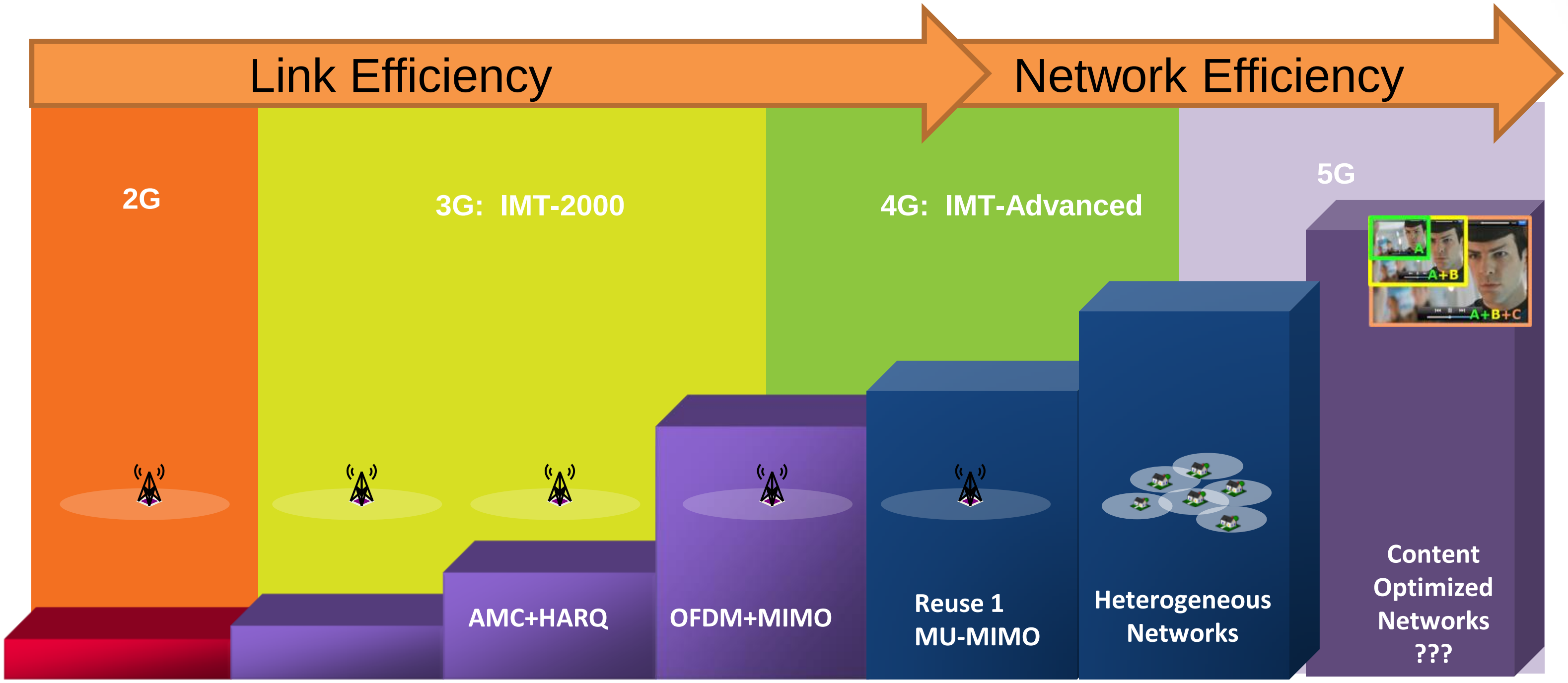
- Small range: lower power consumption at infrastructure, longer battery life for user, lower cost
- Limited functionality: support few users
- Can take advantage of unlicensed (free) spectrum
- Can be deployed easily by user (no site acquisition cost)
- Backhaul cost can be passed to user (in-home)



Source: Johansson at al, ‘A Methodology for Estimating Cost and Performance of Heterogeneous Wireless Access Networks’, PIMRC’07.

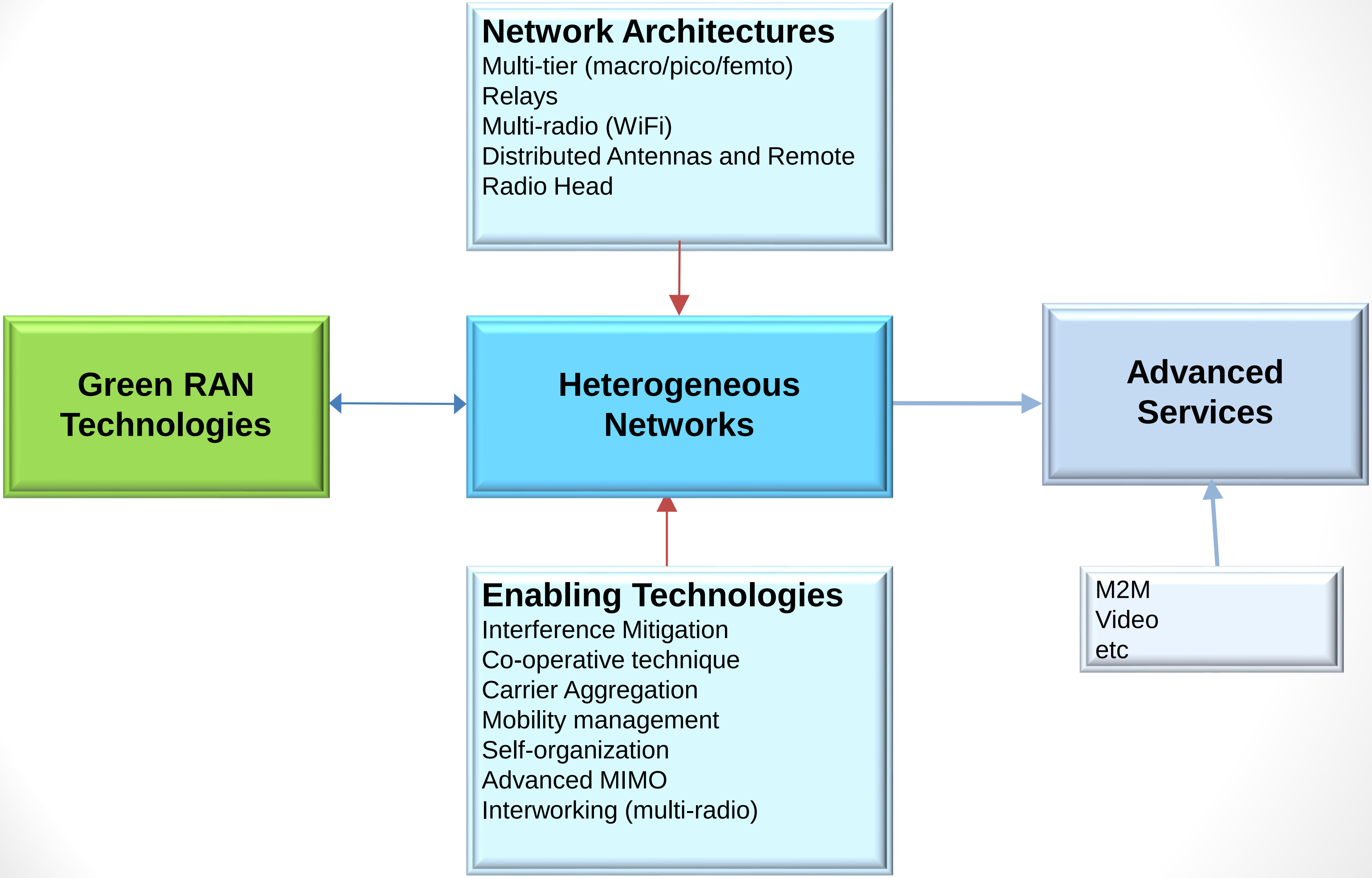
Significant potential savings in **cost per bit** with HetNets

Shift from Link Efficiency to Network Efficiency



- 4G networks have nearly achieved system capacity limits (MIMO, universal frequency reuse, multi-user scheduling)
- Focus of wireless industry shifting to network efficiency (areal capacity)
- Future networks will improve network efficiency in two ways:
  - Continue to Improve efficiency of access network (interference management , co-operative RAN's)
  - Improve efficiency of transmitted information (content aware networks, QOE)

HetNets - in Perspective



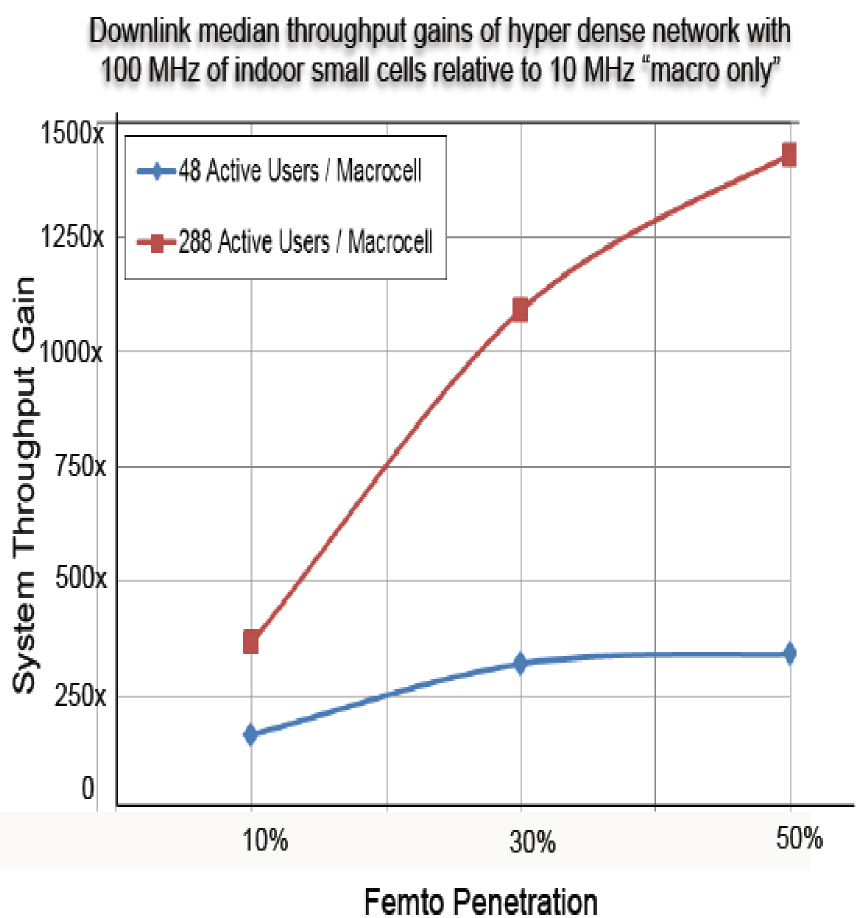
Spectrum Efficiency in HetNet

Potential SE improvement in HetNet with the deployment of small cells

Macro-only network model:
10 MHz @ 2 GHz, 2x2 MIMO, 46 dBm

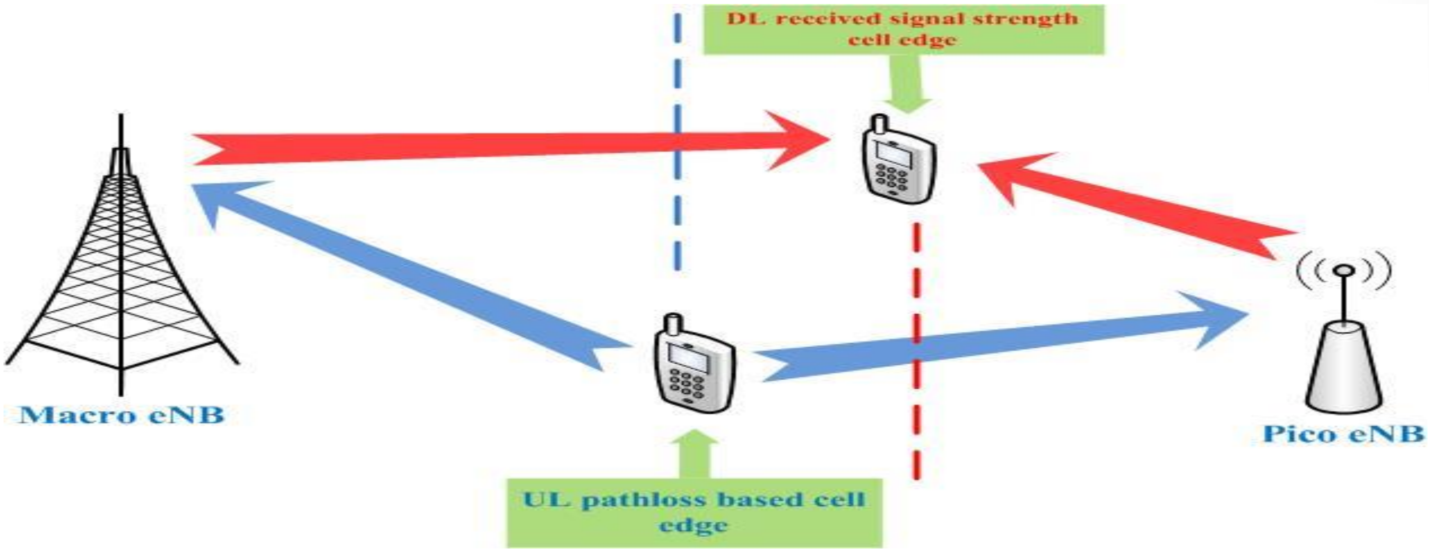
Hyper-dense network model:
10 MHz macro as above + 100 MHz of indoor small cells @ 3.6 GHz, 20 dBm (no wireline limitation)

Dense Urban Simulation Model:
- Population density: 20000 per sq. km
- Macrocell ISD: 500 m
- Multi-floor apt. blocks, multi-wall indoor path loss modeling
- 720 apartments per macrocell area
- 50% femto penetration → 360 femtos per macrocell
- Max. one femto per apt. (dropped randomly)
- 70% indoor users, 30% outdoor users
- Independent user and femto locations (dropped randomly)
- Simulation shows stationary UEs



RWS-120007, 3GPP RAN Rel-12 & Beyond, Qualcomm

HetNet interference



- ❖ Significant imbalance in the DL Tx powers of macro eNB & low power NBs
- ❖ Scenario: Open Access Picos, No Extended Range, No Interference Management
  - ➢ Same DL interference situation as within homogeneous networks but with more complicated UL interference situation.
- ❖ Scenarios with pico cells using extended range or with CSG low power nodes
  - ➢ Interference problems on DL transmission, especially on DL control data.
  - ➢ Interference management mechanisms need some new thinking
    E.g, CA, Almost Blank Subframes (ABSF)

HetNet interference scenarios

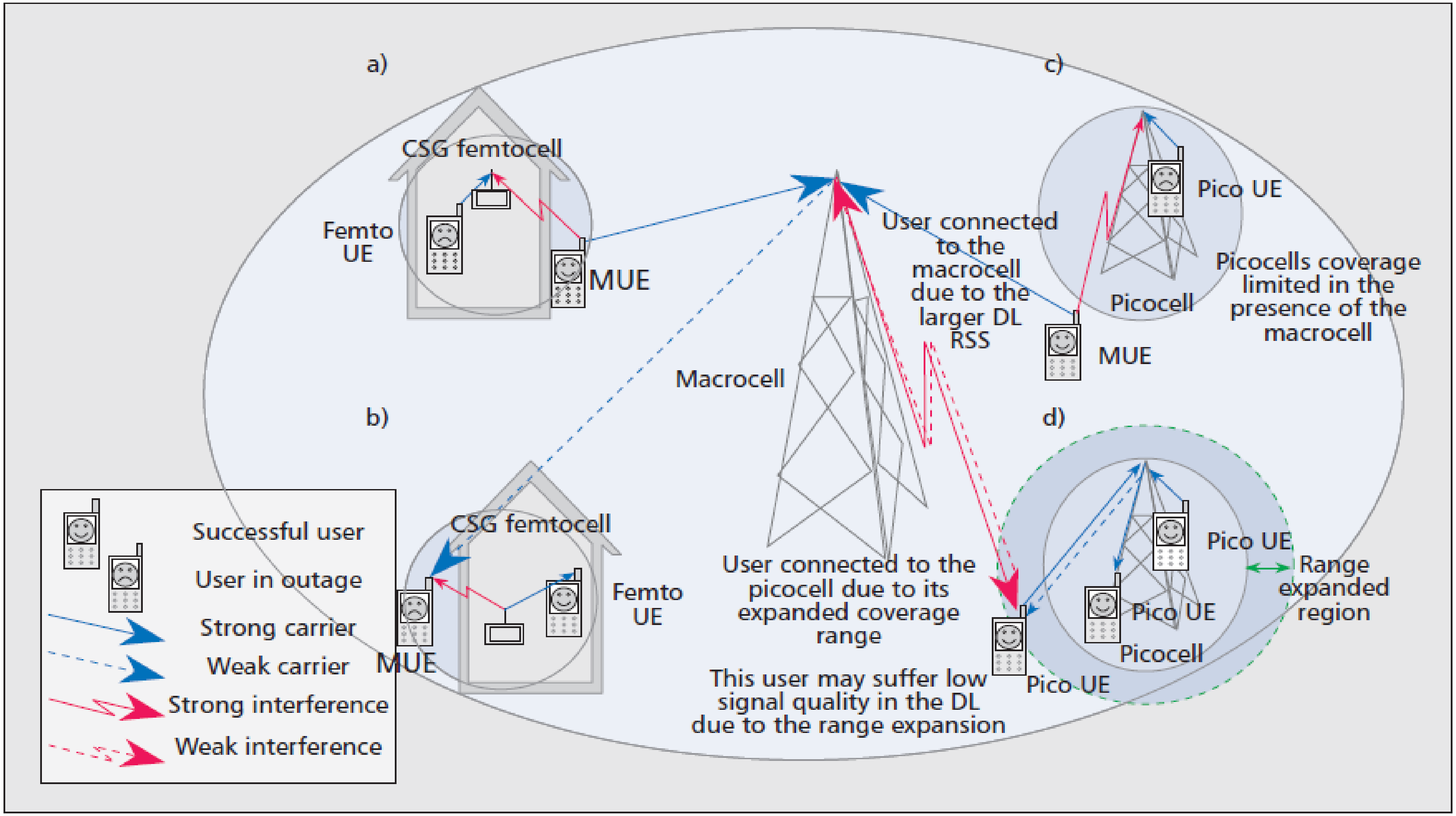


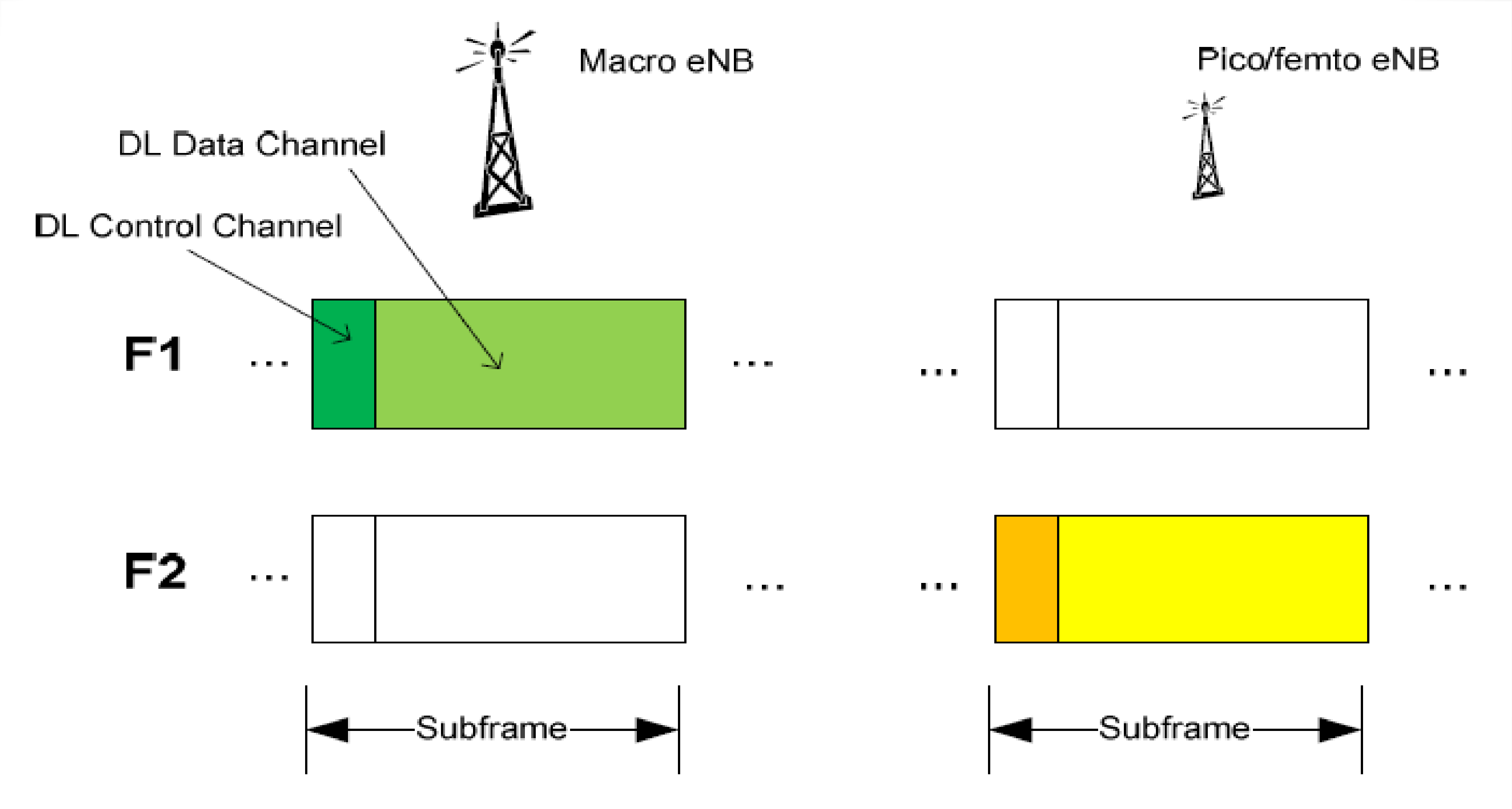
Figure 1. *Dominant DL and UL cross-tier interference scenarios in HetNets: a) macrocell user jamming the UL of a femtocell; b) femtocell jamming the DL of a macro user; c) macrocell user jamming the UL of a nearby picocell; d) range-expanded picocell (mitigates pico UL interference present in Fig. 1c).*

Source: “Enhanced intercell interference coordination challenges in heterogeneous networks”, in IEEEE Wireless Communications Magazine June 2011

ICIC in HetNet

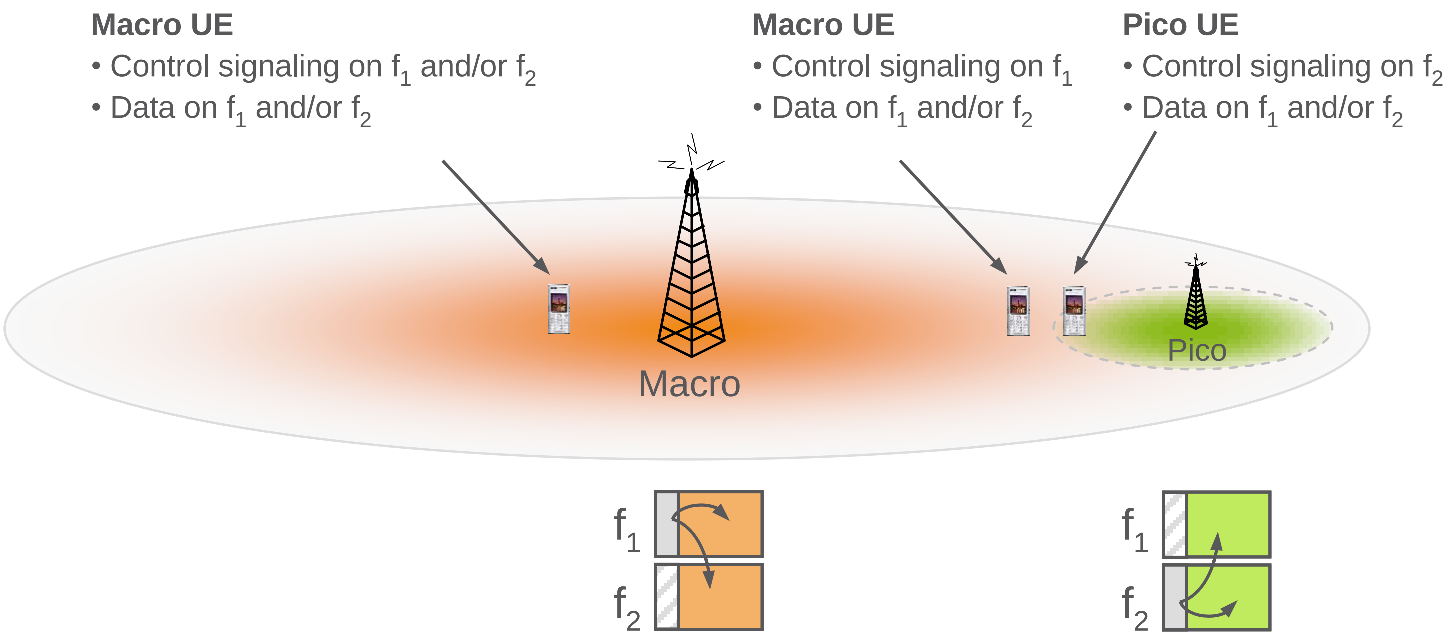
- **Multicarrier deployment**
  - Pico/femoto/relay cells operate on a carrier frequency different than that of the macro network
- **Downlink carrier aggregation**
  - Rel-10 carrier aggregation used for interference management
    - Macro and pico operate DL control signaling on different primary component carriers
    - Macro and pico operate data on same carrier frequencies
  - All building blocks are present in Rel-10
- **“Same carrier” (“single carrier”, “co-carrier”)**
  - Macro and pico operate on the same carrier frequency
  - More coordination efforts

Multicarrer deployment



- Effective in avoiding the interference between macro and pico/femto/relay cells.
- Highly inefficient as it requires at least two carrier frequencies and creates undesirable bandwidth segmentation

Downlink Carrier Aggregation



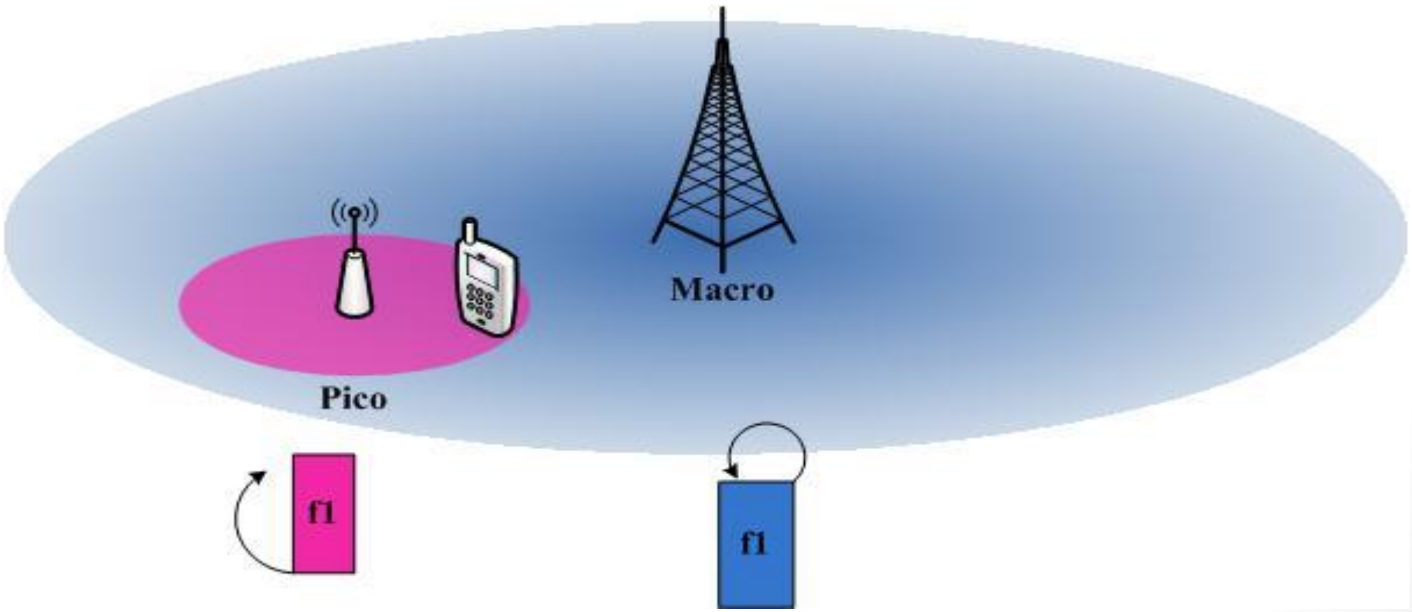
- Data
  - Can use multiple component carriers as determined by ICIC
- L1 Control signaling (including broadcast, synchronization channels & reference symbols)
  - Interference management in frequency domain
  - Macro
    - f1: normal operation (primary component carrier)
    - f2: low/zero-power for control (secondary component carrier)
  - Pico
    - f1: low or zero power for control (secondary component carrier)
    - f2: normal operation (primary component carrier)

Downlink Carrier Aggregation

- Essentially, this creates a frequency reuse for control signaling, while still allowing terminals to dynamically utilize the full bandwidth (and thereby supporting the highest data rates) for the data part

Same Carrier challenges

- ❖ Challenges for co-channel HetNet deployment
  - ➢ Co-channel Rel 8 deployments have limited inter-cell interference coordination (ICIC) and load balancing capacity
  - ➢ Rel 8 mechanism does not provide mechanisms for DL control channel ICIC
    - ✓ Cell association generally based on best DL cell or limited bias negotiated over X2
    - ✓ Limited number of UEs can be associated with low power eNBs, which limits potential for load balancing and increase in network throughput
    - ✓ DL control channel outage is observed when closed HeNBs are deployed in co-channel manner with macro network



HetNet Solution: Range expansion and enhanced inter cell interference coordination

- Range expansion (RE)
  - Refers to UE ability to connect and stay connected to a cell with low SINR
- Enhanced Inter Cell Interference Coordination (eICIC)
  - Effectively extends ICIC to DL control - time domain
  - Requires synchronization at least between macro eNB and low power eNBs in its footprint
  - No negative impact on legacy Rel 8 UEs

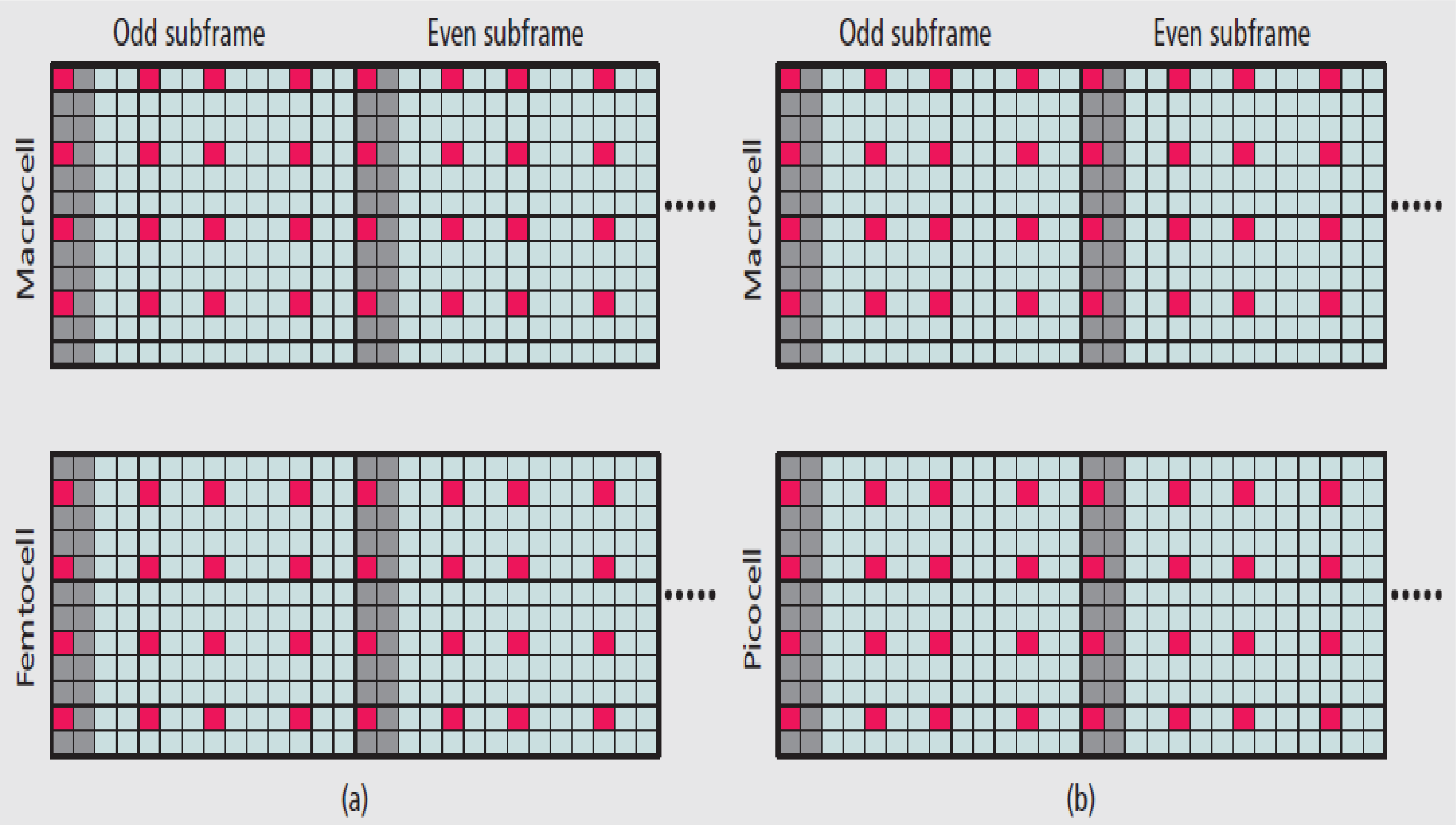
eICIC in control plane

- ❖ L1 Control signaling (PDCCH, PCFICH)
  - ❖ Almost blank subframes (ABSF) -- One layer does not transmit L1 control signaling within given subframe
  - ❖ OFDM symbol shift

Almost Blank Subframes (ABSF)

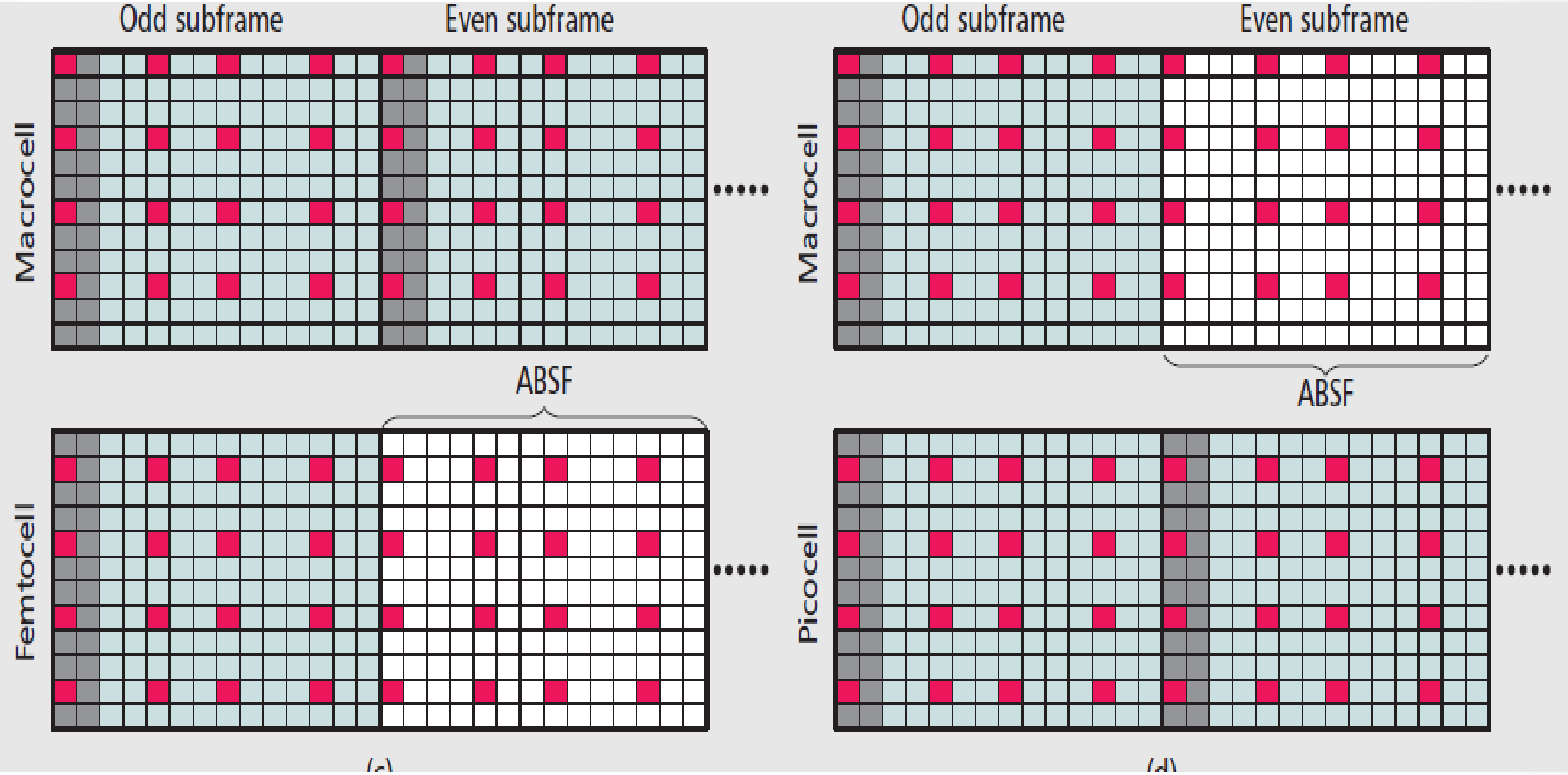
- Backhaul based eICIC for DL control and data channel interference mitigation leads to creation of almost blank subframes
  - Unicast DL data traffic is not scheduled in almost blank subframes
  - Only legacy broadcast signals and channels are transmitted to support legacy UEs
    - PSS/SSS/PBCH and CRS
    - Collisions of subframe muting with PSS, SSS. Hence muting in subframes #0, #1, #5 and #9 should be avoided as far as possible.
  - Use advanced receivers to mitigate interference from broadcast signals and channels transmitted to support legacy UEs

No ABSF



Source: “Enhanced intercell interference coordination challenges in heterogeneous networks”, in IEEEE Wireless Communications Magazine June 2011

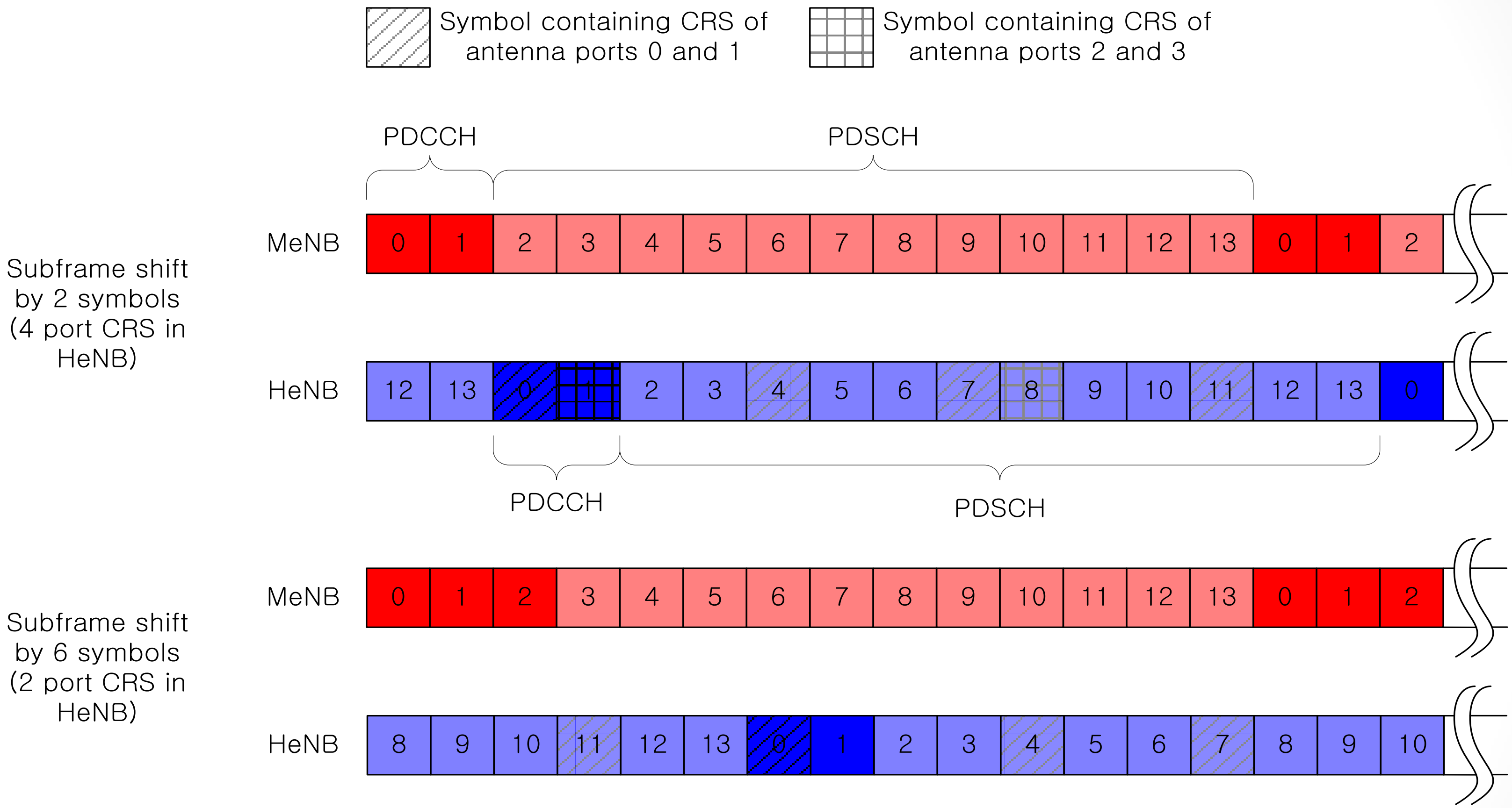
With ABSF



❖Advanced receivers are needed to mitigate interference from broadcast signals and channels transmitted to support legacy UEs

Source: “Enhanced intercell interference coordination challenges in heterogeneous networks”, in IEEEE Wireless Communications Magazine June 2011

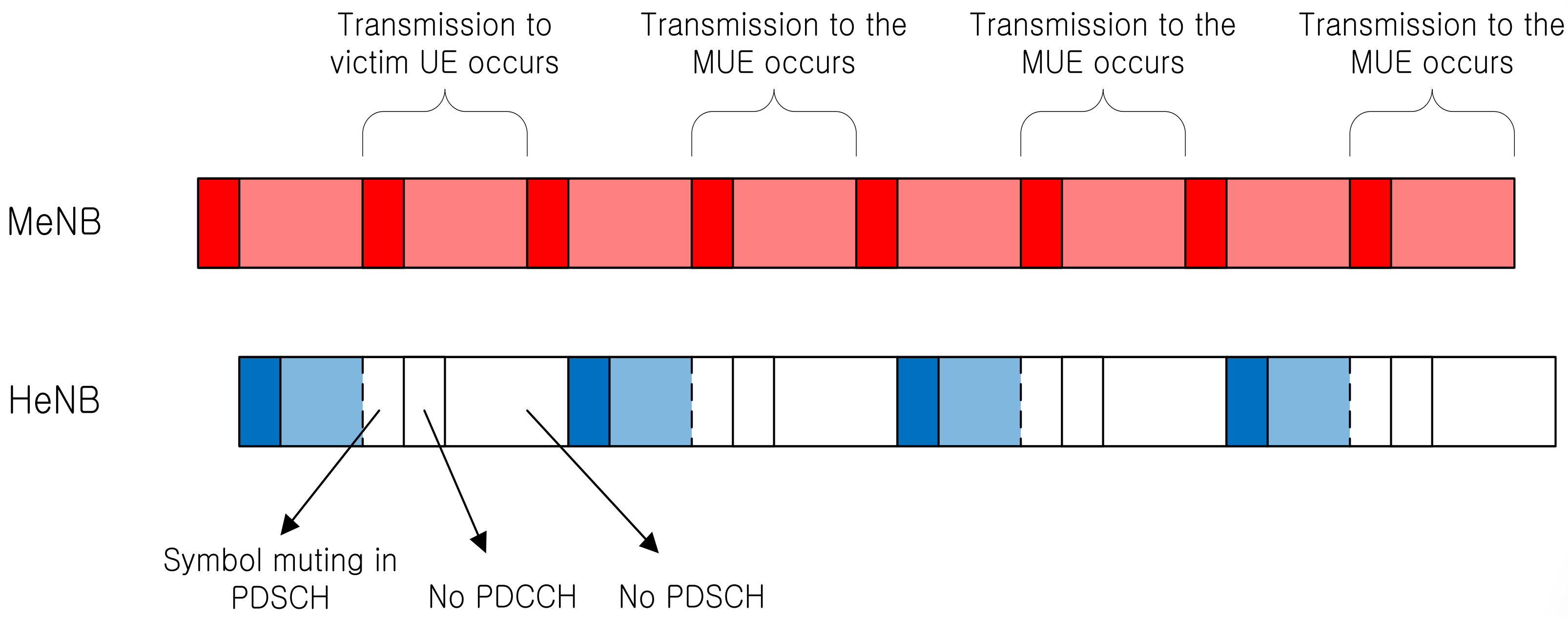
OFDM symbol shift



This symbol-level shift enables the control channel detection of the MUE without being interfered by HeNB's CRS or control channels

3GPP R1-104661

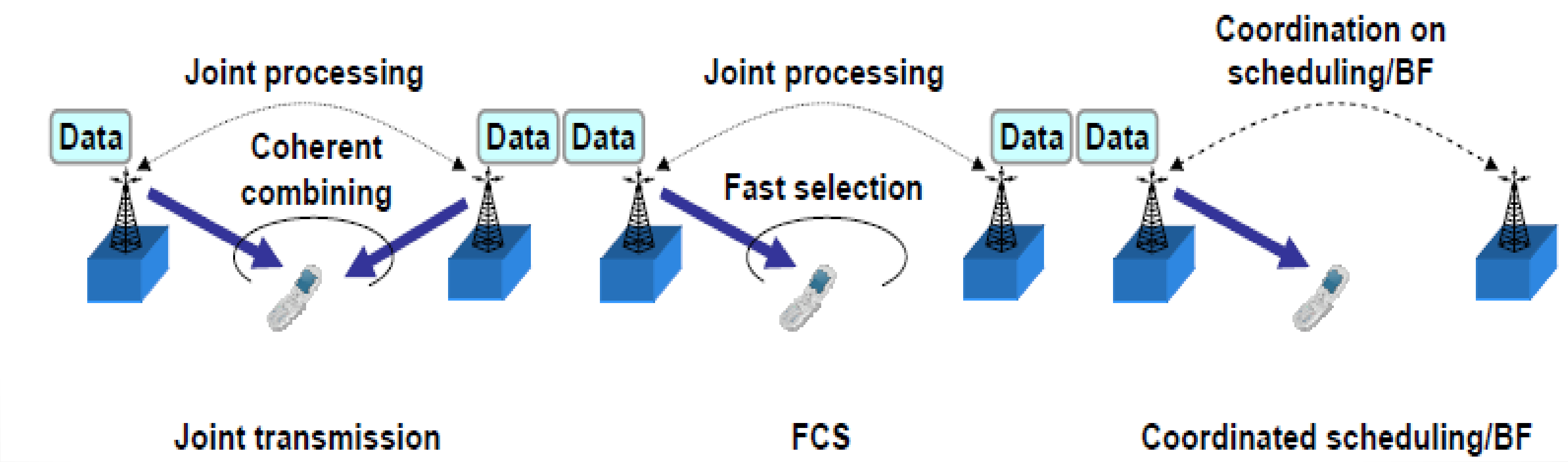
OFDM symbol muting



3GPP R1-104661

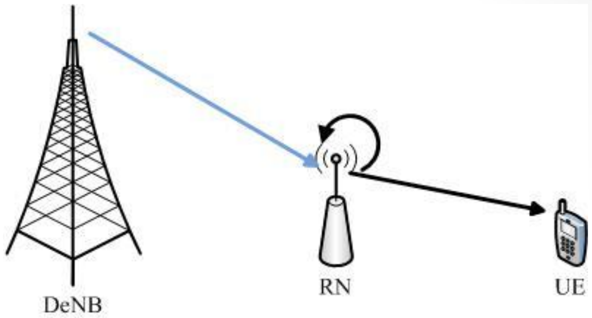
CoMP

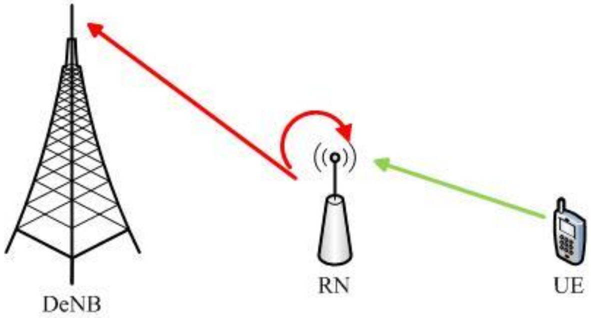
- CoMP transmission schemes on downlink
  - Joint processing
    - Data is available at each point
    - Joint transmission and fast cell selection (FCS) are being studied
      - Joint transmission: data transmitted from multiple point at a time
      - FCS: data transmitted from one point at a time
  - Coordinated scheduling/beamforming (BF)
    - Data is only available at serving cell but user scheduling/BF decisions are made with coordination among cells



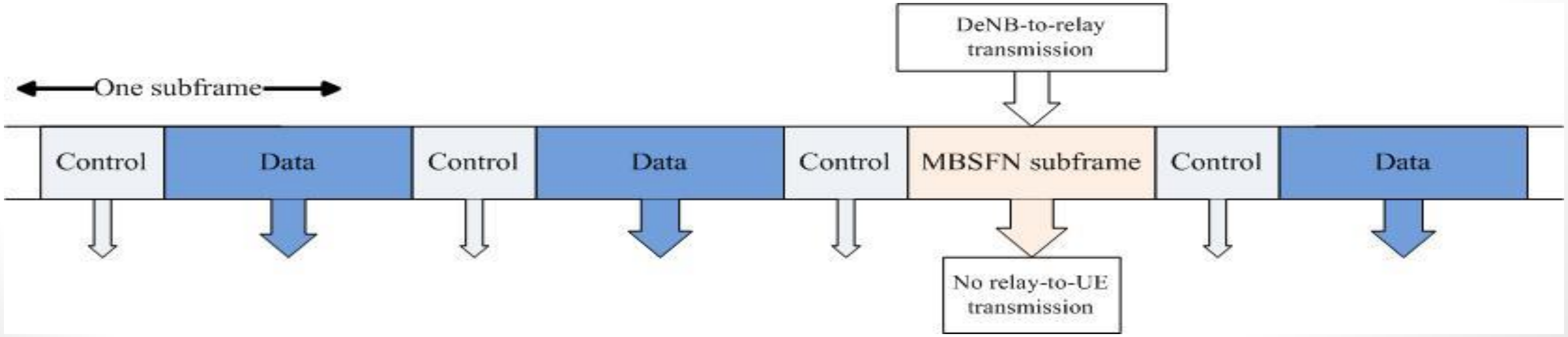
Multi-hop relaying

- ❖ Due to self-interference RNs cannot simultaneously
  - ➢ Transmit on access (DL) and receive on backhaul (DL)
  - ➢ Receive on access (UL) and transmit on backhaul (UL)





- ❖ RN separates backhaul and access in time
  - ➢ Access (backhaul) link operates on access (backhaul) subframes only

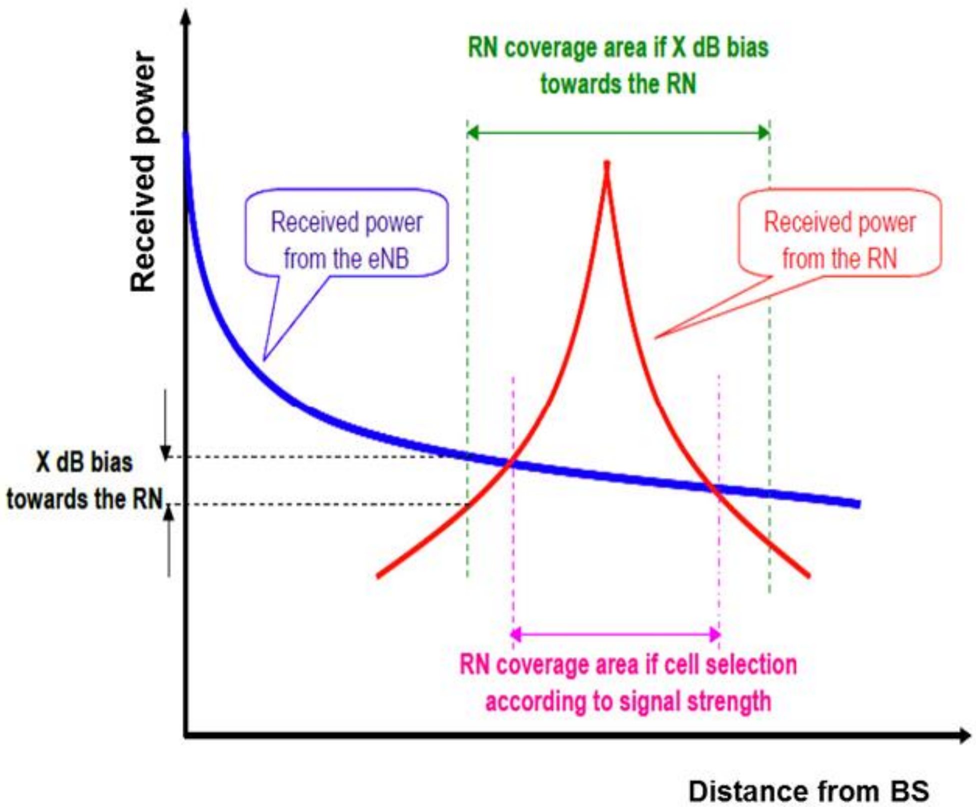


Improving SE with HetNet

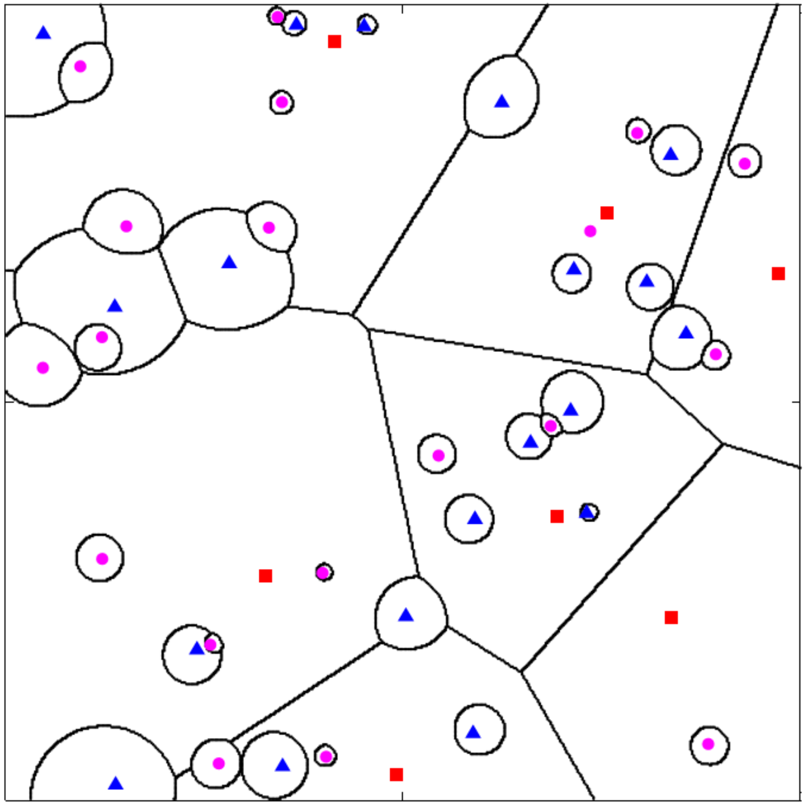
- Challenges in maximizing SE in HetNets
  - Proper coverage region for macro and small cells
  - Proper interference management
  - Proper resource allocation and scheduling
- Technological Solution
  - Mobile association scheme to balance the traffic load among macro and small cells
  - Fractional frequency reuse with proper power control
  - Radio resource allocation scheme considering both SE and fairness

Mobile association in HetNet

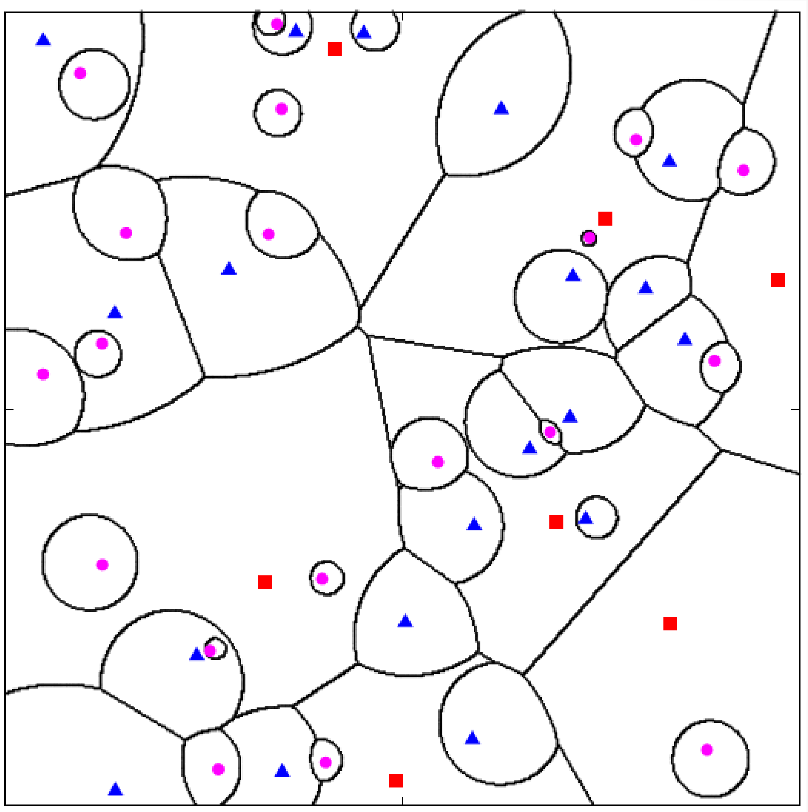
- Default (best-power): UEs are assigned with the micro or macro BSs to be associated with according to their received signal strength
- Range expansion: biased cell selection expands the micro-cell area and hence balance the loads among macro and micro BSs



Coverage area comparison: beset-power vs. range expansion



(a) Best-power



(b) Range-expansion with 10 dB bias

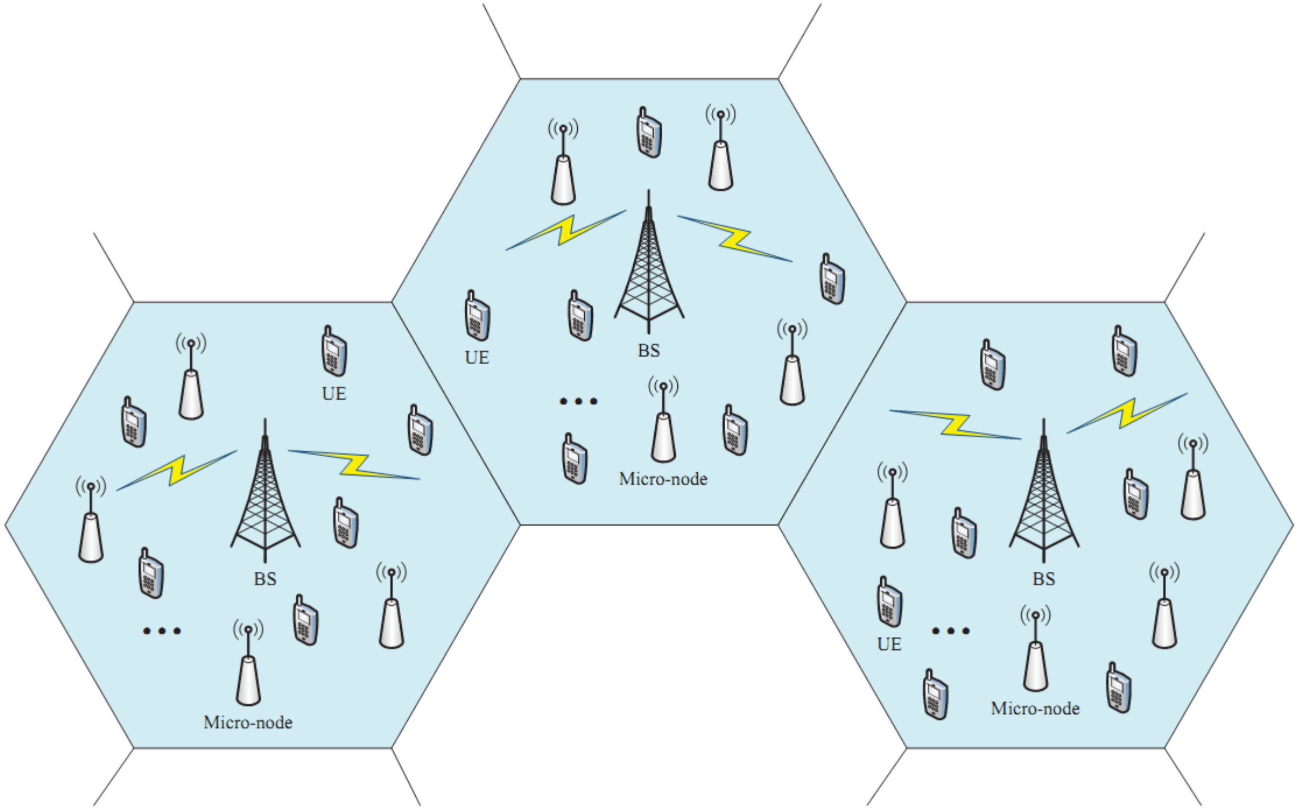
J. G. Andrews, H. Claussen, M. Dohler, S. Rangan, M. C. Reed, “Femtocells: Past, Present, and Future”, IEEE JSAC on Femtocellular Networks, Nov. 2011

Mobile association with traffic load balancing

- Problem with range-extension based mobile association
  - A computational extensive brute-force search is needed to determine the optimal bias value
  - The optimal bias value depends on the traffic status of the network
  - Cells with different load may require different bias values which further complicates the computational complexity
- We propose a load-balancing mobile association scheme with low computational/operational complexity, better performance and capability of on-line implementation
- We use cellular relay network as an example to demonstrate the proposed mobile association scheme. Applications in other HetNet scenarios can follow.

Q. Li, Rose. Q. Hu, Y. Xu, Y. Qian, ""Optimal Fractional Frequency Reuse and Power control in the Heterogeneous Wireless Networks", submitted to IEEE Transactions on Wireless Communications

Cellular Relay Network Model



- In each cell, we have
  - One macro node (BS) as in conventional cellular networks
  - Multiple micro nodes function as mini-BS
  - Each UE can access to either the macro or micro node

Cellular Relay Network Model (2)

- The received SINR at the kth UE from the ith BS is

$$\mathrm{SINR}_{k,0,i} = \frac{|h_{k,0,i}|^2 P_i^b}{\sum_{i' \neq i}^{N_c} |h_{k,0,i'}|^2 P_{i'}^b + \sum_{i=1}^{N_c} \sum_{j=1}^{N_r} |h_{k,j,i}|^2 P_j^r + \sigma_w^2}$$

- The received SINR at the kth UE from the jth RN in the ith sector is

$$\mathrm{SINR}_{k,j,i}^u = \frac{|h_{k,j,i}|^2 P_i^b}{\sum_{i=1}^{N_c} |h_{k,0,i}|^2 P_i^b + \sum_{i=1}^{N_c} \sum_{j' \neq j}^{N_c} |h_{k,j',i}|^2 P_{j'}^b + \sigma_w^2}$$

- Radio resources needed for supporting the kth UE with a QoS requirement Ψ_k can be calculated as

$$c_{k,j,i} = \frac{\Psi_k}{\log(1 + E\{\mathrm{SINR}_{k,j,i}^m)\}}$$

Load-Balancing Based MA with Full Frequency Reuse

- Define $$x_{k,0,i} = \begin{cases} 1 & \text{if } k\text{th UE is associated with } i\text{th BS} \\ 0 & \text{otherwise.} \end{cases}$$

  The LB-MA problem is formulated as

$$\max_{x_{k,j,i}} G(\mathbf{x}) = \rho_1 \sum_{i=1}^{N_c} \sum_{j=0}^{N_r} \sum_{k=1}^{N_u} x_{k,j,i} - \rho_2 \Phi$$

s.t

$$\sum_{k=1}^{N_u} x_{k,0,i} c_{k,0,i} + \sum_{j=1}^{N_r} \sum_{k=1}^{N_u} x_{k,j,i} c_{k,j,i}^b \leq C_i^{\mathrm{BS}} \text{for } i = 1, \cdots, N_c$$

$$\sum_{k=1}^{N_u} x_{k,j,i} (c_{k,j,i} + c_{k,j,i}^b) \leq C_j^{\mathrm{RN}} \text{ for } j = 1, \cdots, N_r$$

$$\sum_{i=1}^{N_c} \sum_{j=1}^{N_r} x_{k,j,i} = 1 \text{ or } 0 \text{ for } k = 1, \cdots, N_u$$

where $$\Phi = \sum_{i=1}^{N_c} \sum_{k=1}^{N_u} x_{k,0,i} c_{k,0,i} + \sum_{i=1}^{N_c} \sum_{j=1}^{N_r} \sum_{k=1}^{N_u} x_{k,j,i} (W c_{k,j,i} + c_{k,j,i}^b)$$

Load-Balancing Based Mobile Association Scheme (2)

- The objective is to maximize the sum throughput and minimize the resource consumption

- By imposing a low weight on resources consumed in the micro-node, more UEs will be associated with the micro-node, leading to a balanced traffic load among the macro and micro nodes

- A pseudo-optimal solution is proposed based on gradient-descent method. The idea is to relax the domain of $x_{k,j,i}$ as $x_{k,j,i} \in [0, 1]$ to represent association probability. The integral programming problem then becomes a linear programming problem

Load-Balancing Based Mobile Association Scheme (3)

- $x_{k,j,i}$ is updated as

$$x_{k,j,i}(t) = x_{k,j,i}(t-1) + \delta \Delta x_{k,j,i}$$

where $$\Delta x_{k,j,i} = \partial G(\mathbf{x}) / \partial x_{k,j,i}$$

$$\frac{\partial G(\mathbf{x})}{\partial x_{k,0,i}} = \rho_1 - \rho_2 c_{k,0,i}, \quad \frac{\partial G(\mathbf{x})}{\partial x_{k,j,i}} = \rho_1 - \rho_2 (W c_{k,j,i} + c^b_{k,j,i})$$

- The update continues until resource constraints in the optimization problem are reached with equality
- We sort the $x_{k,j,i}$ values in the descending order. The $x_{k,j,i}$ ‘s on top of the list are those with high association probability
- The UEs are accepted into the network sequentially in the order specified by the ordered $x_{k,j,i}$ list
- Upon the acceptance of each UE, the resource constraints are checked.
- The procedure stops when all the UEs are accepted in the network (underloaded case) or all the resources are used up (overloaded case)

Load-Balancing Based Mobile Association Scheme (4)

- High association probability happens in the following two scenarios
  - When the required radio resource is low
  - When the number of competing UEs to a same host is low

- The algorithm can be implemented online for a batch of incoming UEs
  - The BSs and RNs can wait until a batch of UEs come into the network and do mobile association jointly
  - The same gradient-descent method based algorithm as in the offline case can be implemented for the batch of UEs over a reduced scope of the entire system resource
  - The scope is reduce for saving resources for the future incoming UEs
  - The size of the UE batch should be properly selected to tradeoff between network throughput and waiting time

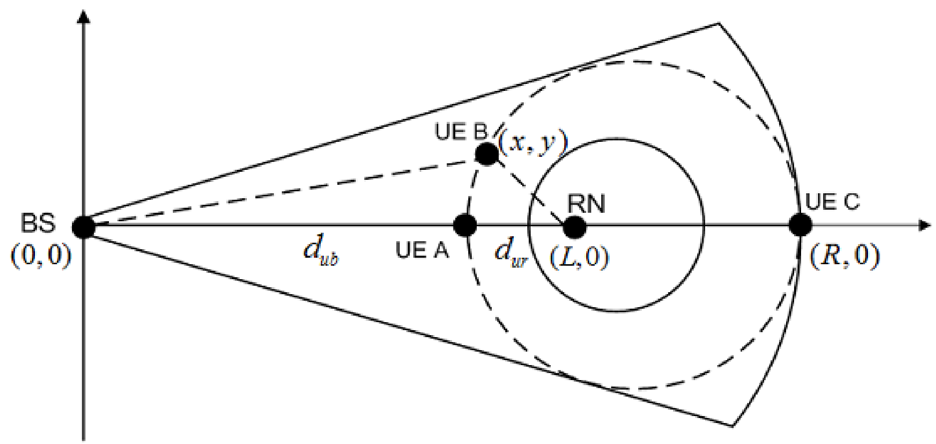
Relay Coverage Extension

$$\frac{(1+\theta_r)K_{ur}}{K_{ub}+\theta_b K_{ur}} = \beta \frac{P_r F_r \mathbb{E}_{k\in\mathcal{K}}\{|h_{k,j,i}|^2\}}{P_b F_b \mathbb{E}_{k\in\mathcal{K}}\{|h_{k,0,i}|^2\}} = \Gamma$$

$$\frac{K_{ur}}{K_{ub}} = \frac{\Gamma}{1+\theta_r-\Gamma\theta_b}$$

$$\frac{S_r}{S_u} = \frac{S_r}{S_c - S_r} = \frac{\Gamma}{1+\theta_r-\Gamma\theta_b}$$

$$W = \frac{(1-\theta_b)^+ \log(1+\mathrm{SINR}^u_{A,j,i})}{\log(1+\mathrm{SINR}^u_{A,0,i})}$$

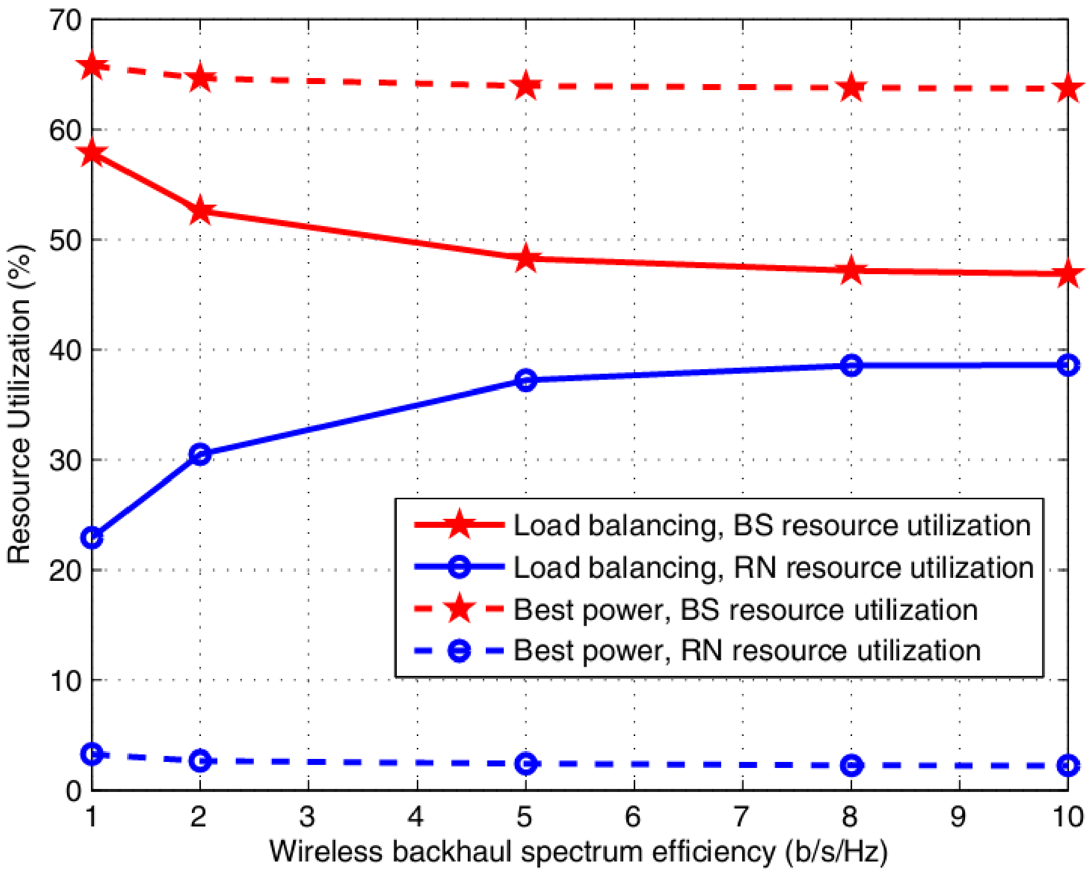


Numerical Results

Simulation Setup:

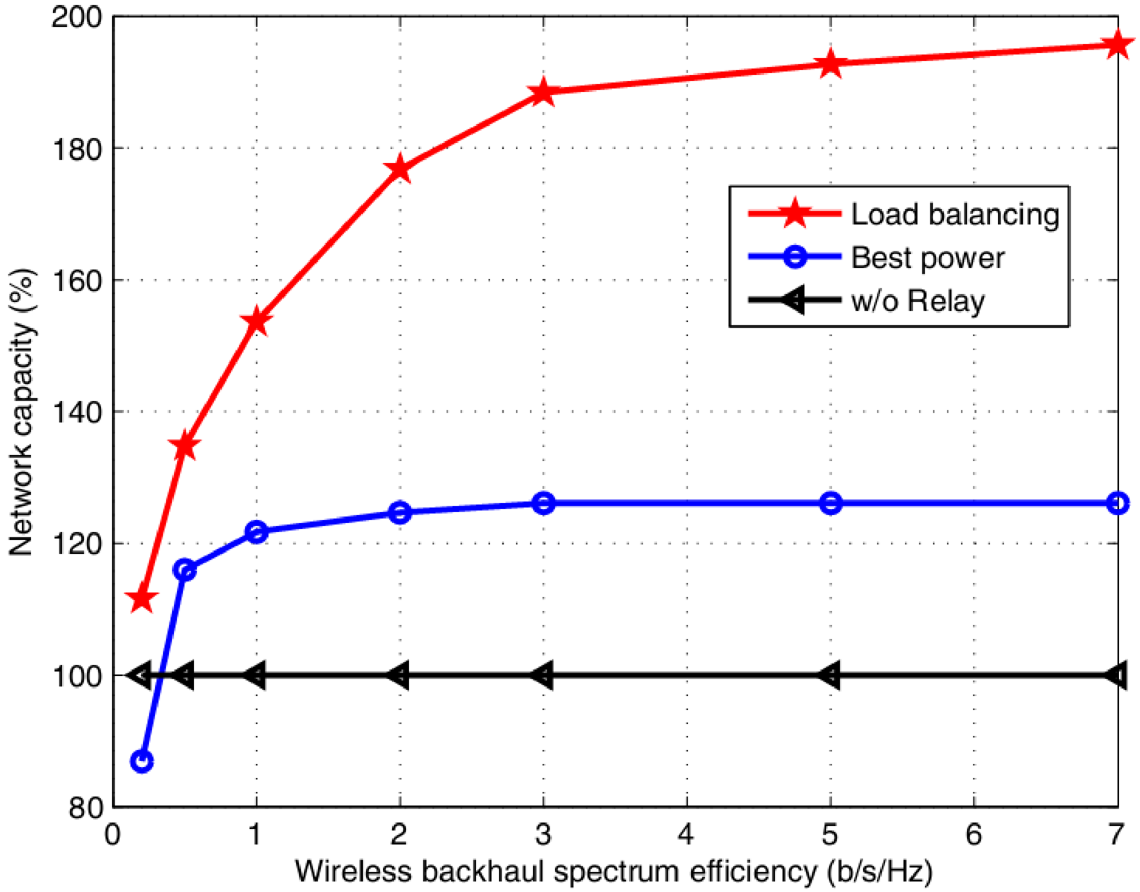
- Simulate a cellular network with a 19-cell, 3-sector three-ring hexagonal cell structure
- Two RNs are uniformly deployed in each sector
- Simulation setup follows Case 1 described in LTE rel-9
- BS transmit power is 46 dBm (40 W) and RN transmit power is 30 dBm (1 W)
- UEs are uniformly distributed in the network with each UE represents an adaptive multi-rate based VoIP user with a rate of 8.6 kbps

Comparison in Resource consumption



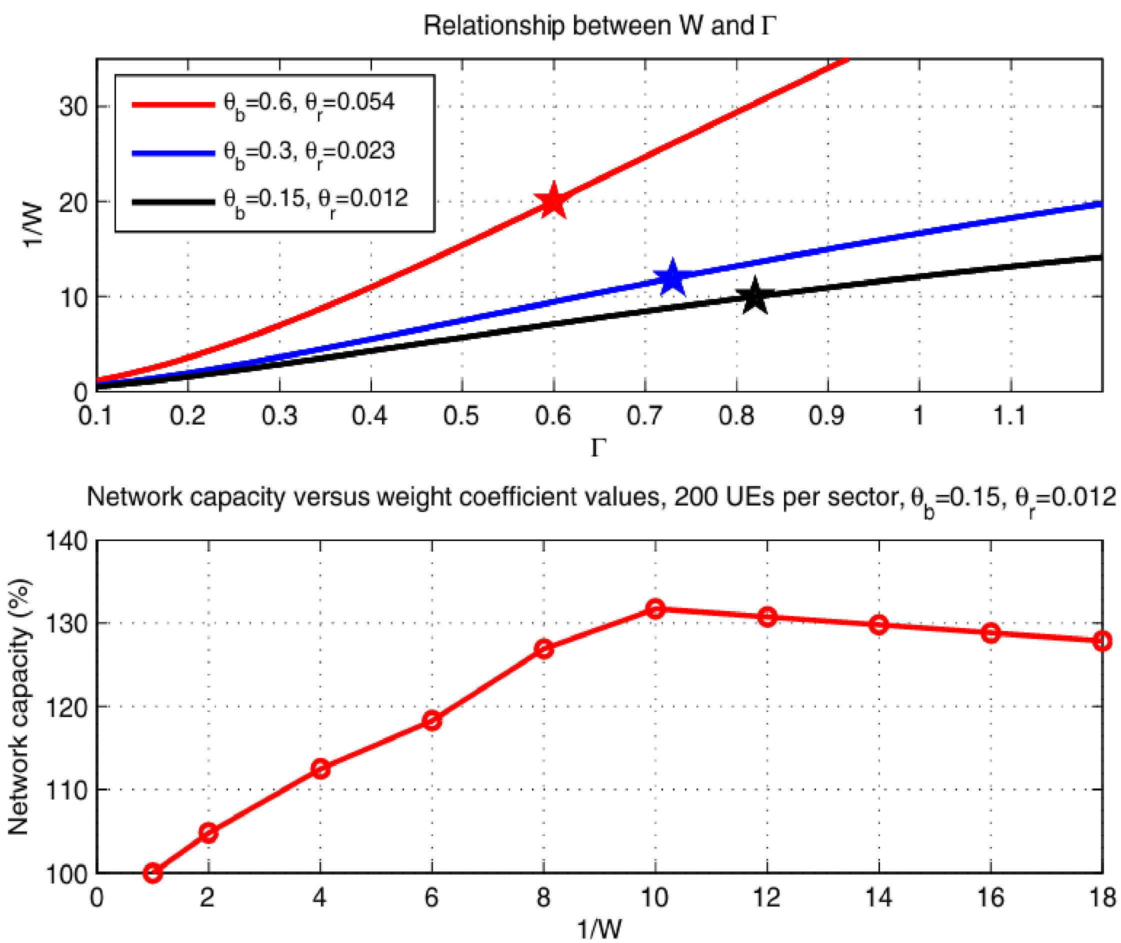
Q. Li, Rose. Q. Hu, G. Wu, Y. Qian, "On the Optimal Mobile Association in Heterogeneous Wireless Relay Networks", in Proceedings of IEEE INFOCOM 2012

Network Throughput



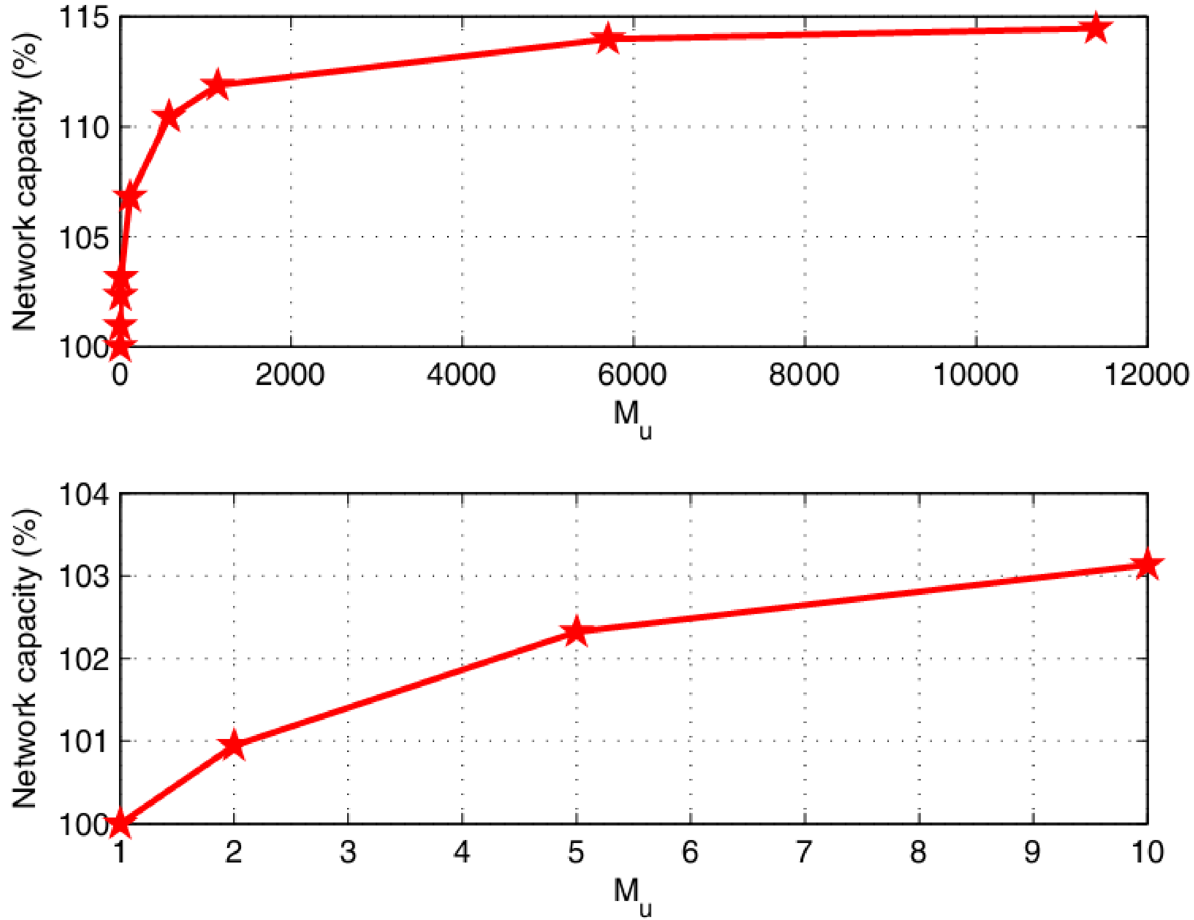
Q. Li, Rose. Q. Hu, G. Wu, Y. Qian, "On the Optimal Mobile Association in Heterogeneous Wireless Relay Networks", in Proceedings of IEEE INFOCOM 2012

RN Weight Selection



Q. Li, Rose. Q. Hu, G. Wu, Y. Qian, "On the Optimal Mobile Association in Heterogeneous Wireless Relay Networks", in Proceedings of IEEE INFOCOM 2012

Performance of Online Algorithm



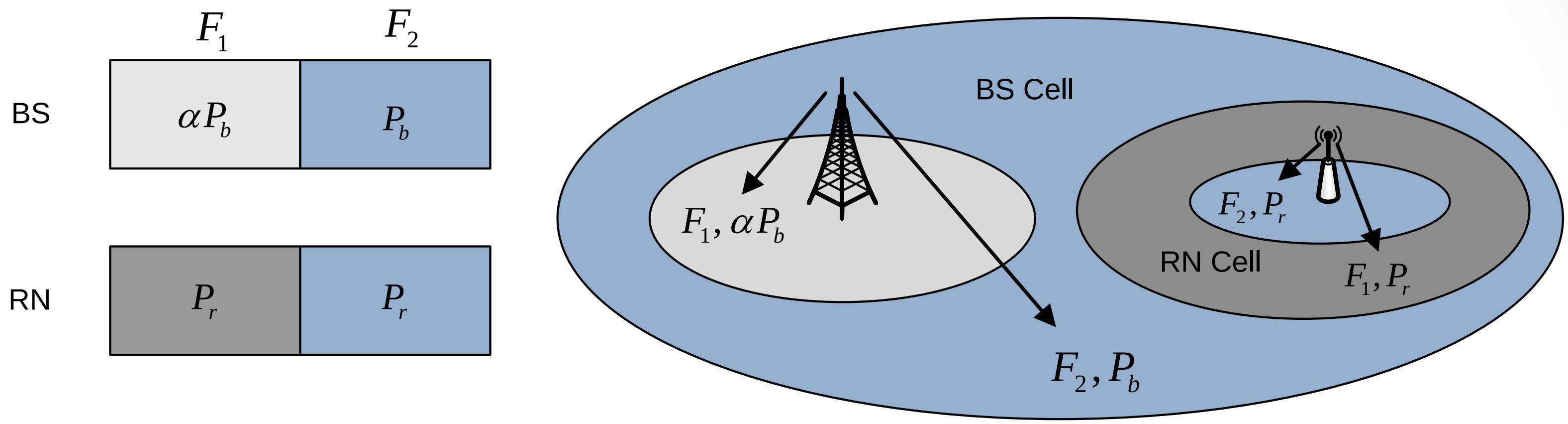
Q. Li, Rose. Q. Hu, G. Wu, Y. Qian, "On the Optimal Mobile Association in Heterogeneous Wireless Relay Networks", in Proceedings of IEEE INFOCOM 2012

Interference management - FFR with Power control

- The high transmit power of the macro BS imposes high interference at the micro BSs, impairing performance of the UEs associated with the micro BSs
- Our numerical results in the mobile association part showed that with frequency reuse, the network throughput can be greatly improved as compared to the case without frequency reuse
- The orthogonal frequency reuse scheme completely eliminate interference, but may not able to fully utilize the spectrum efficiency
- We propose a fractional frequency reuse (FFR) scheme with power control to curb interference as well as improve spectrum efficiency

Q. Li, Rose. Q. Hu, Y. Xu, Y. Qian, "Optimal Fractional Frequency Reuse and Power control in the Heterogeneous Wireless Networks", submitted to IEEE Transactions on Wireless Communications

FFR with power control



- Divide the total frequency band into two parts f_1 and f_2
- In f_1, macro-BSs transmit at αP_b $(0 \leq \alpha \leq 1)$ to the cell center UEs, micro-BSs transmit at full power to the UEs at the edge of the micro cell
- In f_2, both macro and micro BSs transmit at their respective full powers. Macro BSs transmits to the cell edge UEs while micro BSs transmit to the UEs in the center of the micro cell
- Define $\beta = f_1/F$, the task is to determine the optimal α and β values

Problem formulation

$$\min U(\alpha, \mathbf{n}) = -\sum_{m=1}^{2}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r}\sum_{k=1}^{N_u} x_{k,j,i}^{f_m} \log(n_{k,j,i}^{f_m} R_{k,j,i}^{f_m})$$

Subject to

$$\begin{aligned}
\sum_{k=1}^{N_u} x_{k,j,i}^{f_1} n_{k,j,i}^{f_1} &\leq \beta F, \text{ for } i = 1, \cdots, N_c, j = 0, \cdots, N_r \\
\sum_{k=1}^{N_u} x_{k,j,i}^{f_2} n_{k,j,i}^{f_2} &\leq (1-\beta) F, \text{ for } i = 1, \cdots, N_c, j = 0, \cdots, N_r \\
\sum_{m=1}^{2}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r} x_{k,j,i}^{f_m} n_{k,j,i}^{f_m} R_{k,j,i}^{f_m} &\geq R_{\min}, \text{ for } k = 1, \cdots, N_u \\
\sum_{i=1}^{N_c}\sum_{j=0}^{N_r} (x_{k,j,i}^{f_1} + x_{k,j,i}^{f_2}) &\leq 1, \text{ for } k = 1, \cdots, N_u \\
n_{k,j,i}^{f_t} &\geq 0, \text{ for } t = 1, 2; i = 1, \cdots, N_c, j = 1, \cdots, N_r \\
0 \leq \alpha &\leq 1 \\
0 \leq \beta &\leq 1.
\end{aligned}$$

Where $n_{k,j,i}^{f_1}$ denote the spectrum resource in the f_1 th sub-band allocated to the kth UE associated with the j th macro BS in the i th macro sector

Optimal ITIC

- The objective is to find the optimal values of α, β and $n_{k,j,i}^{f_m}$
- Propose a two-loop optimization procedure
  - In the outer loop, optimize α and β values using brute-force search, starting from $\alpha(0) = 0$ and $\beta(0) = 0$ and updated in each step by $\Delta\alpha$ and $\Delta\beta$
  - In the inner loop, for a given set of α and β values, the optimization problem becomes a constraint convex optimization. The optimal $n_{k,j,i}^{f_m}$ values can be found using the dual problem and the KKT condition

Dual Problem

- The Lagrange function of the optimization problem is

$$
\begin{aligned}
L(n_{k,j,i}^{f_m}, \lambda_{j,i}^{f_m}, \lambda_k, \nu_k^{f_m}) \;=\; & -\sum_{m=1}^{2}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r}\sum_{k=1}^{N_u} x_{k,j,i}^{f_m}\log(n_{k,j,i}^{f_m}R_{k,j,i}^{f_m}) \\
& + \sum_{m=1}^{2}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r}\lambda_{j,i}^{f_m}\left(\sum_{k=1}^{N_u} x_{k,j,i}^{f_m} n_{k,j,i}^{f_m} - f_m\right) \\
& + \sum_{k=1}^{N_u}\lambda_k\left(R_{\min} - \sum_{m=1}^{2}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r} x_{k,j,i}^{f_m} n_{k,j,i}^{f_m} R_{k,j,i}^{f_m}\right) \\
& - \sum_{m=1}^{2}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r}\sum_{k=1}^{N_u}\nu_{k,j,i}^{f_m} n_{k,j,i}^{f_m}
\end{aligned}
$$

- The dual function is defined as

$$
g(\lambda_{j,i}^{f_m}, \lambda_k, \nu_{k,j,i}^{f_m}) := \inf_{n_{k,j,i}^{f_m}} L(n_{k,j,i}^{f_m}, \lambda_{j,i}^{f_m}, \lambda_k, \nu_{k,j,i}^{f_m})
$$

- The dual problem is

$$
\begin{aligned}
[\mathbf{P}_2] \qquad & \max \quad g(\lambda_{j,i}^{f_m}, \lambda_k, \nu_{k,j,i}^{f_m}) \\
\text{subject to} \qquad & \lambda_{j,i}^{f_m} \geq 0, \quad \lambda_k \geq 0, \quad \nu_{k,j,i}^{f_m} \geq 0
\end{aligned}
$$

Solve the Dual Problem

- Find the optimal $\lambda_{j,i}^{f_m}$, λ_k, and $\nu_{k,j,i}^{f_m}$ values from the dual problem
  - By calculating the conjugate function, the close-form expression of the dual function can be found as

$$
\begin{aligned}
& g(\lambda_{j,i}^{f_m}, \lambda_k, \nu_{k,j,i}^{f_m}) \\
= & -\sum_{m=1}^{2}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r}\sum_{k=1}^{N_u} \lambda_{j,i}^{f_m} f_m + \sum_{k=1}^{N_u} \lambda_k R_{\min} \\
& + \sum_{m=1}^{2}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r}\sum_{k=1}^{N_u} \left(x_{k,j,i}^{f_m}\left(1-\log(x_{k,j,i}^{f_m})\right) + x_{k,j,i}^{f_m} \log\left(\lambda_{j,i}^{f_m} x_{k,j,i}^{f_m} - \lambda_k x_{k,j,i}^{f_m} R_{k,j,i}^{f_m} - \nu_{k,j,i}^{f_m}\right)\right)
\end{aligned}
$$

  - The optimal $\lambda_{j,i}^{f_m}$, λ_k, and $\nu_{k,j,i}^{f_m}$ values can be found using gradient descent method by updating along the directions

$$
\Delta\lambda_{j,i}^{f_m} = \sum_{k=1}^{N_u} \frac{\left(x_{k,j,i}^{f_m}\right)^2}{\lambda_{j,i}^{f_m} x_{k,j,i}^{f_m} - \lambda_k x_{k,j,i}^{f_m} R_{k,j,i}^{f_m} - \nu_{k,j,i}^{f_m}} - f_m, \quad \Delta\nu_{k,j,i}^{f_m} = \frac{x_{k,j,i}^{f_m}}{\lambda_{j,i}^{f_m} x_{k,j,i}^{f_m} - \lambda_k x_{k,j,i}^{f_m} R_{k,j,i}^{f_m} - \nu_{k,j,i}^{f_m}}
$$

$$
\Delta\lambda_k = R_{\min} - \sum_{m=1}^{2}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r} \frac{\left(x_{k,j,i}^{f_m}\right)^2 R_{k,j,i}^{f_m}}{\lambda_{j,i}^{f_m} x_{k,j,i}^{f_m} - \lambda_k x_{k,j,i}^{f_m} R_{k,j,i}^{f_m} - \nu_{k,j,i}^{f_m}}
$$

KKT condition

- Based on the optimal $\lambda_{j,i}^{f_m *}$, λ_k^*, and $\nu_{k,j,i}^{f_m *}$ values, the optimal $n_{k,j,i}^{f_m}$ value can be calculated from the KKT condition, by solving

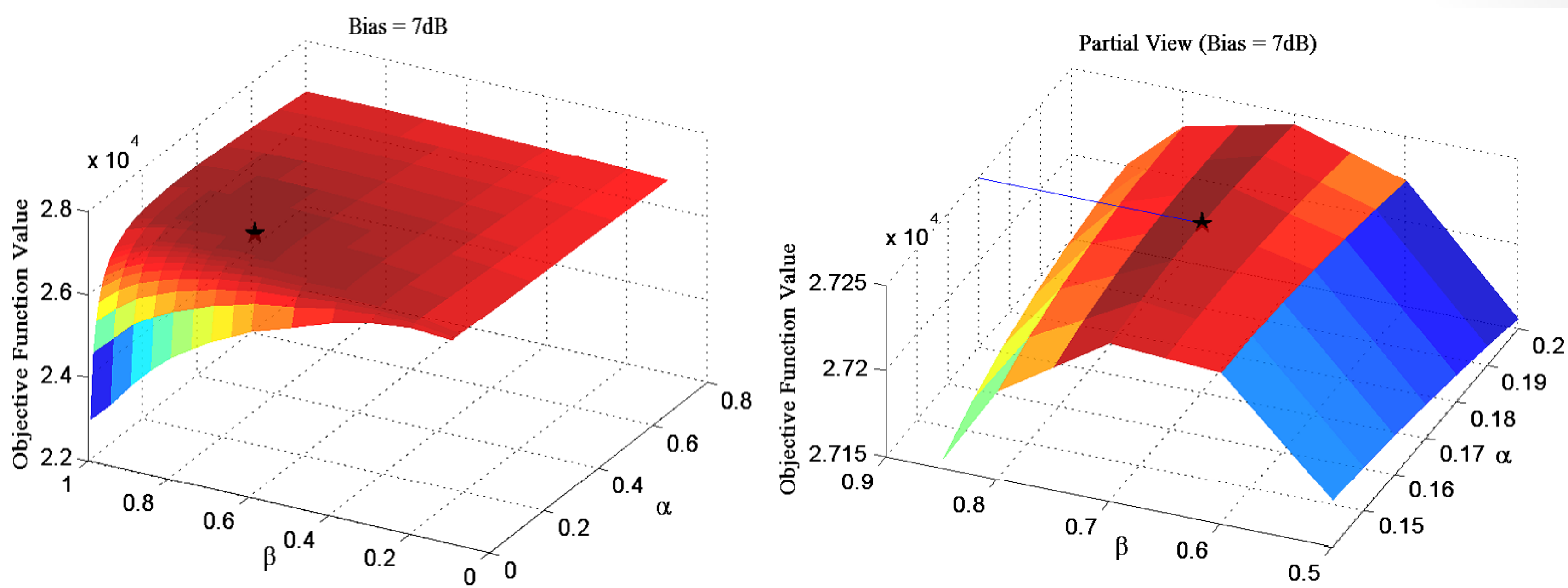
$$\frac{\partial L_{k,j,i}(n_{k,j,i}^{f_m}, \lambda_{j,i}^{f_m *}, \lambda_k^*), \nu_{k,j,i}^{f_m *}}{\partial n_{k,j,i}^{f_m}} = -\frac{x_{k,j,i}^{f_m}}{n_{k,j,i}^{f_m}} + \lambda_{j,i}^{f_m *} x_{k,j,i}^{f_m} - \lambda_k^* x_{k,j,i}^{f_m} R_{k,j,i}^{f_m} - \nu_{k,j,i}^{f_m *} = 0$$

obtaining

$$n_{k,j,i}^{f_m *} = \frac{x_{k,j,i}^{f_m}}{\lambda_{j,i}^{f_m *} x_{k,j,i}^{f_m} - \lambda_k^* x_{k,j,i}^{f_m} R_{k,j,i}^{f_m} - \nu_{k,j,i}^{f_m *}}$$

The obtained $\lambda_{j,i}^{f_m *}$, λ_k^*, $\nu_{k,j,i}^{f_m *}$ and $n_{k,j,i}^{f_m *}$ values satisfies the KKT conditions and thus is the optimal solution for the considered convex optimization problem.

Numerical Results (1)



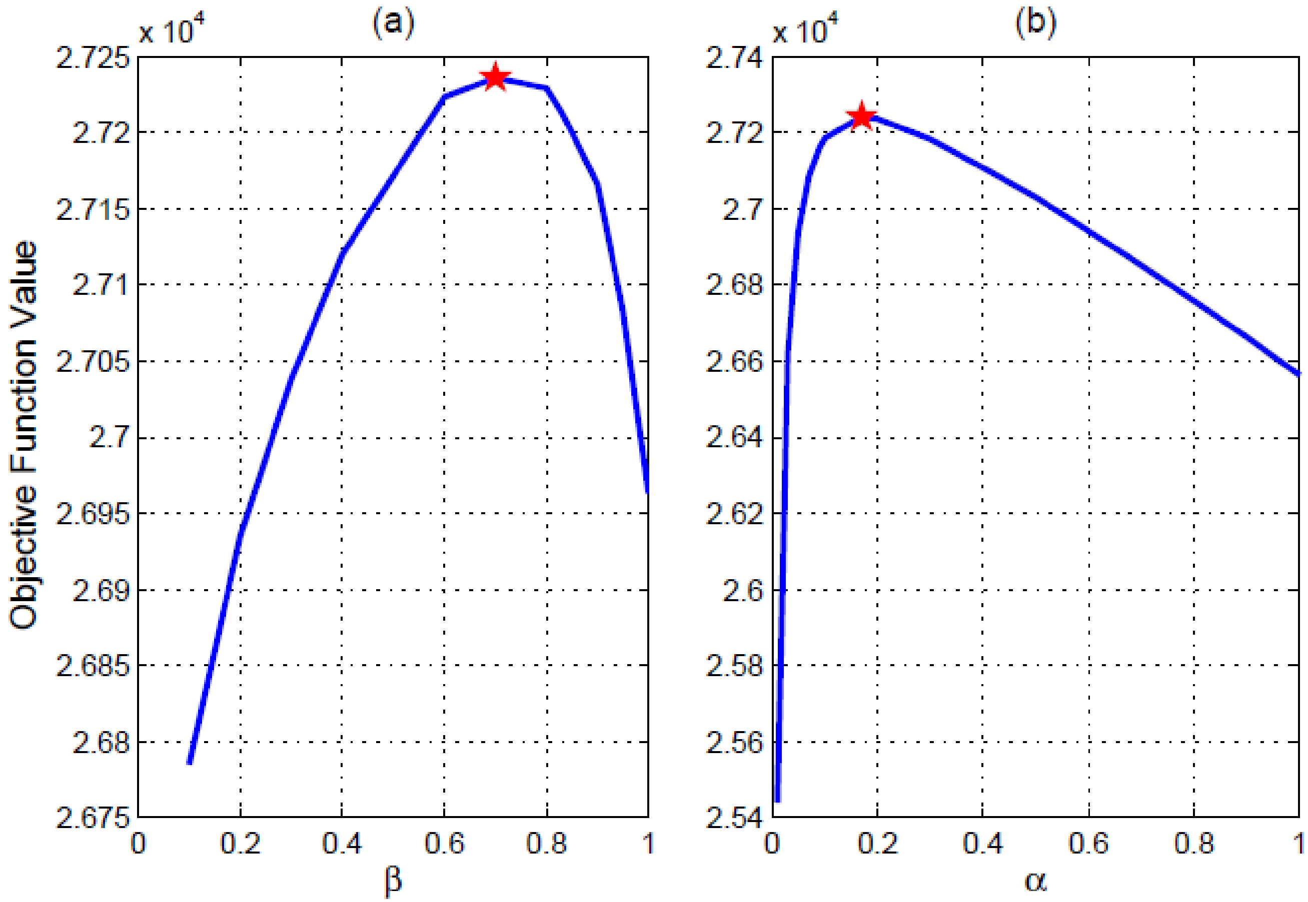
Objective function value for all possible α and β combinations

$$(\alpha^*, \beta^*) = (0.17, 0.7)$$

Allocate f_1 sub-band with about 2/3 of the total frequency resource and let the BSs transmit at a power of 6.8 W at its inner cell

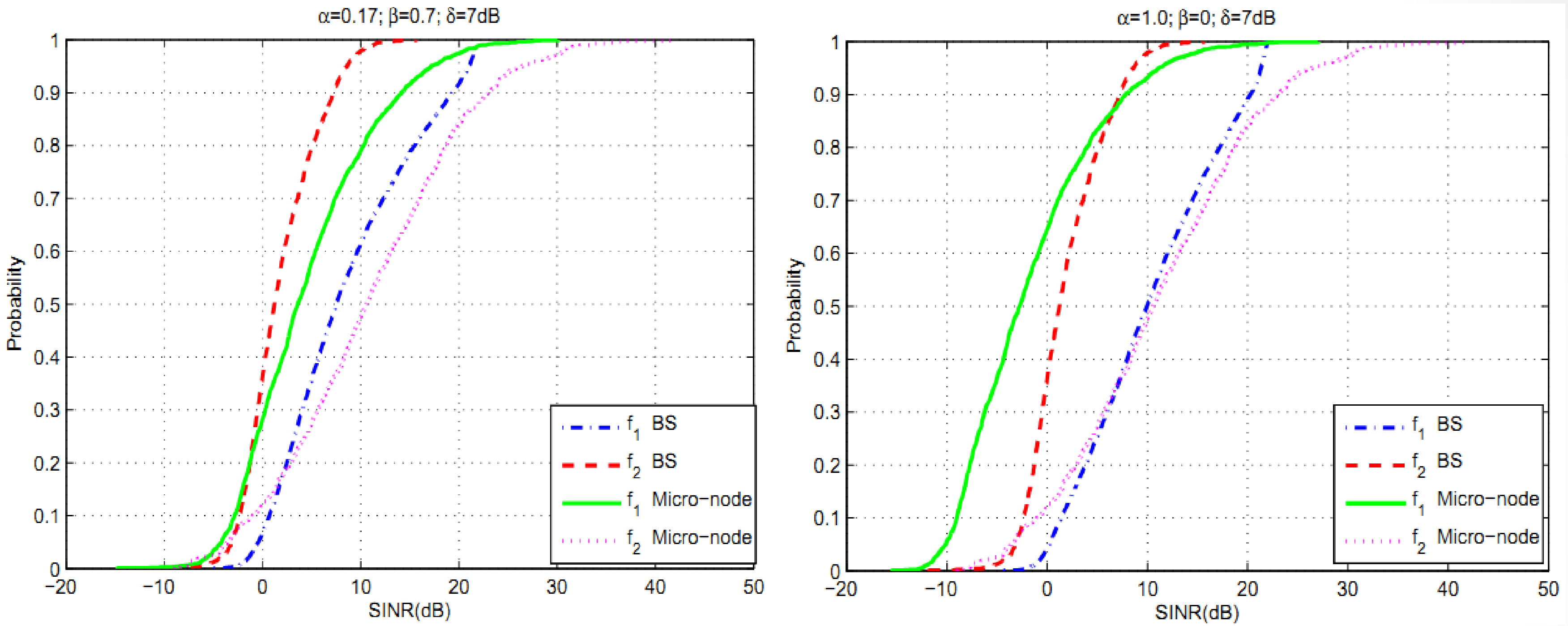
Q. Li, Rose. Q. Hu, Y. Xu, Y. Qian, "Optimal Fractional Frequency Reuse and Power control in the Heterogeneous Wireless Networks", submitted to IEEE Transactions on Wireless Communications

Numerical Results (2)



Q. Li, Rose. Q. Hu, Y. Xu, Y. Qian, "Optimal Fractional Frequency Reuse and Power control in the Heterogeneous Wireless Networks", submitted to IEEE Transactions on Wireless Communications

Numerical Results (3)



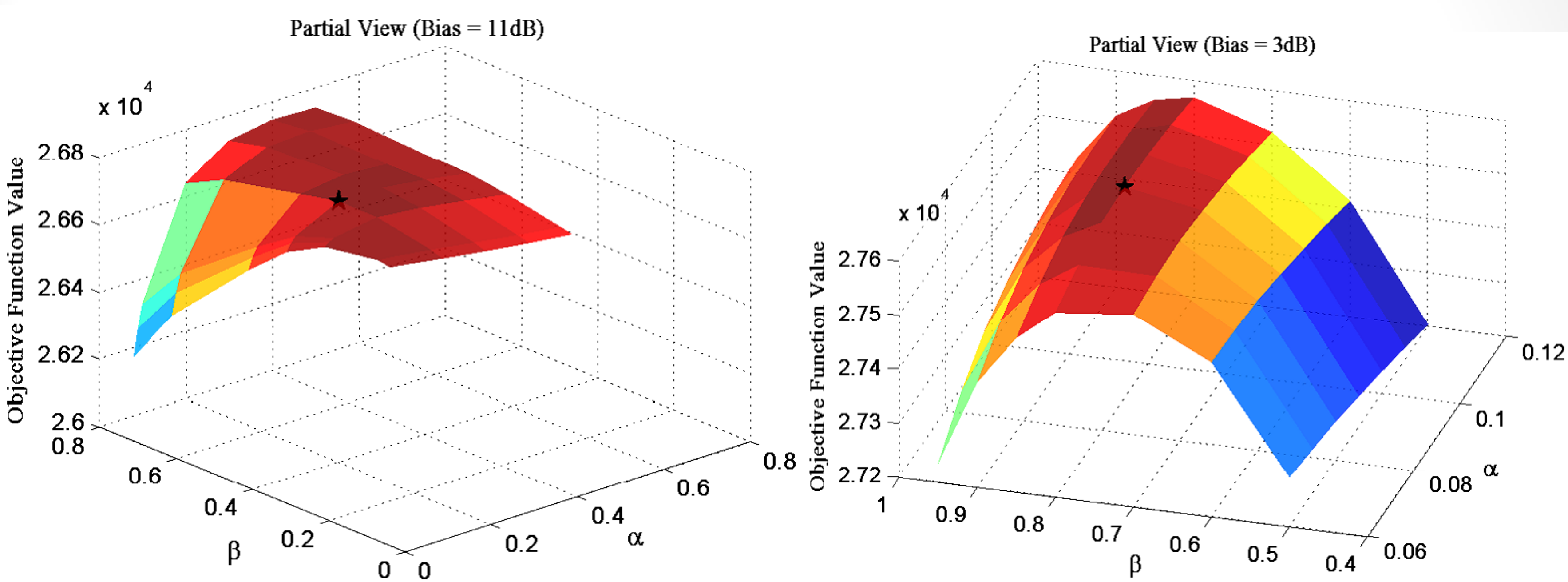
(a) (b)

Empirical cumulative distribution for UEs' SINR under

(a) With ITIC $\alpha = 0.17$ and $\beta = 0.7$ and (b) No ITIC $\alpha = 1$ and $\beta = 0$

Q. Li, Rose. Q. Hu, Y. Xu, Y. Qian, "Optimal Fractional Frequency Reuse and Power control in the Heterogeneous Wireless Networks", submitted to IEEE Transactions on Wireless Communications

Numerical Results (4)



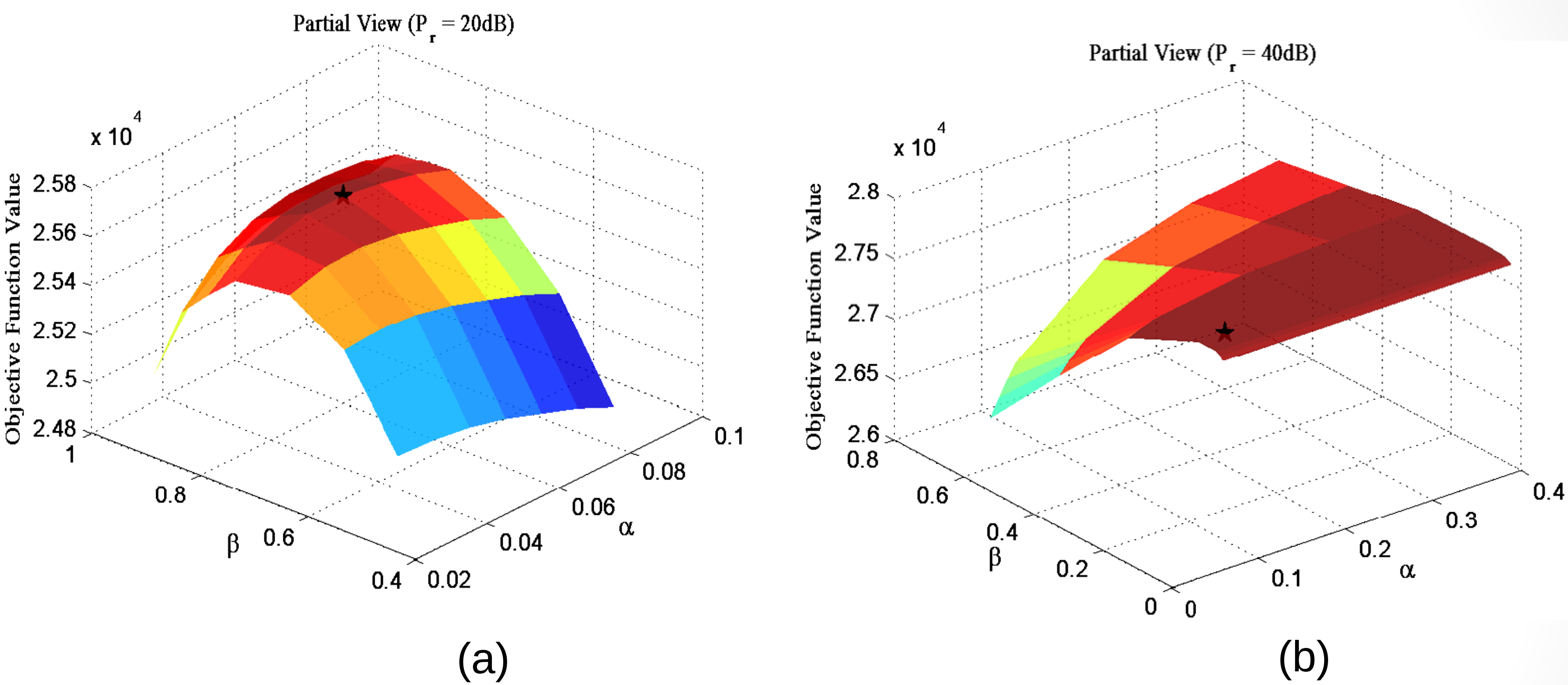
(a) (b)

Objective function value under different mobile association bias

(a) BP $\delta = 11\ \text{dB}$ (b) PL $\delta = 3\ \text{dB}$

Q. Li, Rose. Q. Hu, Y. Xu, Y. Qian, "Optimal Fractional Frequency Reuse and Power control in the Heterogeneous Wireless Networks", submitted to IEEE Transactions on Wireless Communications

Numerical Results (5)



Objective function value under different micro-node transmit powers

(a) $P_r = 20\ \text{dB}$ and (b) $P_r = 40\ \text{dB}$

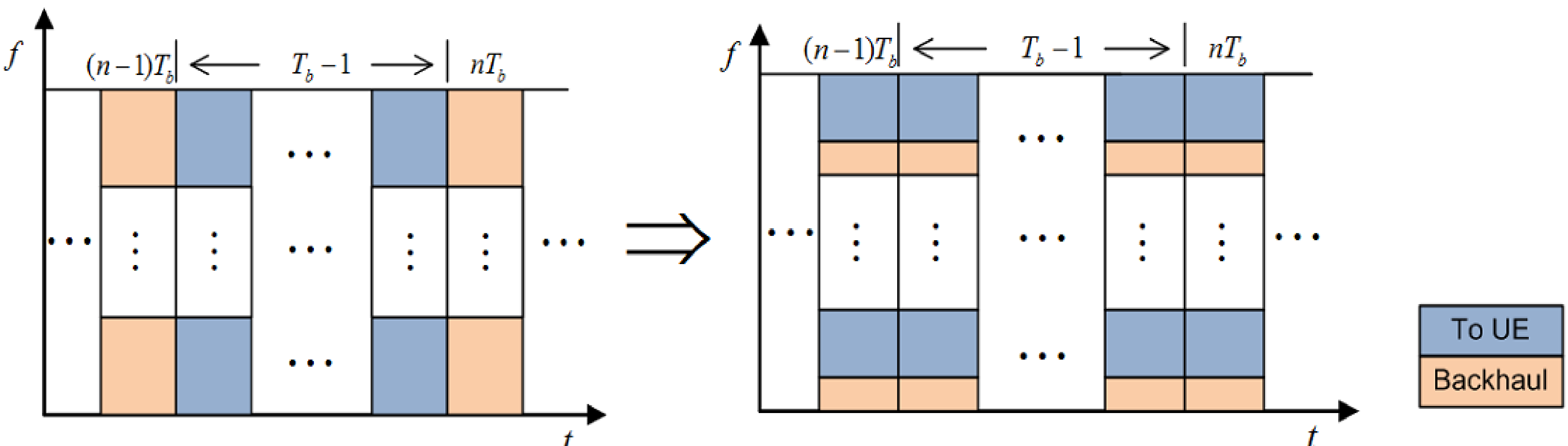
Q. Li, Rose. Q. Hu, Y. Xu, Y. Qian, "Optimal Fractional Frequency Reuse and Power control in the Heterogeneous Wireless Networks", submitted to IEEE Transactions on Wireless Communications

Radio Resource Management: Proportional Fairness based resource allocation

- For time-varying fading channels, radio resources should be allocated to the macro and micro BSs in a timely manner considering spectrum efficiency and QoS requirements of the UEs
- For HetNets with relay nodes (RN), radio resource allocation should also consider the in-band backhaul
- Relevant works have been down on simply relay system where relay works in half-duplex mode and receives and forwards in each half of a time frame
- Simply half-duplex relaying works well when BS-RN link (backhaul) is of similar quality as the RN-UE link. However, for systems with better backhual links, such relaying scheme would lead to inefficient use of the resources
- We consider radio resource allocation and scheduling for HetNets with RNs of full RRM capability

Q. Li, Rose. Q. Hu, Y. Qian, Geng Wu, "A Proportional Fair Radio Resource Allocation for Heterogeneous Cellular Networks with Relays", Accepted by IEEE Globecom 2012

Scheduling Scheme



(a) Practical transmission scheduling

(b) Mathematical Equivalence

- RNs receive information from their donor BS in the backhual link
- Backhaul communication takes place every T_b time slots
- RNs store the received information in its buffer and forward to the corresponding UEs in the appropriate time/frequency as scheduled
- The resources are allocated in the unite of resource block (RB) as shown in Fig.(a). For ease of analysis, we virtually distribute the backhual resource consumption into each RB as shown in Fig.(b)

Optimal scheduling

The resource allocation problem can be formulated as

$$[\mathbf{P}_1] \qquad \max U(\mathbf{R}(t)) = \sum_{k=1}^{N_u} \log(R_k(t))$$

subject to

$$\sum_{k=1}^{N_u} x_{k,0,i} n_{k,0,i}^{f}(t) + \sum_{j=1}^{N_r} \sum_{k=1}^{N_u} x_{k,j,i} n_{k,j,i}^{b,f}(t) \le 1,$$

$$\text{for } i = 1, \cdots, N_c, f = 1, \cdots, F$$

$$\sum_{k=1}^{N_u} x_{k,j,i} n_{k,j,i}^{f}(t) + \sum_{k=1}^{N_u} x_{k,j,i} n_{k,j,i}^{b,f}(t) \le 1,$$

$$\text{for } i = 1, \cdots, N_c,\ j = 1, \cdots, N_r, f = 1, \cdots, F$$

$$n_{k,j,i}^{f}(t) \ge 0,\ \forall i, j, k, f$$

where

$$R_k(t) = \frac{1}{T_c} \sum_{\tau=t-T_c+1}^{t} S_k(\tau), \qquad S_k(\tau) = \sum_{f=1}^{F} \sum_{i=1}^{N_c} \sum_{j=1}^{N_r} x_{k,j,i} R_{k,j,i}^{f}(\tau) n_{k,j,i}^{f}(\tau)$$

Asymptotically Optimal Solution

- By applying gradient-based scheduling, maximize the drift of the objective function given as

$$
\begin{aligned}
&U(\mathbf{R}(t+1)) - U(\mathbf{R}(t)) \\
=&\sum_{k=1}^{N_u}\left(\log\left(R_k(t)+\epsilon_t\left(S_k(t+1)-R_k(t)\right)\right)-\log\left(R_k(t)\right)\right) \\
=&\sum_{k=1}^{N_u}\frac{1}{R_k(t)}S_k(t+1)\epsilon_t-\sum_{k=1}^{N_u}\frac{1}{R_k(t)}R_k(t)\epsilon_t+O(\epsilon_t^2)
\end{aligned}
$$

- The objective of the optimization problem reduces to

$$
[\mathbf{P}_2]\quad \max_{n_{k,j,i}^f(t)}\sum_{k=1}^{N_u}\sum_{i=1}^{N_c}\sum_{j=1}^{N_r}\frac{1}{R_k(t-1)}x_{k,j,i}R_{k,j,i}^f(t)n_{k,j,i}^f(t)
$$

Asymptotically Optimal Solution (2)

- Problem $\mathbf{P}_2$ is convex. By solving from KKT conditions, the optimal solution is given as
- For the ith BS, allocate the fth RB at the tth subframe to the UE with index

$$k_{0,i}^{f*} = \arg\max_{k \in \mathcal{K}_{0,i}} \frac{R_{k,0,i}^{f}(t)}{R_k(t-1)}$$

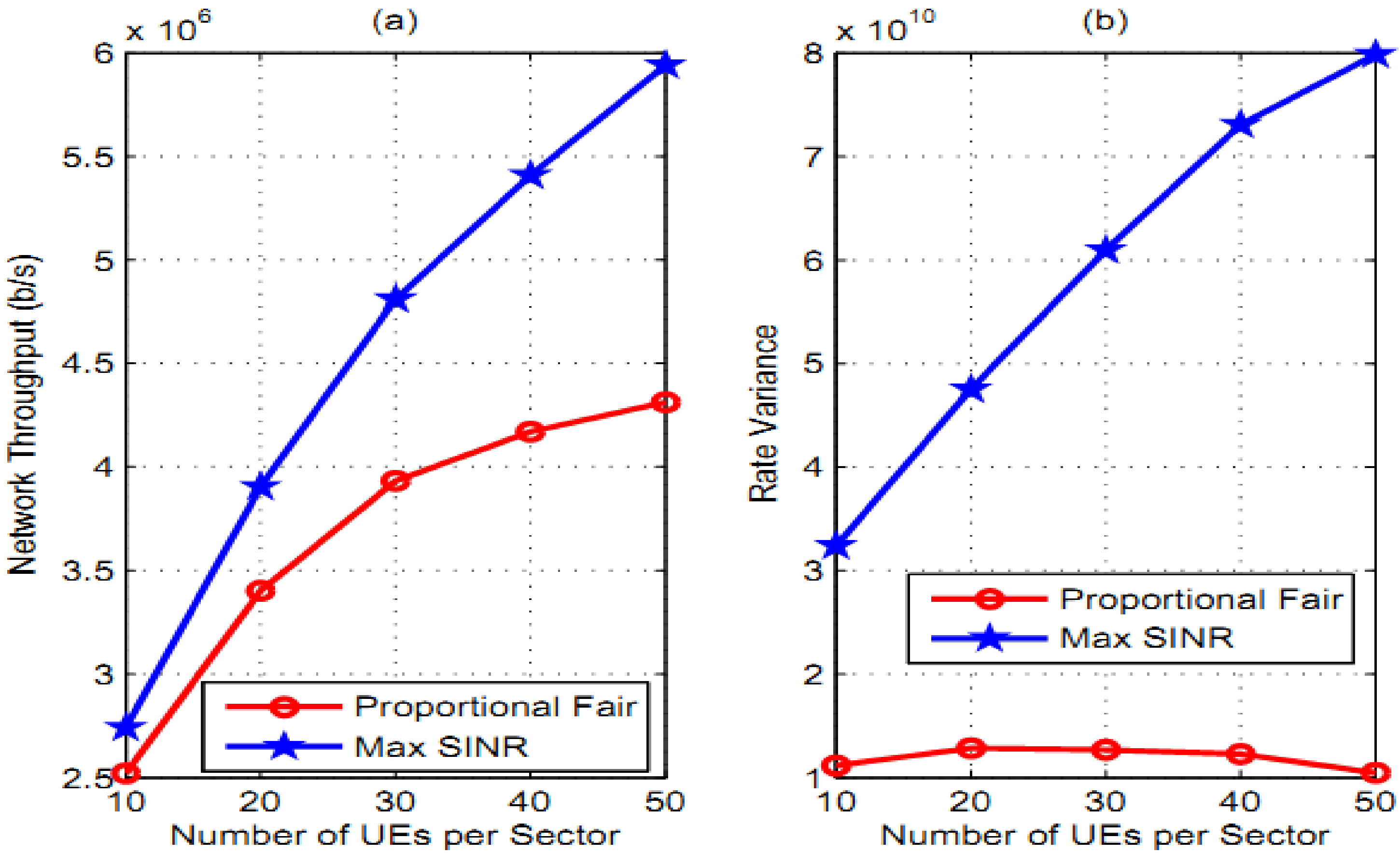
- For the jth RN, allocate the fth RB at the tth subframe to the UE with index

$$k_{j,i}^{f*} = \arg\max_{k \in \mathcal{K}_{j,i}} \frac{1}{1 + a_{k,j,i}^{f}(t)} \left(\frac{R_{k,j,i}^{f}(t)}{R_k(t-1)} - \lambda_i^{f*}(t) a_{k,j,i}^{f}(t) \right)$$

where

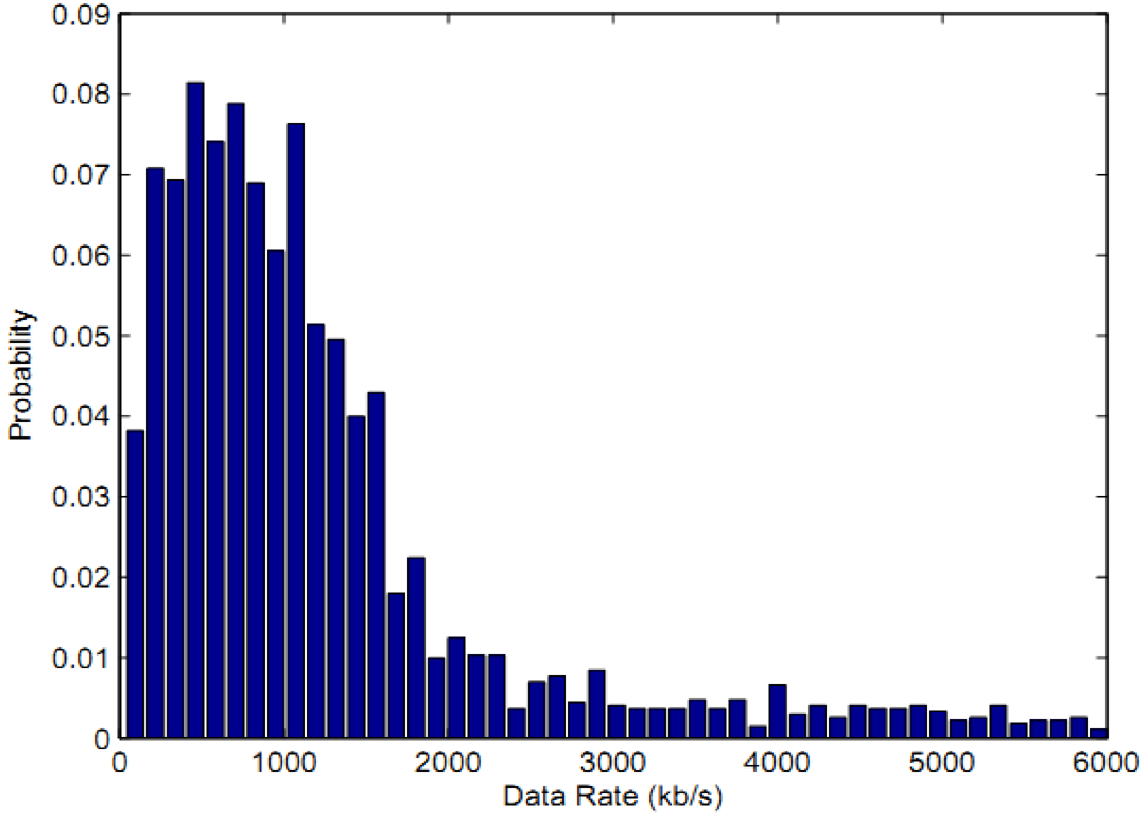
$$a_{k,j,i}^{f}(t) = \frac{R_{k,j,i}^{f}(t)}{R_{0,j,i}^{f}} \qquad \lambda_i^{f*}(t) = \max_{k \in \mathcal{K}_{0,i}} \frac{R_{k,0,i}^{f}(t)}{R_k(t-1)}$$

Performance Evaluation (1)



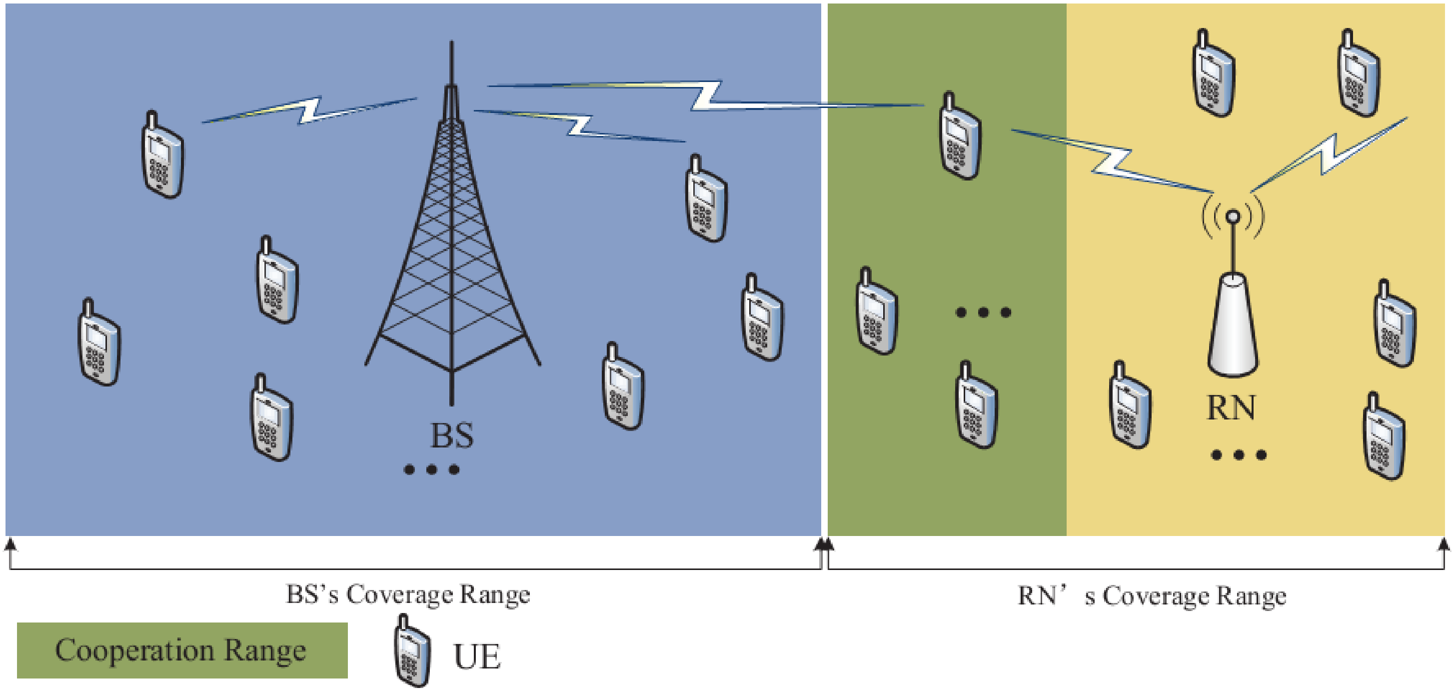
Q. Li, Rose. Q. Hu, Y. Qian, Geng Wu, "A Proportional Fair Radio Resource Allocation for Heterogeneous Cellular Networks with Relays", Accepted by IEEE Globecom 2012

Performance Evaluation (2)



Q. Li, Rose. Q. Hu, Y. Qian, Geng Wu, "A Proportional Fair Radio Resource Allocation for Heterogeneous Cellular Networks with Relays", Accepted by IEEE Globecom 2012

FFR and RRM for HetNets with Intra-Cell CoMP



- UEs in the edge of the RN cell suffer from high interference from the BS
- By intra-cell CoMP, BS and RN transmit simultaneously towards the set of UEs in the edge of the RN cell
- The problem is to determine the set of CoMP UEs, and the resource allocated to the B-UEs, R-UEs, C-UEs.

Q. Li, Rose. Q. Hu, Y. Qian, Geng Wu, "Intra-cell Cooperation and Resource Allocation in a Heterogeneous Network with Relays", Accepted by IEEE Transactions on Vehicular Technology.

Problem Formulation

$$\max \sum_k \log(R_k(t))$$

Subject to

$$\sum_{k=1}^{N_u} x_{k,0,i} n^f_{k,0,i}(t) + \sum_{j=1}^{N_r}\sum_{k=1}^{N_u} x_{k,j,i} x^{c,f}_{k,j,i}(t) n^{c,f}_{k,j,i}(t) + \sum_{j=1}^{N_r}\sum_{k=1}^{N_u} x_{k,j,i} n^{b,f}_{k,j,i}(t) \le 1$$

$$\text{for } i = 1, \cdots, N_c, f = 1, \cdots, F$$

$$\sum_{k=1}^{N_u} x_{k,j,i}(1 - x^{c,f}_{k,j,i}(t)) n^f_{k,j,i}(t) + \sum_{k=1}^{N_u} x_{k,j,i} x^{c,f}_{k,j,i}(t) n^{c,f}_{k,j,i}(t) + \sum_{k=1}^{N_u} x_{k,j,i} n^{b,f}_{k,j,i}(t) \le 1$$

$$\text{for } i = 1, \cdots, N_c,\ j = 1, \cdots, N_r, f = 1, \cdots, F$$

$$n^f_{k,j,i}(t) \ge 0\ \forall i, j, k, f$$

$$n^{c,f}_{k,j,i}(t) \ge 0\ \forall i, j, k, f$$

where

$$R_k(t) = \frac{1}{T_c} \sum_{\tau = t - T_c + 1}^{t} S_k(\tau),$$

$$S_k(\tau) = \sum_{f=1}^{F}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r} \left(x_{k,j,i}(1 - x^{c,f}_{k,j,i}(t)) R^f_{k,j,i}(\tau) n^f_{k,j,i}(\tau) + x_{k,j,i} x^{c,f}_{k,j,i}(\tau) R^{c,f}_{k,j,i}(\tau) n^{c,f}_{k,j,i}(\tau) \right)$$

Asymptotically Optimal Scheduling Scheme

- Based on gradient-based scheduling, an asymptotically optimal solution can be obtained by alternatively optimize

$$\max_{n^f_{k,j,i}(t),n^{c,f}_{k,j,i}(t)} \sum_{k=1}^{N_u}\sum_{i=1}^{N_c}\sum_{j=0}^{N_r} \frac{1}{R_k(t-1)}\Big(x_{k,j,i}(1-x^{c,f}_{k,j,i}(t))R^f_{k,j,i}(t)n^f_{k,j,i}(t)+x_{k,j,i}x^{c,f}_{k,j,i}(t)R^{c,f}_{k,j,i}(t)n^{c,f}_{k,j,i}(t)\Big)$$

- By using KKT conditions, the convex optimization problem can be solved obtaining the asymptotically optimal scheduling scheme
- Define

$$\lambda^f_{i,A}(t) = \max_{k_0\in\mathcal{K}_{0,i}} \frac{R^f_{k_0,0,i}(t)}{R_{k_0}(t-1)} \quad \lambda^f_{i,B}(t) = \max_{j\in\mathcal{J}_{i,1}}\left(\max_{k_2\in\mathcal{K}^c_{j,i}} \frac{R^{c,f}_{k_2,j,i}(t)(1+a^f_{k^*_{1,j},j,i}(t))}{R_{k_2}(t-1)(1+a^{c,f}_{k_2,j,i}(t))} - \frac{R^f_{k^*_{1,j},j,i}(t)}{R_{k^*_{1,j}}(t-1)}\right)$$

$$\lambda^f_{i,C}(t) = \max_{j\in\mathcal{J}_{i,2}} \max_{k_2\in\mathcal{K}^c_{j,i}} \frac{R^{c,f}_{k_2,j,i}(t)}{R_{k_2}(t-1)(1+a^{c,f}_{k_2,j,i}(t))}$$

The asymptotically optimal scheduling scheme is given by the following proposition

- Proposition 1: For the *f* th RB in the *t* th subframe in the *i* th sector
  - When $\lambda_{i,A}^f(t) \geq \max\{\lambda_{i,B}^f(t), \lambda_{i,C}^f(t)\}$, it is optimal to let the *i* th BS serve the k_0^*th B-UE over the whole RB, the RNs with indices $j \in \mathcal{J}_{i,1}$ serve the $k_{1,j}^*$th R-UE over the whole RB, and the RNs with indices $j \in \mathcal{J}_{i,2}$ in idle where

$$k_0^* = \arg\max_{k_0 \in \mathcal{K}_{0,i}} \frac{R_{k_0,0,i}^f(t)}{R_{k_0}(t-1)}$$

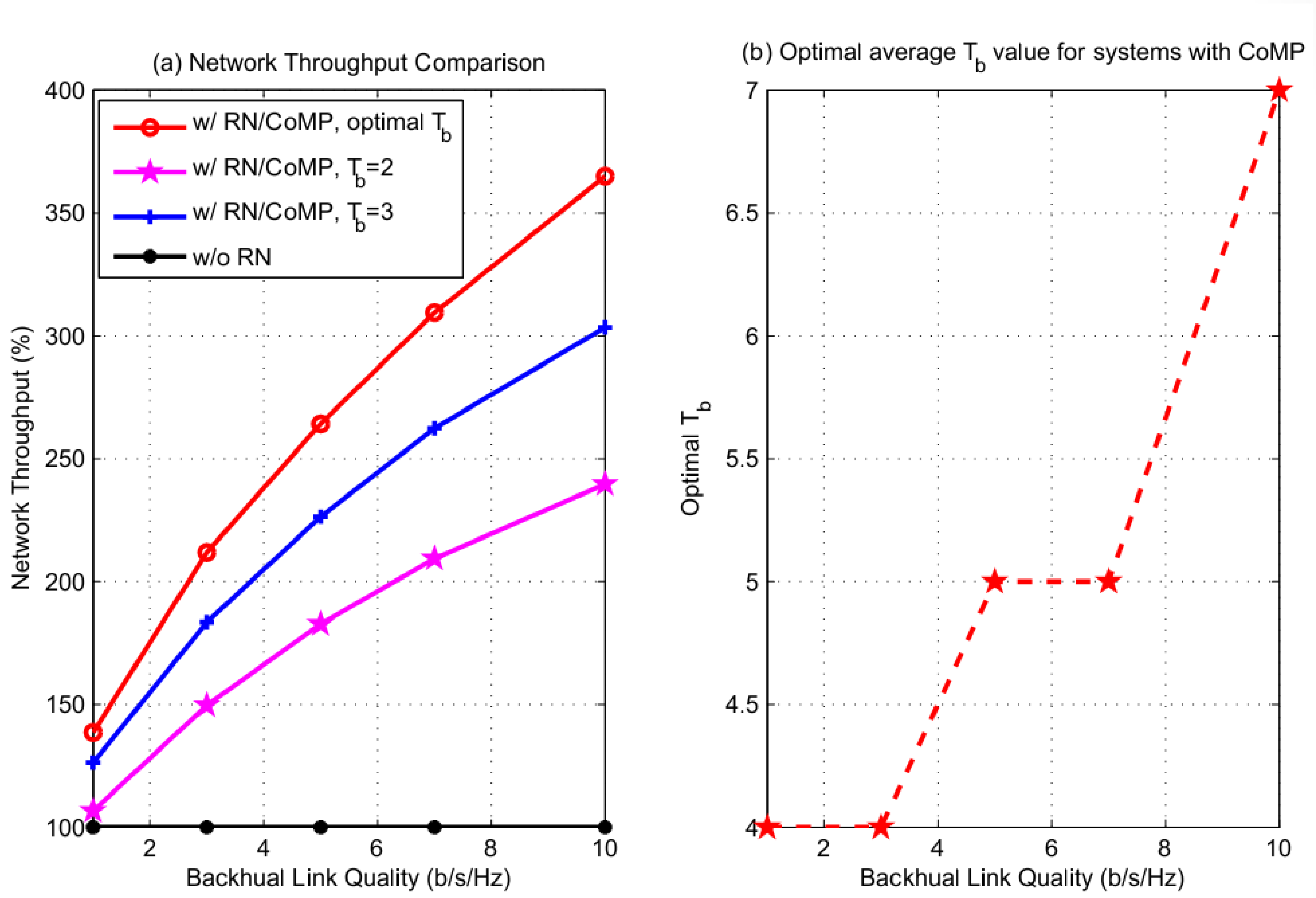
$$k_{1,j}^* = \arg\max_{k_{1,j} \in \mathcal{K}_{j,i}} \frac{1}{1 + a_{k_{1,j},j,i}^f(t)} \left(\frac{R_{k_{1,j},j,i}^f(t)}{R_{k_{1,j}}(t-1)} - a_{k_{1,j},j,i}^f(t) \lambda_i^f(t) \right)$$

  - When $\lambda_{i,A}^f(t) < \max\{\lambda_{i,B}^f(t), \lambda_{i,C}^f(t)\}$, it is optimal to let the *i* th BS and the j^*th RN cooperatively serve the k_2^* th C-UE, the RN with index $j \in \mathcal{J}_{i,1}$ serve the $k_{1,j}^*$th R-UE, and the RN with index $j \in \mathcal{J}_{i,2}$ in idle, where

$$j^* = \begin{cases} \arg\max_{j \in \mathcal{J}_{i,1}} \left(\max_{k_2 \in \mathcal{K}_{j,i}^c} \frac{R_{k_2,j,i}^{c,f}(t)(1+a_{k_{1,j}^*,j,i}^f(t))}{R_{k_2}(t-1)(1+a_{k_2,j,i}^{c,f}(t))} - \frac{R_{k_{1,j}^*,j,i}^f(t)}{R_{k_{1,j}^*}(t-1)} \right) & \text{if } \lambda_{i,B}^f(t) \geq \lambda_{i,C}^f(t) \\ \arg\max_{j \in \mathcal{J}_{i,2}} \left(\max_{k_2 \in \mathcal{K}_{j,i}^c} \frac{R_{k_2,j,i}^{c,f}(t)}{R_{k_2}(t-1)(1+a_{k_2,j,i}^{c,f}(t))} \right) & \text{if } \lambda_{i,B}^f(t) < \lambda_{i,C}^f(t), \end{cases}$$

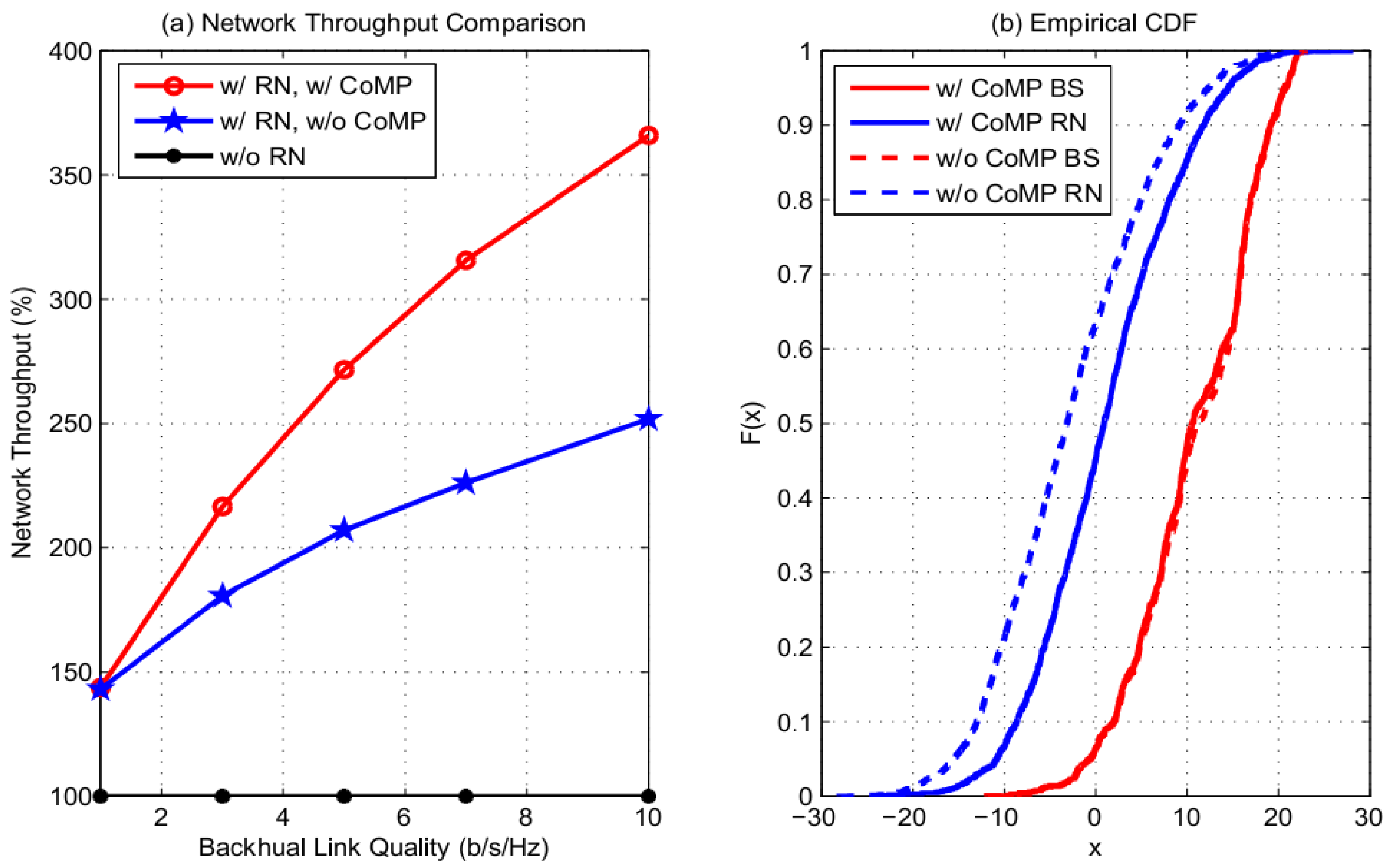
$$k_2^* = \begin{cases} \arg\max_{k_2 \in \mathcal{K}_{j^*,i}^c} \frac{R_{k_2,j^*,i}^{c,f}(t)(1+a_{k_{1,j}^*,j^*,i}^f(t))}{R_{k_2}(t-1)(1+a_{k_2,j^*,i}^{c,f}(t))} & \text{if } \lambda_{i,B}^f(t) \geq \lambda_{i,C}^f(t) \\ \arg\max_{k_2 \in \mathcal{K}_{j^*,i}^c} \frac{R_{k_2,j^*,i}^{c,f}(t)}{R_{k_2}(t-1)(1+a_{k_2,j^*,i}^{c,f}(t))} & \text{if } \lambda_{i,B}^f(t) < \lambda_{i,C}^f(t) \end{cases}$$

Performance Evaluation (1)



Q. Li, Rose. Q. Hu, Y. Qian, Geng Wu, "Intra-cell Cooperation and Resource Allocation in a Heterogeneous Network with Relays", Accepted by IEEE Transactions on Vehicular Technology.

Performance Evaluation (2)



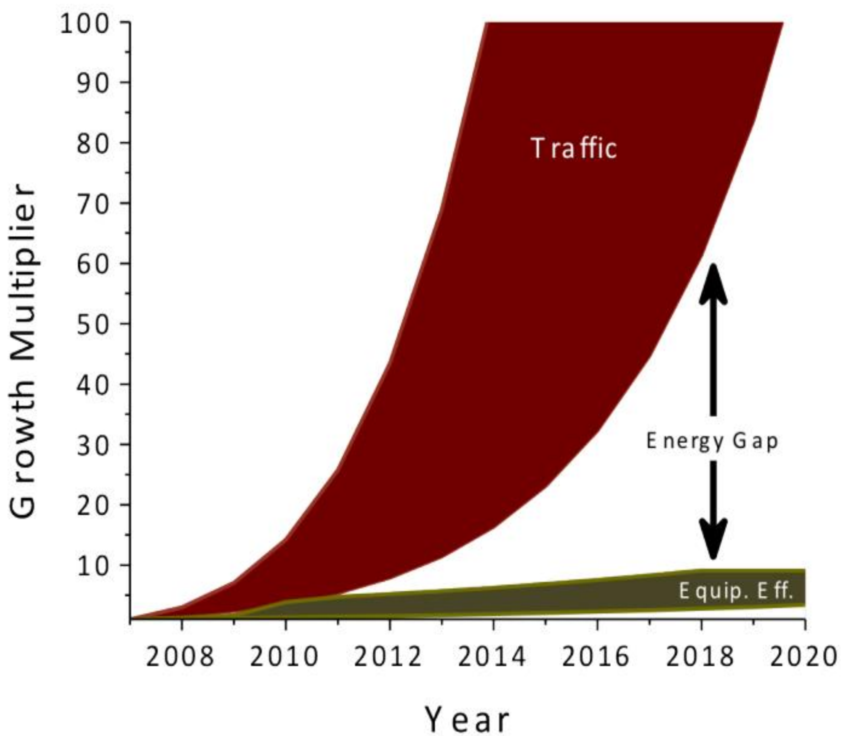
Q. Li, Rose. Q. Hu, Y. Qian, Geng Wu, "Intra-cell Cooperation and Resource Allocation in a Heterogeneous Network with Relays", Accepted by IEEE Transactions on Vehicular Technology.

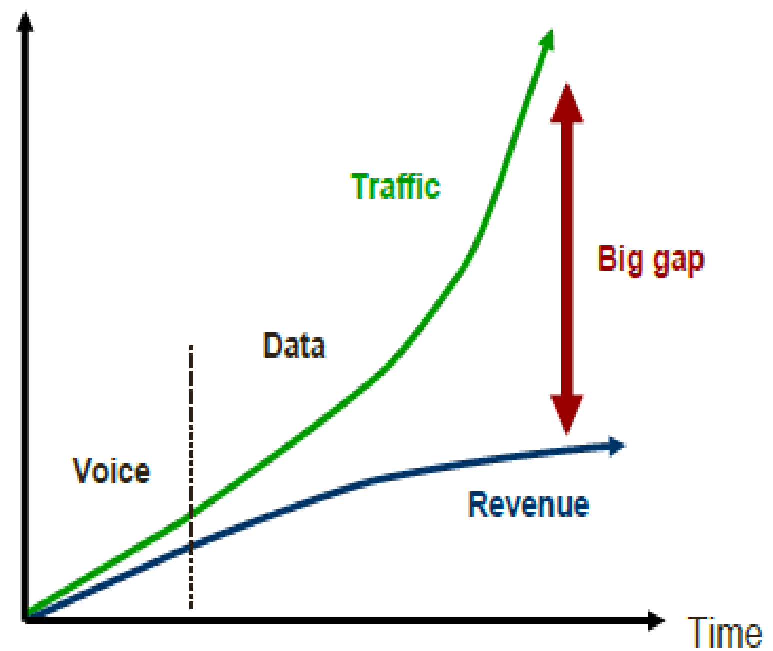
Energy Efficiency in HetNet

Motivations

- Information and Communication industry has the responsibility to reduce global carbon footprint
  - ICT represents around 2% of total carbon emissions of which mobile networks represents about 0.2%, and this is expected to increase every year
- Traffic is growing faster than equipment energy efficiency can be improved
- Operator has the incentive to reduce operational cost
  - For operators with many off-grid sites, energy provision may contribute up to 50 percent of their total operational cost
- Communication traffic pattern and techniques in equipment manufacture and link-level communication leave room for improving energy efficiency

Motivation



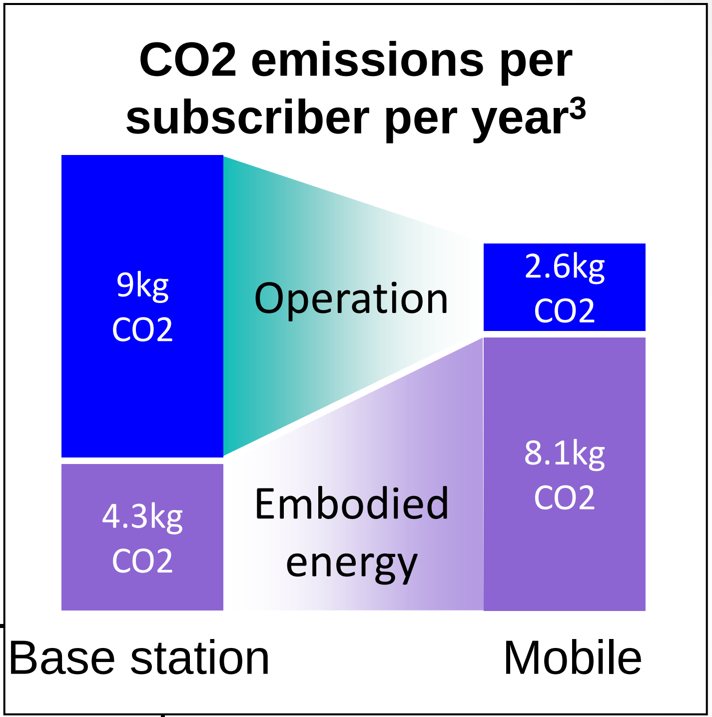


- Consequences
  - Energy use cannot follow traffic growth without significant increase in energy consumption ->must reduce Energy Per Bit
  - Number of base stations increasing -> must reduce Operating Power per cell to save TCO

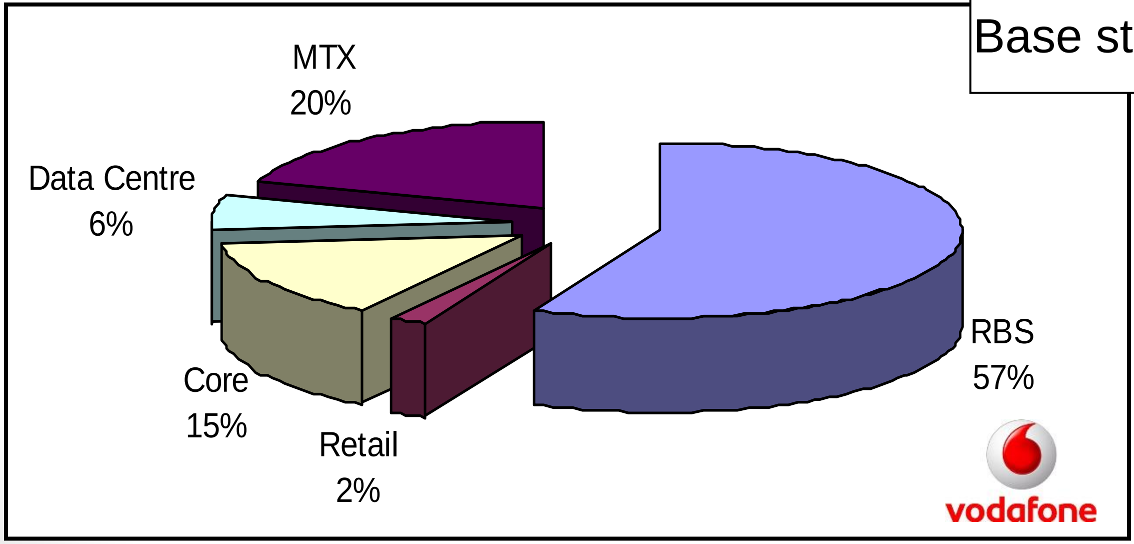
GreenTouch, “2010-2011 annual report”

Where is the Energy Used?

- For the operator, 57% of electricity use is in radio access
- Operating electricity is the dominant energy requirement at base stations
- For user devices, most of the energy used is due to manufacturing



3. Tomas Edler, Green Base Stations – How to Minimize CO2 Emission in Operator Networks, Ericsson, Bath Base Station Conference 2008



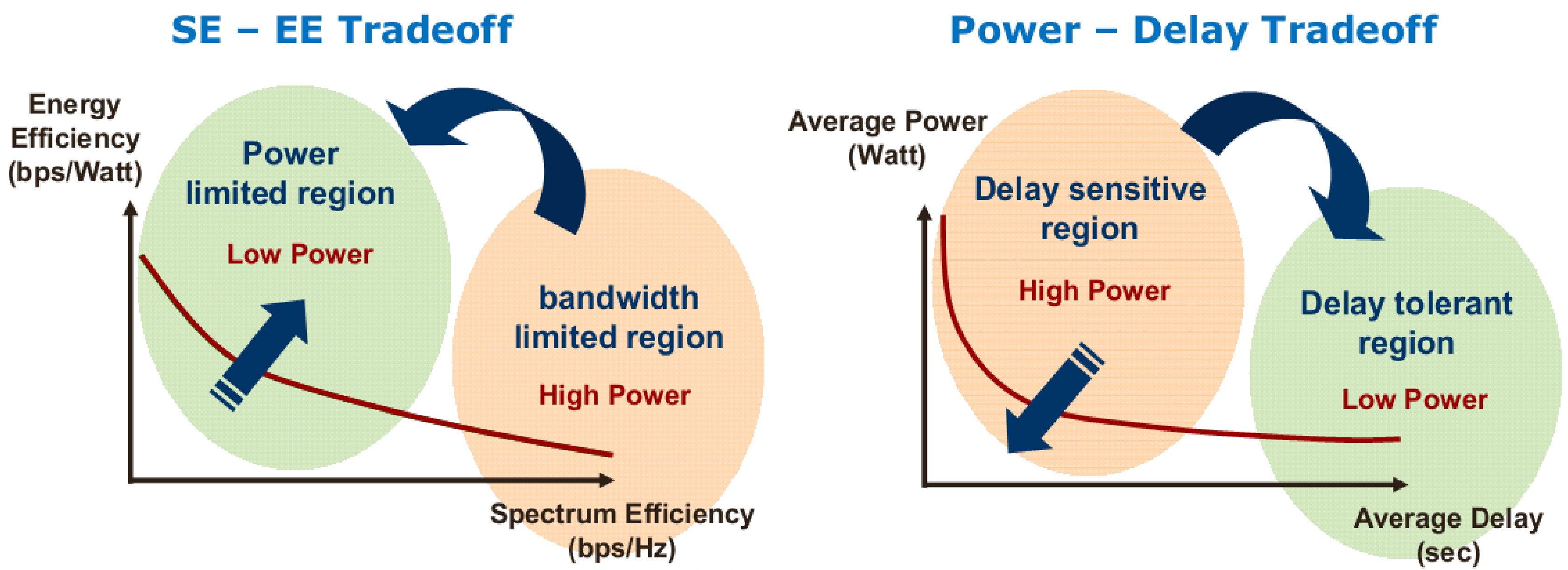
Fundamental Tradeoffs

- *Deployment Efficiency* (DE) - *Energy Efficiency* (EE) tradeoff: to balance the deployment cost, throughput, and energy consumption, in the network as a whole;
- *Spectrum Efficiency* (SE) - EE tradeoff: given a bandwidth available, to balance the achievable rate and the energy consumption of the system;
- *Bandwidth* (BW) - *Power* (PW) tradeoff: given a target transmission rate, to balance the bandwidth utilized and the power needed for the transmission;
- *Delay* (DL) - PW tradeoff: to balance the average end-to-end service delay and the average power consumed in the transmission.

$$R = W \log_2\left(1 + \frac{P}{WN_0}\right)$$

Y. Chen, S. Zhang, S. Xu and G. Y. Li, "Fundamental tradeoffs on green wireless networks", IEEE Communications Mag. June 2011

Fundamental Tradeoffs



Insight from Shannon

- Larger bandwidth → Lower transmit power (for same rate)

Approaches

- Bandwidth expansion
- Advanced technologies to better use bandwidth

Insight from Shannon

- Longer bit transmission time → Lower transmit power

Approaches

- Enlarging transmission time or taking micro sleep to minimize power under delay constraint

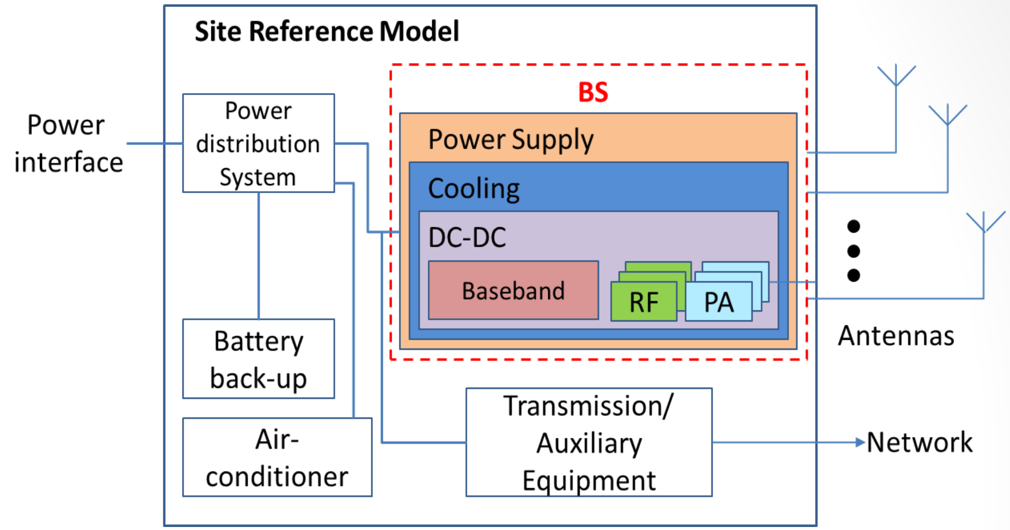
Y. Chen, S. Zhang, S. Xu and G. Y. Li, "Fundamental tradeoffs on green wireless networks", IEEE Communications Mag. June 2011

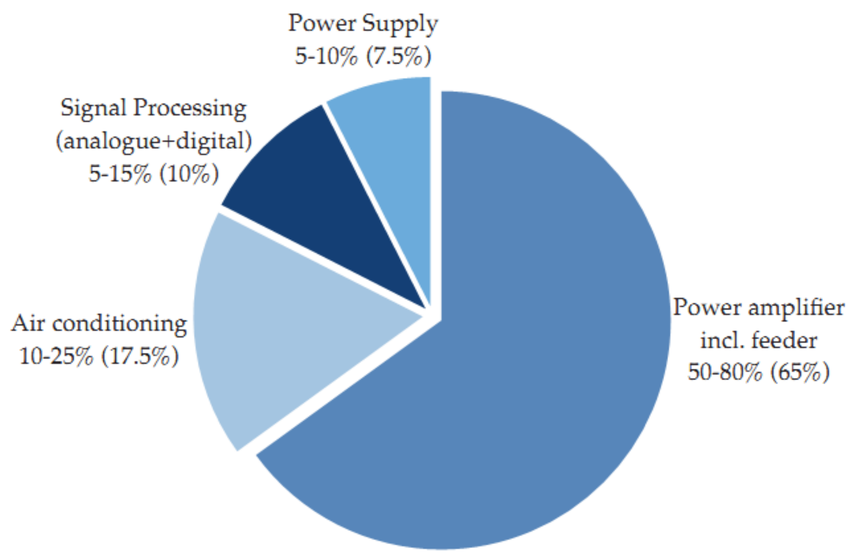
BS power consumption

- Three major parts and overhead contribute to BS power consumption
  - Major parts include Baseband (BB), Radio Frequency (RF) and Power Amplifier (PA)
  - Overhead includes DC/DC, power supply (AC/DC), and cooling

$$P_{\mathrm{BS}} = \beta[N_{\mathrm{TRX}}(P_{\mathrm{PA}} + P_{\mathrm{RF}}) + P_{\mathrm{BB}}]$$

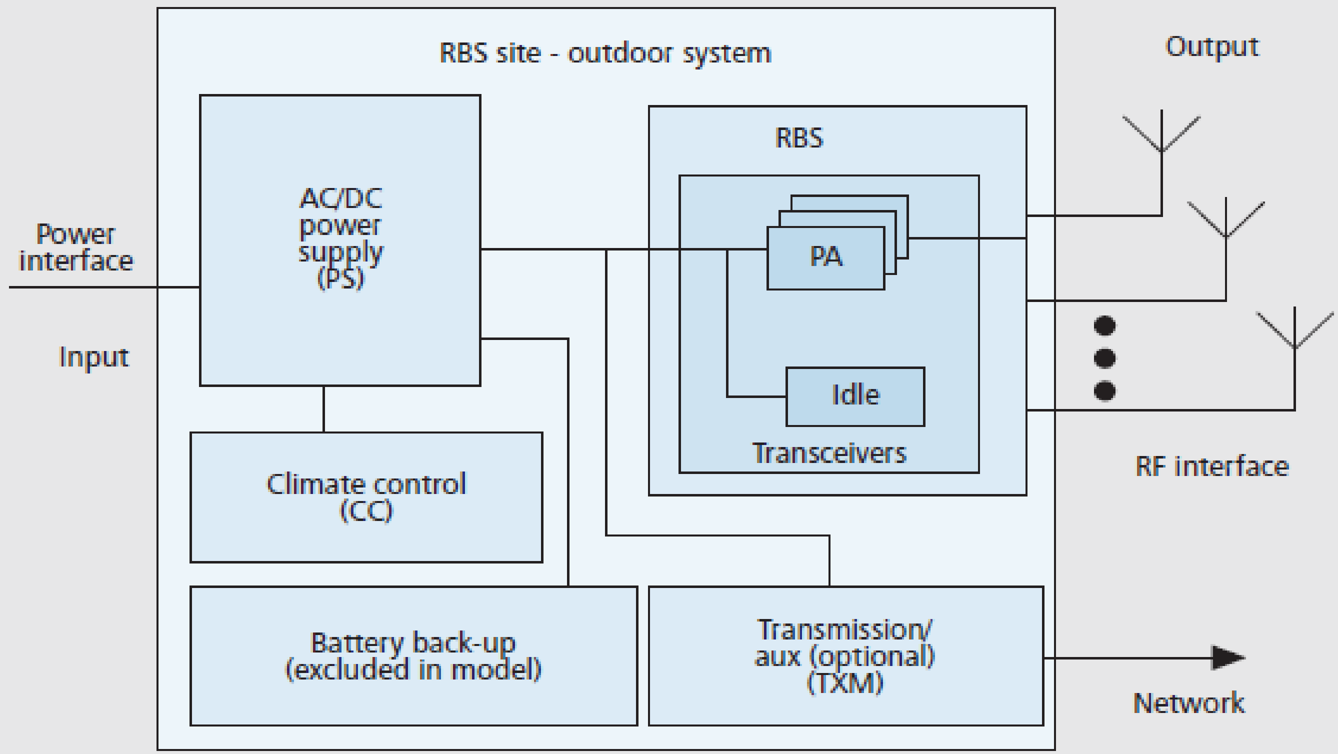
- Due to the power consumed in signal processing and operational overhead, only a portion of the input power being used in radio transmission





GreenTouch, “Architecture and metrics for green wireless network”, Mar. 2012

Energy consumption reference model for BS



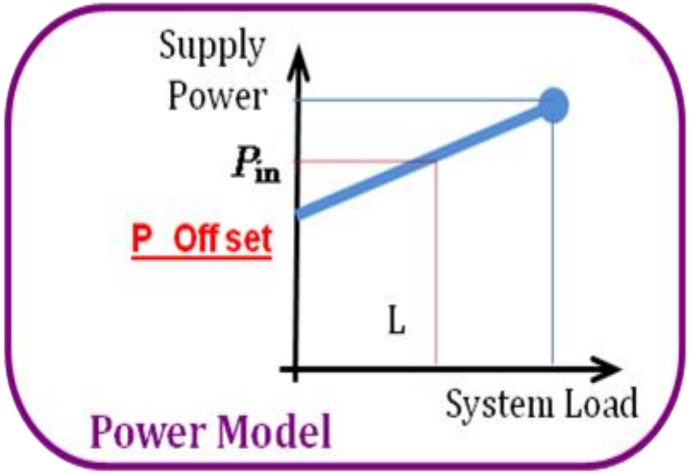
Examples of power consumption values of RBS (unit: watt)

	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

Tao Chen, el, "NETWORK ENERGY SAVING TECHNOLOGIES FOR GREEN WIRELESS ACCESS NETWORKS", IEEE Wireless Communications • October 2011

BS Input-output power relation



- BS power model has strong offset for low utilisation

- High power (PA standby and pilot transmission) consumption for providing coverage
- Efficiency in J/kbit strongly depends on load

- The BS input power can be approximated as a linear function of the output power

$$P_{\mathrm{in}}(t) = P^{1}_{\mathrm{offset}} + 1/\Delta_1 \times P_{\mathrm{out}}(t)$$

- BS output power can be further approximated as a linear function of the system load

$$P_{\mathrm{out}}(t) = P^{2}_{\mathrm{offset}} + 1/\Delta_2 \times L(t)$$

- We can therefore establish a linear relation between BS input power and system load

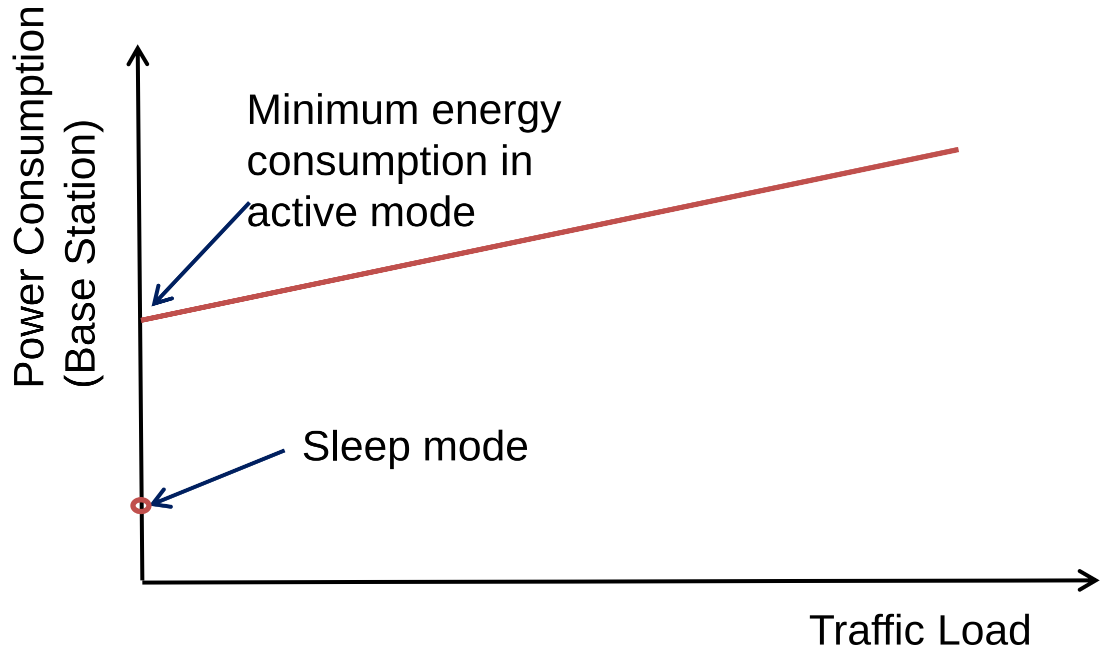
$$P_{\mathrm{in}}(t) = P_{\mathrm{offset}} + 1/\Delta \times L(t)$$

GreenTouch, “Architecture and metrics for green wireless network”, Mar. 2012

Linear parameters of the power model

Parameter	Description	Reason of evolution
Δ_1	Efficiency of input power to output power conversion	Improvement in the hardware (e.g. PA) efficiency
P^1_{offset}	Static Power offset	Reduction of circuit/processing power
Δ_2	Efficiency of output power to useful payload conversion	Improvement in the transmission technology or resource management
P^2_{offset}	Overhead power offset	Reduction of signaling overhead
Δ	Overall efficiency	Combined effect of improving Δ_1 and Δ_2
P_{offset}	Overall power offset	Combined effect of reducing P^1_{offset} and P^2_{offset}, as well as improving Δ_1
P_{sleep}	Power offset when BS sleeps	Exploitation of deeper sleep mode
P^{max}_{out}	Maximum output power	Higher capability PA

Power model with sleeping mode



$$P_{in}(t) = \begin{cases} P_{offset} + 1/\Delta \cdot L(t), & transmitting \\ P_{sleep}, & sleeping \end{cases}$$

Linear parameters of the power model

BS type	# antennas per site	Max output per antenna [W]	Slope 1/Δ per antenna [W_{in}/W_{RF}]	Offset per antenna [W]	Power at no load [W]	Power at full load [W]	Power in sleep mode [W]
Macro	3x2	20	4.7	130.0	780.0	1350.6	450.0
cro with RRH	3x2	20	2.1	84.0	504.0	754.8	336.0
Micro	2	6.3	2.6	56.0	112.0	144.6	78.0
Pico	2	0.13	4.3	6.8	13.6	14.7	8.6
Femto	2	0.05	8.0	4.8	9.6	10.4	5.8

System improvement from EE perspective

- Based on understanding on the fundamental relationship between power consumption, network spectrum efficiency, and QoS, considering the following two major metrics
  - Throughput oriented metric: Joule/bits
    - Mainly used in overloaded systems
  - Coverage oriented metric: Watt/Km^2
    - Mainly used in underloaded systems
- Design advanced hardware/equipment, transmission technology, resource allocation scheme and network architecture to improve network energy efficiency

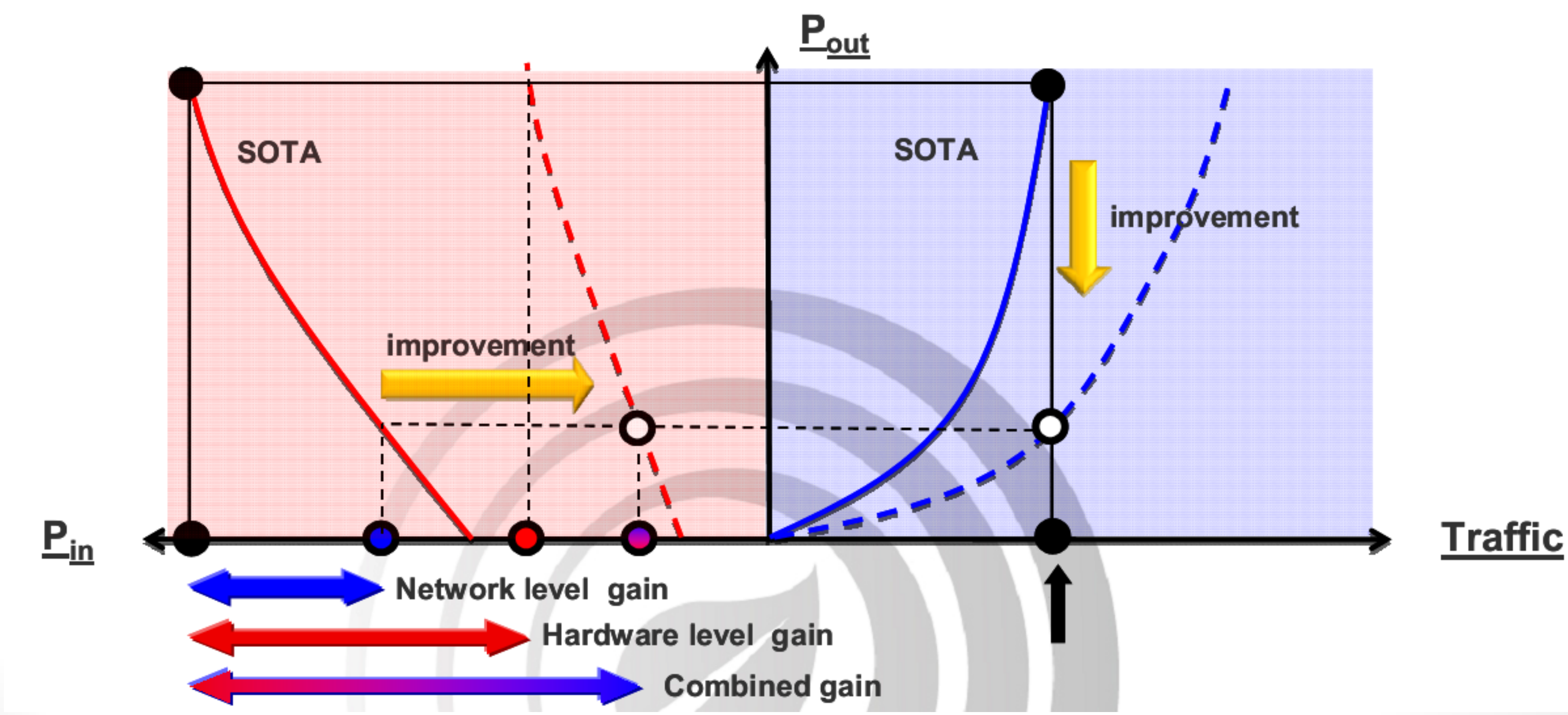
Ways in improving EE

Hardware level

- TRX power model
- Other component savings

Network level

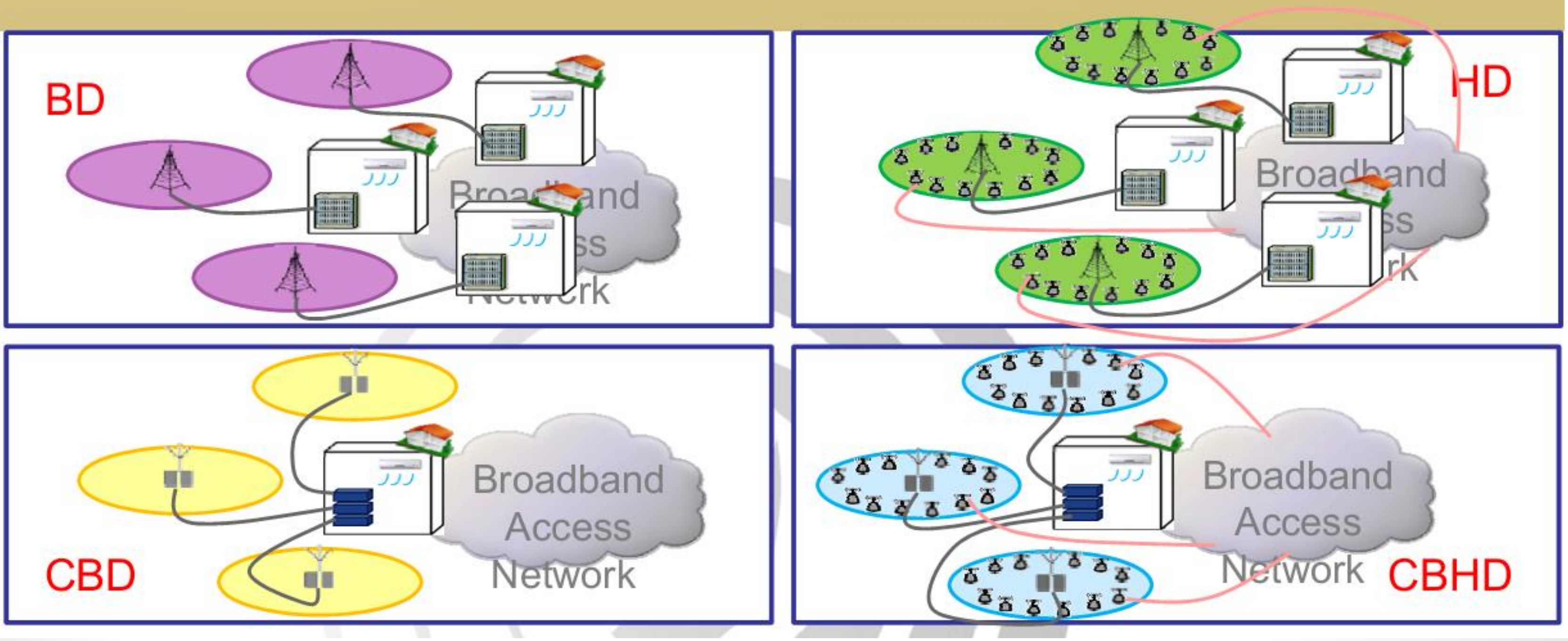
- Advanced Deployment
- Network management, Scheduling
- BS cooperation
- Antenna configuration
- Advanced Air Interface techniques



GreenTouch, "Wireless architecture & Roadmap", presentation, June 2012

EE in HetNets

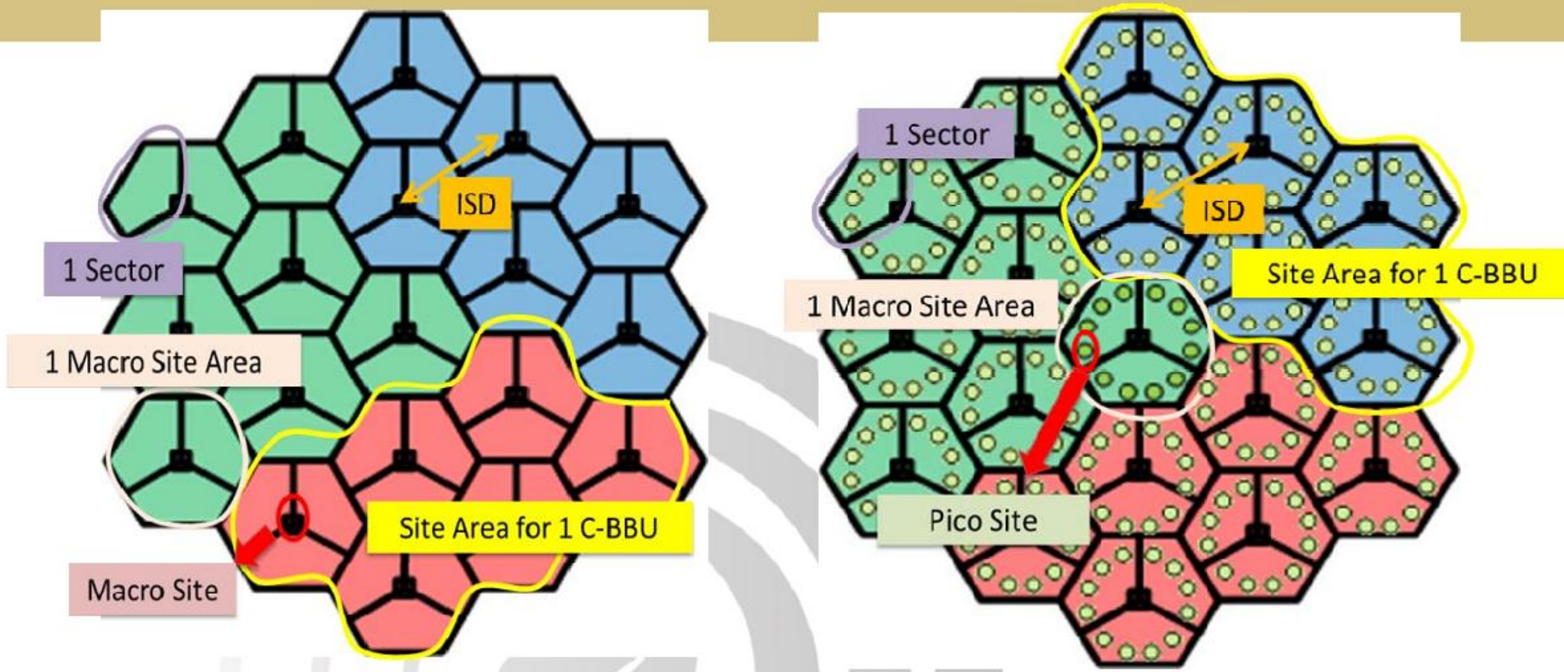
- Deployment scenarios
  - Baseline Deployment (BD): One macro BS per site
  - Centralized BBU Deployment (CBD): Several BBUs are gathered in a room
  - Heterogeneous Deployment (HD): One macro area overlays 12 pico sites
  - Centralized BBU Heterogeneous Deployment (CBHD): Several macro BBUs are gathered in a room



GreenTouch, "Wireless architecture & Roadmap", presentation, June 2012

Deployment model

- In CBD & CBHD, (6,6,7) BBUs are gathered/stacked in one room



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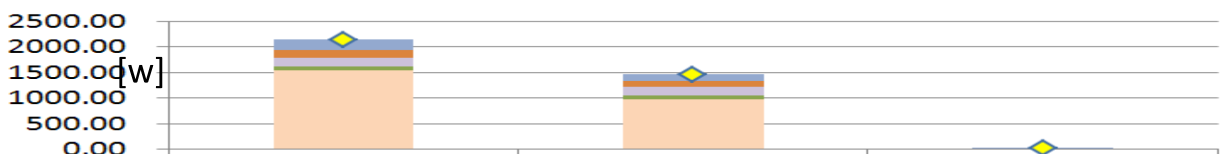
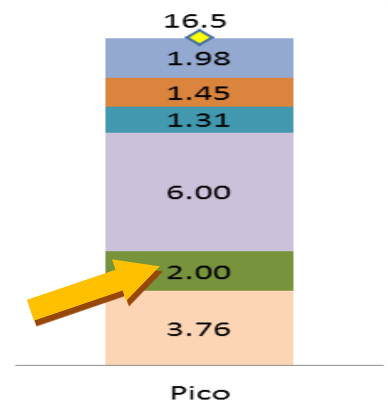
System model parameters

- Example model & Value

$$P_{in} = N_{Sec}\cdot N_{TX}\cdot N_{Carrier}\cdot \frac{\dfrac{P_{out}}{\eta_{PA}\cdot(1-\sigma_{feed})}+P_{RF}+P_{BB}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{Cool})}$$



	Macro	RRH	Pico
MS	192.15	131.36	1.98
DC	155.43	106.25	1.45
Cool	0.00	0.00	1.31
BB	177.60	177.60	6.00
RF	77.40	77.40	2.00
PA	1532.40	966.90	3.76
Total	2135.05	1459.53	16.5



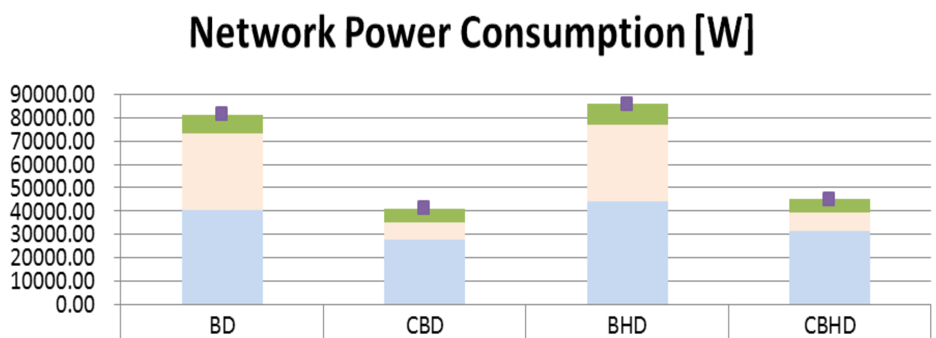
BS type	Pin [W]	N_{sec}	N_{tx}	$N_{carrier}$	σ_{DC}[%]	σ_{Cool}[%]	σ_{MS}[%]	Pout[dBm]	Feeder loss [dB]	η_{pa}[%]	P_{PA}[W]	P_{RF}[W]	P_{BB}[W]
mI (Macro)	2135.05	3	2	1	8	0	9	46	3	31.1	255.41	12.9	29.6
mD (macro RRH)	1459.53	3	2	1	8	0	9	46	1	31.1	161.15	12.9	29.6
pI (Pico)	16.50	1	2	1	10	10	12	21	0	6.7	1.88	1	3

C.H. Tang, "Reference Architecture & Power Model", Chunghwa Telecom, Greentouch presentation, June 2012

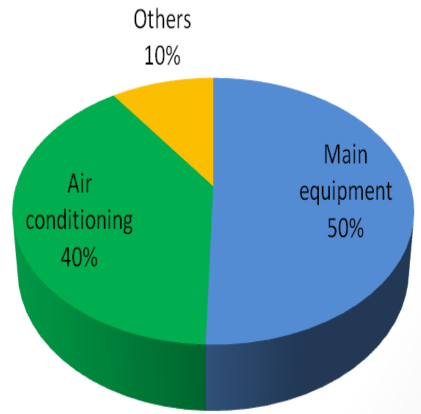
Total site power consumption

- Site power model & example value

Scenario	P_{total}[W]	Power Consumption Ratio		
		BS	AC	Others
BD	81132	0.50	0.40	0.10
CBD	40963	0.68	0.19	0.14
BHD	85645	0.52	0.38	0.10
CBHD	45477	0.69	0.17	0.14



	BD	CBD	BHD	CBHD
Others	8113.20	5546.22	8865.39	6298.42
AC	32452.80	7686.19	32452.80	7686.19
BS	40566.00	27731.12	44326.97	31492.09
Total	81132.00	40963.53	85645.17	45476.70

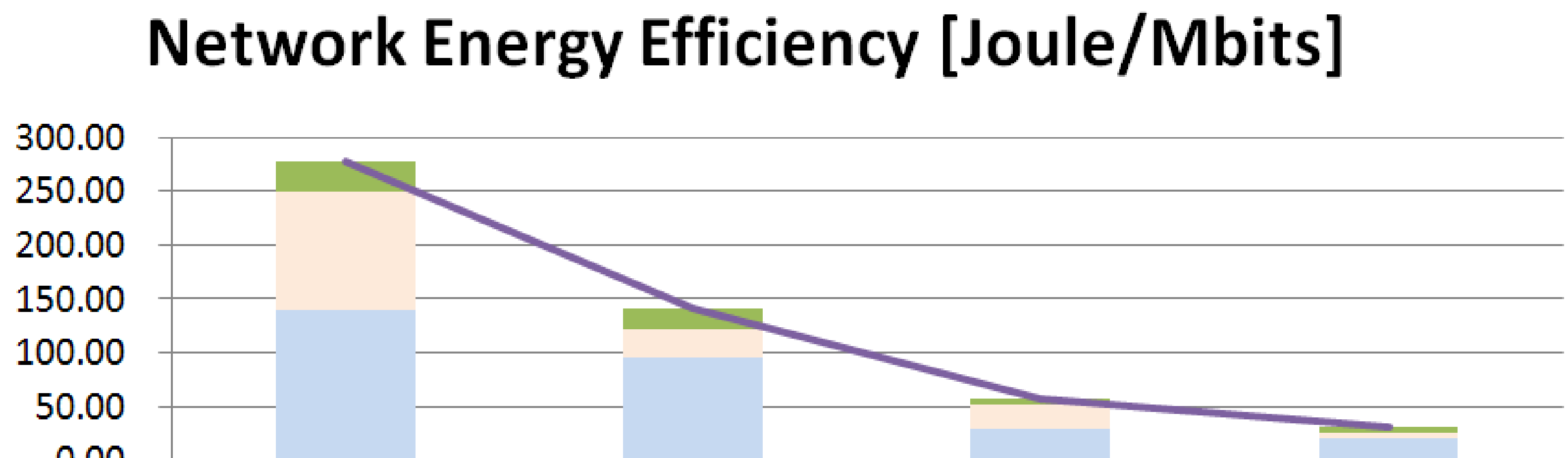


Power consumption breakdown of Macro BS site

C.H. Tang, "Reference Architecture & Power Model", Chunghwa Telecom, Greentouch presentation, June 2012

Throughput-oriented energy efficiency

Scenario	ISD (m)	Number of user per cell	User density*(pls/km²)	System throughput (Mbits)
Homogeneous(BD,CBD)	700	10	3535	291.90
Heterogeneous(HD,CBHD)	700	10	3535	1484.85



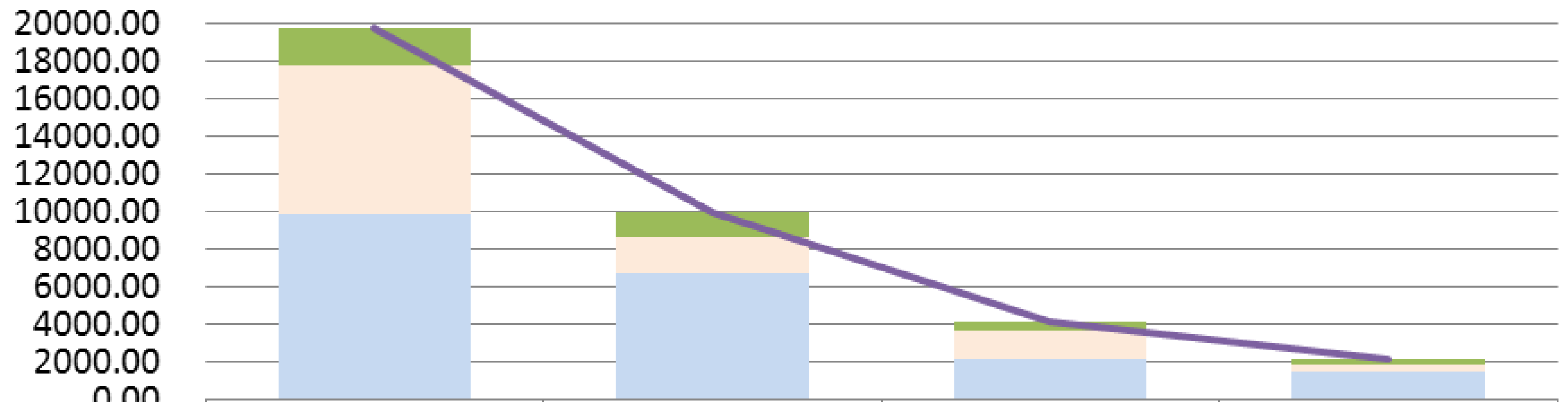
	BD	CBD	BHD	CBHD
Others	27.79	19.00	5.97	4.24
AC	111.17	26.33	21.86	5.18
BS	138.97	95.00	29.85	21.21
Total	277.93	140.33	57.68	30.63

C.H. Tang, "Reference Architecture & Power Model", Chunghwa Telecom, Greentouch presentation, June 2012

Coverage-oriented energy efficiency

Scenario	ISD (m)	Number of user per cell	User density* (pls/km²)	Average UE throughput (Mbits)	Area (km²)
Homogeneous(BD,CBD)	500	9	6250	1.44	0.2165
Heterogeneous(HD,CBHD)	1120	44	6250	1.44	1.0863

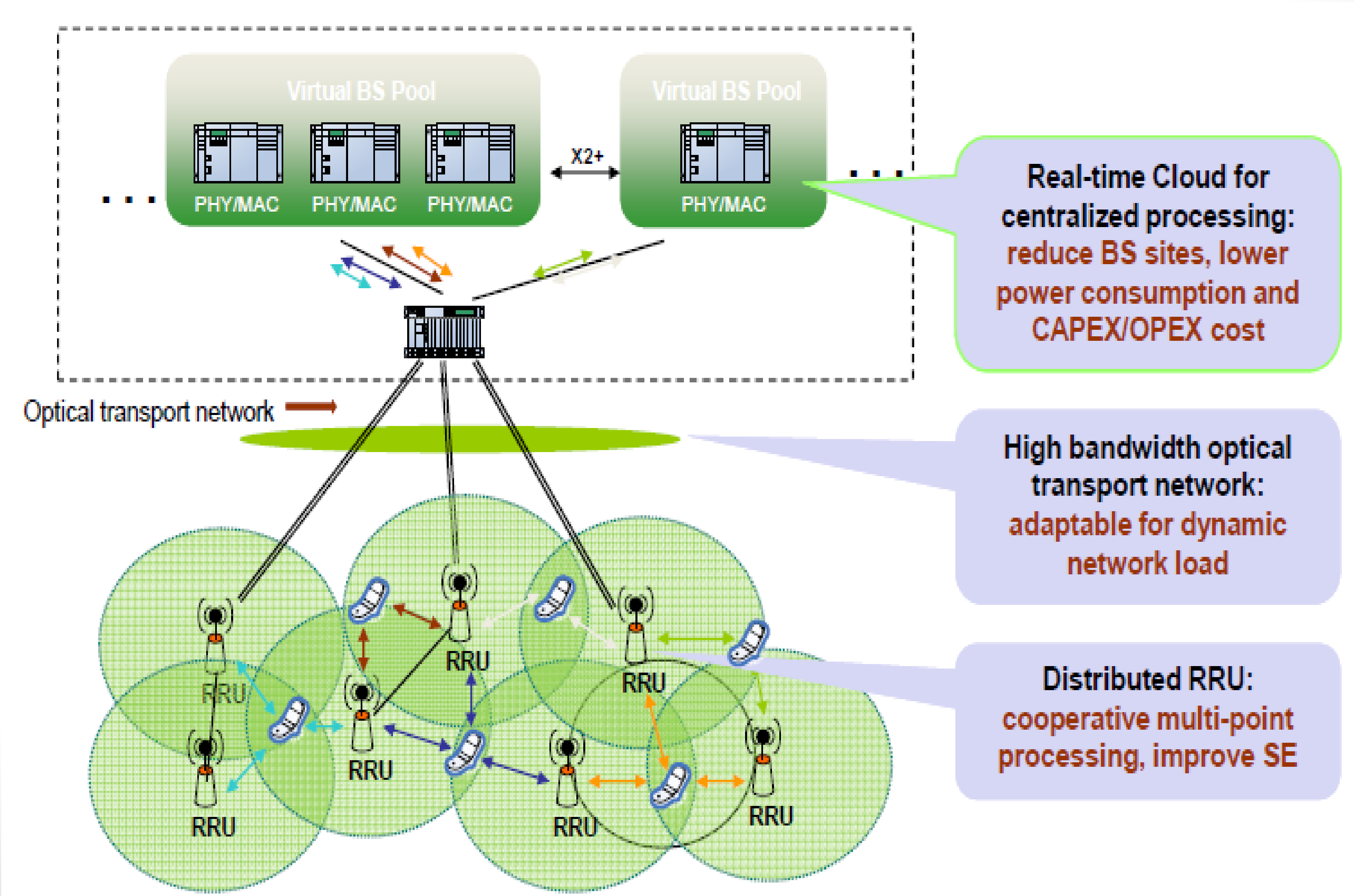
Network Energy Efficiency [W/km²]



	BD	CBD	HD	CBHD
Others	1972.33	1348.30	429.53	305.16
AC	7889.34	1868.53	1572.35	372.40
BS	9861.67	6741.49	2147.66	1525.80
Total	19723.35	9958.32	4149.54	2203.36

C.H. Tang, “Reference Architecture & Power Model”, Chunghwa Telecom, Greentouch presentation, June 2012

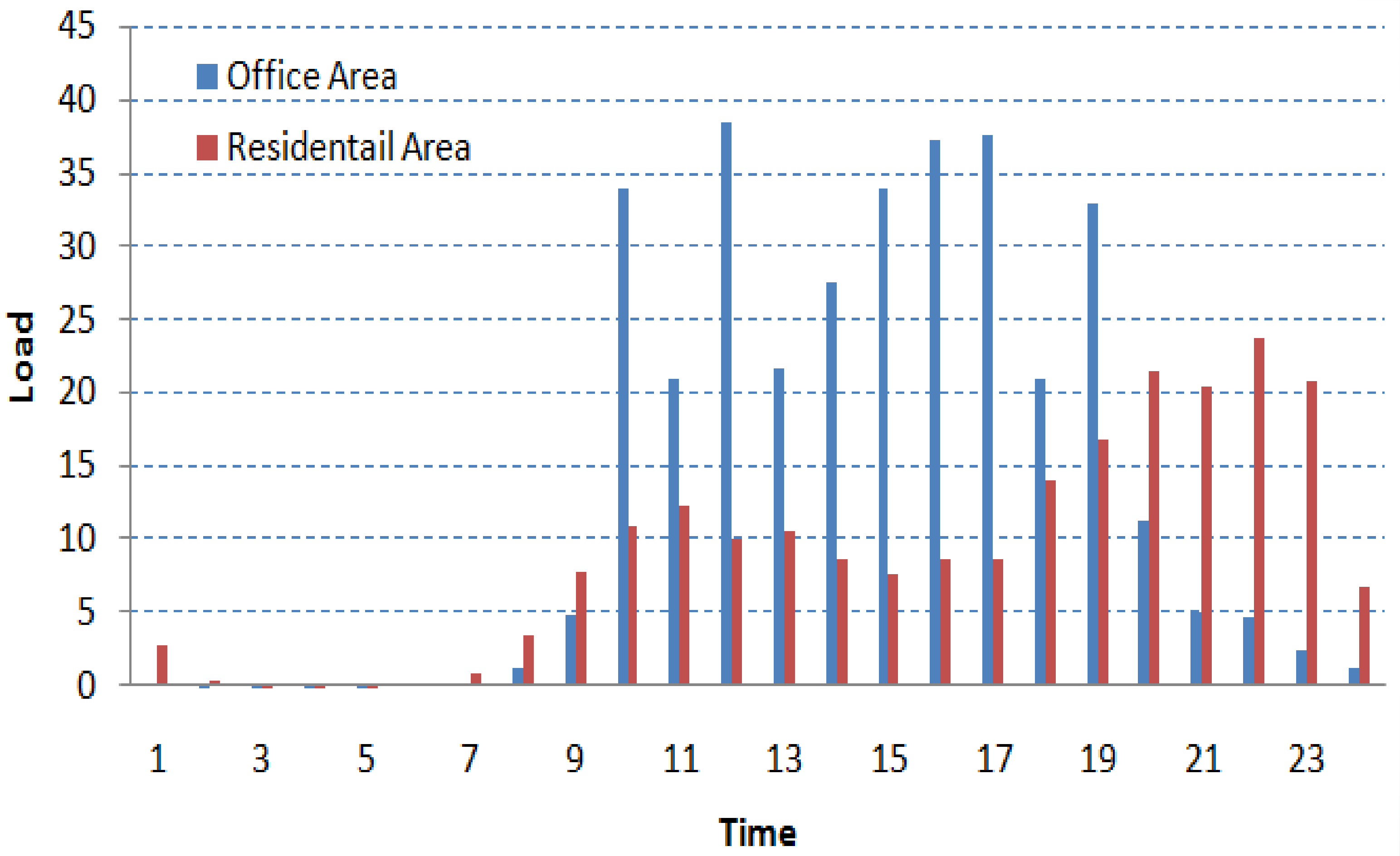
Vision of Cloud-RAN



Benefits of Cloud-RAN

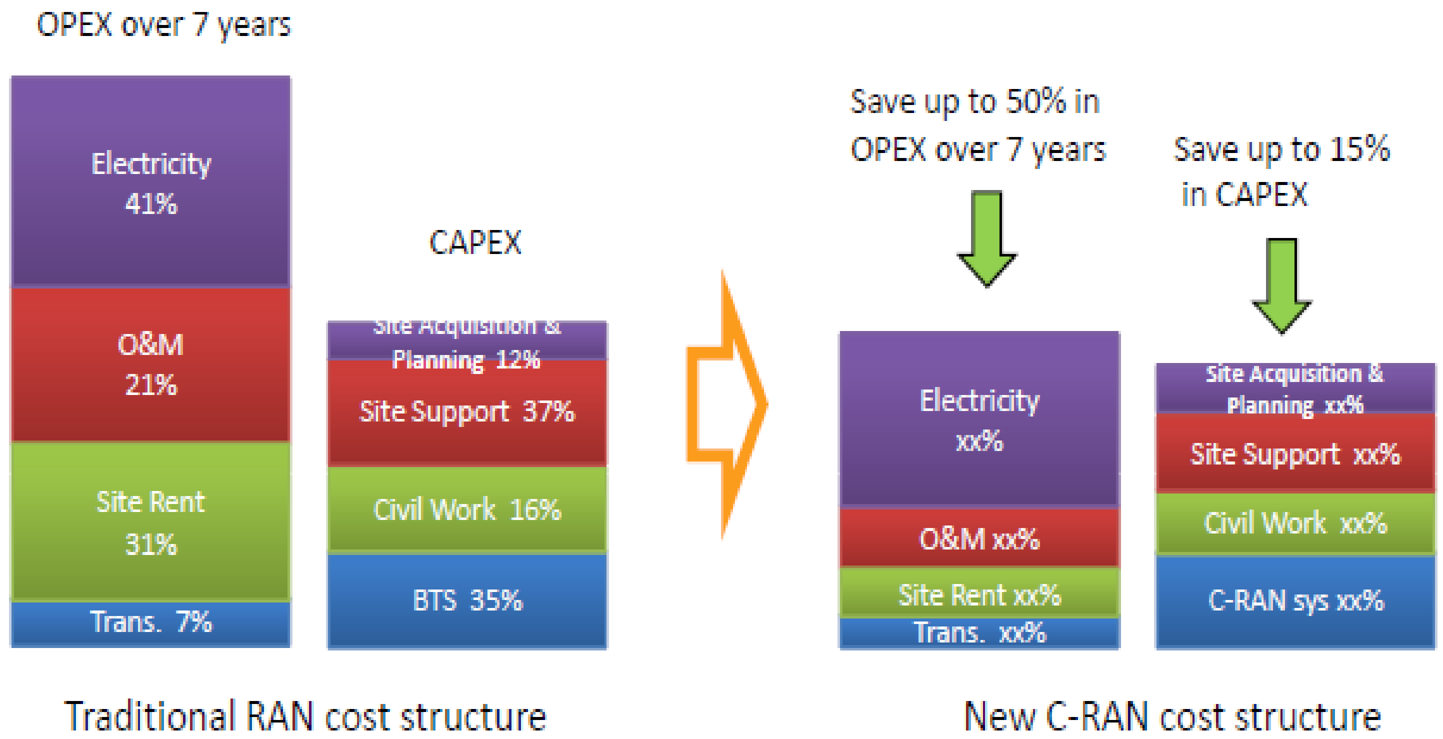
Traditional RAN	Cloud-RAN
•Large number of BS • High power consumption • High CAPEX/OPEX	•Centralized BBU pool • Low power consumption • Low CAPEX/OPEX
•Isolated BS • Low BS utilization rate	•Resource aggregation • High utilization rate
•Interference limited • Hard to improve SE • Low energy efficiency	•Cooperative multipoint processing • Improve SE • Improve energy efficiency
•Low efficient PA • High power consumption	•High efficient linear PA • Low power consumption

C-RAN allows better resource sharing



Source: China Mobile

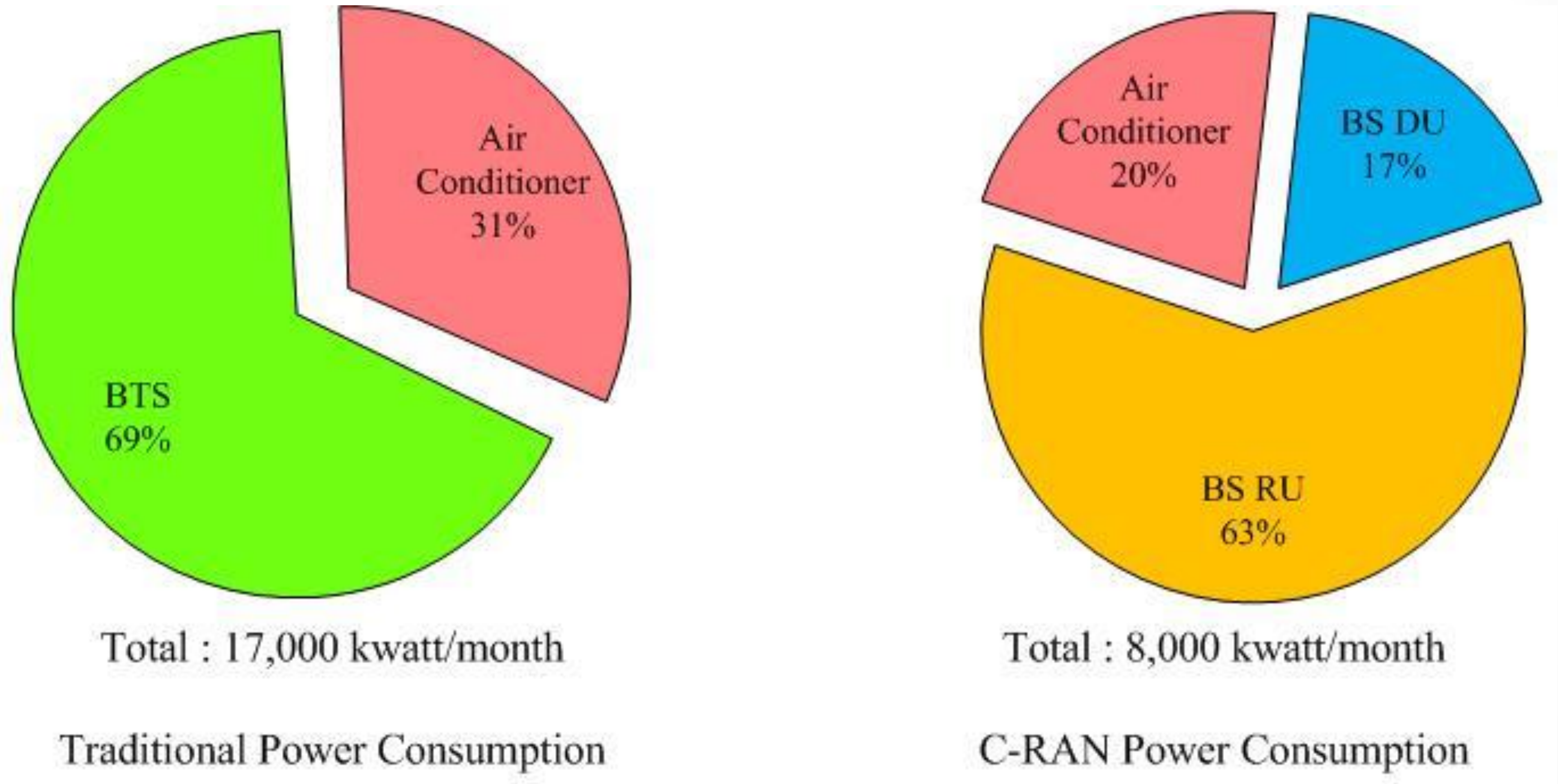
Save Cost of Deployment



- **C-RAN allows low cost and fast deployment of network**
  - **Compared with traditional deployment, may save up to 50%* in OPEX**
  - **Compared with traditional deployment, may save up to 15%* in CAPEX**

* Notes: data estimated on typical dense city deployment scenario, China Mobile

C-RAN Energy Saving



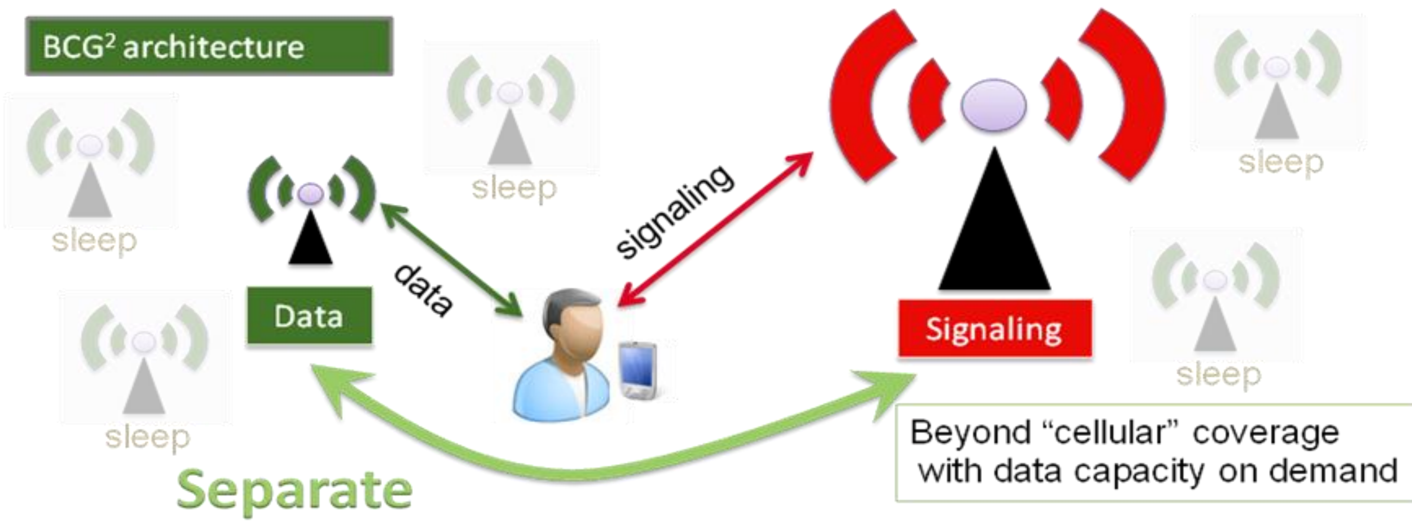
Source: China Mobile

Key techniques of Cloud-RAN

- Cloud computing architecture
  - ✓ SDR based multi-protocol baseband processing platform
  - ✓ Virtualization and computing/memory resource scheduling
  - ✓ Load balancing and CPRI signal routing
- CPRI signal transmission
  - ✓ CPRI over OTN/DWDM
  - ✓ CPRI over WDM-PON
- Dynamic cell architecture and multi-cell joint scheduling
  - ✓ Dynamic cell architecture adapting areal traffic varying
  - ✓ User centric (per-user) dynamic cell architecture
  - ✓ Multi-cell joint radio resource scheduling and interference avoidance
- Physical layer enhancement
  - ✓ Network MIMO and interference cancellation
  - ✓ Very high order modulation (128QAM and 256QAM)

Beyond Cellular Green Generation (BCG^2)

BCG^2: Basic idea

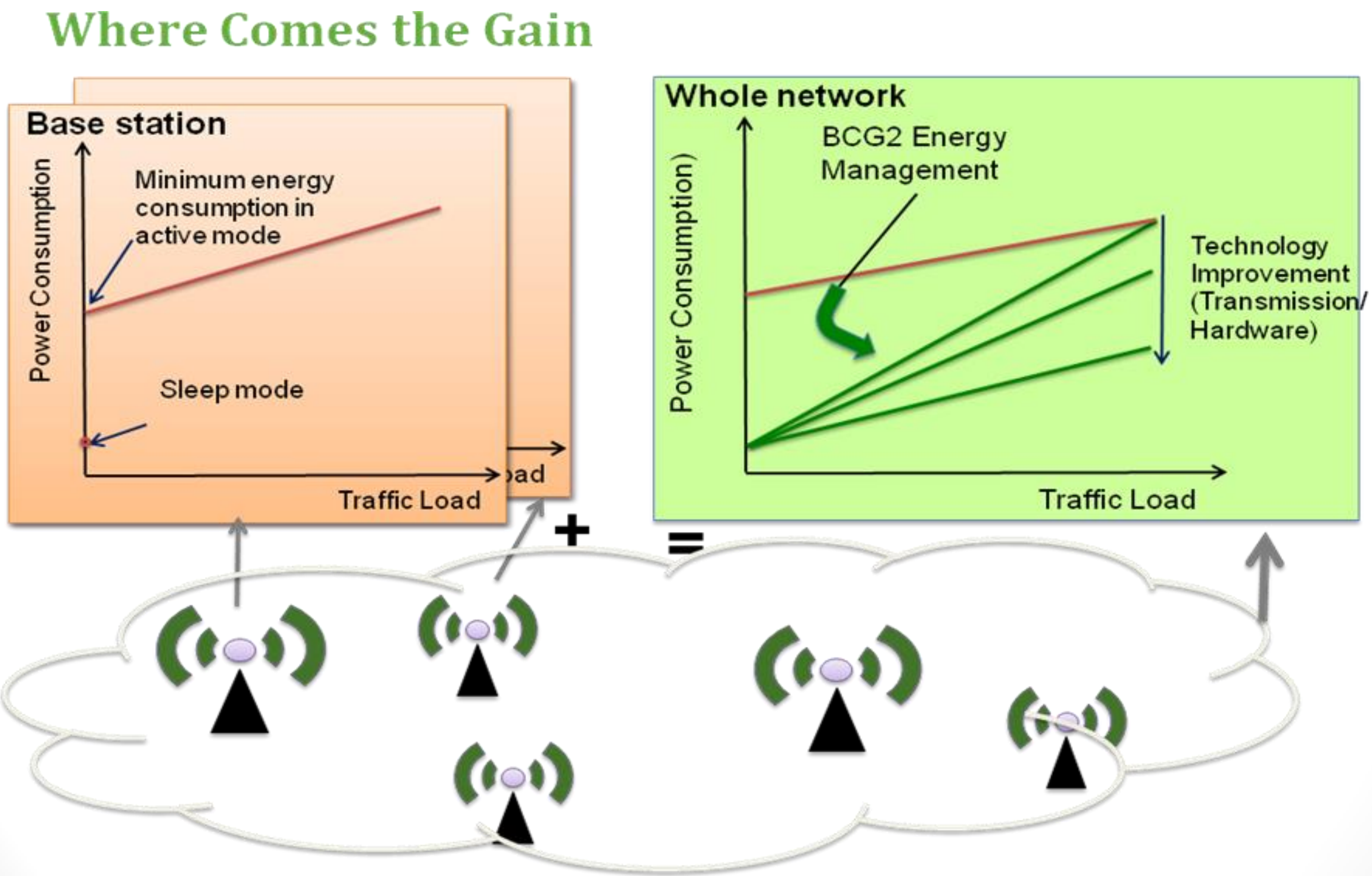


Separation of signaling and data functions at the radio interface:

- Full Coverage and always available connectivity ensured by signaling base stations only
- Data access capacity provided by data base stations on demand
- Adaptive network capacity and high energy efficiency

GreenTouch, "Architecture and metrics for green wireless network", Mar. 2012

Potential of BCG^2 in improving EE



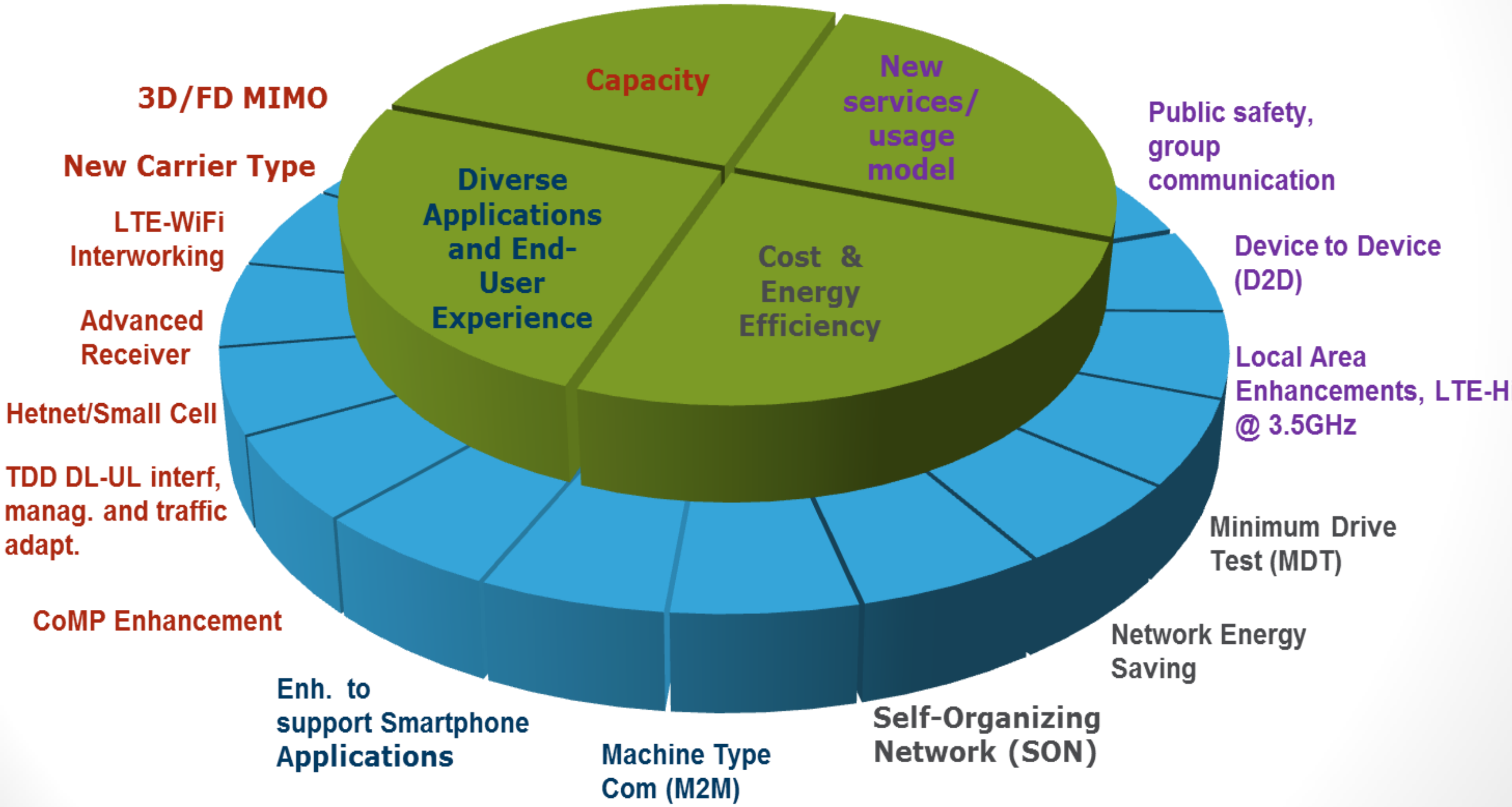
GreenTouch, “Architecture and metrics for green wireless network”, Mar. 2012

BCG^2 Deployment

- Signal Network
  - Macro-cell only layout
  - DVB-type layout, large coverage per BS
    - Similar layout is now used for digital terrestrial video broadcasting
  - C-RAN layout
- Data Network
  - Homogeneous deployment with only macro data BSs
  - Heterogeneous deployment with a mixed macro and micro data BSs
  - Cooperative MIMO transmission

Progresses on LTE Rel-12

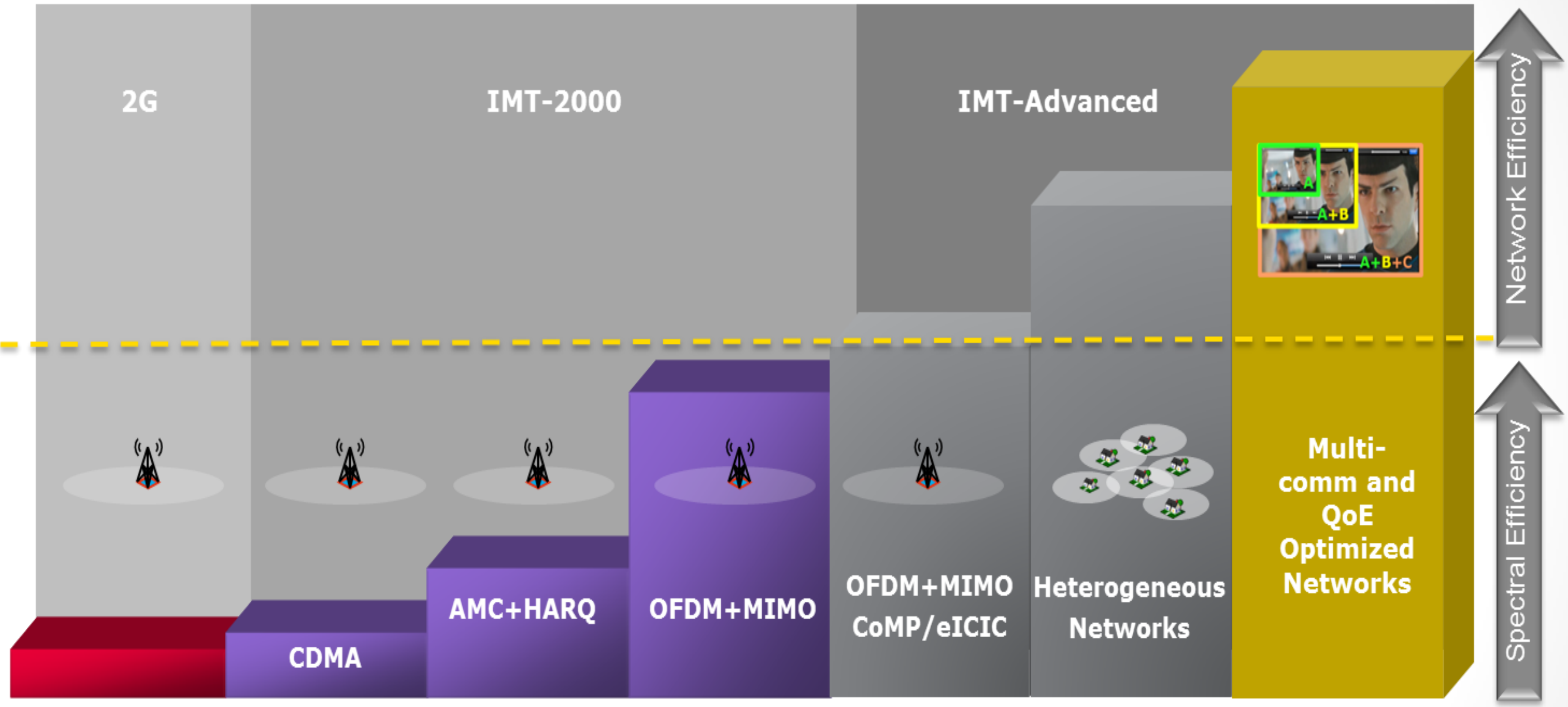
Rel-12 Key Technology Components



LTE Rel-12 On-Going RAN 1/2 Study Items and Work Items

- Small cell enhancements SI
- LTE D2D SI
- 3D-MIMO channel model SI
- Network assisted IC and suppression SI
- WLAN/LTE radio interworking SI
- MTC and other mobile data application enhancements SI
- Support for BeiDou navigation satellite system WI

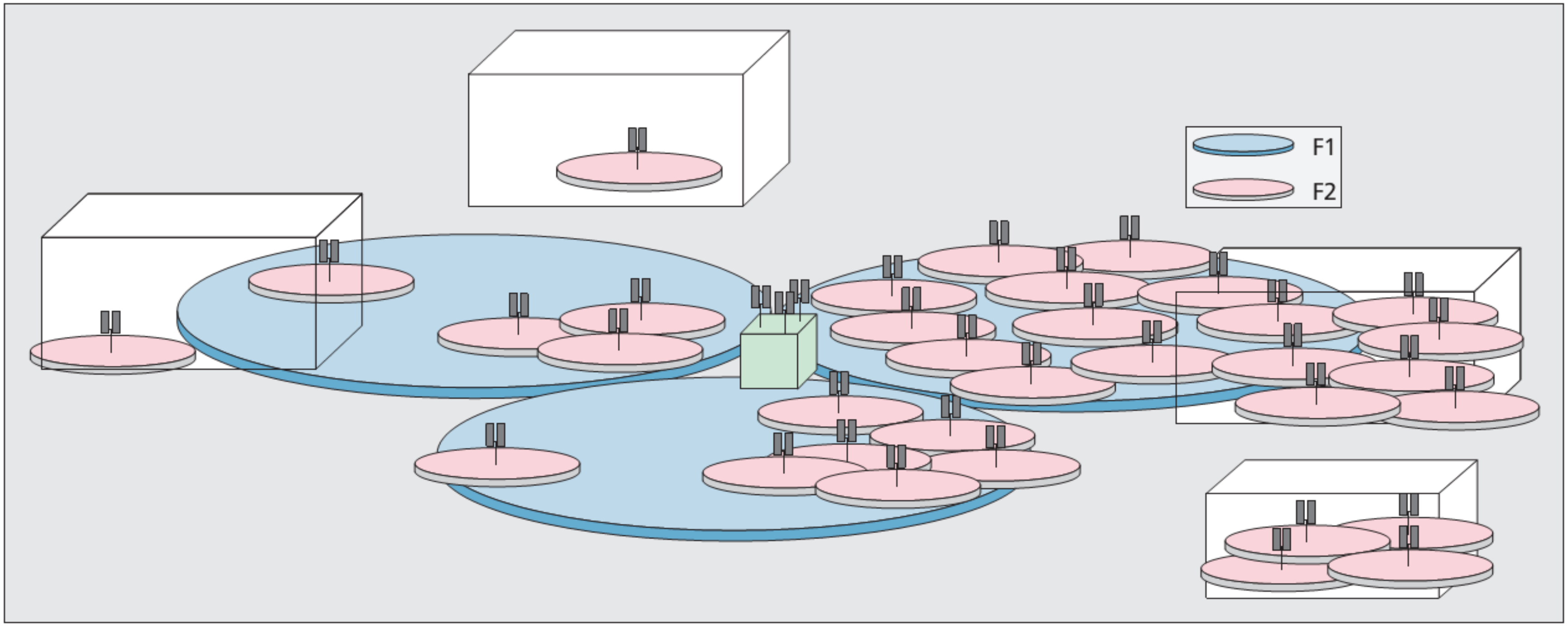
Small Cell Enhancement (1/5)



Network architecture innovation would be the key impetus for further network capacity enhancement

Small Cell Enhancement (2/5)

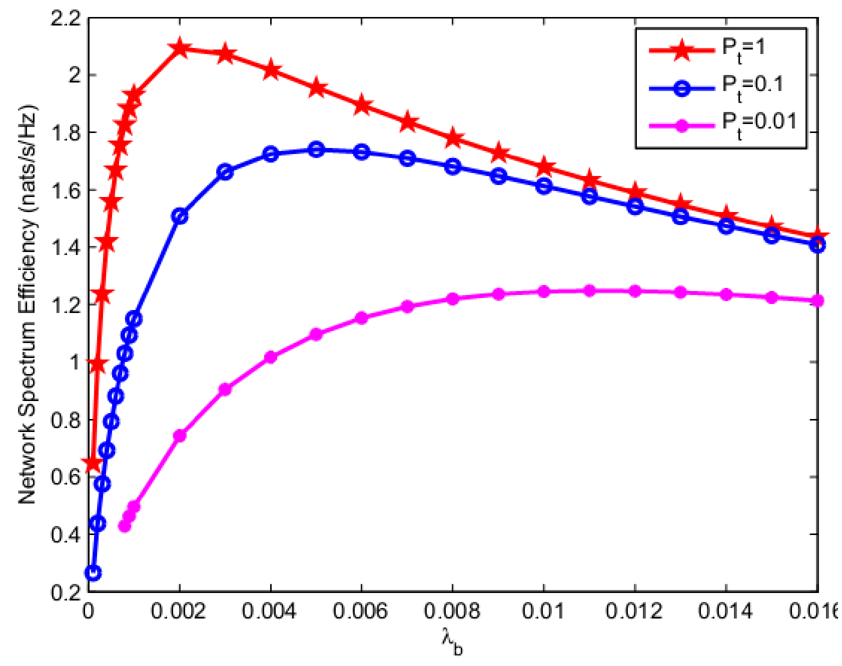
- Deployment Scenarios



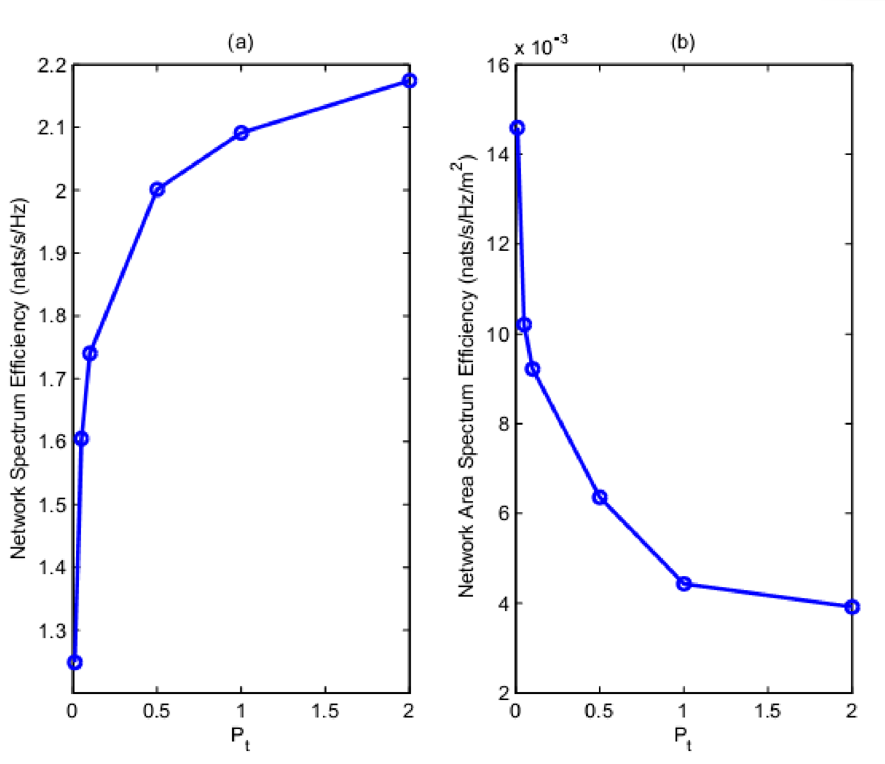
“Trends in small cell enhancements in LTE advanced”, IEEE Communications Mag., Feb. 2013

Small Cell Enhancement (3/5)

- Spectrum Efficiency



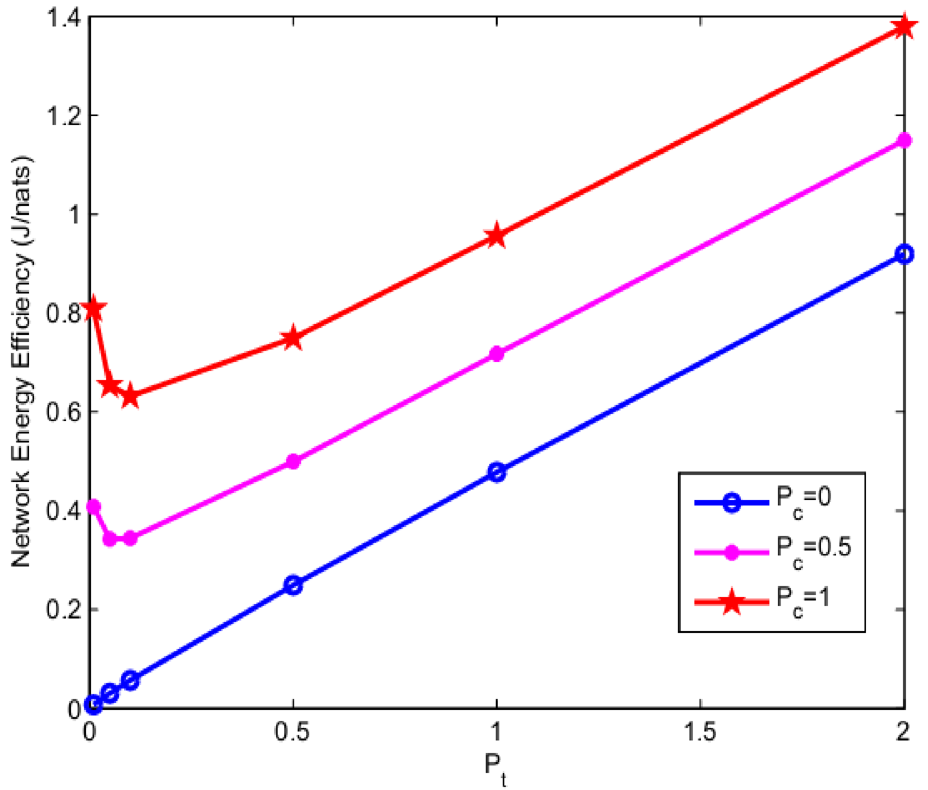
Network spectrum efficiency under different cell density values and eNB transmit powers



Network spectrum efficiency and network area spectrum efficiency under different eNB transmit powers

Small Cell Enhancement (4/5)

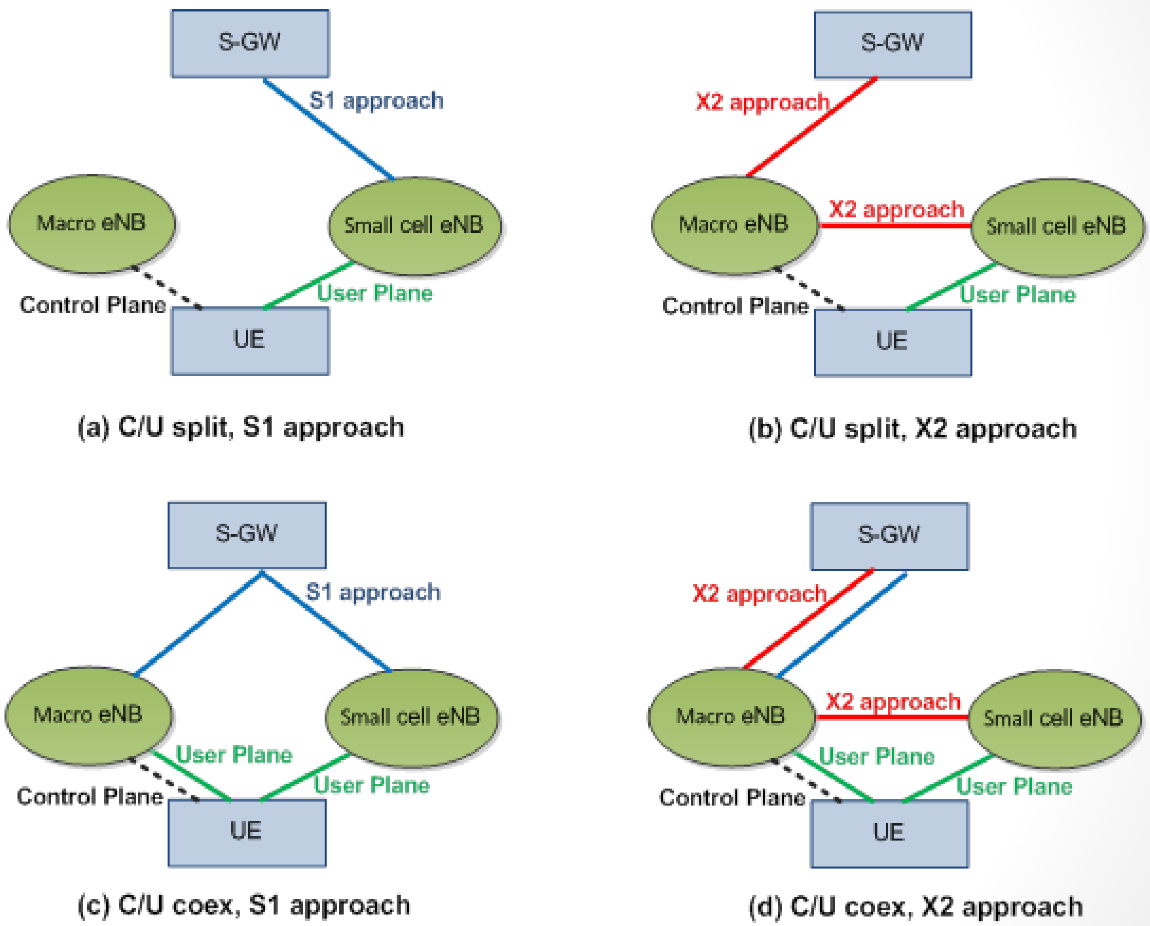
- Energy Efficiency



Network energy efficiency under different transmit powers

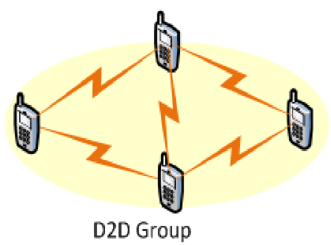
Small Cell Enhancement (5/5)

- Anchor-booster based architecture
  - Macro eNB as anchor BS for C/U-plane information transmission
  - Small cell eNB as booster BS for U-plane data transmission
  - Simplify small cell eNB processing
  - Facilitate mobility management

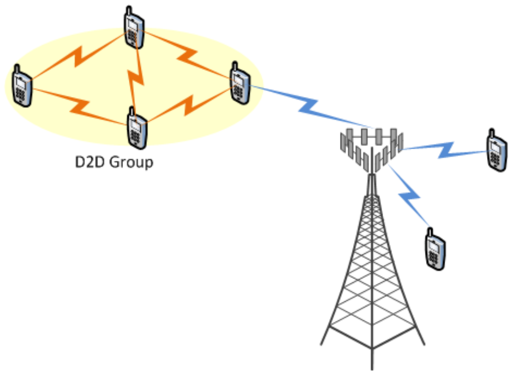


LTE D2D (1/4)

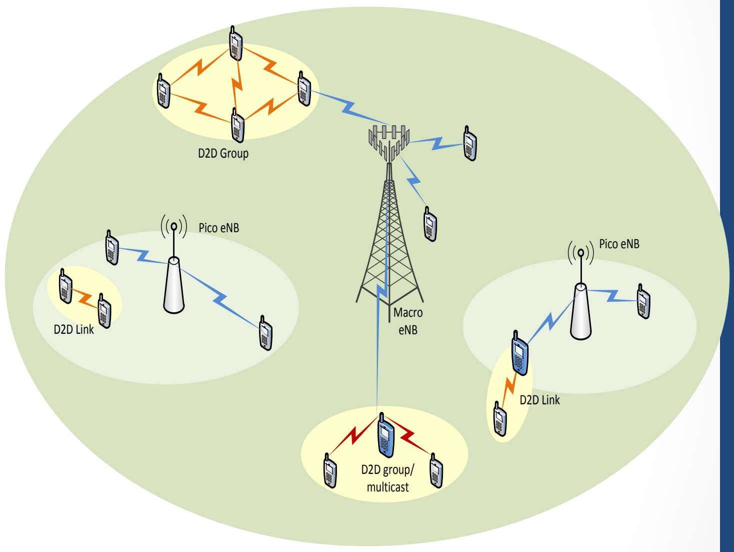
- Deployment Scenarios



Stand-alone
and
Self-organizing



Network Assisted
or
Network Controlled



Network Integrated
and
Heterogeneous Network

LTE D2D (2/4)

- D2D requirements

	Range	Data Rate	Battery Life	Privacy	Scalability
Social Networking	✓✓✓	✓	✓✓✓✓✓	✓✓✓✓✓	✓✓✓✓✓
Network Offloading	✓	✓✓	✓✓	✓✓	✓✓
Alternative network	✓✓✓✓✓	✓✓	✓	✓✓	✓✓✓
Media sharing	✓	✓✓✓✓✓	✓✓✓	✓✓	✓

Notes:

- These are only a few D2D application examples
- Technical requirements may vary widely depending on the exact use scenarios, applications and device capabilities

LTE D2D (3/4)

- Technical Challenges
  - UE centric vs. network-centric. Seamless to user
  - Privacy vs. convenience
  - Operator's role and cloud services
  - Synchronous vs. asynchronous operation
  - Need link budget improvement for longer range application
  - Standalone, network-assisted loose coupling, vs. integrated

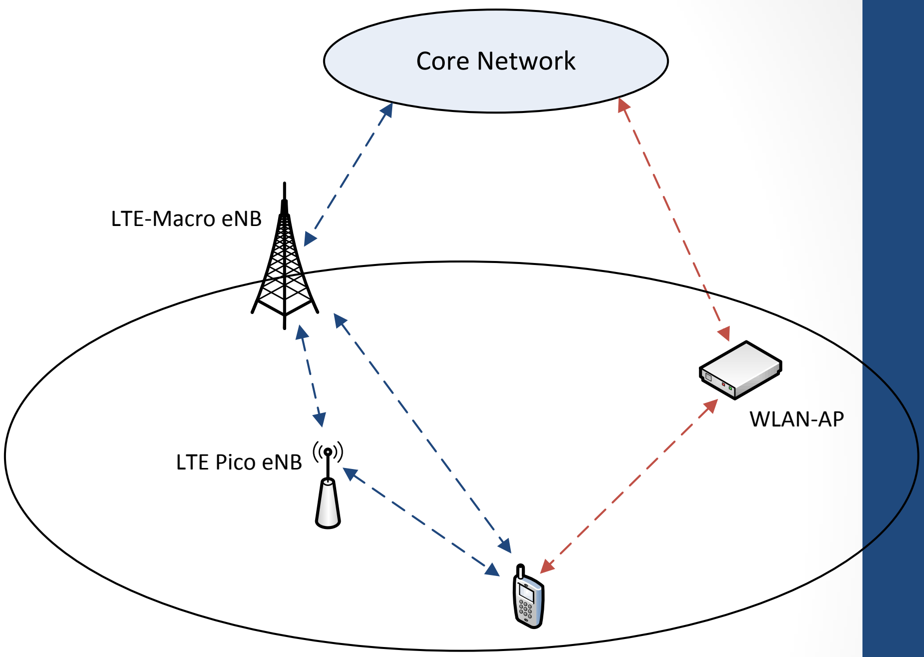
User experience and applications will ultimately determine solutions

LTE D2D (4/4)

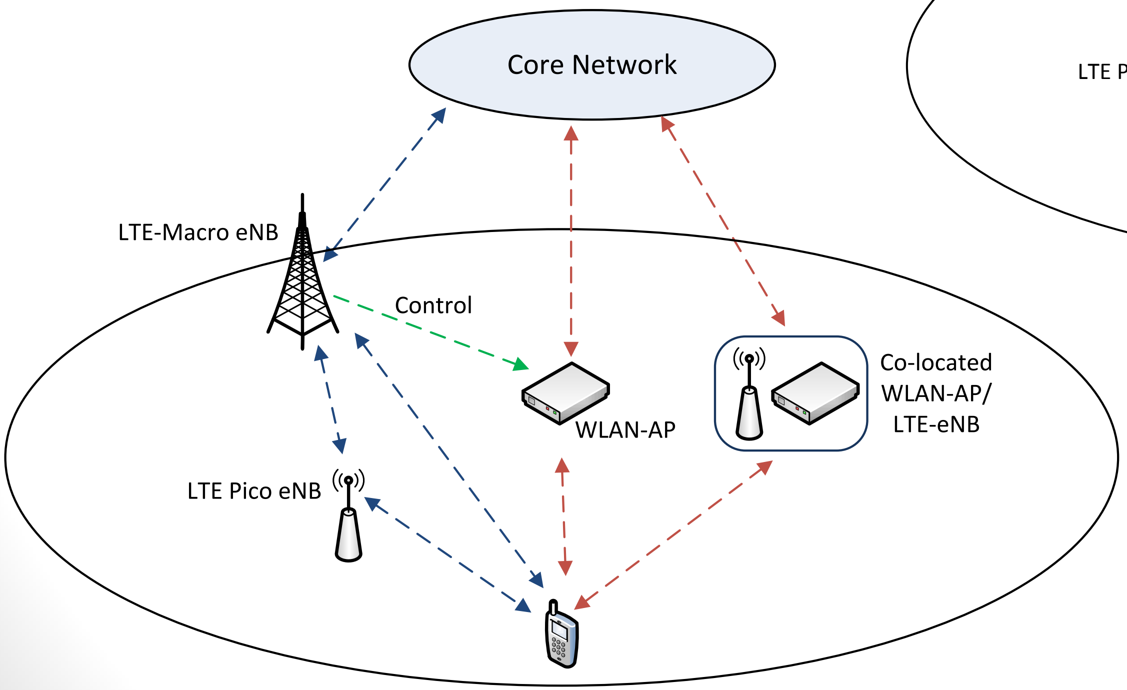
- Key Ingredients
  - LTE D2D discovery
    - Network assisted discovery
    - UE-based distributed discovery
    - Cluster based hybrid discovery
  - LTE D2D communication
    - Centralized network scheduled D2D communication
    - Distributed contention-based D2D communication
    - Hybrid cluster based D2D communication

WLAN/LTE Interworking

- CN level – Current approach
- RAN level – New SI
  - Stand-alone WLAN AP
  - Co-located WLAN/LTE AP



CN level



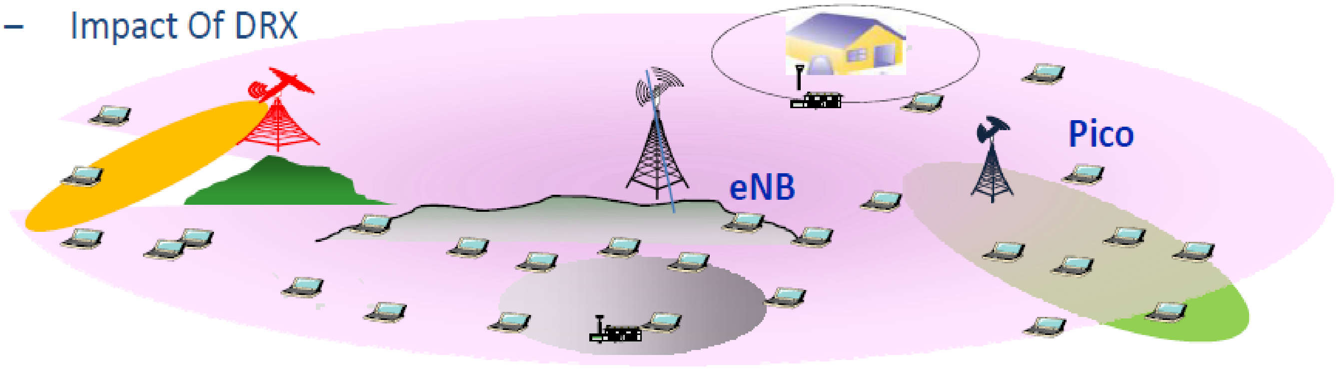
RAN level

- RAN-level
  - Tighter control on WLAN
  - Facilitate traffic offload
  - Compensate coverage holes of LTE systems

Technical Challenges in HetNet

HetNet Mobility

- **Motivation**
  - Seamless and Robust Mobility between Macro & Pico Layers to Enable Offload Benefits.
  - More Pico Layers and Multiple Carriers may lead to More Potential Error Cases
    - Additional re-establishment procedures could help to improve the overall system robustness.
  - Efficient Offload From Macro to Small Cells requires fast Small Cell Discovery
  - Requirement on improved UE Mobility State Estimation
    - Current UE mobility state estimation is based on number of cell changes, but without explicitly taken the cell-size into account.
- **Main Issues**
  - Small Cell Discovery
  - Mobility State Estimation
  - Impact Of DRX



RWS-120029, "Views on LTE Rel-12 & Beyond", by China Mobile Communications Corporation

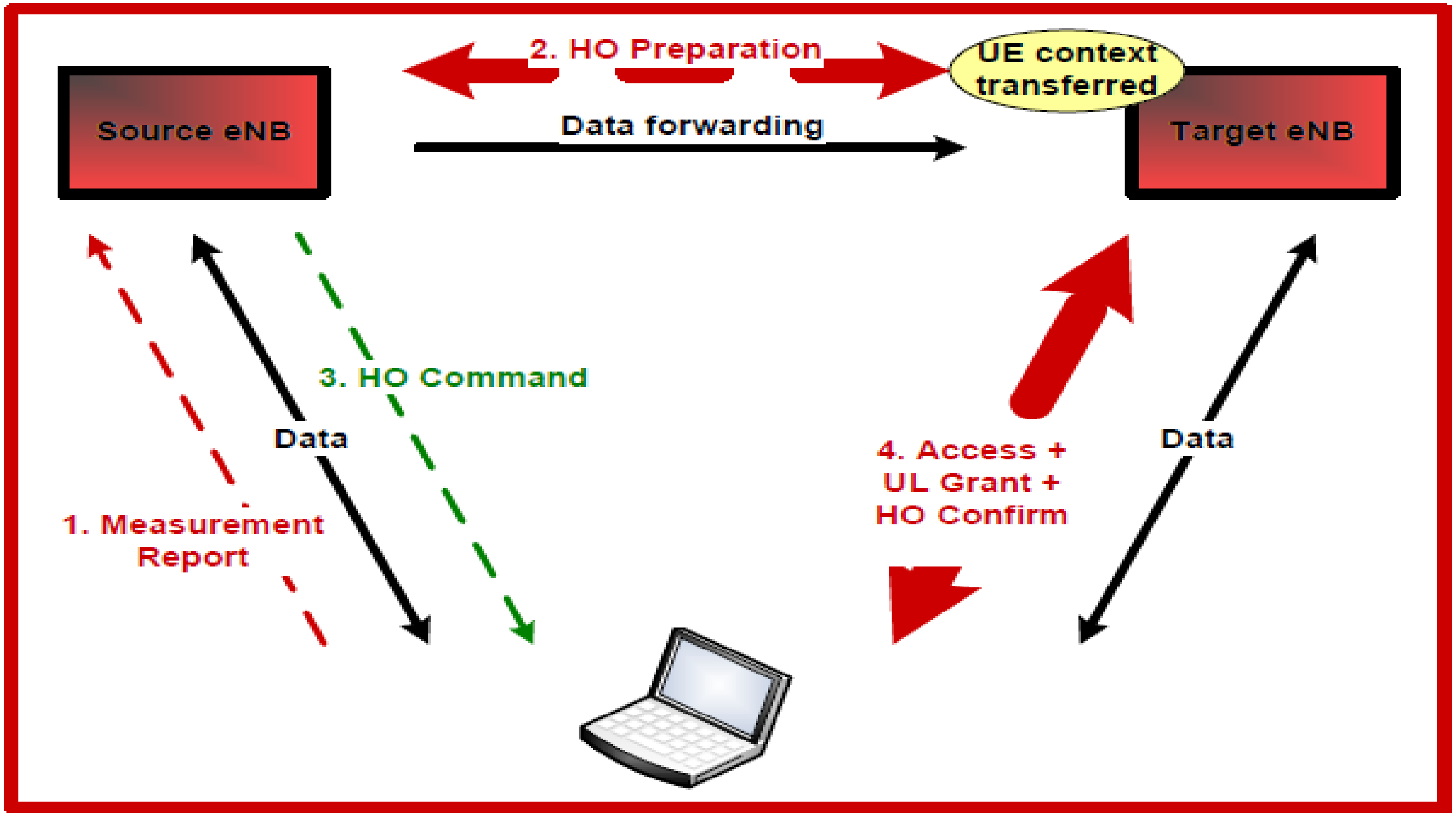
LTE IDLE mobility

- The Idle mode is a power-conservation state for the UE, where typically the UE is not transmitting or receiving packets.
- Idle mode UE does not inform the network of each cell change. The network knows the location of the UE to the granularity of a few cells, called the Tracking Area (TA).
- Idle mode mobility is a UE based mobility.
  - Normally called cell selection/reselection.
- The purpose of cell selection/reselection is to ensure that the terminal in Idle mode is camped on the best cell in terms of signal strength and quality.

LTE active mode mobility - handover

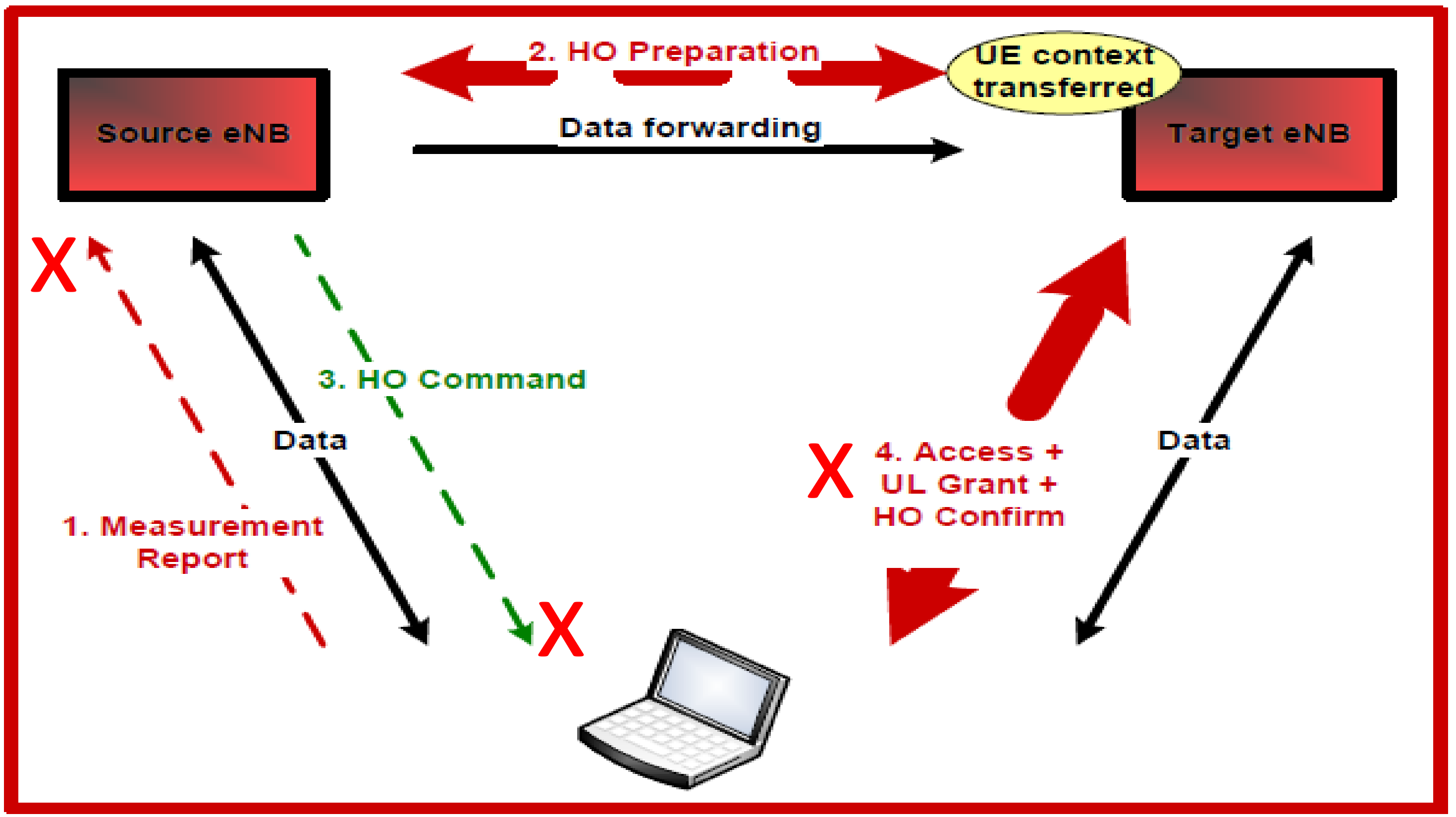
- In Active mode, the network knows the cell to which the UE belongs and can transmit/receive data from the UE.
- UE active mode mobility is mainly a network controlled mobility.
  - Normally it is called handover.
- The E-UTRAN decides when to make the handover and what the target cell is.
- During handover, the source cell, based on measurement reports from the UE, determines the target cell and queries the target cell if it has enough resources to accommodate the UE.
- The target cell also prepares radio resources before the source cell commands the UE to handover to the target cell.

Handover Procedure

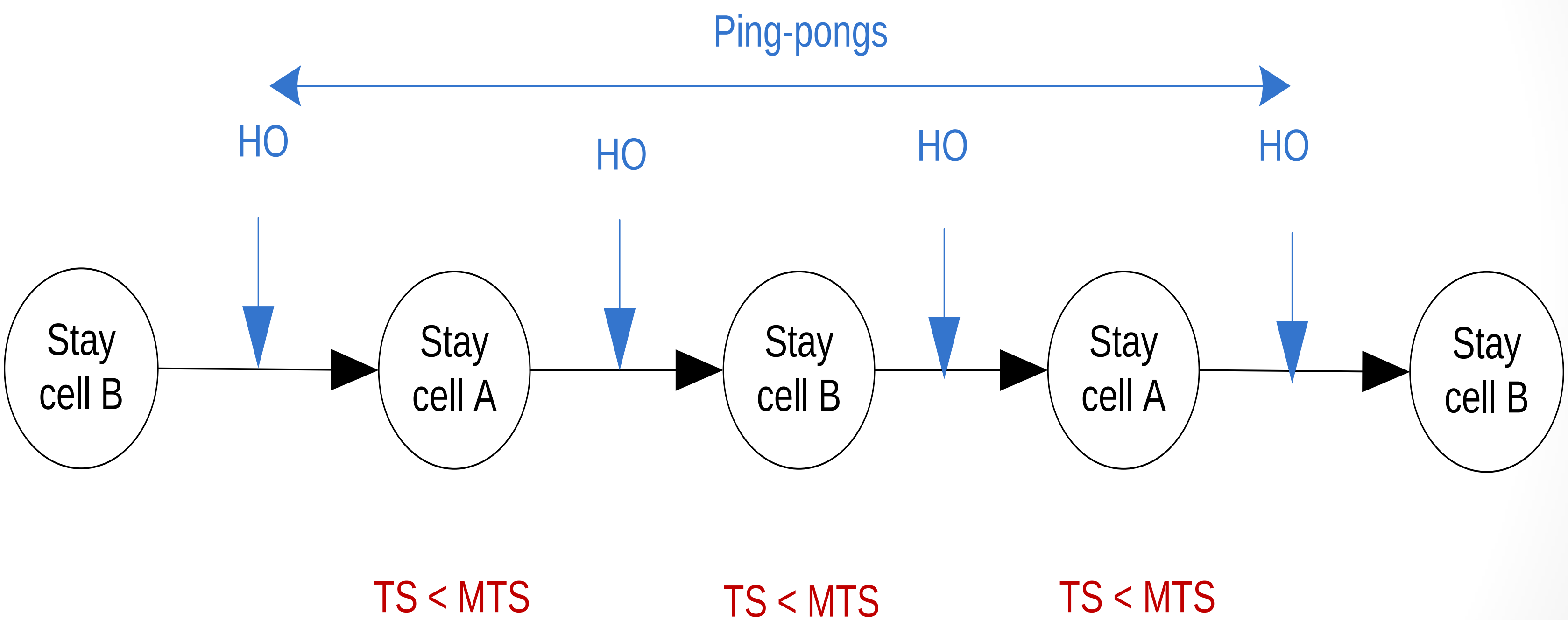


Source: “LTE Mobility Enhancement”, Qualcomm Technical Report.

Handover Failure

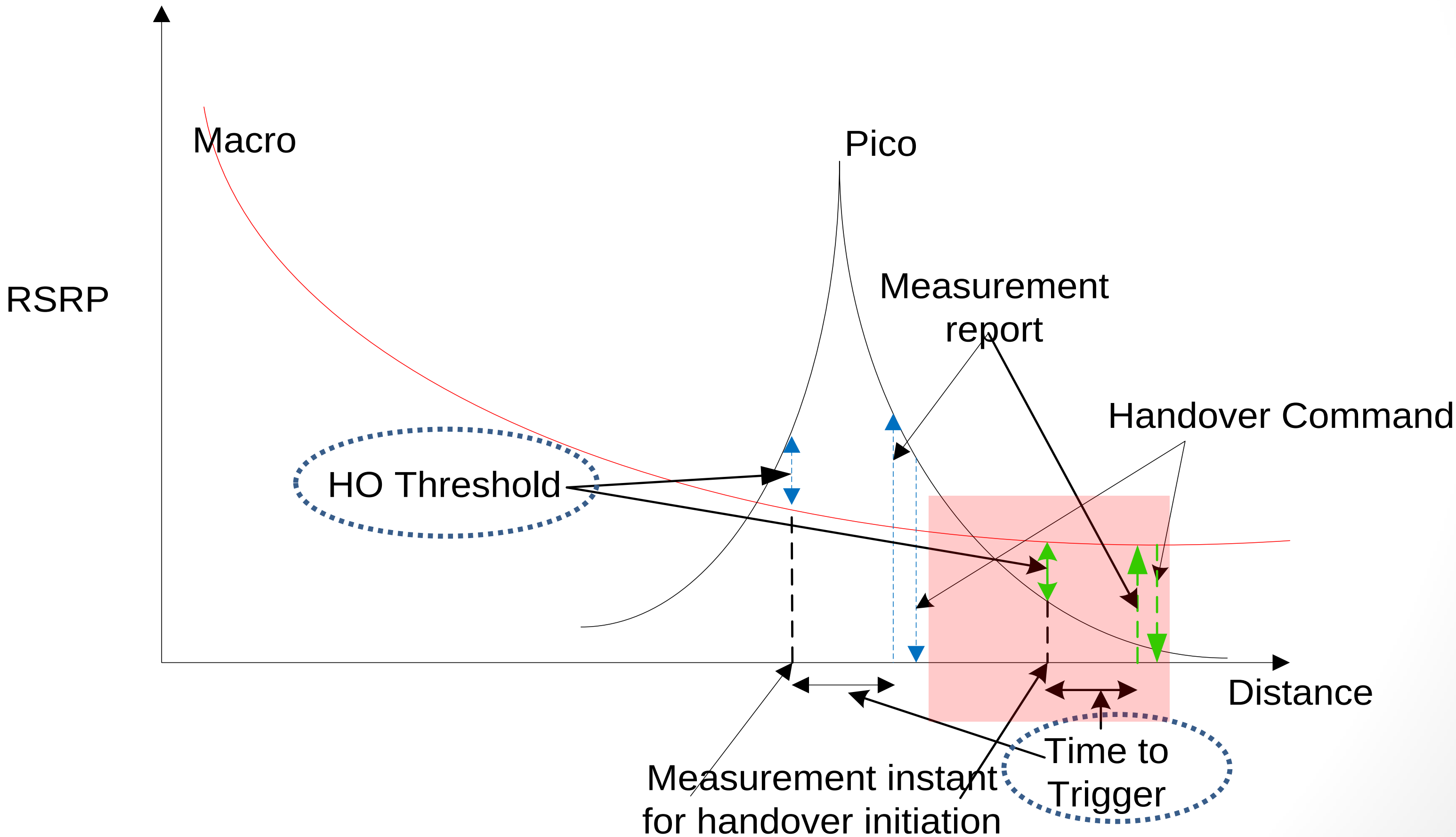


Ping-pong

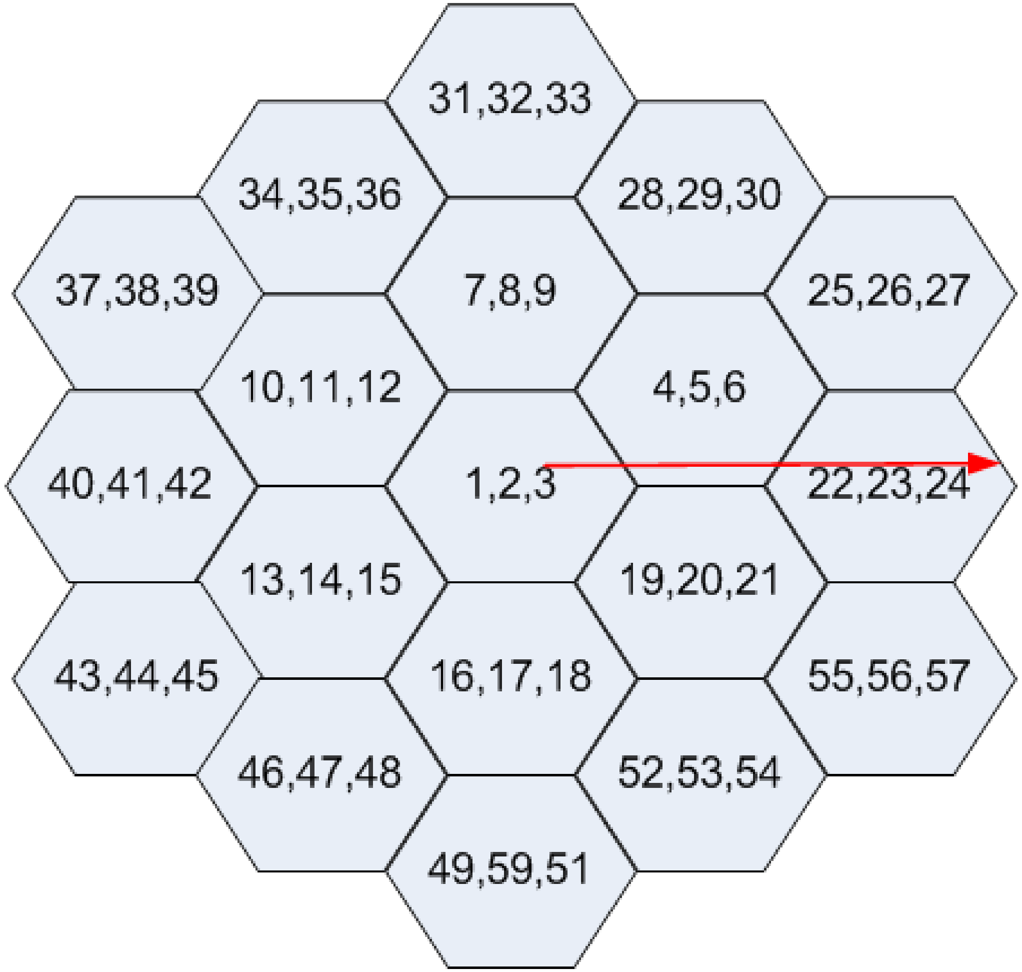


Ping-pongs
HO
HO
HO
HO
Stay cell B
Stay cell A
Stay cell B
Stay cell A
Stay cell B
TS < MTS
TS < MTS
TS < MTS

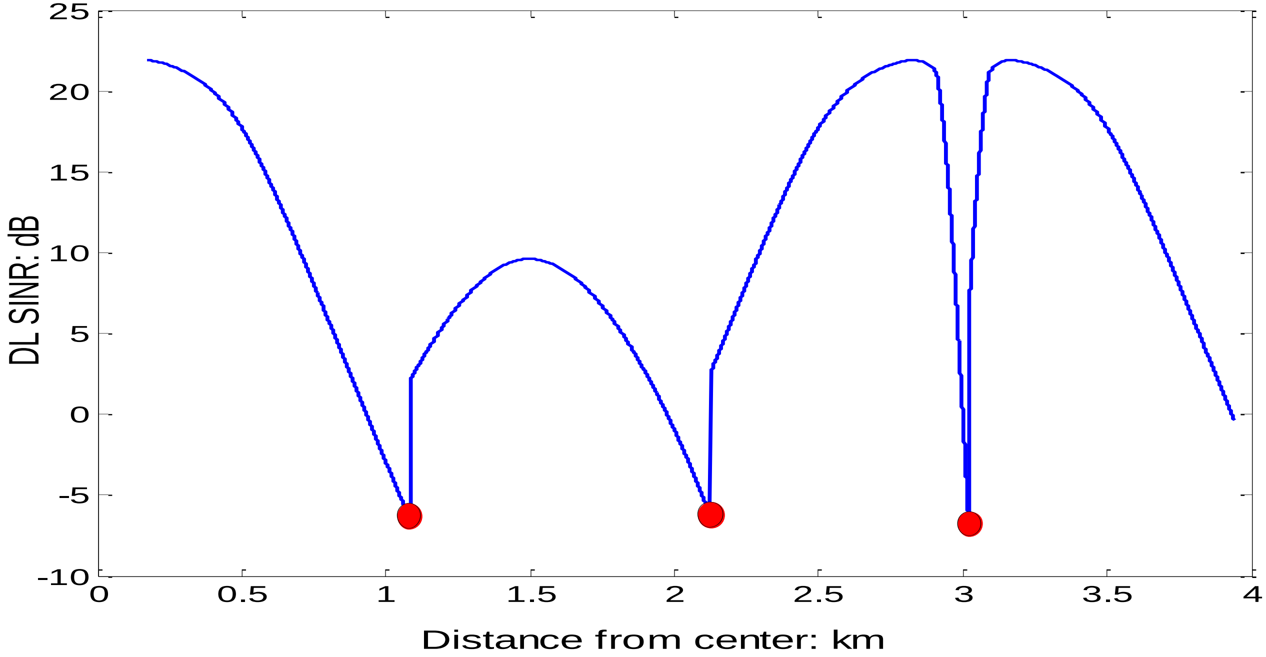
HO Robustness in HetNet



LTE HetNet Mobility Example

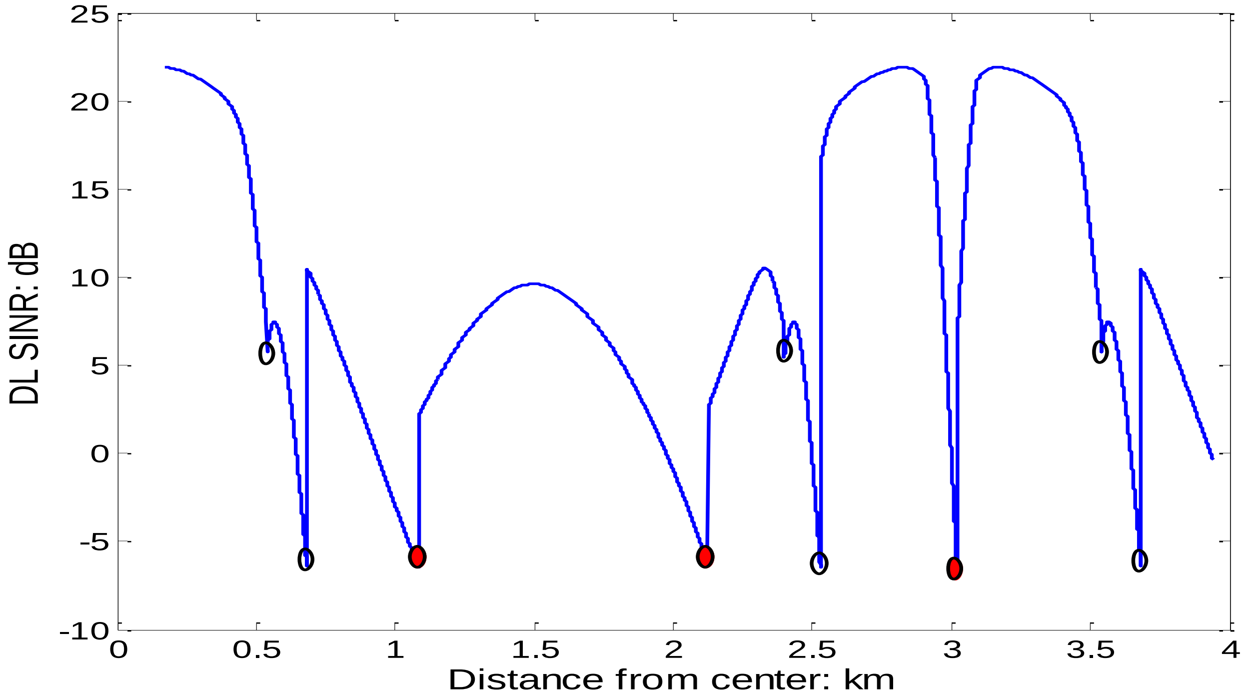


Handover in a homogenous network



Num. of Handovers	3
Avg. SINR	11.3 dB
Avg. CL	114.3 dB

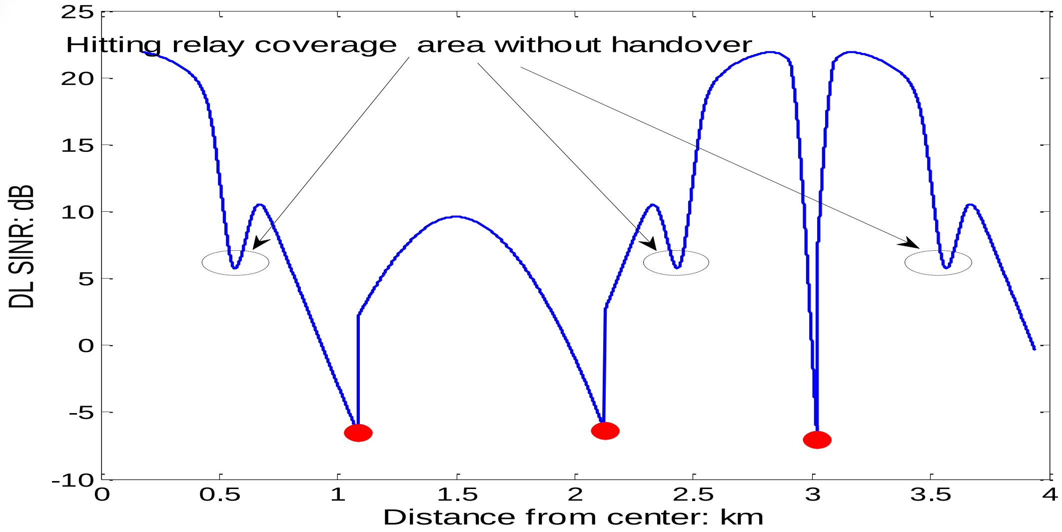
DL SINR-based Handover in HetNet

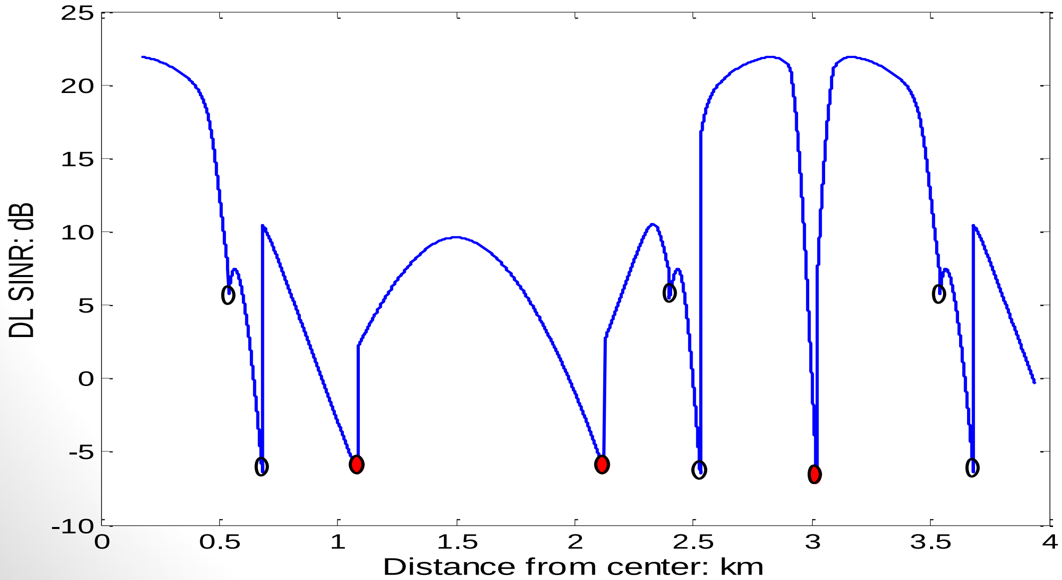


Num. of Handovers	9
Num of eNB handovers	3
Num of RN handovers	6
Avg. SINR	9.74 dB
Avg. CL	112.2 dB

- Handover is based on DL power.
- Compared with no relay, number of handovers is increased.
- With relay, the average UE DL SINR actually decreases.
- With relay, the average coupling loss improves.

Handover for small cell discovery



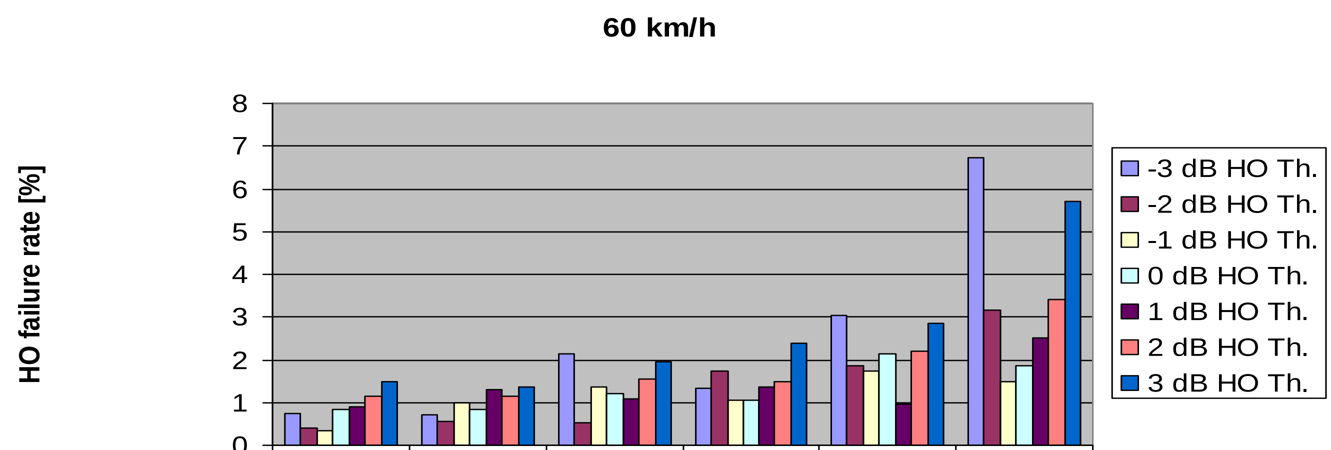


	no relay	with relay
Num. of Handovers	3	9
Num of eNB handovers	3	3
Num of RN handovers	0	6
Avg. SINR	10.6	9.74

- For UEs moving with high speed in a relay network
  - Choosing target cells only among macro-eNBs reduces the number of handovers greatly.
  - By doing so, the SINR is getting batter.

Handover Performance in HetNet

- Shorter TTT and smaller HO offset (even negative offset) helps to reduce HO failure rate, especially for high speed mobiles;



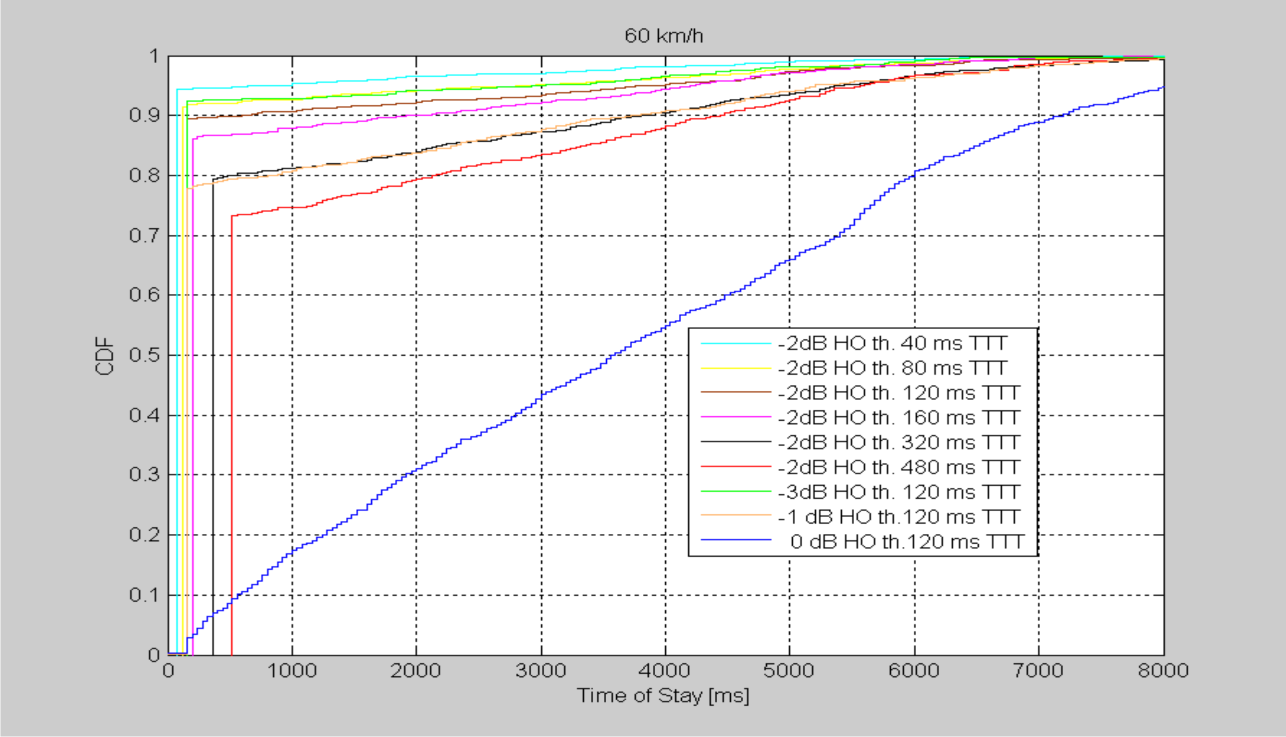
	40	80	120	160	320	480
-3 dB HO Th.	0.75	0.7	2.1425	1.346	3.0439	6.7265
-2 dB HO Th.	0.3976	0.5489	0.5424	1.743	1.8463	3.15
-1 dB HO Th.	0.3497	0.9985	1.3493	1.049	1.7509	1.5
0 dB HO Th.	0.8504	0.8479	1.2024	1.05	2.1511	1.8519
1 dB HO Th.	0.9005	1.3007	1.1006	1.35	0.95	2.5025
2 dB HO Th.	1.1512	1.1512	1.55	1.5008	2.2011	3.4051
3 dB HO Th.	1.5008	1.3507	1.952	2.4012	2.85	5.7029

Time to Trigger [ms]

Source: R2-110396 “Handover Performance and Improvements in Co-channel HetNet”, Alcatel-Lucent

Handover Performance in HetNet

- Shorter TTT and negative HO offset causes more ping-pongs;



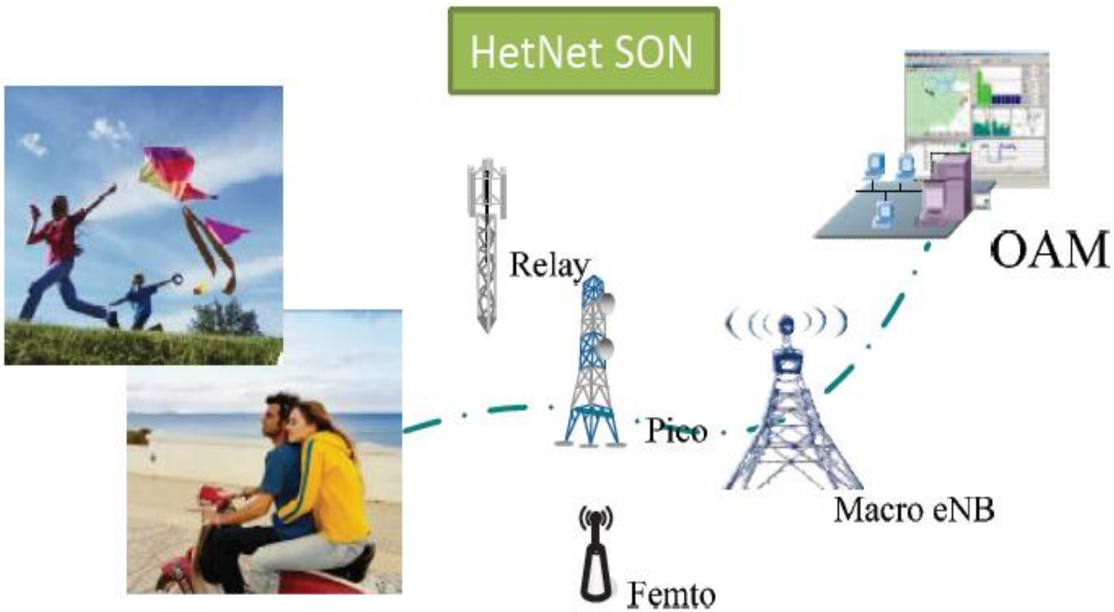
Source: R2-110396 "Handover Performance and Improvements in Co-channel HetNet", Alcatel-Lucent

HetNet Mobility Enhancement

- Cell association:
  - Enabling proper association to the cells with low geometry;
    - Further enhanced ICIC mechanism to enable control and data channel decoding in the low geometry environment
- Handover robustness:
  - Enabling fast and reliable small cell discovery;
    - HO parameter optimization, proximity information assistance, ...
  - Enabling fast and reliable re-establishment procedure to quickly recover from handover failure without loss of data;
    - Forward HO (UE-based HO), ...
  - Enabling enhanced UE mobility state estimation and taking cell size into consideration to better determine the HO parameter scaling factor;
- On-going work in 3GPP LTE Rel-11…

HetNet SON

- **HetNet SON Consideration**
  - Extending current SON features like MRO to low power nodes, e.g. Pico/Relay/HeNB
  - Considering mobility as the most significant issue
  - Self-checking and self-healing for low power nodes



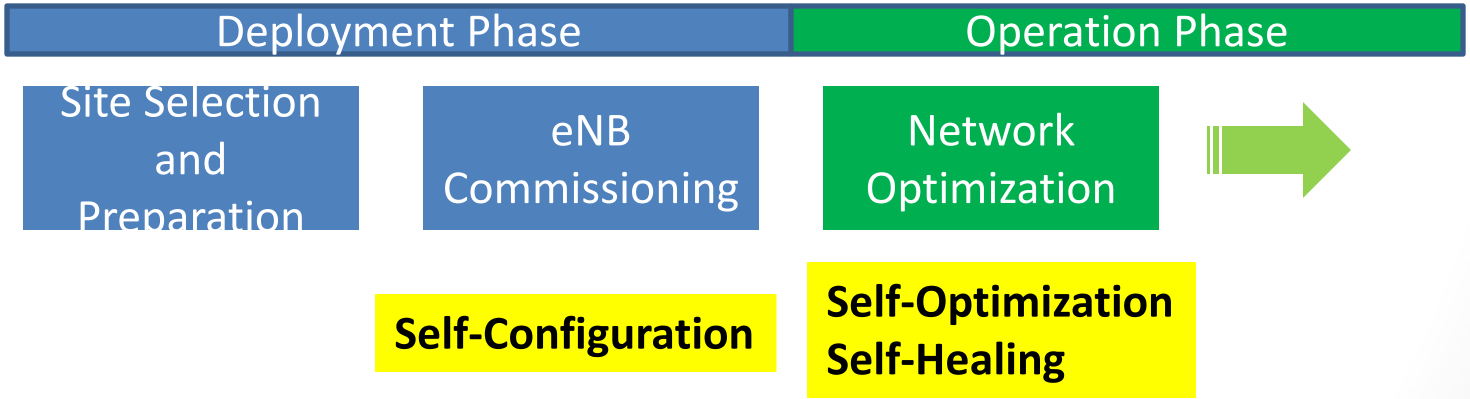
RWS-120029, "Views on LTE Rel-12 & Beyond", by China Mobile Communications Corporation

Motivation for SON

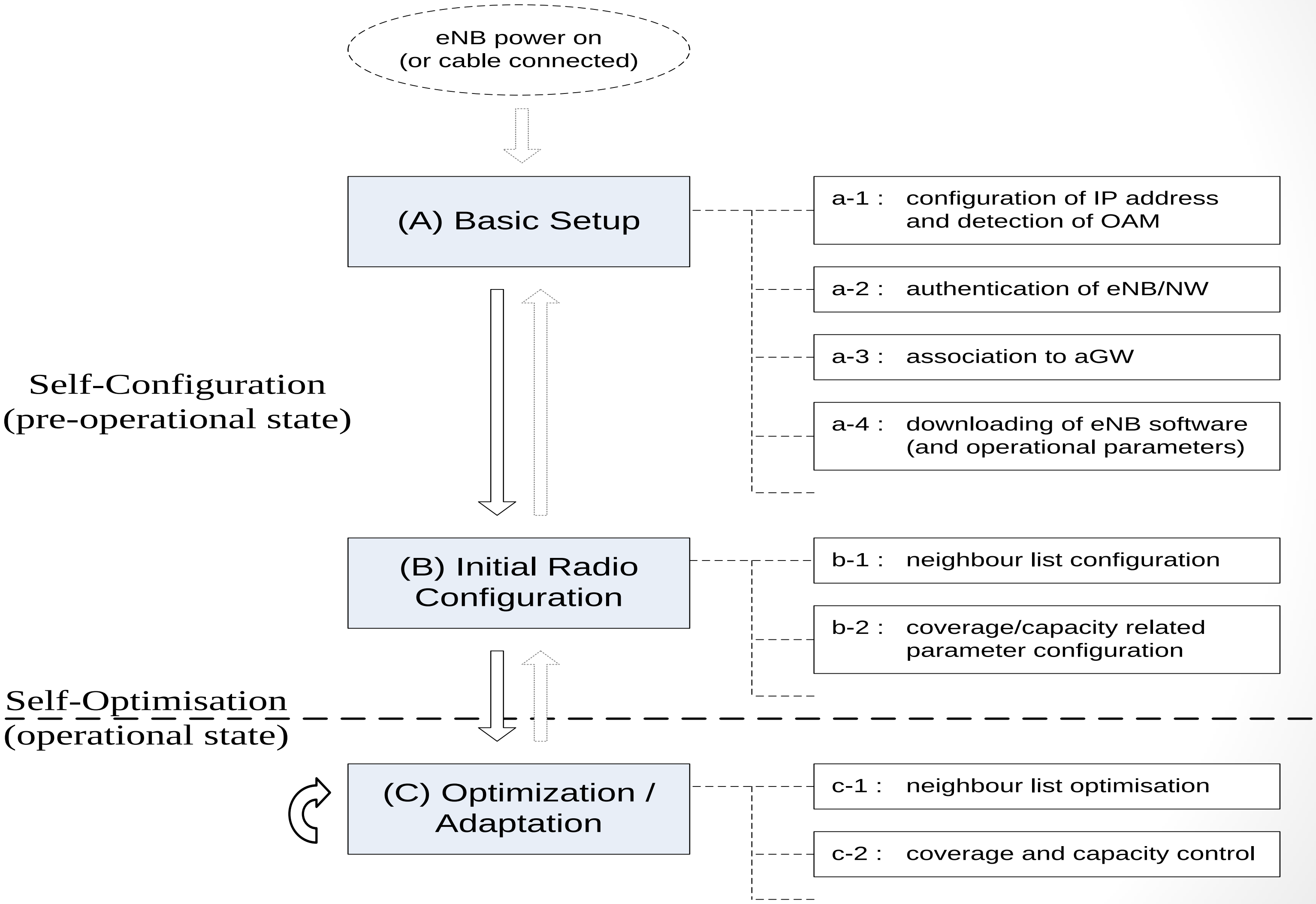
- Manual configuration in current network management:
  - Time and labor consuming;
  - Error-prone;
  - Slow react to the dynamic and fast evolving network operation;
  - One-size-fit-all
- Network becomes more complex
  - Multiple RATs
  - Multiple bands
  - Multiple layers (HetNet)
- Increasing pressure to
  - Reduce the network CAPEX and OPEX
  - Improve network performance to maximize the network efficiency and user experience

What is SON

- Maximizing automatic network deployment and operation by
  - Self-configuration: Plug and play
  - Self-optimization: auto-tune the operational setting
  - Self-healing: outage prediction, detection and compensation



SON in LTE Rel-10

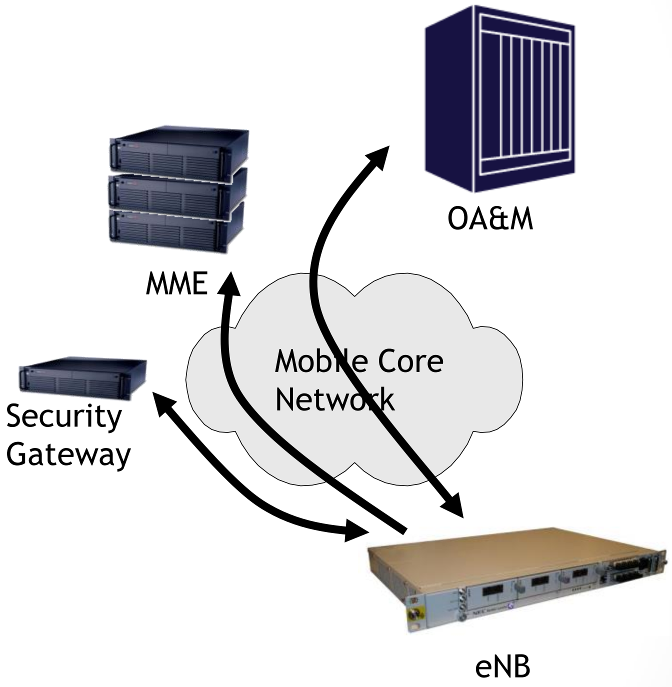


Source: TS36.300 v10.3.0, 3GPP

Self-Configuration

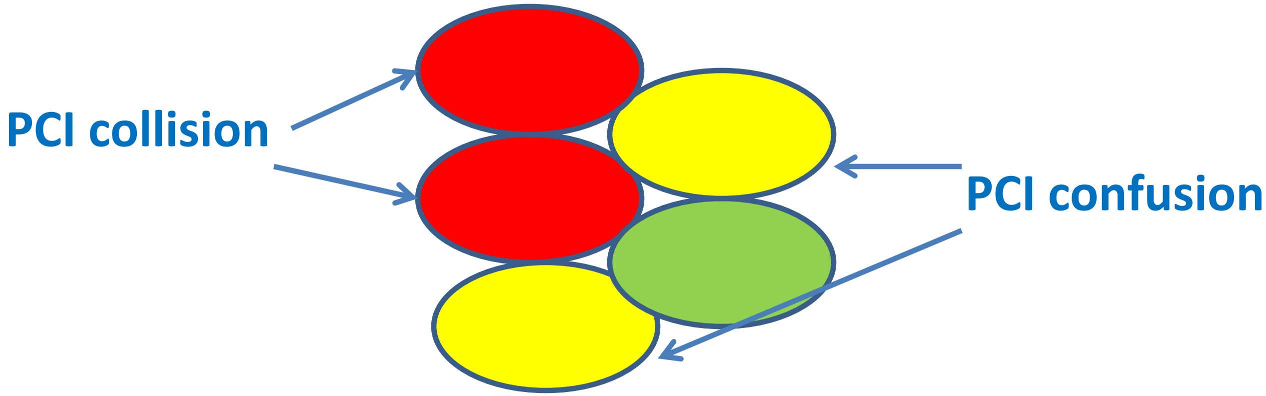
- Self-configuration enablers:
  - Dynamic configuration of S1-MME
  - Dynamic configuration of X2
  - Automatic Neighbour Relation Function
  - PCI selection
  - TNL address discovery

- Easy plug-and-play is critical for HetNet deployment



PCI Selection

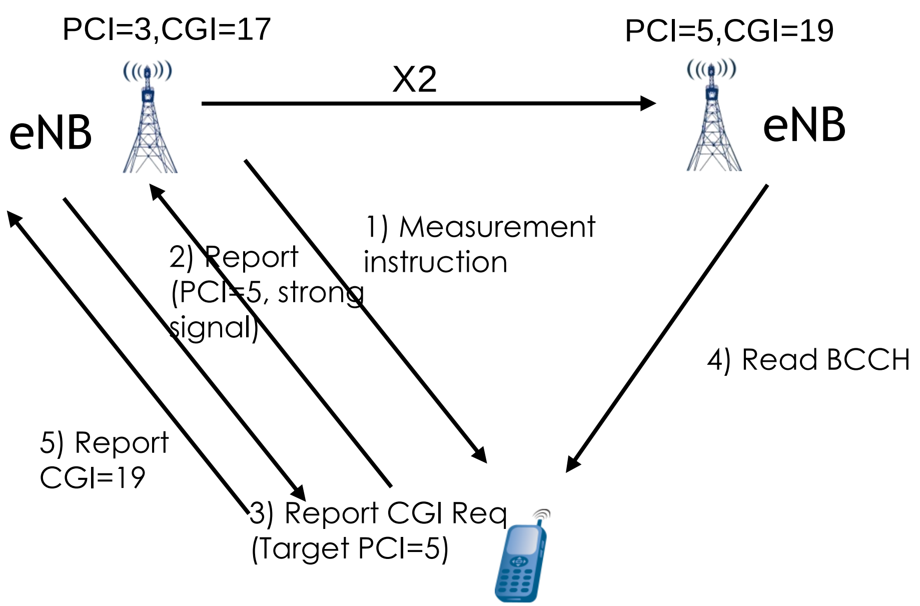
- LTE supports 504 unique physical cell IDs (PCIs);
- PCI collision and confusion shall be avoided;



- Critical for HetNet deployment due to large number of small cells on top of macro layer;
- Can be assigned via centralized algorithm or distributed algorithm;

Automatic Neighbor Relation

- ANR improves neighbor list accuracy
  - Incorrect/incomplete neighbor list leads to HO failure
- ANR can detect PCI collision and confusion



- Critical for HetNet deployment due to small cells being added from time to time;

Self-Optimization

- Self-optimization enablers:
  - Mobility load balancing
    - To distribute cell load evenly or to transfer part of the traffic from congested cells
  - Mobility robustness optimization
    - To detect and resolve HO failure and unnecessary inter-RAT HO
  - RACH optimization
  - Energy saving
    - To switch off capacity booster cell to save energy
  - Additional handling to reduce ping-pongs in HetNet is proposed to be discussed in LTE Rel-11
- Minimization of drive tests:
  - Logging and reporting of various measurement data (e.g., location information, radio link failure events, throughputs) by the UE and collection of data in a server to minimize drive tests run by operators.

HetNet in China

- China Mobile WiFi deployment:
  - 2.2 million APs deployed
  - Goal is to carry internet traffic for both PCs and smart phones.
  - So far mainly carry data from PCs. Only offload 2% data from cellular handsets.
  - Better WiFi and cellular network coupling will improve utilization and user experience. This requires enhancements on more unified user/device credential, device management, and service delivery.
- Huawei/ChinaMobile/Datang Telecom LTE-Hi initiative.