Heterogeneous Networks – Theory and Standardization in LTE

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Tutorial Outline

- ❑An Introduction to Heterogeneous Networks
- ❑Typical HetNet Deployments
- ❑Interference Management in HetNets (Theory)
- ❑Mathematical modeling of HetNets (Theory)
- ❑Standardization Impacts on HetNets
- ❑Concluding Remarks
- ❑References

Tutorial Outline

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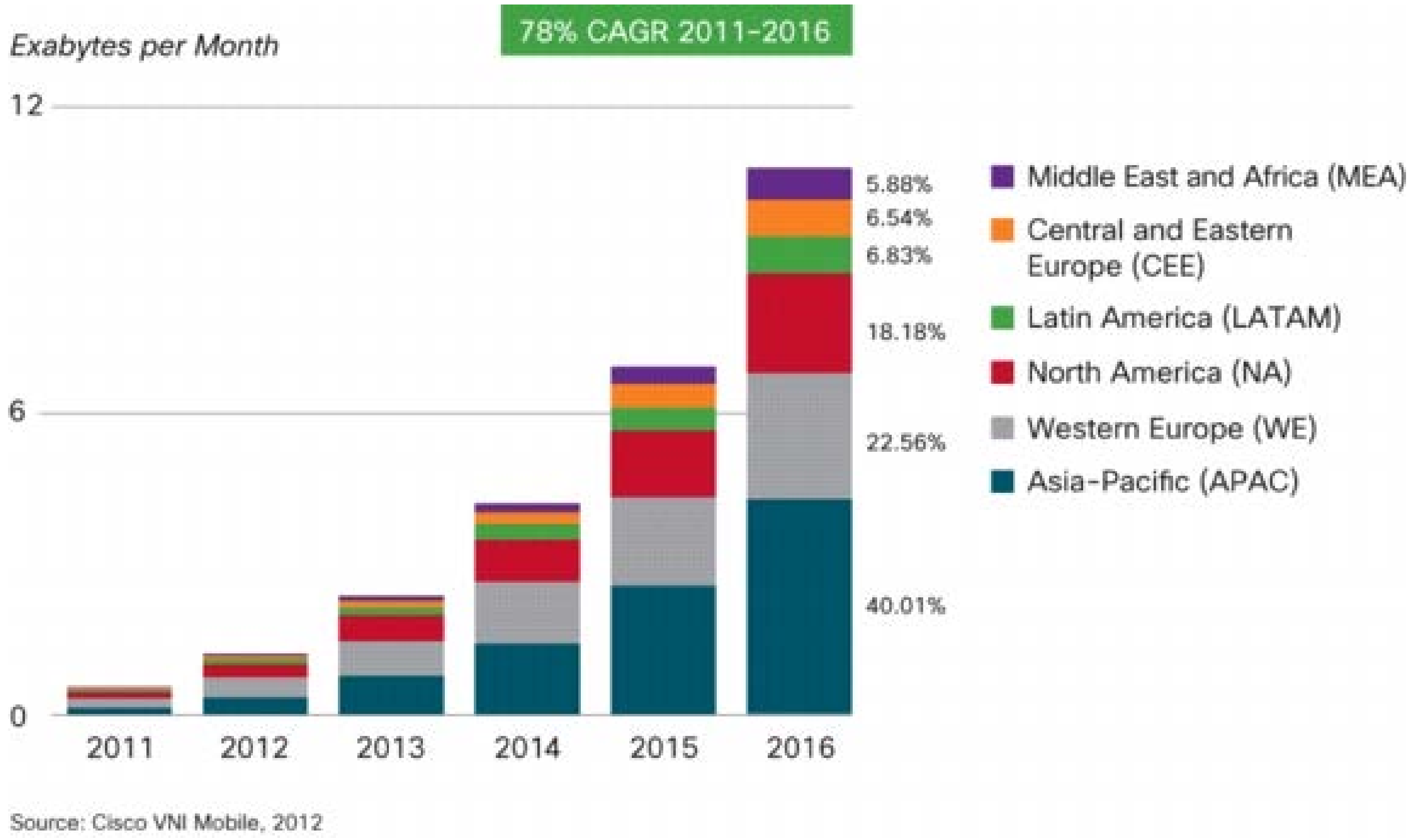
- An Introduction to Heterogeneous Networks
  - Growing demand of data
  - Need for heterogeneous networks (HetNets)
  - Market trends for HetNets
- Typical HetNet Deployments
- Interference Management in HetNet (Theory)
- Mathematical modeling of HetNets (Theory)
- Standardization Impacts on HetNets
- Concluding Remarks
- References

Increased Demand for Data



Exponential rise in demand for data esp. in Asia Pacific, North America and Europe

Growth in Mobile Broadband

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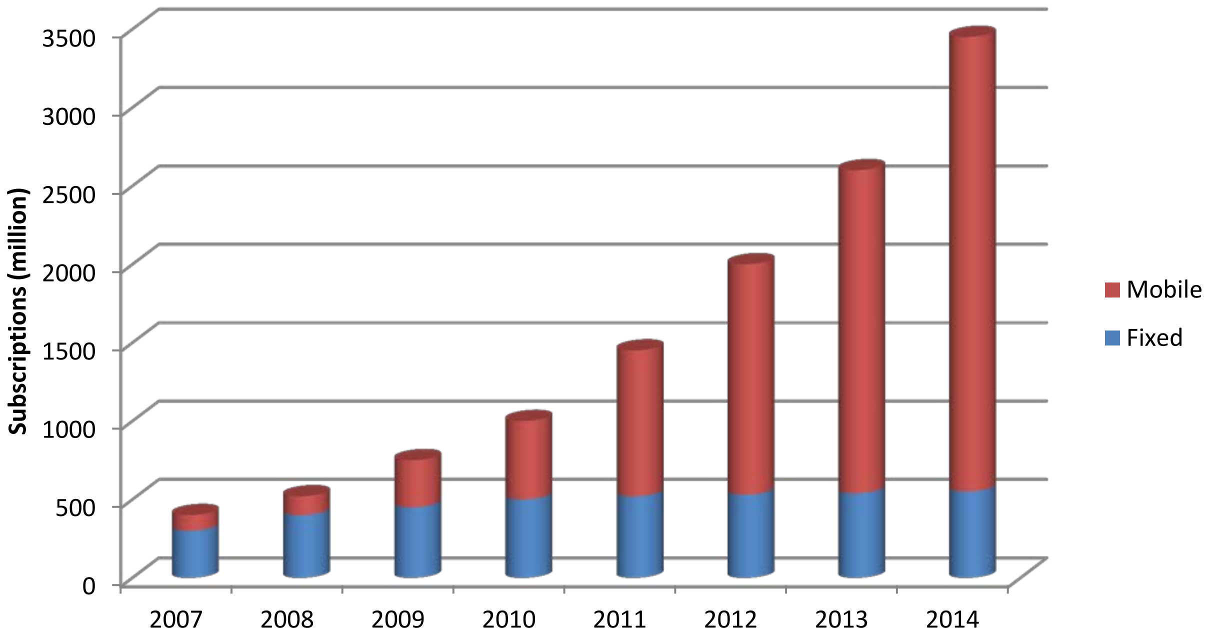
- Subscription trends in broadband service
  - Mobile Broadband : CDMA2000 EV-DO, HSPA, LTE, Mobile WiMAX, TD-SCDMA
  - Fixed Broadband : DSL, FTTx, Cable modem, Enterprise leased lines



- Thus rapid adoption of cellular based mobile broadband

Source: Infonetics Research Femtocell equipment market size, share and forecast, 4Q11, March 2012

Spectrum Reuse

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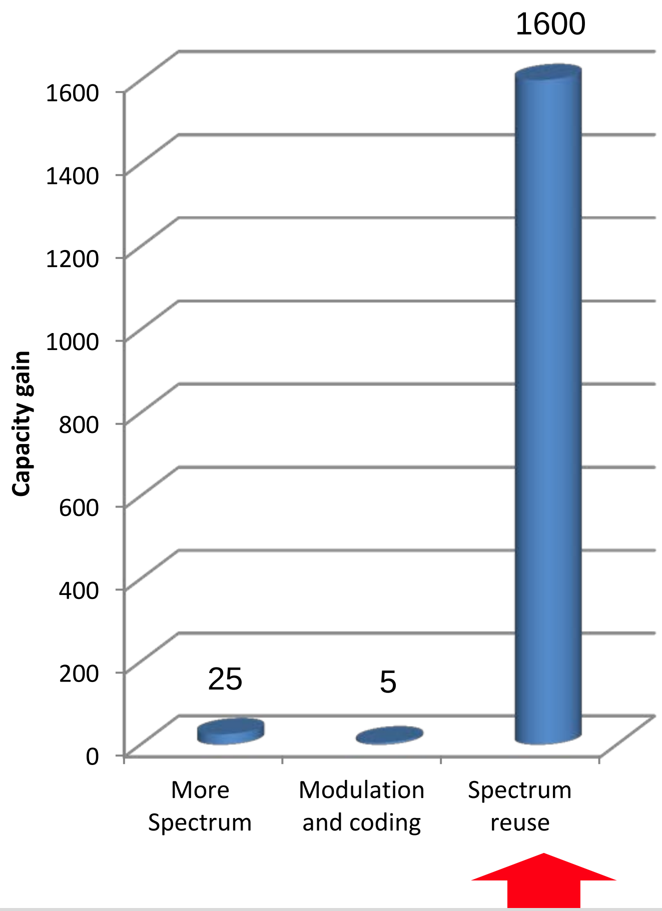
- Cooper's law
  - The data rate available to a wireless device doubles roughly every 30 months
- Method to increase capacity gain
  - More spectrum
  - Modulation and coding
  - Spectrum reuse
    - Achieved by cell splitting



Most Capacity gain comes from spectrum reuse

Source: J. Andrews et al, "**A Tractable Framework for Coverage and Outage in Heterogeneous Cellular Networks**", ITA workshop, Feb 2010

Heterogeneous Networks (HetNets)

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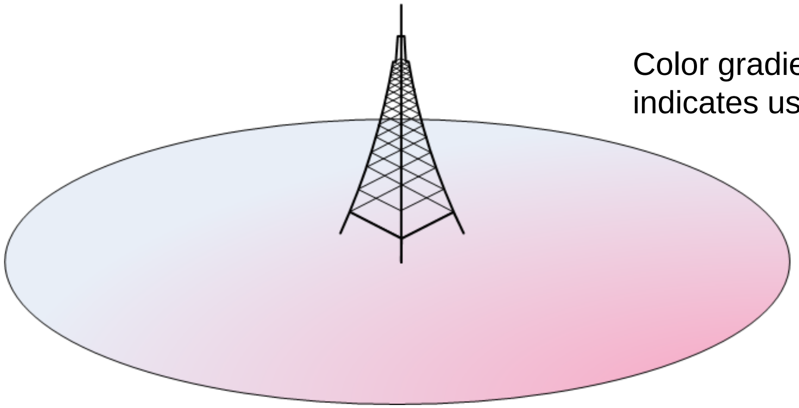
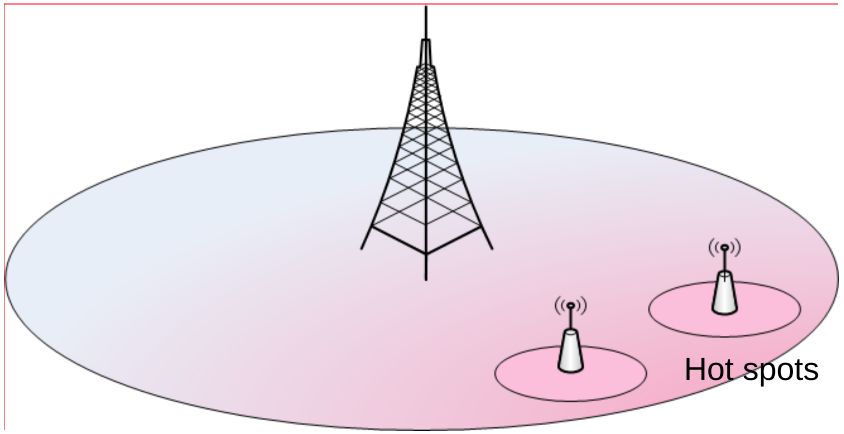
- Deployment of low power nodes (small cells) throughout a macro-cell layout.
- Achieves spectrum reuse via cell splitting

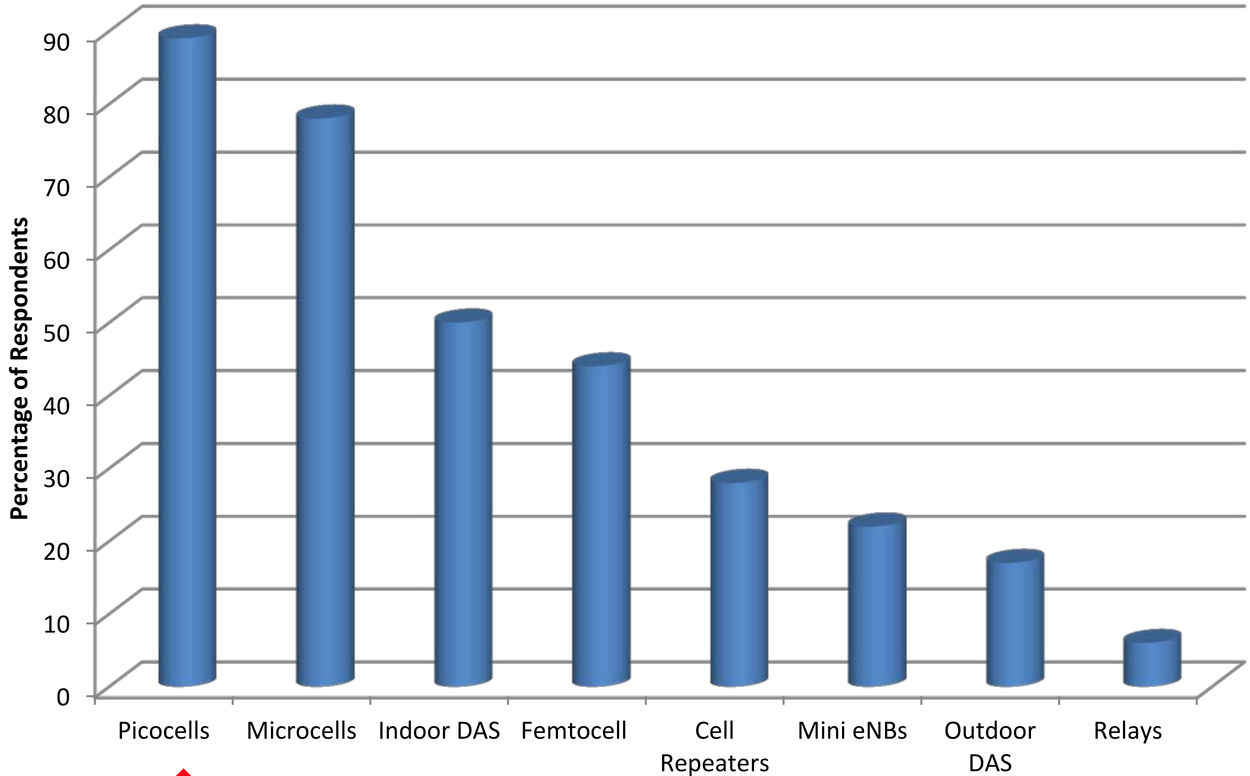




- High Power macro nodes
- Large Coverage area
- Non uniform user experience

- Additional low power nodes
- In dense user locations
- Small Coverage area
- Localized interference

Adoption Statistics of HetNets



Pico cells most preferred by operators

Infonetics Research Femtocell equipment market size, share and forecast, 4Q11, March 2012

Summary

- Future networks have huge demand of data rates
  - New applications and increasing user populations
- Spectrum reuse: most effective to increase network capacity
- Heterogeneous networks (HetNets) achieve this
  - Overlay low power nodes (pico/femto) in high power macro area
- HetNets are being increasingly deployed by operators
  - Pico cells most preferred

Outline

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- ❑ An Introduction to Heterogeneous Networks
- ❑ Typical HetNet Deployments
  - ➢ New nodes and deployments
  - ➢ Cell association and bias
  - ➢ Interference scenarios
- ❑ Interference Management in HetNets (Theory)
- ❑ Mathematical modeling for HetNets (Theory)
- ❑ Standardization Impacts on HetNets
- ❑ Concluding Remarks
- ❑ References

Centralized to Decentralized Deployment

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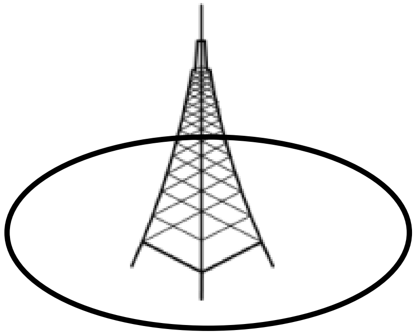
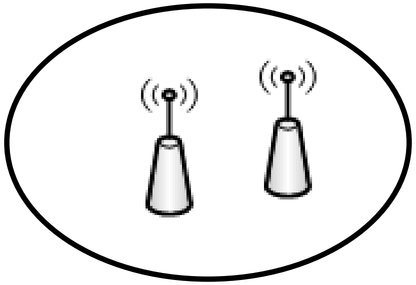
- From planned operator deployment to uncoordinated user deployments
- Smaller Cell Sizes and Lower Transmit Powers
- Increased need for interference management algorithms
- Mobility management and SON issues critical

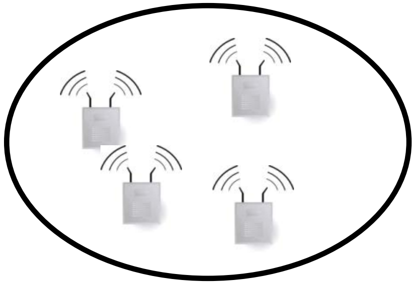
Operator deployed Macro Cells



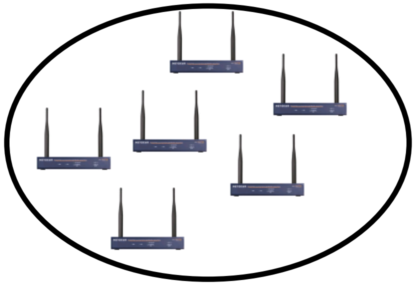
Operator deployed Micro/Pico/RRH



Enterprise Femto Cells



User deployed HeNBs with CSG (closed subscriber groups)

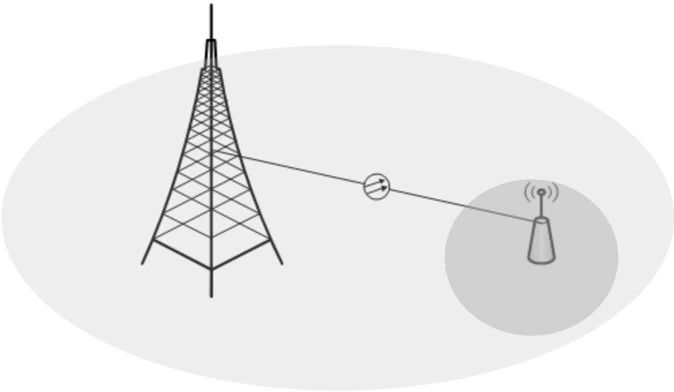


Categorization of New Nodes

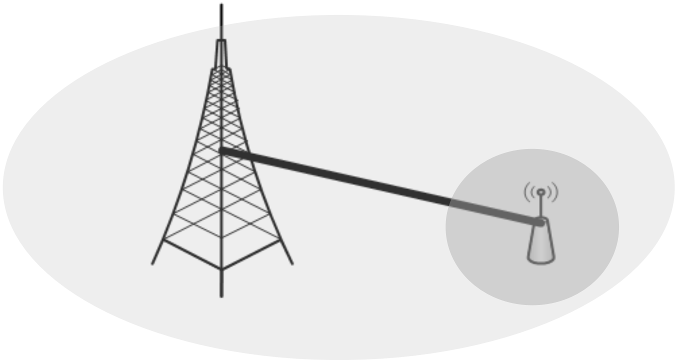
Node Type	Backhaul	Access	Notes
Remote radio head (RRH)	Several µs latency to macro	Open to all UEs	Placed indoors or outdoors
Pico eNB (i.e. node for Hotzone cells)	X2	Open to all UEs	Placed indoors or outdoors. Typically planned deployment.
HeNB (i.e. node for Femto cells)	No X2 as baseline	Closed Subscriber Group (CSG)	Placed indoors. Consumer deployed.
Relay nodes	Through air-interface with a macro-cell (for in-band RN case)	Open to all UEs	Placed indoors or outdoors

Source: 3GPP TS 36.814

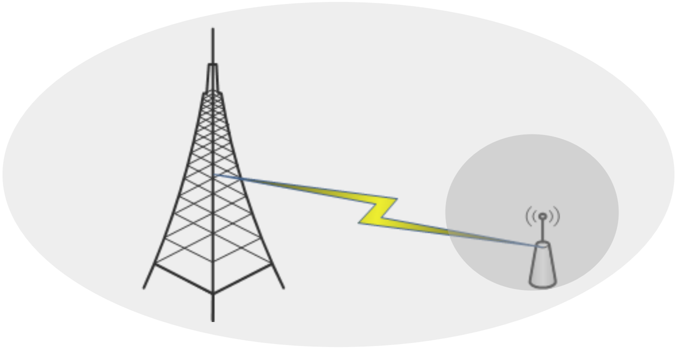
Backhaul Between Macro and Small Cells



- ❑ Fiber Connectivity
- ❑ Low latency
- ❑ E.g.: macro-RRH connectivity



- ❑ Cable connectivity
- ❑ Medium latency
- ❑ E.g. macro-macro, macro-pico
- ❑ X2 interface protocol defined



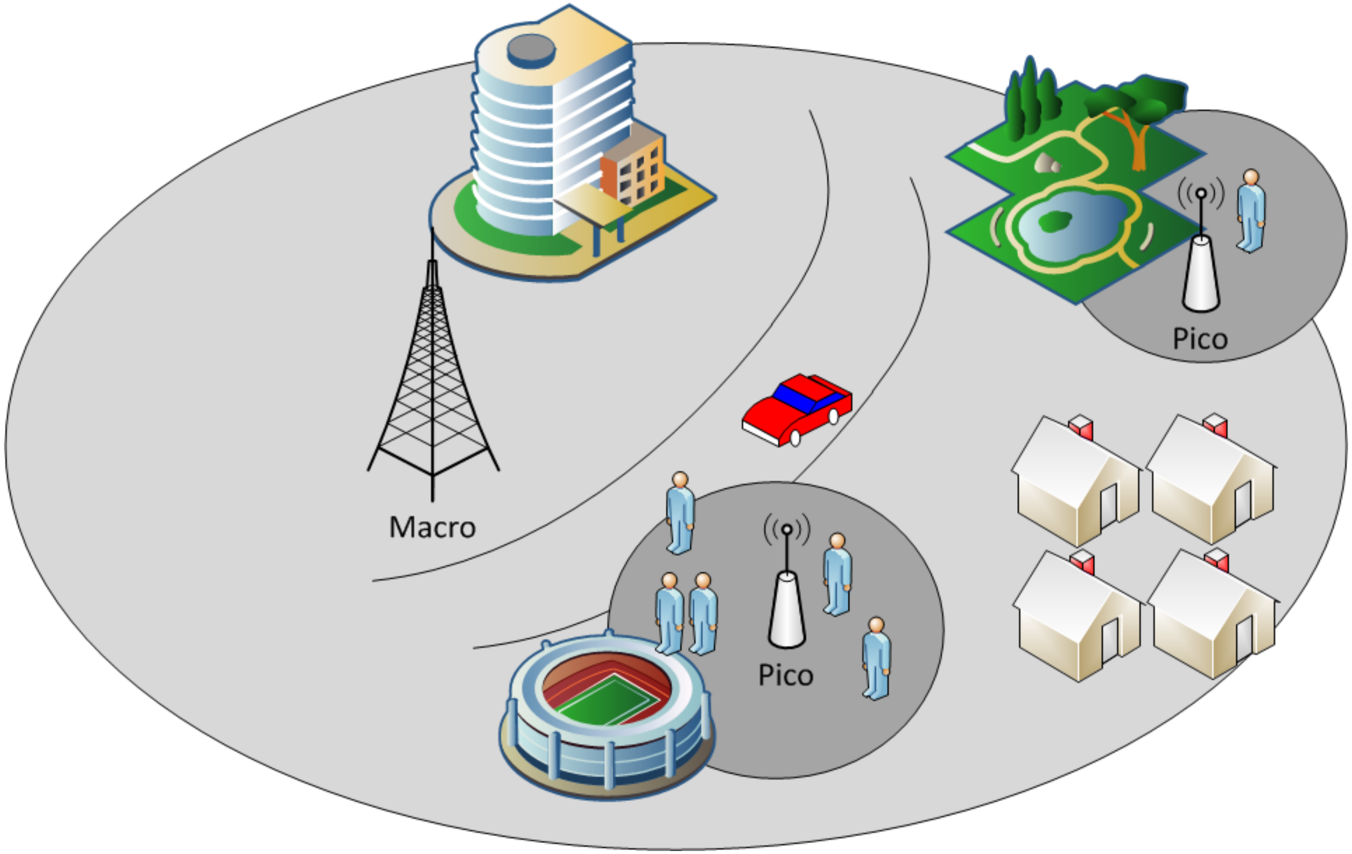
- ❑ Through air interface
- ❑ More latency
- ❑ E.g. macro-relay nodes

3GPP HetNet Deployment Scenarios

Environment	Deployment Scenario	Node
Macro + Indoor	Macro + Femtocell	Femtocell
	Macro + Indoor relay	Indoor relay
	Macro + Indoor RRH/Hotzone	E.g. Indoor pico
Macro + Outdoor	Macro + Outdoor relay	Outdoor relay
	Macro + Outdoor RRH/Hotzone	E.g., Outdoor pico

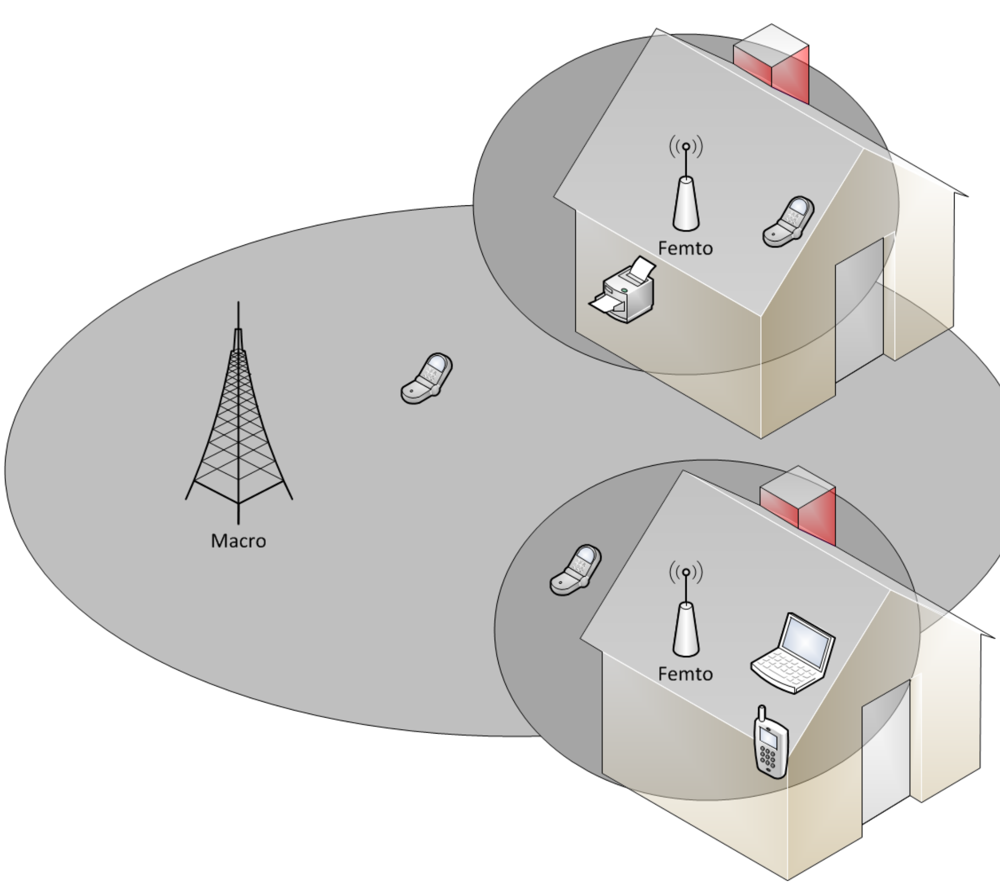
Source: 3GPP TS 36.814

Outdoor Macro-Pico Deployment



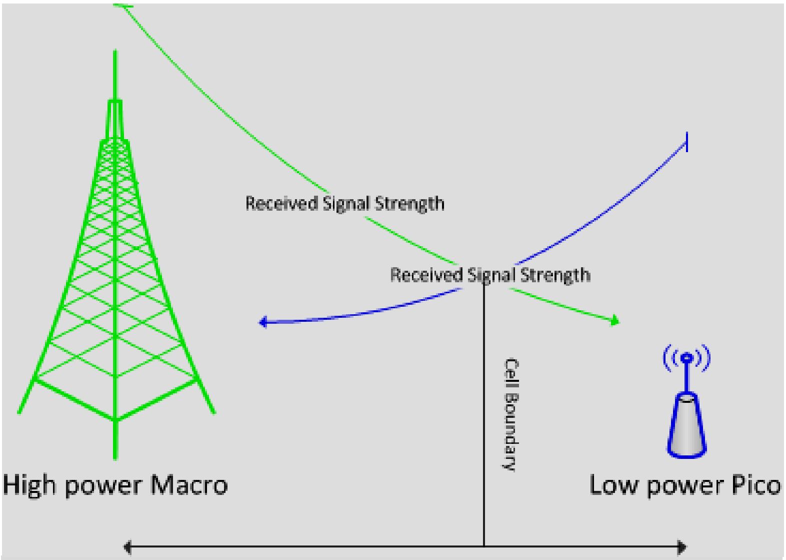
- ❑ Picos are deployed on the macro cell edge or hotspot to improve coverage or throughput.
- ❑ Picos are open to all UEs

Indoor Macro-Femto Deployment

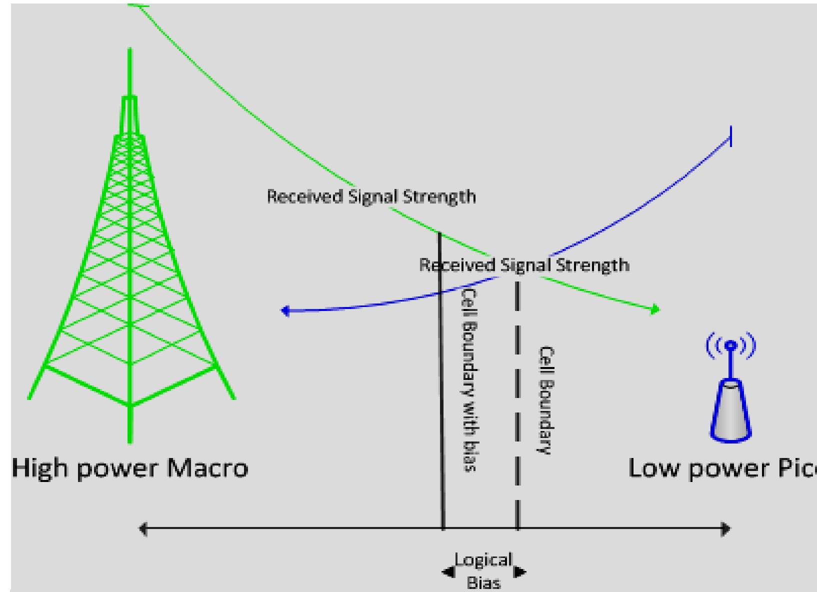


- ❑ Femtos are deployed indoor to enhance the throughput
- ❑ Femto cells are open to specific UEs – called CSG (Closed Subscription Group)
- ❑ A UE close to femto can’t connect to femto if it is not in CSG (connects to macro instead)

Cell Association and Bias

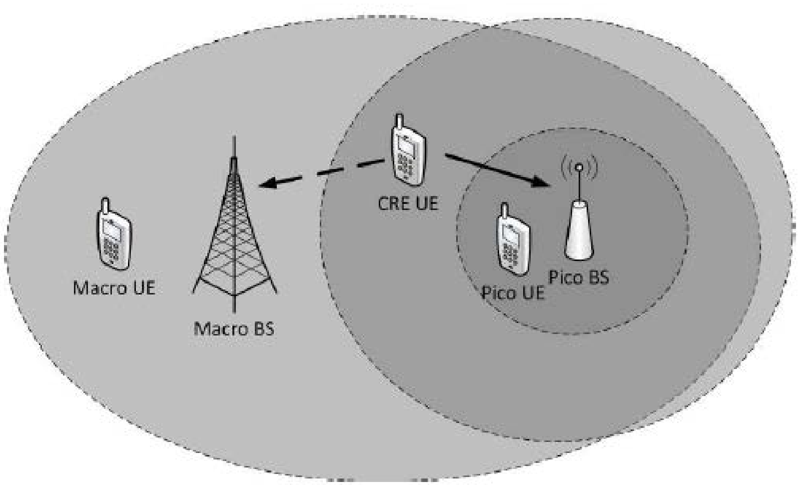


- ❑ UE association by DL Rx power
- ❑ Large # UEs associate to macro
- ❑ Increased macro traffic load

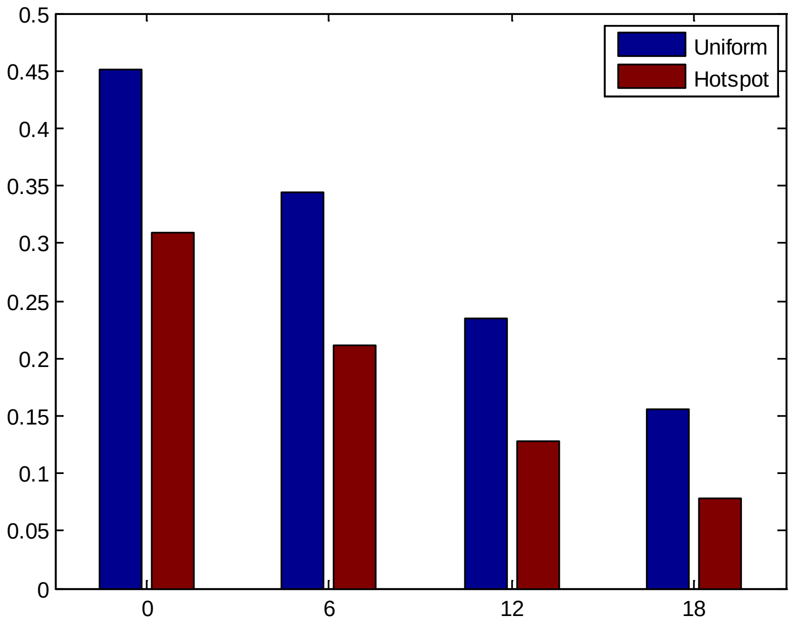


- ❑ Logical bias during association
  - ➢ CRE (Cell Range Expansion)
- ❑ Load on macro reduced
- ❑ Large macro interference
  - ➢ Cell edge Pico UEs

How Bias Values Affect Association



- 3GPP HetNet use cases
- 3 sector, 19 cell macro, 500 m cell
- 4 picos/cell uniformly distributed
- Macro-> UE (Urban macro), Pico->UE (Urban micro)
- Tx power: Macro: 46 dBm, Pico: 30 dBm
- User distributions
  - Uniform distribution (Config. 1)
  - Hotspots around pico area (Config. 4b)



- Association Ratio of macro plotted for different bias
  - Percentage of UEs associated with macro
- Ratio decreases with bias values
- Advantages of pico deployments for hotspots
  - Higher CRE offloads more traffic from macro

Interference Situations in HetNets

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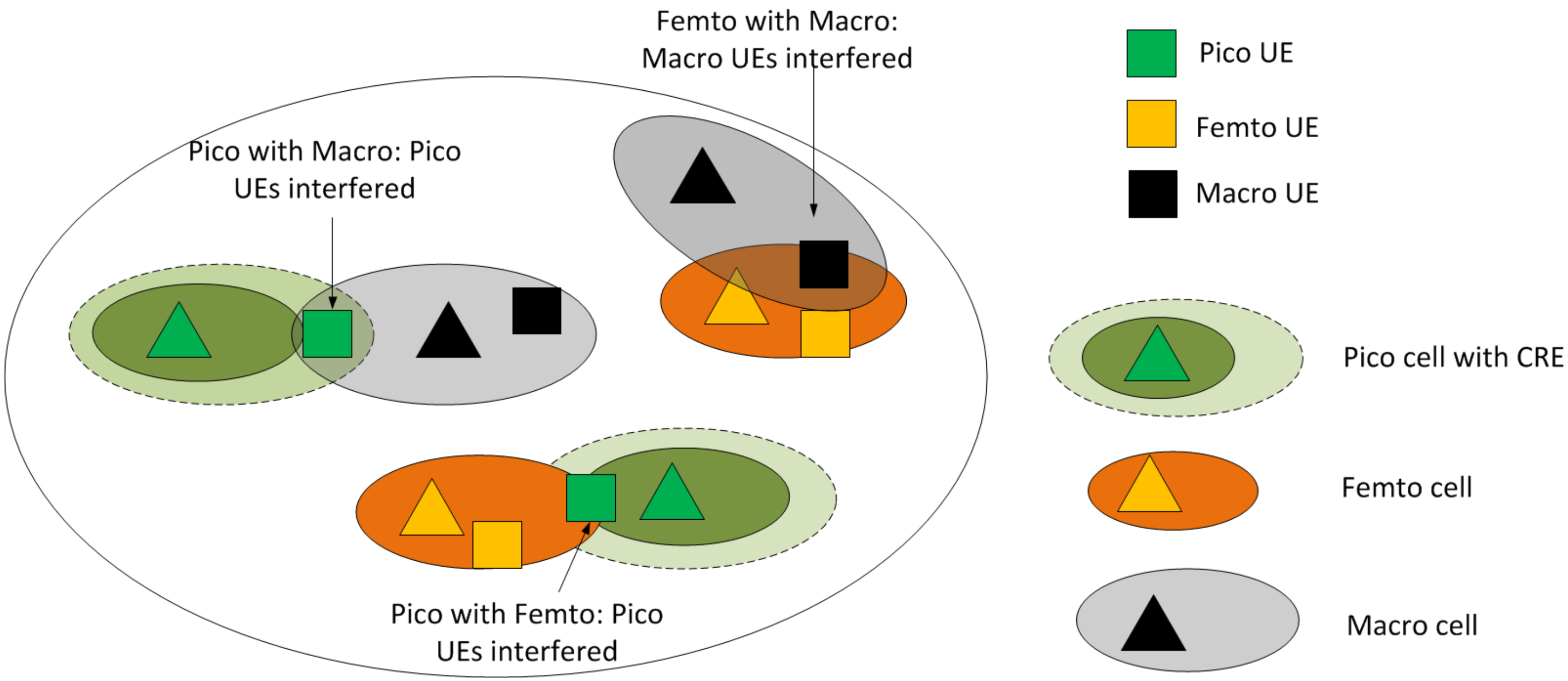

Interference management is the most significant issue in HetNets.

Macro + Femto Interference Scenario

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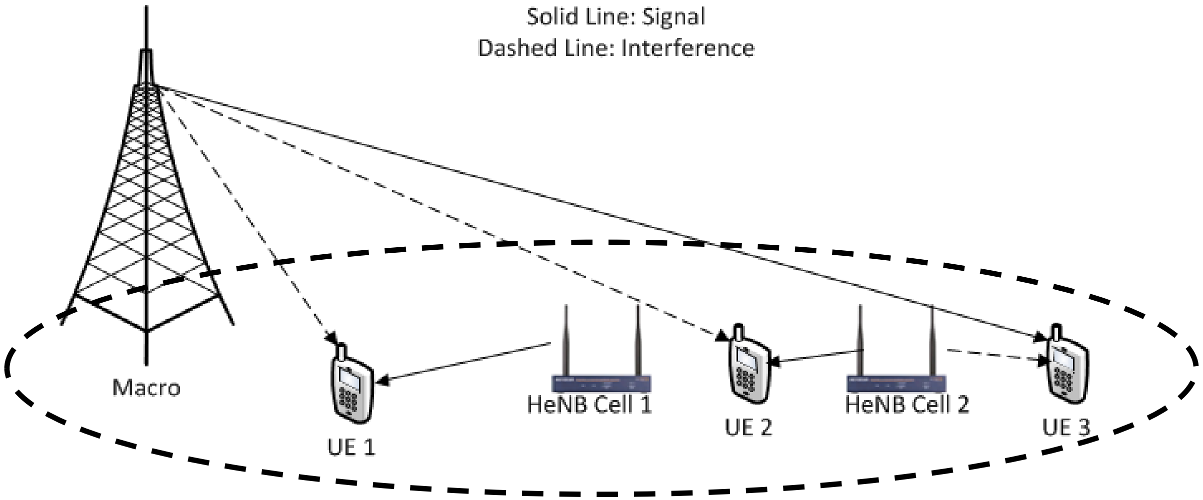
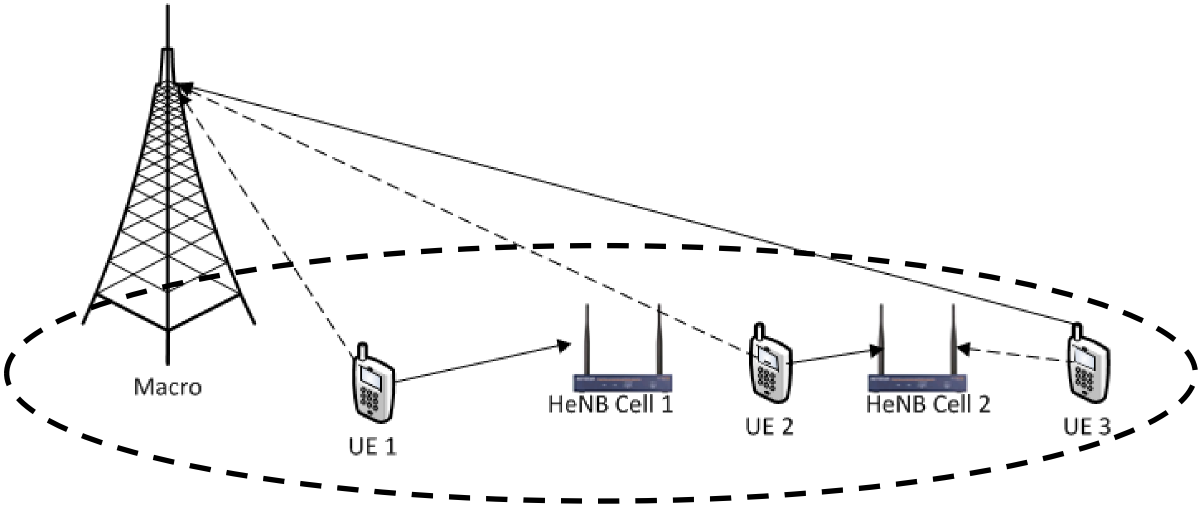


Downlink Interference

- UE 3 can't connect to femto (HeNB) as it is not part of CSG and connects to macro
- HeNB transmission causes severe interference to the UE 3



Uplink Interference

- UE 1 is connected to HeNB and causes interference to macro
- Causes UL macro coverage problems

Macro + Femto Interference Scenario

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Interference Type	Influence Level	Comments
Femto-to-femto interference in femto downlink	Moderate	Adaptive power control
Macro-to-femto interference in femto downlink	Low	Number of affected UEs is small
Femto-to-macro interference in macro downlink	**High**	**A non CSG UE close to femto still connects to macro**
Femto-to-femto interference in femto uplink	Moderate	Limit UE power
Macro-to-femto interference in femto uplink	Low	Limit UE power
Femto-to-macro interference in macro uplink	Moderate	Limit UE power

Femto to macro interference in DL is most significant

HetNet vs. WiFi

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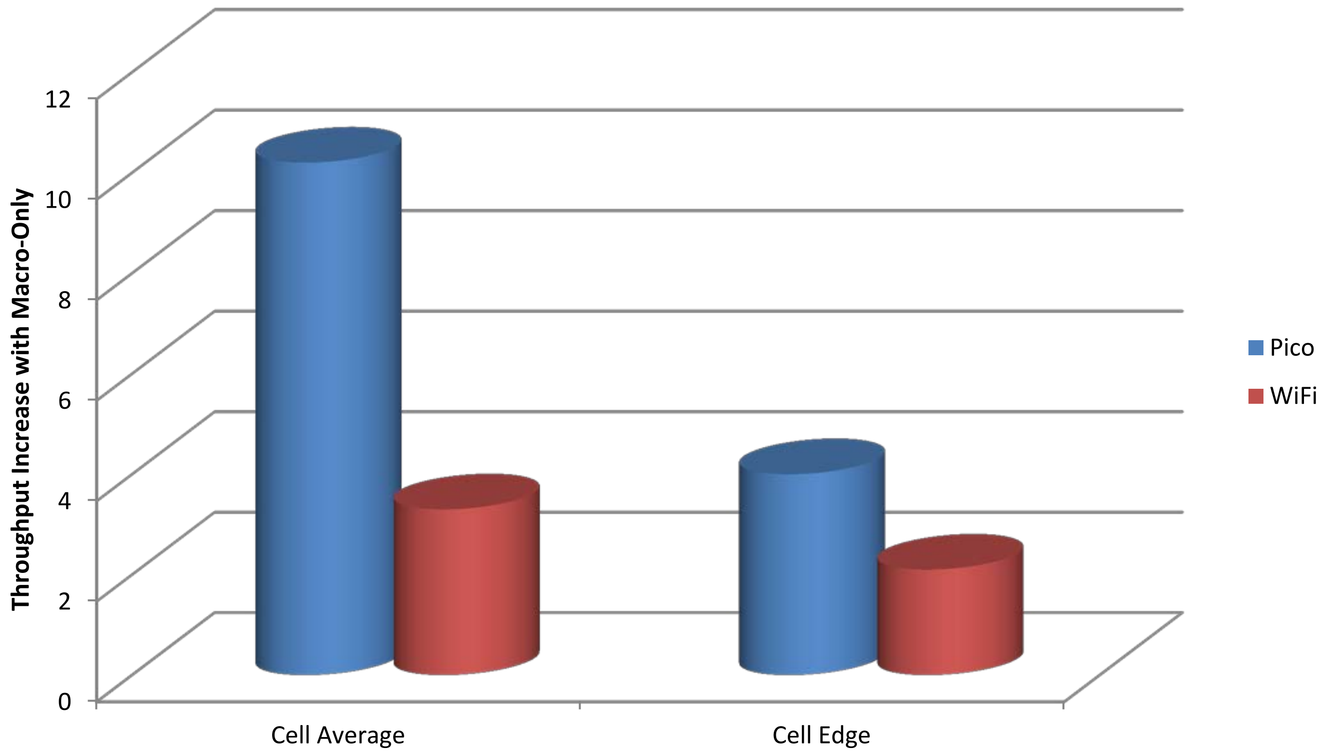
- ❑ Hotspot scenario: many UEs are located in the vicinity of low power cells



- ❑ WiFi APs can provide 230% performance gain in terms of DL cell average throughput
- ❑ Picos (HetNets) can provide even higher gain: 920% for DL cell average throughput
- ❑ Improved gain of HetNets come from well defined macro pico coordination

Source: White paper, “A Comparison of LTE Advanced HetNets and Wi-Fi” , Qualcomm, 2011

Summary

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- New nodes range from centralized to decentralized deployment
  - Cell radius, transmit power, backhaul, user access
- 3GPP defines typical HetNet deployments
  - Macro-pico (outdoor), macro-femto (indoor)
- Cell Range association bias reduces load on high power macro
  - Logically associates UE with pico having lesser DL link gain
- HetNets lead to several situations involving high interference

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- ❑Concluding Remarks
- ❑References

HetNet Interference Management: Power Control

- Advent of HetNets brings new challenges
  - Proper interference management crucial for obtaining gains
- Transmission power is key design parameter in wireless
  - Controls interference between different nodes
  - Minimizes energy consumption and enhances battery life
  - Helps a node to maintain connectivity in fluctuating fades
- Widely studied in industry and academia
  - Power control and convergence, utility maximization
  - Adopted in IS-95, EVDO, LTE etc.

Macro-Femto Interference Situation

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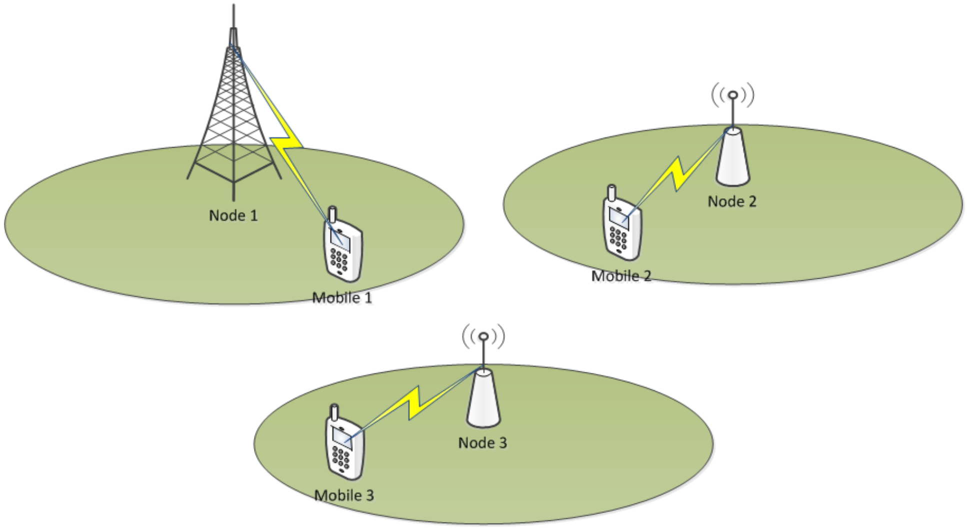

- ❑ Assume a group of nodes transmitting to their users
- ❑ Nodes can adjust power to reduce interference and maximize own performance
  - ➢ Node i and UE i form the link i
  - ➢ N: Number of links
  - ➢ G_{ij}: Link gain between Node i and mobile j

$$SINR_i = \frac{G_{ii} p_i}{\sum_{j \neq i} G_{ji} p_j + \sigma^2}$$

  - ➢ Υ_i: SINR target for link i

Basic Power Control Formulation

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$$\min_{p_i} \sum_i p_i$$

$$s.t.\ \ SINR_i \geq \gamma_i$$

Define

$$F_{ij} = \begin{cases} G_{ji}/G_{ii},\ j \neq i \\ 0,\ j = i \end{cases}$$

$$D = diag(\gamma_1, \cdots \gamma_N)$$

$$\mathbf{v} = \left\{ \frac{\gamma_1 \sigma^2}{G_{11}}, \cdots \frac{\gamma_N \sigma^2}{G_{NN}} \right\}$$

The constraints can be rewritten as

$$(I - DF)p \geq v$$

p: Power vector of all the nodes

- ❑ Foschini-Miljanic algorithm solves this problem
- ❑ Shows existence of solution
- ❑ Provides a distributed power update equation at each node
  - ➢ Power updated at each slot
- ❑ Shows convergence of the distributed algorithm
- ❑ Yates shows convergence for general class of interference functions

Extensions of Basic Power Control

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- Many possible extensions studied in academia
  - Robust distributed power control
  - Power control for optimal SINR assignment
  - Opportunistic power control
  - Non cooperative power control
  - Joint power control and beamforming
  - Joint power control, beamforming for utility maximization
  - Joint power control and time/frequency domain scheduling
- For details refer M. Chiang et. al, “Power control in wireless cellular networks” NOW Publishers

Special Case of Macro-Femto

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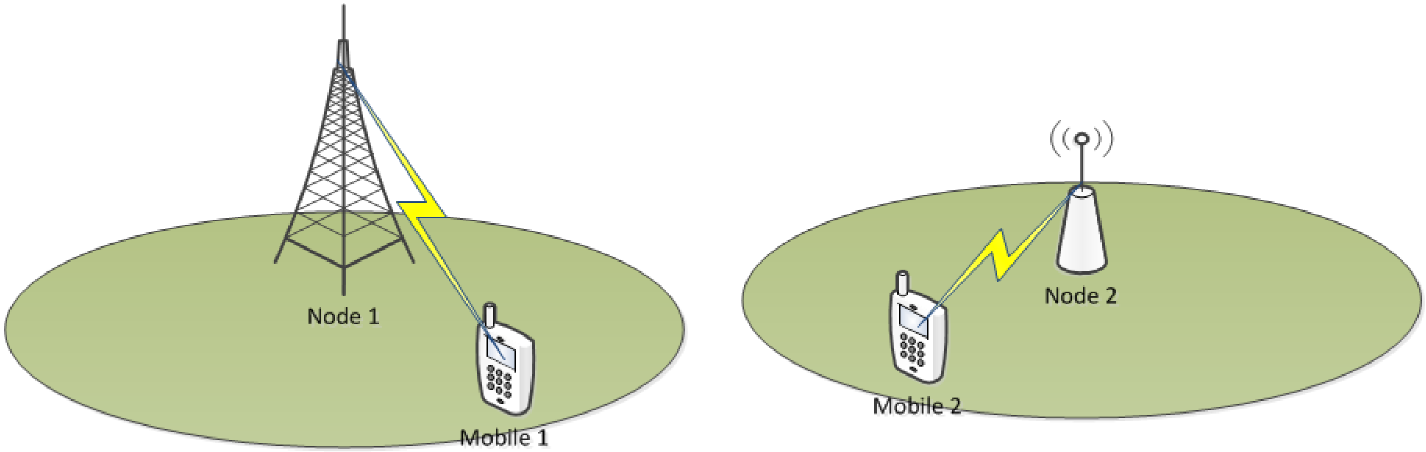

- Consider system with one macro and one femto where macro transmits with full power
- In order for femto UE SINR to be above threshold ϒfemto

$$\frac{G_{22} p_{femto}}{G_{12} p_{macro} + \sigma^2} \geq \gamma_{femto}$$

- This can be re-written as $p_{femto} \geq \frac{\gamma_{femto}}{G_{22}} \left(G_{12} p_{macro} + \sigma^2 \right)$
- Thus the following observations can be made
  - Femto transmit power should increase for higher macro transmit power (macro interference)
  - Femto transmit power upper bounded by interference it causes to macro
    - Later on we will show how power control in 3GPP standard is related to this

Power Control in Practical Systems

- Practical limitations exist in many of these approaches
  - Macro/pico transmit powers updated infrequently
    - Limitation of current signaling protocols

- Power control depends on level of coordination
  - For dynamic macro-pico coordination involving X2
  - Limited coordination when no X2 interface exists

- Limited form of power control in current systems
  - Advanced techniques possible in future 3GPP systems

Summary

- Power control in wireless is a well researched field
  - Provides theoretical solutions to interference management
- Basic formulation minimizes total transmit power of all nodes
  - Subject to each node achieving minimum SINR threshold
  - A feasible solution and its distributed implementation exists
  - Many theoretical extensions possible
- Practical algorithms in standards are influenced by theory
  - Simpler algorithms used in current systems

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Network-Level Analysis of HetNets

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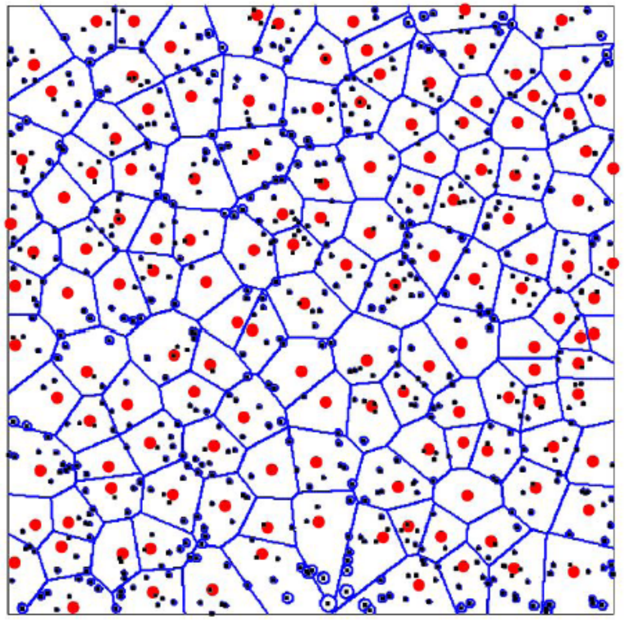
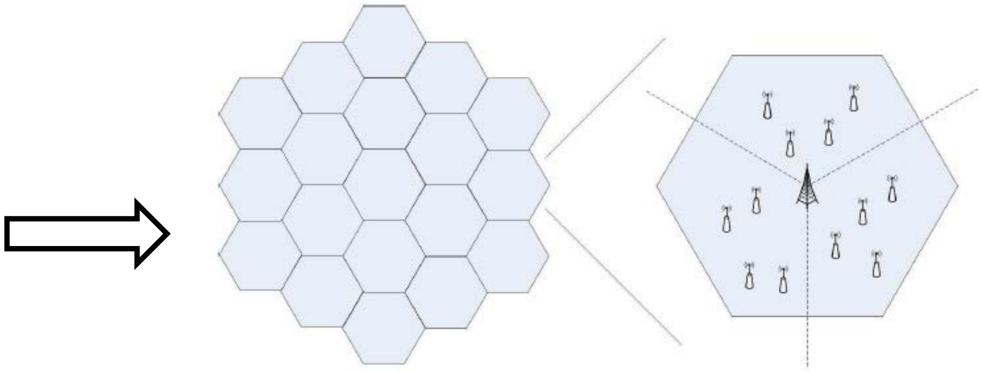


Practical deployment
Red: Macro, Blue: Pico/Femto



- Model used for evaluations in 3GPP
  - Macro location: Hexagonal grid
  - Pico location: Uniformly distributed in each macro cell
- Easy for simulation but difficult for analysis!
- Network level analysis yields important insights towards system design

Source: A. Ghosh, J. G. Andrews, et al “Heterogeneous Cellular Networks: From Theory to Practice” *IEEE Comm. Mag.* June 2012.

System Model

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- Model a HetNet as a K-tier Network
  - Each tier models the BSs of a class (e.g., macro, pico, femto)
- The BSs in each tier are spatially distributed
  - Follow Poisson Point Process (PPP).
  - Node density at i^{th} tier is λ_i
  - The CRE bias at i^{th} tier is B_i
- Channel model used
  - Rayleigh fading
  - Distance based path loss

Downlink SINR Expression

$$SINR(x_i) = \frac{P_i h_{x_i} \left| x_i \right|^{-\alpha}}{\sum_{j=1}^{K} \sum_{x \in \Phi_j \backslash x_i} P_j h_x \left| x \right|^{-\alpha} + \sigma^2}$$

x_i : Random variable for distance of target UE from a BS in tier i
P_i: Transmit power of BS in tier i
h: Random variable for rayleigh fading
α : Path loss exponent
K: Number of tiers
Φ_j : Set of BS in tier j
σ^2 : Noise variance

Coverage Probability

- A UE is in the coverage of i^th tier if

$$\max_{x \in \Phi_i} SINR(x) > \beta$$ SINR threshold

- The probability that the UE is in coverage is calculated to be

$$P_c = \frac{\pi}{C(\alpha)} \beta^{-2/\alpha}$$

The coverage probability is independent of number of tiers, BS density and BS transmit power

Association Probability

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$$A_k = \left(1 + \frac{\sum_{j=1, j \neq k}^{K} \lambda_j \left(P_j B_j \right)^{2/\alpha}}{\lambda_k \left(P_k B_k \right)^{2/\alpha}} \right)^{-1}$$

- ❑ Association Probability A_k of tier k
  - ➢ The probability that a UE is associated with a BS in tier k
- ❑ A UE prefers to connect to a tier with higher BS density
- ❑ BS density is more dominant in determining the association probability than BS transmit power and CRE bias

Association in Realistic Deployments

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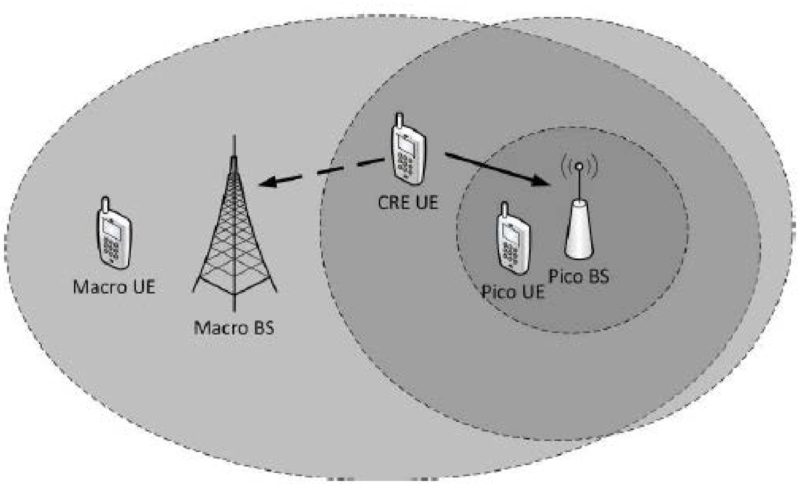
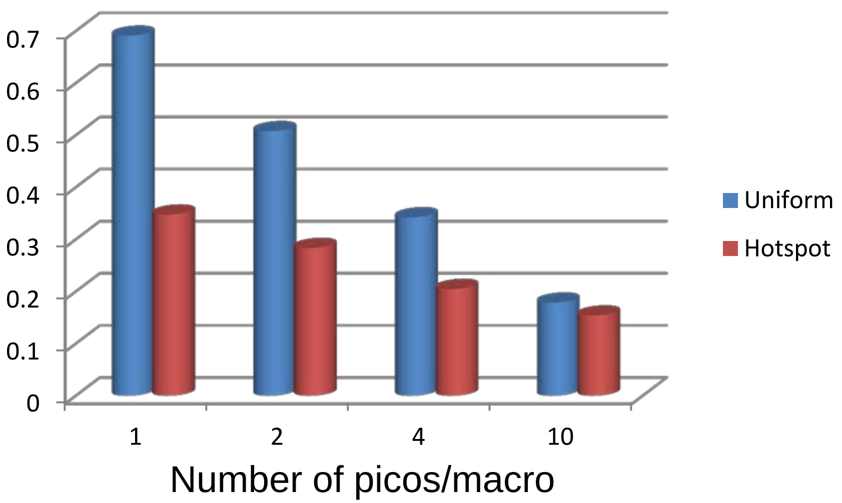


- ❑ 3GPP HetNet Simulation Environment
- ❑ 3 sector, 19 cell macro, 500 m cell
- ❑ N Picos/ cell uniformly distributed
- ❑ Macro-> UE (Urban macro), Pico->UE (Urban micro)
- ❑ Tx power: Macro: 46 dBm, Pico: 30 dBm
- ❑ User distributions
  - ➢ Uniform distribution (Config. 1)
  - ➢ Hotspots around pico area (Config. 4b)



- ❑ Association Ratio of macro for varying pico density
- ❑ CRE bias = 6 dB

- ❑ Ratio increases sharply with pico density
- ❑ **Aligned to theoretical results**

Summary

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- Mathematical model proposed to analyze HetNets
- Using continuous base station distributions
- Model provides interesting insights
- Model predictions in sync with realistic deployment results
- Can provide basis for better system design in future

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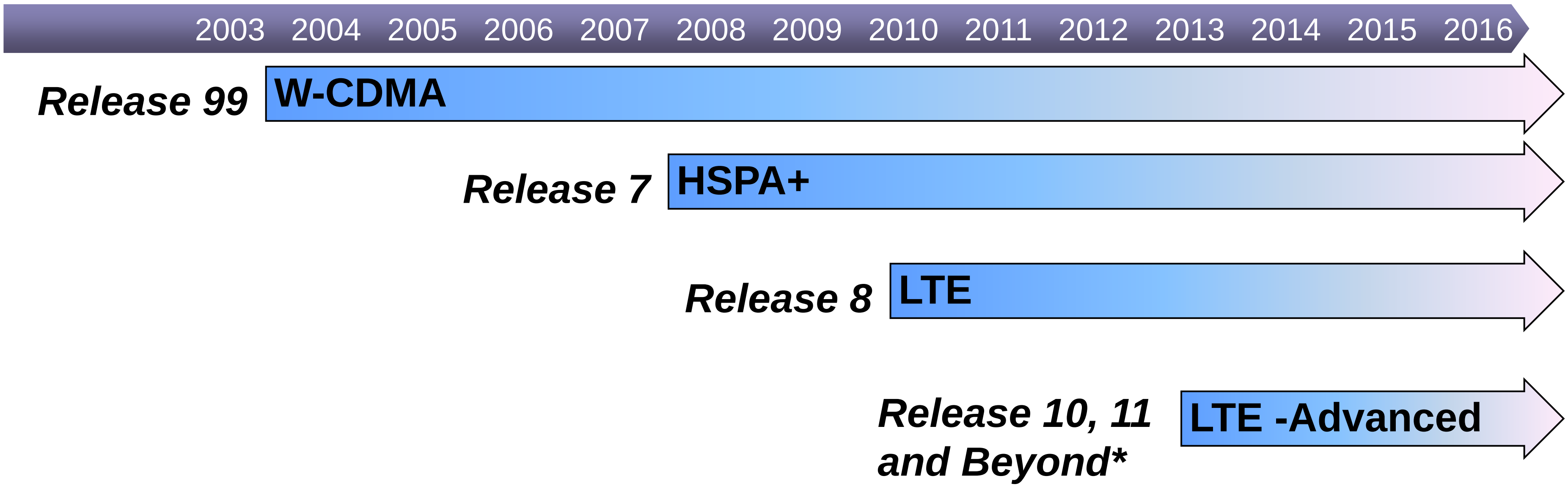
- ❑ Standardization Impacts on HetNet
  - ➢ LTE standard essentials
  - ➢ ICIC: Interference management schemes in LTE HetNets
  - ➢ Case studies from realistic deployments
- ❑ Concluding Remarks
- ❑ References

Evolution of cellular networks to LTE



Release	WCDMA	HSPA+	LTE	LTE-A
DL Peak Rate	384 Kbps	42 Mbps	150 Mbps	1 Gbps
UL Peak Rate	128 Kbps	11 Mbps	75 Mbps	500 Mbps

** Some parts of Rel-10 and most for Rel-11 are under active discussion in standardization bodies*

LTE Architecture: Core Network and Nodes

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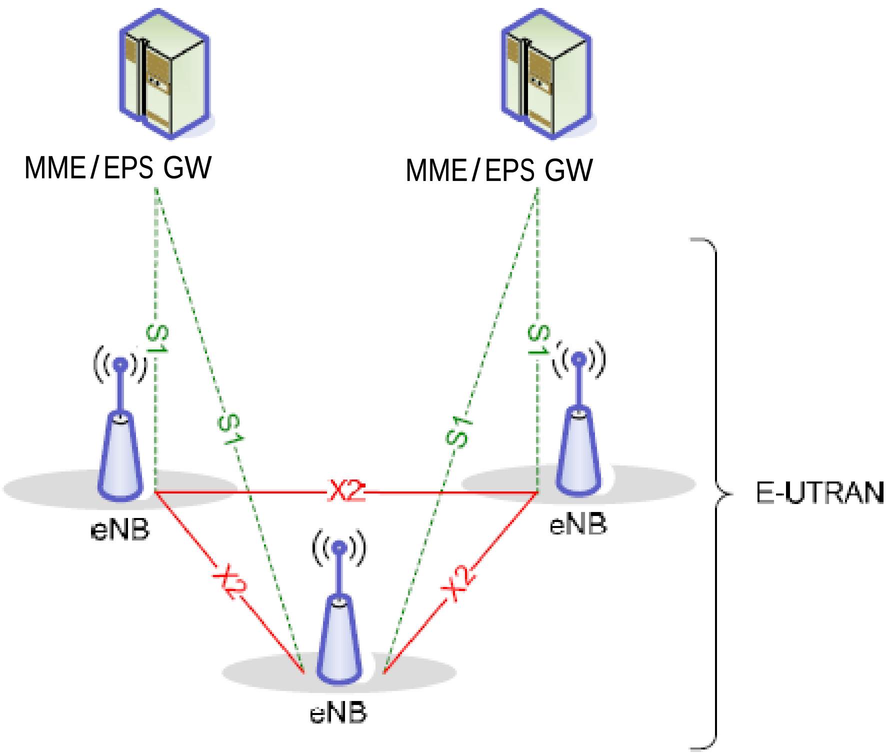
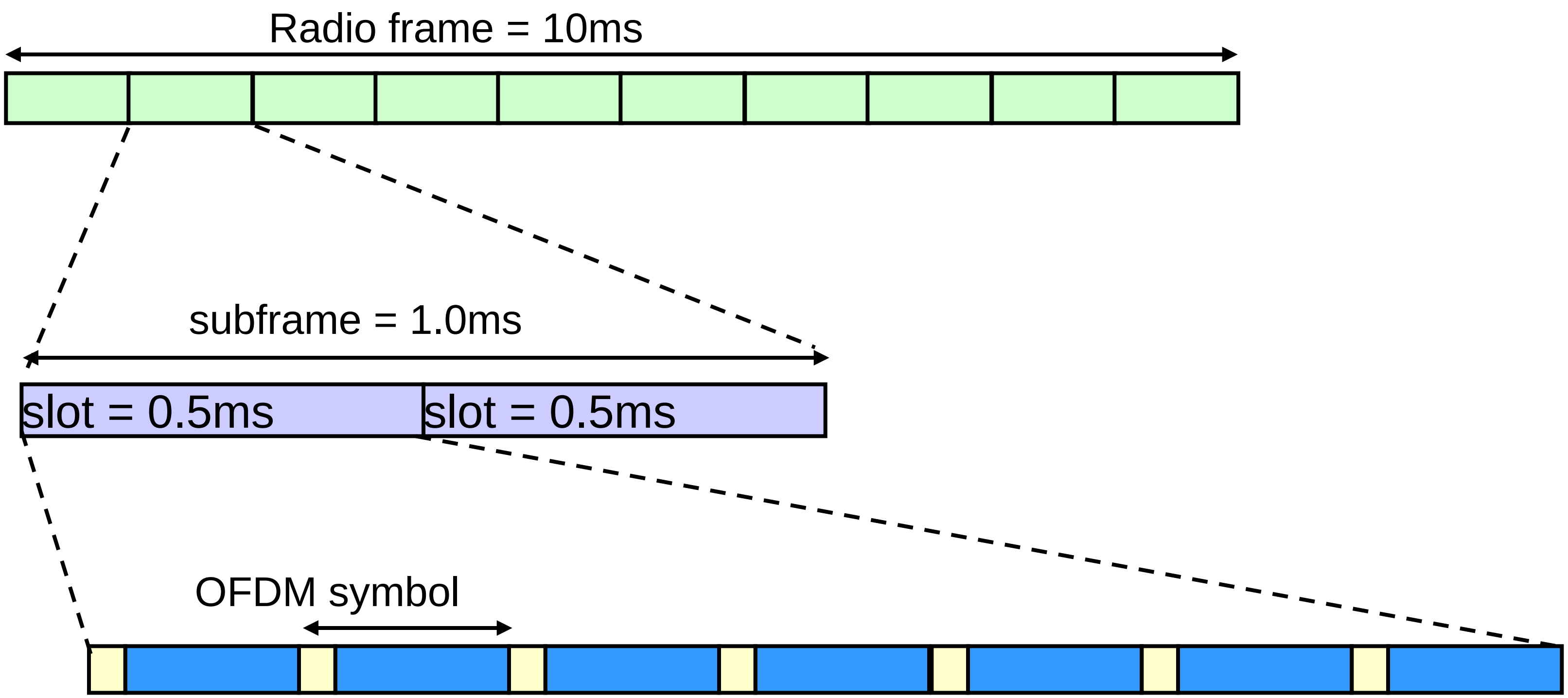
LTE Core Network and Radio Access Network



- ❑ X2 interface is a logical interface
  - ➢ Connect eNBs with each other
  - ➢ Facilitate seamless mobility
  - ➢ Facilitate Interference management
- ❑ Physical connections between BS may be achieved via cables
- ❑ eNB handles all radio level signal processing
- ❑ The core network (consisting of MME and EPS gateways) handle authentication, mobility management etc.

LTE Downlink Frame Format



- Subframe length is 1ms
  - consists of two 0.5ms slots
- 7 OFDM symbols per 0.5ms slot → 14 OFDM symbols per 1ms subframe
- 6 OFDM symbols for extended CP → 12 OFDM symbols

LTE Downlink: Channel Structure

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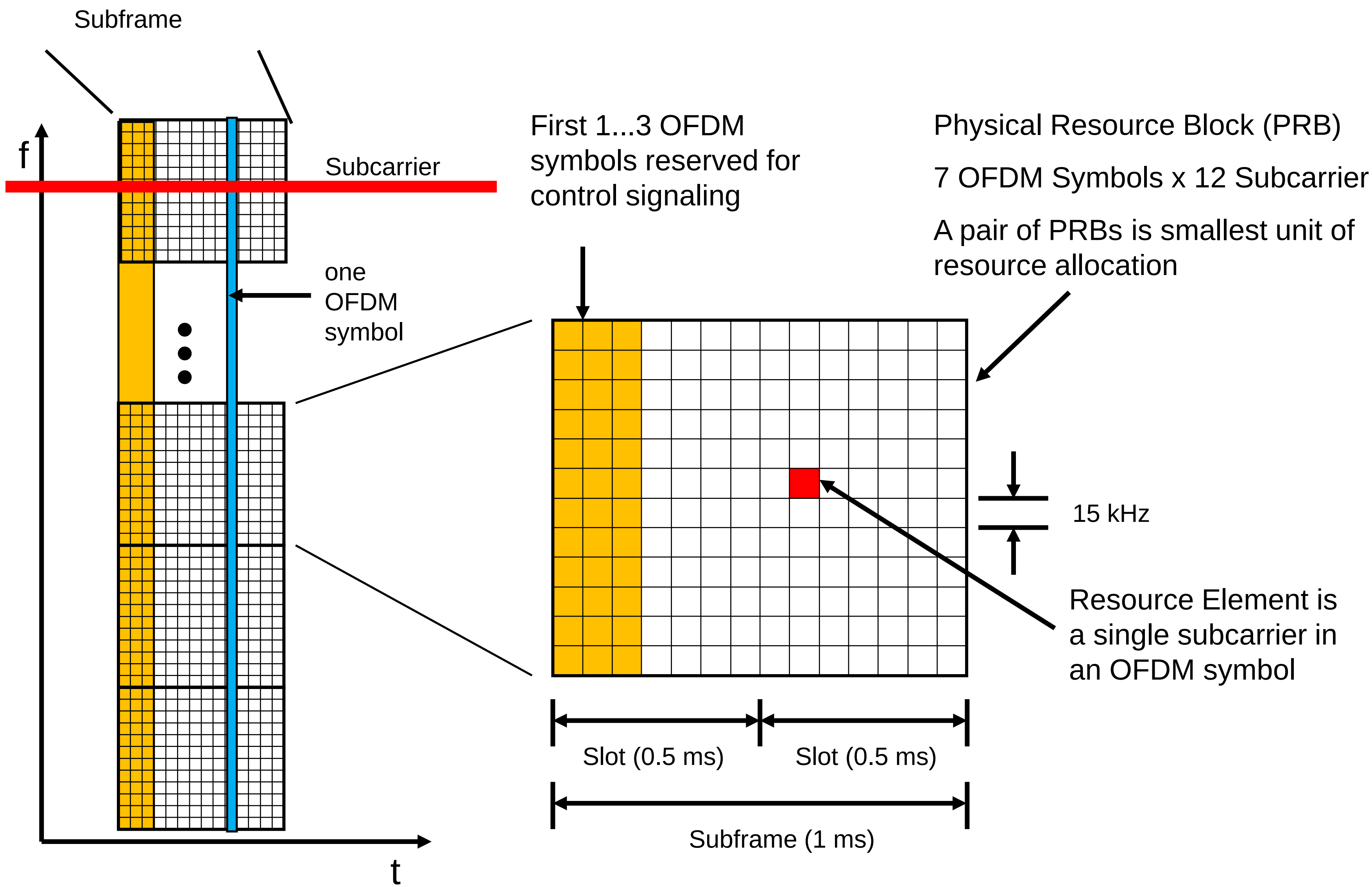
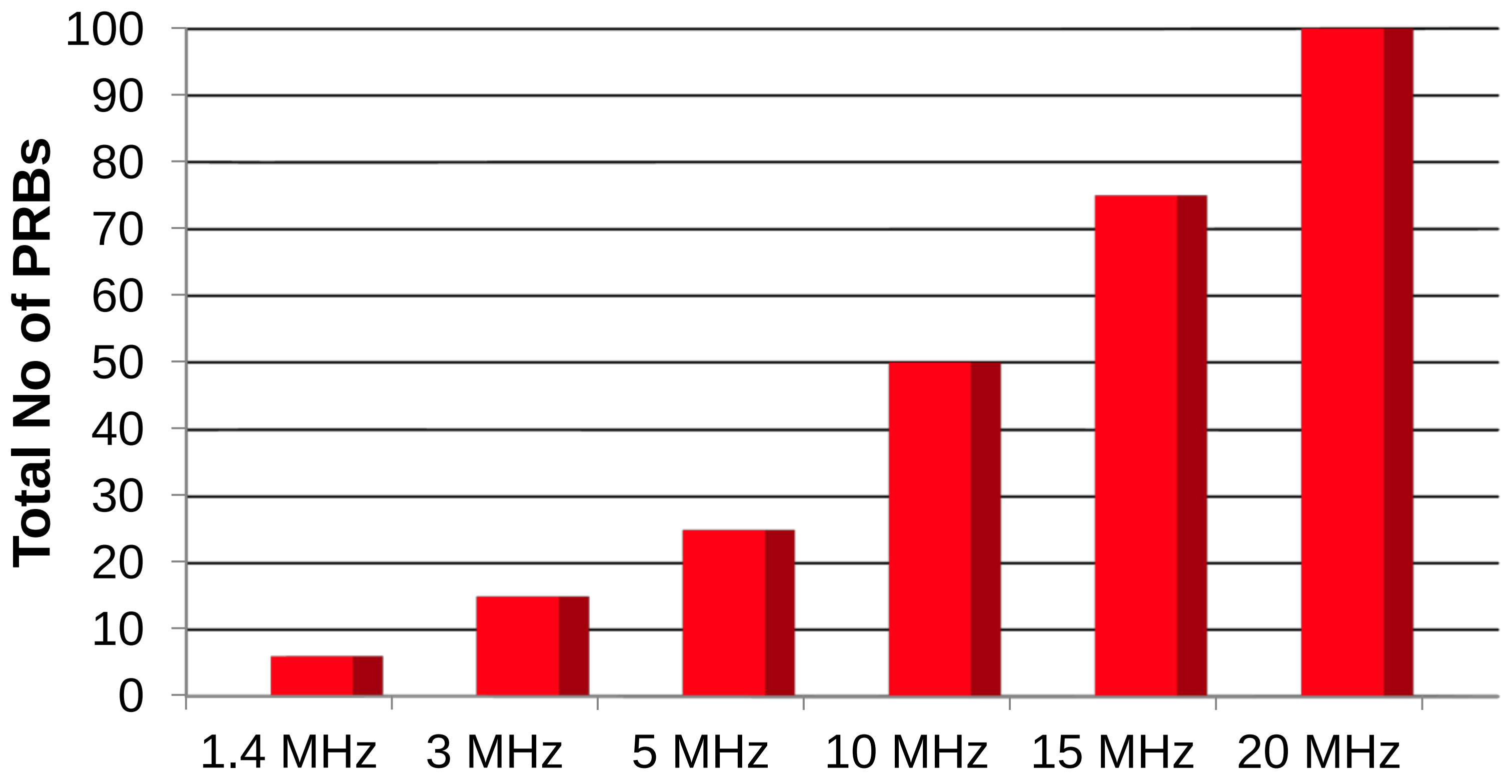
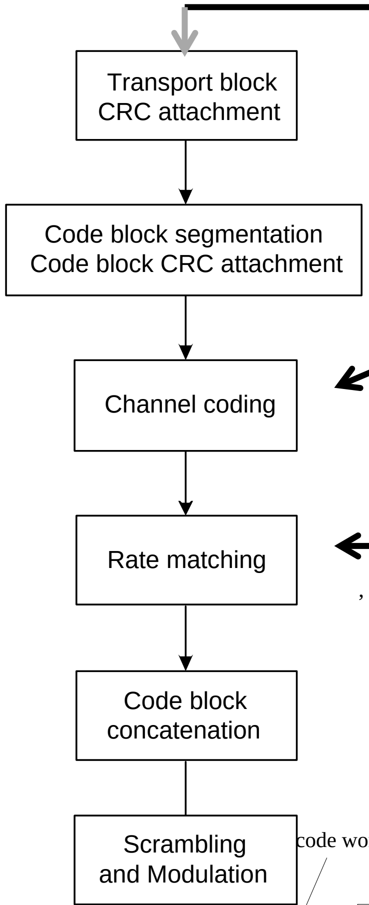


Resource Blocks and Bandwidth



LTE Scheduler decides how many PRBs to allocate to a given UE in a subframe

LTE DL Signal Processing

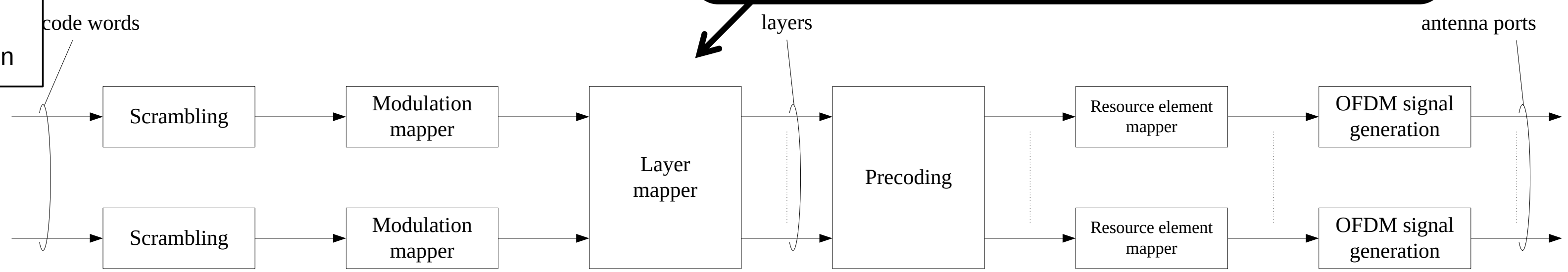


- In each subframe, 1 or 2 transport blocks are processed from MAC layer.
- Size of transport block depends on channel conditions and number of PRBs allocated

- Channel coding is based on 1/3 rate turbo code with trellis termination to approach Shannon capacity

- Circular buffer rate matching
- Modulation (QPSK/16 QAM/ 64 QAM)

- Layer mapping and precoding for MIMO



Reference Symbol (RS) in LTE

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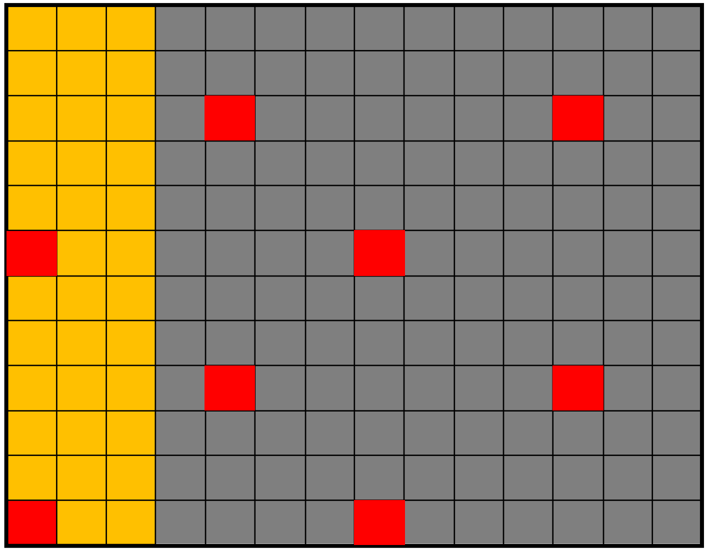
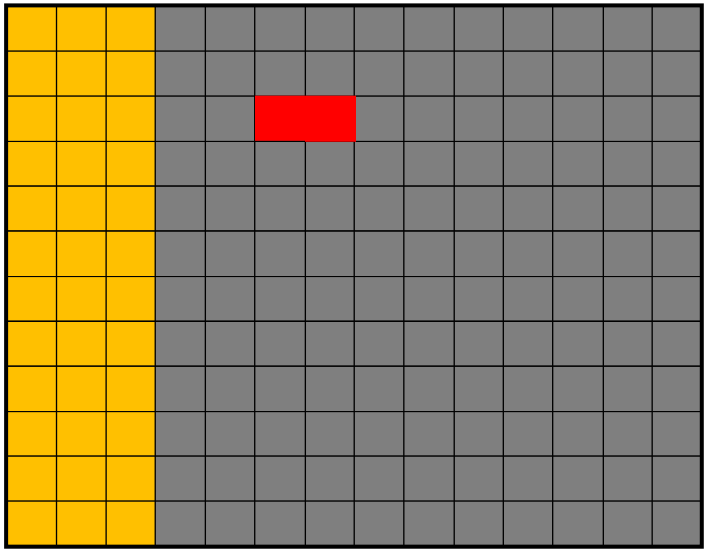
- ❑Reference signal (RS) are pilot symbols in certain REs for channel estimation
- ❑UE subtracts estimated channel from received pilot signal to estimate interference + noise
- ❑Usually transmitted at higher power than data REs to aid in estimation

Rel-8 CRS (Common Reference Signal)



- ❑Cell Specific transmission
- ❑RE locations well defined
- ❑Transmitted with 1 ms periodicity
- ❑Defined for up to 4 antenna ports
- ❑8 REs/port/PRB for 1, 2 antenna ports

Rel-10 CSI-RS (Channel State Info RS)



- ❑UE specific configuration
- ❑RE locations configurable
- ❑Transmitted with 5/10/15 ms periodicity
- ❑Defined for up to 8 antenna ports
- ❑0.5 RE/port/PRB density

CRS Structure for various Antenna Ports

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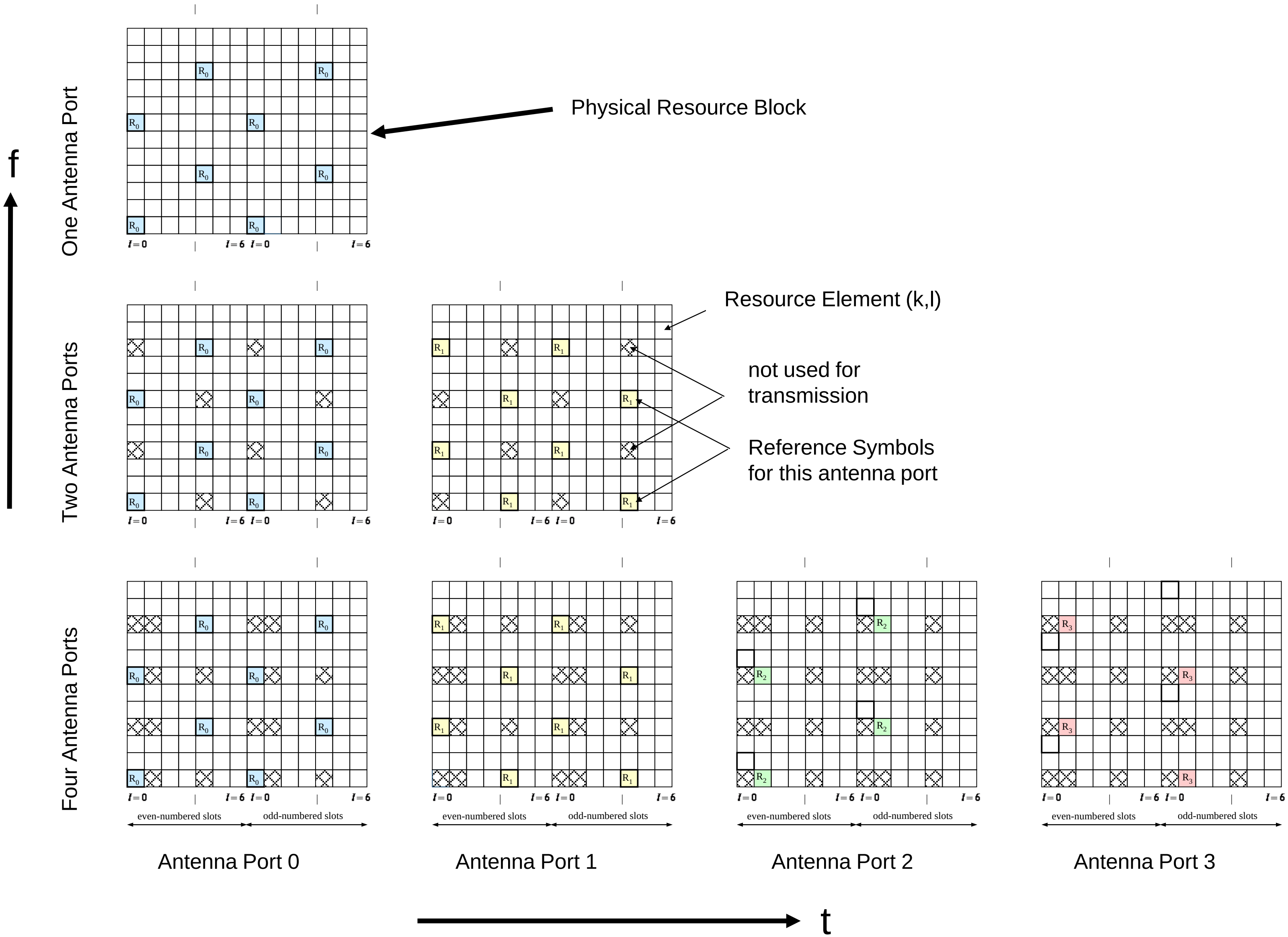

PRB-Level Inter-cell Interference (ICI)

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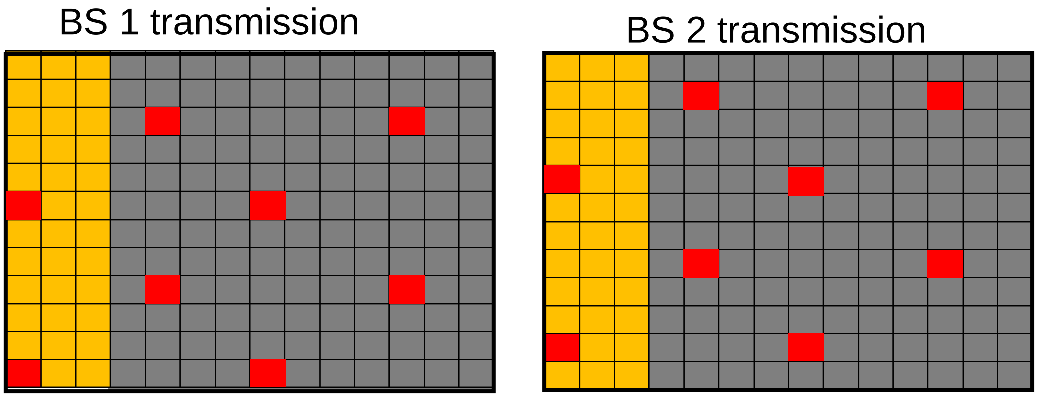
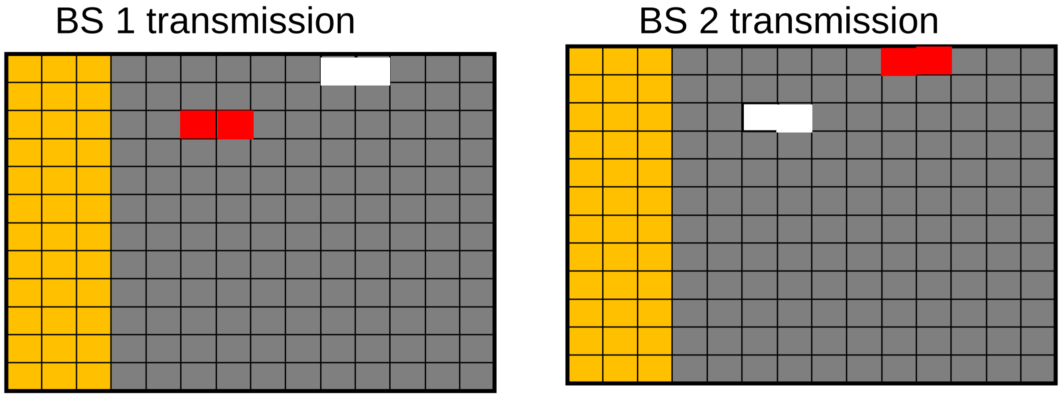
Rel-8 Transmission



- CRS symbols of adjacent cells shifted
- Avoids CRS-CRS interference
- ICI in a CRS RE is data of another BS
- ICI in a data RE can be CRS of another BS

Rel-10 Transmission



- CSI-RS symbols of adjacent BSs shifted
- BS can mute its transmission when adjacent BS is transmitting CSI-RS
  - Called zero power CSI-RS
- Aids in channel estimation but can lead to incorrect interference estimation

Summary

- LTE is a flat, all IP architecture, with OFDMA based PHY
- LTE transmission happens in time-frequency grids
  - 1 frame: 10 ms, 1 subframe: 1 ms, 1 slot = 0.5 ms (6 or 7 OFDM symbols)
  - RE: OFDM symbol time X subcarrier spacing – basic unit
  - PRB: 7 symbols X 12 subcarriers – basic unit for resource allocation
- Some REs carry control information, others carry data
  - Some control REs carry RS that are used for channel estimation
    - RS from adjacent cells can be shifted or muted to avoid interference
- Data or control information is signal processed before putting in REs
  - Adaptive modulation, coding, rate matching, MIMO processing etc.

Inter-cell Interference Coordination (ICIC)

- Rel-8/9 ICIC
  - Limited frequency domain interference information exchange

- Rel-10 eICIC (enhanced ICIC)
  - Dynamic time domain interference coordination
    - Based on Almost Blank Subframes (ABS)
  - Power control

- Rel-11 FeICIC (Further enhanced ICIC)
  - Enhanced transceiver signal processing for ABS
  - Reduced power ABS

ICIC in Rel-8 LTE

- Primarily to help cell edge UEs
- Involves coordination between neighboring eNBs
  - Using the X2 interface
  - ICIC related X2 messages are defined in standard
- A eNB can use information provided by neighboring eNB
  - During its scheduling process
- Static and limited coordination

UL ICIC in Rel-8 LTE

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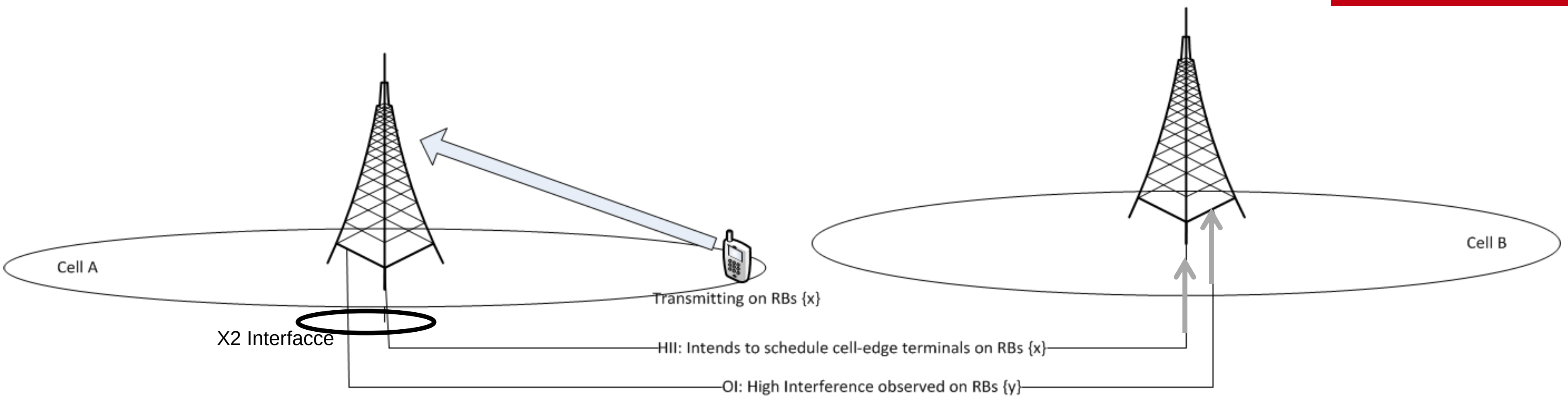

HII: High Interference Indicator

❑ Informs set of RBs in which a eNB is likely to schedule UL transmissions to cell-edge terminals.
❑ Proactive tool to prevent high interference scenarios for the neighbor.

OI: Overload Indicator

❑ Indicates three levels (high/medium/low) of UL interference that is experienced due to the transmission from the neighbor eNB
❑ Reactive tool to request neighboring eNB to reduce its interference

- ❑ Nothing explicitly defined as to how eNBs react to these messages
- ❑ Left to proprietary implementation
  - ➢ Cell B can avoid scheduling on RBs {x} to avoid interference from cell A
  - ➢ Cell B can reduce activity on RBs {y} to reduce interference to cell A

DL ICIC in Rel-8 LTE

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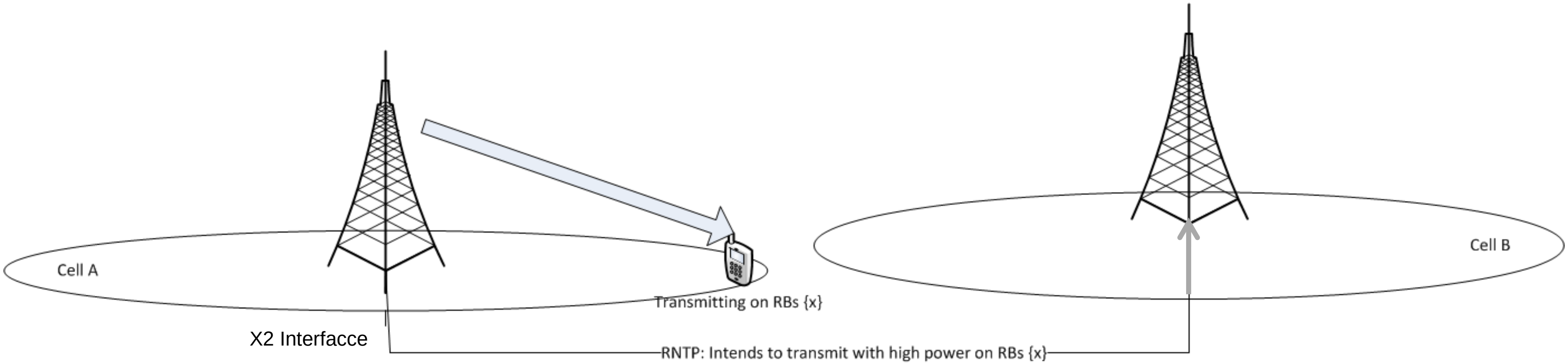

RNTP: Relative Narrowband Transmit Power

❑ Provides information about set of RBs in which a eNB is likely to schedule DL transmissions to cell-edge terminals, for benefit of a neighboring eNB

❑ Similar to HII for UL ICIC.

❑ Cell B can avoid scheduling its UE in RB {x}

Enhanced ICIC (eICIC) in Rel- 10 LTE

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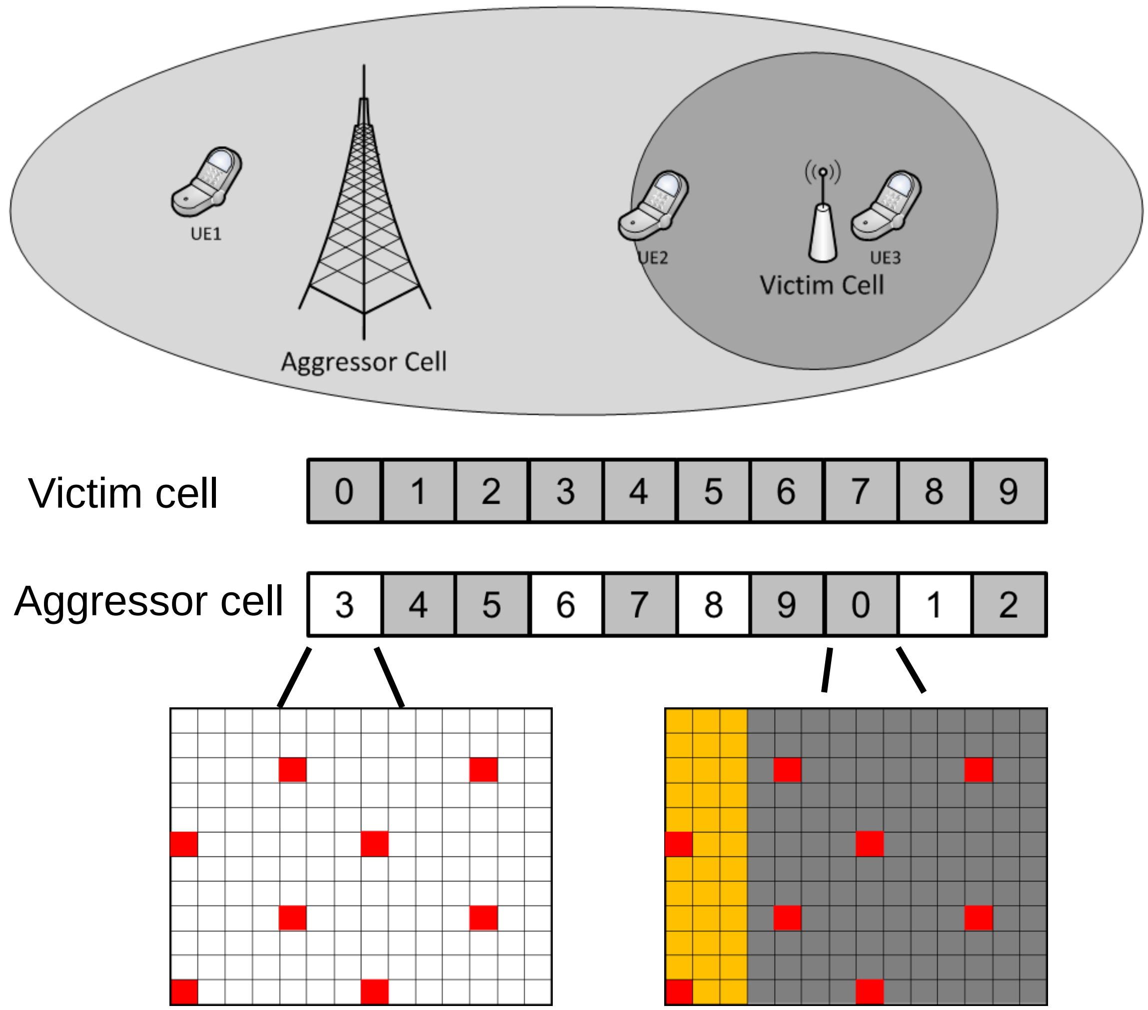
- Rel 8 ICIC methods are not standardized
  - Proprietary implementation, no QoS guarantees
  - Can’t mitigate control channel interference
    - RNTP etc only apply to reduced power in data region
  - Not suitable for HetNets due to high interference possibilities
    - Particularly unsuitable for high CRE bias
- New ICIC schemes needed
  - Tailored towards HetNet deployments
  - Pico should know better what macro interference to expect
  - More detailed standardized protocols needed

Time-Domain eICIC: Almost Blank Subframes



- ❑ ABS carries no data, only essential control information,
- ❑ Since most REs are blank (zero power), interference is reduced.
- ❑ In macro-pico setup with CRE, macro is the aggressor and pico is the victim

UE Scheduling with ABS

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- Presence of ABS leads to new issues in scheduler
  - Macro cells have less subframes to schedule their UEs
    - Macro UEs (UE 1) scheduled only in non-ABS subframes
  - Pico UEs can be scheduled in both subframes
    - Schedule cell center UEs (UE 2) in both subframes
    - Schedule cell edge UE (UE 3) in ABS subframe

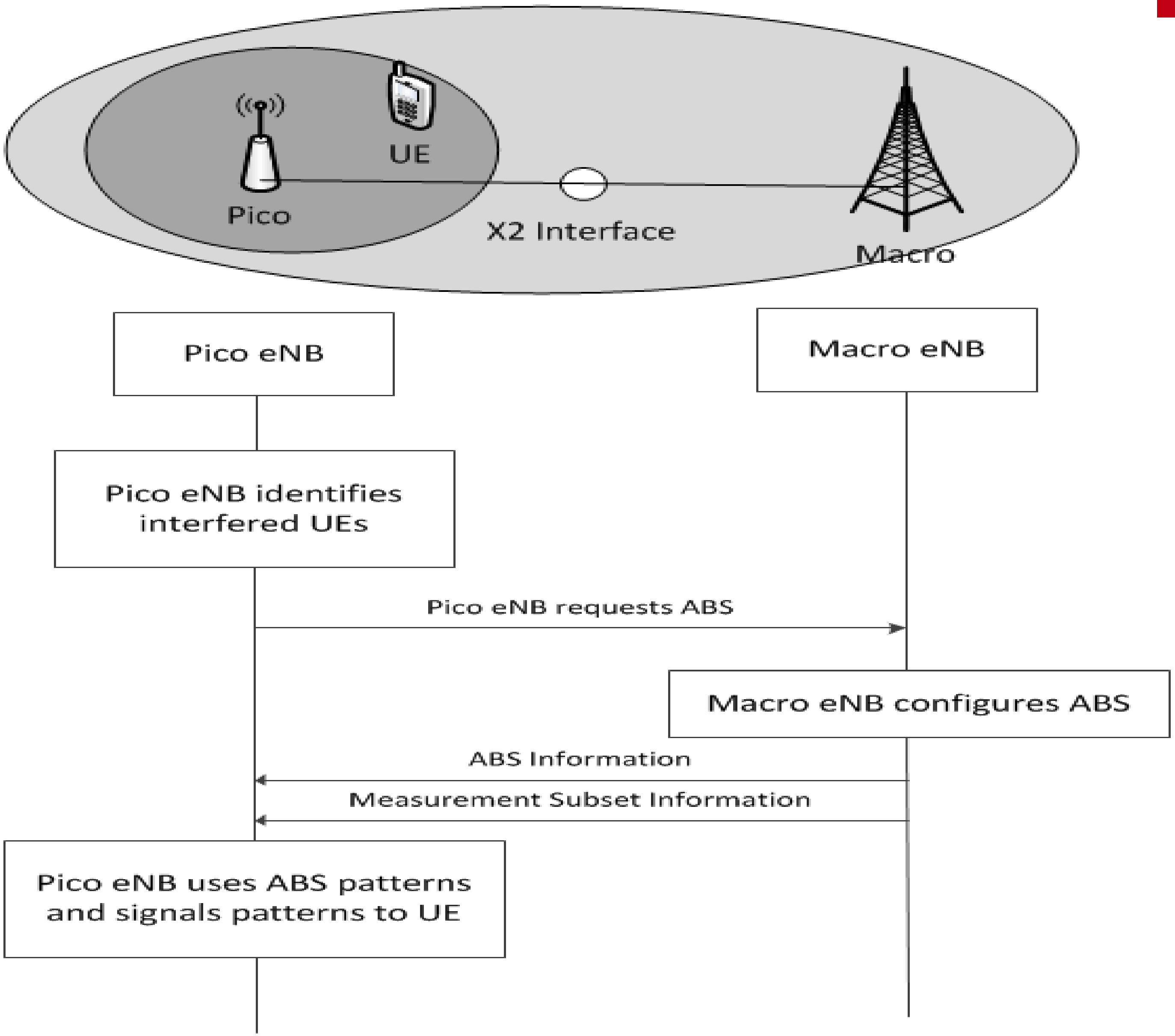
- How to decide number of cell-edge UEs
  - Based on signal strength to serving cell
  - Chosen proportional to number of ABS subframes in a frame

Resource Restricted CSI Measurement

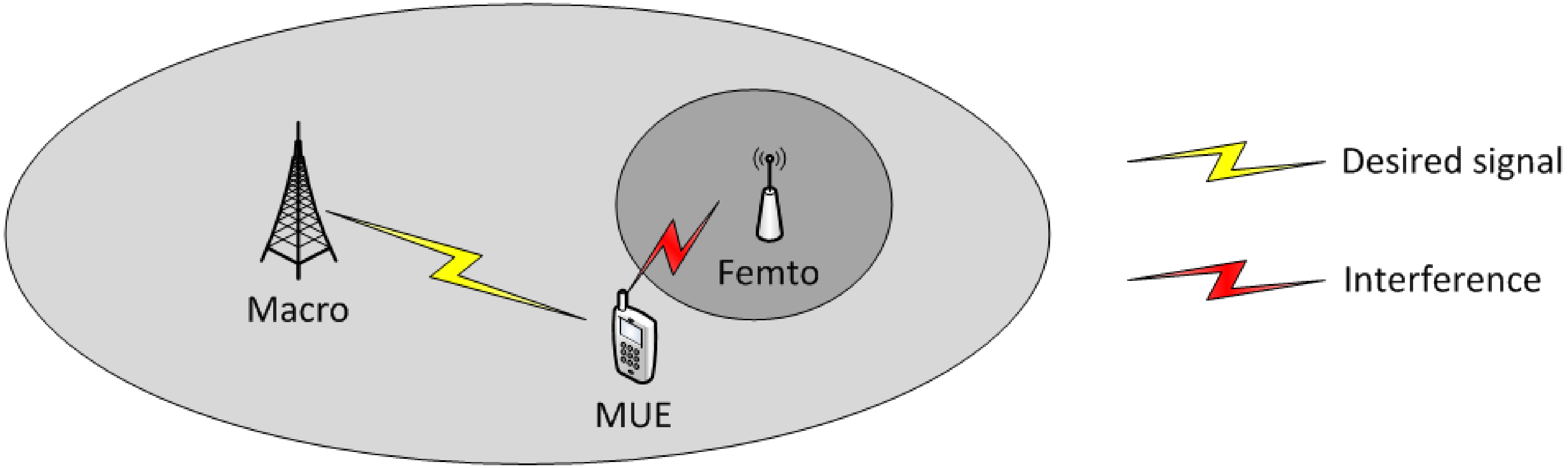
- UE needs to feedback CSI measurements to the BS
  - Measurement usually averaged over several subframes
    - Assuming interference statistics stays similar across subframes
  - Not true for pico UE in ABS/non-ABS subframes
    - Interference higher in non ABS subframes

- Pico BS may configure a pico UE to report separate CSIs
  - For ABS and non-ABS subframes
  - Pico BS signals to Pico UEs, the two separate set of subframes

Exchange of ABS Information via X2



eICIC via Power Control



- Femto cells have no X2 connection to macro cells
- Hence time domain eICIC (ABS) not possible
- Femto does power control instead to reduce interference
  - By measuring DL received power from macro

RECALL: Power Control

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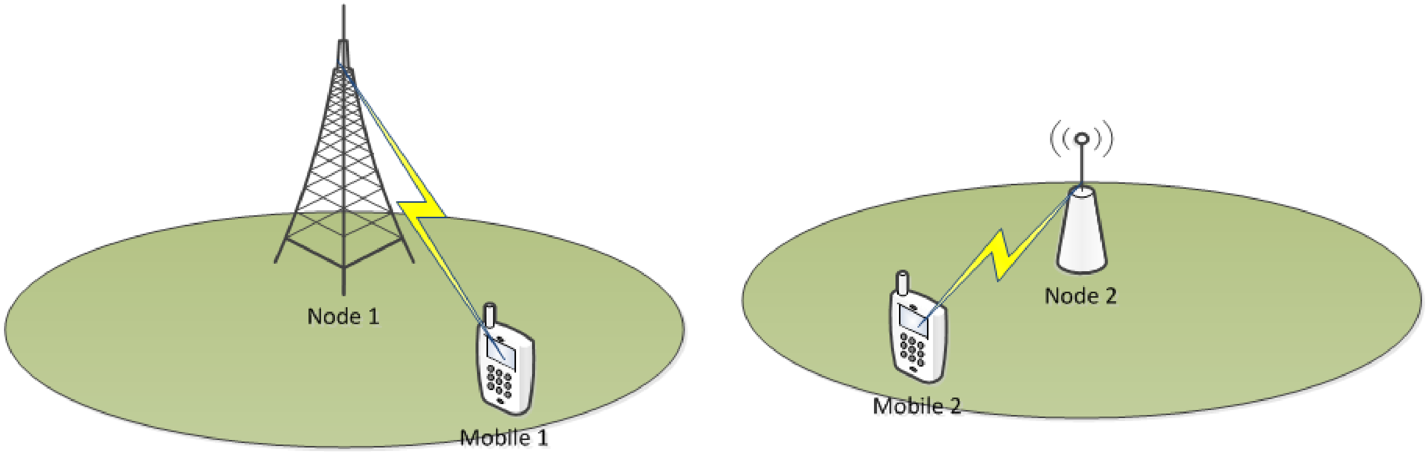
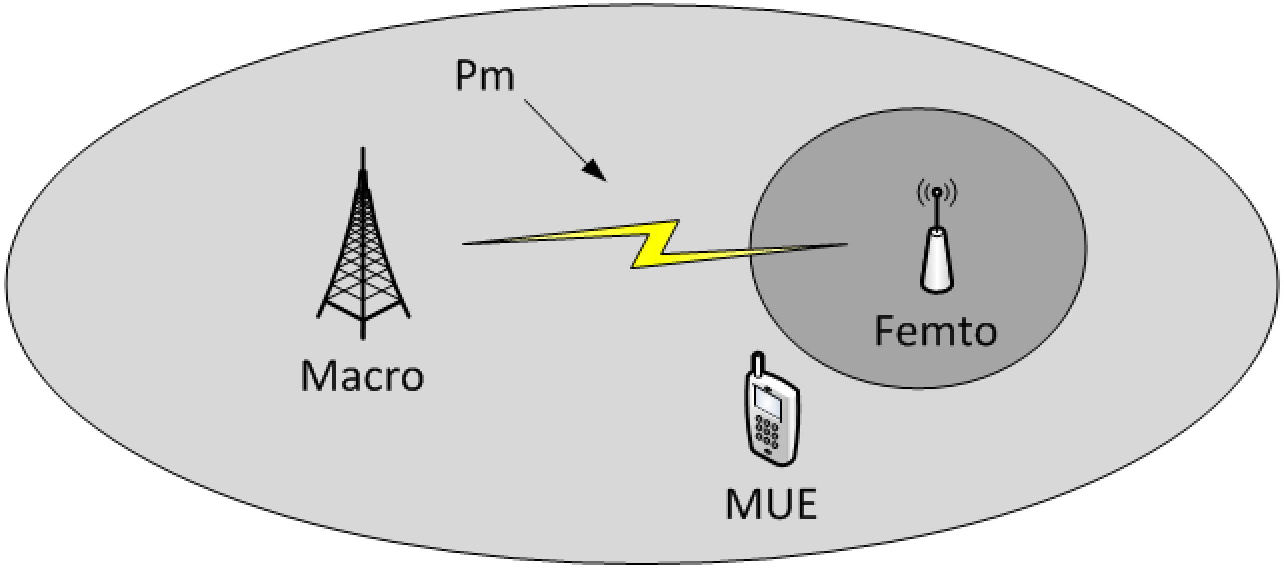


- Consider system with one macro and one femto where macro transmits with full power
- In order for femto UE SINR to be above threshold ϒfemto

$$\frac{G_{22} p_{femto}}{G_{12} p_{macro} + \sigma^2} \geq \gamma_{femto}$$

- This can be re-written as $p_{femto} \geq \frac{\gamma_{femto}}{G_{22}} \left(G_{12} p_{macro} + \sigma^2 \right)$
- Thus the following observations can be made
  - Femto transmit power should increase for higher macro transmit power (macro interference)
  - Femto transmit power upper bounded by interference it causes to macro

Femto Power Control - Method 1



$$P_{Tx} = \min\left(\max\left(\alpha P_m + \beta, P_{\min}\right), P_{\max}\right)$$

P_{max}: maximum femto transmit power
P_{min}: minimum femto transmit power
P_m: received power from nearest macro BS
α, β: are the parameters for fine tuning

Source: 3GPP dcoument TS 36.921 Section 7.2.3.2

Femto Power Control - Method 2

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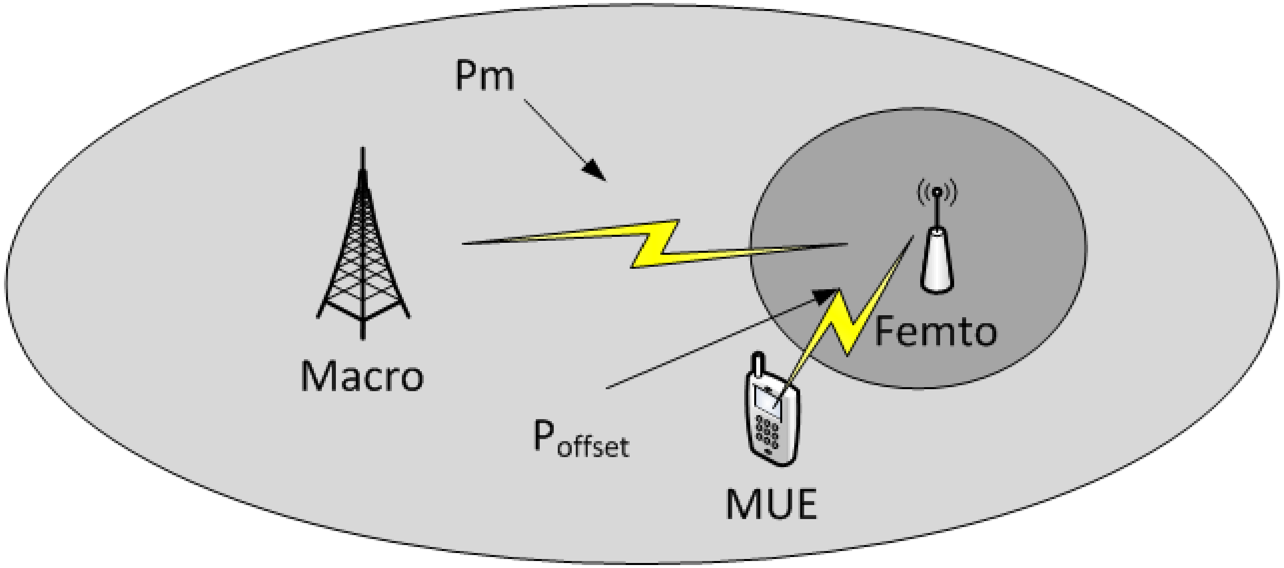

$$P_{Tx} = \min\left(\max\left(P_m + P_{offset}, P_{\min}\right), P_{\max}\right)$$

P_{max}: maximum femto transmit power
P_{min}: minimum femto transmit power
P_m: received power from nearest macro BS
P_{offset}: Related to path loss between femto cell and macro UE

Source: 3GPP document TS 36.921 Section 7.2.3.3

Further Enhanced ICIC (FeICIC) in Rel- 11

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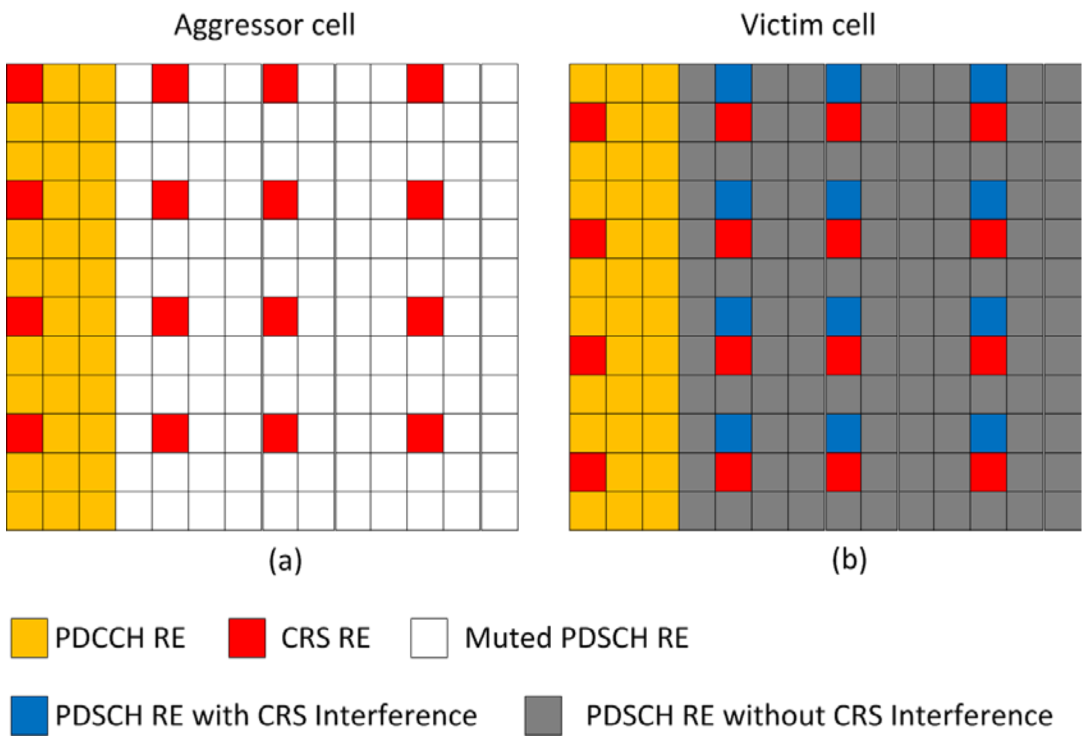
- ❑ Rel-10 ABS still has CRS symbols from aggressor cell
- ❑ Rel-11 FeICIC deals with this remaining interference
  - ➢ Rx based Puncturing
  - ➢ Rx based Interference Cancellation
  - ➢ Tx based Muting
  - ➢ Reduced Power ABS
- ❑ Currently under discussion in 3GPP



- ❑ PDCCH (Physical DL Control Channel)
  - ➢ Carries dynamic control information
- ❑ PDSCH (Physical DL Shared Channel)
  - ➢ Carries data
- ❑ PBCH (Physical Broadcast Channel)
  - ➢ Carries system control information

Rx-based PDSCH Puncturing

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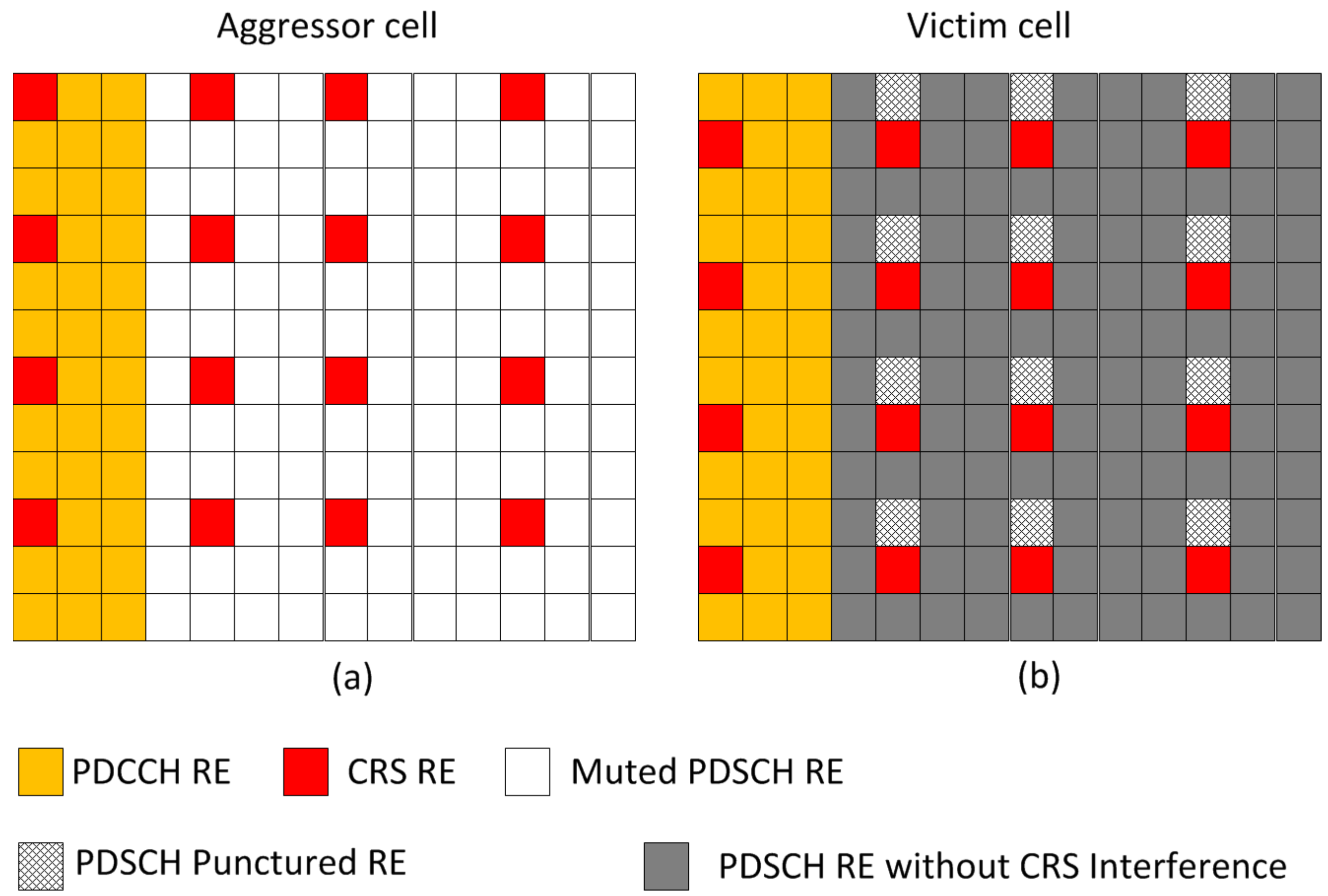
- The data REs with strong CRS interference are punctured at the UE before feeding into the turbo decoder.



RX-based Interference Cancellation (IC)

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- Interference cancellation needed for proper decoding of
  - Control information (PSS/SSS, PBCH, CRS)
  - Data (PDSCH)
- First estimate the interfering signal
  - Possible as cell ID of interferer is known/signaled to UE
- After estimation subtract interfering signal from the received signal
  - Iterative process may be needed to subtract multiple interferers

Signaling Aspect

- Standardization support for CRS interference handling at UE
- The following can be provided by the serving cell via higher layer signaling
  - List of cell ID(s) of interfering cells
  - Parameters for each cell in the list of cell ID(s):
    - Location of interfering CRS REs

TX-based PDSCH Muting

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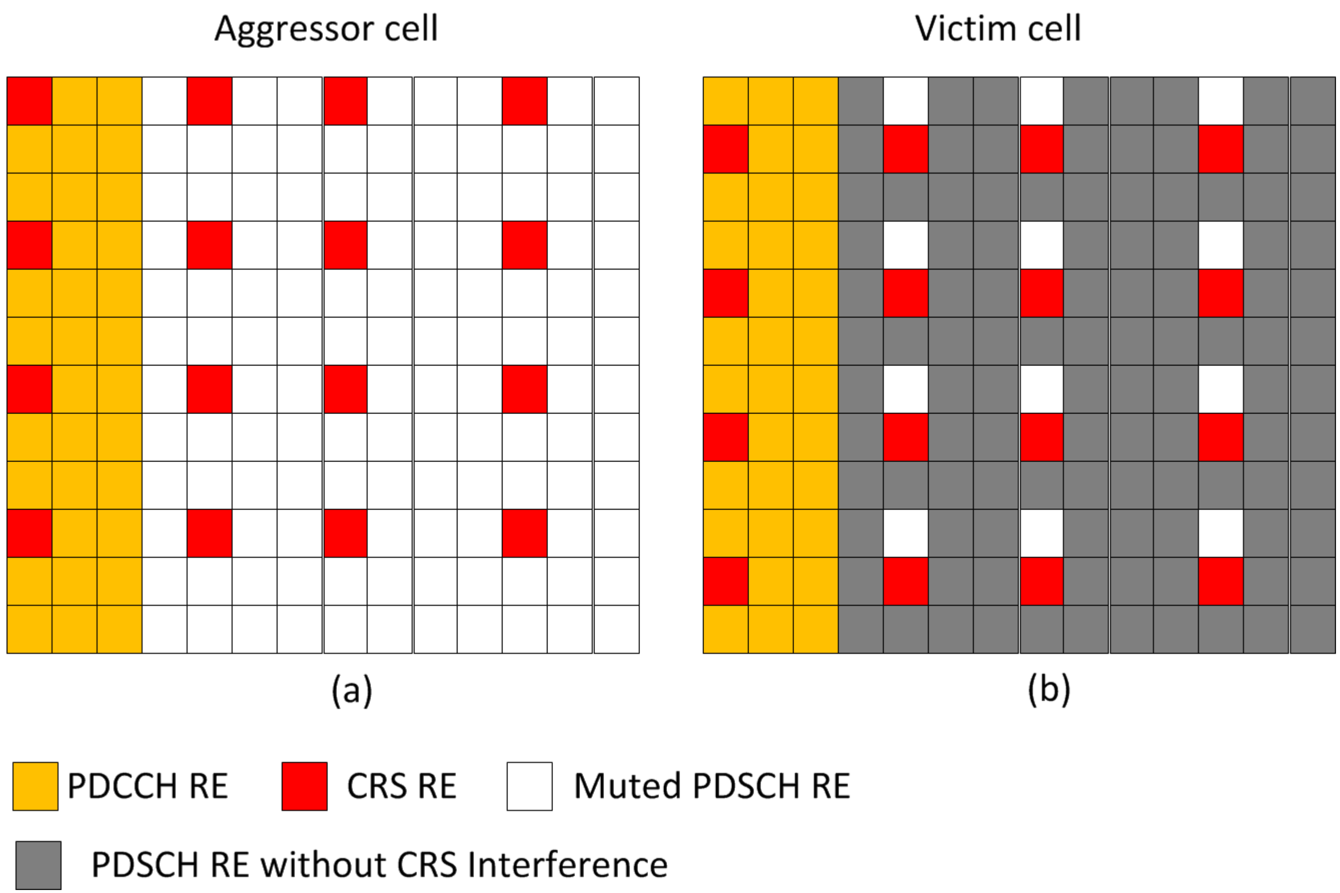
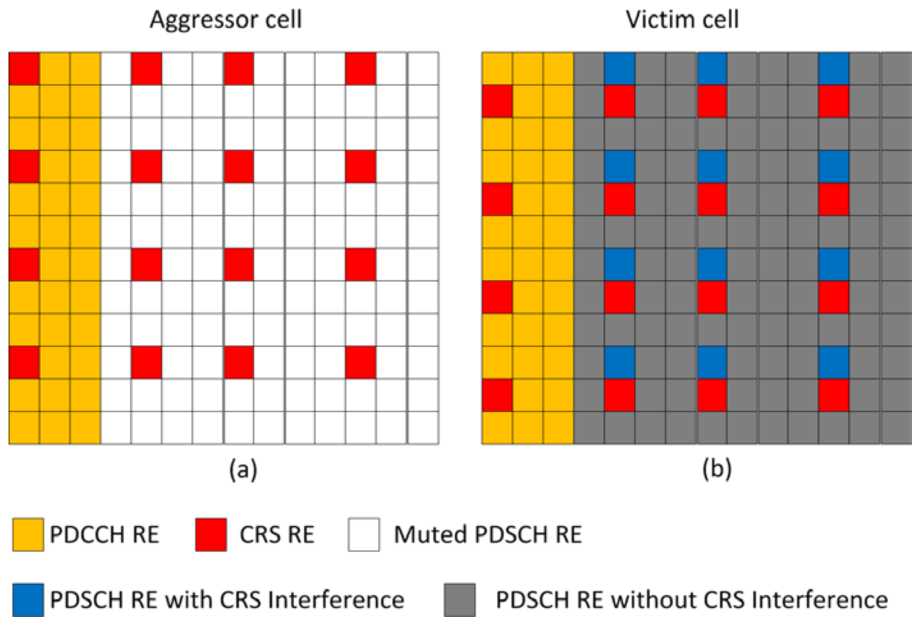
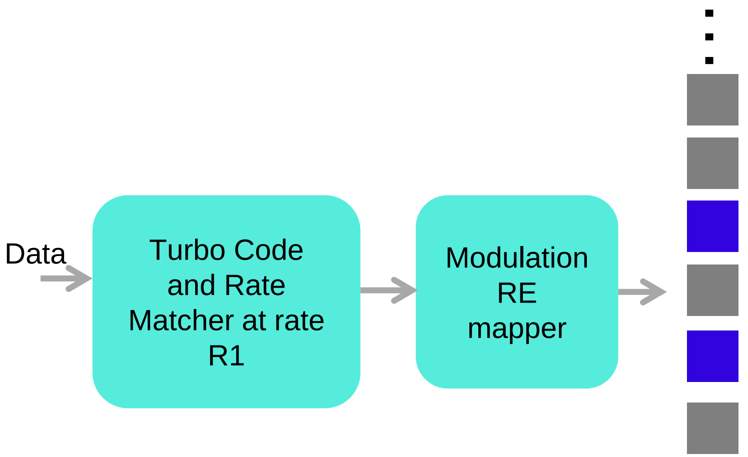
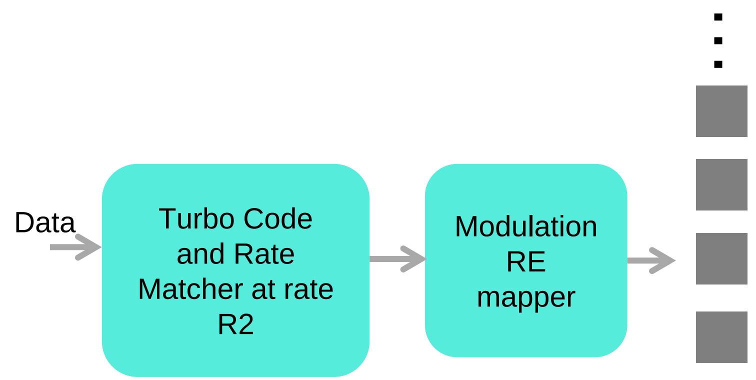
- The REs with strong CRS interference are muted and rate matching is then applied.



TX-based PDSCH Muting







Conventional system

- ❑ Data put in REs with high interference

Tx Based Muting

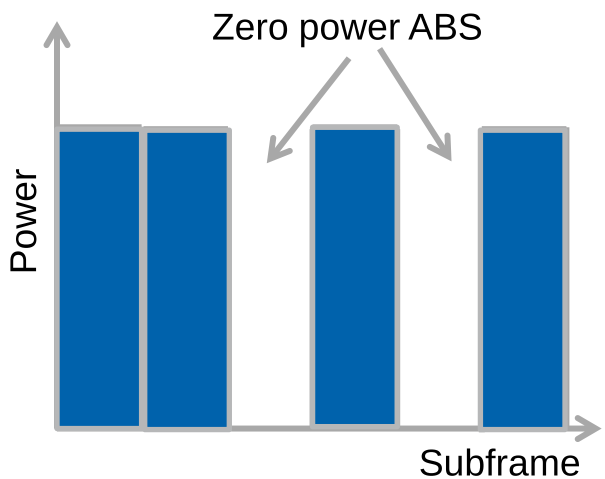
- ❑ High interference REs avoided
- ❑ Same data encoded at higher rate R2
    - ➢ to fit in reduced number of REs

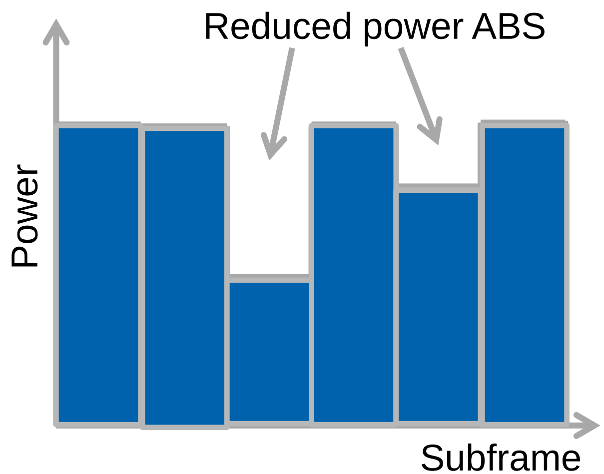
Signaling Aspect

- Standardization support for Tx muting at Transmitter
- The following can be provided to the UE
  - Parameters related to muted RE locations
    - Number of antennas of interfering cell
    - CRS locations of interferer
    - Interferer subframe type (ABS or non ABS)
  - Provided via higher layer signaling (semi-static) or physical layer signaling (dynamic)

Reduced Power ABS

- ABS lessens scheduling subframes for macro UEs
- But what if macro UEs are still scheduled in ABS frames, but with much less power?
  - No problem for cell center macro UEs
  - Interference to victim UEs not much due to less transmit power
- Called Reduced Power ABS





- Signaling support for reduced power ABS
  - Macro UE needs to know the exact value of transmit power for demodulation
  - Has to be signaled to the UE by the BS

Summary

- Rel-8/9 ICIC
  - Limited frequency domain information exchange followed by proprietary action
  - Proactive: eNB informs neighbor that certain RBs will have high interference
  - Reactive: eNB informs neighbor if it experiences high interference in certain RBs
- Rel-10 eICIC (enhanced ICIC) tailored towards Hetnets
  - Dynamic time domain interference coordination
    - Based on ABS where aggressor cells stops transmission
    - Information about ABS cycle etc signaled to UEs
    - New issues in scheduler design
  - Power control for macro-femto situations
- Rel-11 FeICIC (Further enhanced ICIC) for ABS
  - Receiver puncturing to drop data in highly interfered REs
  - Interference cancellation at receiver
  - Transmitter side muting to avoid REs with high interference and rate matching
  - Reduced power ABS

Case Studies

- Provide simulation results from practical deployments
  - UE throughput and signaling issues
- Case Study 1
  - Rel-10/11 ICIC for outdoor macro-pico deployment
- Case Study 2
  - Rel-10 ICIC for indoor femto, outdoor macro deployment
- Case Study 3
  - Rel-11 CoMP for HetNet

Case Study I: Macro-Pico Deployment

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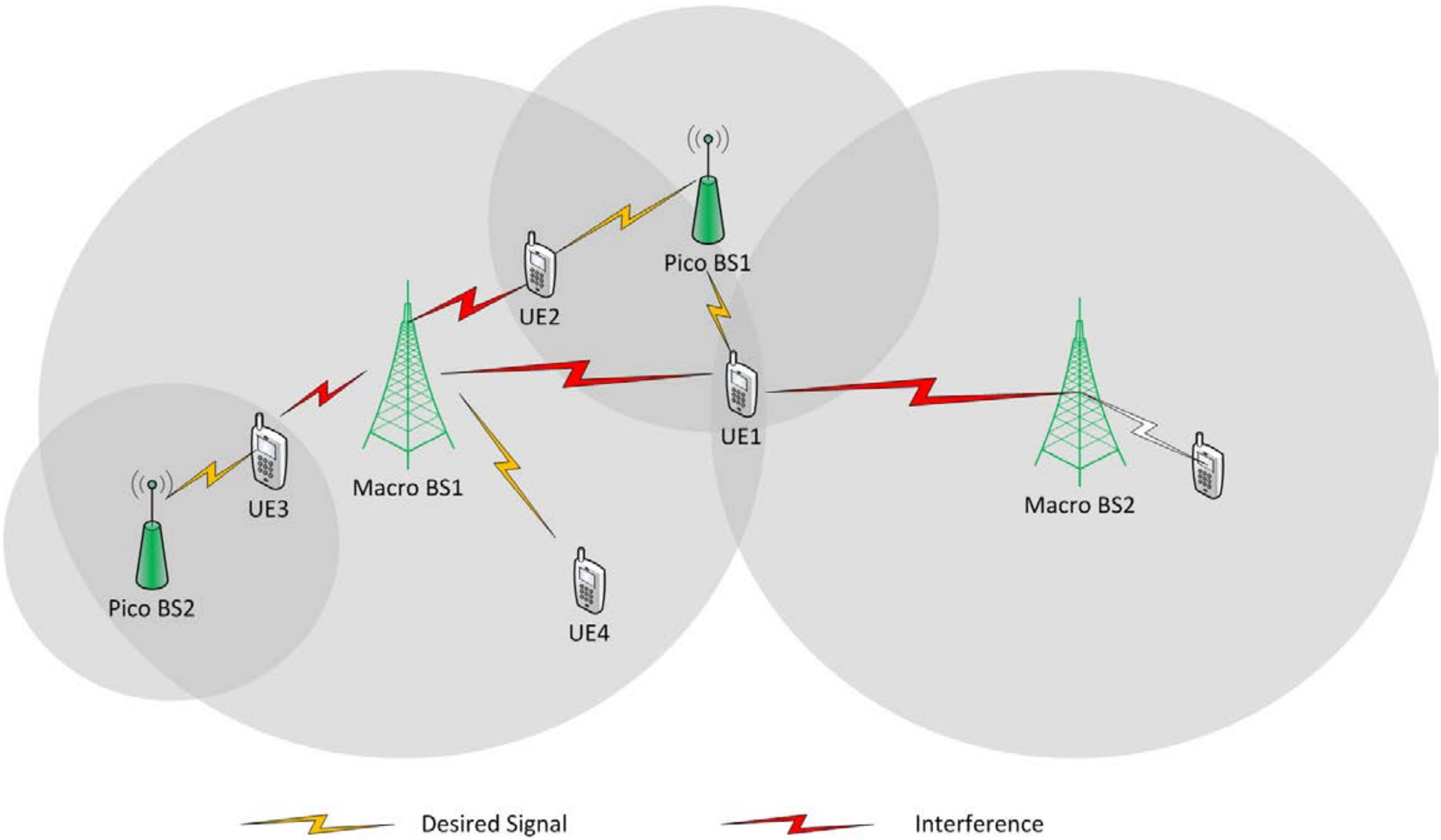

- ❑Throughput results for macro pico deployment (Rel 10, 11)
- ❑ Weak cell detection due to CRE bias

Simulation Setup

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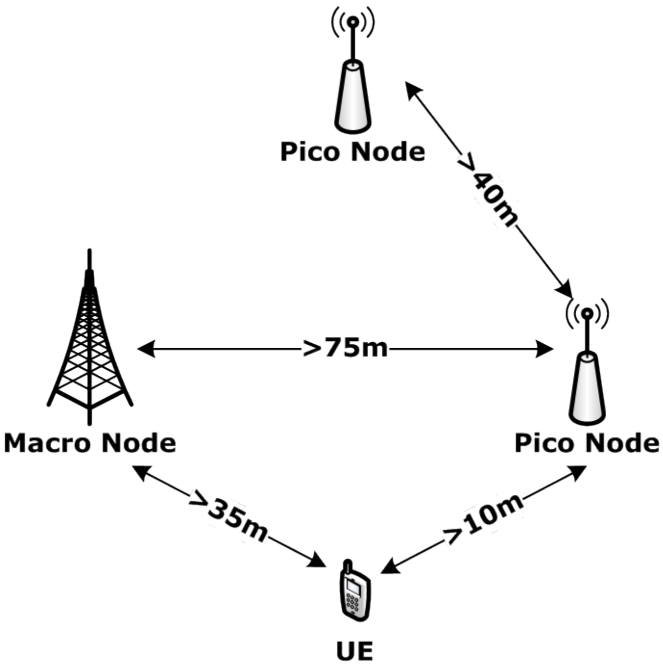
❑ Network deployment

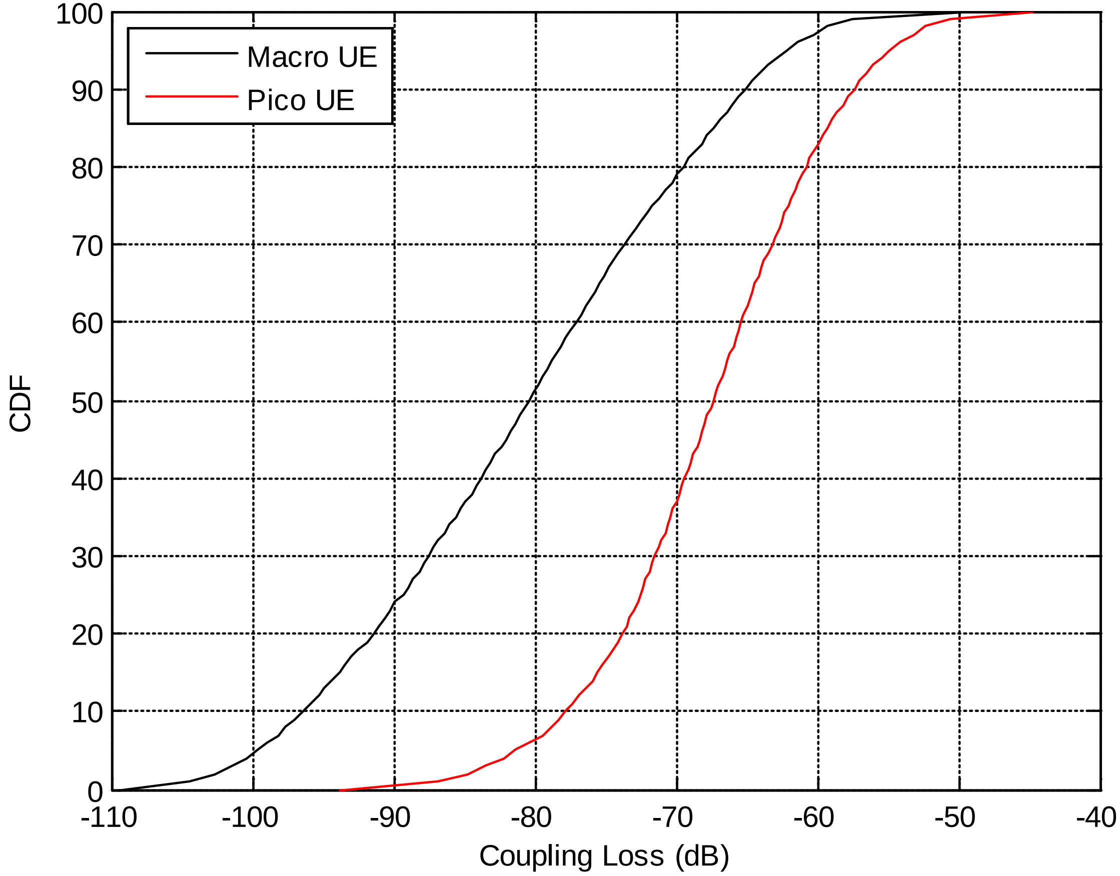
- Macro nodes: hexagonal structure
- Pico nodes: uniform distributed
- UEs: uniform distributed (3GPP configuration 1)
- Minimum distance requirements between various nodes and UEs



Simulation Setup (2)

- Channel model
  - ITU UMa for Macro, UMi for low power node
  - UMa
    - UE speed : 3km/hr
    - Spatial Channel Model (SCM) based correlated small scale fading
  - UMi
    - 100% UEs dropped outdoors
    - SCM channel with correlated small scale fading

Coupling Loss (Tx-Rx Link Gain)



Pico UE have better link gains due to small cell nature of picocells

Wideband SINR

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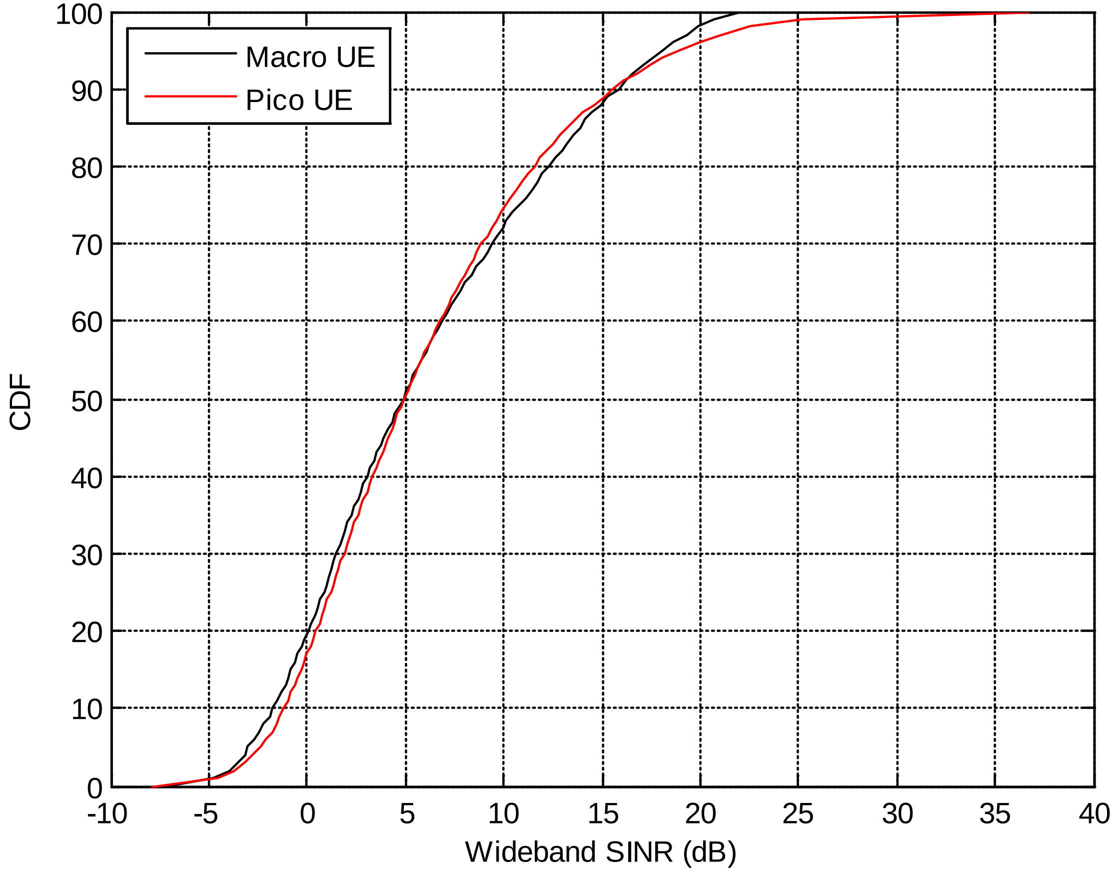
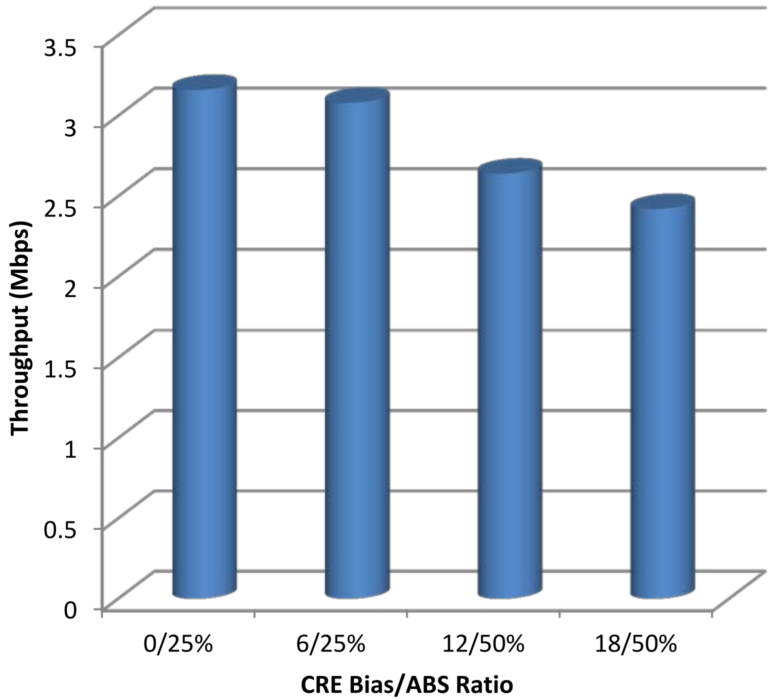
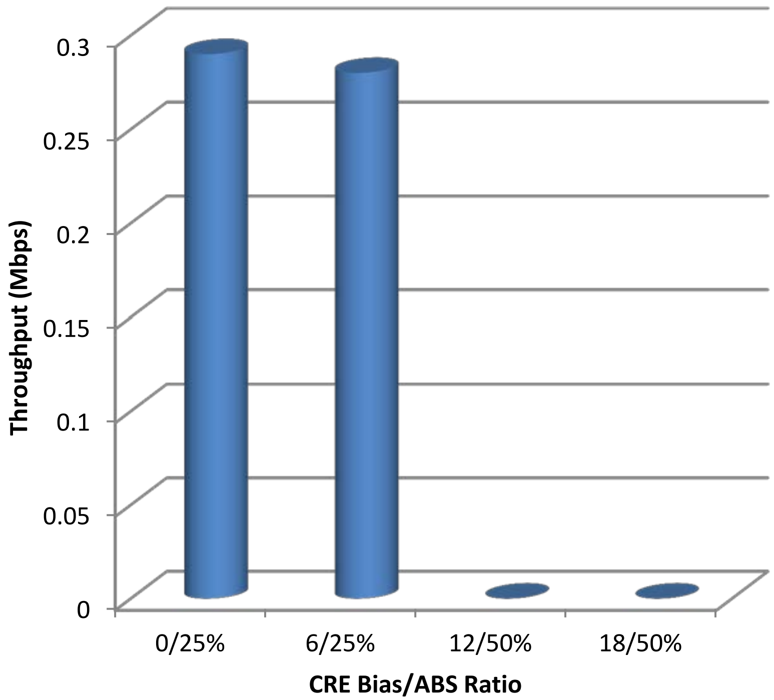


Both UEs have similar SINR characteristics due to interference limited nature of channel

Rel-10 eICIC Throughput



Cell average throughput



Cell edge throughput

- ❑ Large bias values decrease macro load but increase DL interference
- ❑ Cell edge UEs experience zero throughput with large CRE bias

Rel-11 Puncturing Receiver

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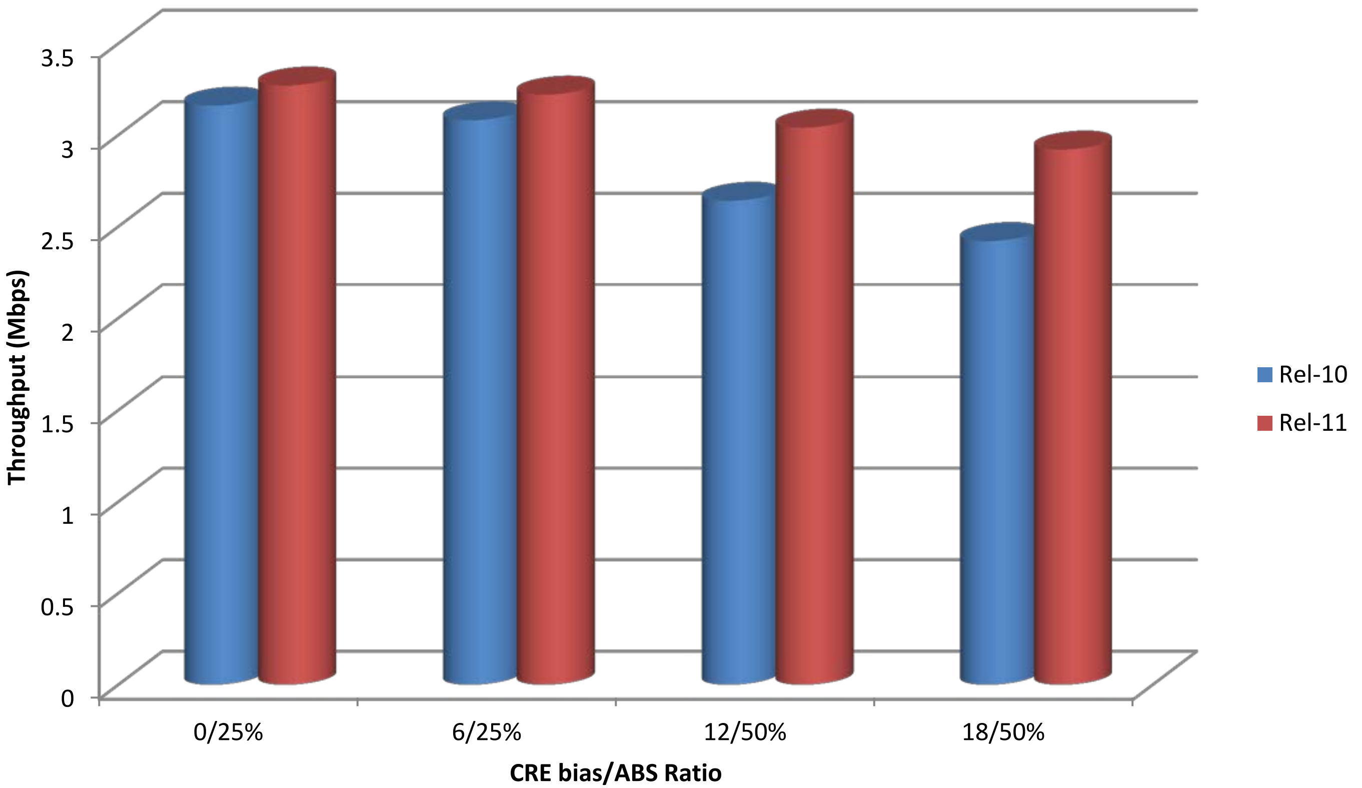

Cell average throughput

Puncturing improves cell average throughput especially for high bias values

Rel-11 Puncturing Receiver (2)

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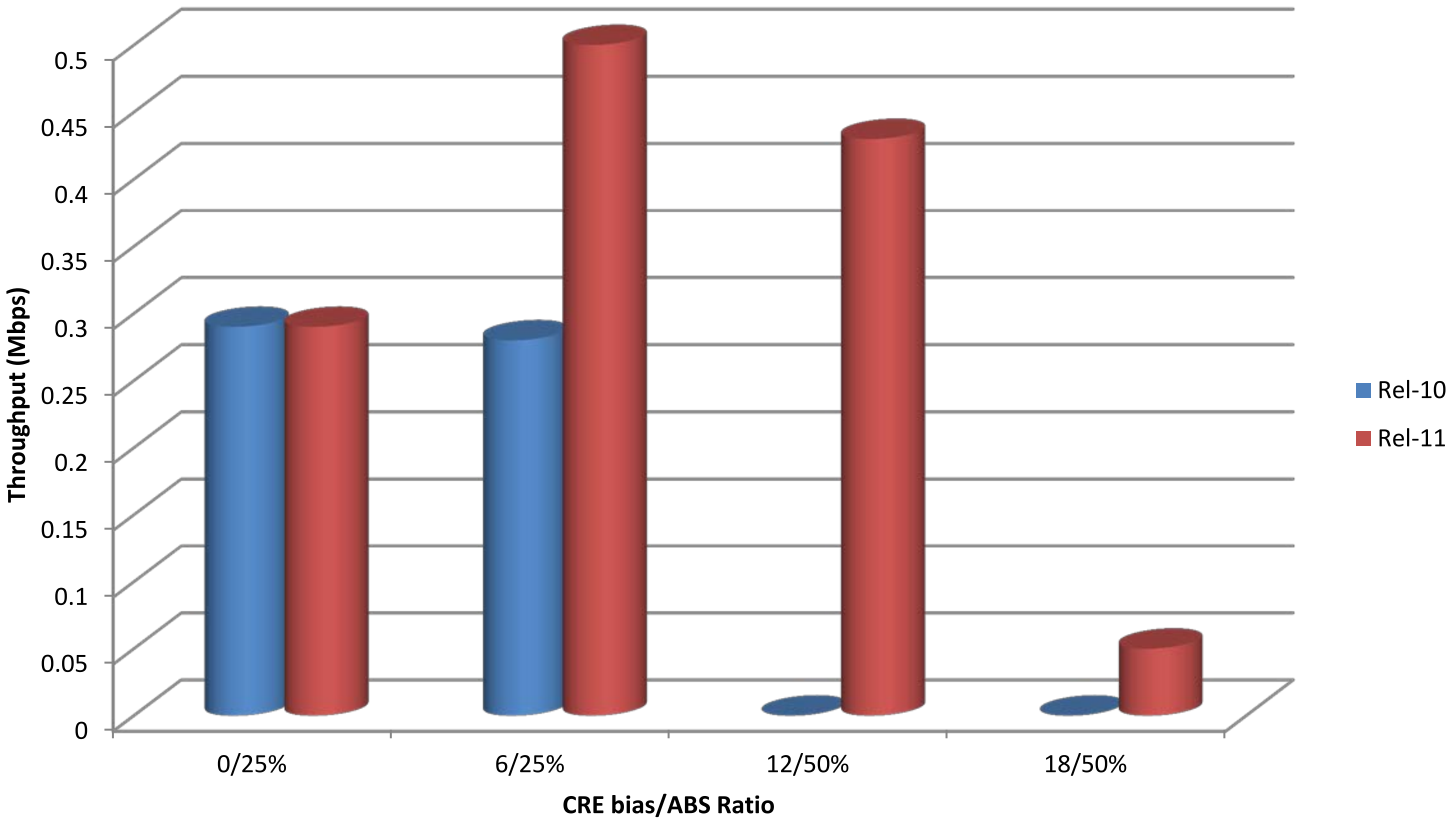
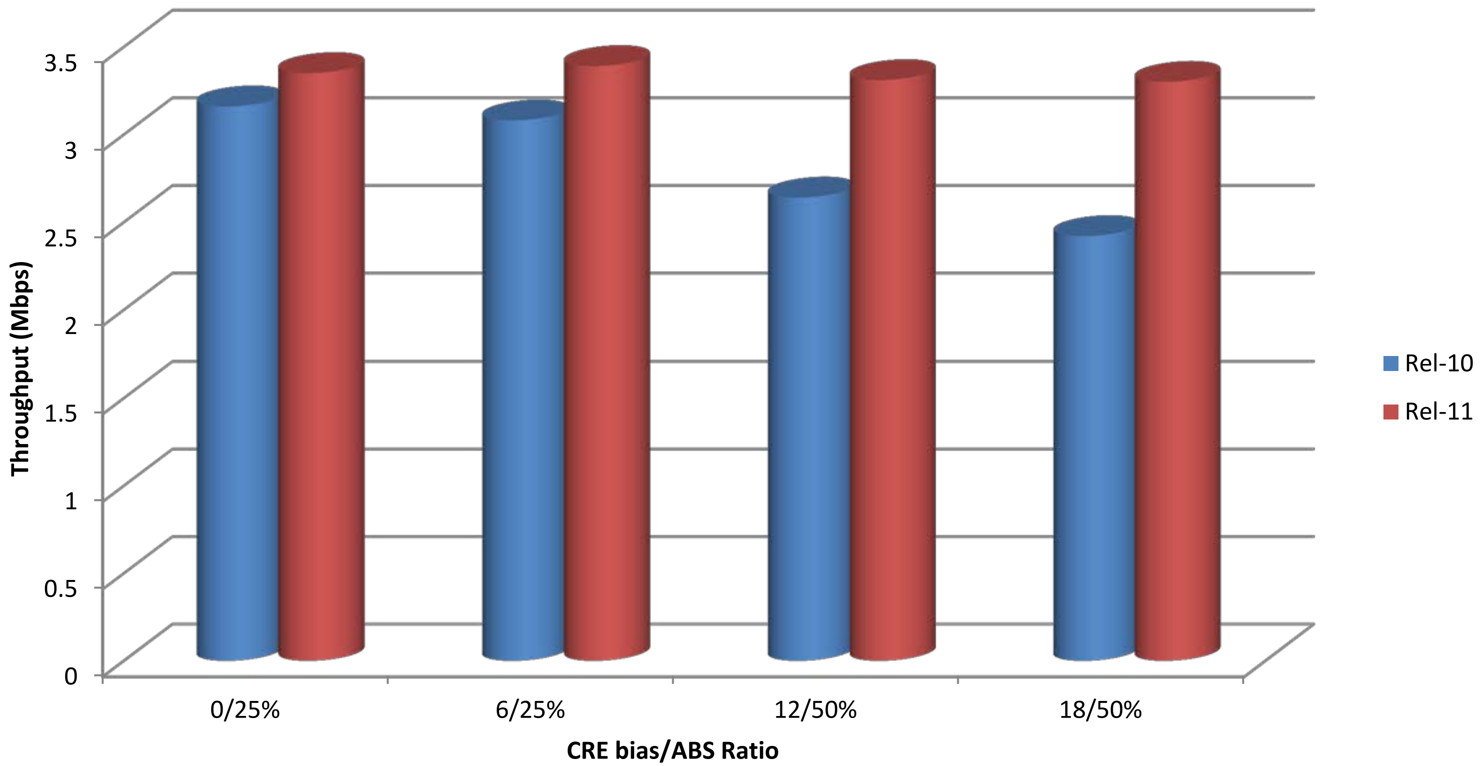


Cell edge throughput

Puncturing can improve the cell edge throughput for medium CRE bias configurations.

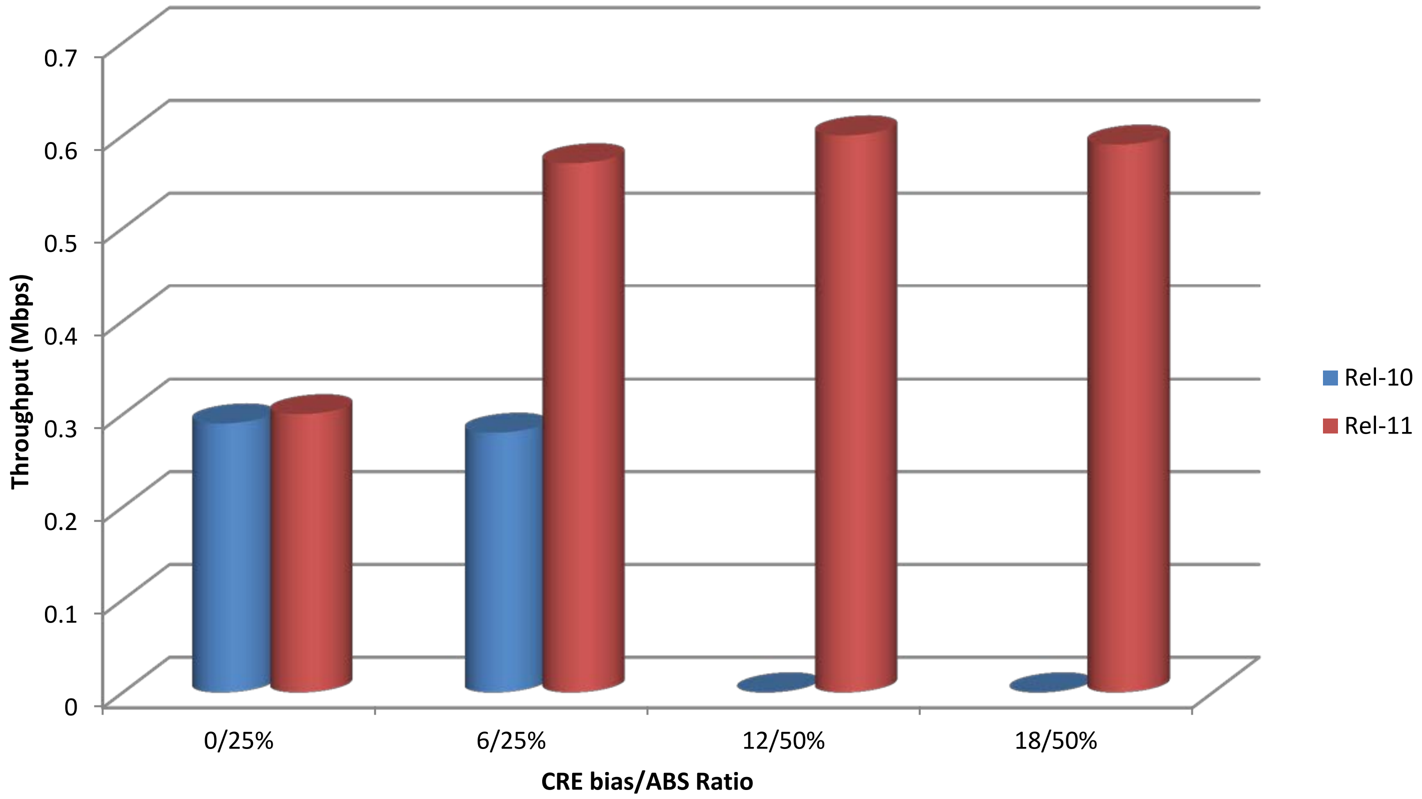
Rel-11 IC Receiver



Cell average throughput

Interference cancellation improves cell average throughput especially for high bias values

Rel-11 IC Receiver (2)



Cell edge throughput

- ❑ Interference cancellation can dramatically improve the cell edge throughput for all CRE bias configurations.
- ❑ **6 dB bias value optimum for system design**

Comparison between Rel-10 and Rel-11

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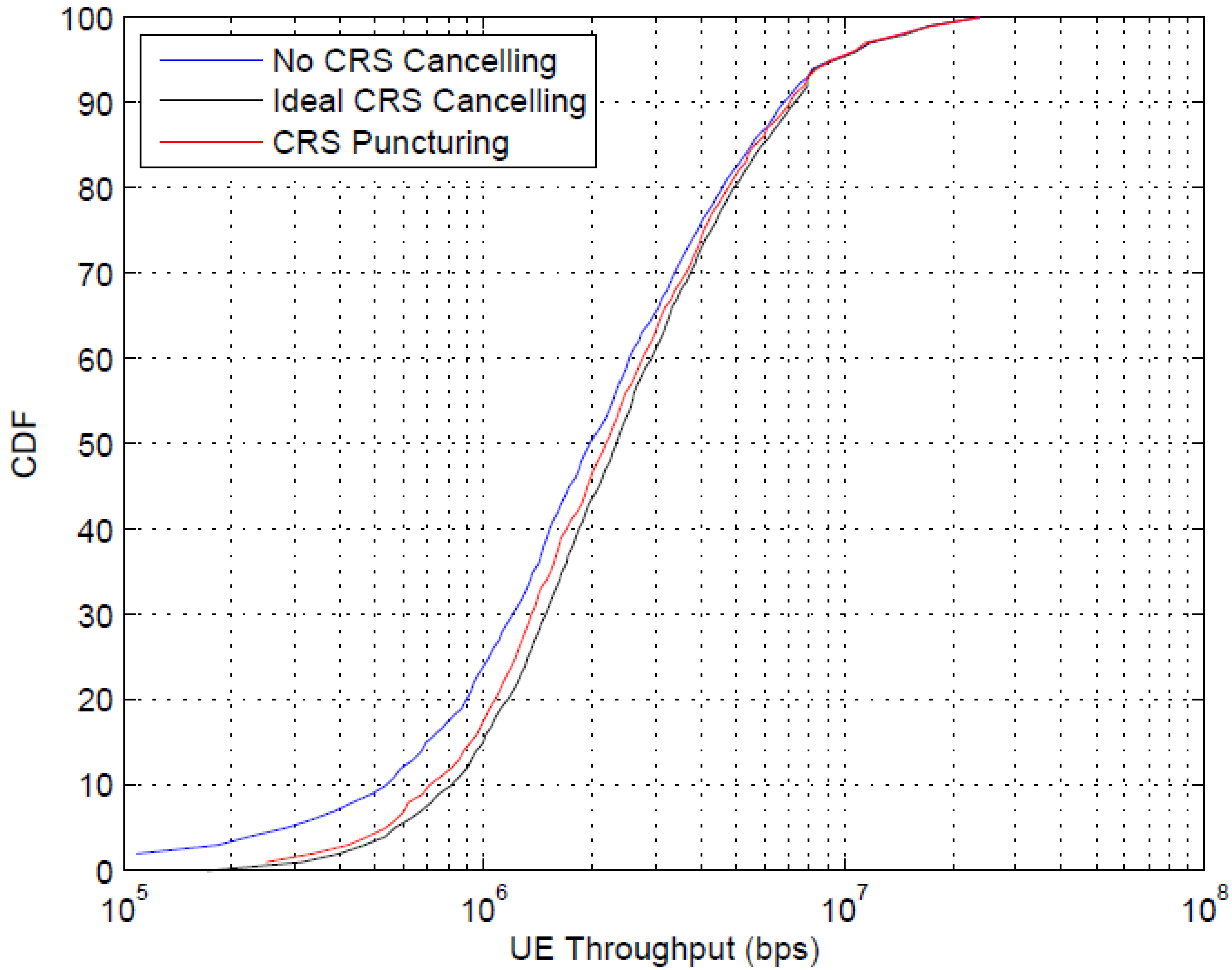

Cell detection with CRE - Weak Cell Detection

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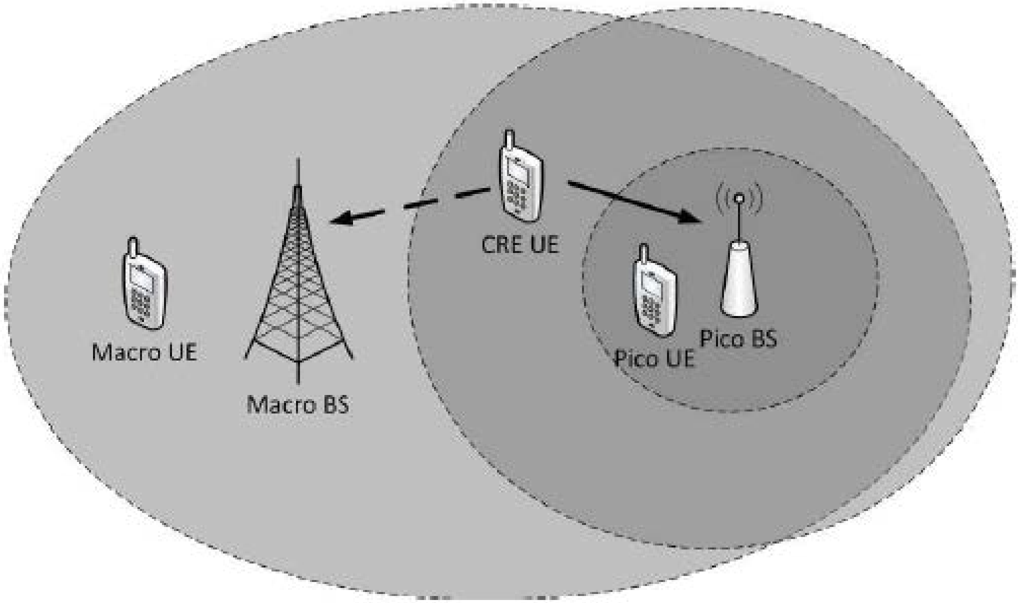

- CRE bias is a logical operation
  - E.g. UE wants to connect to pico with 10 dB CRE
  - Macro then tries to hand over the UE to the pico cell
  - UE has to detect control information from pico BS which is 10 dB weaker than macro
  - If this fails, handover fails (no CRE possible)

Handover Process for Enabling CRE

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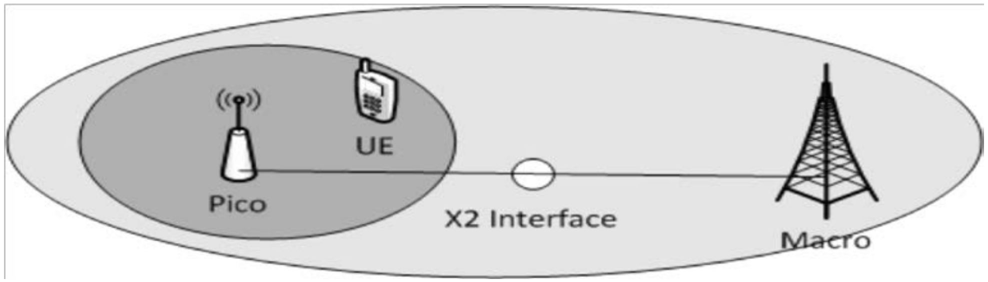
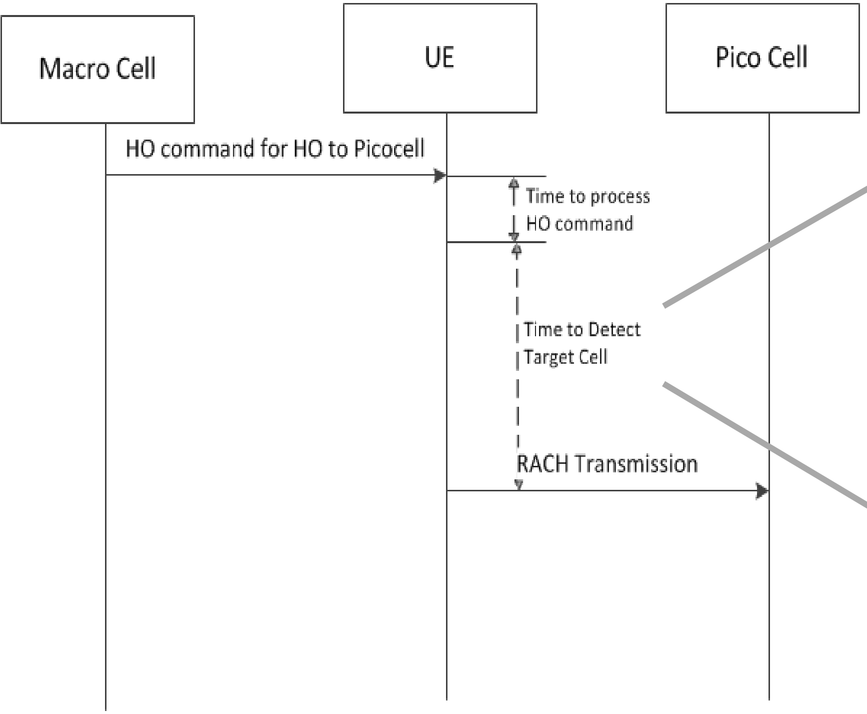
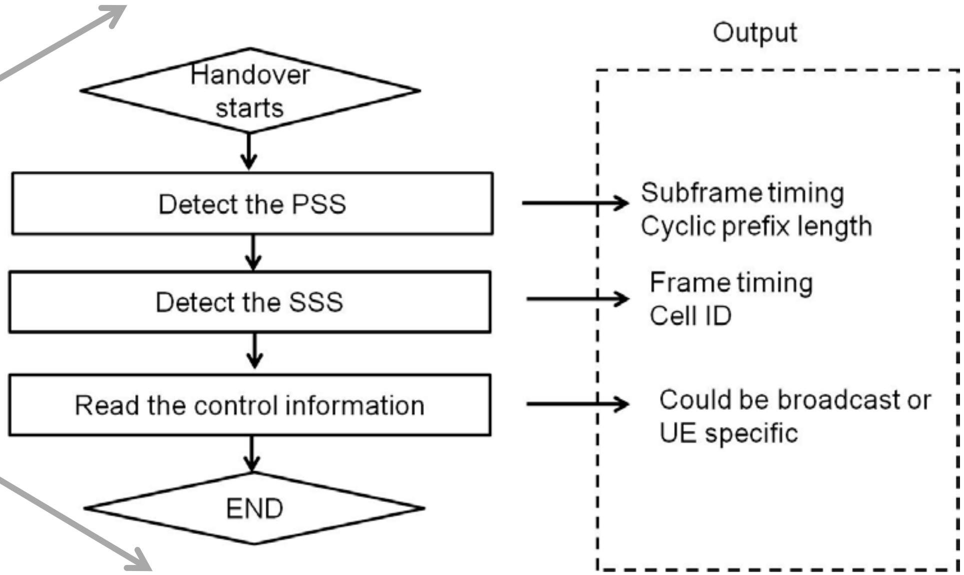




Target cell detection process



Cell detection of weaker cell is very important for handover

Weak Cell Detection

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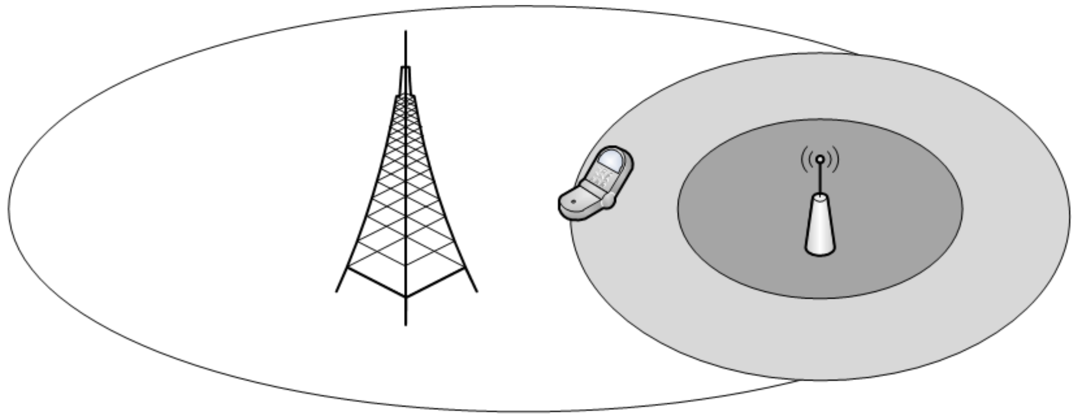
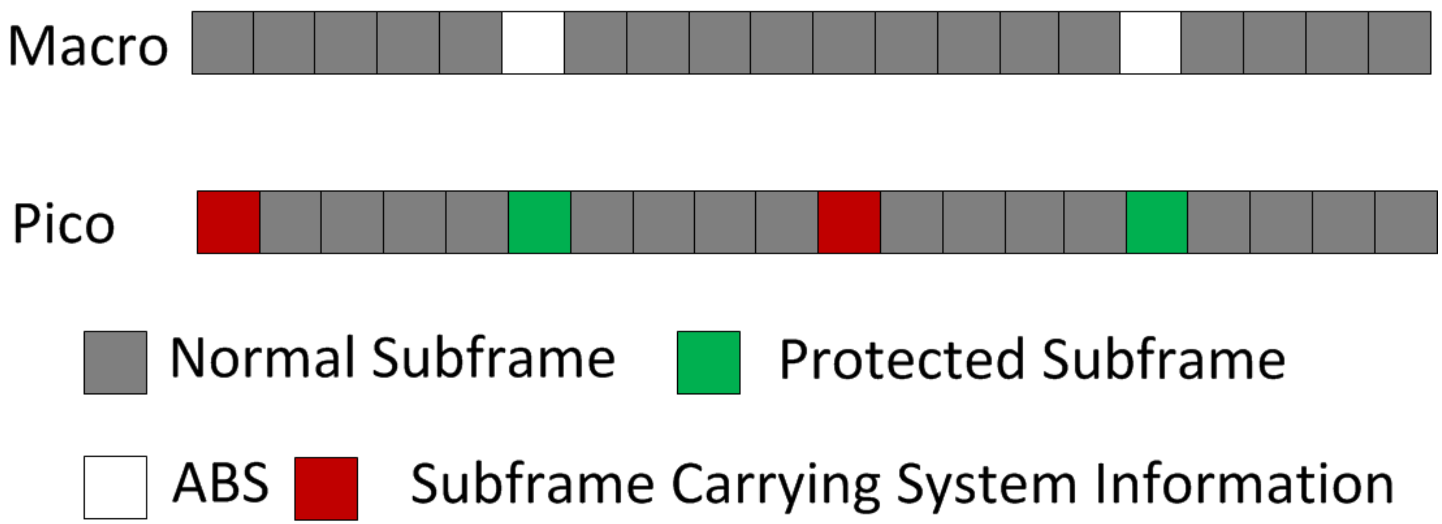




Weak Cell Detection (2)

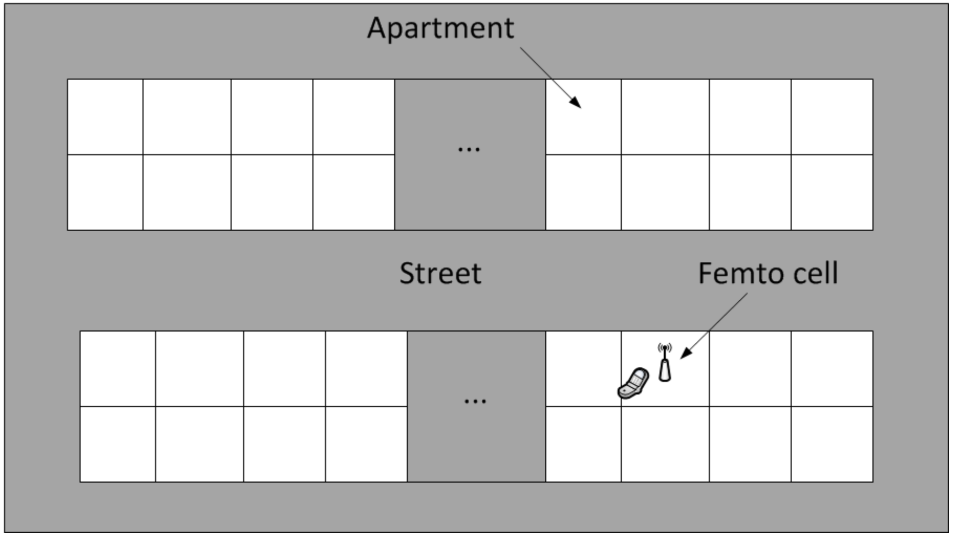
- Network may assist UE for handover to weaker cell
  - Thus CRE can be realized for high bias values
- During handover from a stronger cell, it indicates
  - Essential information of weaker cell via higher layer signalling
    - The cell ID, cyclic prefix length, and frame structure type
    - Broadcast channel information

Source: 3GPP Document R1-120465

Case Study II: Macro Femto Interaction

- Interaction of femto (indoor) and macro (outdoor)
- Radio level case study
  - Control channel outage
    - Probability that macro/femto UE can't decode the control channel
    - Assuming -6 dB SINR threshold and interference from the other node
    - Control channel elements send at rate 1/3 QPSK symbols
  - UE throughput
    - Subsequent data rates after decoding control channel
    - Adaptive modulation and coding
    - Both cell average and cell edge throughputs
- Signaling case study
  - Introduction of CSG (closed subscription group) for femtocells
  - Signaling for handover

Femto Modeling



Femto Modelling Parameters

K (number of cells per column)	4
N (number of cells per row)	10
M (number of blocks per sector)	1
L (number of floors per block)	6
R (deployment ratio)	0.1
P (activation ratio)	1
Probability of macro UE being indoors	35%

Simulation Setup for Femto

Carrier Bandwidth	10 MHz
Femto Frequency Channel	Same as macro
Cell radius	10 m
Minimum separation UE to femto	3 m
Tx antenna at Femto	1
Femto antenna pattern	Omni directional
Femto antenna gain	5 dBi
Min/Max Tx power femto	-10/20 dBm
Max number of femto UE	1 per femto

Power control at Femto

- Method 1: $P_{Tx} = \min\left(\max\left(\alpha P_m + \beta, P_{\min}\right), P_{\max}\right)$
- Method 2: $P_{Tx} = \min\left(\max\left(P_m + P_{offset}, P_{\min}\right), P_{\max}\right)$

Simulation Setup for Macro

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Cellular layout	7 cell 3 sector hexagonal layout
Inter site distance	500 m
Carrier frequency	2 GHz
Shadowing standard deviation	8 dB
Auto correlation distance of shadowing	50 m
Shadowing correlation	0.5 (between cells) 1 (between sectors)
Antenna pattern	Sectorized antenna with 14 dBi gain (macro) , Omni (UE)
BS noise figure	5 dB
Tx antenna	1 Tx at macro and UE
UE noise figure	7 dB
Total BS Tx power	46 dBm
UE distribution	Uniform
Minimum distance between UE and macro	35 m
UE speed	3 kmph

UE Control Channel Outage

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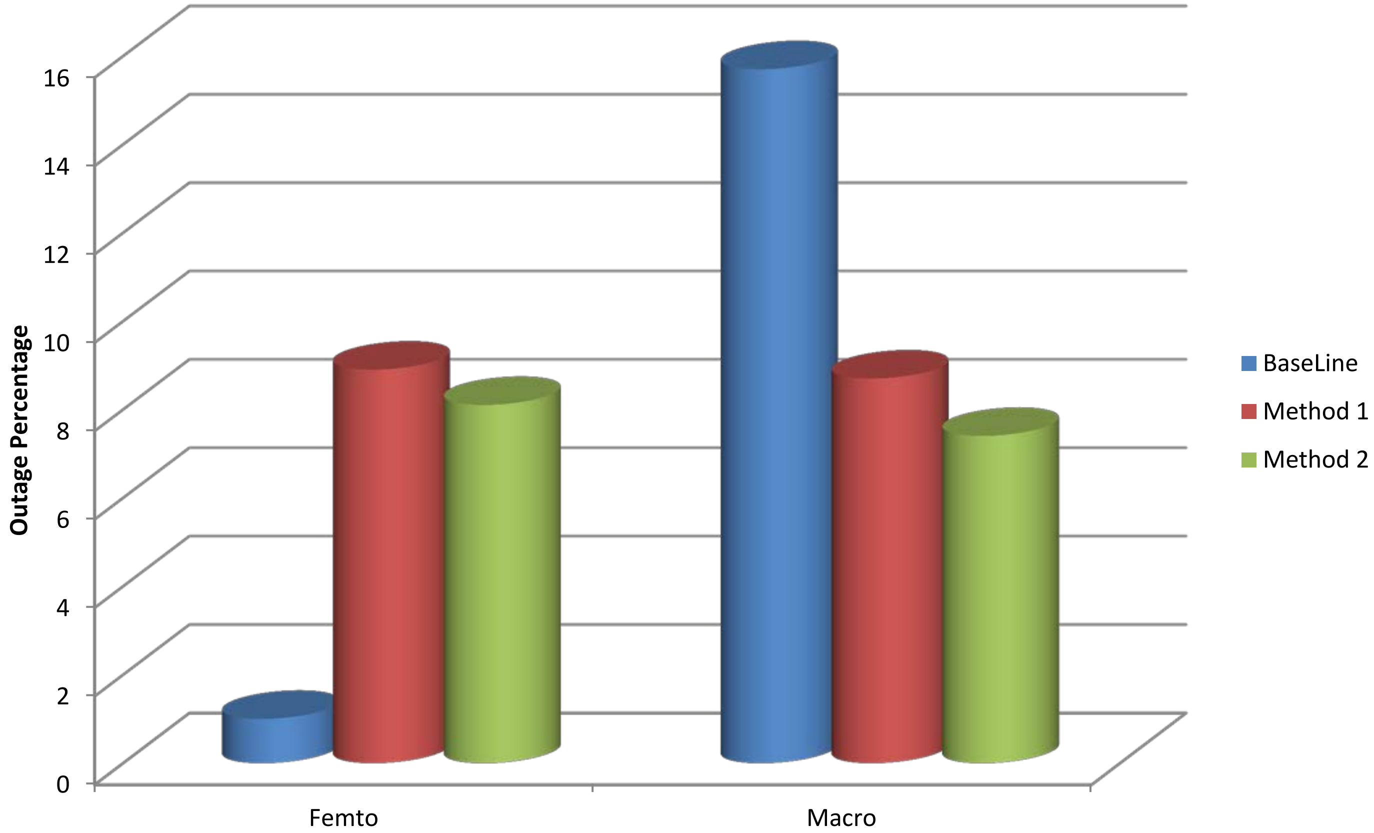
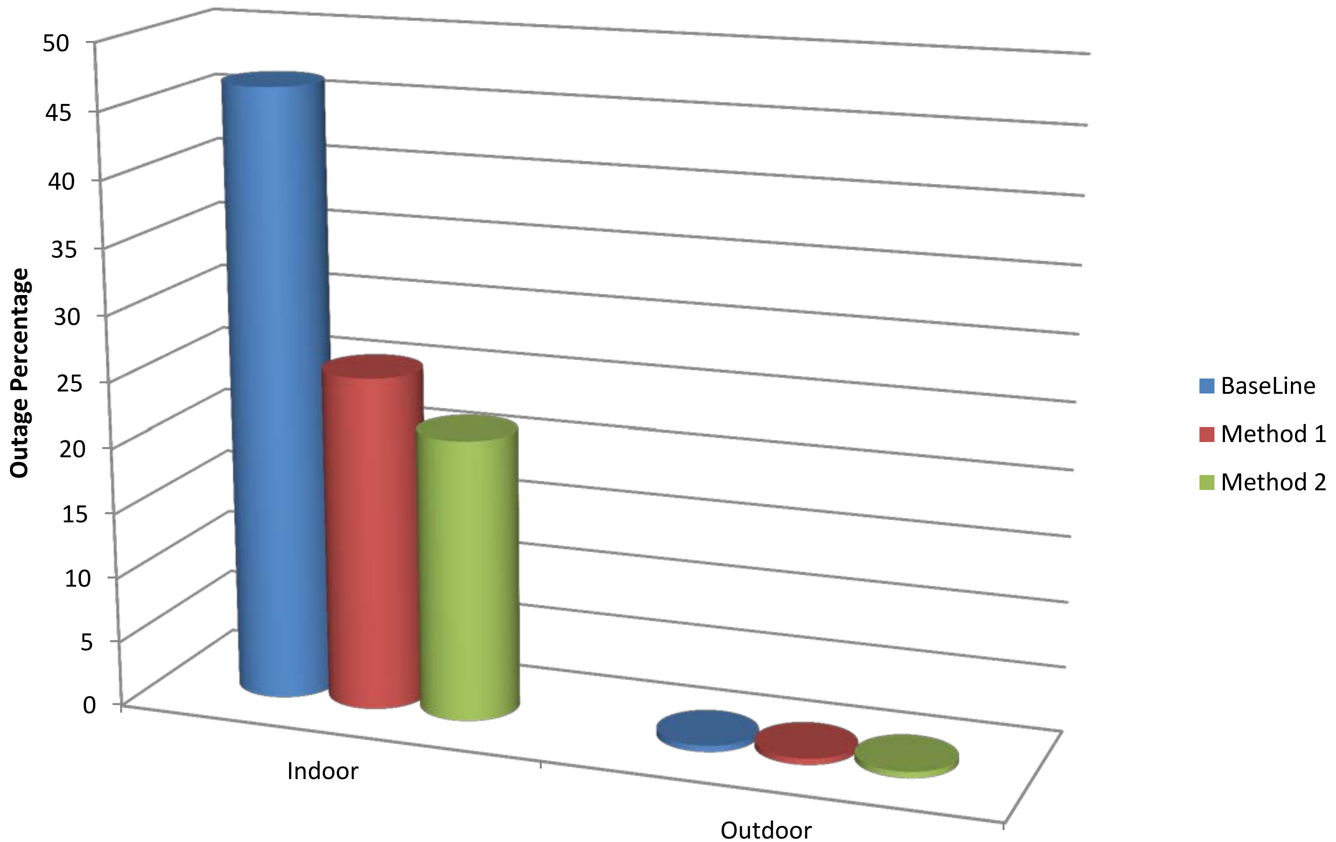


The power control schemes can provide good balance on the outage of macro and femto UEs.

Source: R1-104102

Macro UE Control Channel Outage



- ❑ The power control schemes at femto significantly reduces the outage of indoor macro UEs.
- ❑ Outdoor macro UEs are not significantly interfered by femto BS
  - ➢ Hence all methods have low outage probability
  - ➢ Hence power control at femto is not that essential

Source: R1-104102

Throughput for Macro UEs

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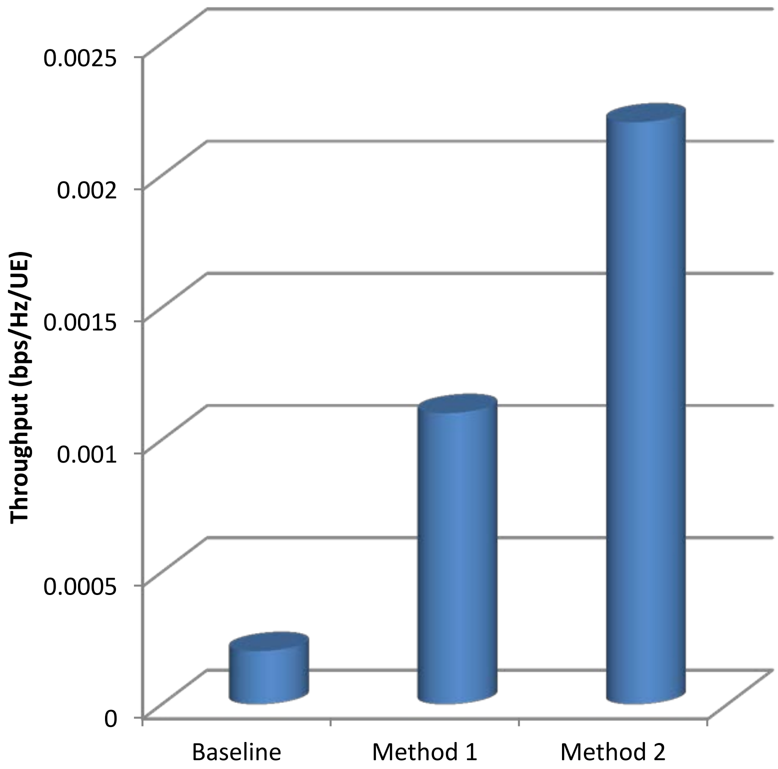
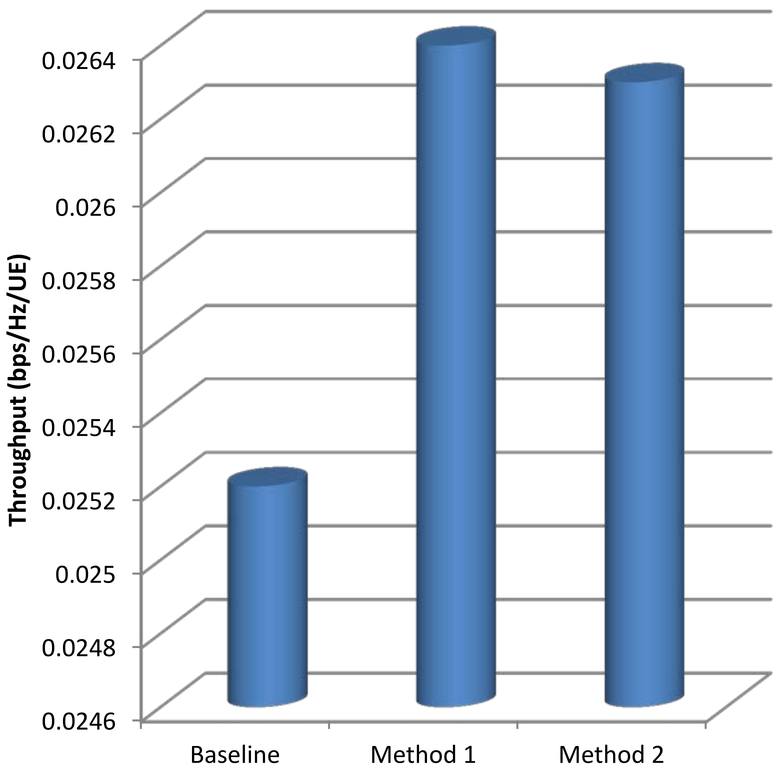


Cell edge throughput

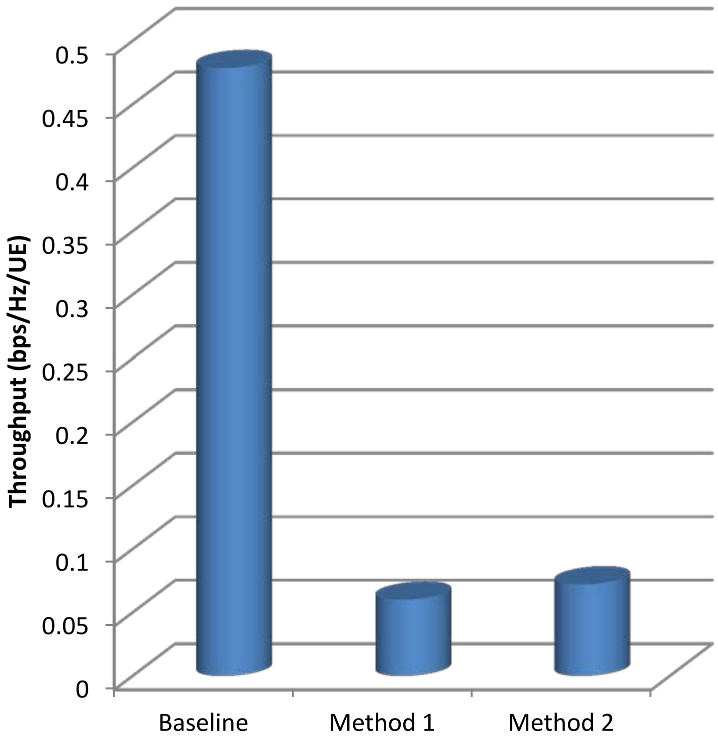


Cell average throughput

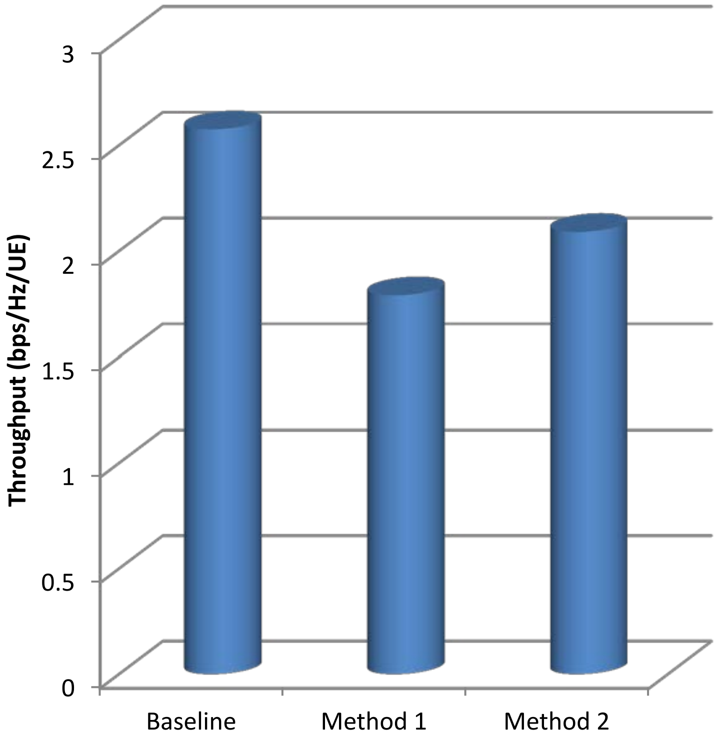
The power control schemes provide 2-4 times throughput gain for cell-edge UEs.

Source:R1-104415

Throughput for Femto UEs



Cell edge throughput



Cell average throughput

The power control schemes reduce the cell-edge throughput.

Source:R1-104415

Network Architecture for Signaling

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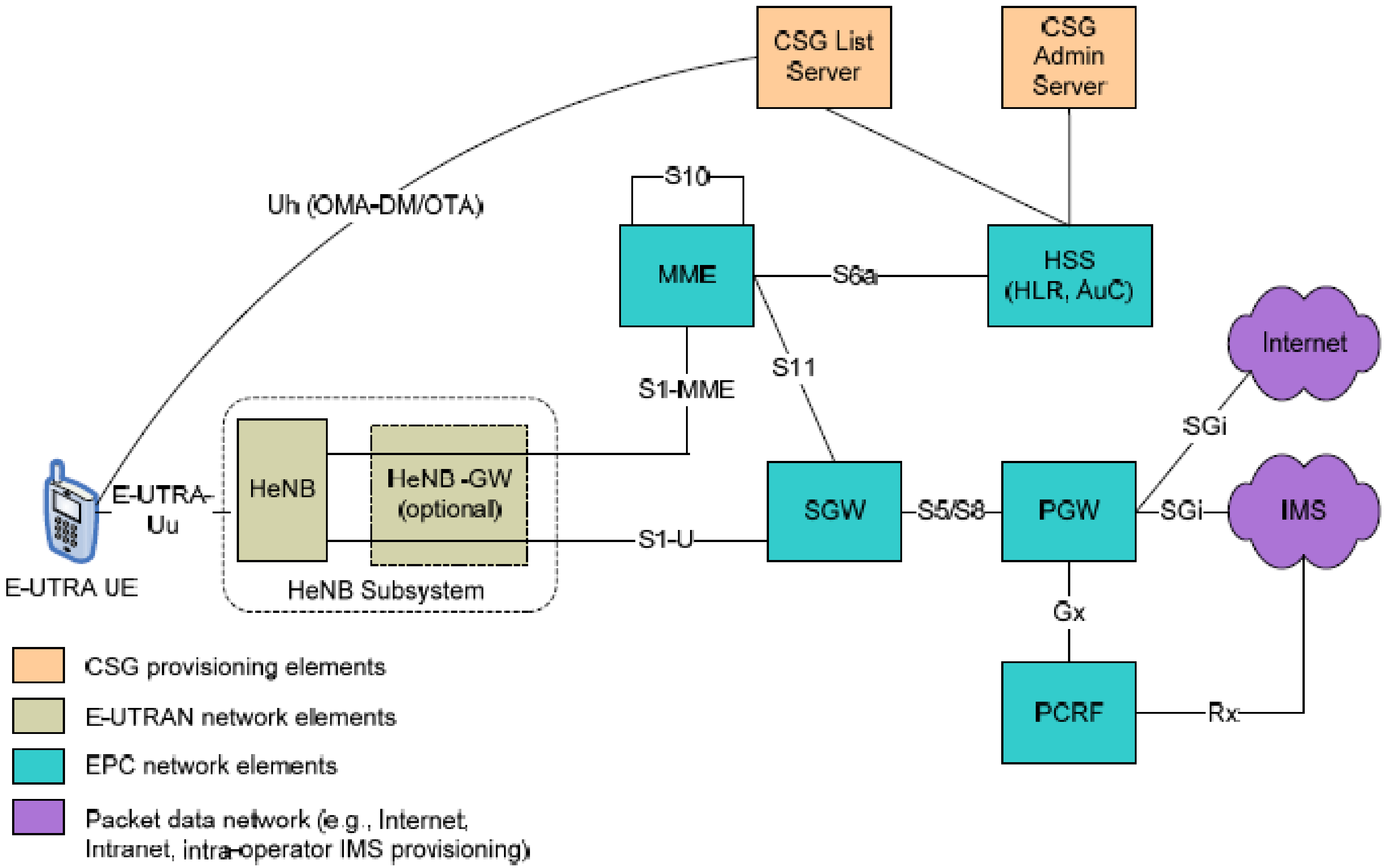

Source: 3GPP femto cell: architecture and protocols, Qualcomm, 2010

CSG Provisioning for Femto

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- CSG (Closed Subscription Group)
  - List of femtocells that an UE is allowed to connect
  - CSG femtocells are not open for all UEs
- CSG list server manages the list of subscribers for a CSG
  - A single list manages all the femtos for a CSG
- CSG admin server manages
  - How CSG information is stored in the UE and the network.
    - Provisioning of the allowed CSG list on the UE
    - Storage of CSG subscription info in network for access control

Initial Acquisition Procedure

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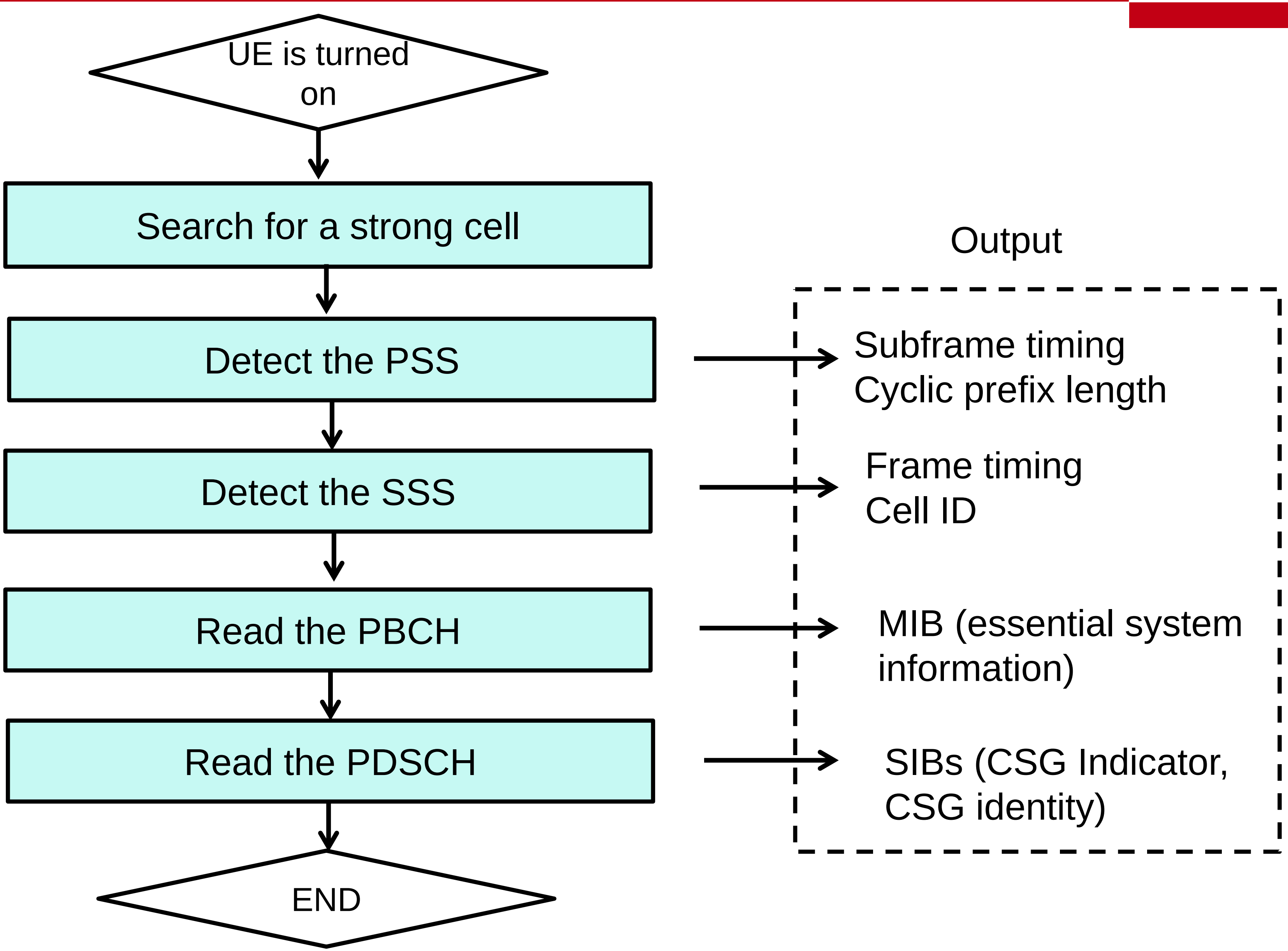
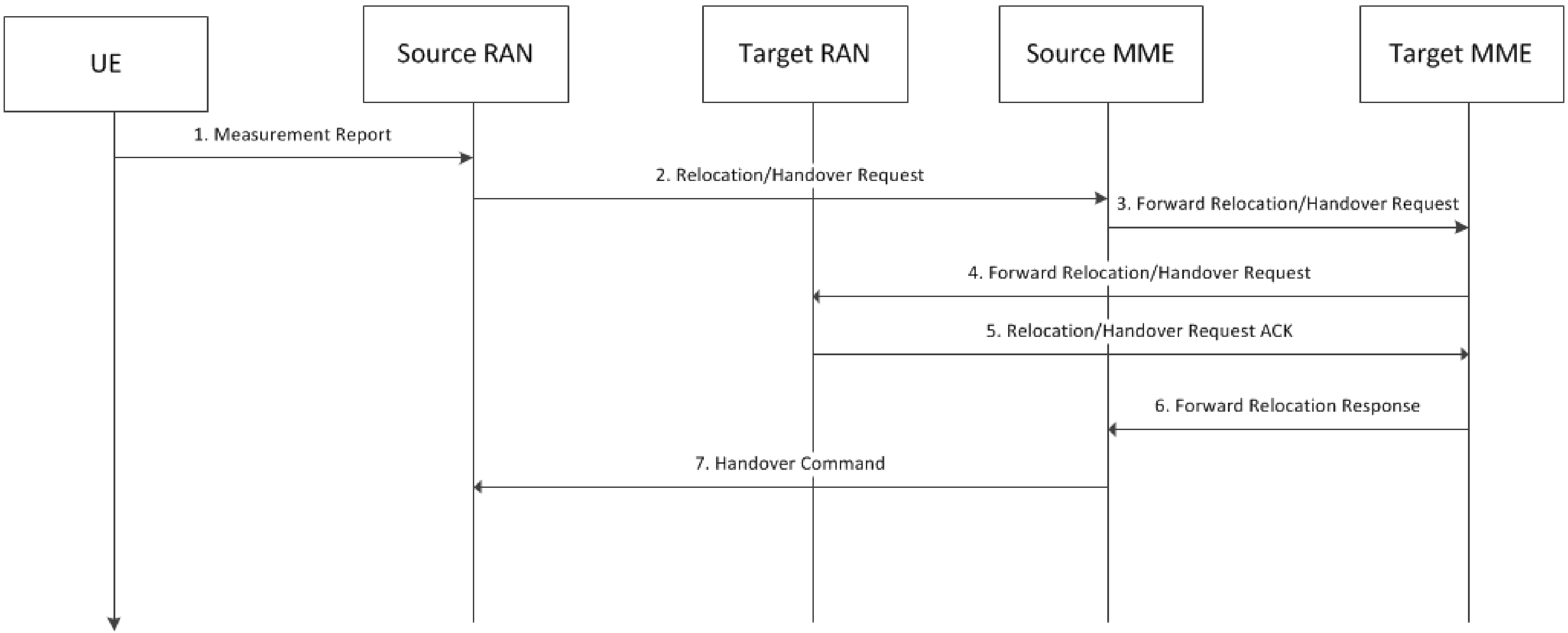


CSG related Control Information

- ❑ UE specific control information configured by higher layers
- ❑ Carried in various SIBs (System Information Blocks)
- ❑ Transmitted in UE allocated data resource blocks
- ❑ Configured semi-statically and infrequently
  - ➢ Unlike dynamic control information such as scheduling and resource allocation

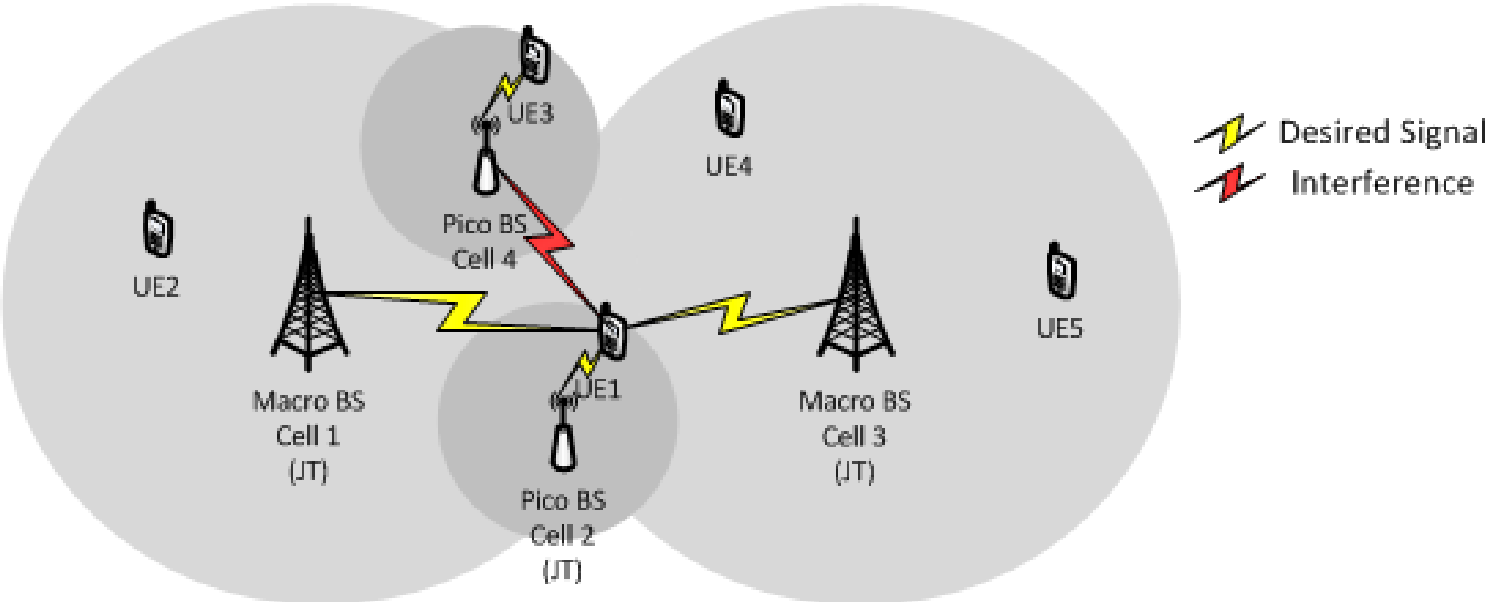
CSG Information IE	Broadcast in	Sent by
CSG Indicator	SIB	CSG cells {TRUE}, open and hybrid cells {FALSE}
CSG Identity	SIB 1	CSG and hybrid cells only
Femto name	SIB 9	CSG and hybrid cells only

Handover Process



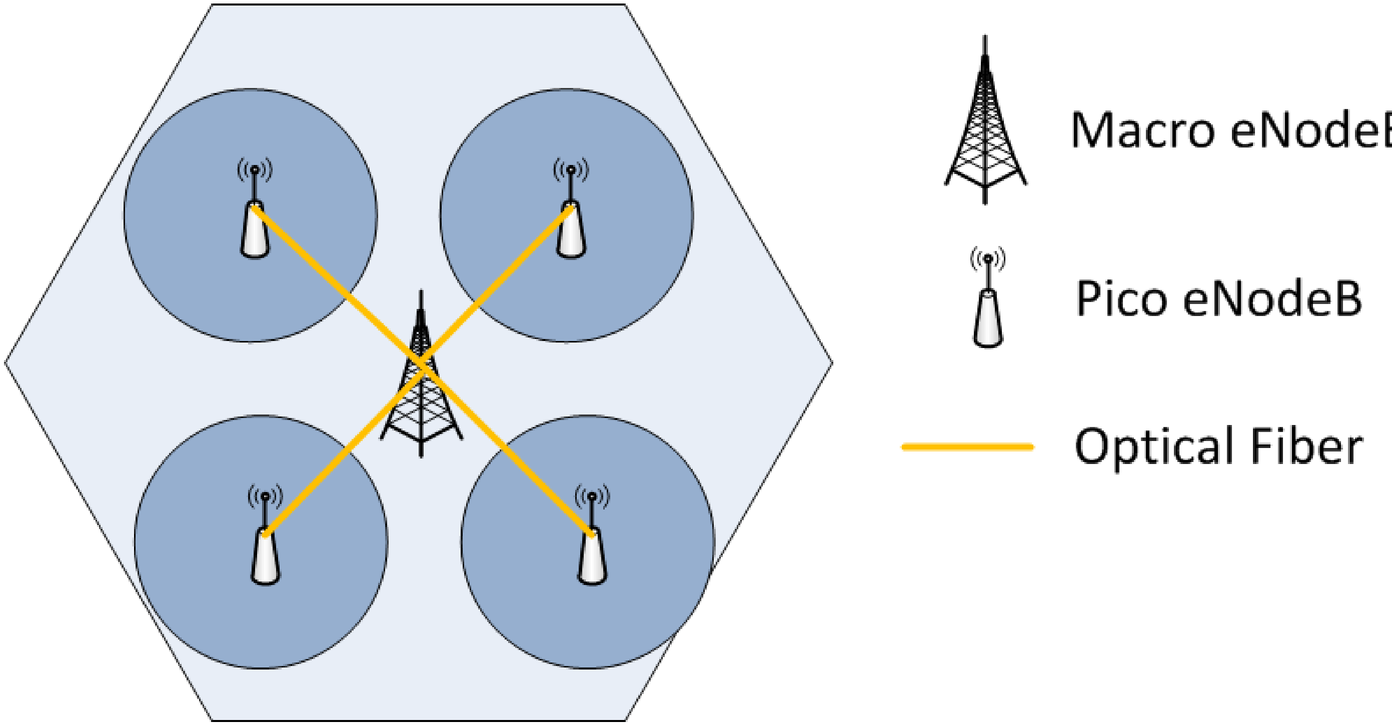
- Target RAN is femto and UE has better signal strength to it
- Handover to femto possible if UE can access the femto (CSG list)
- Target MME (of femto) accesses information from CSG server for handover

Case Study III: CoMP for HetNet



- ❑Throughput results for CoMP (Rel-11)
- ❑Interference measurement
- ❑CSI feedback

Two HetNet Scenarios for Rel-11 CoMP



- Macro transmits with high power, pico transmits with low power
- The macro and picos use different cell ID in HetNet Scenario 1
- The macro and picos share the same cell ID in HetNet Scenario 2

Three CoMP Schemes

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- **Joint Transmission (JT)**
  - Data To a UE is simultaneously transmitted from multiple points
    - Coherent JT vs. Non-Coherent JT
- **Dynamic point selection (DPS)/muting**
  - Data transmission from one point in a time-frequency resource
  - The transmitting/muting point may change over time
- **Coordinated Scheduling/Beamforming (CS/CB)**
  - Data for an UE is only available at and transmitted from one point
  - UE scheduling/beamforming decisions are coordinated among multiple points

Simulation Setup for CoMP Evaluation

Parameters	Configurations
System bandwidth	10 MHz
Layout	57 cells with wrap-around
Number of RRHs per macro	4, configuration #1
UE load	25 UEs per macro
Macro TX power	46 dBm
Pico TX power	30 dBm
Number of antennas	Macro 4, RRH 4, UE 2
Antenna configuration	ULA
Traffic model	Full buffer
Scheduling scheme	Proportional fair
UE speed	3 km/h

Simulation Results

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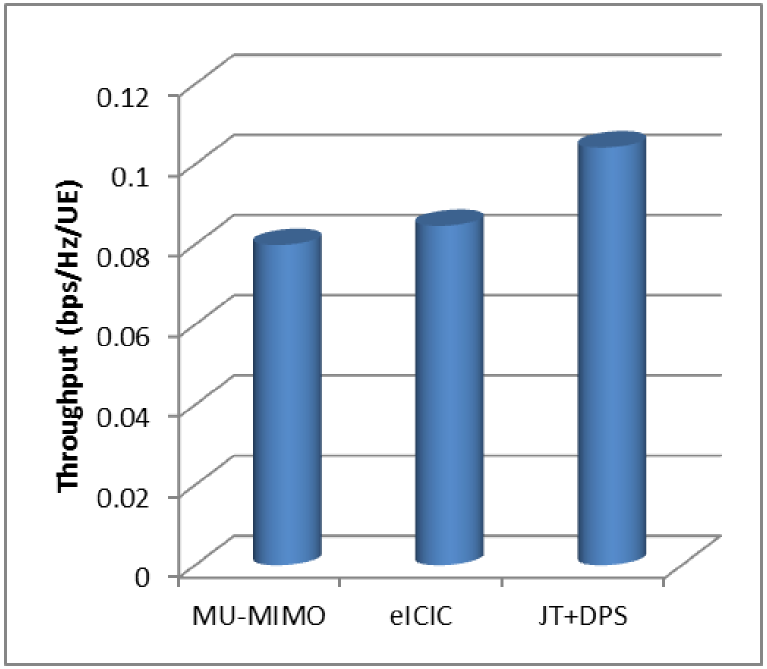
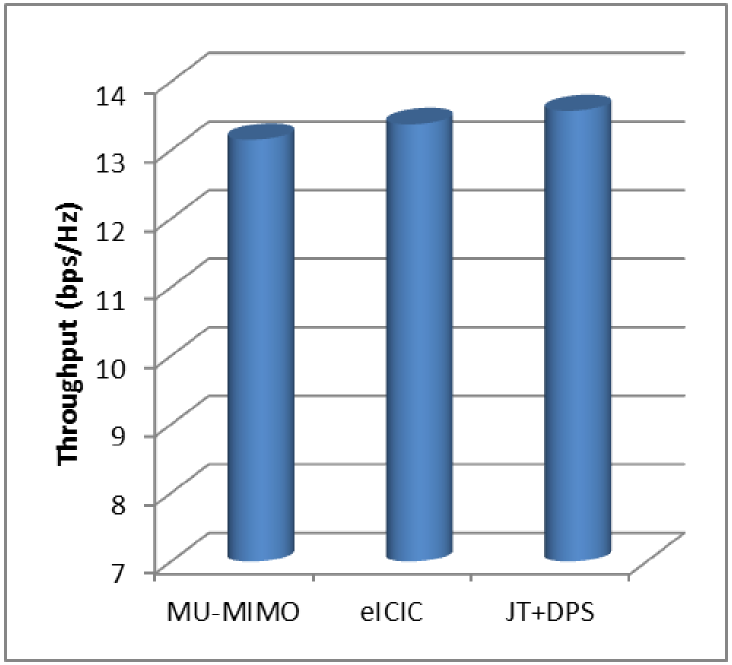


Cell edge throughput



Cell average throughput

The JT CoMP scheme provides 30.46% and 6.01% throughput gain over single cell MU-MIMO for cell edge and cell average, respectively.

Source:R1-112039

Interference Measurement

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- Rel-8/10 CSI feedback: $y = hxRS + z + I$ (RS tones)
  - UE measures channel h_{est} from pilot signals (CRS/CSI-RS)
  - Subtracts $h_{est}x_{RS}$ from y to estimate $z + I$
- Not efficient method for interference estimation
  - Subtraction process may lead to errors
  - Interference in data REs is different from RS REs
    - Interference in RS REs is due to other RS REs (not data)
- Rel-11 CoMP has special REs for interference measurement
  - No simultaneous channel estimation: $y = z + I$
  - I is chosen by BS to reflect actual interfering data transmission
  - Called interference measurement resource (IMR)

CSI Estimation Example

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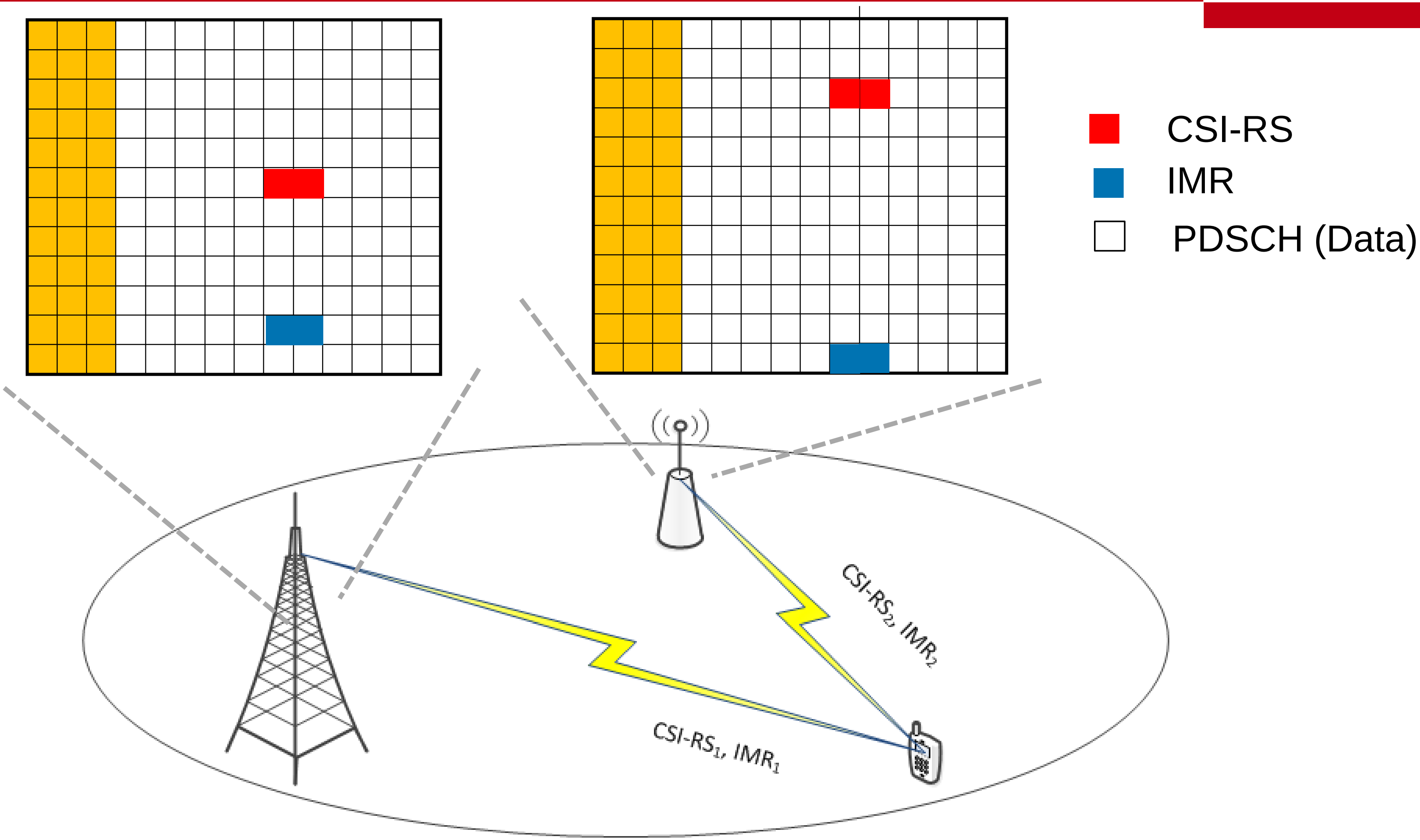

❑ To enable CoMP a UE has to estimate CSI of multiple eNodeBs

CSI Feedback

- A base station configures a UE with different *CSI processes*
  - A CSI process = {configured CSI-RS, configured IMR}
    - Analogous to CSI feedback for Rel 8 -10
  - UE feeds back CSI for each process over time
    - Periodic for periodic processes, based on BS triggering for aperiodic
  - E.g. UE configured with 4 CSI processes for macro+pico case

CSI Process Index	CoMP Sceheme	Nodes transmitting CSI-RS in CSI-RS REs	Nodes transmitting PDSCH in IMR
1	DPS (macro)	Macro	Pico
2	DPS (pico)	Pico	Macro
3	DPS (pico) + macro blanking	Pico	-
4	JT	Macro and Pico	-

Practical Issues about CSI Feedback

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- Inheritance and Reference Processes
  - Multiple processes may have same CSI-RS or IMR
    - Process 2 and 3 have same channel measurement (CSI-RS)
    - Process 3 and 4 have same interference measurement (IMR)
  - To reduce overhead multiple processes can share feedback info
    - UE feeds back channel info in process 2 and not in process 3
    - Channel info in process 3 is inherited from process 2
    - Process 2 is the PMI reference process for process 3
  - Rank, CQI of a process can be inherited from other processes
- Increases base station complexity
  - Determining transmit precoder, MCS from various CSI feedback

Summary

- Case Study I: ABS for outdoor macro-pico deployment
  - 6 dB bias values optimal for cell average and edge throughput
  - CRE (where UE switches from macro to pico) is a logical operation
    - First UE detects pico and then macro does handover
    - Network assistance may be needed for high bias
- Case Study II: Power control for indoor femto, outdoor macro deployment
  - The power control schemes provide good balance on outage of macro and femto UEs.
  - Power control methods increase cell average but reduce cell edge throughput
  - EPC maintains CSG functionality of femto cells
- Case Study III: CoMP for HetNet
  - The CoMP schemes provide considerable throughput gain on cell edge
  - Interference management and CSI feedback are key issues for CoMP implementation

Conclusion

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- Heterogeneous networks are the future of cellular systems
  - Promise large network capacity and coverage
  - Actively being deployed worldwide
- Interference management is a major challenge
  - Physical layer signal processing and scheduling
  - Time, frequency and space domain solutions needed
  - Algorithms with high performance at reduced complexity
- Lot of research and development accomplished
  - Academic works in network capacity, 3GPP standardizations

Future Directions

- Ample scope of future work
  - Heterogeneous networks information theory
    - Results from interference channel?
  - 3GPP Rel-12 small cell deployment
    - Interference avoidance and coordination
    - Small cell discovery and mobility management
    - Control plane and user plane separation
    - Dynamic TDD
- HetNet R&D will continue to be important in years to come !