Interference Management in femto-overlaid LTE-A networks

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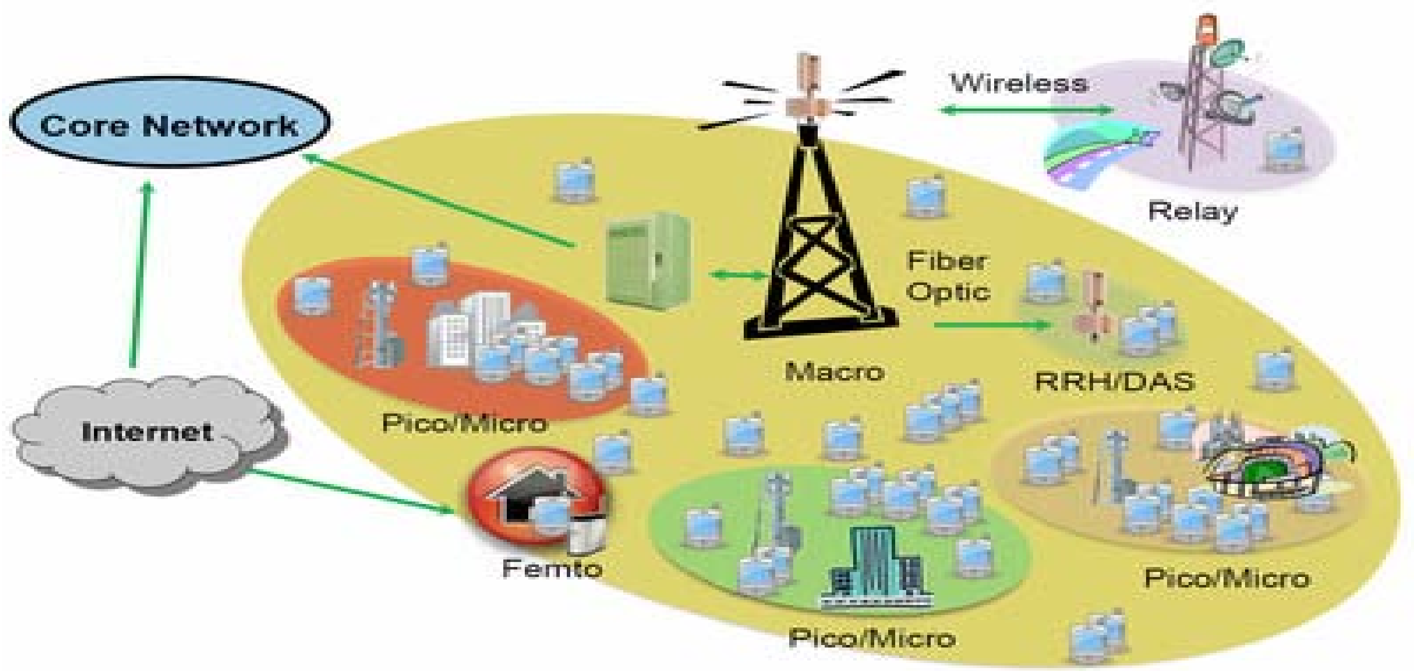
Femto-overlaid cellular networks

Current cellular networks

- **Macrocells**
  - They cover a large cell area providing services to operator's subscribers.
- **Picocells/microcells**
  - Picocells include all the macrocell's functionality but covers smaller areas e.g. malls. They are also deployed by the operator providing services to all the operator's subscribers located inside its range.
- **Relay nodes**
  - They are practically picocells with a wireless backhaul connection.
  - A relay node is used commonly to improve coverage under unplanned scenarios e.g. an exhibition. There are in-band relays that use the same spectrum band for their backhaul link and the access links and out-band relays that use different spectrum over backhaul and access link.
- **Distributed antennas (DA) - Remote radio headers (RRH)**
  - They are practically antennas with the minimum functionality needed to pass the traffic to the macrocell BS. Commonly, a fiber backhaul connection is used.

Current cellular networks

- **FEMTOCELLS**
  - Small, low-power cellular base stations, typically designed for use in a home or small business, deployed by the end-consumers
  - They connect to the service provider's network via broadband (such as DSL or cable)



Current cellular networks + femtocells

Why we need femtocells?

- **Spectrum is expensive and in scarcity, while the traffic increases rapidly**. Thus, more efficient spectrum utilization schemes are needed

Martin Cooper's law:

"The wireless capacity doubles every 30 months"

- This enormous gain comes mainly from smaller cell sizes arise from efficient spatial reuse of spectrum or, alternatively, higher area spectral efficiency

Thus, the <u>spatial</u> spectrum reuse seems to be the dominant technique for more efficient spectrum utilization

Current cellular networks + femtocells

Why we need femtocells? (continue..)

- In the near future the most of the data traffic, will originate from indoor users

Thus, an efficient way to handle the indoor traffic is required

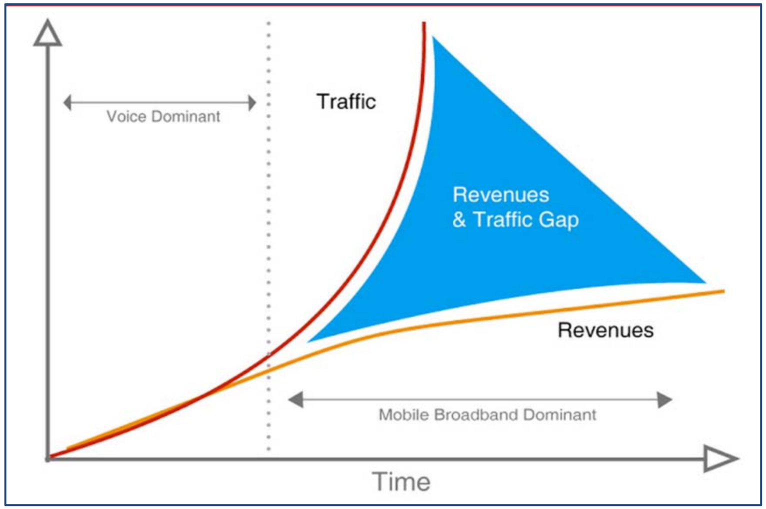
- **How about WiFi?**
  - Exploits the ever more crowded unlicensed spectrum
  - Coordination is more easy in femtocells
  - Theoretically, femtocells provide more efficient setup, mobility, QoS
  - > need for interoperability
- **New Femtozone Applications**

Current cellular networks + femtocells

Why we need femtocells? (more..!)

- **Observations of the last 5 years show that**
  - 25X increase in traffic
  - and 2X increase in revenues (!)
- **Choices for the operators**
  - Strictly meter or restrict data usage,
  - charge in proportion to bits consumed

--> Decrease Euros/bit (exponentially)



Femtocells capital expenditure and operational expenditure are low

End-users purchase the femtocell access points

Traffic goes through the internet

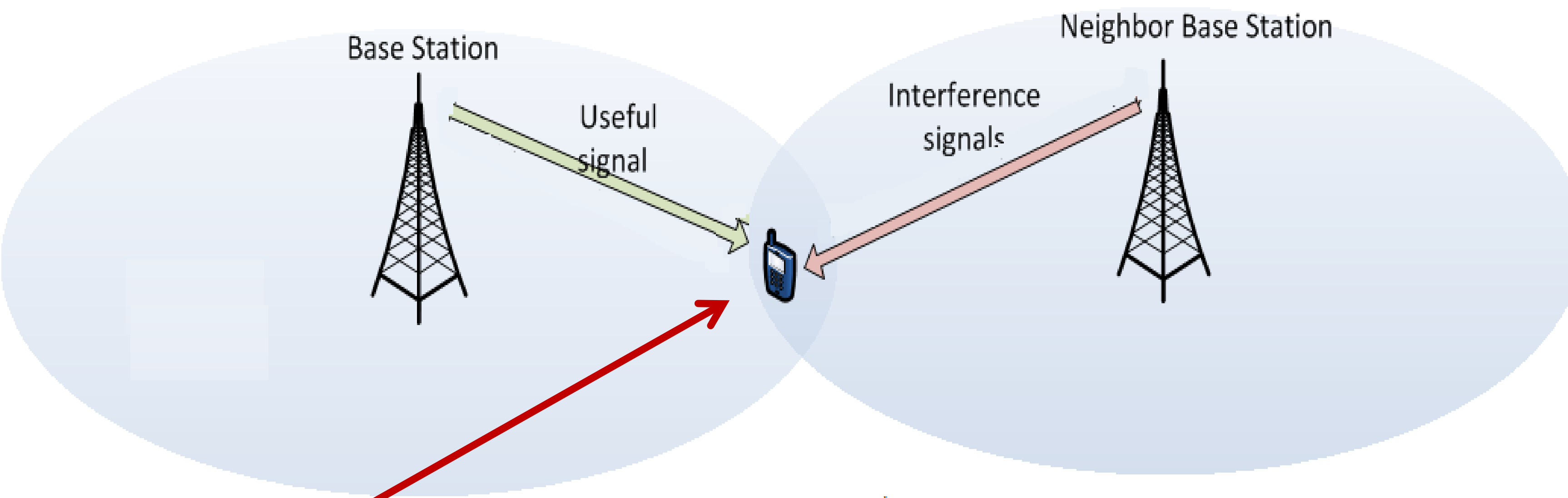
Femtocells in Market

- Vodafone Full Σήμα / sure Σημα
- Cosmote Τέλειο σήμα

Interference problem

Interference problem
Traditional cellular networks

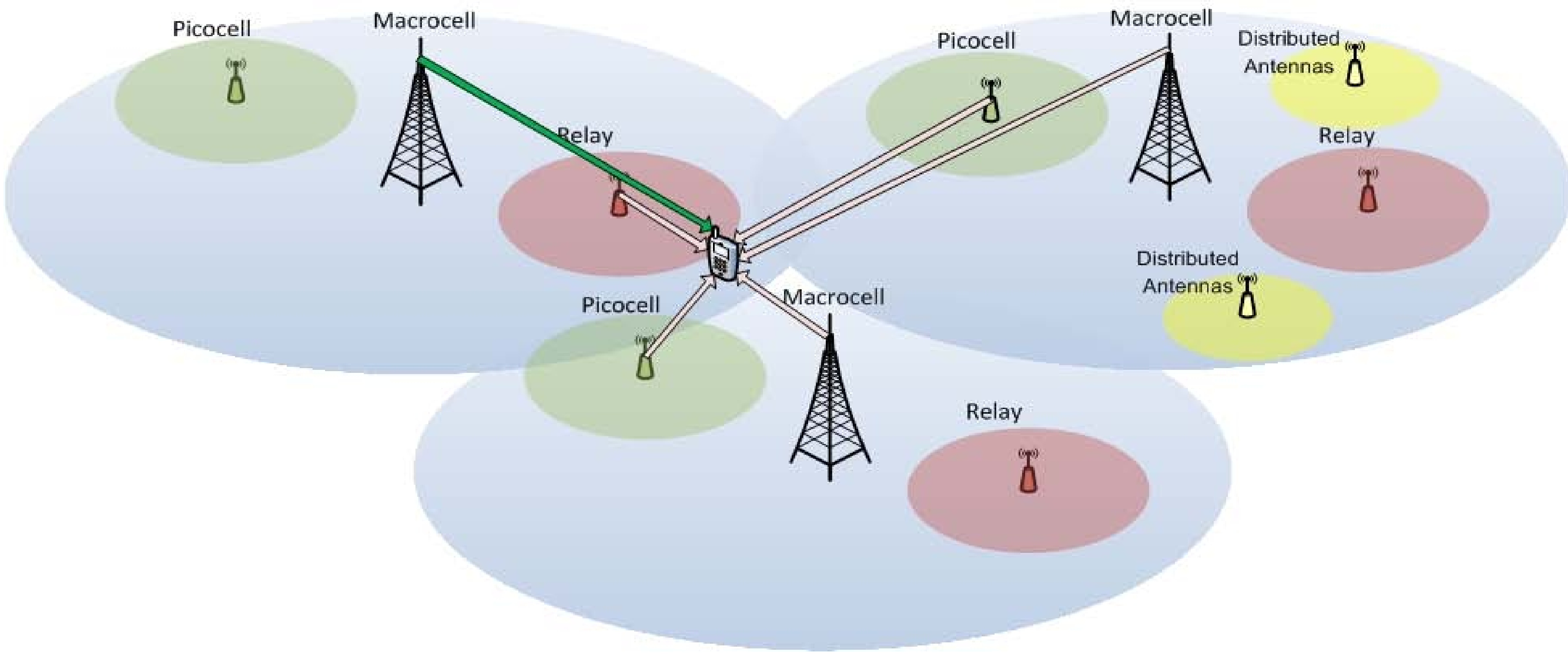
Interference at the receiver -> affects the SINR



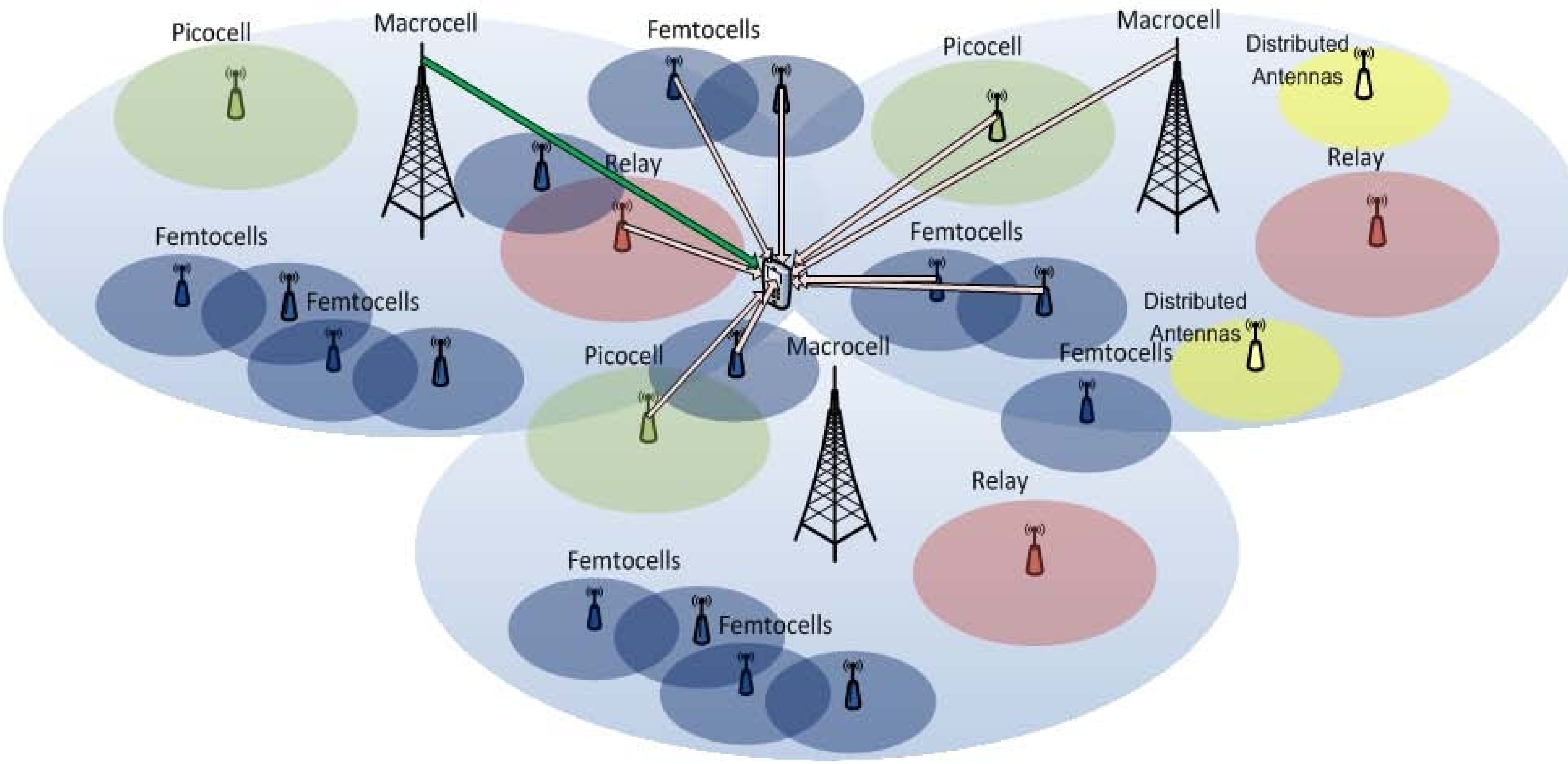
$$\text{SINR} = \frac{\textit{Received power (useful signal)}}{\textit{Received power (intrerference signals)} + \textit{Noise power}}$$

Interference problem
Current cellular networks

Multiple Transmitters -> higher Interference
More dense network -> higher Interference



Interference problem
Current cellular networks + femtocells



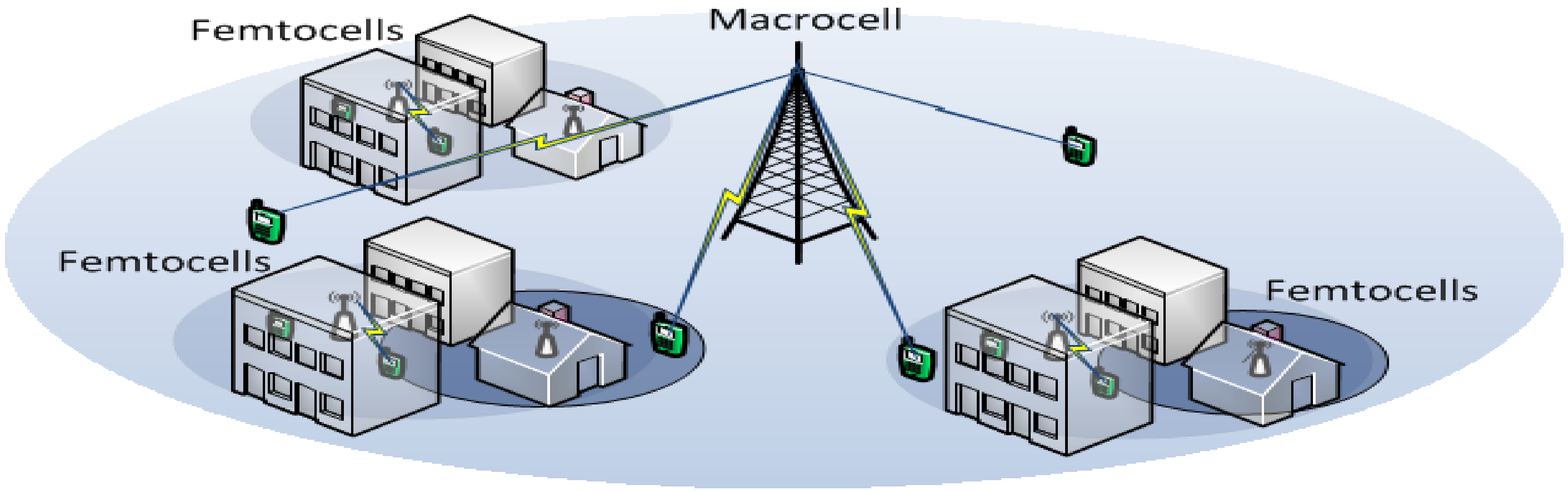
Interference problem
The role of deployment

Interference in Femto-overlaid networks

- A highly dense network is created
- Femtocells are deployed by the end-consumers i.e., in a random/unplanned deployment manner
- A heterogeneous network is created (two-tier network)- Femtocells are expected to spatially reuse licensed spectrum defining the co-channel deployment
- They can provide the option to serve only a limited set of subscribed users through the closed subscriber group (CSG) mode (no handover option for non-subscribed users)

Interference Problem

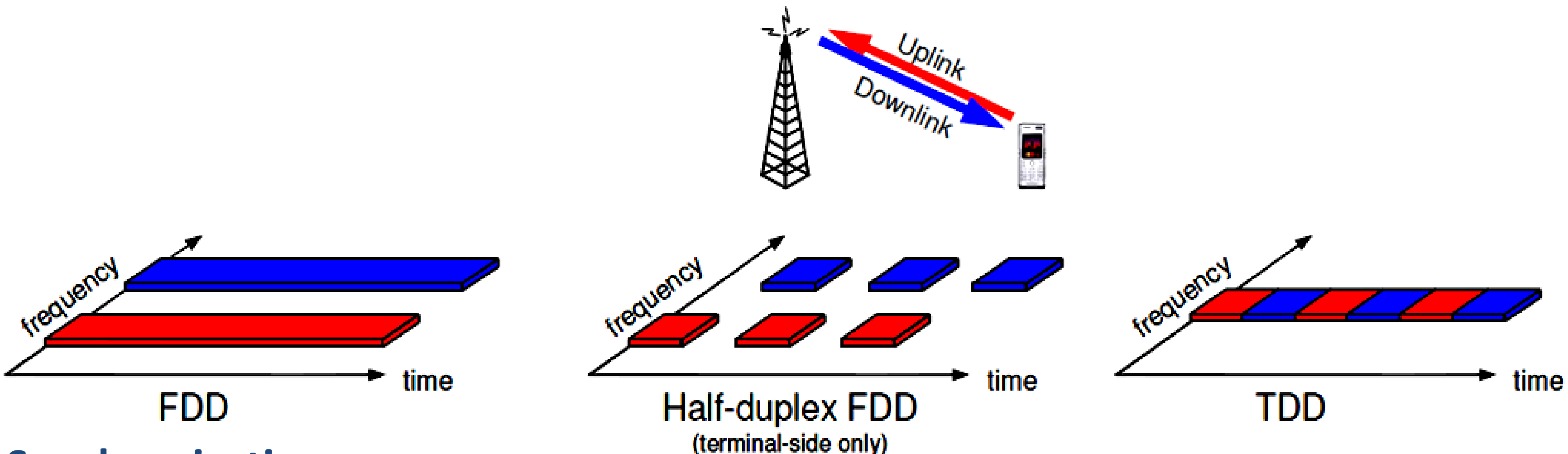
The role of deployment



Index	Aggressor	Victim	UL/DL	Cross/Co-tier
1	Macro User	Femto BS	UL	Cross-tier
2	Macro BS	Femto User	DL	Cross-tier
3	Femto User	Macro BS	UL	Cross-tier
4	Femto BS	Macro User	DL	Cross-tier
5	Femto User	Femto BS	UL	Co-tier
6	Femto BS	Femto User	DL	Co-tier

Interference problem

The role of synchronization and duplex type



Synchronization

- If femtocells and macrocells are synchronized the interference problem is more manageable. However, **synchronization is an open issue since femtocells backhauls data through a broadband gateway**.

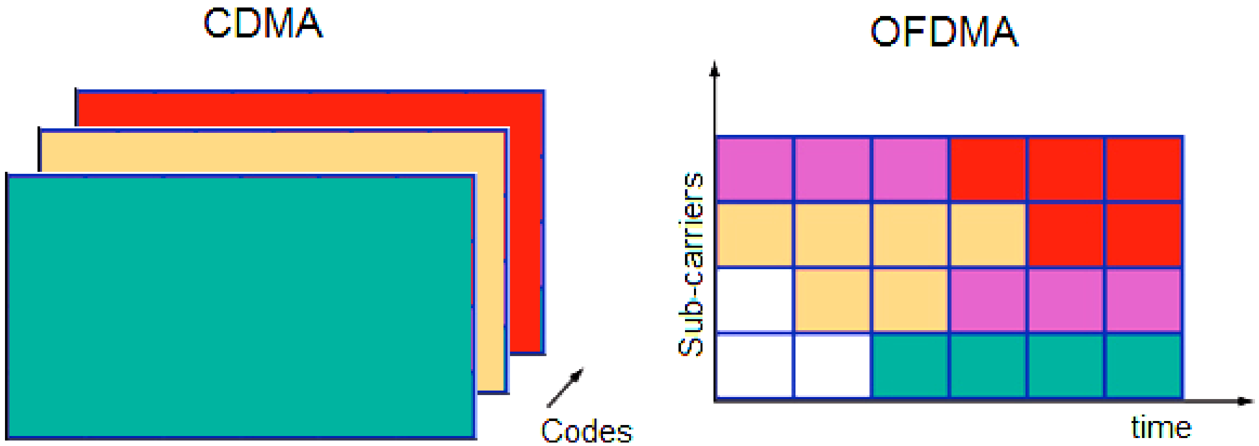
Duplex type

- In TDD mode different UL/DL configurations are available. Theoretically, each femtocell and macrocell can select a different one exacerbating the Interference problem.

Interference problem

The role of the PHY

(Multiplexing – Multiple Access)



The interference is strongly correlated with the adopted PHY

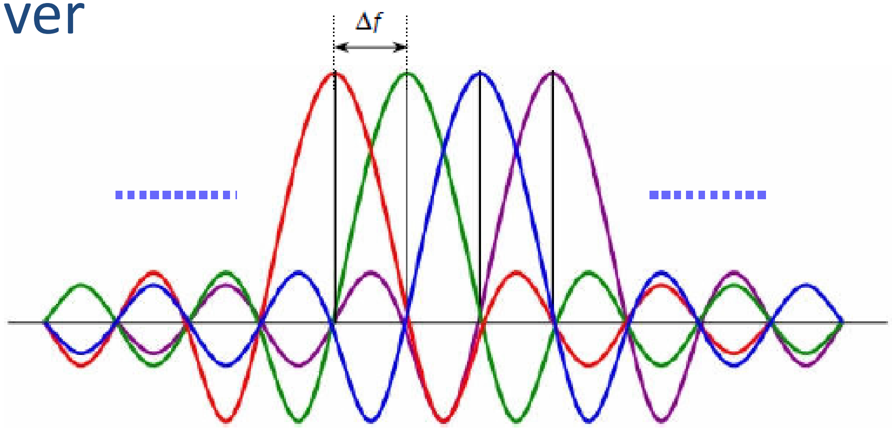
- CDMA - Orthogonal Codes
  + average freq. distortion
  - difficult MIMO, equalization
- **OFDMA - Frequency and time regions** (based on OFDM)
  +easy MIMO, dynamic allocation, Flexible resource allocation
  - Inter-carrier interference

Interference problem
The role of the PHY

Co-channel interference and Adjacent channel interference

Adjacent channel interference in OFDM

- Out of Band/Spurious emissions
- Adjacent Channel Leakage
- Non-perfect filter at the receiver



Interference problem

Summary

The role of network deployment

-> Femtocell characteristics – multiple/unplanned interference

The role of Synchronization

-> UL/DL configuration – inter-slot Interference

The role of PHY layer

-> OFDMA in LTE-A – frequency selective Interference

-> adjacent channel interference

Interference Management

Interference Management

1. Interference Detection
2. Interference Coordination
3. Interference Avoidance
4. Interference Mitigation
5. Interference Cancelation
6. Interference Exploitation (!)

Interference Management

Interference detection

Directly (Measurements)

A base station or a user can measure the surrounding environment and estimate the level of perceived interference

- A deteriorated useful signal is an evidence

Indirectly (Messages)

- A Base station can use neighbor information or specific messages reported by users or other Base stations

e.g. An attempt for handover from a victim user

➢ **Challenges**

- How frequent measurements and in which spectrum portions
- Reliability in indirect detection – false detection
- Reduce signaling

Interference Management

Interference Coordination

Use of Interference Indicators

exchanging of interference messages

- **Proactive interference coordination**
  messages that inform neighbor base stations for the near future resource and power allocations
- **Reactive interference coordination**
  messages are exchanged if interference (via measurements) or an interfered node are detected

➢ **Challenges**

- How to mitigate signaling
- Signaling reliability – over the air ? Fiber?

Interference Management

Interference Avoidance

Static or dynamic split of the spectrum

- **Static**: predefined different spectrum portions are allocated to macros and femtos
  - \+ Interference avoidance
  - – Inefficient – scarce spectrum resources
    - Hardly applicable for avoiding interference between femtos
- **Dynamic:** different spectrum portions are dynamically allocated to macros and femtos
  - \+ Reactive Interference avoidance / better spectrum utilization
  - – complex solution
  - – Hardly applicable in dense femto-overlaid networks

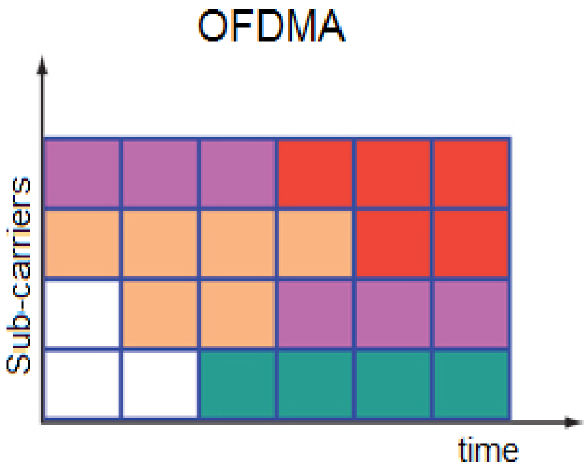
Interference Management

Interference Avoidance

Dynamic Resource Allocation (RA)

Applicable to OFDMA systems

- Femto and Macro base stations allocate appropriately the resources to users towards avoiding interference
  - \+ Dynamic, can be reactive and proactive
  - – Coordination or measurements are needed
  - – Difficult to applied for cross-tier interference avoidance



Dynamic (RA) + spectrum split

Interference Management

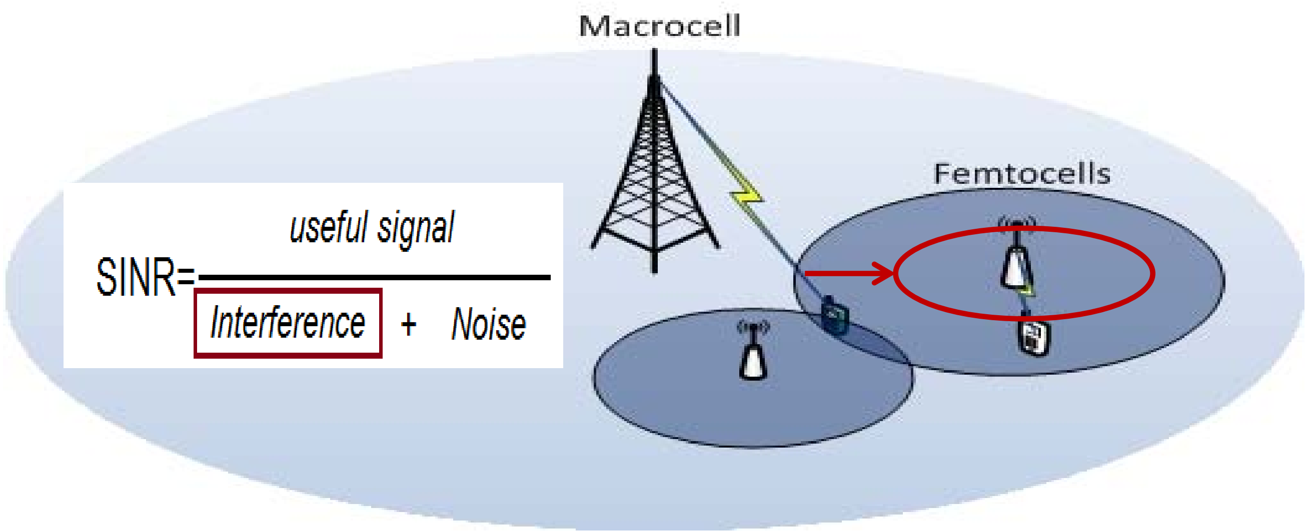
Interference Mitigation

Power Control (PC)

Reduce the transmit power of the interference aggressor

➢ **Challenges**

- avoid false alarm for interference protection
- Protection of the serving users is needed



Interference Management

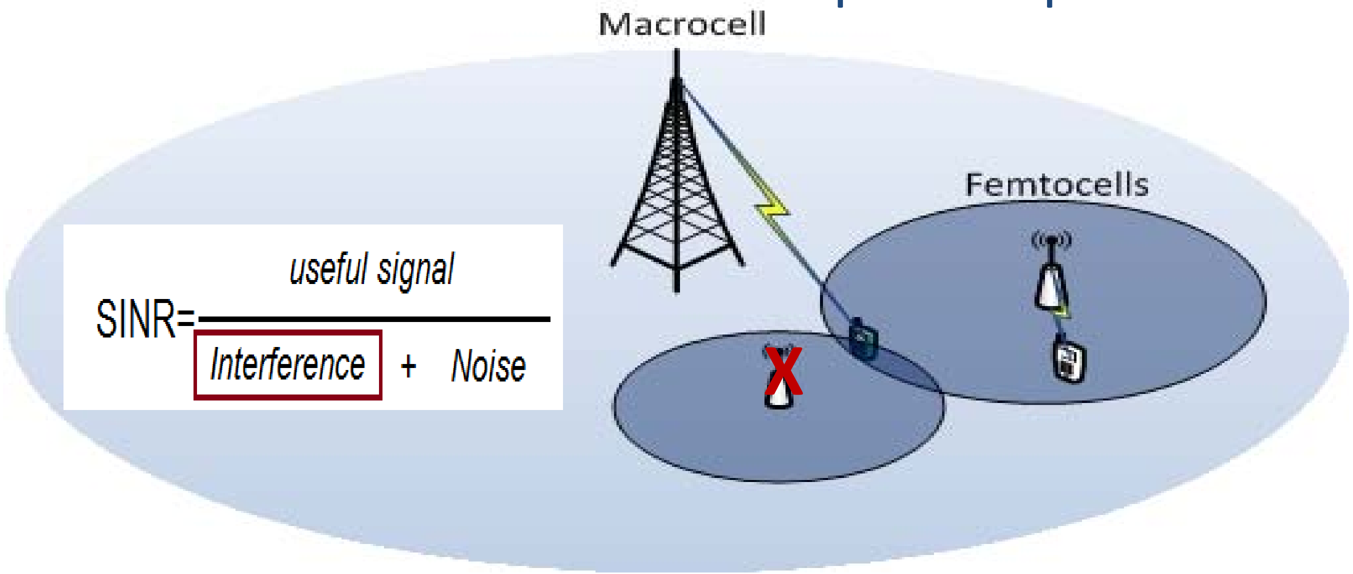
Interference Mitigation

<u>Discontinuous Transmissions</u>

Switch off dynamically some of the HeNBs

➢ **Challenges**

- Use of interference detection/ coordination/ measurement
- Silence and transmit duration are important parameters



Interference Management

Interference Cancelation

Interference is cancelled after the signal is received
(signal processing approach)

➢ **Challenges**

- Reduce the cost
- knowledge of the characteristics of the interfering signal

Interference cancelation in OFDMA

- **Successive interference cancellation (SIC)**

  - Detects one user per stage. The strongest received signal is detected first, then the next strongest…

  - Complex if there are many users

Interference Management

Interference Cancelation

- **Parallel interference cancellation (PIC)**

  - detects all users simultaneously

  - detection is repeated and this process is repeated over several stages

- **Multistage SIC**

  - A group of users are detected in parallel, and then their aggregate interference is subtracted from the composite received signal.

Interference Management

Interference Exploitation

Use Multiple Antennas to take advantage of self-interference

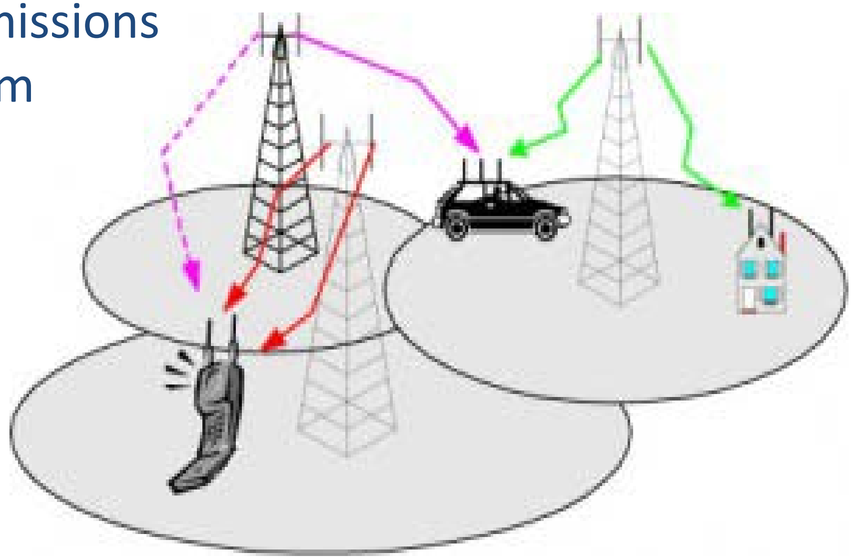
single user MIMO

A good solution for self-interference exploitation

Self –interference = interference through the multipath effect

multi user MIMO

Useful for broadcasting - Multicast transmissions to different users using the same spectrum



Interference Management

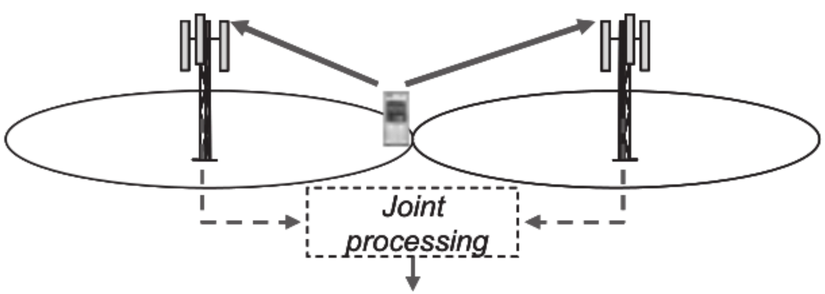
Interference Exploitation

multi cell MIMO – CoMP

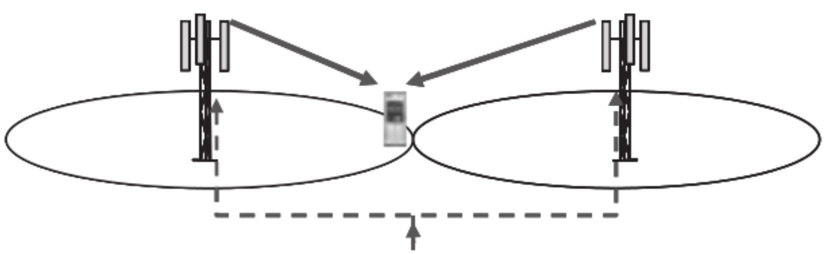
Use Multiple Antennas to Improve resistance to interference

- A good solution for the scenario of distributed antennas
- Launches the Idea of Coordination Multipoint (CoMP) transmission and reception

Joint receiver processing



Joint transmission



➢ **Challenges**

- Fast connections required– practically applicable only for DA

Interference Management issues

Summary

1. **Interference Detection**
   -> use measurements / available info to identify the problem
2. **Interference Coordination**
   -> set a signaling protocol to coordinate BS for IM
3. **Interference Avoidance**
   -> Avoid the problem by using different spectrum (static/dynamic)
4. **Interference Mitigation**
   -> reduce the interference signals due PC
5. **Interference Cancelation**
   -> PHY layer technique – subtract the interference after signal reception
6. **Interference Exploitation (!)**
   -> MIMO approaches – CoMP

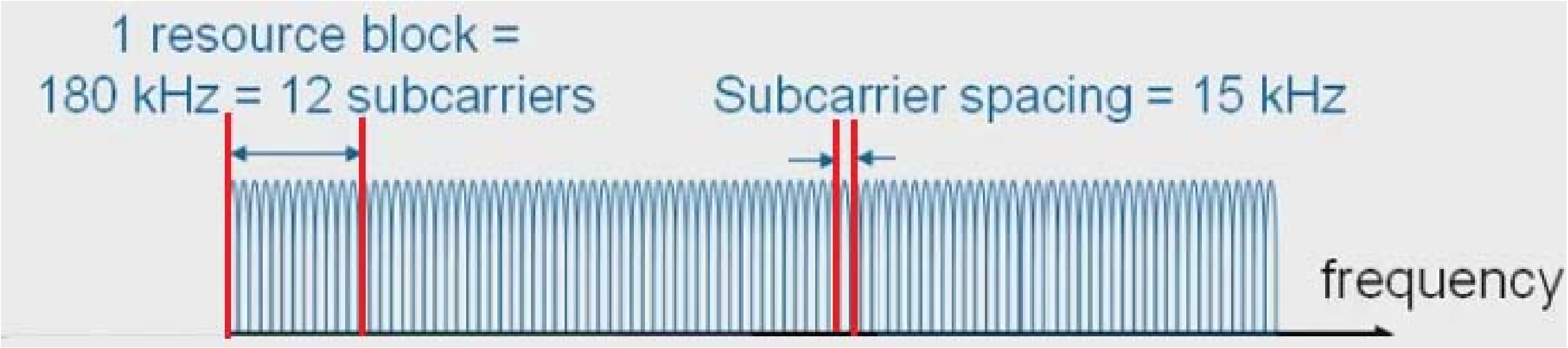
LTE-A tools for Interference Management

LTE-A PHY

LTE-A IM tools

LTE-A PHY

Frequency domain structure



LTE-A PHY

Frequency domain structure

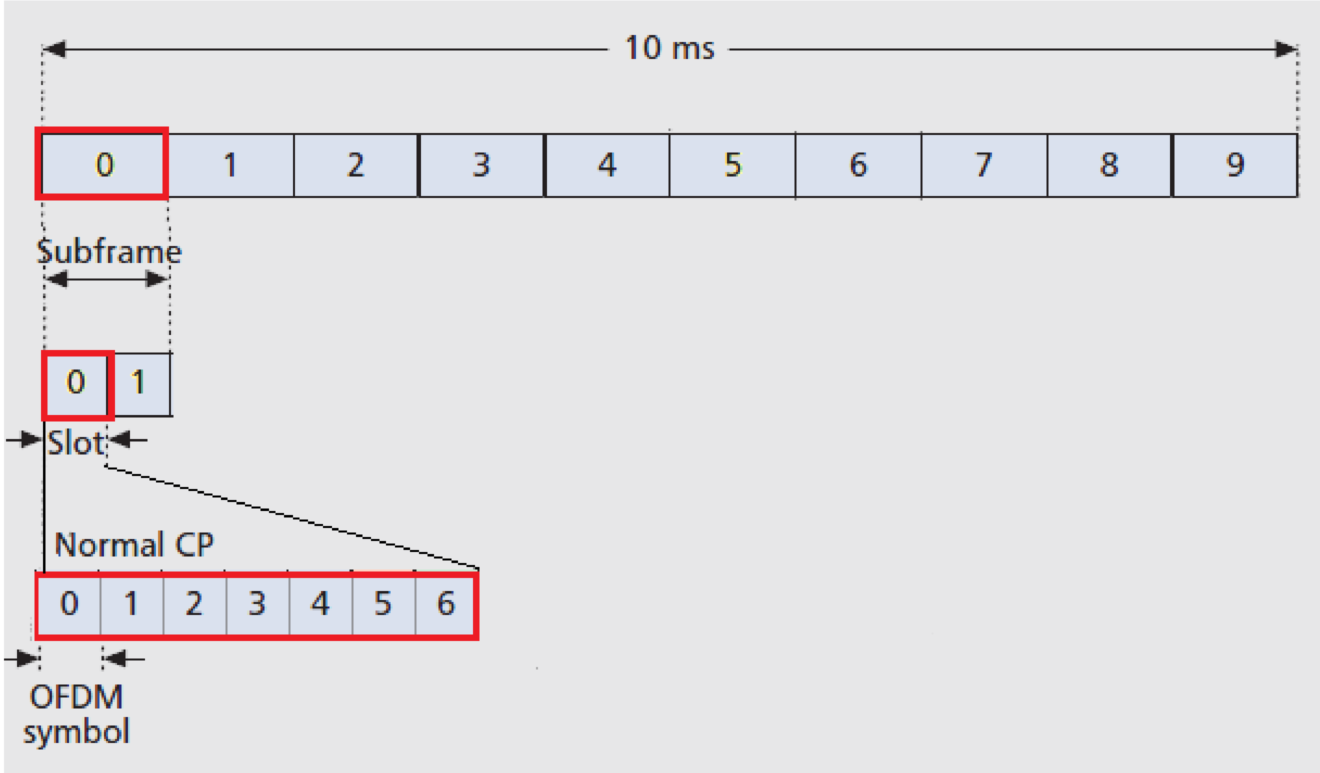
- There are 6 different bandwidth sizes
- Each bandwidth is divided into subcarriers of 180 KHz each and
- 12 adjacent subcarriers compose a Resource Block (RB)

Channel bandwidth $BW_{Channel}$ [MHz]	1.4	3	5	10	15	20
Number of resource blocks	6	15	25	50	75	100

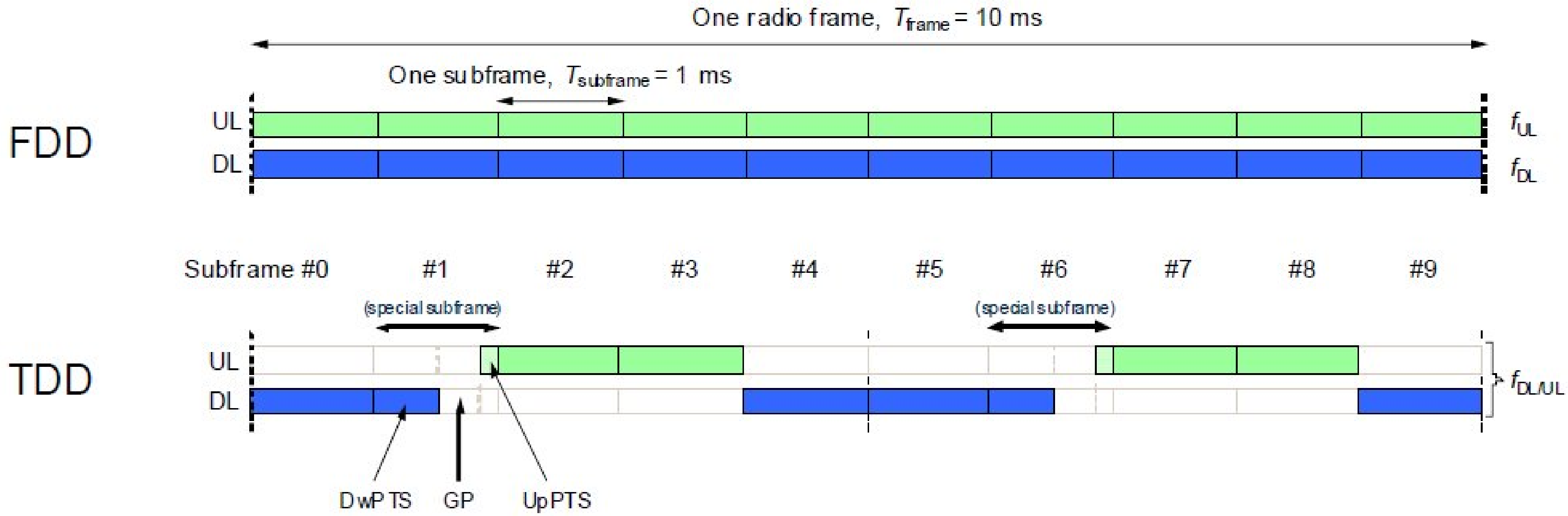
- Carrier Aggregation allows the expansion of the bandwidth to 100MHz

LTE-A PHY

Time domain structure



LTE-A PHY
Available duplex types



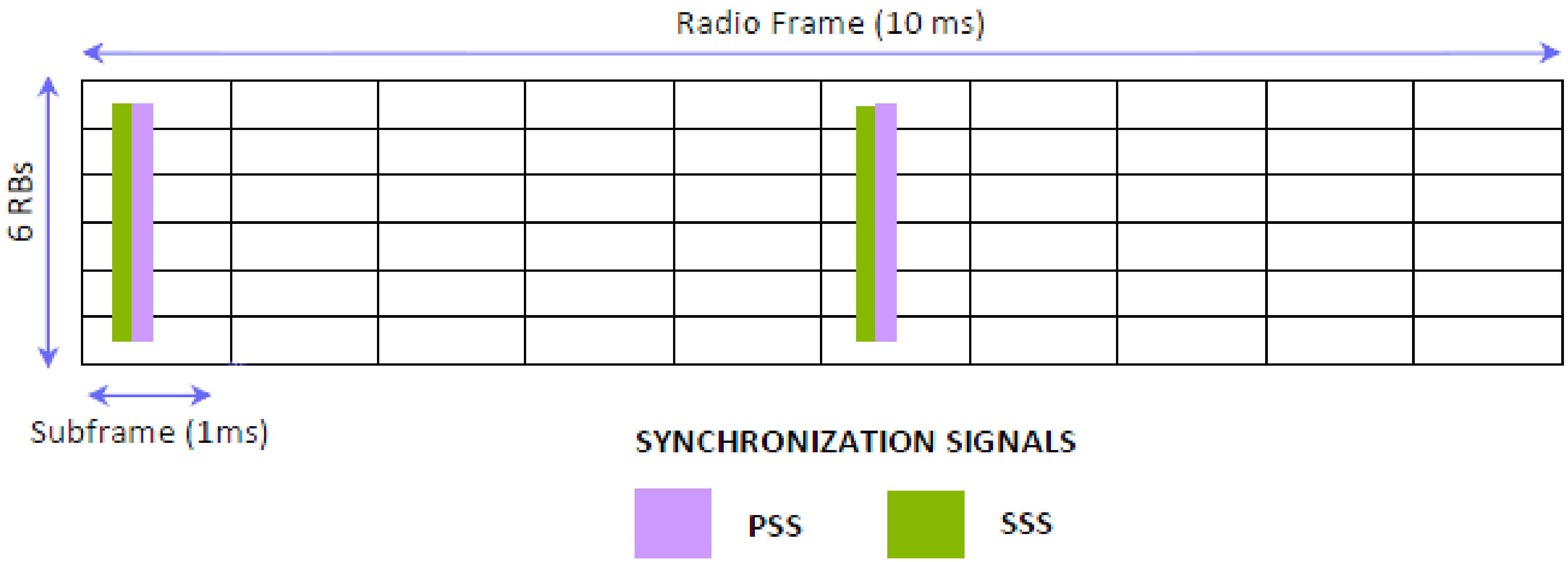
For TDD type LTE-A defines 7 different configurations for DL, UL and S subframes

		0	1	2	3	4	5	6	7	8	9
0	5 ms	D	S	U	U	U	D	S	U	U	U
1	5 ms	D	S	U	U	D	D	S	U	U	D
2	5 ms	D	S	U	D	D	D	S	U	D	D
3	10 ms	D	S	U	U	U	D	D	D	D	D
4	10 ms	D	S	U	U	D	D	D	D	D	D
5	10 ms	D	S	U	D	D	D	D	D	D	D
6	5 ms	D	S	U	U	U	D	S	U	U	D

LTE-A PHY

Time domain structure

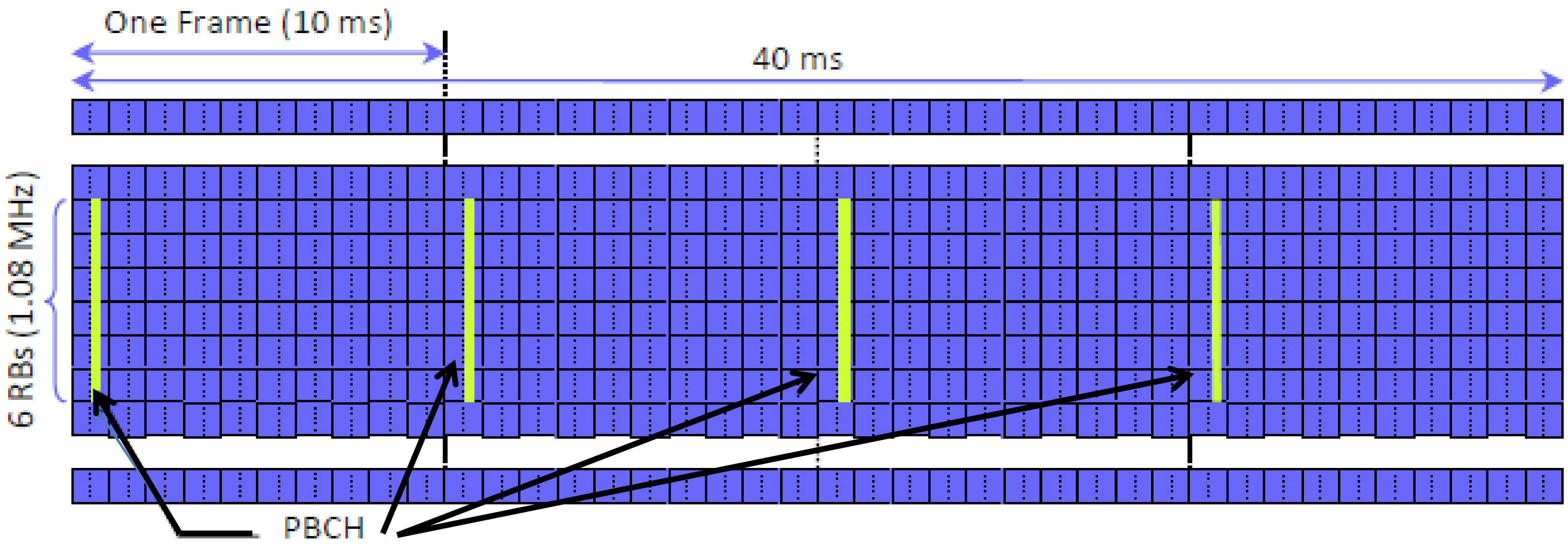
Primary Synchronization Sequence (PSS) and Secondary Synchronization Sequence (SSS). The detection of these signals allows the UE to complete time and frequency synchronization and to acquire useful system parameters such as cell identity, cyclic prefix length, and access mode (FDD/TDD).



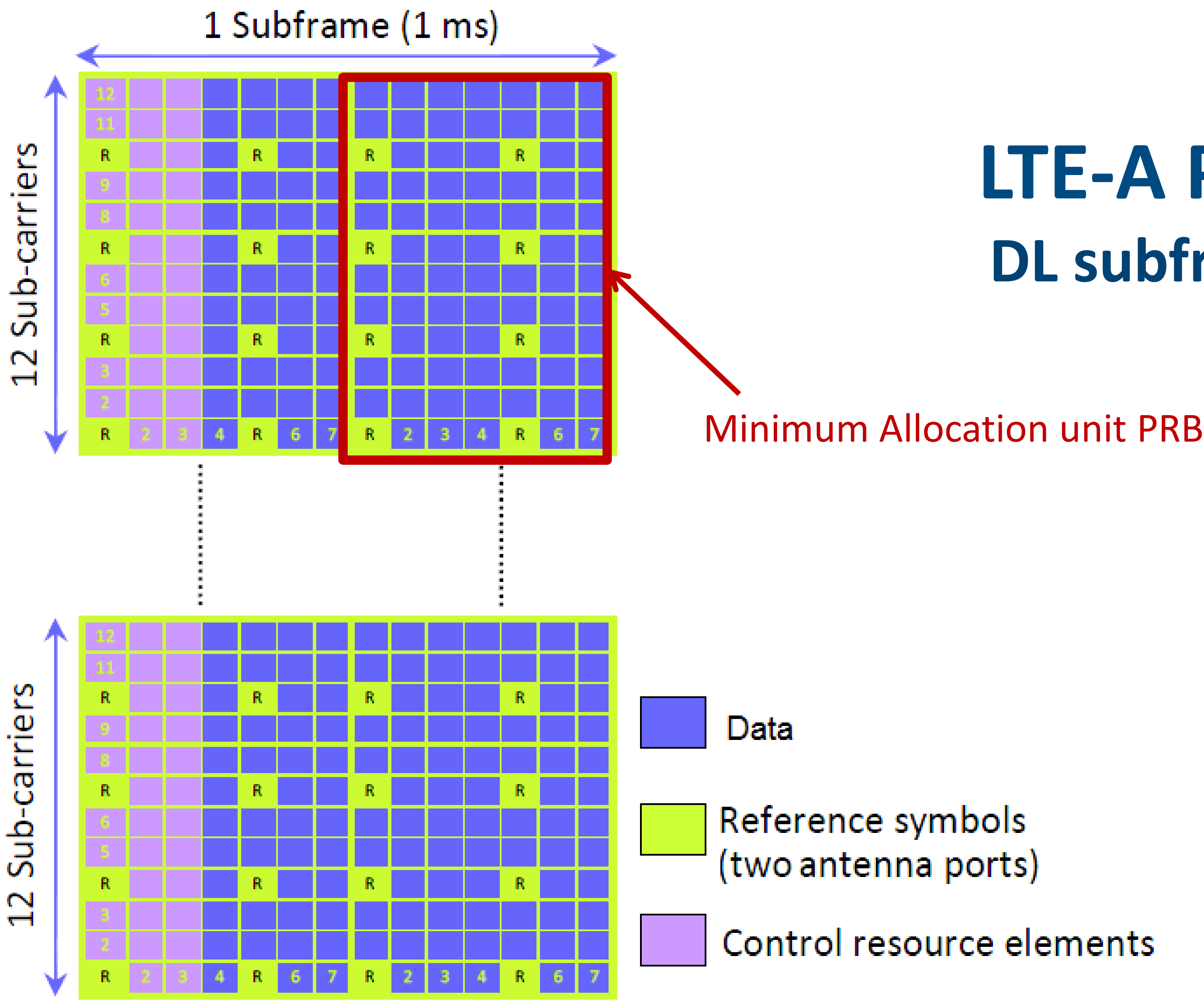
LTE-A PHY

Time domain structure

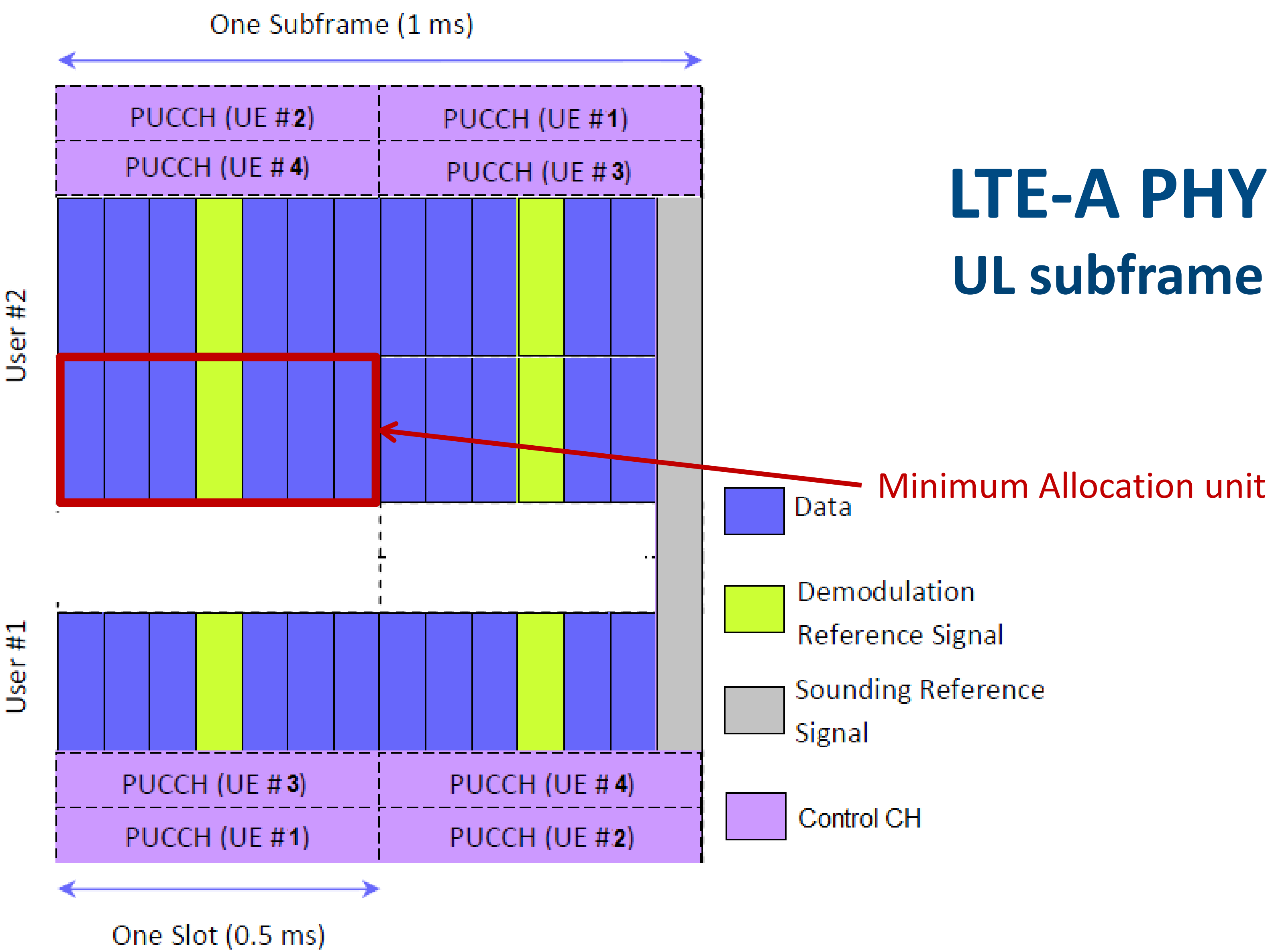
Physical Broadcast Channel (PBCH). The PBCH broadcasts a limited number of parameters essential for initial access of the cell such as downlink system bandwidth, the Physical Hybrid ARQ Indicator Channel structure, and the most significant eight-bits of the System Frame Number.



LTE-A PHY
DL subframe



LTE-A PHY
UL subframe



Interference Categories from the perspective of the LTE-A PHY

Data /Control / Reference / Synchronization / broadcast channels

- The content of control channels is very important, bad control signals can lead to link/access failure – in contrast, bad data signal can lead to lower signal quality
- No retransmission available in some Control Signals
- No flexibility in Resource allocation – specific spectrum regions are used for control signals
- Fixed location for the reference/synch/broadcast signals

LTE-A Interference Management tools

1. Measurements
2. X2 Interference indicators
3. Carrier Aggregation
4. Almost blank subframes

Measurements

Collected through:

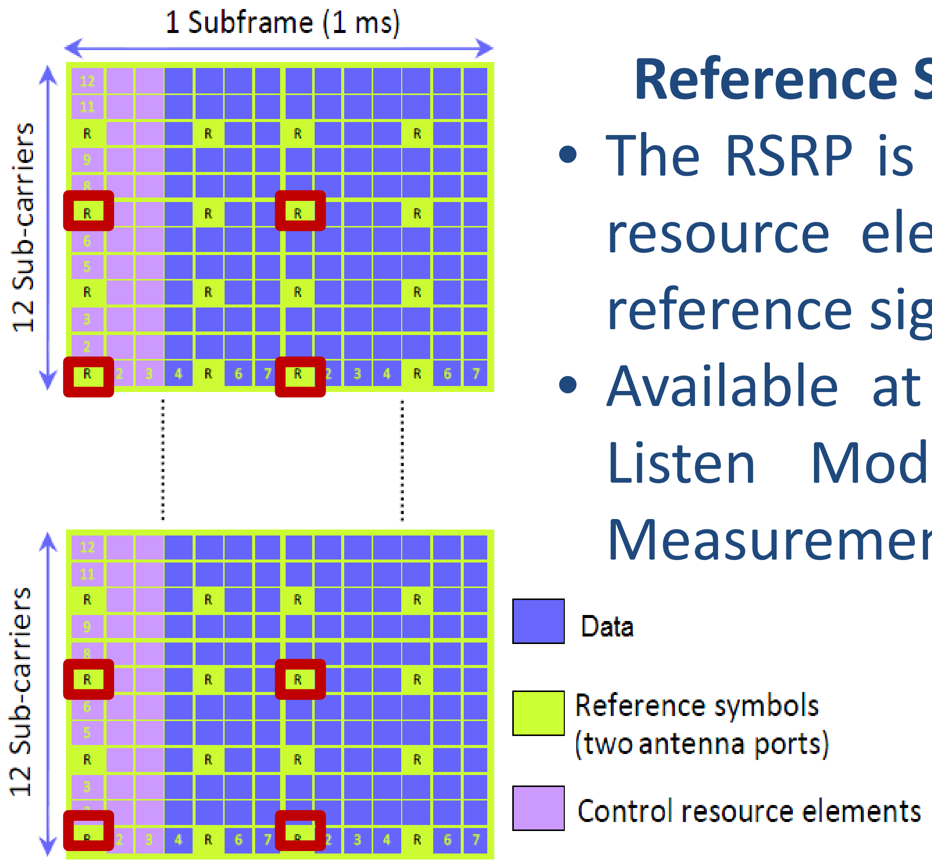
- Connected Mode UEs attached to (H)eNB
- UL Receiver function and DL Receiver function within (H)eNB – (Network Listen Mode (NLM), Radio Environment Measurement (REM) or "HeNB Sniffer“)

Some of the most useful measurement for IM are:

- Reference Signal Received power (RSRP)
- Reference Signal received Quality (RSRQ)
- Received Interference Power (RIP)
- Reference Signal Transmission Power
- Physical and Global Cell ID

Measurements and IM (example 1)

- Measurements can be used for **Power Control**



Reference Signal Received Power (RSRP)

- The RSRP is the average of the power of all resource elements which carry cell-specific reference signals over the entire bandwidth
- Available at the UEs and HeNBs (Network Listen Mode (NLM), Radio Environment Measurement (REM) or "HeNB Sniffer")

Measurements and IM (example 1)

- Measurements can be used for **Power Control**

Power Control at HeNBs

- refers to power assignment for DL transmissions
- This procedure is open to operators and different approaches can be used; However, one of the proposed by 3GPP approaches is:

$$P_{tx} = \text{median}\,(\boldsymbol{P}_{\mathbf{eNB-HeNB}} + PL_{HeNB-MUE}, P_{max}, P_{min})$$

Where

P_{tx} represent the transmit power of the eHeNB

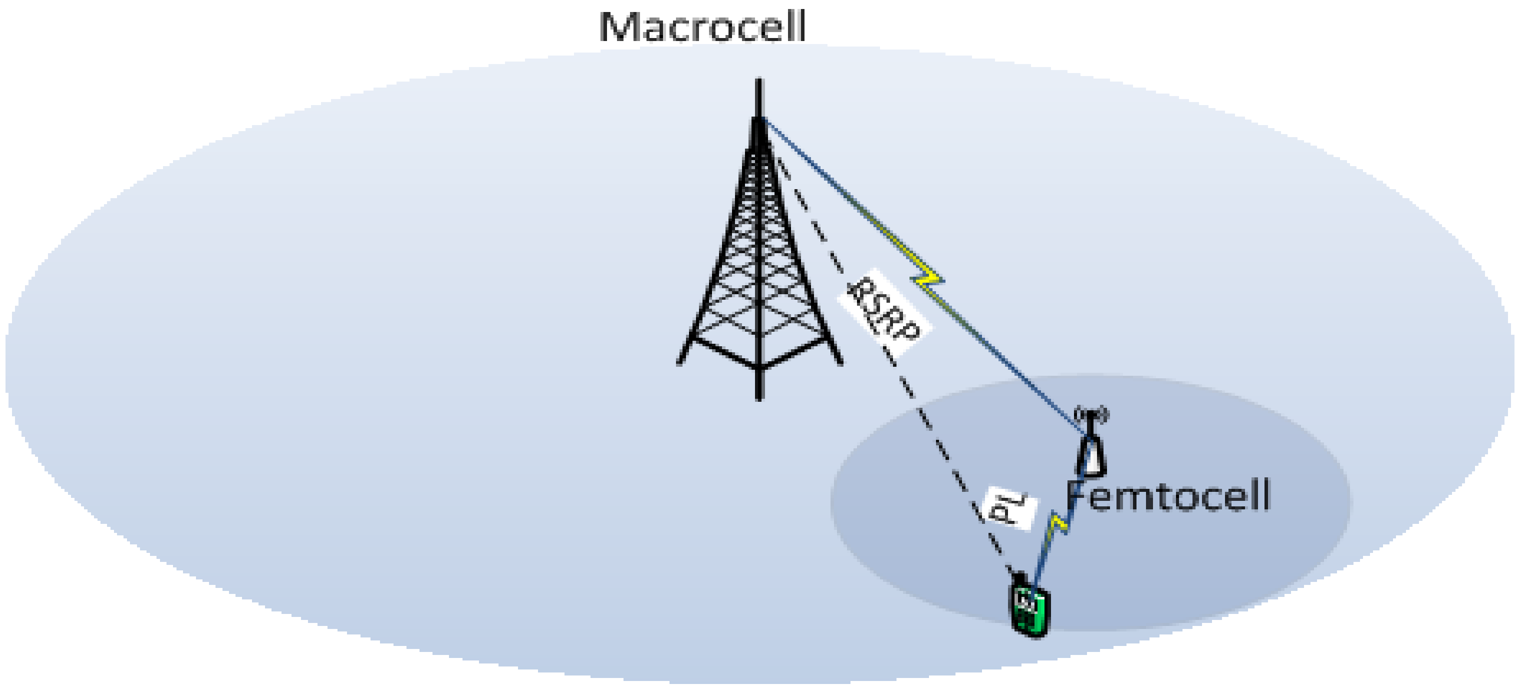
$P_{eNB-HeNB}$ the measured **RSRP** from the eNB

$PL_{HeNB-MUE}$ depicts the pathloss between the HeNB and victim MUE.

P_{max} and P_{min} parameters refer to predefined maximum and minimum transmit power settings, respectively.

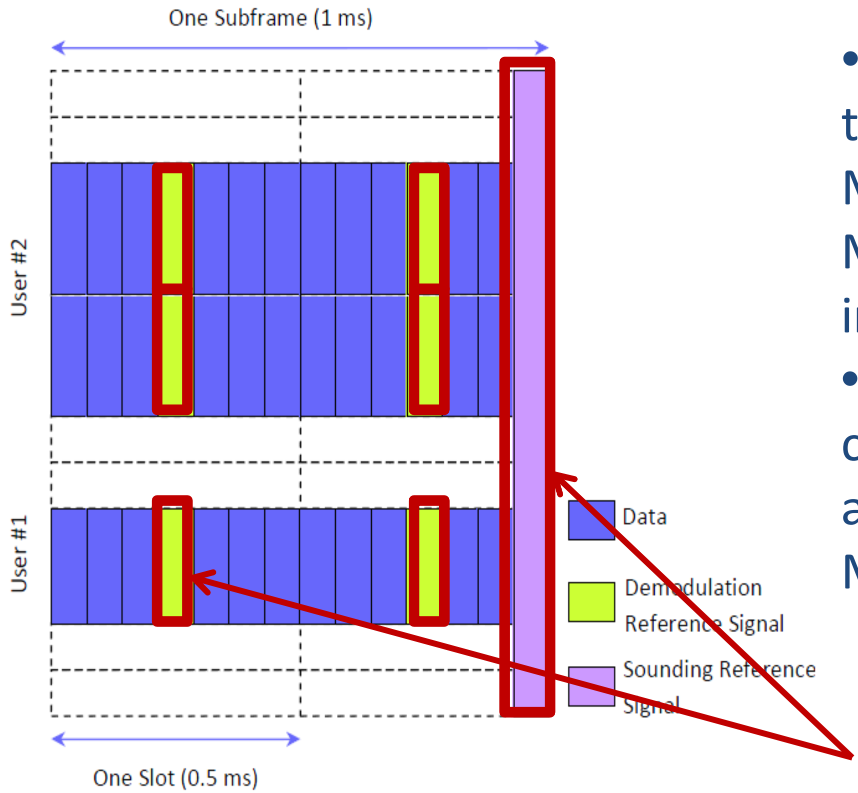
Measurements and IM (example 1)

- Measurements can be used for **Power Control**
- **Illustration of the 3GPP scheme**



Measurements and IM (example 2)

- Measurements can be used for **detecting a victim UEs**

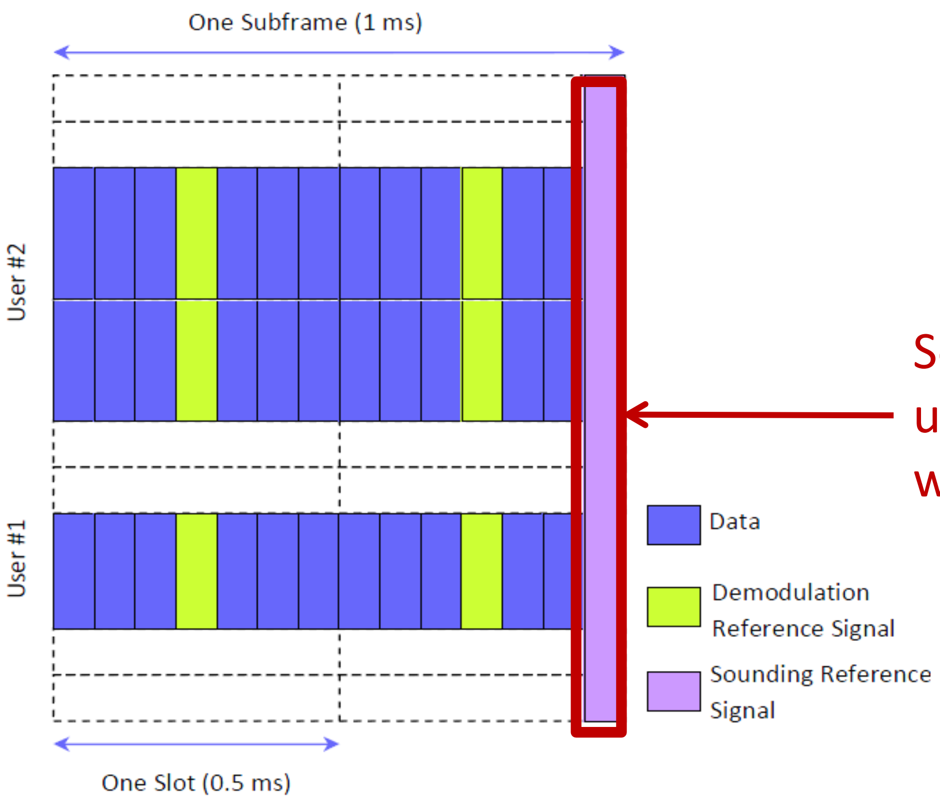


- **RIP** value larger than a pre-defined threshold would mean that at least an MUE is close to the HeNB and that the MUE's Tx power would cause interference towards the HeNB.
- This value may be used in calculating path loss between the HeNB and the MUE assuming that a single MUE dominates the interference.

the properties of the uplink reference signals can be used

Measurements and IM (example 3)

- Measurements can be used for **Interference-aware RA**

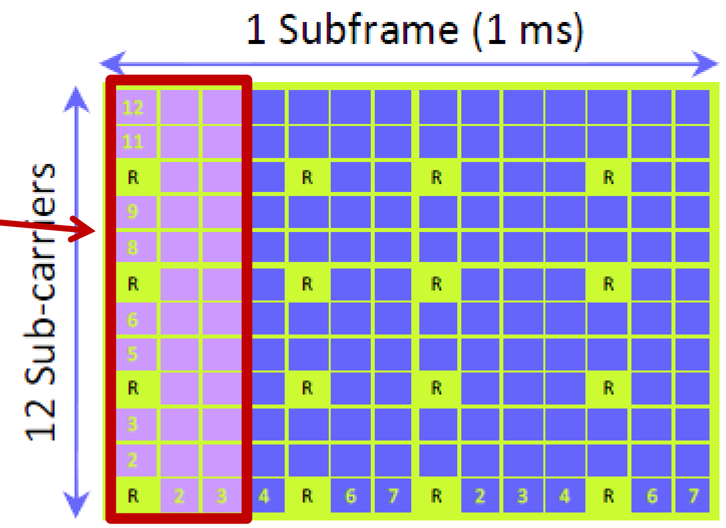


Sounding reference signals can be used for allocating UEs to resources with the lower interference

Measurements and IM (example 4)

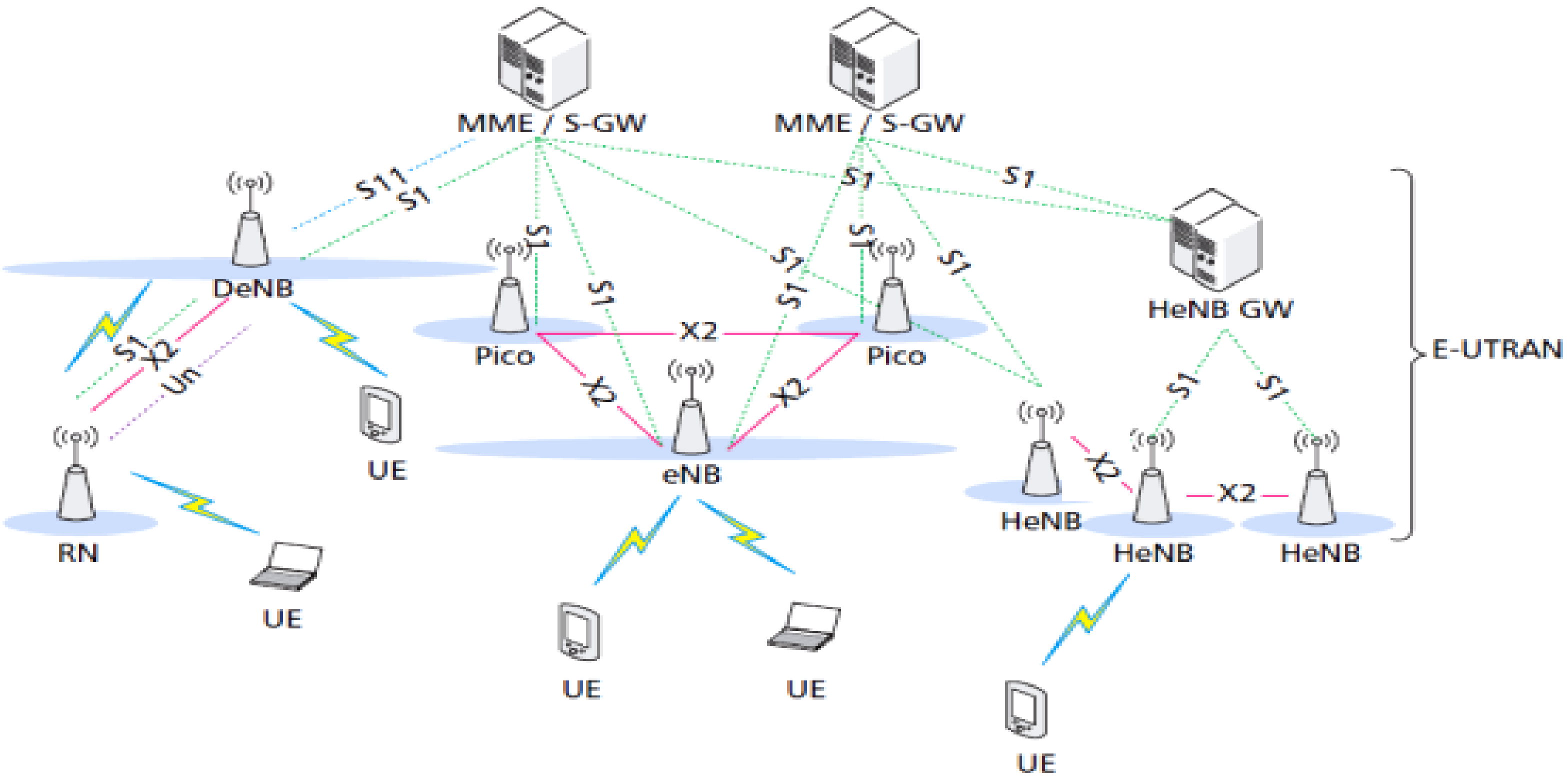
- Measurements can be used for **control channel protection** e.g. **Cell ID manipulation for control channel protection**

Specific location of Control channels based on cell ID value



X2 interference indicators

LTE-A Architecture



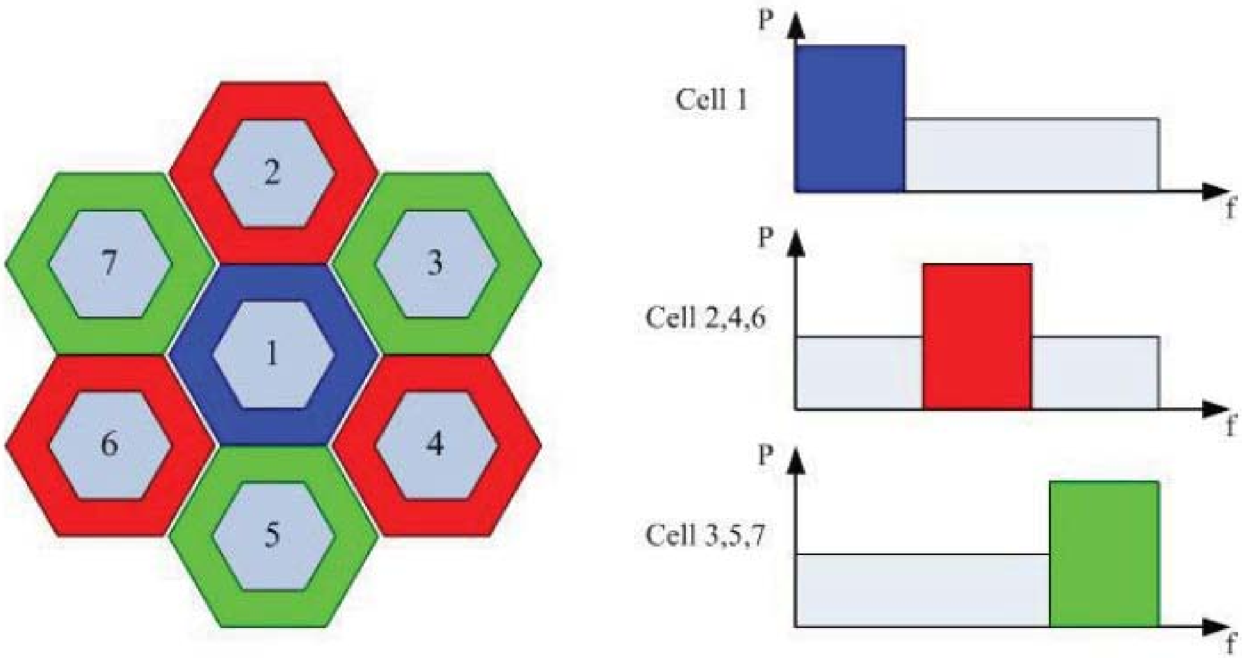
- X2 interface is used for exchanging interference indicators

X2 interference indicators

- **Relative Narrowband Transmit Power Indicator (RNTP)**
  - This message contains information about the transmission power level that will be used in each resource block (RB) for the DL transmission.
  - One bit per RB indicates if it is expected the transmission power to exceed a predefined threshold. (every 200ms)
- **High Interference Indicator (HII)**
  - HII can be considered as an RNTP indicator for the UL transmissions.
  - One bit per PB indicates if a neighbor (H)eNB should expect high interference power in the near future. (every 20 ms)
- **Overload Indicator (OI)**
  - OI is referred to the UL transmissions, however it is triggered only when high-interference is detected by an (H)eNB (every 20 ms)

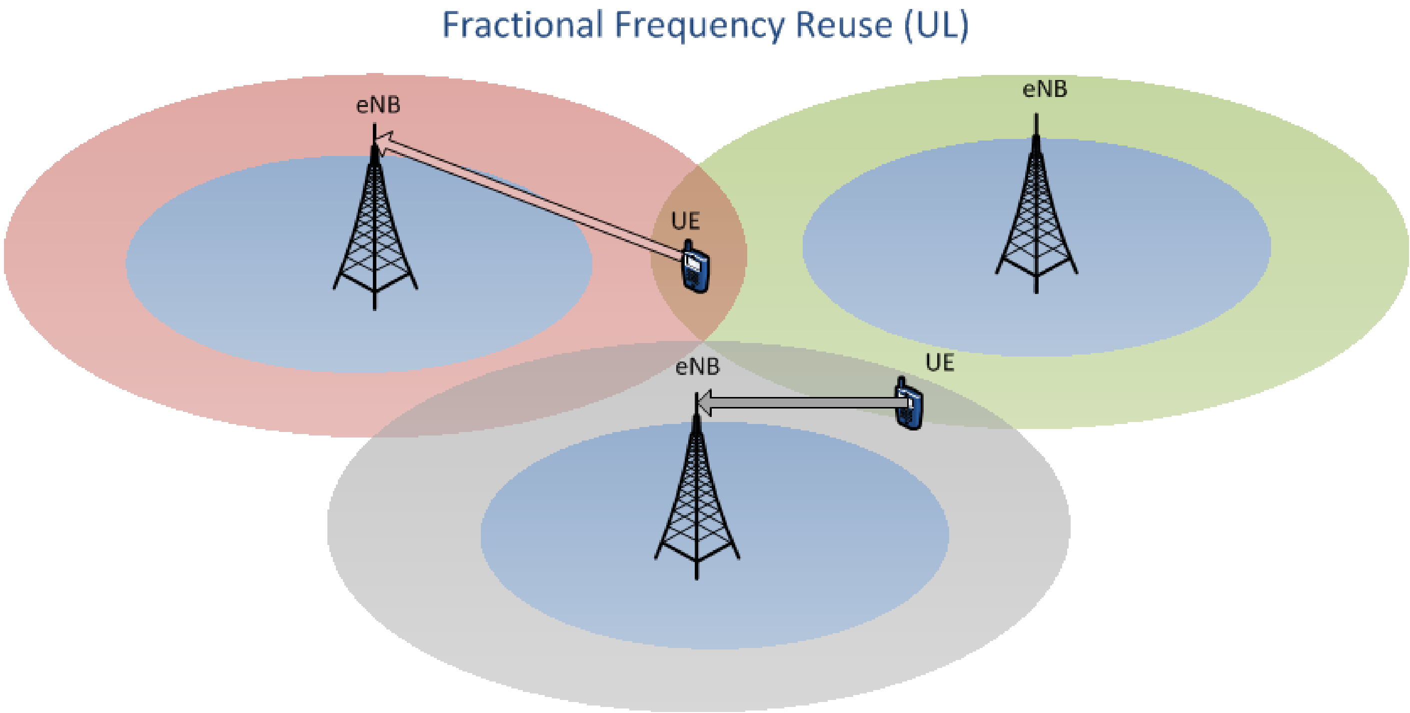
X2 interference indicators and IM

- Use of X2 Interference Indicators for **Inter-Cell Interference Coordination (ICIC)**
- **ICIC example 1:** Adaptive Soft Frequency Reuse (DL)



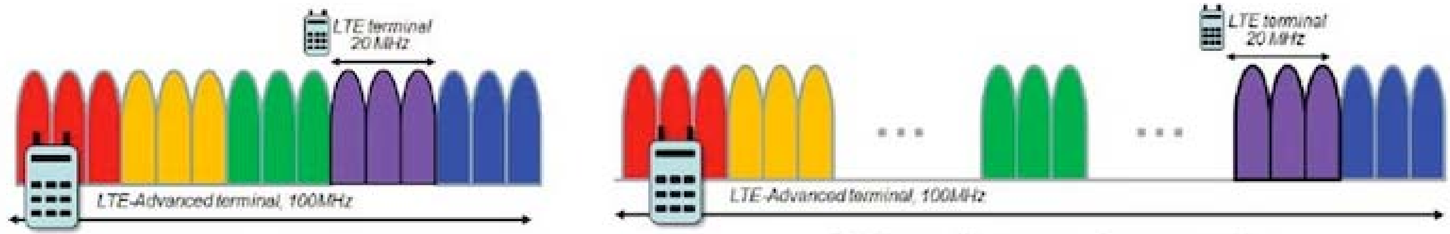
X2 interference indicators and IM

- Use of X2 Interference Indicators for **Inter-Cell Interference Coordination (ICIC)**
- **ICIC example 2:** Adaptive Fractional Frequency Reuse (UL)



Carrier Aggregation

- Scalable expansion from 20MHz to 100MHz by aggregating carriers, each group of carrier is referred to as a component carrier CC.
- The available bandwidths of each CC are 10 MHz and 20 MHz
- continuous (adjacent) or non-continuous CC located in the same or different spectrum bands can be aggregated
- There are two categories:
  - **Primary component carrier:** This is the main carrier in any group. (a primary downlink CC and an associated uplink primary CC)
  - **Secondary component carrier:** There may be one or more secondary component carriers



(a) Contiguous carrier aggregation   (b) Non-contiguous carrier aggregation

Carrier Aggregation and IM (example 1)

Carrier Aggregation = more Spectrum

+

Each femtocell will serve few users

Enhanced Frequency Partitioning (spectrum spliting) schemes for Femto-to Femto interference management

Find ways for allocating different (primary) CC to neighboring HeNBs

Carrier Aggregation and IM (example 1)

Centralized Approach

Resources are assigned by a central controller

+ More efficient resource utilization than the distributed approach
- Needs extra signaling between the BSs and the controller
- High computational complexity at the controller

Distributed Approach

Resources are assigned autonomously by BSs

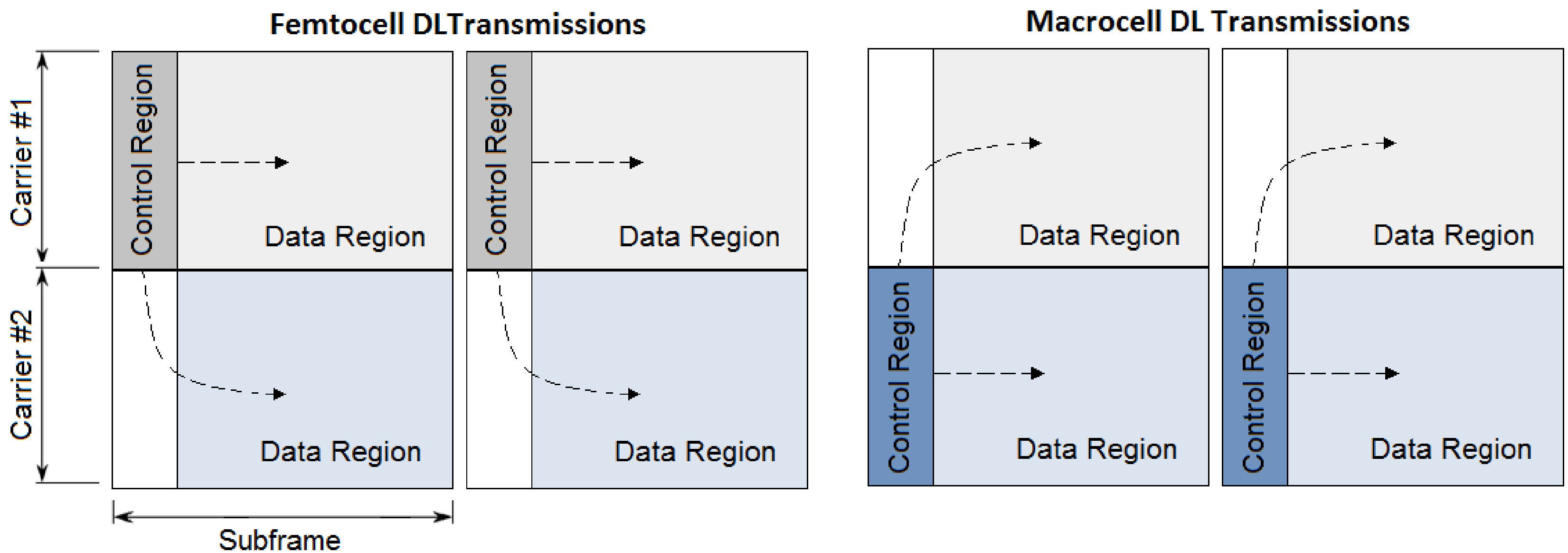
+ Low complexity
- High signaling overhead
- Requires long time period to reach a stable partitioning

Carrier Aggregation and IM (example 2)

Cross-Carrier Scheduling

- Refers to the ability to schedule a UE transmission/reception in multiple secondary CCs, while the allocation (control) messages are transmitted in a particular primary CC

Control channel protection



Carrier Aggregation and IM (example 2)

Cross-Carrier Scheduling

Advantages

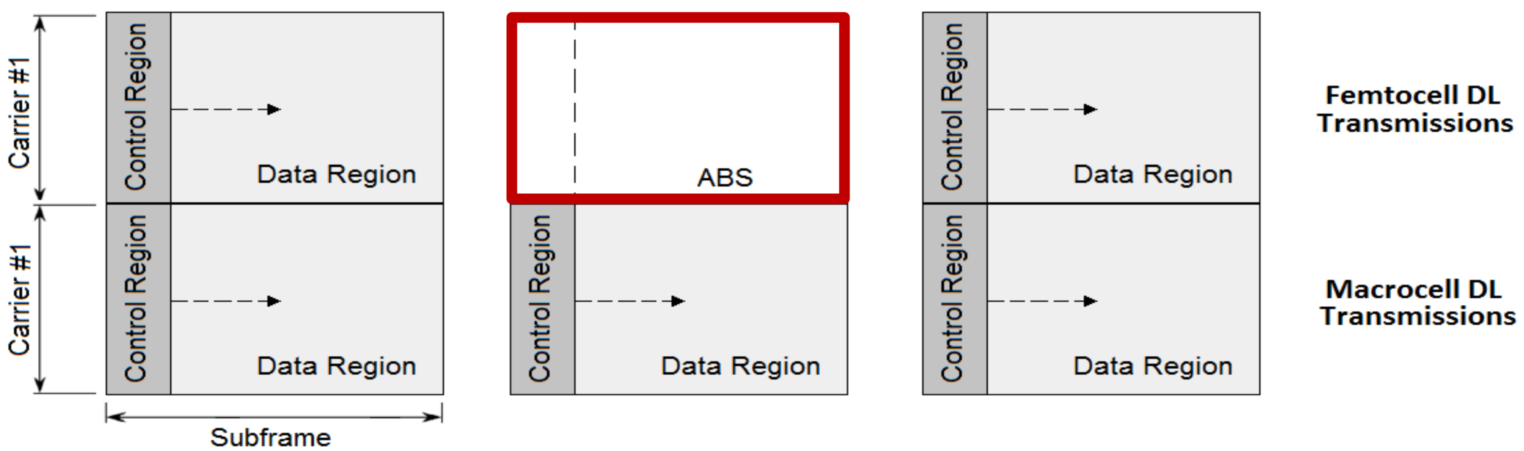
- Interference avoidance in the very important control channels with no decrease in the available spectrum

Disadvantages

- The same as in the Frequency partitioning schemes
- Problems on mapping the PDCCH of multiple CC in the control region of the primary CC
- Backwards incompatible (Rel.8,9 UEs can not take advantage of this technique)

Almost Blank Subframes

- ABSs can be constructed either by configuring the multicast/broadcast over single-frequency network (MBSFN) subframes or by avoiding to schedule unicast traffic in certain subframes
- **Data and control channels are not included**, making room for interference-free transmissions/receptions by victim UEs

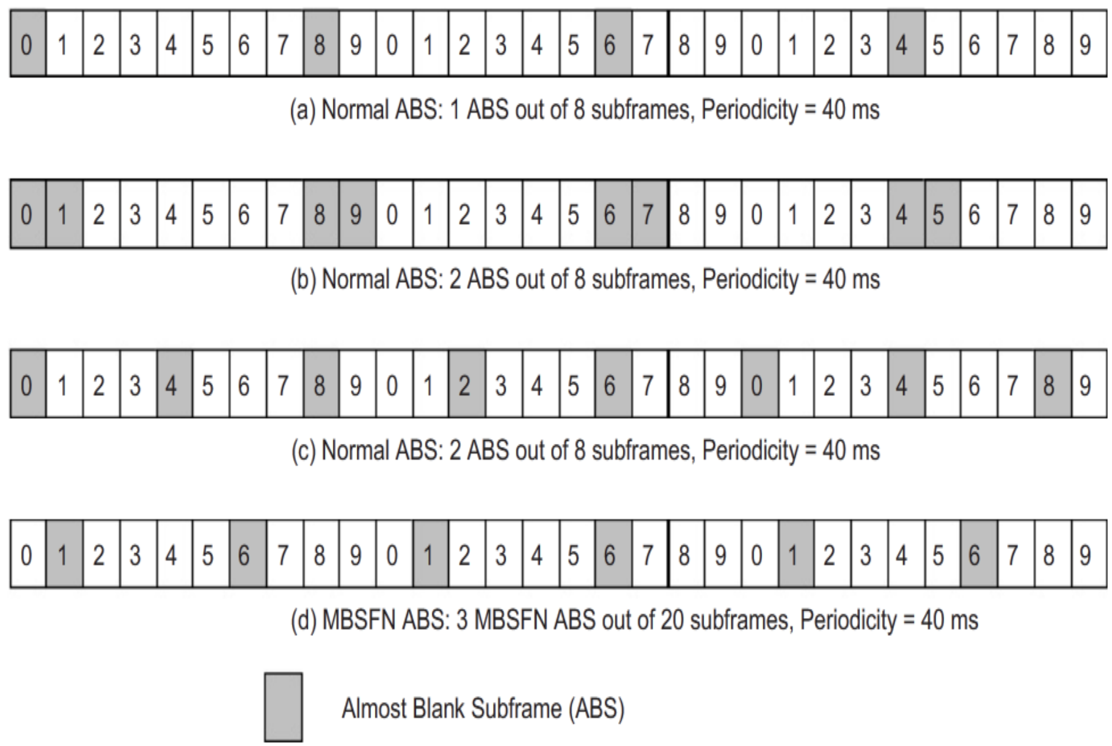


Almost Blank Subframes

Two types of ABS bitmap patterns can be exchanged through the X2 interface to configure ABSs among (H)eNBs

– **ABS Pattern**
referred to as the time-domain Relative Narrow-Band Transmit Power (RNTP) indicator

– **Measurement Subset**,
informs the receiving (H)eNBs on the set of subframes that can be used for measurements



(a) Normal ABS: 1 ABS out of 8 subframes, Periodicity = 40 ms

(b) Normal ABS: 2 ABS out of 8 subframes, Periodicity = 40 ms

(c) Normal ABS: 2 ABS out of 8 subframes, Periodicity = 40 ms

(d) MBSFN ABS: 3 MBSFN ABS out of 20 subframes, Periodicity = 40 ms

Almost Blank Subframes and IM

- The neighbor (H)eNBs can be informed for the ABS transmissions in order to transmit control signals and/or allocate resources for victim UEs in these subframes

Advantages

- Interference-free resources for control and data channels

Disadvantages

- Lose of resources for the (H)eNB that transmits the ABSs
- **channel measurements made by UEs deteriorate** including in their average estimations measurements of empty (blank) subframes

LTE-A Interference Management tools
Summary

1. In LTE-A PHY, special measurements have been introduced for IM
2. X2 interface is mainly used for ICIC
3. Frequency domain IM - CA with cross-carrier scheduling
4. Time Domain IM - ABS technique

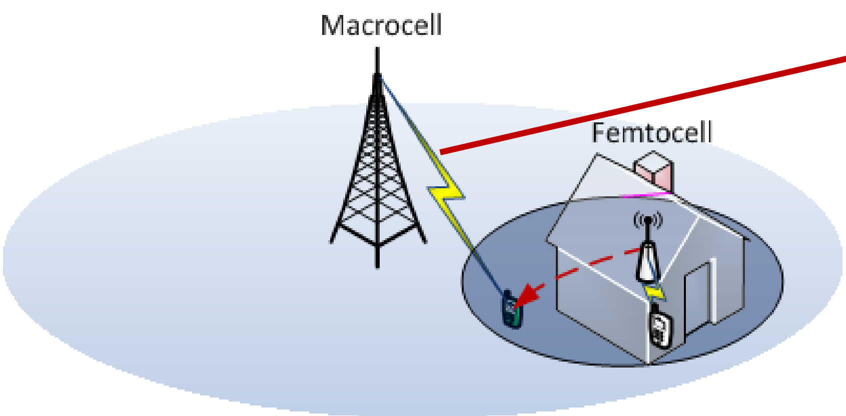
Specific solutions for IM in LTE-A networks

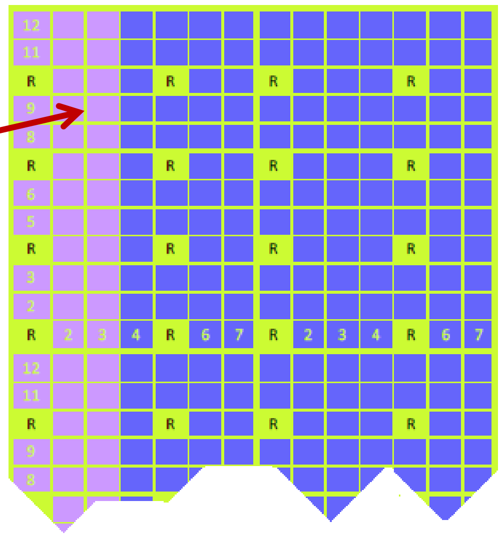
Study on DL control channel interference management
QoE-aware Power Control

Study on DL control channel interference management

Qualitative and quantitative performance comparison of 4 techniques standardized by 3GPP for LTE-A networks

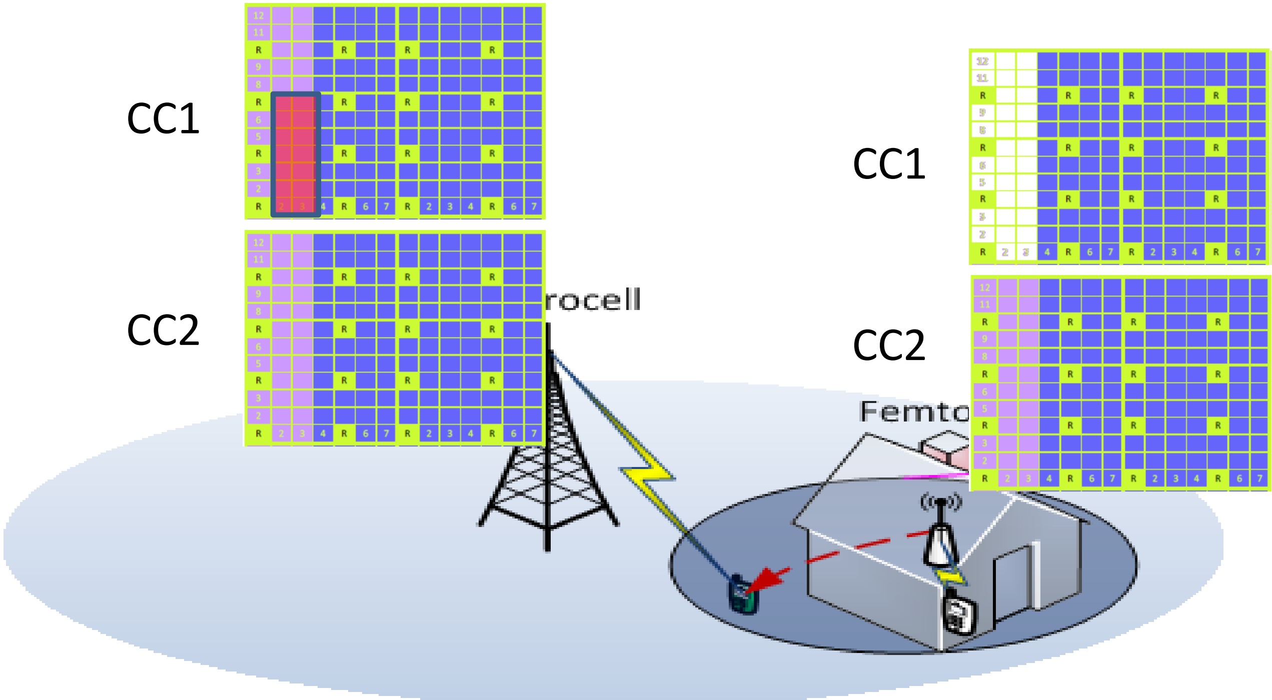
- Technique 1: Carrier aggregation with cross carrier scheduling
- Technique 2: Almost blank subframes (ABS)
- Technique 3: Control channel allocation
- Technique 4 : Power Control





Study on DL control channel interference management

- **Technique 1:** Carrier aggregation with cross-carrier scheduling

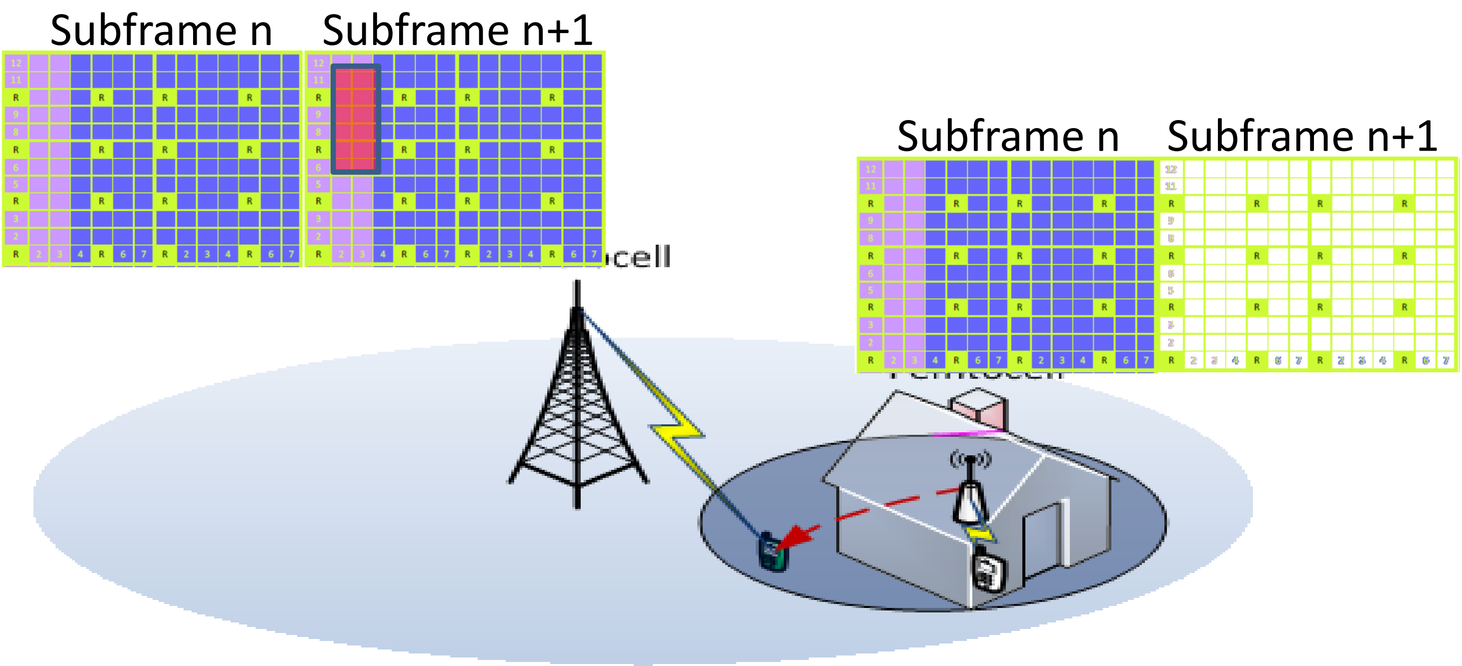


(+) Interference avoidance / no loss of data channels

(-) Problems on mapping the control channel /Cannot be used by Rel. 8 users/ Static method

Study on DL control channel interference management

- **Technique 2:** Almost Blank Subframes (ABS)

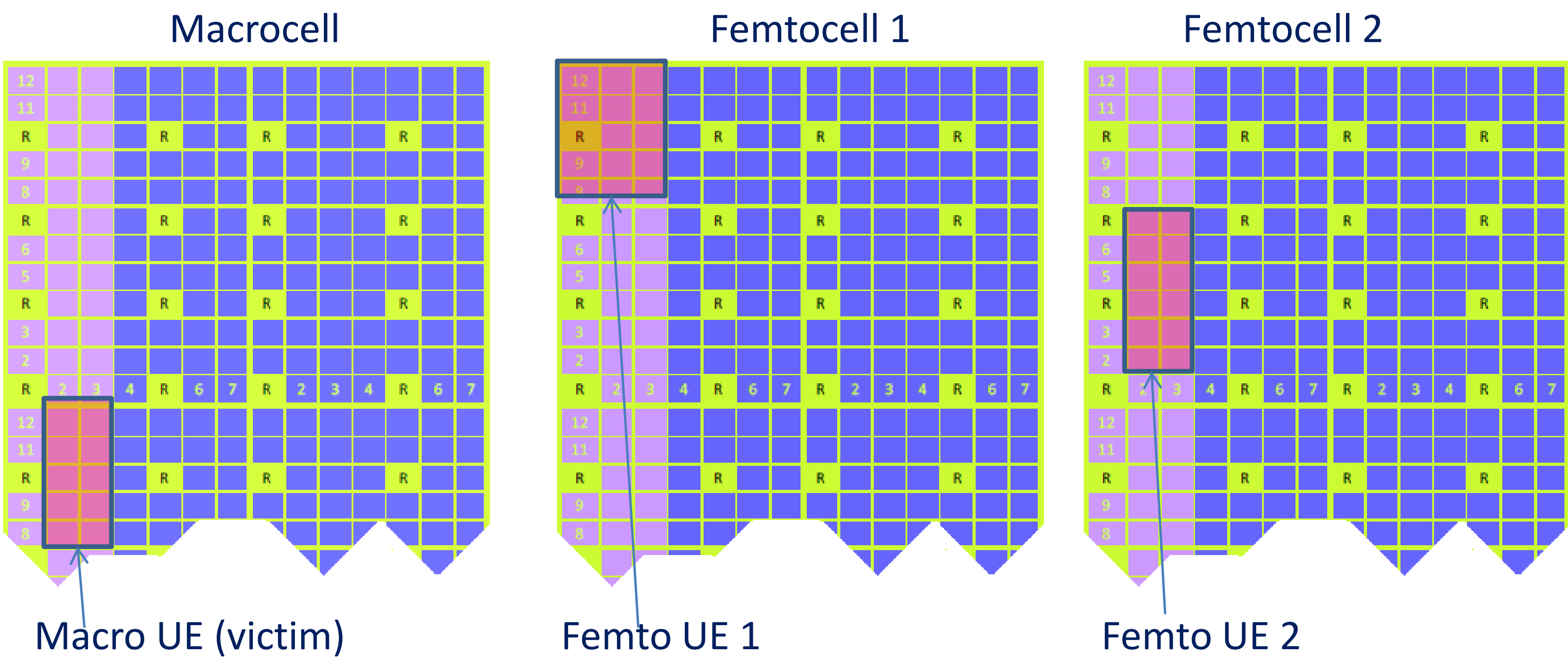


(+) Reactive approach / Interference avoidance

(-) Side effect in UEs channel measurements / Cannot be used by Rel. 8 users /loss of data channels

Study on DL control channel interference management

- **Technique 3:** Control channel allocation

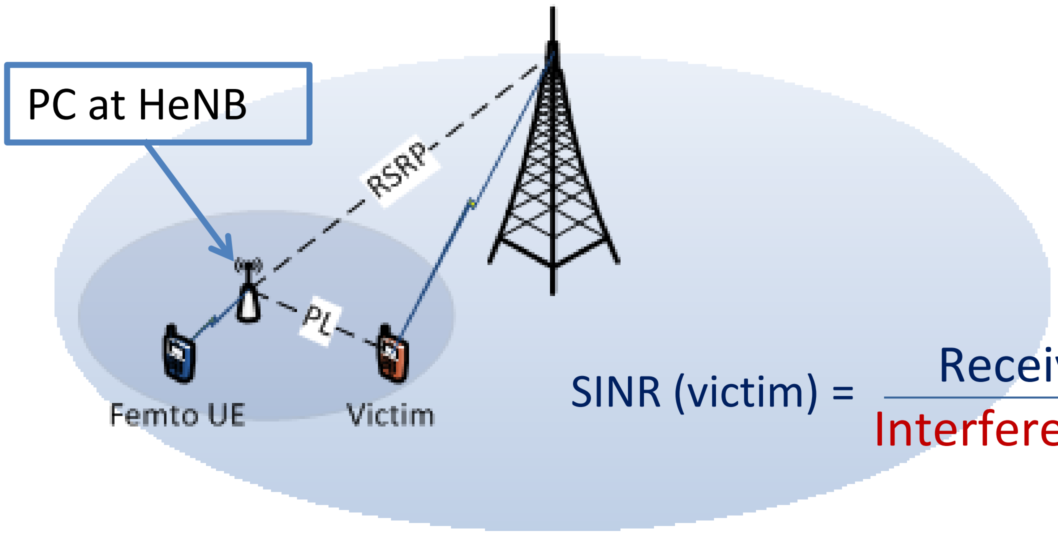


(+) No impact on femto UE performance

(-) Sophisticated PCI selection is required

Study on DL control channel interference management

- **Technique 4:** Power Control (PC)
- Adjust the transmit power at HeNB



SINR (victim) = $\frac{\text{Received power}}{\text{Interference} + \text{Noise}}$

$$P_{Tx} = median(P_{eNB-HeNB} + PL_{HeNB-MUE}, P_{max}, P_{min})$$

(+) Reactive / applied to all interferers
(-) Interference mitigation (not avoidance) / Impact on femto UE performance

Study on DL control channel interference management

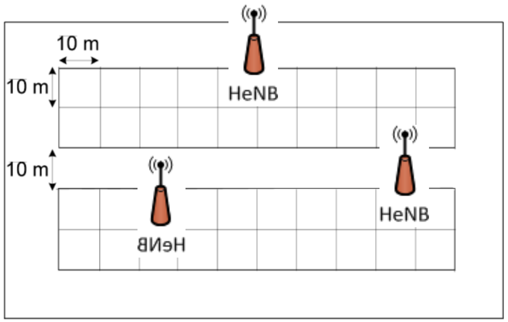
Performance evaluation schemes

- For technique 1:
  - **4 CCs sequentially allocated to HeNBs**
- For technique 2:
  - **ABSs are used by the strongest HeNB interferer**
- For technique 3:
  - **Maximum mutually disjoint allocations of the control channel**
- For technique 4:
  - **Power control formula proposed by 3GPP**

Study on DL control channel interference management

- Link level simulations

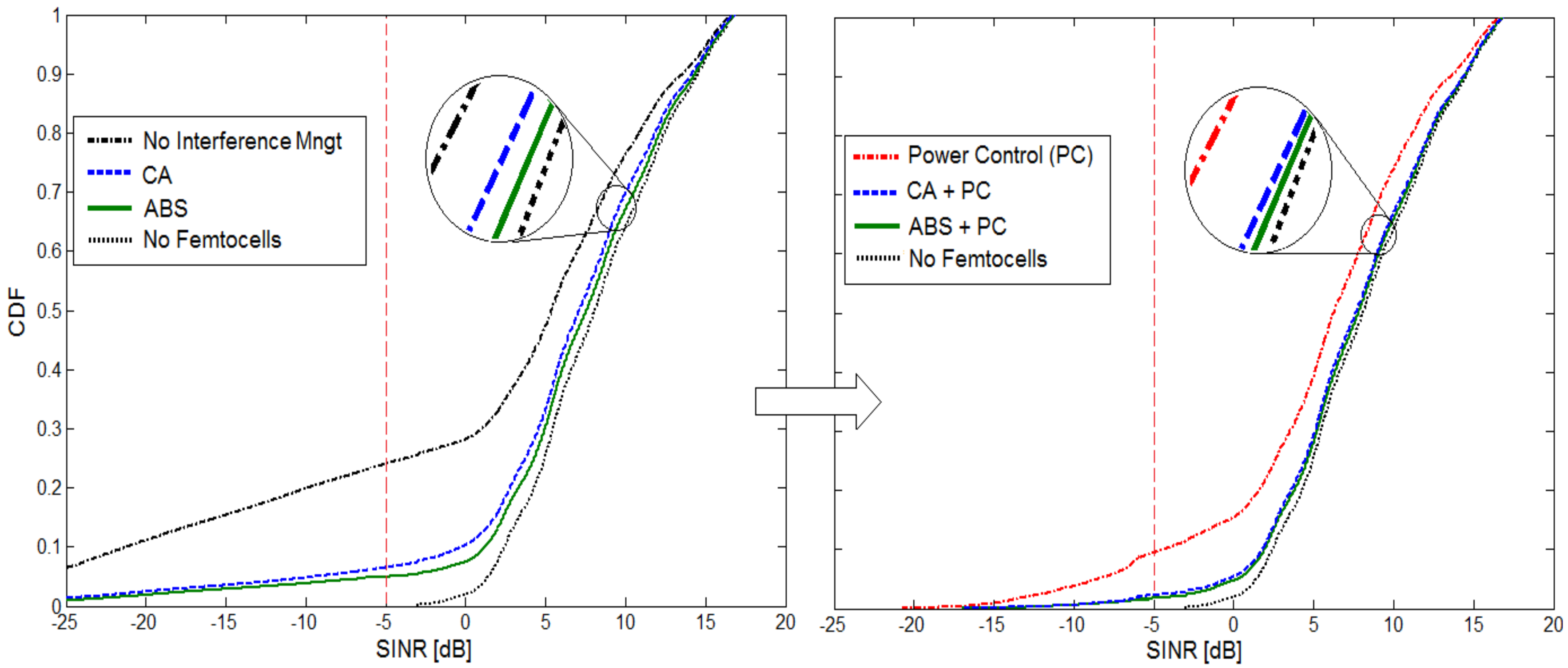
Dual stripe building blocks



Parameter	Value
eNBs deployment grid	Hexagonal
HeNB deployment grid	Random
eNBs Reuse factor	1
Duplex mode	FDD
Inter-eNB distance	1000m
Frequency	2GHz
Channel Bandwidth	10MHz (4x10MHz for CA)
Cyclic prefix (CP)	Normal
eNB antenna type	3GPP TR36.942
eNB antenna transmission scheme	2x2
eNB TX power	43dBm
HeNB antenna type	Omnidirectional
HeNB TX power	20dBm fixed and 3GPP TR36.921 PC
Number of Dual-Stripe Blocks	21 per sector
Number of floors per stripe	3
Apartment size	10x10m
Target Block distance from eNB	225m
Probability of HeNB being in an Apartment	0.1
Pathloss model	Dual-stripe based on 3GPP TR36.814
Environment	Urban
Penetration losses	20dB
Control Channel Decoding Threshold	-5dB
Channel model	AWGN
Control channel modulation	QPSK (1/12)

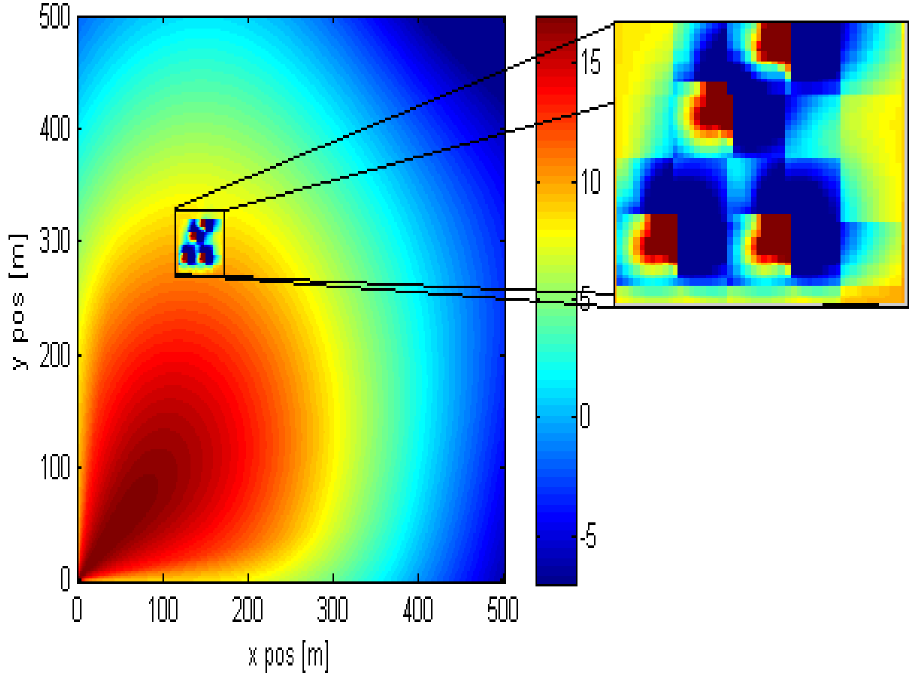
Study on DL control channel interference management

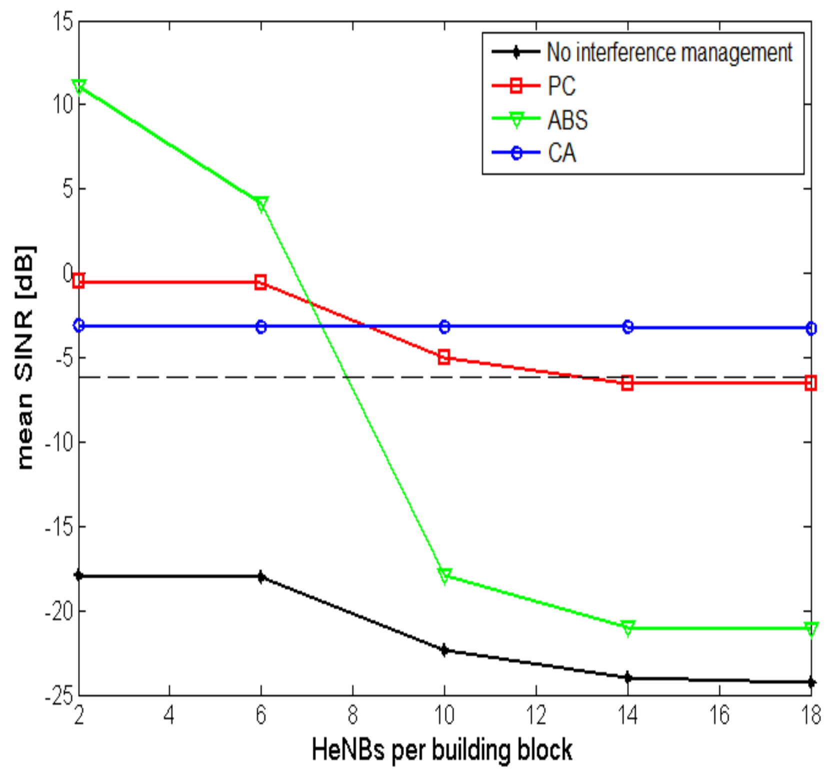
Result: CDF of SINR at victim Macro UEs - in total macrocell region



Study on DL control channel interference management

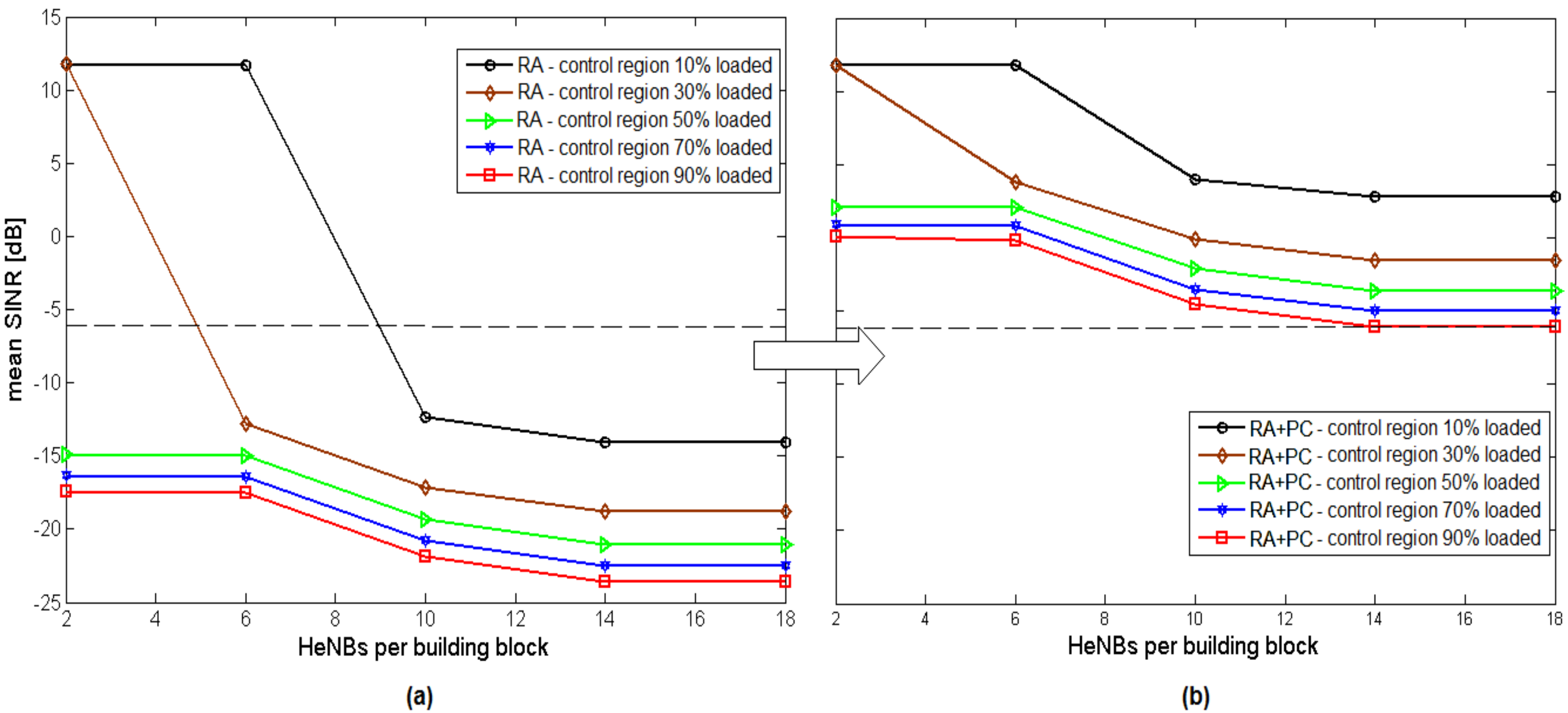
Mean SINR perceived by indoor Macro UEs victims





Study on DL control channel interference management

SINR values of the PDCCH perceived by a single victim MUE – assume the maximum mutually disjoint allocations



Specific solutions for IM in LTE-A networks

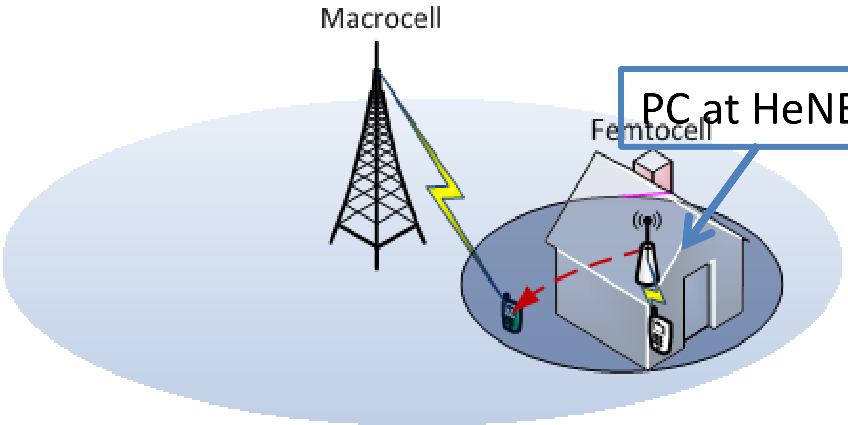
Study on DL control channel interference management
QoE-aware Power Control

QoE-aware Power Control

- **3GPP Altruistic Power Control (PC)**
- Extension of the 3GPP approach

$$P_{Tx} = median(P_{eNB-HeNB} + PL_{HeNB-MUE}, P_{max}, P_{min})$$

- P_{Tx} : transmit power of the interference aggressor
- $P_{eNB-HeNB}$: received power from the eNB (serves the victim MUE),
- $PL_{HeNB-MUE}$: pathloss between the HeNB and the victim MUE.



QoE-aware Power Control

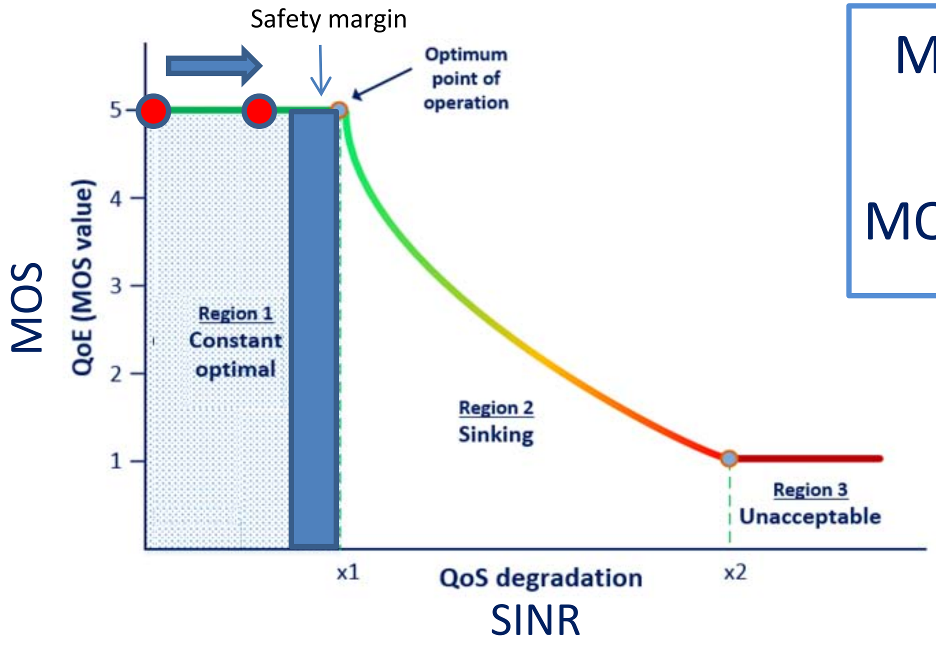
Proposed Scheme (be more altruistic!)

- Enhance the 3GPP Power Control IM scheme

$$P_{Tx} = median(P_{eNB-HeNB} + PL_{HeNB-MUE}, P_{max}, P_{min})$$

$$\downarrow$$

$$P'_{Tx} = max\left(P_{min}, P_{Tx(3GPP)} - \Delta P_{COR,opt}\right), \quad if\ \Delta P_{COR,opt} > 0$$



Monitoring

(Through E-Model)

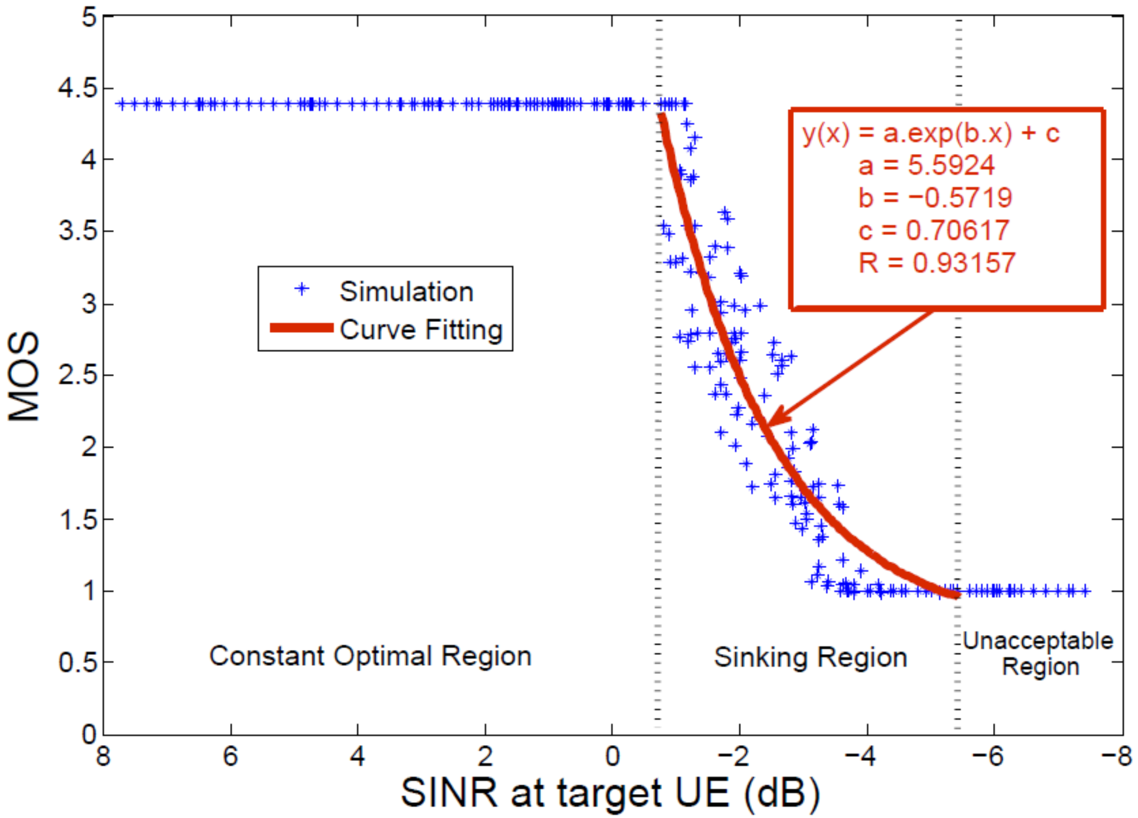
MOS *Vs* SINR

SINR in COR

$\Delta P_{COR,opt}$

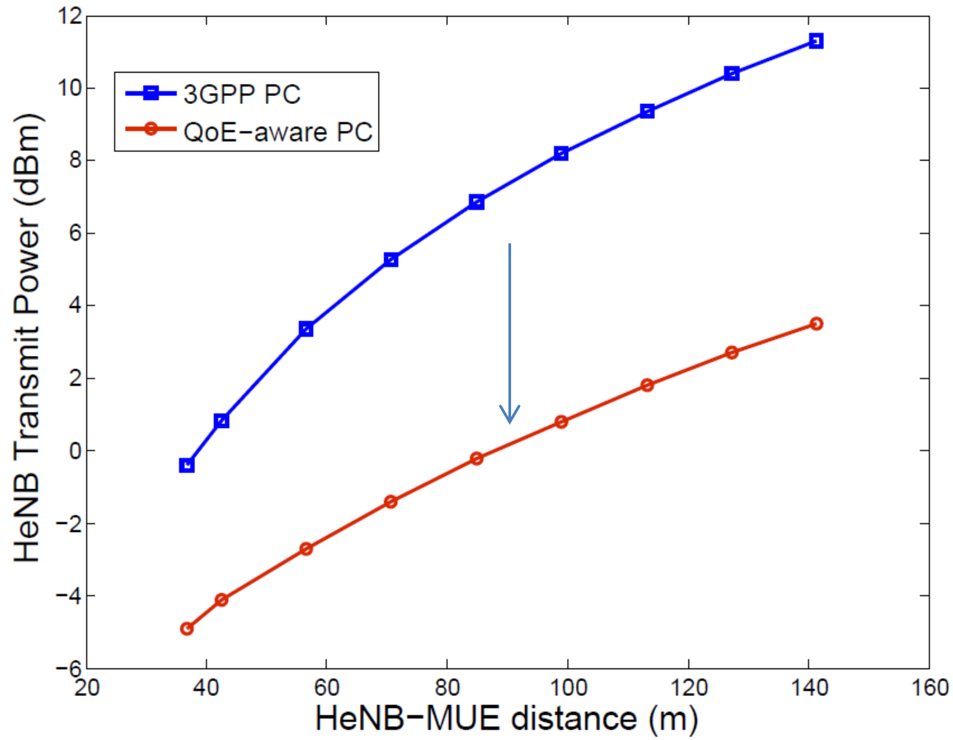
QoE-aware Power Control

Result : Monitoring phase



QoE-aware Power Control

Result: HeNB Transmit power



Indirect interference mitigation and energy saving

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[1] D. Tsolkas, N. Passas, and L. Merakos, "Alleviating Control Channel Interference in Femto-Overlaid LTE-Advanced Networks", IEEE Communications Magazine, vol. 51, issue 10, Oct. 2013.

[2] ITU-T: Methods for Subjective Determination of Transmission Quality. Rec. P.800, 1996

[3] Piro, G., Grieco, L.A., Boggia, G., Capozzi, F., Camarda, P.: Simulating LTE Cellular Systems: An Open-Source Framework. IEEE Transactions on Vehicular Technology. 60, 498–513 (2011)

Thank you!