Coordinated Multi-Point in Cellular Networks

From Theoretical Gains to Realistic Solutions and Their Potentials

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INTRODUCTION

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From Theoretical Gains to Realistic Solutions and Their Potentials

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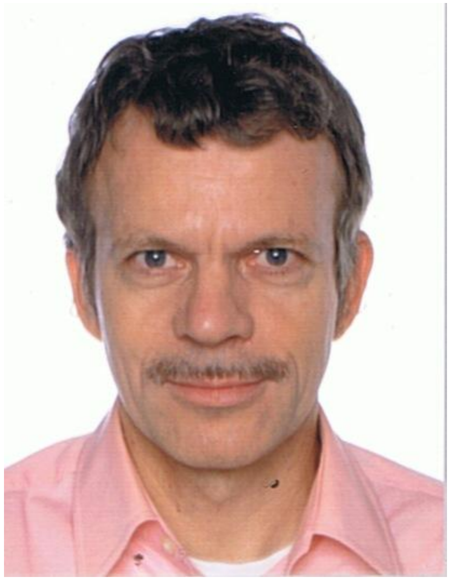


This tutorial is based on cooperative work done in the EU research project

Artist4G

Our story in a nutshell:

- Interference can be suppressed by coordinating multiple sites. This should theoretically provide large gains.
- But gains seem hard to attain in realistic settings.
- Message: Large gains can be attained,

  but you have to construct the solution carefully.

Our story in a nutshell:

- Interference can be suppressed by coordinating multiple sites.
  This should theoretically provide large gains.
- But gains seem hard to attain in realistic settings.
- Message: Large gains can be attained,
  but you have to construct the solution carefully.

Outline:

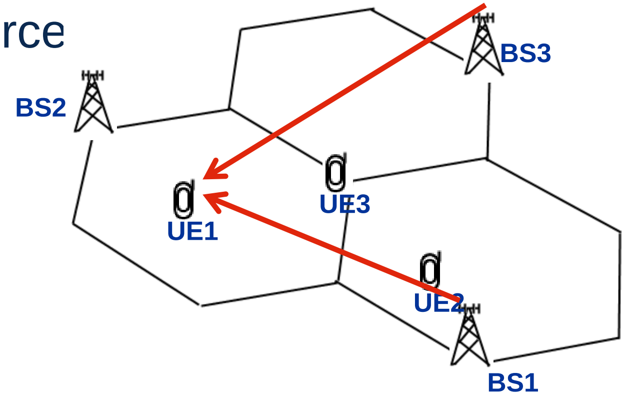
- Theory and Practice: MIMO, Network MIMO and LTE status
- Key challenges and enablers for downlink joint transmission
- A harmonized downlink framework: Outcomes of the EU *Artist4G* Project
- Uplink aspects and Joint Detection

Interference in Cellular Networks

Cellular networks:

- Cell: Logical entity (with Cell-ID) within which transmission resources can be tightly controlled.
- A cell is controlled by a base station (BS).

  (3GPP eNB may control several cells/sectors.)
- Interference ***within*** cells controlled by resource allocation (time, frequency, codes, spatial).
- ***Interference between cells*** remains.



$$\mathit{SINR} = \frac{\mathit{useful\ received\ power}}{\mathit{interference + noise}}$$

Interference-limited cellular networks:

- Inter-cell interference (rather than noise) limits spectral efficiency.

  Example: LTE macro cellular systems with high load, outdoor users, inter-site distance (ISD) 500 m.

Frequency Reuse Factor > 1

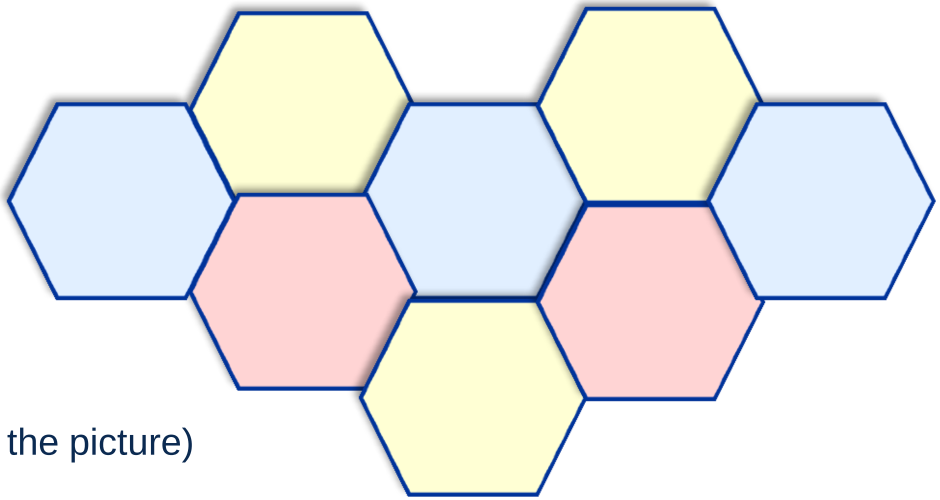
The traditional way of controlling inter-cell interference

Frequency (transmission resource) reuse factor n:

- Area is covered by regular clusters of *n* cells.
- Each cell in a cluster uses different orthogonal transmission resources.
- Distance to nearest interferers in neighbouring clusters ("reuse distance") increases with *n.*
- => Inter-cell interference will decrease with *n.*

- But: The fraction of total resources available in each cell is then *1/n*

n=3:



(Heterogenous networks complicate the picture)

Coordinated MultiPoint Transmission (CoMP)

Sharing of User Data? Two basic options:

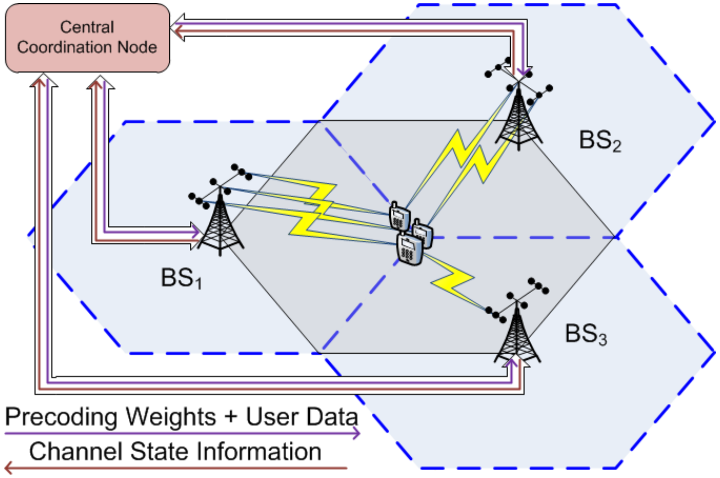
Coordinate transmission/reception within a Cooperation Area (CA)

=> More flexible interference control than static frequency reuse.

CoMP without sharing of user data:

Data to/from single user via one point:

- Coordinated scheduling
- Coordinated beamforming
- Inter-Cell Interference Coordination (ICIC, eICIC, feICIC).



CoMP with sharing/distribution of user data *(higher potential gains):*

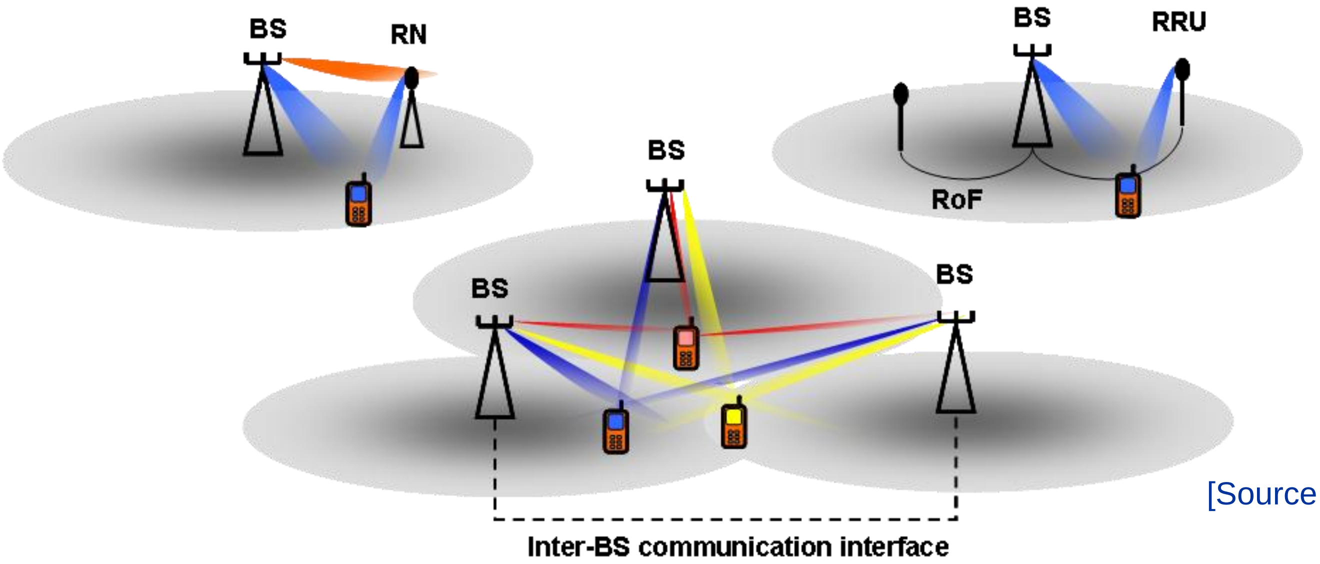
A main focus of this tutorial

- Joint Transmission (JT) in downlinks (coherent or non-coherent).
- Joint Detection (JD) in uplinks.

CoMP Architectures

Coordinate transmission/reception within a Cooperation Area (CA)

=> More flexible interference control than static frequency reuse.



[Source: Winner+ Project]

Possible coordinated entities:

- Remote Radio Units (RRUs)
- Cells with intra-site or inter-site coordination
- Relay nodes (RNs).

May use multi-cell coordination with BSs, RRUs and RNs within the cells.

Some History:

1983: F. M. J.Willems and M.J. Frans:

“The discrete memoryless multiple access channel with partially cooperating encoders”

2000: T. Weber, Meurer, P.W. Baier: JT/JD for TD-CDMA

Chinese-Siemens Cooperation Project ‚FUTURE‘ → CoMP activities in China

Joint transmission (JT) or joint reception (JR) for local area → ‚Service Area‘ Concept

2001-2004: Theoretical investigations, e.g. [Shamai et.al. 2001,2002], [Jafar et. al. 2002,2004].

2003: COVERAGE project: ‚cooperative multi stage relaying‘

2004: 3GET project extension of Service Area Concept to macro-cellular networks

2005-2006: Series of theoretical investigations finding large potential gains (Foschini et.al.)

2010: German project ‚Easy C‘: CoMP testbeds in Dresden and Berlin

2010-2012: EU FP7 ARTIST4G project (Used the CoMP testbeds in Dresden)

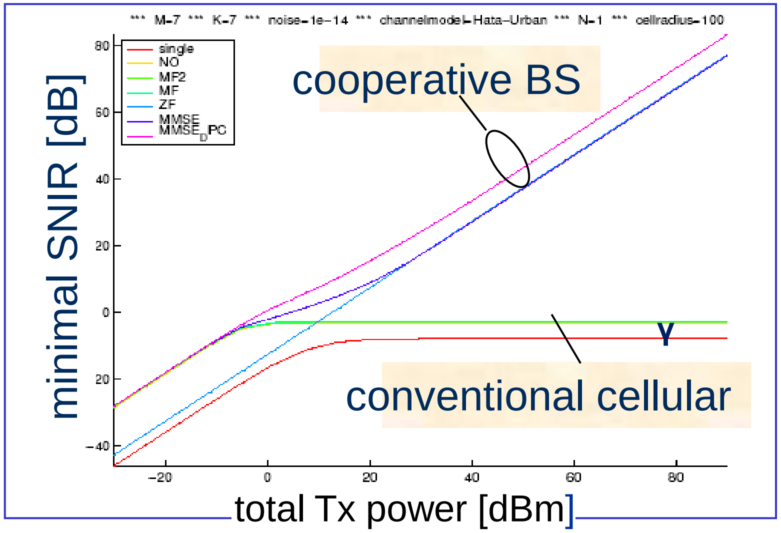
3GPP LTE Rel 10: CoMP Study Item / Rel 11 CoMP Work Item

3GPP LTE Rel 11: No supporting functions for JT CoMP, due to challenging time-/frequency synchronization.

Motivations for CoMP

1. Overcome interference limitations in cellular radio networks

- Reduce gap between single- and multi-cell performance.
- Large theoretical network capacity gains for *network-wide* and *coherent* joint transmission:



[Source: Distributed Antenna Systems by M. Schubert et.al.]

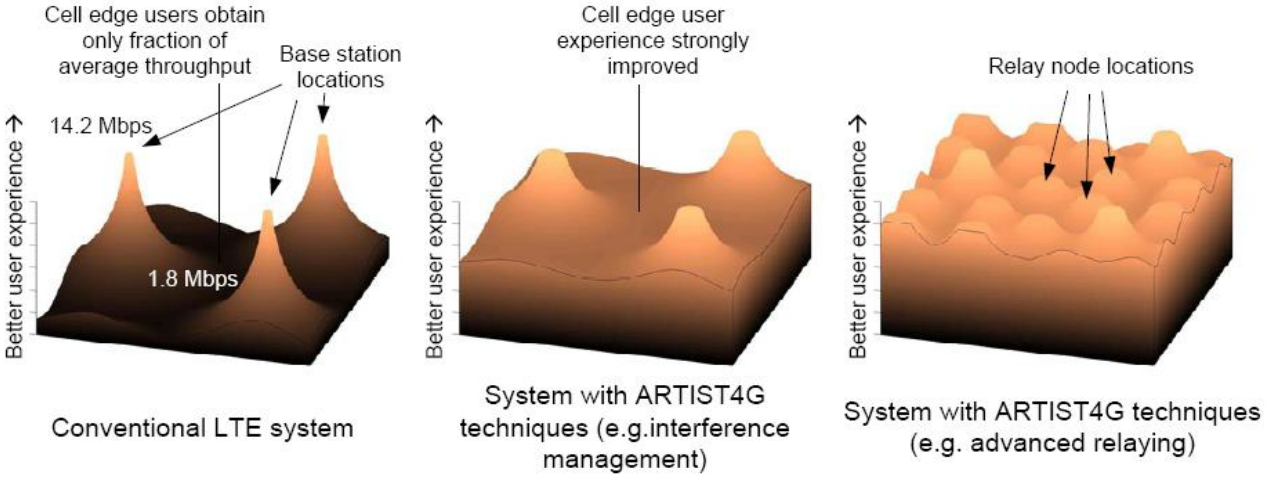
- Mechanisms for interference control:
  - ❑ ***Interference avoidance***, by Coordinated scheduling/beamforming. Most effective at low-to-medium loads (taking fairness into account).*
  - ❑ ***Interference cancellation***: Coherent joint transmission reduces interference by cancellation. Works also at high loads (if channel estimates are good).

*[See e.g. 3GPP TR 36.819 V11.0.0]

Motivations for CoMP

2. Coverage gains

- A more even distribution of capacity and user experience between cell center and cell edge UEs:



Conventional LTE system

System with ARTIST4G techniques (e.g.interference management)

System with ARTIST4G techniques (e.g. advanced relaying)

[Source: Artist4G project]

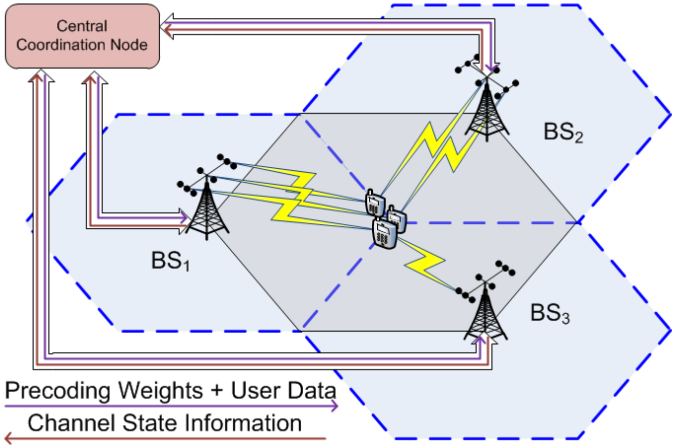
- Flexibility: Allocate capacity to where the users are active.
- Reduce power/noise limitations for highly shadowed UEs.
- Exploit macro diversity gains, including MIMO channel rank improvements.

Motivations for CoMP

3. Efficient use of existing infrastructure

- Cooperative transmission over several cells and sites using already deployed antennas and RF front-ends.

- Enable multi-user MIMO transmission/reception (network MIMO) with cooperating (distributed) antennas at the network side.



But…

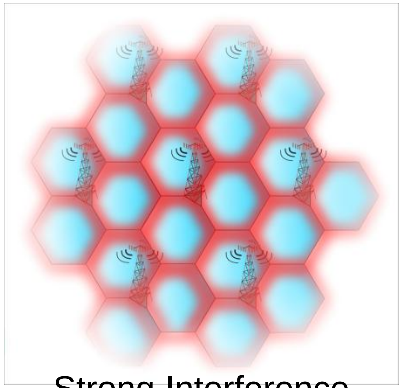
- This requires adequate communication/coordination links and intelligence within the cooperation areas.
- Antennas/BSs will have different distances to a user. Can they then still cooperate efficiently? If not always, then under what conditions?

(Cancelling weak interference components can provide significant SINR gains.)

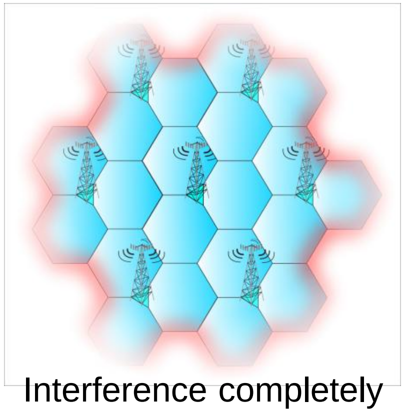
Cooperation Areas

Different degrees of cooperation have different influence on interference

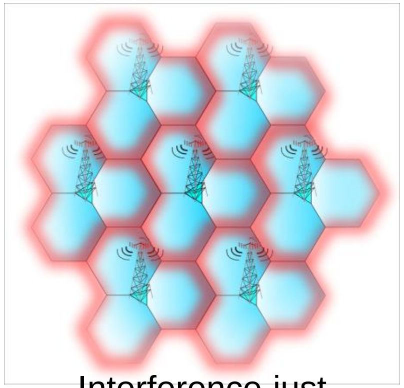
- ❑ No Cooperation
  - Strong interference between cells
- ❑ Full Cooperation
  - Interference completely avoided
  - Needs full CSI for the whole network (not realistic)
- ❑ Cooperation area (*'CA'*)
  - Cooperation only inside of a limited number of sectors



Strong Interference without cooperation



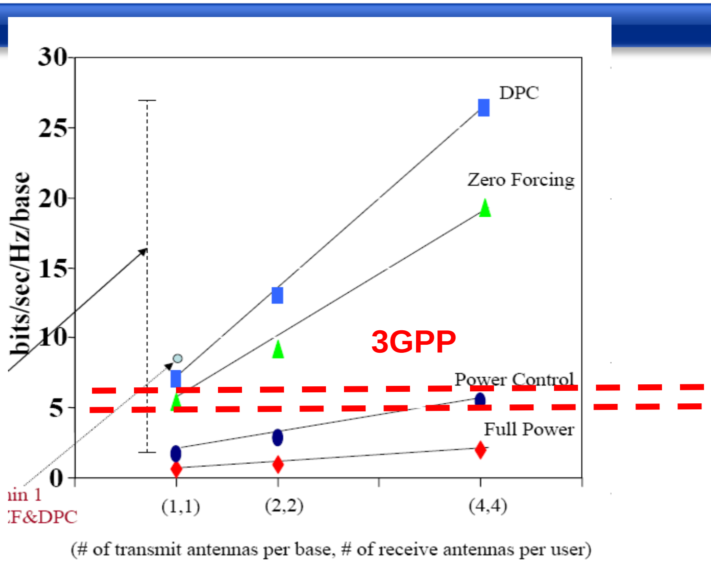
Interference completely avoided by full cooperation



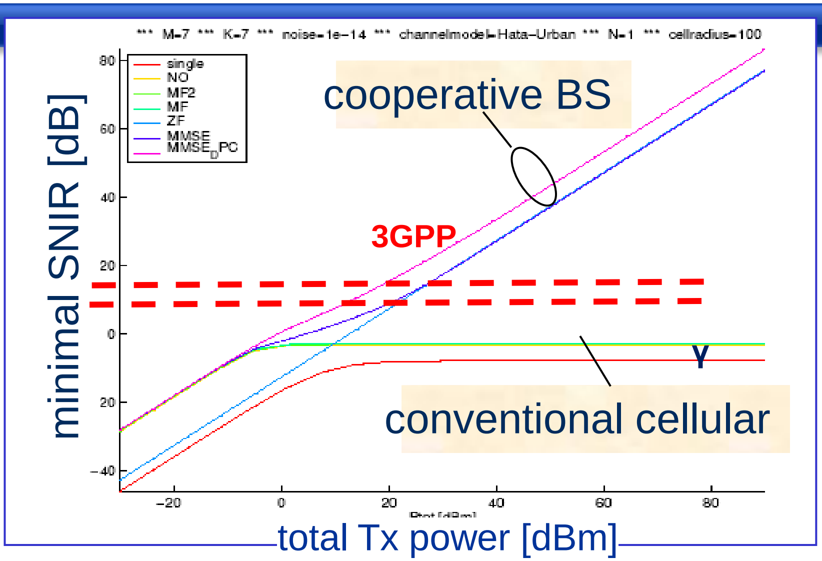
Interference just between cooperation areas

However….

Theoretical versus simulated CoMP gains:



[Source: Foschini et.al. 2006]



[Source: M. Schubert et.al.]

Where do we loose??

Are there fundamental limits??

ULA			source 1	source 3	source 12
MU-MIMO 2x2		Cell avg	2.069		1.86
		Cell-edge	0.0548		0.058
MU-MIMO 4x2		Cell avg	3.163	3.05	
		Cell-edge	0.0863	0.1	
MU-MIMO 8x2		Cell avg			4.5
		Cell-edge			0.151
JT MU-MIMO 2x2	9 cells	Cell avg	2.713		2.77
		Cell-edge	0.0879		0.107
	> 9 cells	Cell avg		2.35	
		Cell-edge		0.102	
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reference Rel10

27% gain

best JT result in

3GPP CoMP SI

(ideal)

[Source: 3GPP,
TR 36.819 V11.0.0
(2011-09), Table 7.2.1.2-5]

How to attain more of the theoretical gains?

A preview of where we are heading:

1. Cooperation areas have to be designed carefully to provide gains for most users.
2. Interference from outside the CA needs to be reduced so that it does not swamp the intra-CA gains.
3. Groups of users that cooperate in a resource block need to be selected well, but still fast and efficiently.

How to attain more of the theoretical gains?

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   need to be selected well, but still fast and efficiently.

Additional important aspects and practical constraints:

- Channel estimation/prediction accuracy
- Channel reporting feedback: accuracy and load in FDD
- Transmit power constraints
- Control signalling load, data distribution load limits
- Time synchronization limitations to/from multiple sites.

(All these issues e.g. limit the practical cooperation area size.)

Main aspects/techniques in focus in this Tutorial:

- System design aspects, inter-relationships that affect the performance
- Joint transmission/detection (for performance reasons)
- Centralized coordination (for performance reasons)
- Linear, mainly coherent, precoding (complexity and performance).

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THEORY AND PRACTICE

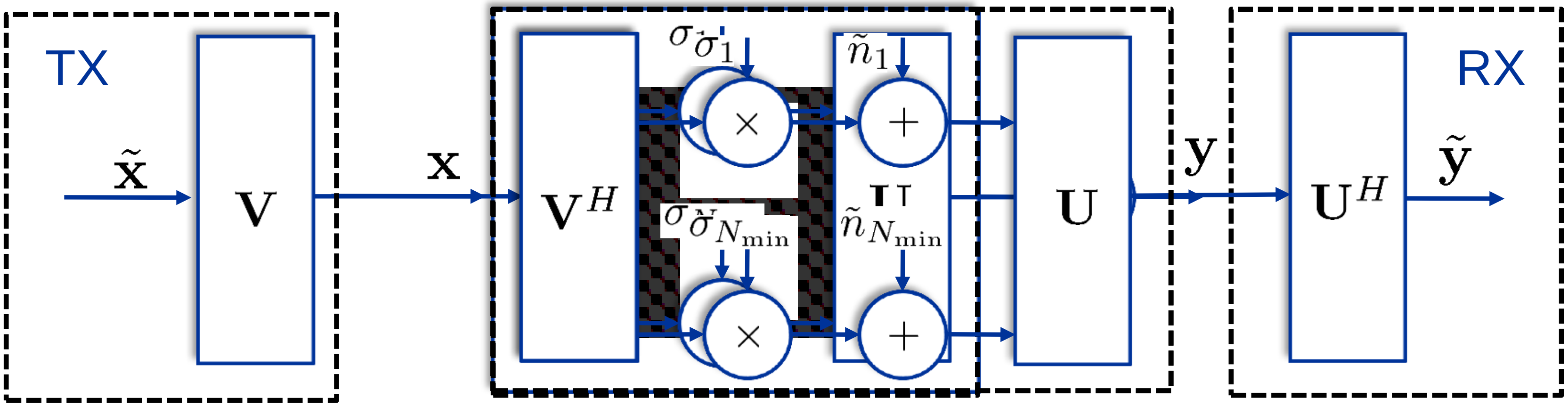
Section Overview

- Precoding and equalization
- Multi-user MIMO systems
- Network MIMO systems
- Toy scenario results
- Practical impairments
- 3GPP results

From MIMO to Network MIMO

MIMO Precoding and Equalization

- singular value decomposition (SVD) and parallel channels
  - A matrix can be decomposed such that $\mathbf{H} = \mathbf{U}\mathbf{\Sigma}\mathbf{V}^H$



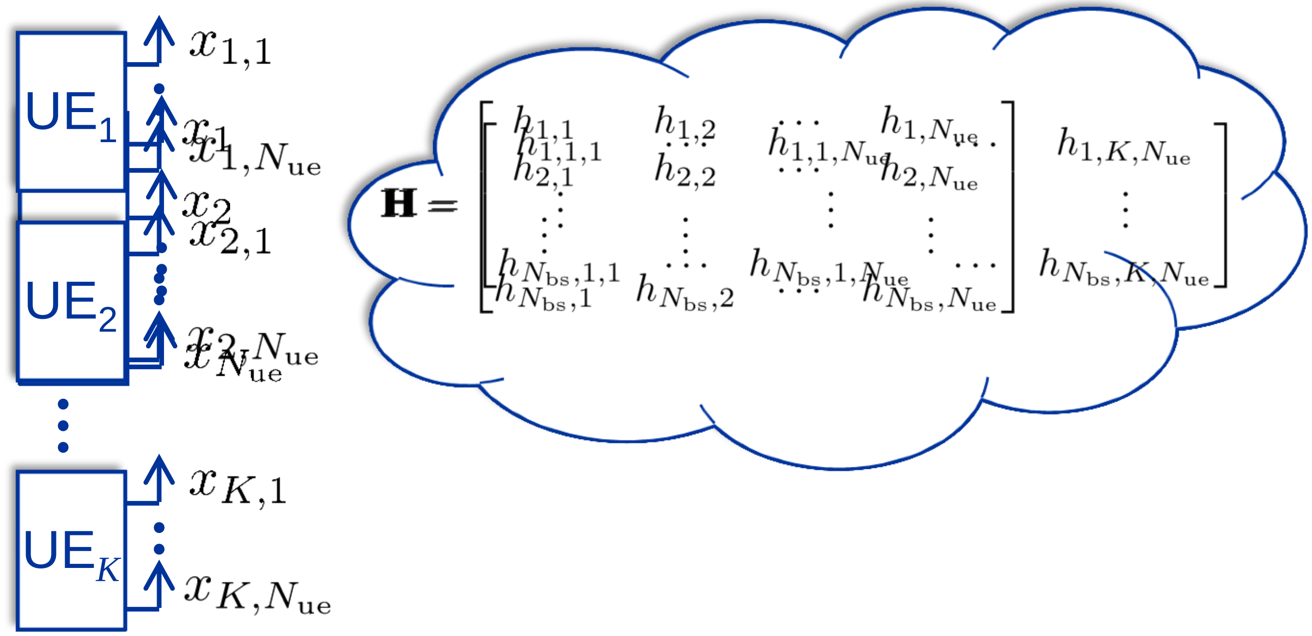
$$\tilde{\mathbf{y}} = \mathbf{U}^H\mathbf{U}\mathbf{\Sigma}\mathbf{V}^H\mathbf{V}\tilde{\mathbf{x}} + \tilde{\mathbf{n}}$$

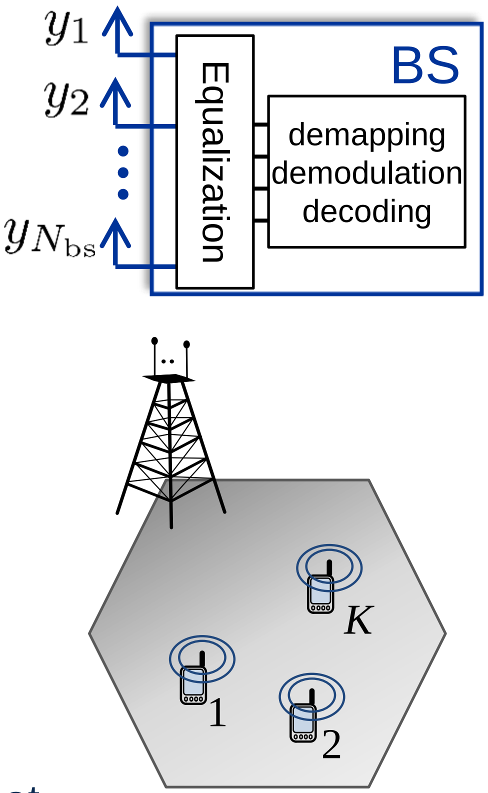
- Linear **spatial** precoding and equalization parallelizes the channel into its Eigenmodes
- This opens the door for power control (waterfilling) to maximize capacity
  - use all modes in case of high SNR
  - one or few strongest modes in case of low SNR
  - optimal because Shannon formula is concave in the power
- Precoding requires transmitter CSI

From MIMO to Network MIMO

Multi-User MIMO

MIMO multiple access system, Uplink:



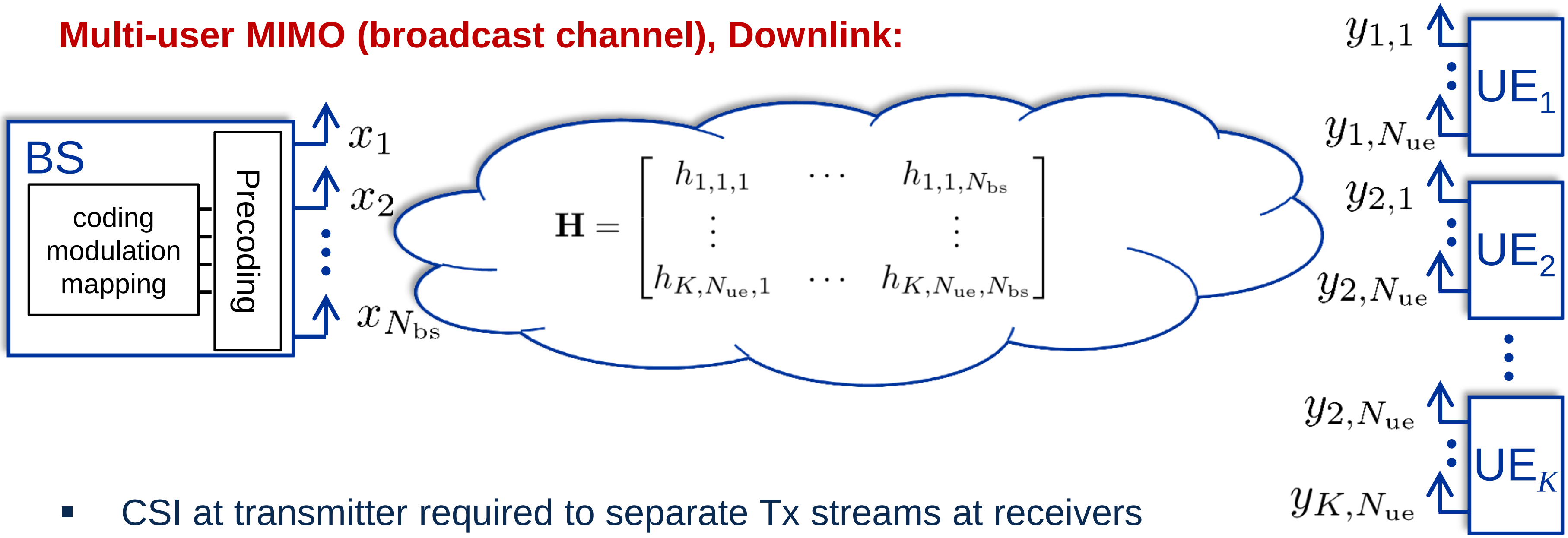


- UEs might transmit one or several data streams
- Spatial equalization (decorrelation) done at the BS
- Links of UEs experience different pathloss & large scale fading that might be compensated by power control
- Timing of received signals at BS can be aligned using timing advance

From MIMO to Network MIMO

Multi-User MIMO

Multi-user MIMO (broadcast channel), Downlink:

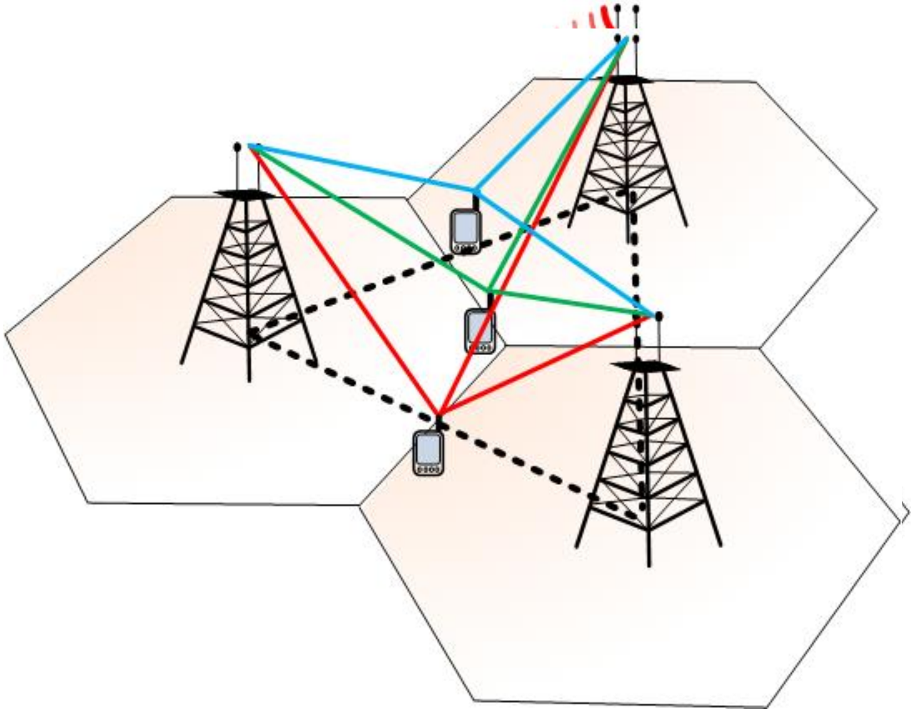


- CSI at transmitter required to separate Tx streams at receivers
- Dirty paper coding is capacity achieving
- Linear precoding techniques (e.g. ZF for channel inversion at the transmitter) allow min(N_{bs},N_{UE}) increase of data rate at high SNR
- Potentially, combination of precoding and equalization if UEs are equipped with several receive antennas

From MIMO to Network MIMO

network MIMO

- Consider a cellular system **with frequency reuse one**
- High performance when users located in vicinity of assigned base stations
- Interference problem when users are located at cell edges
- **In general:** Cellular communications systems with independent base stations are interference limited -> low SINR at cell edges



➡ network MIMO to

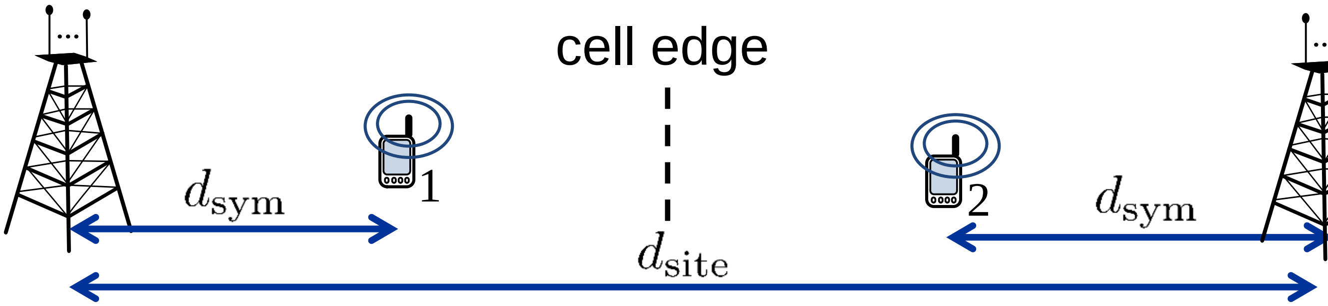
  - Jointly transmit/detect
  - Mitigate interference
  - Increase spectral efficiency

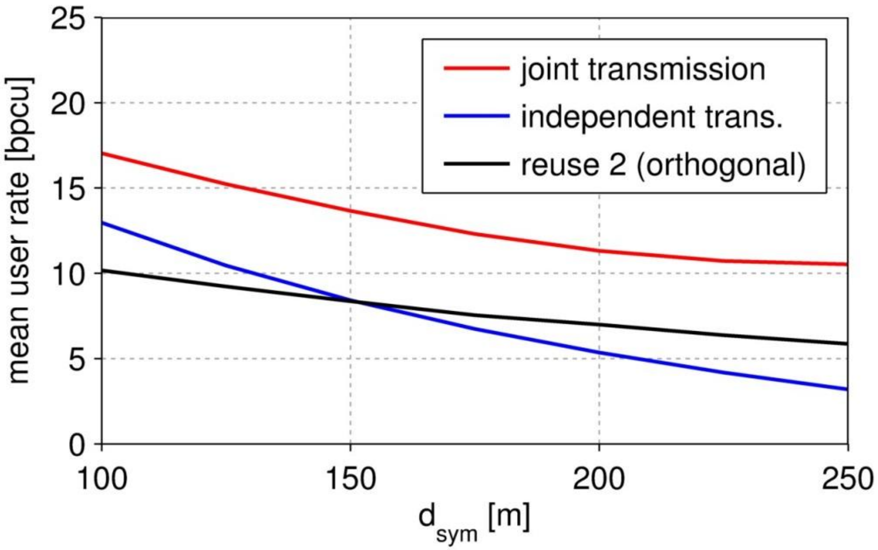
However

  - Base station time (and frequency) synchronization of base stations is required
  - Received symbol timing cannot be aligned due to propagation delays on different paths

From MIMO to Network MIMO

network MIMO



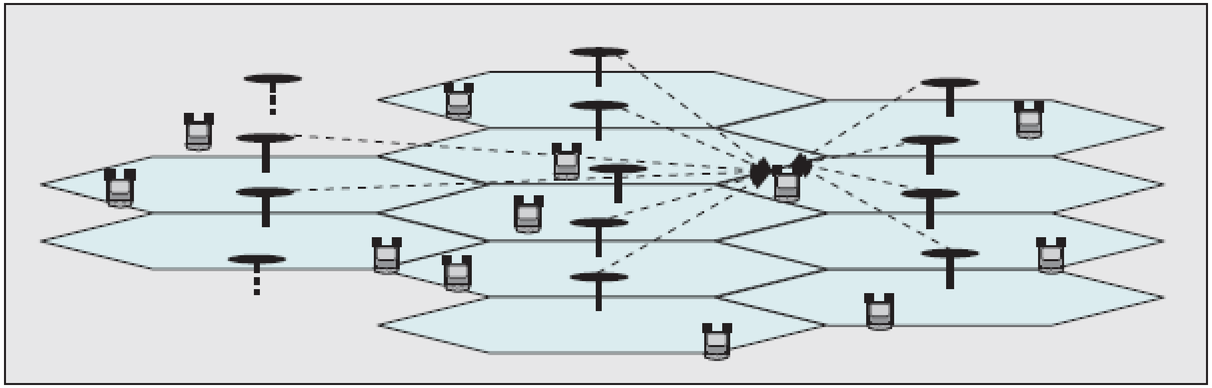


- pathloss exponent = 3.5
- omnidirectional antennas
- d_{site} = 2000 m
- cell-edge SNR = 18 dB
- N_{ue} = 2, N_{bs} = 2
- Uncorrelated Rayleigh fading
- no shadow fading
- ML receiver

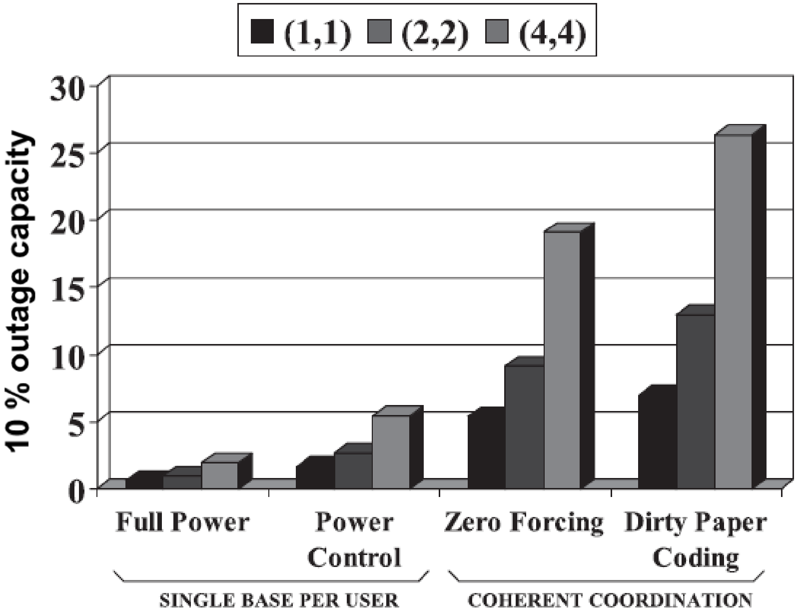
- Potentially larger gains in cellular systems
  - due to shadowing
  - due to universal frequency reuse

From MIMO to Network MIMO

network MIMO



[Source: Foschini et.al. 2006]



[Source: Foschini et.al. 2006]

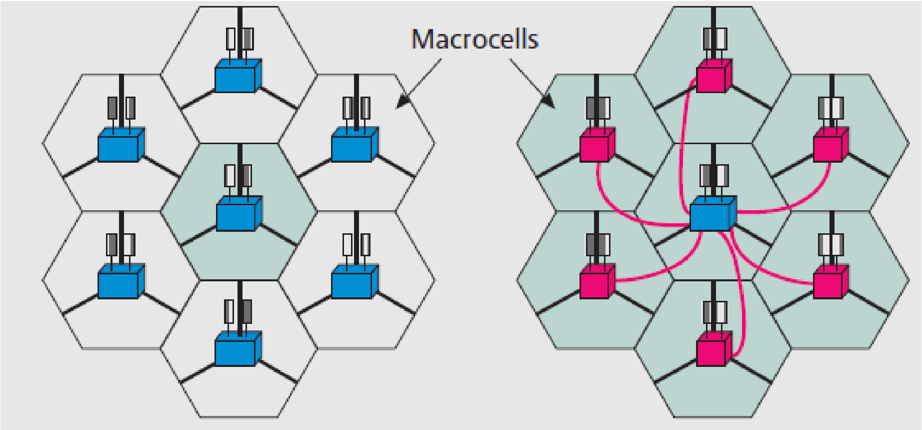
- pathloss exponent = 3.8
- coordination in user centric clusters of 19 cells
- no outer cluster interference
- d_{site} = 500 m
- cell-edge SNR = 18 dB (strong interference limitation)
- Uncorrelated Rayleigh fading
- shadow fading included
- perfect transmitter CSI

Current Status in 3GPP

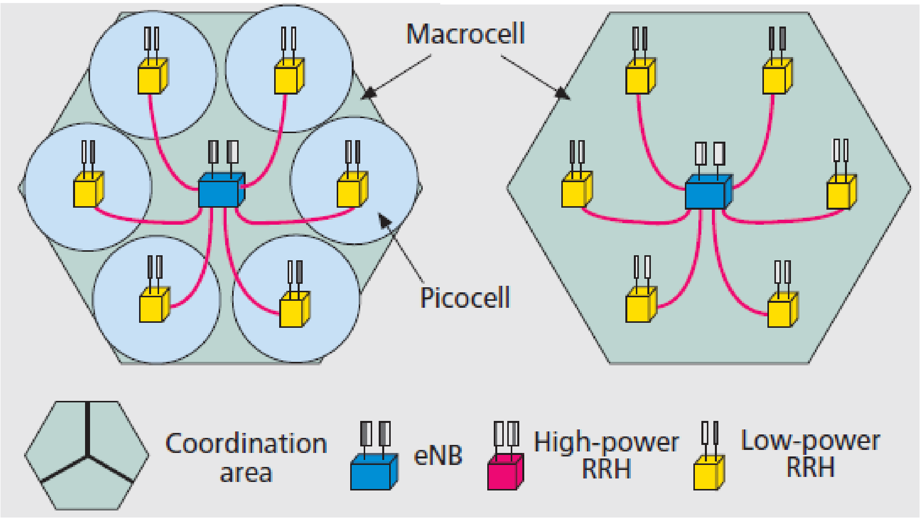
CoMP Scenarios used for evaluation

- Homogeneous as well as heterogeneous scenarios with macro cells and low power nodes

1) intra site CoMP **2) homogeneous inter site CoMP**



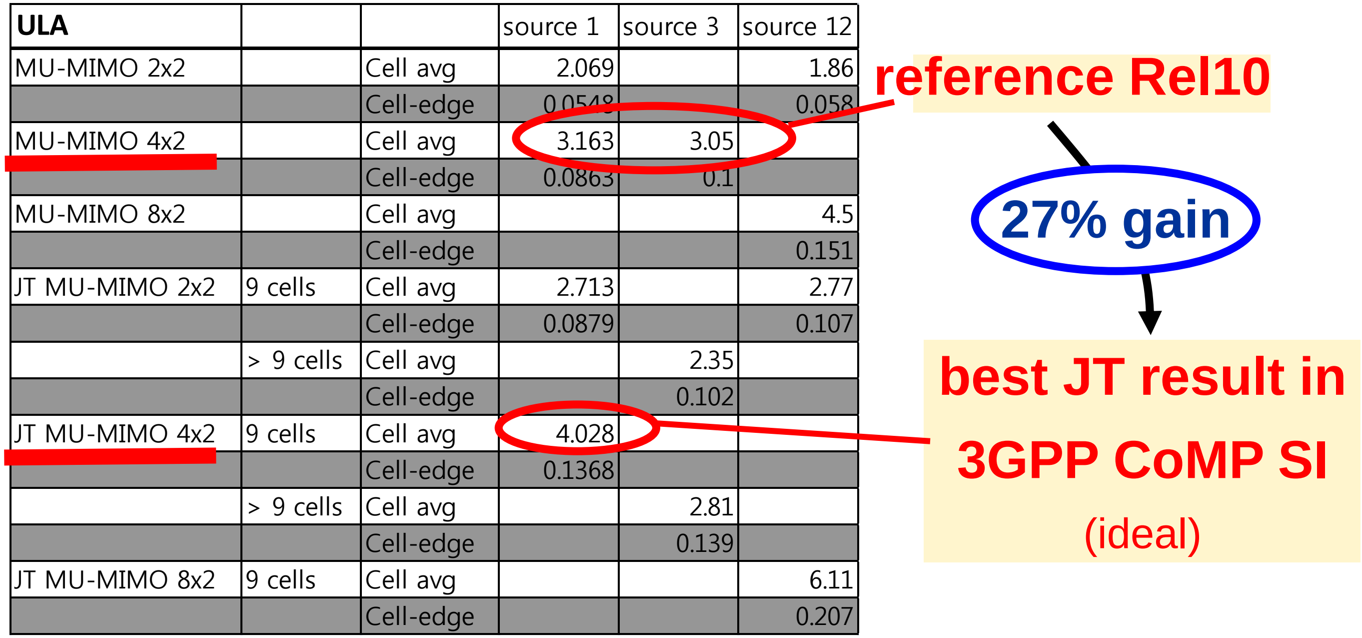
3) heterogeneous setup independ cell ID **4) heterogeneous setup same cell ID**



[Source: Lee et.al. 2012]

Current Status in 3GPP

3GPP simulated CoMP gains



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[Source: 3GPP,
TR 36.819 V11.0.0
(2011-09), Table 7.2.1.2-5]

Current Status in 3GPP

- Up to 8 transmit antennas in the downlink
- Differences between theory and 3GPP:
  - Rayleigh channel models in theory, SCM in 3GPP
  - Evaluations with perfect channel estimation also in 3GPP
  - Network wide (theory) vs. clustered (3GPP) precoding
  - Outdoor to indoor penetration loss in 3GPP leads to noise limitation.
- Tools for interference measurements in Release 11
- No specific support for joint transmission CoMP in Release 11
  - Improved feedback would need to be standardized
  - No new Reference symbols
- Specification for MIMO can potentially be used for CoMP as well
  - CSI reference symbols defined in Release 10 probably adequate
  - Channel feedback
- Uplink joint detection can potentially be implemented without changes on the air interface.

Theory and Practice

Main messages of Section

What we learned from theory

- Linear MIMO gain requires high S(I)NR and uncorrelated channel realizations.
- Cell edge SINR in a non-cooperative cellular system is very low due to inter-cell interference or penetration loss for indoor users.
- Joint signal processing (network MIMO) can be used to exploit inter-cell propagation.
- Large gains of joint signal processing in toy scenarios and simplified system level simulations with network wide cooperation.

What we see in practical implementations

- Additional practical impairments.
- 3GPP system level simulation results show small network MIMO gains.

EVALUATION OF KEY CHALLENGES AND ENABLERS FOR DOWNLINK JOINT TRANSMISSION

Downlink JT Key Challenges and Enablers

Signal Processing and System Design

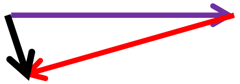
- Transmitter CSI
    - ☐ Channel estimation, accuracy requirements
    - ☐ CSI feedback: Outdating, overhead and quantization
    - ☐ Channel prediction
    - ☐ Zero-forcing linear precoding
    - ☐ Use of accuracy estimates in robust linear precoders
- Complexity of network wide cooperation
    - ☐ Clustering: Cooperation areas
    - ☐ Inter-cluster interference floor, complexity of cooperation
- Backhaul aspects (topologies, technologies, capacity, latency)
- Time and frequency synchronization of base stations

CSI: Special Needs for Downlink CoMP

Channel estimation and prediction

- Coordinated beamforming requires information on ”forbidden” directions /signal subspaces for interference avoidance.

- Coherent joint transmission furthermore requires ***accurate channel phase estimates*** for interference cancellation.
  Signal subtraction (interference cancellation) is sensitive:



- ***Channel estimates from several base stations*** in cooperation area:
  - ❑ Adequate estimation quality for the weakest channels?
  - ❑ Orthogonal reference signals within CA: density/overhead tradeoff.

- FDD Downlinks: ***Uplink reporting load*** for channel estimates.

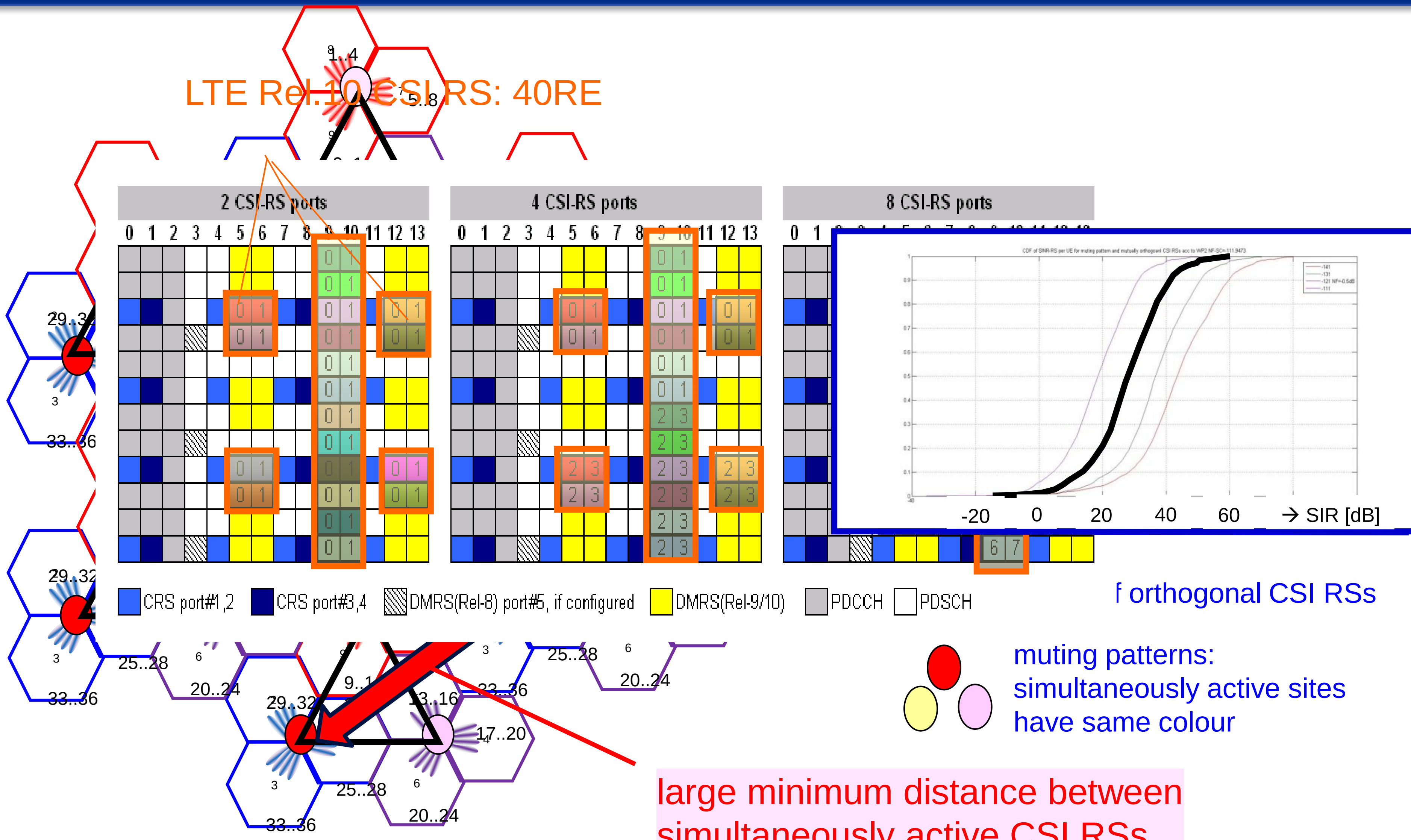
- Non-static users, transmission feedback delay + CoMP delays
  => ***Channel outdating.*** Problems already at pedestrian velocity.
  => Need for channel ***prediction,*** based on most recent estimates.

- Residual phase rotation of channels (synchronization inacuracies, phase noise) can be tracked by channel predictors.

CSI: Channel Estimation, LTE Rel 10 CSI RSs

- including interference floor shaping. Ref. signal SIR statistics

LTE Rel.10 CSI RS: 40RE



f orthogonal CSI RSs

muting patterns:
simultaneously active sites
have same colour

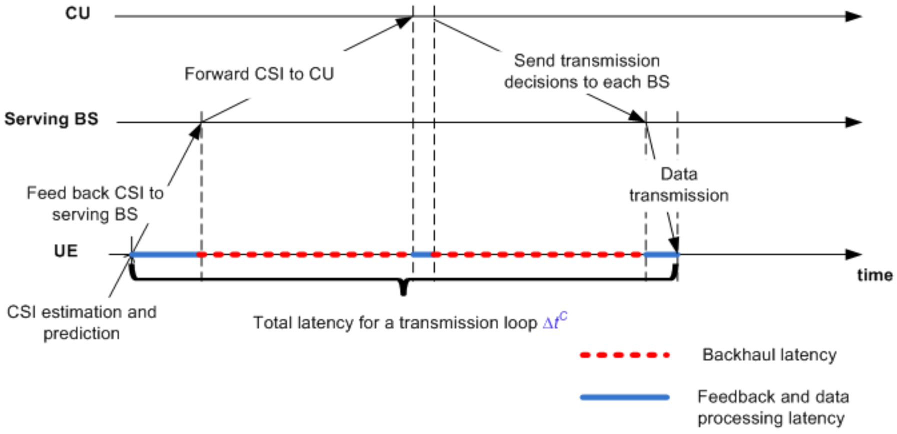
large minimum distance between simultaneously active CSI RSs

CSI Feedback

Outdating, overhead and quantization for Centralized joint transmission

FDD systems:

- Outdating: *Feedback +proc.delay(5 ms) +2 x Backhaul latency(1-20ms)*. Problematic at pedestrian velocities at > 2.0 GHz carriers.
- Uplink overhead: A few Mbit/s over a 10-20 MHz uplink* (complex numbers or gain + phase).



TDD systems:

Using uplink estimates for downlink:

- Outdating: *2 x Backhaul latency*.
- Overhead: Uplink pilots from *all users, in all utilized RBs*, detected in *all* cells.

Out-of CA-interference is not reciprocal. May need uplink feedback as in FDD.

Quantization:

8 bits per complex channel results in small linear precoder performance loss.

Should also report CSI reliability!

***[EU FP7 Artist4G Project Deliverable D1.4, Section 5.3.3. https://ict-artist4g.eu/]**

CSI: Channel Prediction Performance

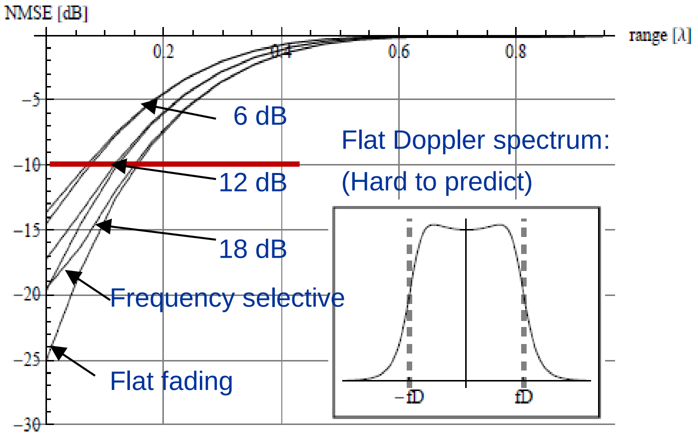
using Kalman prediction (optimal linear MMSE prediction)

Example: Predicting 4 channels for

- Different Doppler spectra
- Ref. signal SIR = 6 ,12 & 18 dB.

e.g. prediction NMSE -10 dB (indicated) is attainable for 0.1- 0.3 wavelength horizon, or 8 ms – 24 ms at 5 km/h at 2.66 GHz.

Attainable dB cancellation by coherent JT CoMP = Normalized Mean Square Error (NMSE) of channel estimates.



6 dB

12 dB

18 dB

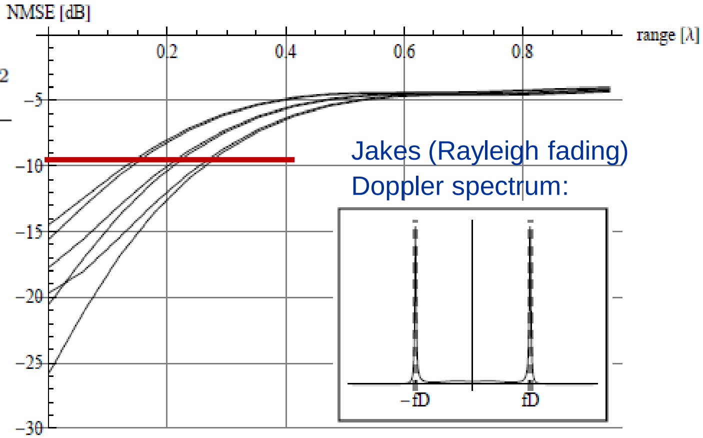
Frequency selective

Flat fading

Flat Doppler spectrum:

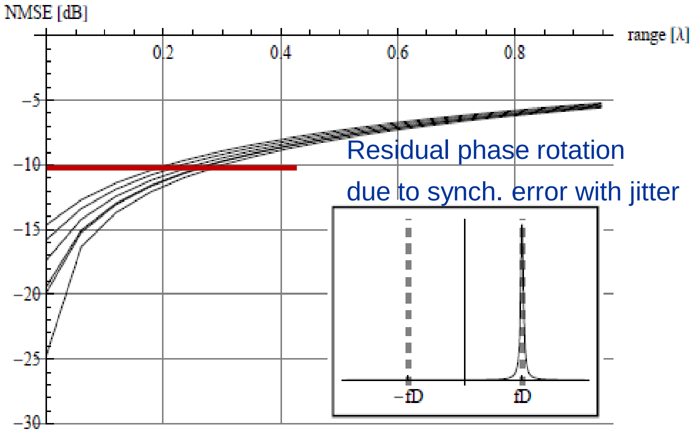
(Hard to predict)

$$NMSE = \frac{\sum_{t=1}^{N} |\hat{h}_t - h_t|^2}{\sum_{t=1}^{N} |h_t|^2}$$



Jakes (Rayleigh fading)

Doppler spectrum:



Residual phase rotation

due to synch. error with jitter

[See Daniel Aronsson, *Channel Estimation and Prediction for MIMO OFDM Systems: Key design aspects of Kalman-based algorithms*. PhD Thesis, Signals and Systems, Uppsala University, March 2011, Chapter 6.5.]

CSI: Zero-Forcing (ZF) Linear Precoder

using estimated/predicted channels from transmitters in CA

Downlink channels within OFDM resource block: Complex matrix *H.*

Pre-inversion by zero forcing precoder *W* when estimate $\hat{H}$ is invertible:

$$W = \left(\hat{H}\right)^{-1} D$$

When # transmitters > # receiver antennas within cooperation area:

Regularized pre-inversion or ***Moore-Penrose pseudoinverse:***

$$W = \left(\hat{H}^{*}\hat{H} + \rho \mathrm{I}\right)^{-1} \hat{H}^{*} D \qquad W = \hat{H}^{*}\left(\hat{H}\hat{H}^{*}\right)^{-1} D$$

The precompensated channel matrix is ideally $HW = D$

The „target matrix“ D is (block)diagonal and contains per-stream gains.

These gains can be optimized to maximize e.g. a weighted sum rate, under per transmit antenna power constraints.

Large eigenvalue spread of channel matrix leads to precoders that have small gains for nearest BS => Still interference cancellation, but bad SNR. ***Power normalization loss problem***.

CSI: Robust Linear Precoder

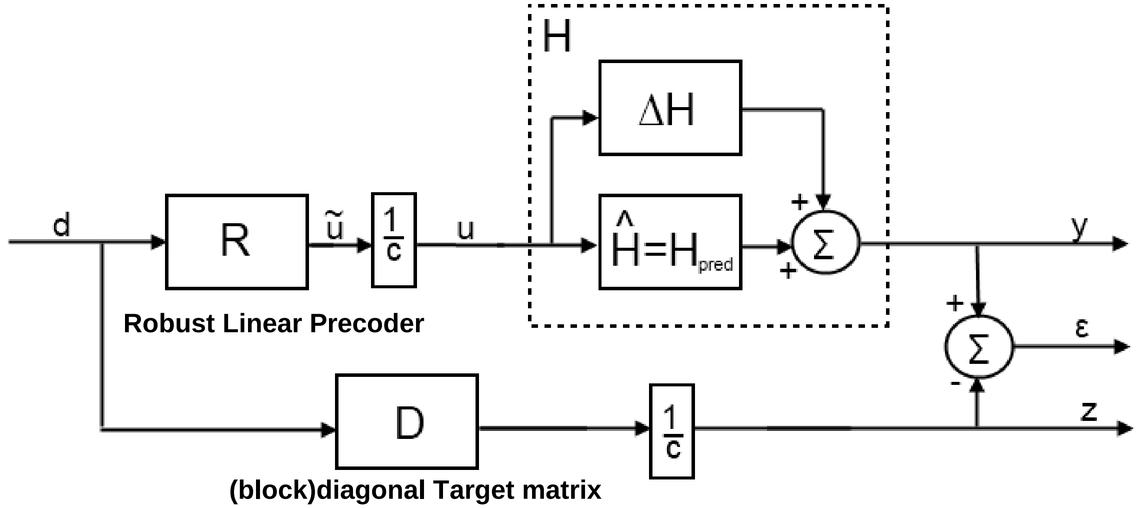
Taking channel accuracy (covariance) information into account

Kalman predictors provide prediction uncertainty $\bar{E}\{\Delta H^*\Delta H\}$.

CoMP precoder should be designed by taking all relevant information into account.

- We may use a scalar criterion: $J = \bar{E}\left[E|V\varepsilon(t)|^2 + E|Su(t)|^2\right]$
- The precoder minimizing J is then:* $R = \left(\hat{H}^* V^* V \hat{H} + S^* S + \bar{E}\left[\Delta H^* V^* V \Delta H\right]\right)^{-1} \hat{H}^* V^* V D$

Weights V and S can be adjusted iteratively to optimize *SINR, local capacity, utility*…**



d(t)	Transmit symbols for *M* users
u(t)	Transmit signal, *N* transmitters.
y(t)	Received signal excl. noise
z(t)	Target signals at receivers
ε(t)	Error signal (*M*-vector)
R	Precoding matrix (*N* x *M*)
H	Channel matrix (*M* x *N*)
H_{pred}	Predicted channel matrix
ΔH	Prediction error matrix, E(ΔH)=0
D	Target system (*M* x *M*), diagonal
S	Transmit power penalty matrix (*N* x *N*), usually diagonal, ≥ 0
V	Error penalty matrix (*M* x *M*),>0
c	Scalar transmit scaling factor

*** K. Öhrn, A. Ahlén and M. Sternad, ”A Probabilistic approach to multivariable robust filtering and open-loop control”, *IEEE Trans. on Autom. Contr, vol. 40,* March 1995, pp. 405-417 .**

**** R. Apelfröjd, M. Sternad and D. Aronsson ”Measurement-based evaluation of robust linear precoding in downlink CoMP”, *IEEE ICC 2012, Ottawa* .**

CSI: Accuracy Requirements per CA

- example ARTIST4G

$$\hat{\mathbf{H}} = \mathbf{H} + \Delta\mathbf{H}$$

$$\mathbf{W} = pinv(\mathbf{H})$$

$$\hat{\mathbf{W}} = pinv(\hat{\mathbf{H}})$$

$$\Delta\mathbf{W} = \mathbf{W} - \hat{\mathbf{W}}$$

Channel quantization and prediction errors cause violation of multi-user orthogonality!

$$\hat{\mathbf{Y}} = \mathbf{H}\hat{\mathbf{W}}; \quad \mathbf{SIR} = \frac{diag(\hat{\mathbf{Y}})}{\sum(\hat{\mathbf{Y}} - diag(\hat{\mathbf{Y}}))}$$

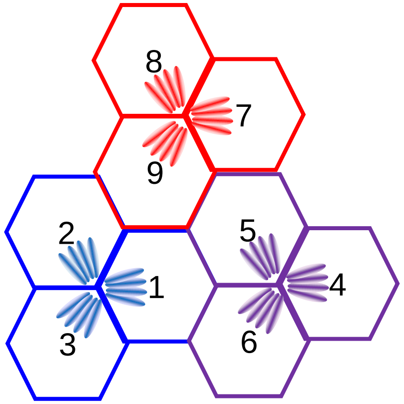
$$\overset{<-26\ldots40\text{dB!}}{\Delta \mathrm{CSI}_{\max}} \le \underbrace{\overset{-20\text{dB}}{\Delta \mathrm{CSI}_{target}} + \overset{0..-20\text{dB}}{\Delta \mathrm{CSI}_{PNL}}} + \overset{\text{xxxdB}}{\Delta \mathrm{CSI}_{\Delta W}}(\Delta\mathbf{H}) + \overset{-1..-5\text{dB}}{\Delta \mathrm{CSI}_{prediction}} - \overset{+1..x\text{dB}}{\Delta \mathrm{CSI}_{IP}}$$

system design
+
fine tuning

depends on
quantization
+
# of relevant CCs

depends on
prediction range
+
UE mobility
+
channel variations

interpolation gain
# of RSs, PRS,f+t-variation



4 WB beams per cell
full cooperation
3 active UEs / cell

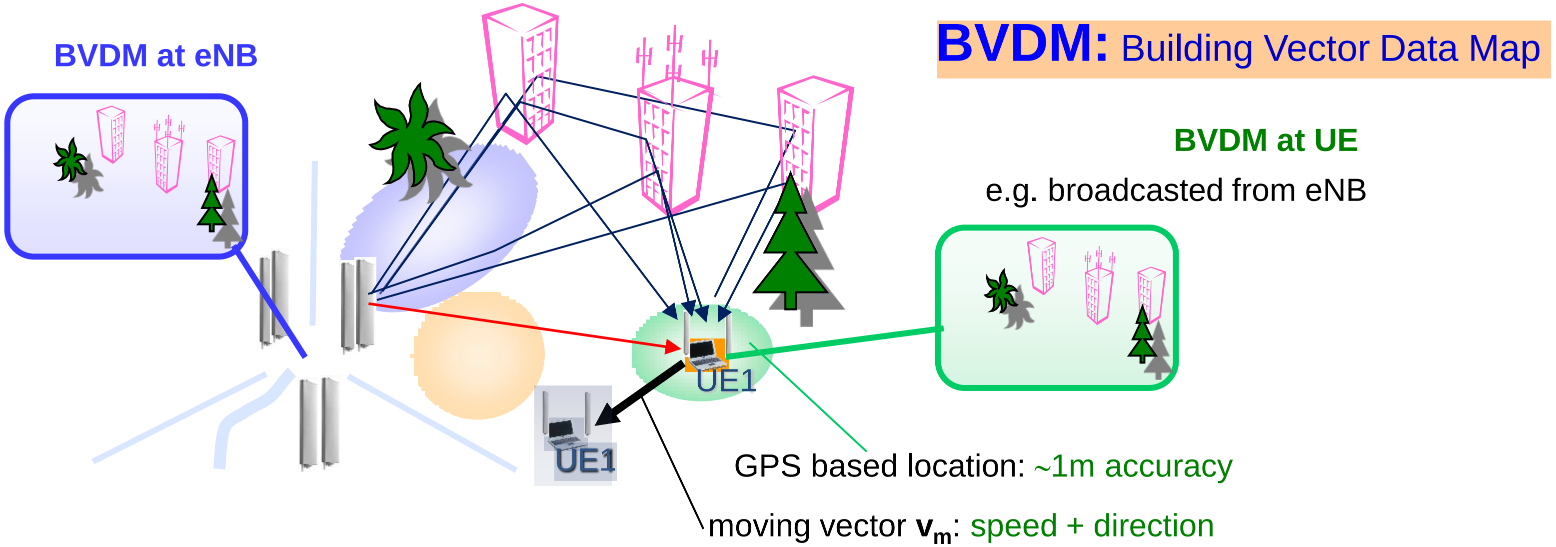
CSI: Long-term Vision

- Model Based Channel Prediction

Massive MIMO and JT CoMP: CSI accuracy is the main limitation

SoA: Wiener or Kalman filtering → prediction to about 0.1 λ - 0.3 λ

Approach: combine SoA with model based channel prediction.



BVDM: Building Vector Data Map

BVDM at eNB

BVDM at UE

e.g. broadcasted from eNB

GPS based location: ~1m accuracy

moving vector $\mathbf{v}_m$: speed + direction

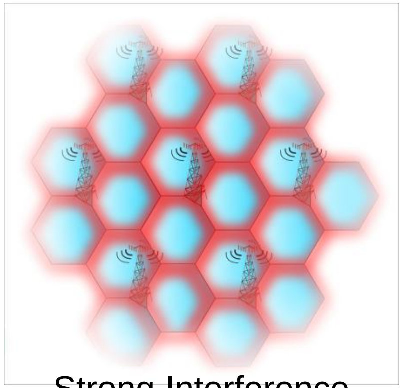
- **eNB** broadcasts **BVDM** and **CSI RSs**
- **UE Positioning** within BVDM (GPS localization + channel matching)
- **Feedback** of UE 3D Position + moving vector + ΔCSI extreme FB compression!!??
- **eNB**: **reconstruction** of DL CSI within BVDM
- **predict CSI** evolution based on moving vector $\mathbf{v}_m$

Complexity of Network-wide Cooperation

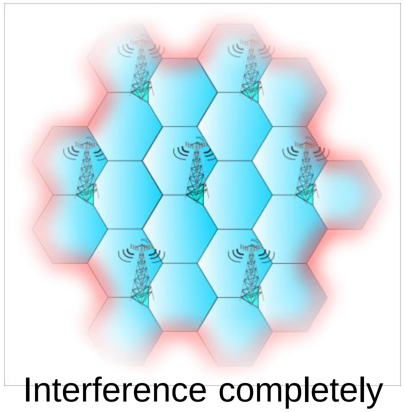
Cooperation Areas

Different degrees of cooperation have different influence on interference

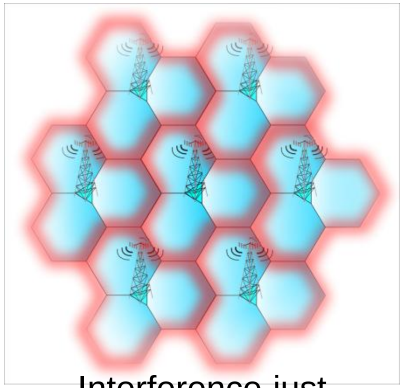
- No Cooperation
  - Strong interference between cells
- Full Cooperation
  - Interference completely avoided
  - Needs full CSI for the whole network (not realistic)
- Cooperation area (*'CA'*)
  - Cooperation only inside of a limited number of sectors
  - **Inter-CA interference limits gains, even for large CAs!**



Strong Interference without cooperation



Interference completely avoided by full cooperation



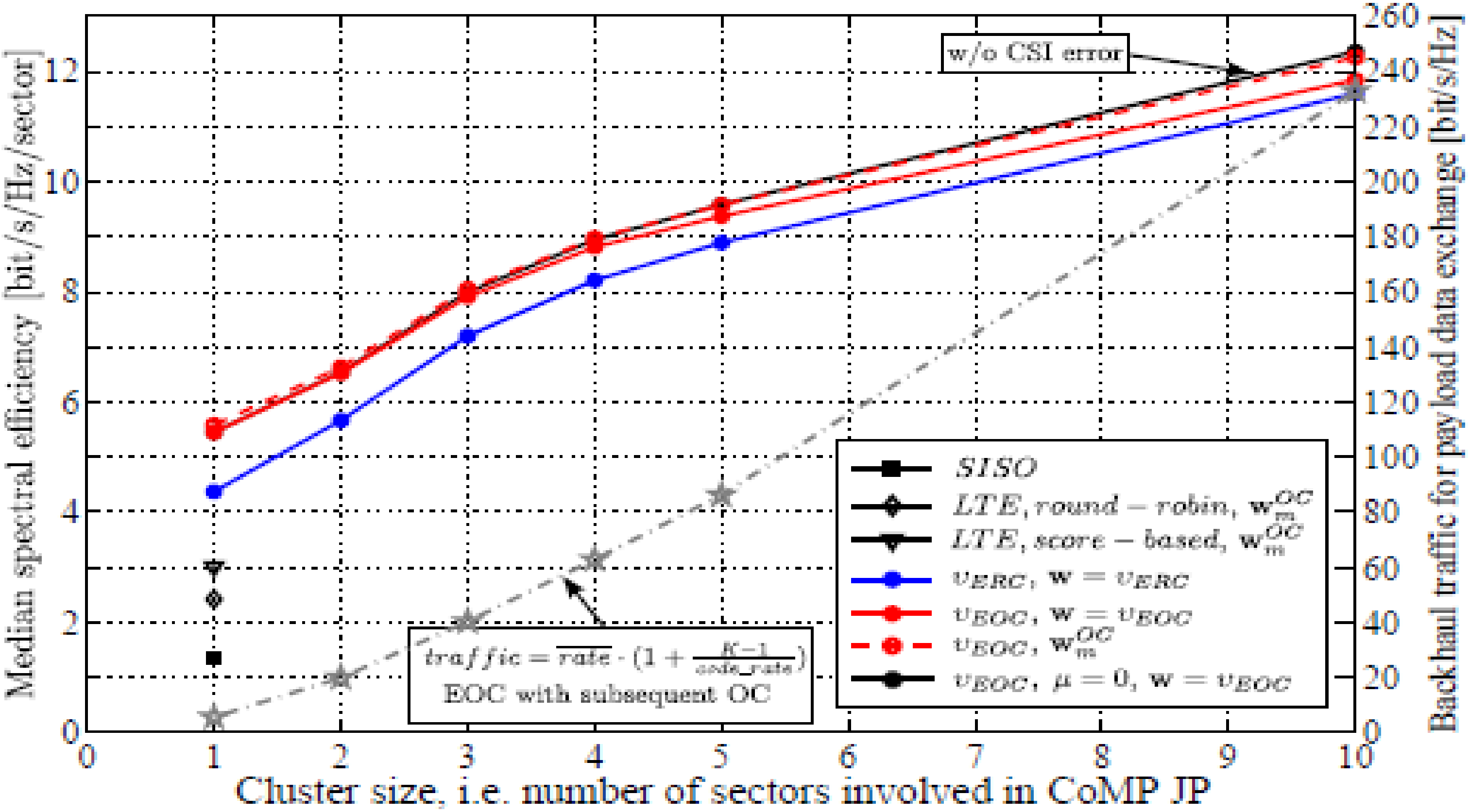
Interference just between cooperation areas

Complexity of Network-wide Cooperation

Inter-cluster interference floor vs CA size

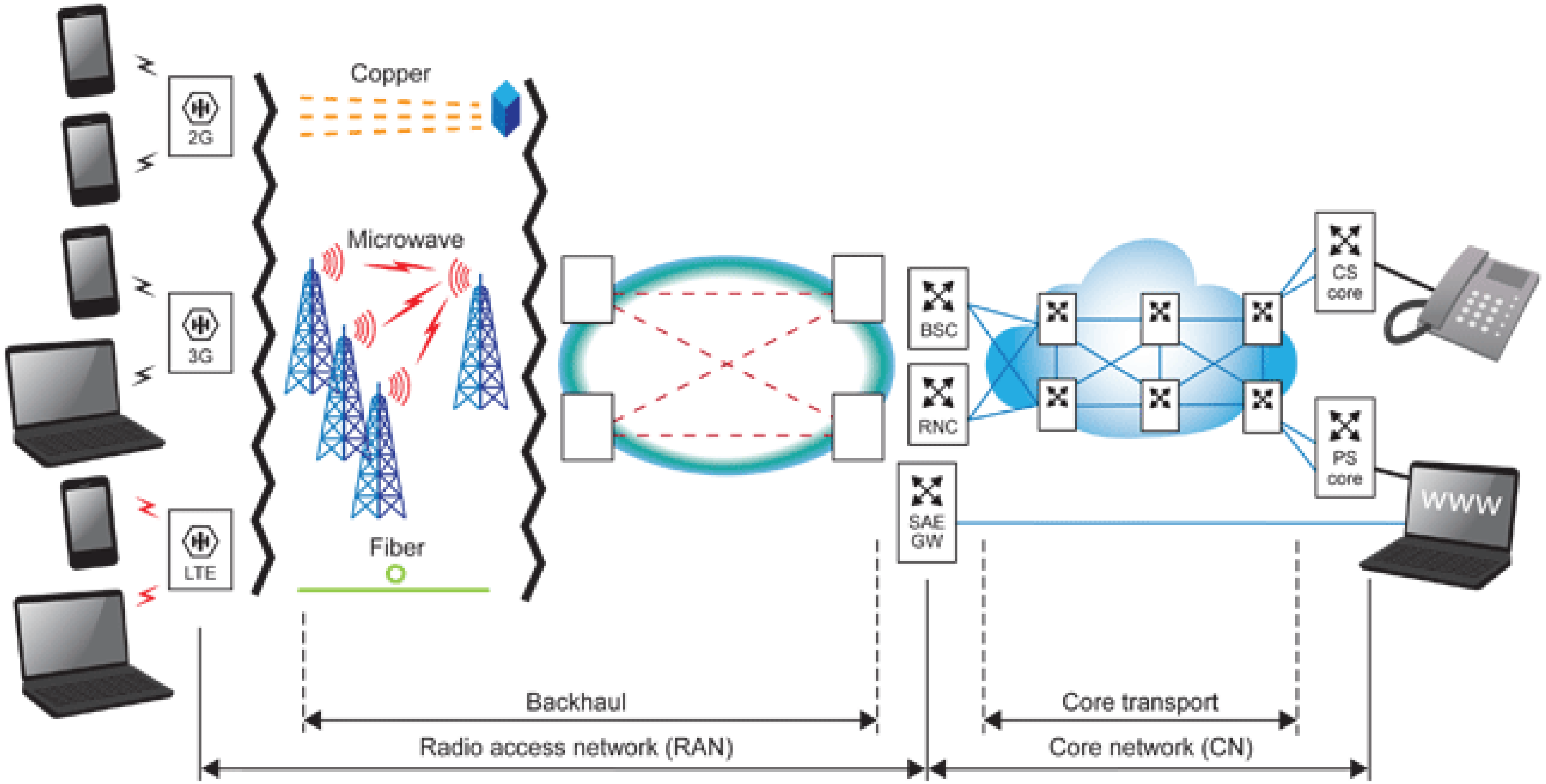
Performance asymptotically increasing with cluster size

Inter-cooperation area interference is a serious limitation.

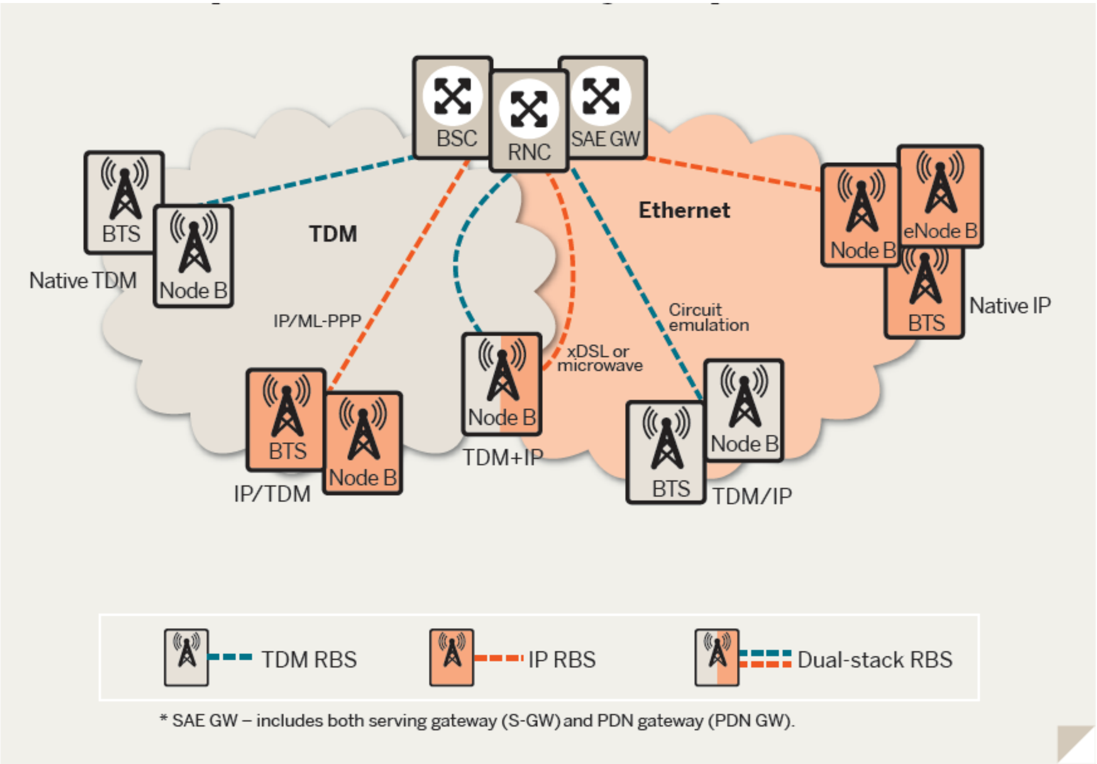


[Source: Lars Thiele et.al., Chapter 6.3 in P.March ed. *Coordinated Multipoint in Mobile Communications*, 2011]

Backhaul Media and Architecture

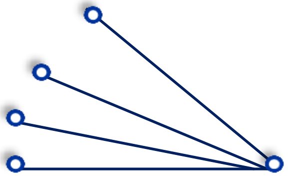


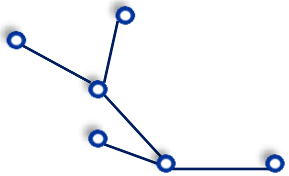
Backhaul Protocols and Topologies

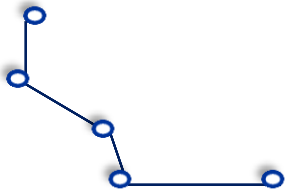


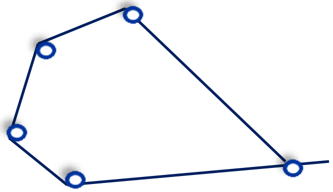
* SAE GW – includes both serving gateway (S-GW) and PDN gateway (PDN GW).

Source: R. Chundury "Mobile broadband backhaul: Addressing the challenge", Ericsson Review No. 3, 2008. © Ericsson AB 2013- All Rights Reserved.

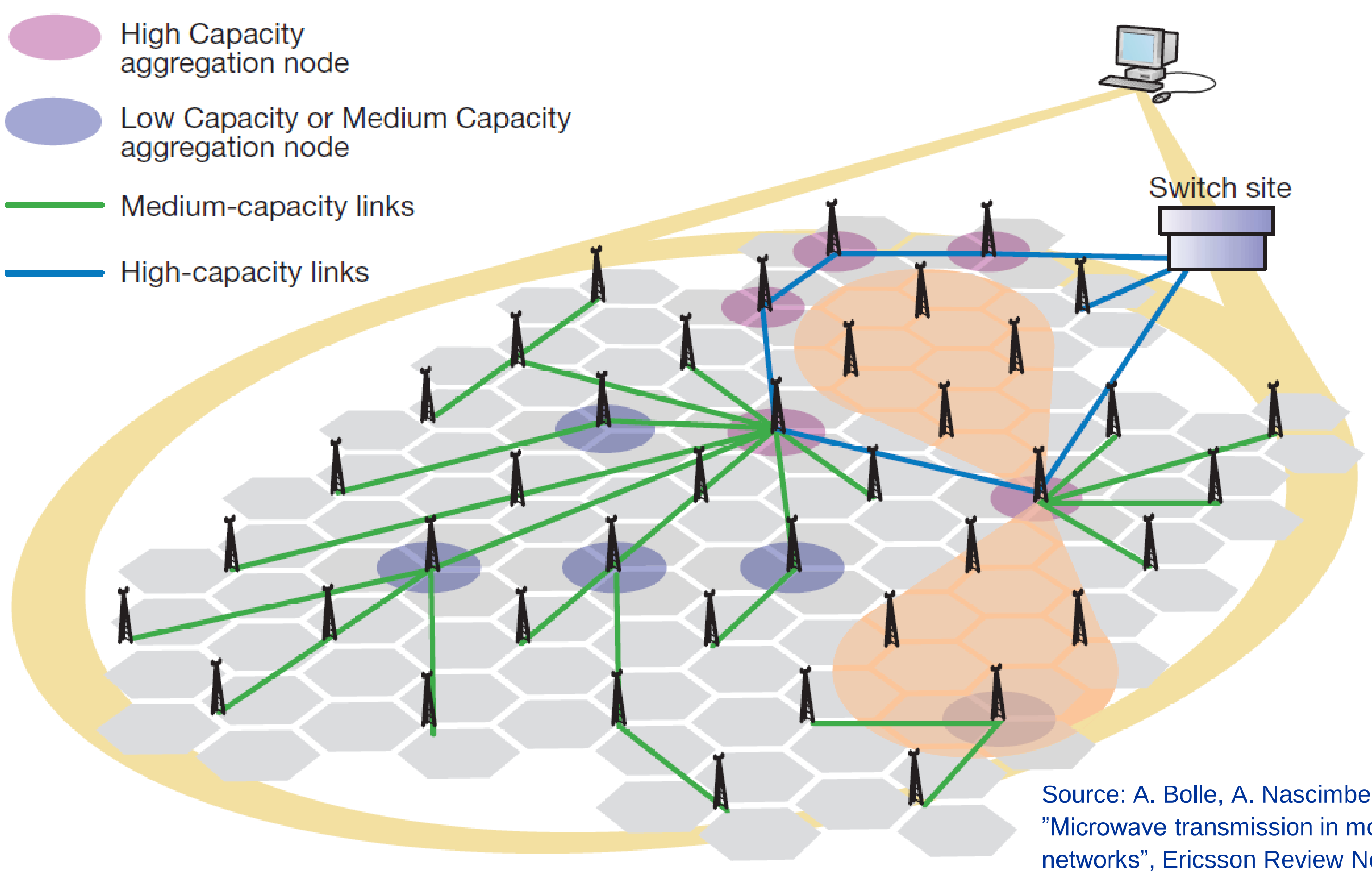

Star


Tree


Chain


Ring

Backhaul Networks

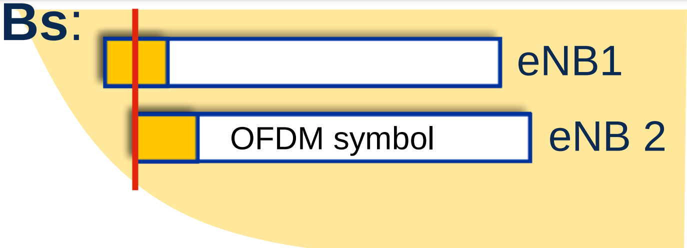


Source: A. Bolle, A. Nascimbene ”Microwave transmission in mobile networks”, Ericsson Review No. 3, 2002. © Ericsson AB 2013- All Rights Reserved.

- => Heterogenous Backhaul networks
- => Inter-BS connections with heterogeneous connectivity, capacity and latency.

Synchronization Issues

- **Time- and frequency synchronization btw eNBs**:
  - is essential basic enabler
  - In 3GPP sometimes argument against JT CoMP



GI should cover: Δt_{sync} + delay spread + $\Delta\tau_{1\text{-}2}$

- **Requirements** [**LTE**: SC spacing 15kHz, SF length 1ms, GI: 4.7μs, FB delay 10ms]:
  - **Time**: within fraction of an OFDM guard interval (< one to very few μs)
  - **Frequency**: ideally below 0.1ppb at RF of 2.6GHz
  - **Phase Noise** (>100Hz): can't be compensated → requires high Q LOs

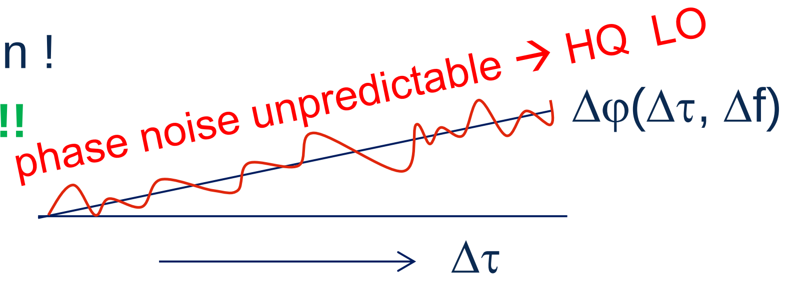
- **Options for frequency synchronization**:
  - *GPS + tight synchronization* with extremely stable TXOs (see demo systems)
  - IEEE 1588v2 - precision time protocol (PTP): avoids GPS, accuracy unclear
  - *over the air synchronization*: based on UE feedback (single value per eNB!)
  - *CSI reporting with channel prediction*
    - e.g. based on simple linear prediction

Frequency Synchronization

A) Inter carrier interference: neglectable for typical Δf of about 100Hz ☺

B) inter eNB phase drift:

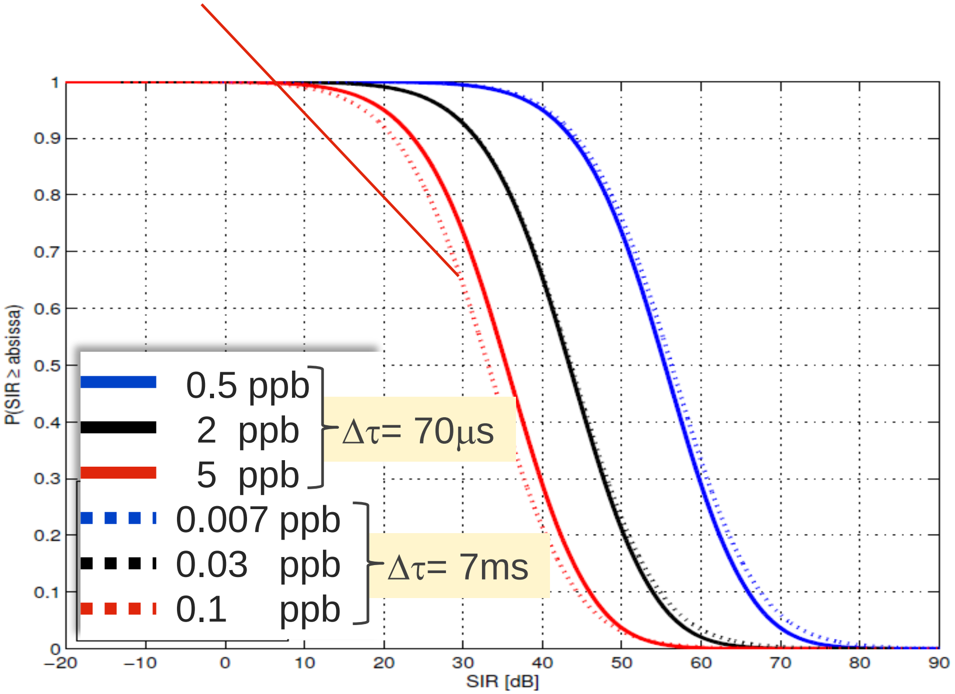
- ☐ Δτ= 10ms and Δf= 100Hz →Δφ(10ms) = 0.01*100Hz= 360° !!!
- ☐ tight synchronization or (linear) CSI prediction !
- ☐ **0.1 ppb →** Δφ(7ms) = 0.007*0.26Hz= **0.6° !!!**



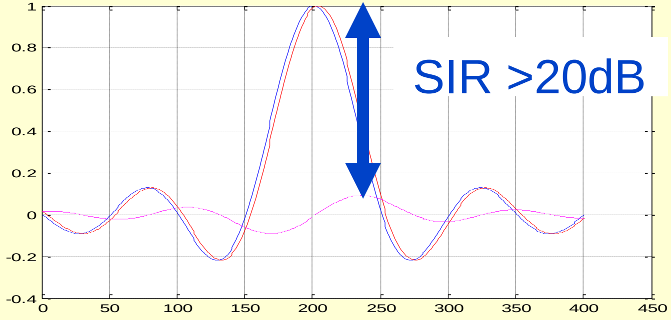
phase noise unpredictable → HQ LO

Δφ(Δτ, Δf)

Δτ



A) Inter carrier interference



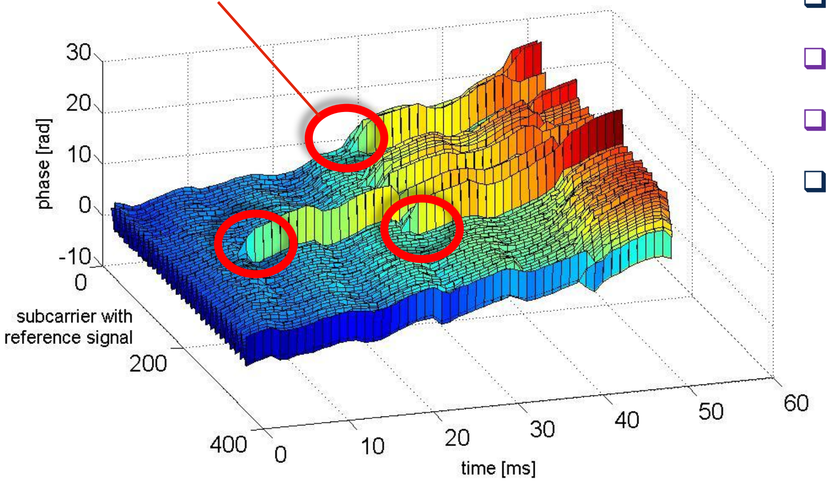
Inter carrier interference for Δf=500Hz

LTE: Δf=<100Hz

[K. Manioakis, V. Jungnickel, "Synchronization requirements for OFDM-based cellular networks with coordinated base stations: Preliminary results"]

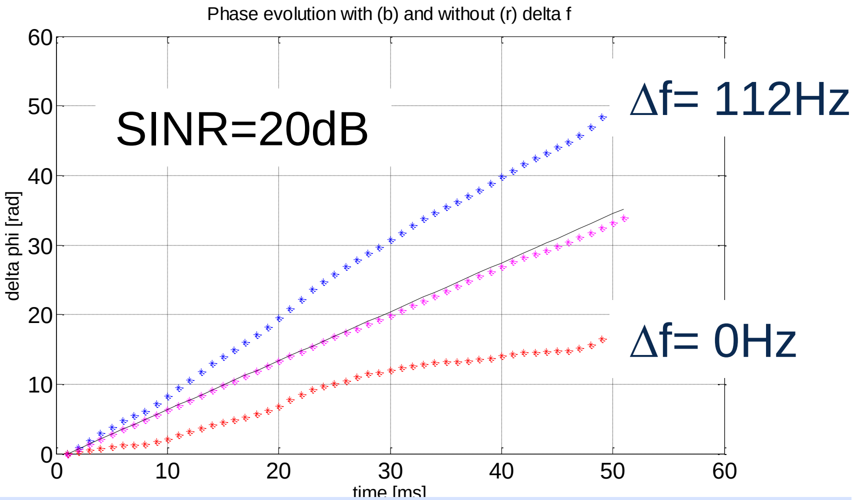
Frequency Offset Estimation + Feedback

advanced → detect phase jumps



- phase evolution of radio channel
- **UE speed = 10m/s**
- **Δf = 112Hz**
- Ray tracing simulation including birth and death of multi path components

- **red**: mean phase evolution, Δf= 0Hz
- **blue**: mean phase evolution, Δf= 112Hz
- **magenta**: est. phase rotation
- **black**: phase rotation for Δf= 112Hz



- linear Δf estimation → **few Hz** estimation error
- advanced estimation → **< 1Hz possible**

ARTIST4G HARMONIZED FRAMEWORK

Goal: To Increase Attainable CoMP Gains

Signal Processing and System Design

Creative engineering thinking

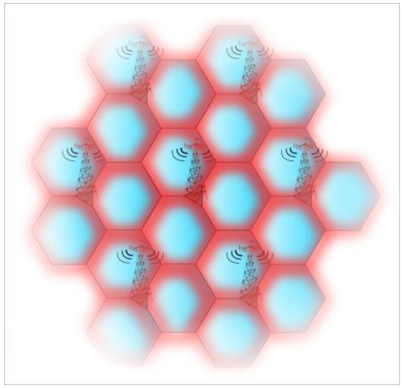
- What are the potential game changers?
- In which research directions should we go?

- System level concept: Some pieces of the puzzle:
  - ❑ clustering
    - interference floor shaping
  - ❑ user grouping, (robust) precoding, scheduling and resource allocation
    - what is the optimum based on interference function?
    - optimal linear beamforming (including power constraints)
    - relationships between user grouping and linear/non-linear precoding
    - effects of resource allocation, loading and DoF
    - recognize practical limitations and implementation constraints
  - ❑ receiver capabilites
    - use of interference rejection combining

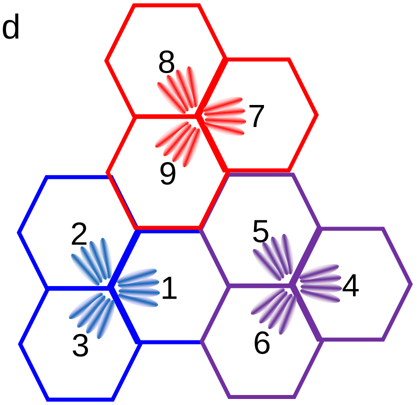
Main Investigated Scenario

- **Target scenario close to 3GPP case 1**:
  homogeneous macro cellular network with19 sites and overall 57 (128) cells

Number of eNBs:	57
Number of sites:	19
Cells per site:	3
Sector width:	120 deg
Height of UEs / eNBs:	1.6 / 25m
Number of PRBs:	32
Bandwidth per PRB:	180 kHz
TxAEs, RxAEs:	4 x 2
Antenna configurations:	ULA, $\lambda/2$ spacing
Algorithm for JP:	ZF or robust JT
Channel modell:	SCME
ISD:	500m
CSI:	Ideal
Number of UEs per cell:	10



Interference limited
macro scenario

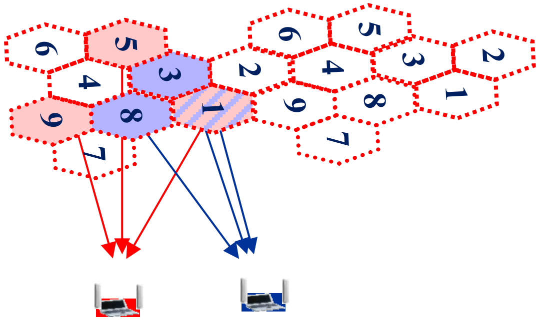


4 static wideband
beams per cell

→no flashlight effect
→ small loss compared to free TX beamformers

Clustering

Clustering: Enlarged Cooperation Areas



User-centric clustering would be ideal.

Problem with User-centric clustering :

very low number of UEs wish same set of cells

→ low penetration rate and / or low CoMP gain

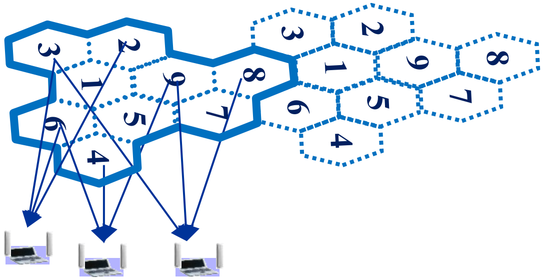
even w extensive optimization unsolvable!!

Solution Step 1): ***Use static, but enlarged, cooperation areas***

3 sites a' 3 cells leads to CAs of 9 cells

practical approach with limited number of backhaul links

high number of UEs having 3 strongest cells in one 9-cell-CA



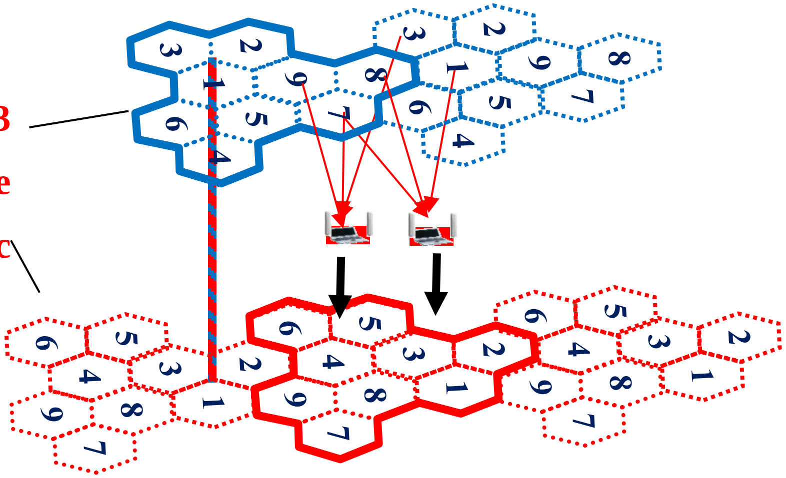
Clustering: Cover Shifts

Solution Step 2): Cover Shifts

Cover shifts are orthogonal resources like frequency subbands or time slots used for *overlapping* setup of cooperation areas

eNBs schedule UEs into one or more best fitting cover shift(s)

→ e.g. 90% of UEs served user centric (3 strongest cells within CA)



cover shift 1

cover shift 2

With six cover shifts all UEs having their 3 strongest cells within 3 adjacent sites are being served user centric

Note: this remains a frequency reuse 1 system!

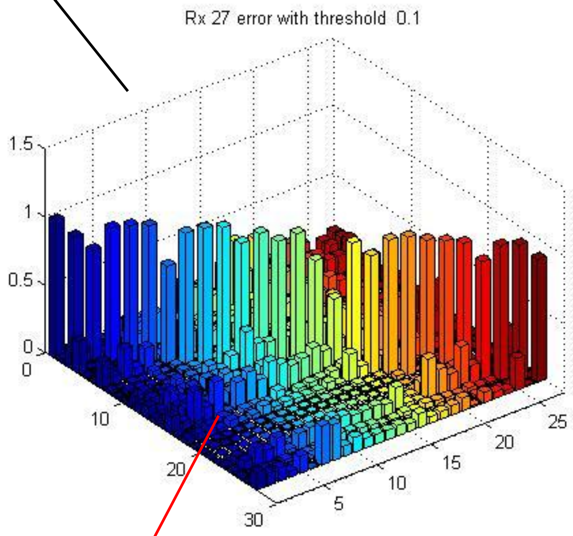
Partial Reporting, to limit feedback overhead

Solution Step 3): Partial Reporting = partial CoMP

a) semi-static feedback of pathloss based on RSRP measurements

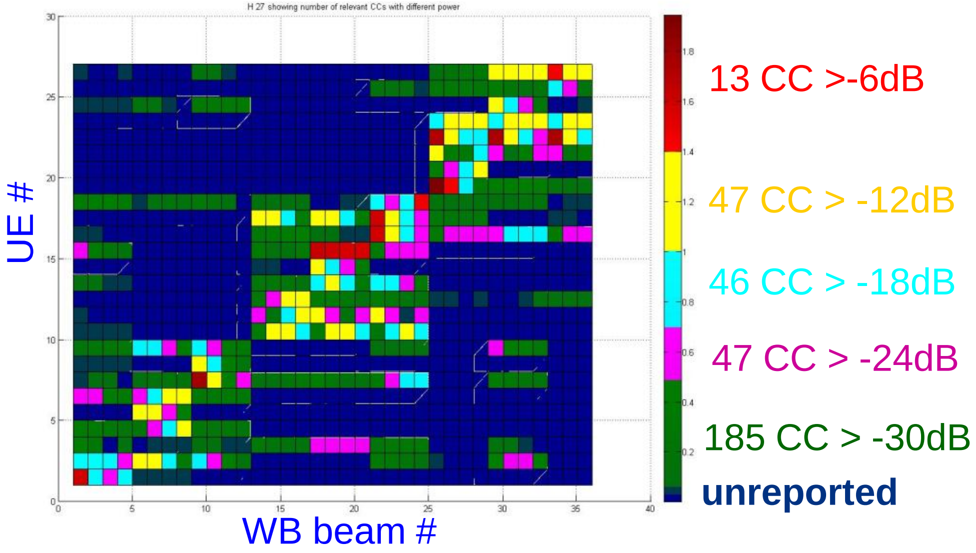
b) limit reporting to channel components > predefined threshold.

Y = H * W', **W'** is precoder matrix calculated for partially reported CSI



Rx 27 error with threshold 0.1

channel matrix **H**: 27UE x 36WB beams



13 CC >-6dB

47 CC > -12dB

46 CC > -18dB

47 CC > -24dB

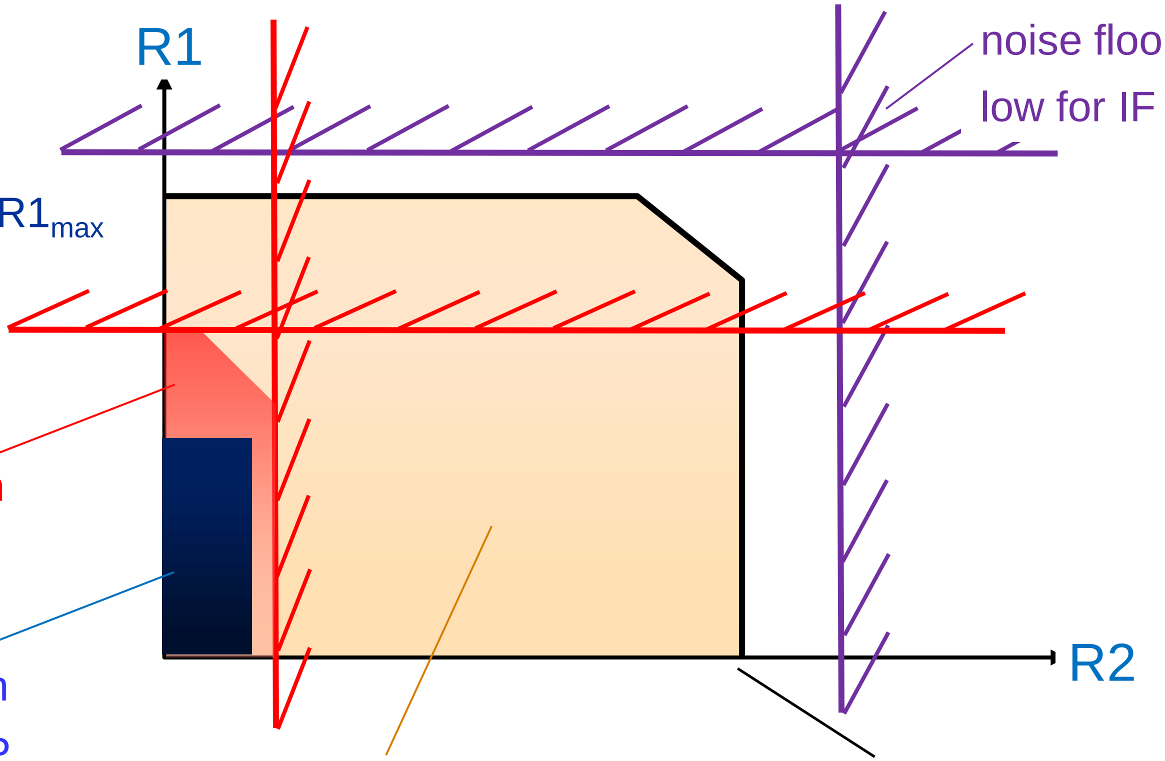
185 CC > -30dB

unreported

off diagonal elements due to precoding errors require careful system design

Interference Floor Shaping

Rate Regions versus Interference Floor



noise floor:

low for IF limited scenarios

max MCS → R1$_{max}$

rate region

w IF floor

rate region

w/o CoMP

optimum rate region for CoMP

max MCS → R2$_{max}$

Significant loss due to IF floor &

small gain over non CoMP case

Interference Floor Shaping: ‘Tortoise’ Concept

Goal: Reduce inter-CA interference

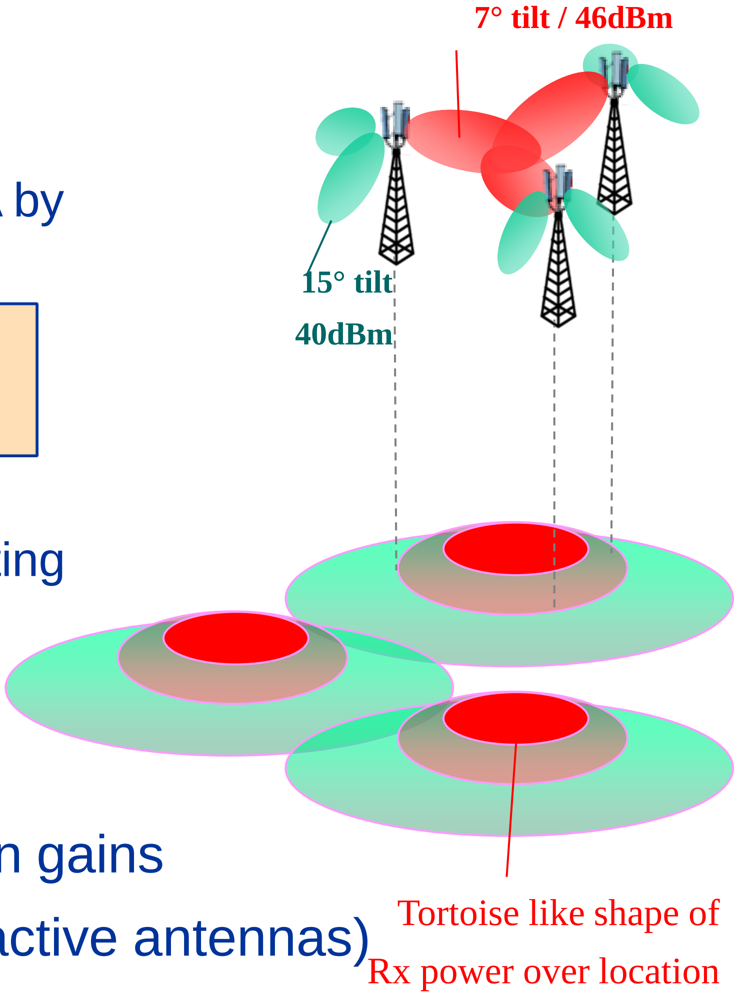
Tortoise Concept:

Generate tortoise like power distribution per CA by cell specific antenna tiltings:

> CA **center**/**outbound** wideband beams
> with **low**/**strong** tilt & **strong**/**low** Tx power

Per cover shift, serve mainly CA-centric UEs

(CA edge UEs are scheduled into other best fitting cover shift.)

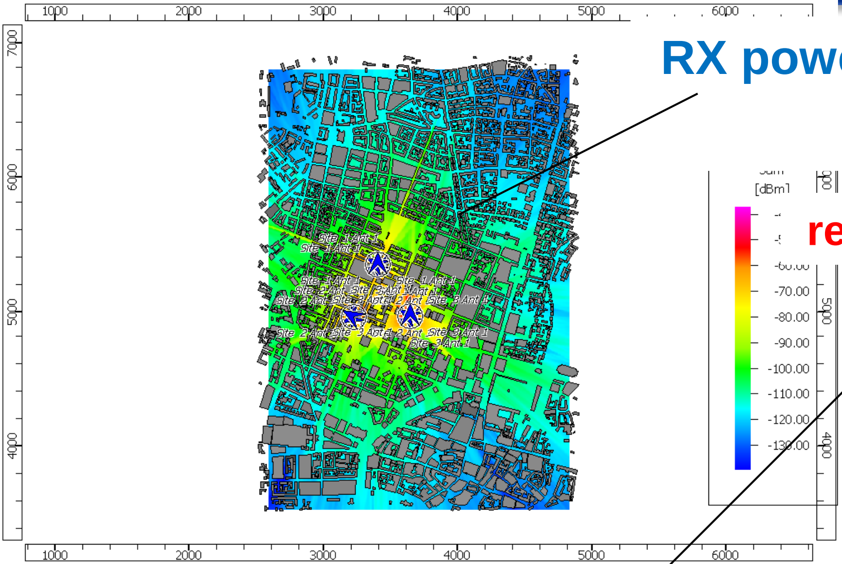


Benefits:

- Approaching network wide cooperation gains
- Robust and simple solution (e.g. use active antennas)
- Decoupling of CAs → optimization per CA possible.

Interference Floor Shaping:

Evaluation by ray tracing simulation

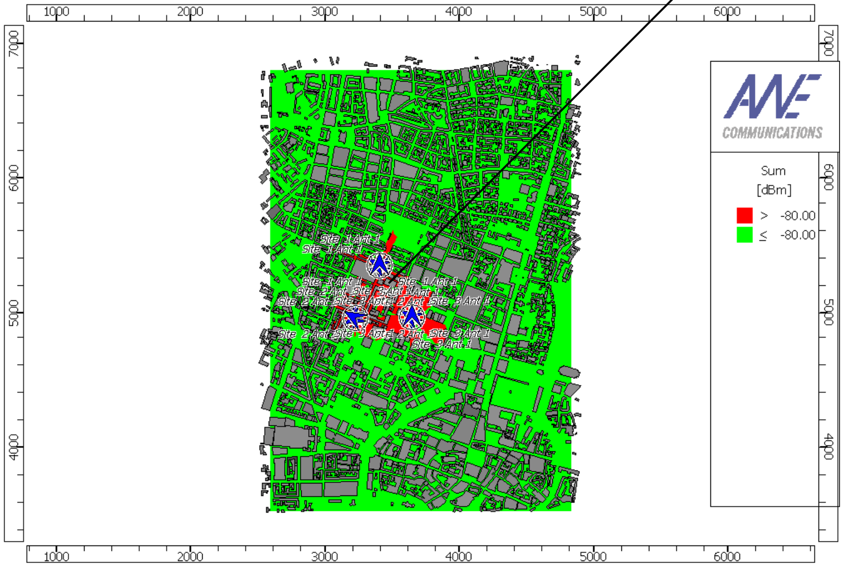


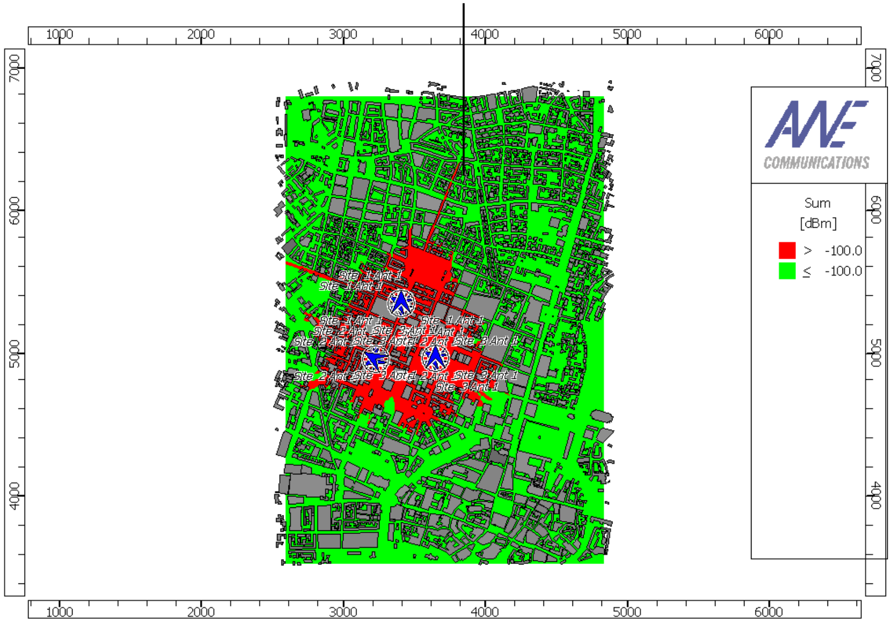
RX power for single tortoise (3 sites) in Schwabing area of Munich

red: CA center with zero dB Rx power

→ fast decline of IF power

green: Rx power <-20dB





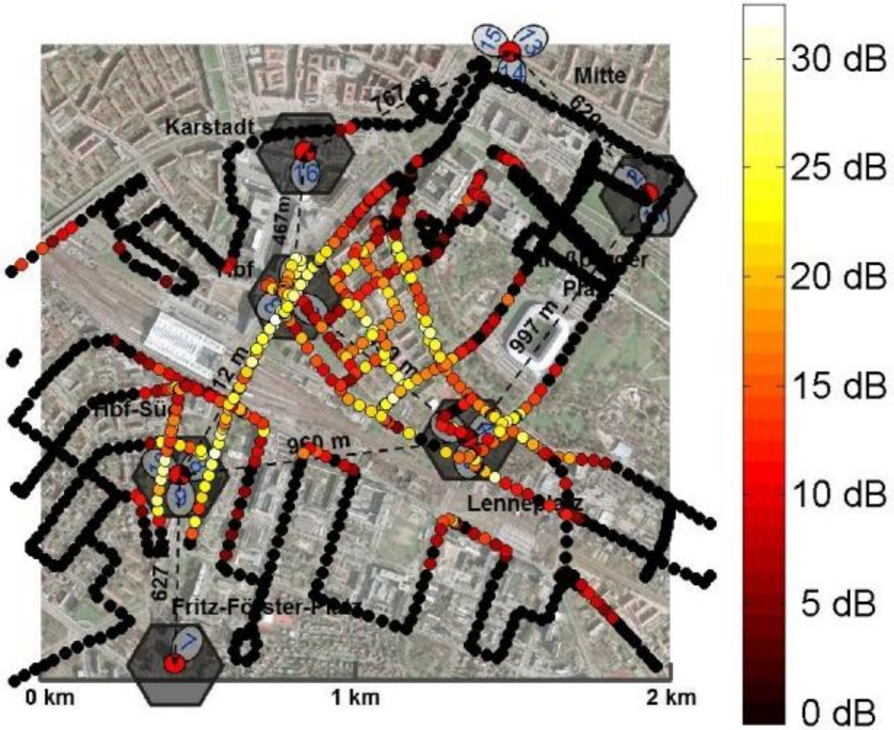
Interference Floor Shaping:

TUD real world measurements of tortoise concept

TUD testbed: pathloss measurements for 27 cells

→ realistic serving and interfering cells

→ close to intended ideal ‚tortoise‘ shape

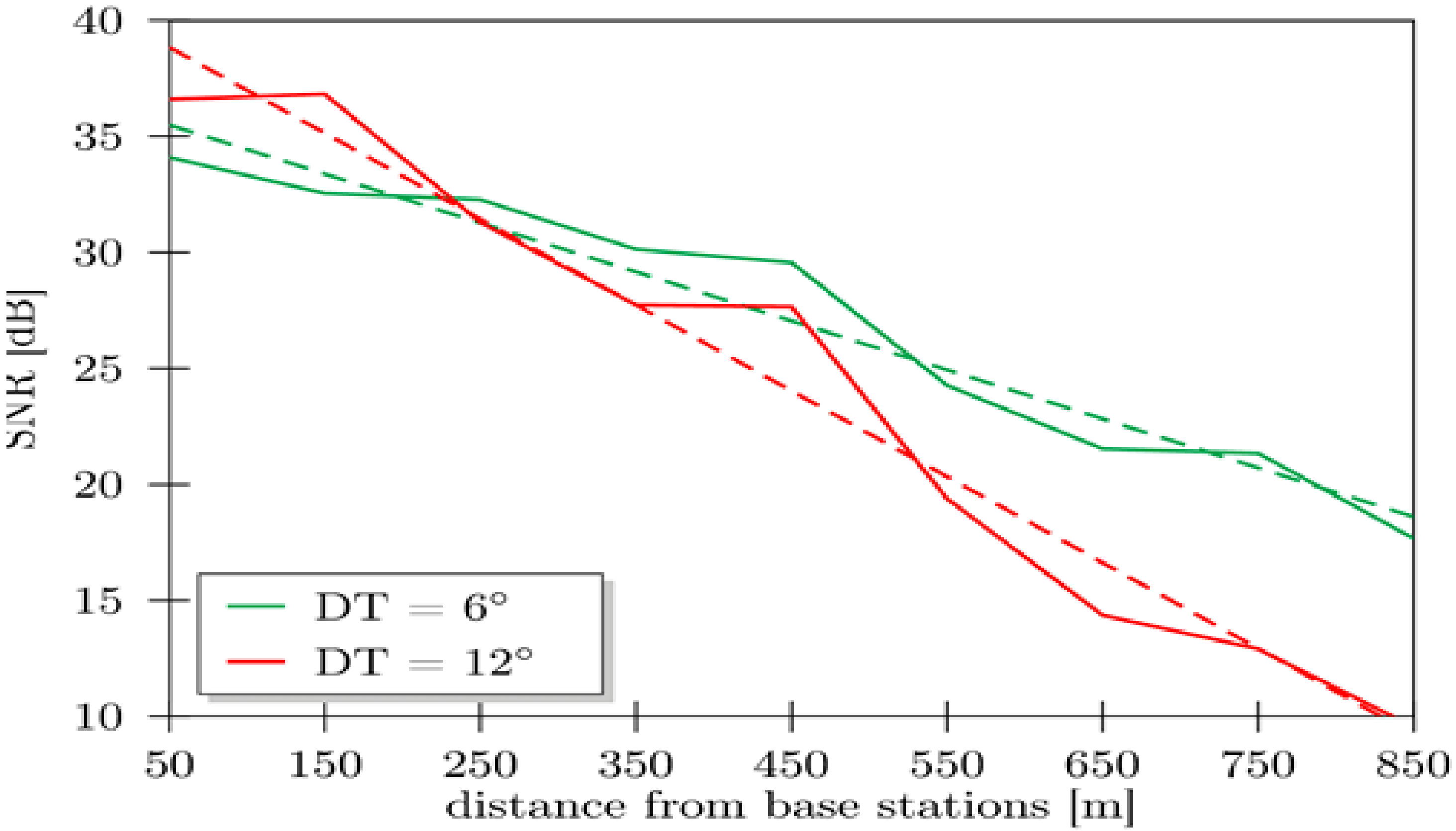


[Mennerich et. al]

single tortoise Rx power

Interference Floor Shaping:

TUD real world measurements of Tortoise concept



Effect of antenna tilting similar to modeled and close to ray tracing investigations.

Two Stage Scheduler

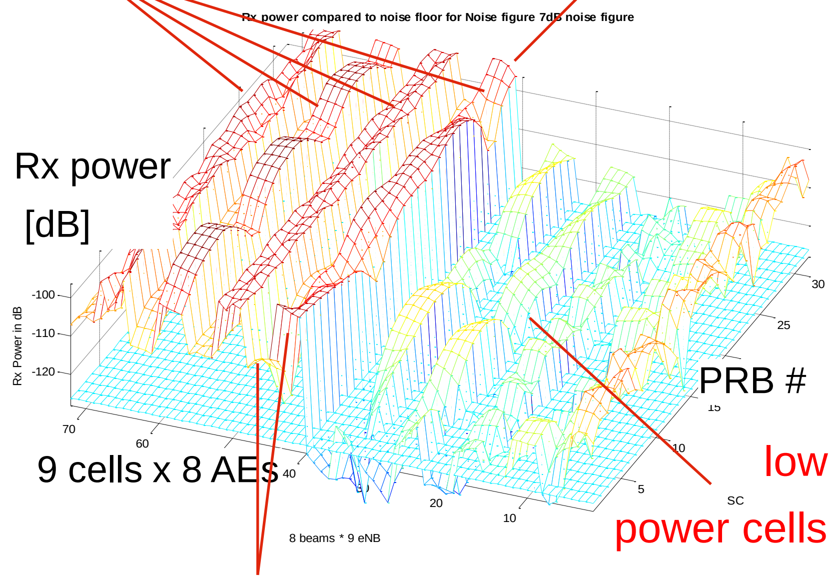
Radio Channel Conditions Within a CA

Power differences and (large) Singular value spread

- **The radio channel conditions:** (SCME case 1)
  - ❑ define the upper performance bound
  - ❑ are very important for a proper system design
  - ❑ Relevant parameters are e.g. correlations, power distributions, etc.

inter cell rank enhancement

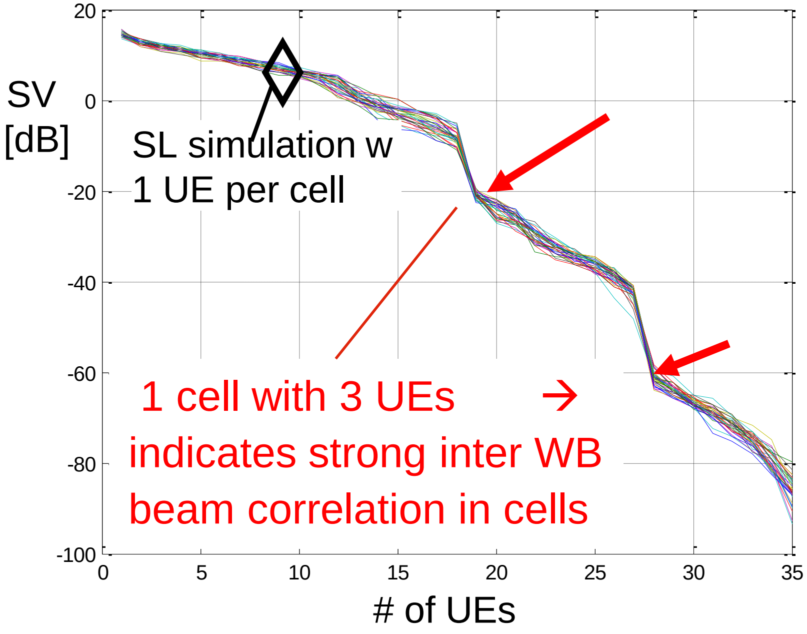
WB beam correlation per cell



low power cells

power variation due to antenna tilt

Singular values for randomly chosen UEs



SL simulation w 1 UE per cell

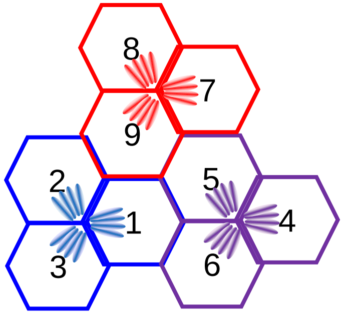
1 cell with 3 UEs → indicates strong inter WB beam correlation in cells

=> Coherent JT CoMP problematic for random user locations

Two Stage Scheduling Strategy

Stage 1: Scheduling (and MU-MIMO) designed per cell

- **Goal**:
  - ❑ Suitable performance versus complexity trade off
  - ❑ Reuse current LTE schedulers as far as possible



single CAs

- **Approach**: Exploit inherent physical channel properties
  - ❑ Co-located antenna elements per cell with high correlation

    → in depth optimization per cell:
    - ‘Exhaustive’ search of optimum user groups per cell (3 out of 10 UE)
    - Proportional fair scheduling btw user groups → MU frequency scheduling gain
    - Include feedforward DL signaling for advanced Rx receivers (IRC-MMSE)
  - ❑ low correlation between sites → exploit rank enhancements
  - ❑ Tortoise → Optimization per CA sufficient

Result from this cell-specific user selections and beamforming: **User grouping.**

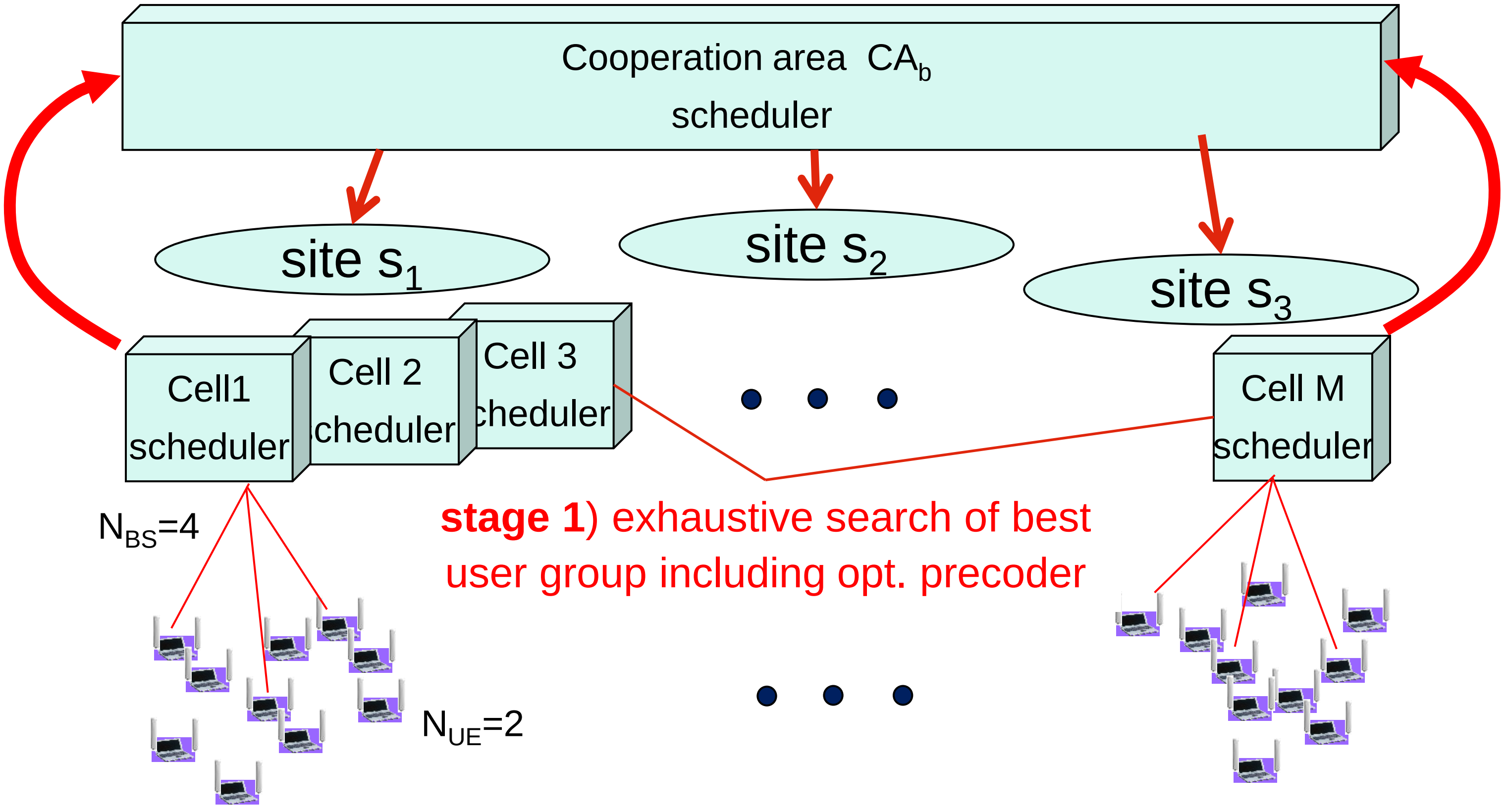
Sets of users in the CA with much better conditioned CA-wide channel matrices.

Two Stage Scheduling Strategy

Stage 2: CA-wide precoder design w. user groups by Stage 1

stage 2) calculate CA wide precoder for per cell user groups

\+ robust precoding + some fine tuning



stage 1) exhaustive search of best user group including opt. precoder

K=10 UEs per celll

Note: Cell schedulers assume no inter cell interference → single cell MU MIMO

Relative Performance Gains (ideal CSI)

Main evaluation case: 4 Tx, 2 Rx antennas, 3 site (9 cell) CAs

	SINR [dB]		**Spectral efficiency** bits/s/Hz/cell	**SE gain** [%]
	cell edge	average		
Network wide CoMP (1)	-	-	**8 / 15**(2)	**160**
Network wide CoMP with nonlinear precoding(1)	-	-	**11 / 20**	**250**
3GPP MU-MIMO	-	-	**3.1**	**0** (reference)
3GPP JP-CoMP	-	-	**4.0**	**30**
9-cell CoMP (3)	**-2**	**12**	-	-
+ cover shift (3)	**4**	**17**	-	-
+ IF floor shaping (3)	**12**	**23**	-	-
+ 2-stage scheduler (4)	**5**	**15**	**7.5 / 13** (2)	**140**

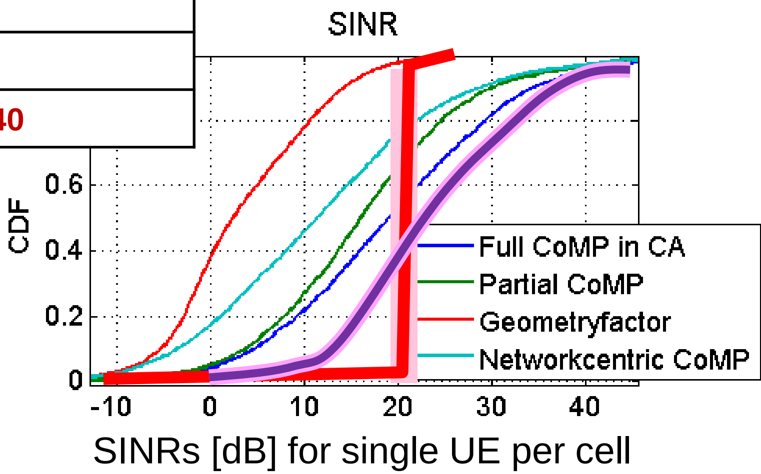
(1) Simulation conditions are not fully comparable; higher values are for nonlinear precoding

(2) Values after backslash ignore LTE overhead of 43%;

(3) SINR for single UE per cell and for 4x2;

(4) SINR for 2 to 3 out of 10 simultaneously scheduled UEs per cell and 4x2 configuration

Perfect transmitter CSI assumed in all evaluations above.

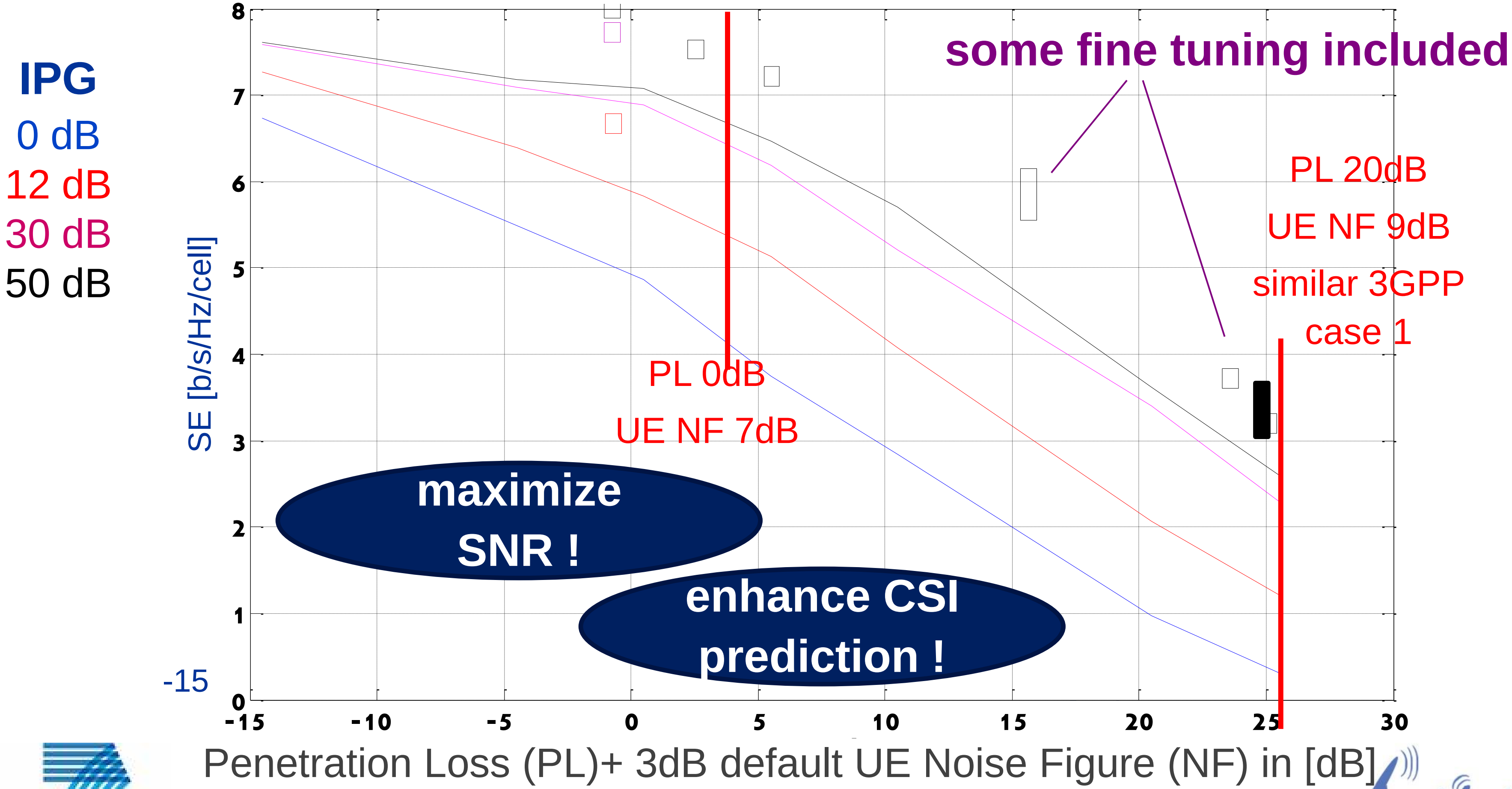


Downlink JT CoMP Performance with Imperfect CSI

Effects of Channel Estimation and SNR

Main evaluation case: 4 Tx, 2 Rx antennas, 3 site (9 cell) CAs

Effects of SNR and Channel estimator interpolation gains (IPG) = – (SNR-NMSE) [dB].



some fine tuning included

PL 20dB

UE NF 9dB

similar 3GPP

case 1

PL 0dB

UE NF 7dB

maximize SNR !

enhance CSI prediction !

PL: outdoor to indoor penetration loss; IPG: Interpolation Gain

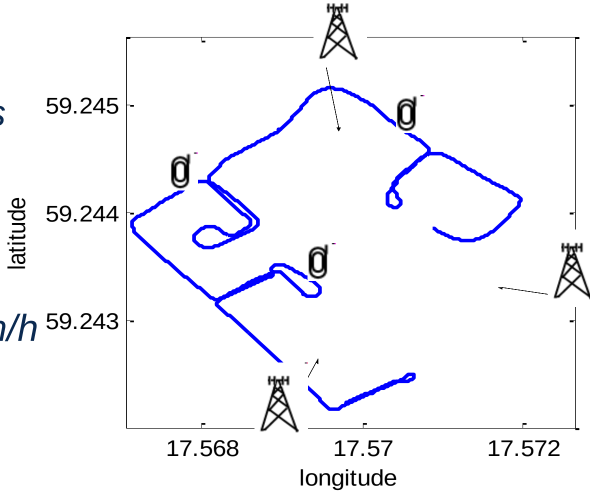
Performance Example. *1: Channel prediction*

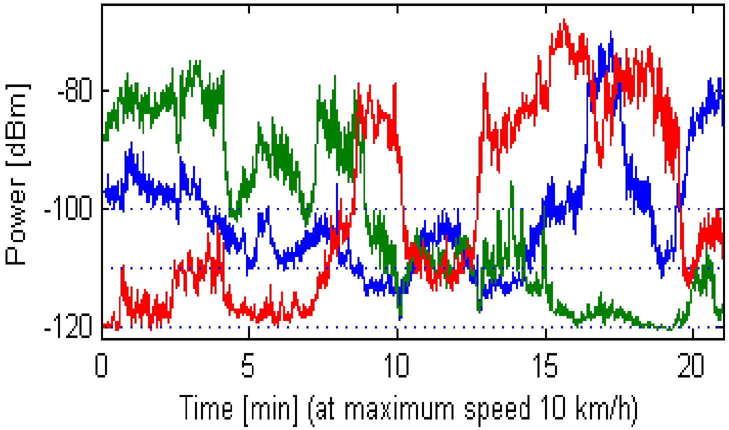
Using channel sounding data from Stockholm (by Ericsson)

Simultaneous Kalman prediction of single-antenna channels from three sites:

Measurements:

- *Single-antenna transmitters*
- *20 MHz OFDM channels*
- *15 kHz subcarriers*
- *2.66 GHz carrier*
- *Upsampled from 30 to 5 km/h*





Channel prediction:

- *Orthogonal ref. signals,*
- *Total RS overhead 1/9,*
- *Frequency-domain Kalman based on AR4 fading models.*

Average (over positions and subcarriers) prediction NMSEs, at noise level -120 dBm:

Prediction horizon (wavelengths)	In ms, at 5km/h	NMSE, weakest of 3 channels (Kalman)	Average NMSE for all channels (Kalman)	[By using *outdated CSI*:]
0	0 ms	- 12.7 dB	**- 23.9 dB**	- 23.9 dB
0.06	5 ms	- 9.4 dB	**- 15.3 dB**	- 12.5 dB
0.13	10 ms	- 7.4 dB	**- 12.9 dB**	- 7.9 dB
0.19	15 ms	- 5.9 dB	**- 11.2 dB**	- 5.0 dB
0.28	23 ms	- 4.1 dB	**- 9.2 dB**	- 2.1 dB

[EU FP7 Artist4G Project Deliverable D1.4, Appendix A4-2. https://ict-artist4g.eu/]

Performance Example. *2: User Grouping*

Two-stage scheduler for three single-antenna BS

The User groups are directly generated by the cellular scheduling

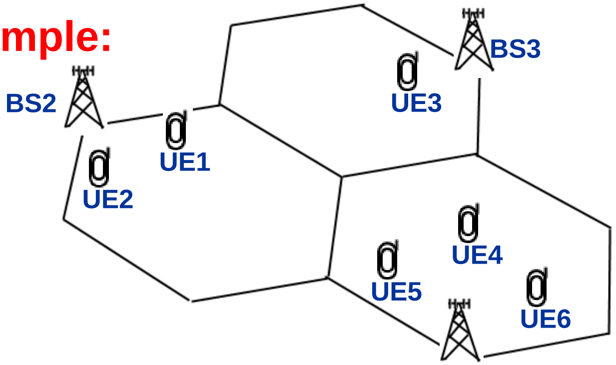
- Each user is allocated to a cell within the CA (the strongest BS).
- Scheduling performed *per cell* on orthogonal time-frequency resource blocks.
- A CA-wide joint transmission linear precoder is then designed for each RB.

⇒ All users in a RB belong to *different* BS/cells. They have different strongest BS.

⇒ Diagonal-dominant and well conditioned 3 x 3 channel matrices for each RB.

“Cellular grouping”

Example:



RB	UE1	UE2	UE3	UE4	UE5	UE6
1	🟥		🟥	🟥		
2		🟥	🟥		🟥	
3	🟥		🟥			🟥
4		🟥	🟥	🟥		
5	🟥		🟥		🟥	
6		🟥	🟥			🟥

<= CoMP group 1

<= CoMP group 2

•

•

•

[EU FP7 Artist4G Project Deliverable D1.4, Appendix A2-2. https://ict-artist4g.eu/]

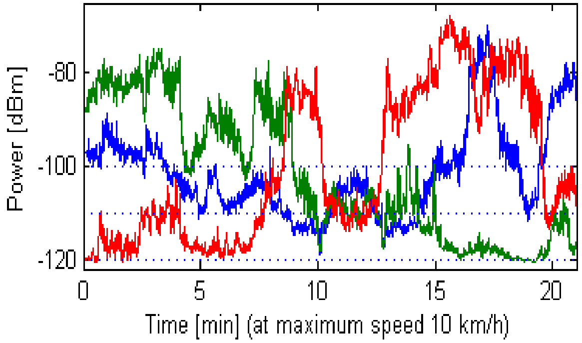
Performance Example. *3: Results*

CoMP vs reuse 1 cellular, for three single-antenna BS

- ***Measured channels*** for 1000 sets of 9 randomly placed users at (up to) 5 km/h.
- ***Kalman predicted channels, 10 ms horizon,*** used for precoding. Average IPG -11dB.
- User grouping (selecting 3 out of 9 users):
  ”Cellular grouping” as described above and **random grouping.**
- Round Robin (RR) and Score-based (SB) opportunistic scheduling.
- Interference: Similar to as when using ”Tortoise” scheme. Median SINR 24dB.
- Zero forcing (ZF) linear precoding used below.

Comparing Sum Shannon rates [bit/s/Hz/cell] (without overhead):

- **ZF JT CoMP with *random user grouping* is not competitive with cellular.**
- **55% improvement of average rates for *CoMP with cellular grouping* vs cellular.**



Transmit scheme => **Grouping and Sheduling:**	**CoMP** **Average**	**CoMP** **5% percentile**	**Cellular** **Average**	**Cellular** **5% percentile**
Random grouping with RR	**4.7**	0.79	**-**	-
”Cellular grouping” with RR	**7.6**	3.5	**4.9**	2.3
”Cellular grouping” with SB	**8.5**	4.8	**5.5**	3.5

[EU FP7 Artist4G Project Deliverable D1.4, Appendix A2-2, Table A.1 https://ict-artist4g.eu/]

Artist4G Harmonized Downlink Framework

Summary of main design principles, coherent joint transmission

1. Cooperation areas have to be designed carefully to provide gains for most users.

   Use large (at least 3-site) and overlapping cooperation areas.

   Almost all users are then in the center area of some CA in some cover shift.

2. Interference from outside the CA needs to be reduced.

   Use combination of power control, frequency-specific downtilt or possibly fractional frequency reuse.

3. User groups per resource block need to be selected well, but fast and efficiently.

   Use two-stage scheduling and a linear CoMP precoder. Users are first allocated frequency/spatial resources within cells. This reduces singular value spreads and improves performance of linear CoMP precoders.

In addition:

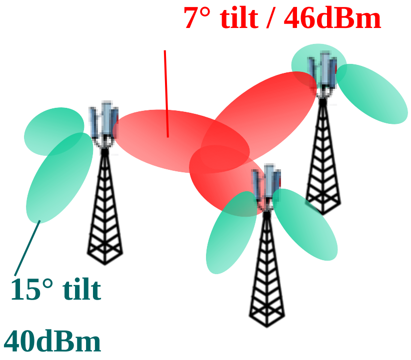
- Use partial reporting of channels to reduce feedback and estimation load.
- We recommend the use of channel prediction, to improve performance and robustness.
- We recommend the use of robust linear precoders, to better handle difficult cases.

ALTERNATIVE SOLUTIONS AND OPEN ISSUES

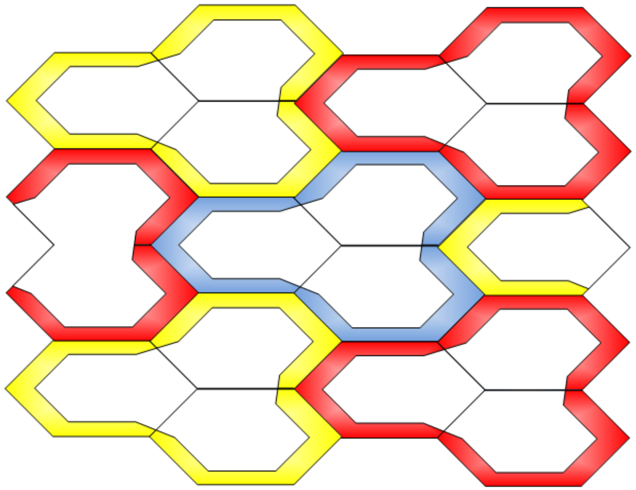
Alternative Solutions

Fractional frequency reuse for interference suppression

- Inter-CA interference suppression efficient with power control and large downtilt to the outside of CAs.
- But this assumes frequency-dependent downtilts (per Cover shift). May not be avaliable in present networks.



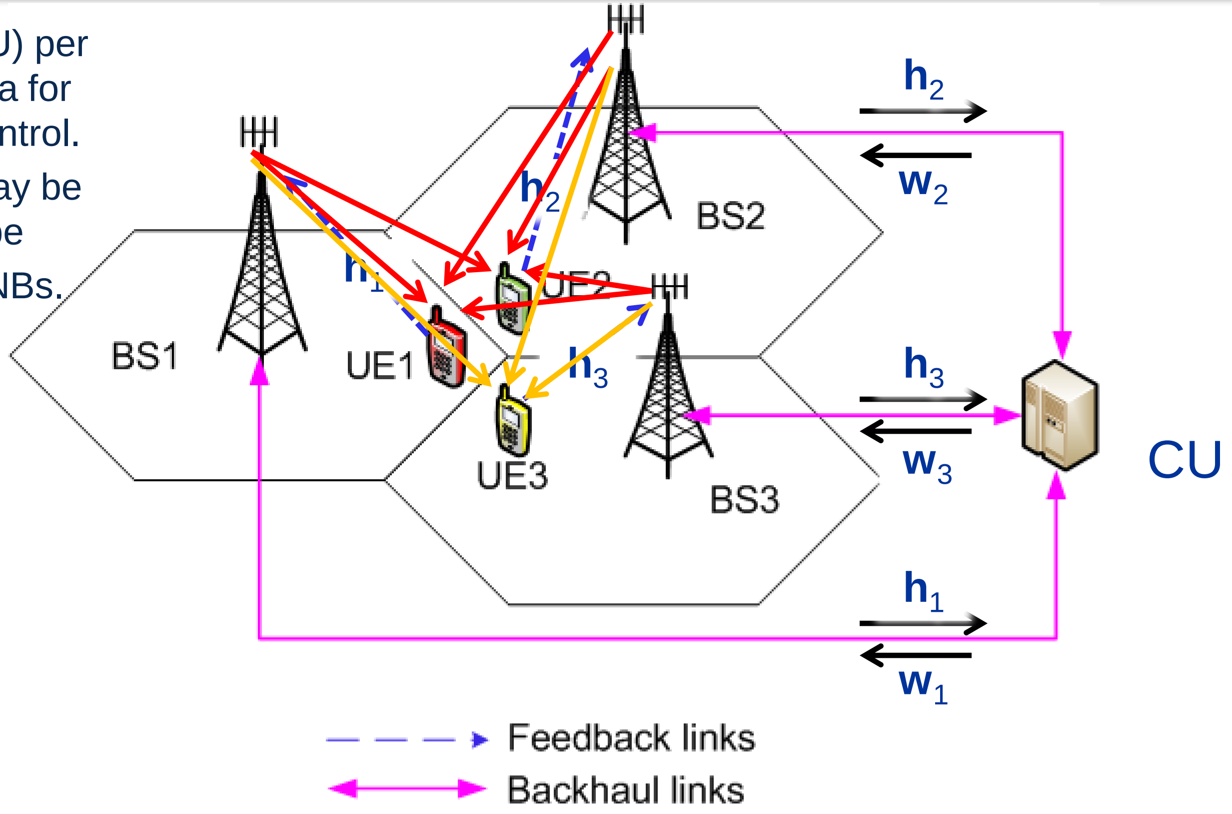
- Simpler alternative: Use fractional frequency reuse within cooperation areas:



Baseline for Downlinks in Previous Section:

Centralized processing coordination architecture

- Central Unit (CU) per cooperation area for transmission control.
- Data queues may be centralized, or be distributed to eNBs.



$$\mathbf{H} = \begin{bmatrix} \mathbf{h}_1 \\ \mathbf{h}_2 \\ \mathbf{h}_3 \end{bmatrix}$$

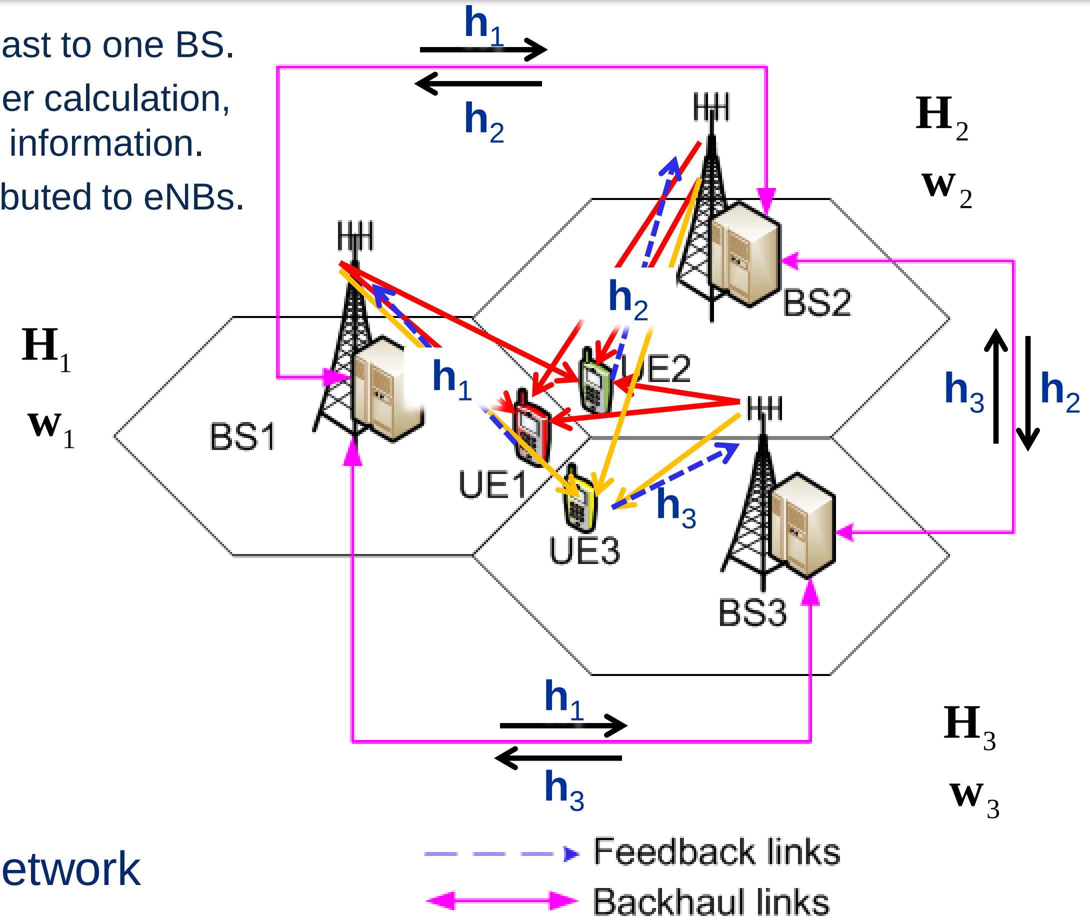
$$\mathbf{W} = \begin{bmatrix} \mathbf{w}_1 \\ \mathbf{w}_2 \\ \mathbf{w}_3 \end{bmatrix}$$

- A star-like network
- Coordinated BSs are connected to a control unit (CU) via backhaul links
- Total latency for an entire transmission loop, $\Delta t^C = \Delta F + \mathbf{2}\Delta B$

Alternative Solution to Reduce Delays

Semi-distributed processing

- CSI feedback unicast to one BS.
- Distributed precoder calculation, based on identical information.
- Data queues distributed to eNBs.

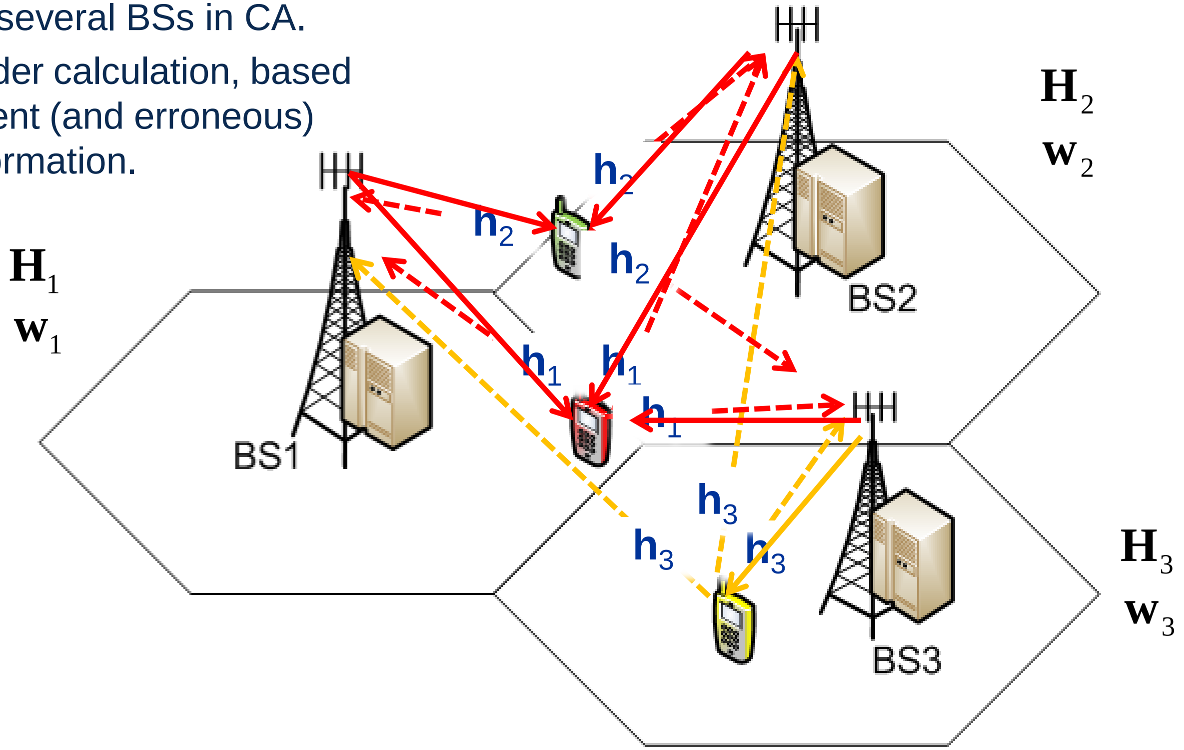


- A meshed network
- A CU is co-located at each BS
- Total latency for an entire transmission loop: $\Delta t^{SD} = \Delta F + \Delta B$

Alternative Solution to Reduce Delays

Fully distributed processing

- CSI broadcast to several BSs in CA.
- Distributed precoder calculation, based on possibly different (and erroneous) CSI feedback information.



- A CU is co-located at each BS
- Each user broadcasts the CSI to ***all*** the BSs
- $\Delta t^{FD} = \Delta F$, more sensitive to errors introduced via low-quality feedback channels

Performance Example:

CoMP transmit schemes vs Coordination architectures

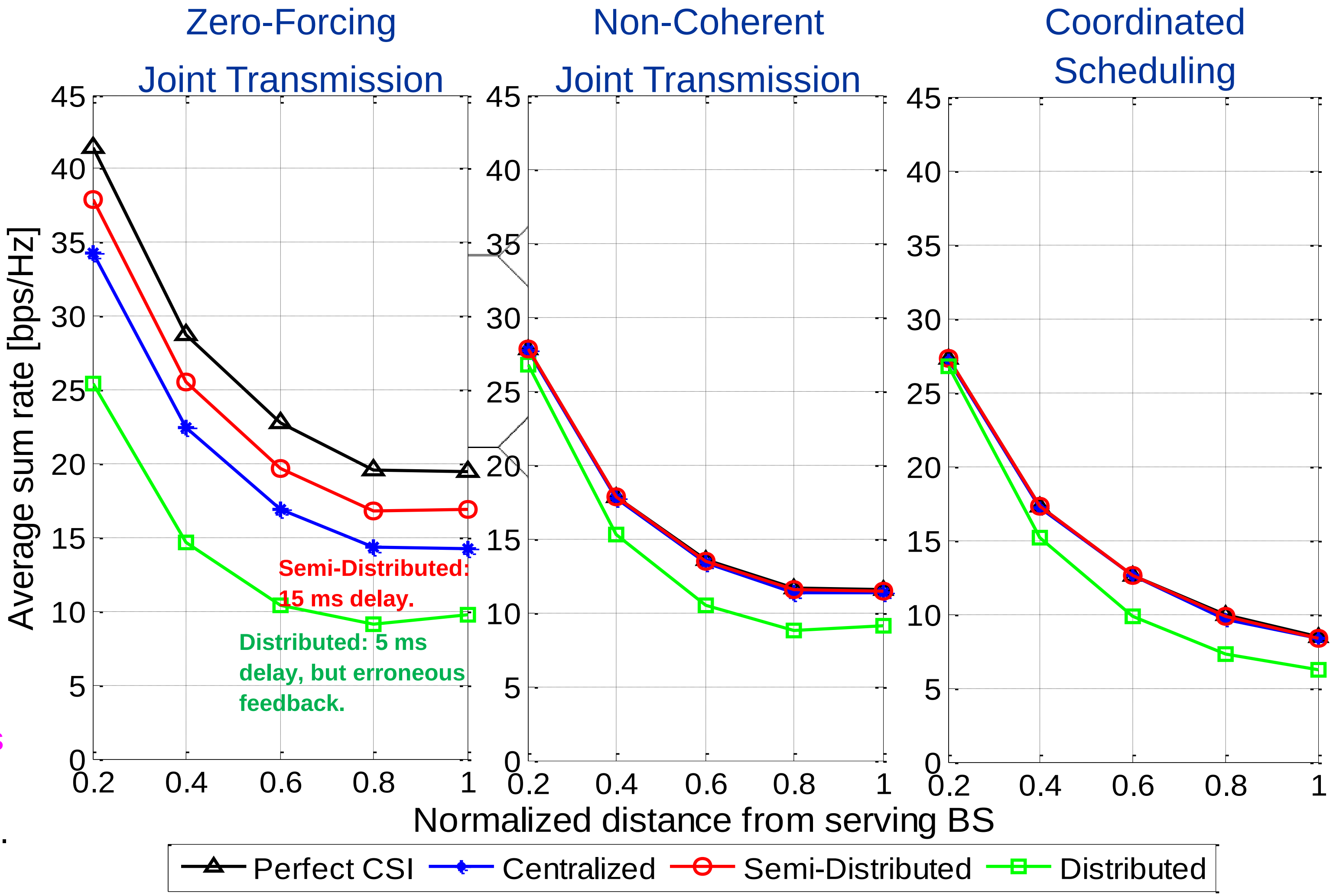
2.0 GHz,

3.0 km/h,

ΔF = 5ms

ΔB =10ms

Kalman Prediction.

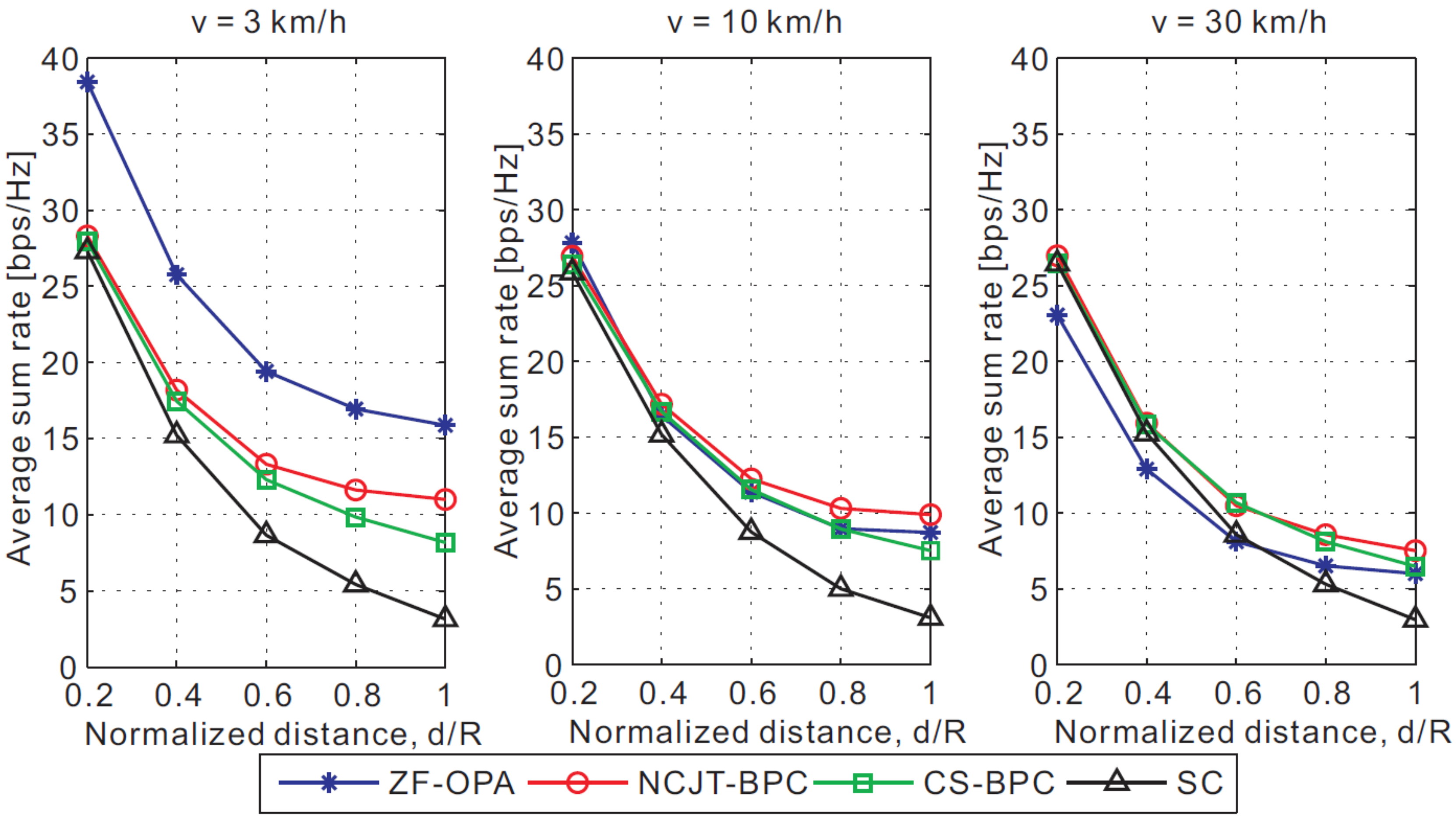


Semi-Distributed: 15 ms delay.

Distributed: 5 ms delay, but erroneous feedback.

Performance Example:

CoMP Transmit schemes vs Speed



2.0 GHz, Semi-distributed,

ΔF = 5ms

ΔB =10ms

Kalman Prediction.

[Source for this and previous 4 slides: Licentiate Thesis presentation by Jingya Li, Chalmers, Feb.12 2013. See Li et. al. IEEE PIMRC 2012]

UPLINK ASPECTS AND JOINT DETECTION

Uplink Aspect and Joint Detection

Uplink Power Control

- Less uplink power (P_{max} = 23 dBm)
- uplink power control in LTE
  - ❑ Goals: achieve fairness & minimize interference at other cells
  - ❑ single link (serving cell) closed loop/open loop power control

$$P_{\mathrm{TX}} = \min\{P_{\mathrm{max}}, P_0 + \alpha \mathrm{PL}_{\mathrm{DL}} + 10\log_{10}(\mathrm{RB}) + \Delta_{\mathrm{MCS}} + \delta\}$$

  - ❑ Parallel to partial CSI feedback (for downlink)
  - ❑ With joint detection, power control should take the links to all eNBs in the cooperation cluster into account.
    - UE needs to know which eNBs actually cooperate
    - additional UE-eNB signaling required
    - UL CoMP can be implemented transparent to the UE which allows support of legacy UEs
    - closed loop power component δ could be used to adjust UE transmit power

Uplink Aspect and Joint Detection

Channel State Information

- Channel information available without feedback delay
  - BSs measure the radio links and exchange the measurement reports to joint detector (potentially a BS)
  - If the channel of uplink and downlink is reciprocal UL measurements could be leveraged for adapting downlink transmissions
    - However, since interference is not reciprocal, UE feedback is always desirable to obtain an estimate of the downlink interference experienced by a UE
    - If you want to do scheduling, you need the channels of many users.
  - interference floor shaping can be applied

- Control Channels
  - In general uplink and downlink transmission need control channels, but some control loops are only required in the uplink
    - UL power control
    - uplink timing advance

Uplink Aspect and Joint Detection

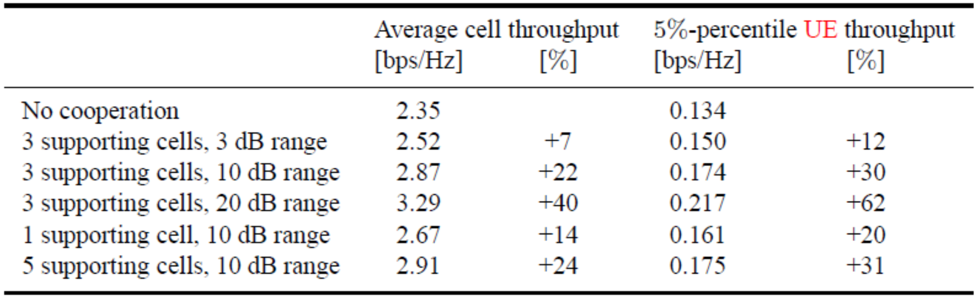
HARQ Issues

- LTE HARQ protocol requires strict timing constraints
- UL HARQ is based on synchronous re-transmissions
- A negative HARQ achnowledgement (NACK) has to be transmitted 4ms after the initial transmission
- cooperation (exchange of information over a backhaul) causes additional delays
  - Delay depends mostly on the core/backhaul network topology and the backhaul technology
  - Today, inter-eNB communication is not sensitive to communication latency, i.e. latencies in the order of 10 ms are sufficient and occur.
- Current technologies that support delays < 1 ms are
  - Ethernet (over fiber)
  - Microwave in E-Band (71 – 76 GHz, 81 – 86 GHz) provide up to 1 Gbits/s at about 100 µs delay
  - Passive optical networks XGPON

Uplink Aspect and Joint Detection

Backhaul

- Backhaul limitation
  - Basic combining approaches
    - Intra-site uplink CoMP can be efficiently implemented, and there are large gains. [Frank et. al] report 22% and 26% in average spectral efficiency and cell edge performance, respectively.
    - Inter-site CoMP can provide additional gains. [Hoymann et al.] reports the following gains



	Average cell throughput [bps/Hz]	[%]	5%-percentile UE throughput [bps/Hz]	[%]
No cooperation	2.35		0.134	
3 supporting cells, 3 dB range	2.52	+7	0.150	+12
3 supporting cells, 10 dB range	2.87	+22	0.174	+30
3 supporting cells, 20 dB range	3.29	+40	0.217	+62
1 supporting cell, 10 dB range	2.67	+14	0.161	+20
5 supporting cells, 10 dB range	2.91	+24	0.175	+31

  - The backhaul traffic between BSs is a challenge for the backhaul.
    - [Hoymann et al.]: partial threshold based distributed forwarding of received complex baseband signals from cooperating BSs
    - [Frank et. al]: restrict the cooperation to a subset of the available subcarriers per Physical Resource Block (PRB) combined with a threshold as in [Hoymann et al.].
  - In general, there are different backhaul requirements for the exchange of
    - processed user data or received signals
    - channel state information
    - scheduling information
    - signaling information

CONCLUSIONS, OUTLOOK AND FUTURE WORK

Conclusions

- Difference theoretical versus 3GPP results
  - Rayleigh distr. of channel components: Easily tractable, but unrealistic
  - LTE overhead in the order of 40 to 50% has to be taken into account
  - Inter-cluster interference might destroy large parts of the potential gains
- ARTIST4G Interference Mitigation Framework
  - Under ideal conditions (full CSI) close to network wide precoding
  - Main pillars: cover shifts, partial reporting, interference floor shaping, 2 stage scheduler, …
  - Directly benefits from improved CSI knowledge and high SNR
- What's next
  - Analyze optimized channel estimation and prediction solutions going beyond state of the art → model based channel prediction
  - Generate 3GPP friendly overall system concepts
    - Reasonable UE processing power
    - Reasonable feedback overhead, etc.

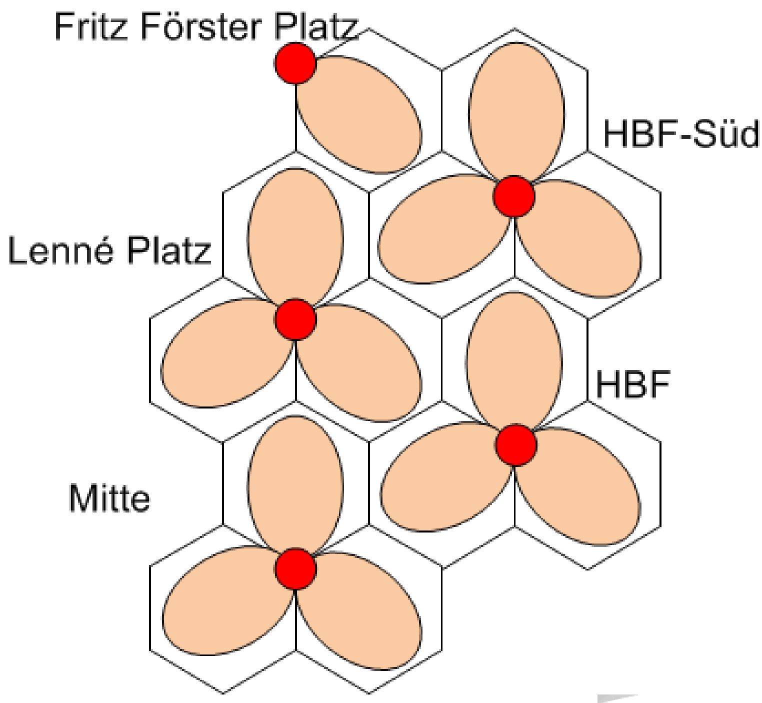
FIELD TRIAL RESULTS AND DEMONSTRATION

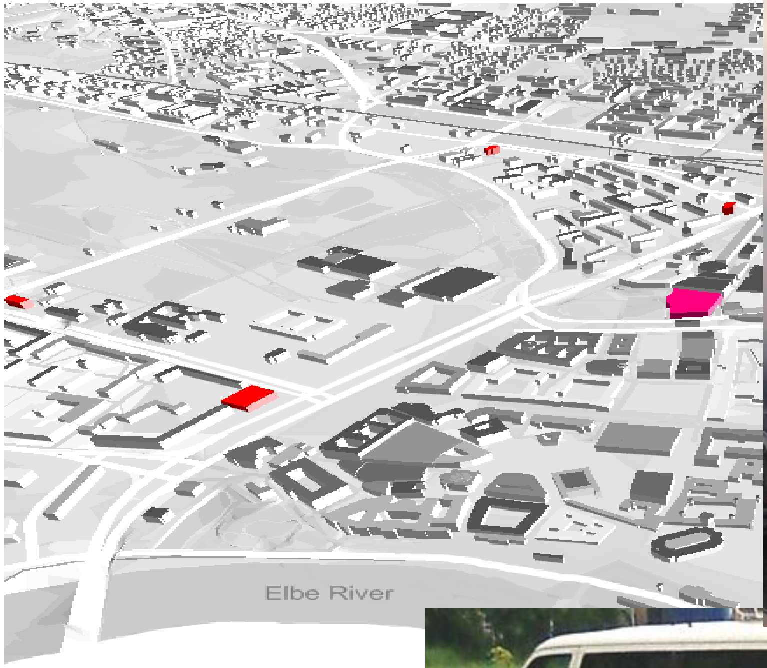
Introduction

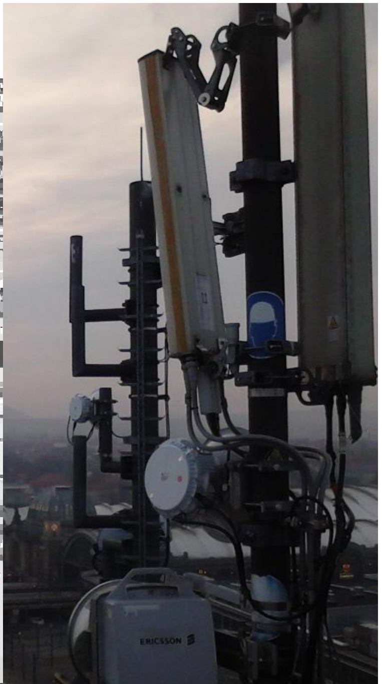
- Theoretical analysis and simulations promise vast increases in spectral efficiency and currently available technology seems to be ready to support these ambitious concepts.
- Nonetheless, the challenges faced when bringing CoMP to the market have proven to be manifold. Examples are
  - required synchronization of all cooperating entities in time and frequency
  - multi-cell channel estimation
  - backhaul efficient multi-cell signal processing
- Even though significant progress has been made, the often isolated examination of certain problems is not sufficient to prove the maturity of CoMP concepts.
- System concepts should be evaluated using real channels and hardware.
- And system complexity and performance needs to be assessed under real-world conditions, and thus simulation studies have to be accompanied by field trials.

LTE Advanced Testbed

- LTE-Advanced testbed with a total of 5 sites and 13 sectors

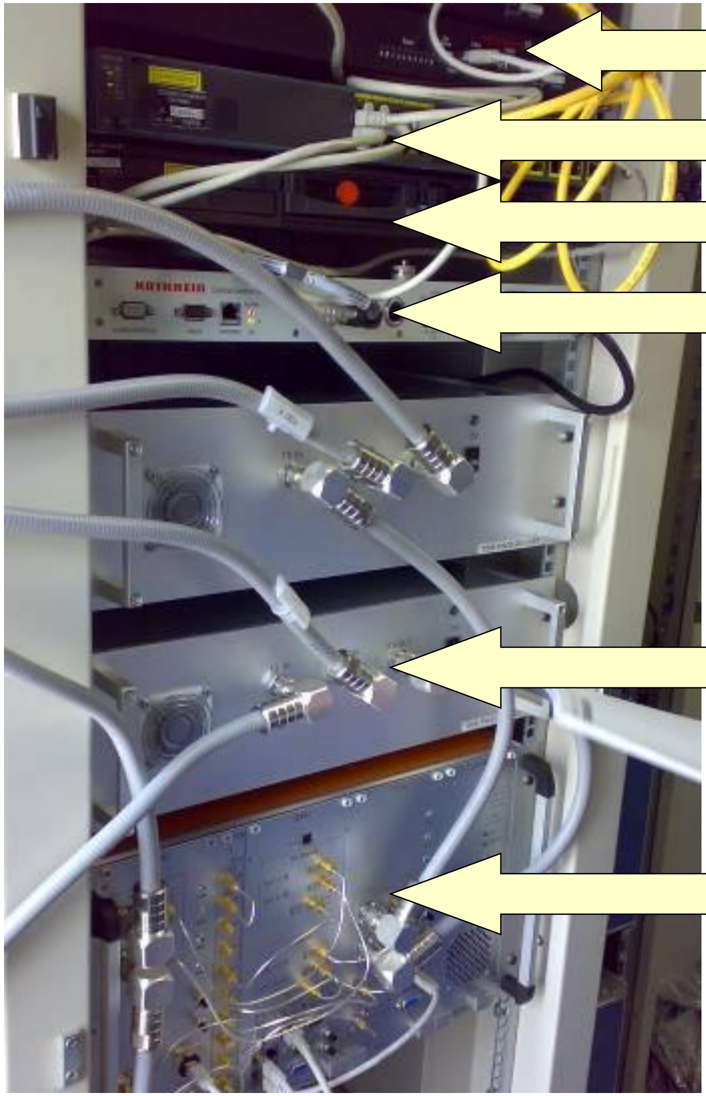






- **Microwave links between sites**
- **Focus on physical layer; only minimal MAC layer implemented**
- **Sites synchronized through GPS and reference normals**
- **Offline signal processing**

LTE Advanced Testbed



Switchable power supply

Switch

Control computer

KATHREIN device for electr. downtilt etc.

Not visible:

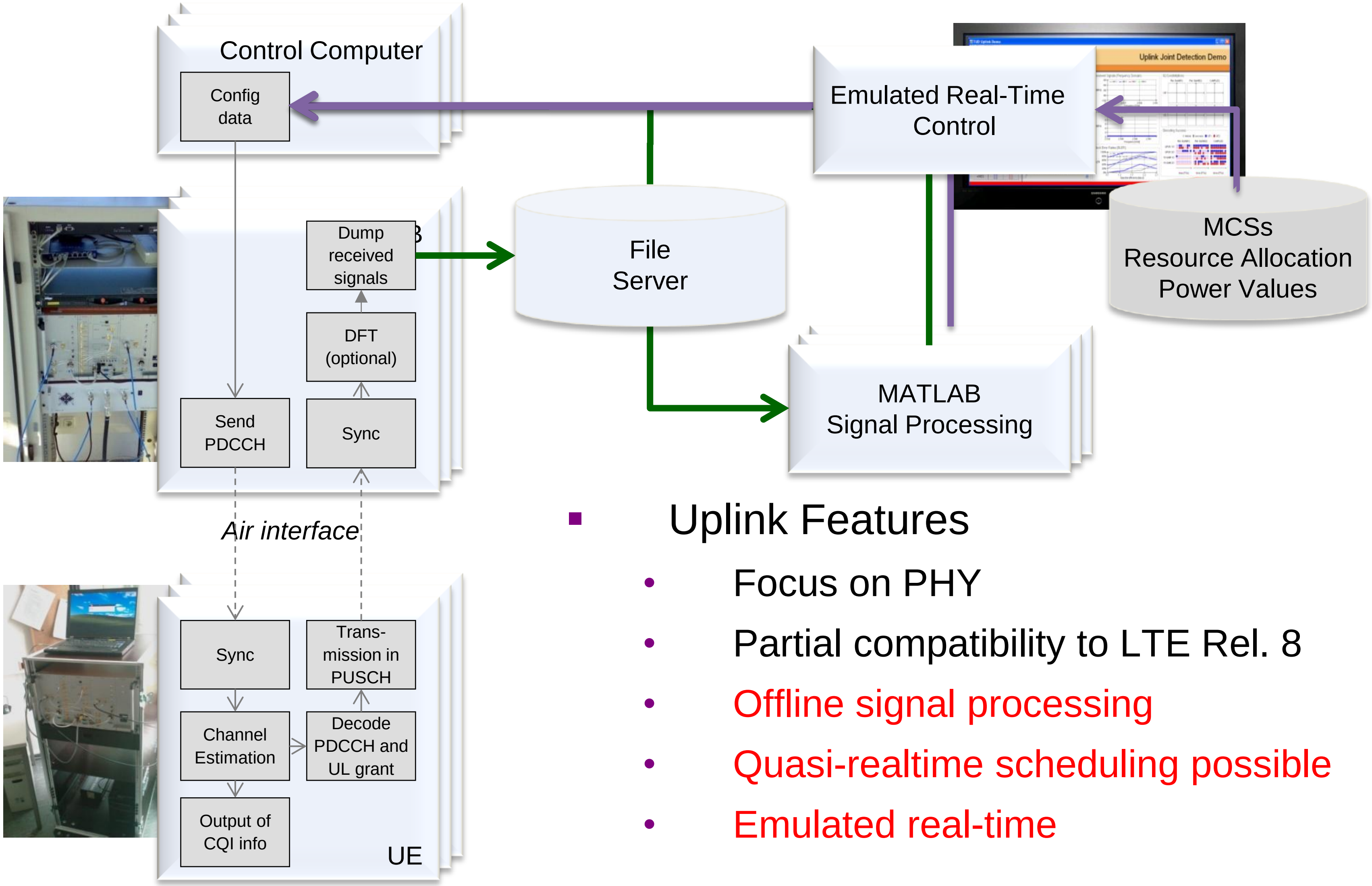
- GPS unit for time and frequency sync.
- Frontend for microwave link

Power amplifier and duplexer built by TES (20W peak, 2520-2540MHz & 2670-2690MHz)

eNodeB prototyping platform from Signalion / TU Dresden

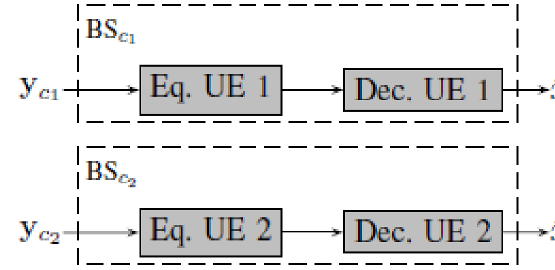
LTE Advanced Testbed

LTE Advanced Testbed / Uplink Setup

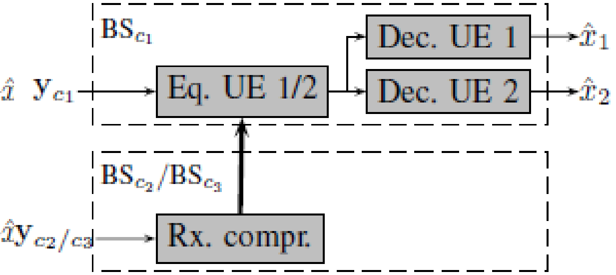


- Uplink Features
  - Focus on PHY
  - Partial compatibility to LTE Rel. 8
  - Offline signal processing
  - Quasi-realtime scheduling possible
  - Emulated real-time

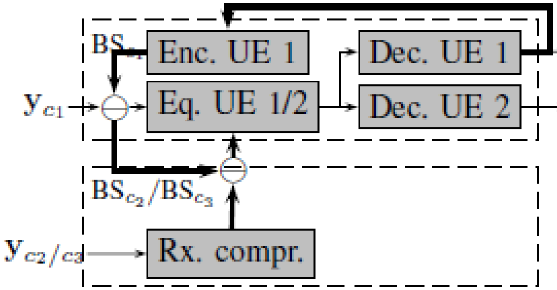
Signal Processing Architecture



a) non coop: decode at different BS



b) Joint Decoding (2/3 BSs)



c) JD (2/3 BSs) + SIC

Rate adaptation

- offline evaluation; emulation of optimal rate adaptation

Channel estimation

- LTE pilot positons
- Code orthogonal pilot positions

Soft demodulation and decoding

- Standard soft demodulation and decoding
- Error vector magnitude SINR estimation

Noise covariance estimation

- Estimation of noise on empty sub-carriers

MCS#	Mod. scheme	Code rate	Peak rate (Mbps)	Bit per channel use (bpcu)
1	4QAM	3/16	1.3	0.375
2	4QAM	1/2	3.46	1.0
3	4QAM	3/5	5.04	1.27
4	16QAM	2/5	5.62	1.6
5	16QAM	4/7	7.99	2.29
6	16QAM	3/4	10.6	3.0
7	16QAM	6/7	12.3	3.43
8	16QAM	98/100	15.6	3.94
9	64QAM	3/4	16.3	4.5
10	64QAM	7/8	18.72	5.25

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