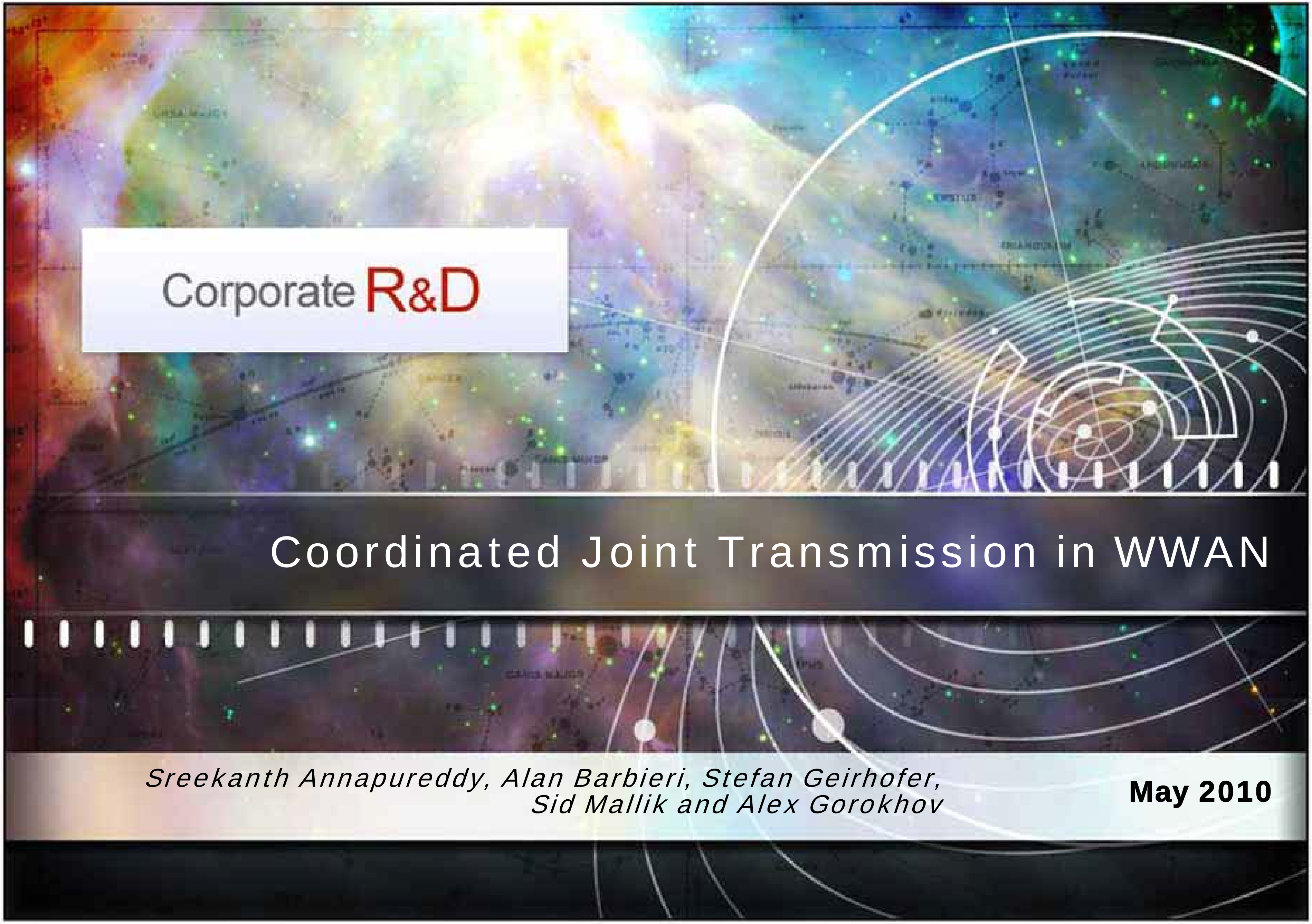


Corporate R&D

Coordinated Joint Transmission in WWAN

Sreekanth Annapureddy, Alan Barbieri, Stefan Geirhofer,
Sid Mallik and Alex Gorokhov

May 2010

Multi-cell system model

- Think of entire deployment as a large broadcast channel
  - optimal capacity region achievable w/ TX precoding and DPC
    - Shannon limit can be computed theoretically: convex problem
    - modulation constraint & processing losses make it less tractable
  - performance achievable w/ linear multi-point equalizer (**MPE**)

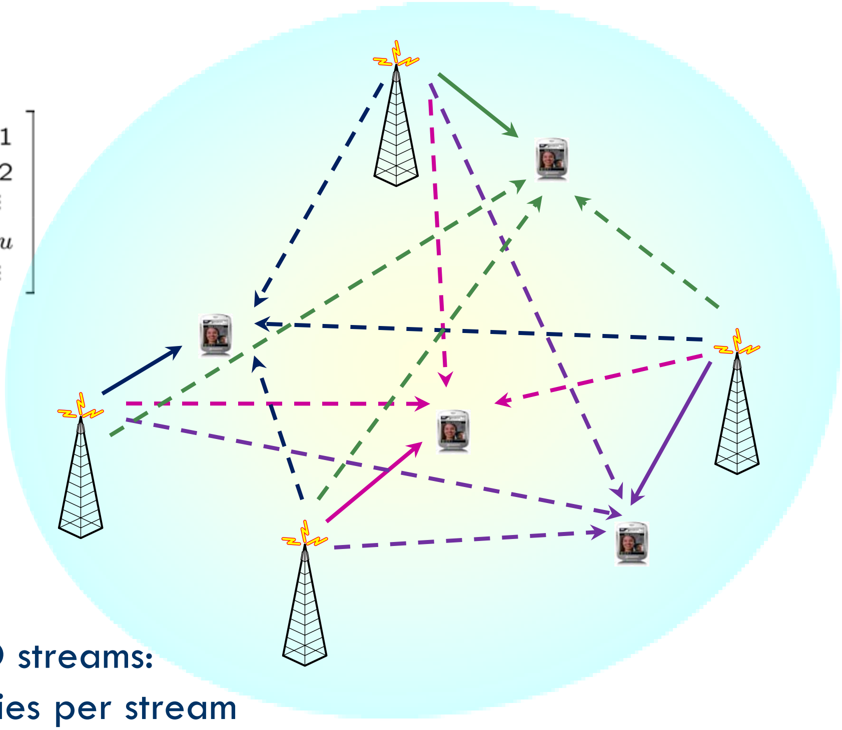
$$\overbrace{\begin{bmatrix} \boldsymbol{H}_{1,1} & \boldsymbol{H}_{1,2} & \cdots & \boldsymbol{H}_{1,c} & \cdots \\ \boldsymbol{H}_{2,1} & \boldsymbol{H}_{2,2} & \cdots & \boldsymbol{H}_{2,c} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \ddots & \ddots & \cdots \\ \boldsymbol{H}_{u,1} & \boldsymbol{H}_{u,2} & \cdots & \boldsymbol{H}_{u,c} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix}}^{\textit{Channel matrix}} \overbrace{\begin{bmatrix} \boldsymbol{W}_{1,1} & \boldsymbol{W}_{1,2} & \cdots & \boldsymbol{W}_{1,u} & \cdots \\ \boldsymbol{W}_{2,1} & \boldsymbol{W}_{2,2} & \cdots & \boldsymbol{W}_{2,u} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ \vdots & \vdots & \ddots & \ddots & \cdots \\ \boldsymbol{W}_{c,1} & \boldsymbol{W}_{c,2} & \cdots & \boldsymbol{W}_{c,u} & \cdots \\ \vdots & \vdots & \vdots & \vdots & \vdots \end{bmatrix}}^{\textit{MPE matrix}} \begin{bmatrix} s_1 \\ s_2 \\ \vdots \\ s_u \\ \vdots \end{bmatrix}$$

Channel from Cell$_c$ to UE$_u$

Packet to UE$_u$

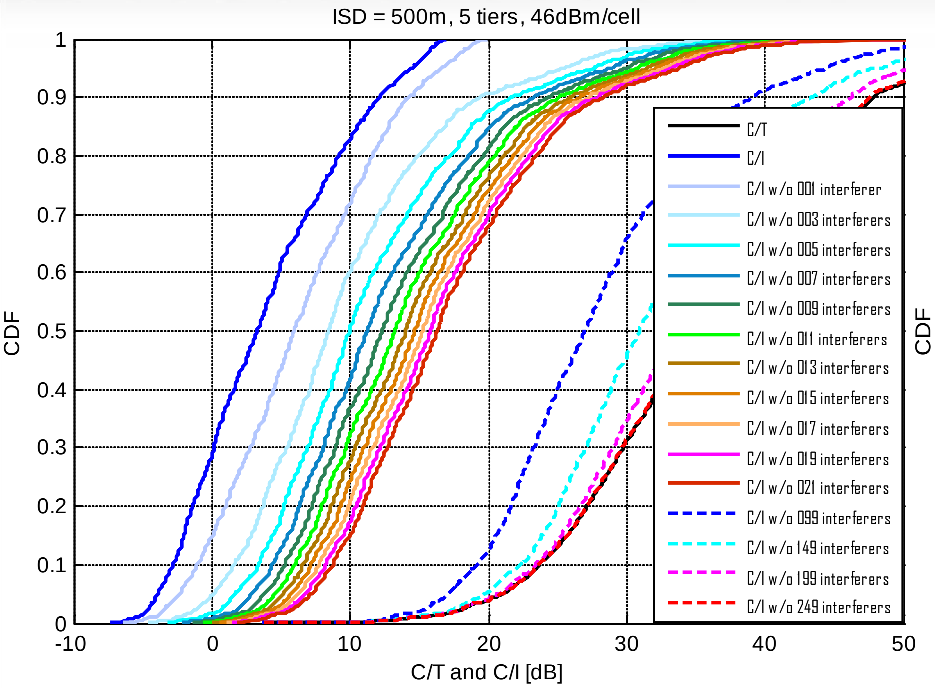
Signal-to-leakage ratio (SLR)

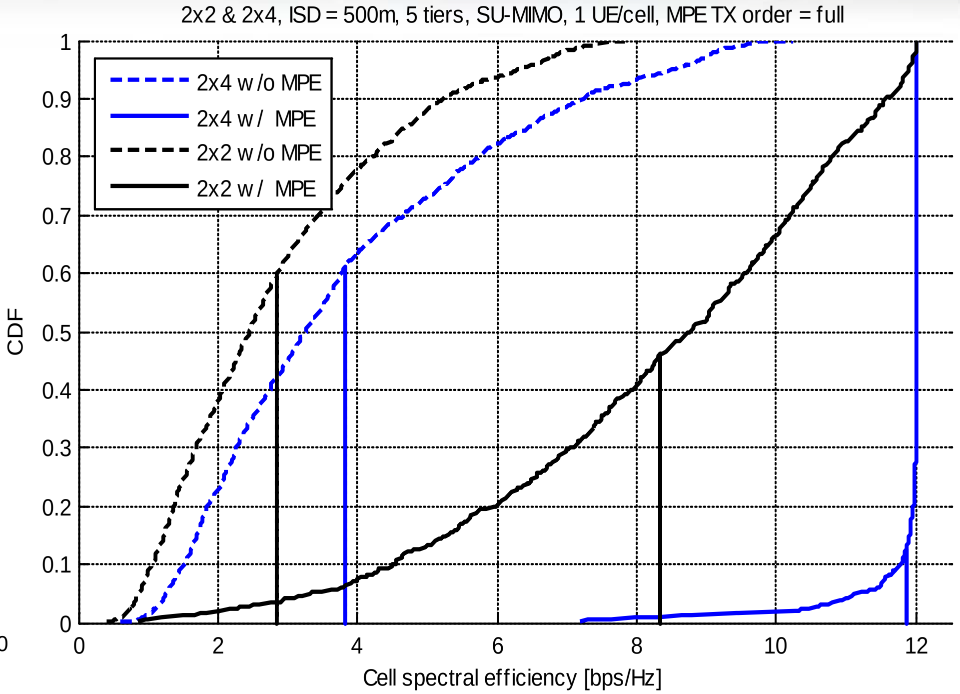
$$\boldsymbol{W}_{:,u} = \arg \max_{\|\boldsymbol{w}\|^2 = P_s} \frac{|\boldsymbol{H}_{u,:}\,\boldsymbol{w}|^2}{1 + \sum_{u' \neq u} \left|\boldsymbol{H}_{u',:}\,\boldsymbol{w}\right|^2}$$



★ In the case of multiple RX antennas and/or MIMO streams:
RX beams matched to the serving cell & SLR applies per stream

Joint transmission & full coordination: ISD = 500m

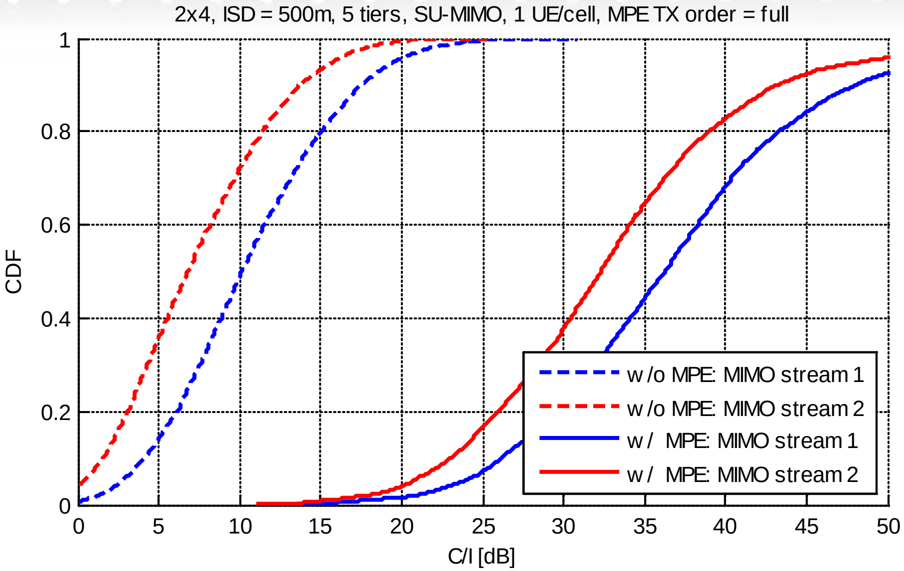

ISD = 500m, 5 tiers, 46dBm/cell

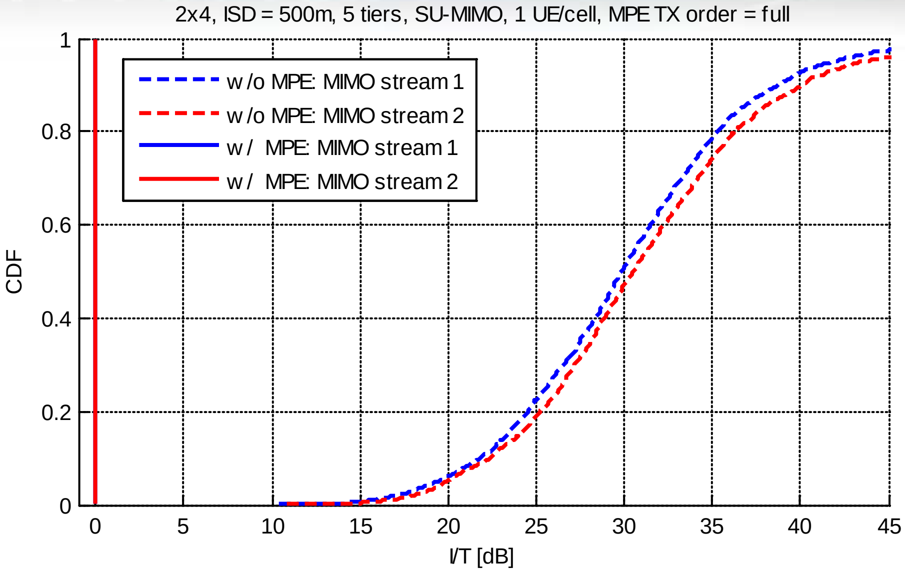

2x2 & 2x4, ISD = 500m, 5 tiers, SU-MIMO, 1 UE/cell, MPE TX order = full

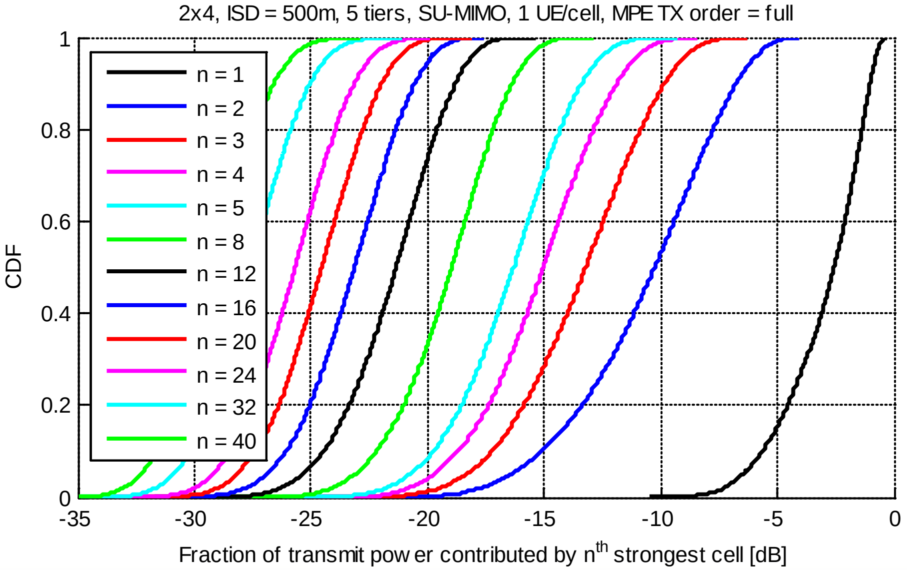
- Ideal fully coordinated multi-cell transmission takes most UEs to the peak rate when there are enough degrees of freedom to ensure TX/RX interference nulling
  - w/ 4 TX and 2 RX: the total number of TX degrees of freedom exceeds the total number of MIMO streams across UEs by 2
  - w/ 2 TX and 2 RX: the number of degrees of freedom and total MIMO streams are balanced

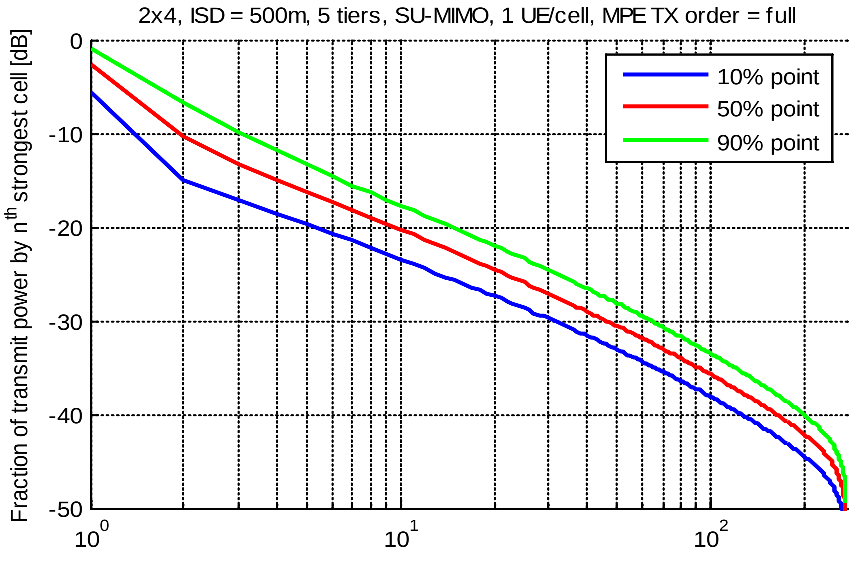
Scenario	2x2		2x4	
	Rank 1	Rank 2	Rank 1	Rank 2
w/o MPE	77%	23%	42%	58%
w/ MPE	01%	99%	00%	100%

Joint transmission, full coordination: 2x4, ISD 500m

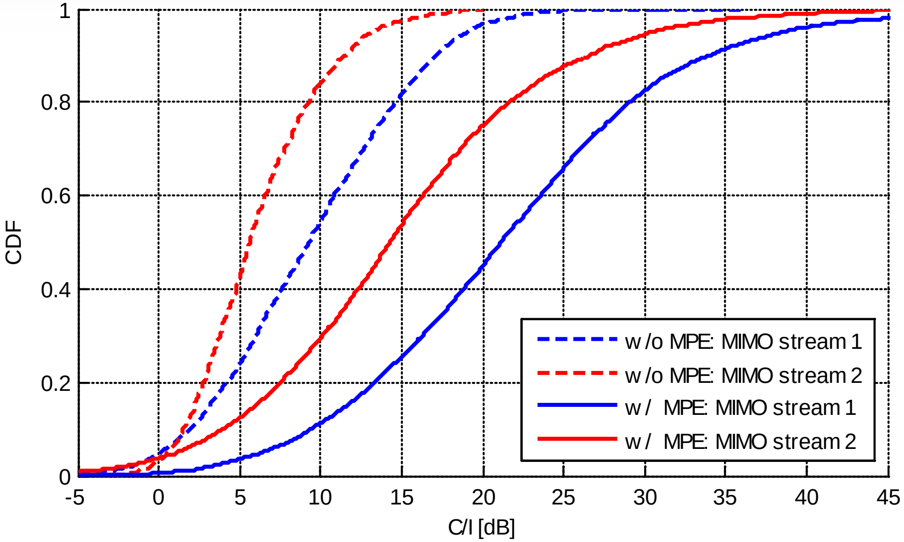

2x4, ISD = 500m, 5 tiers, SU-MIMO, 1 UE/cell, MPE TX order = full

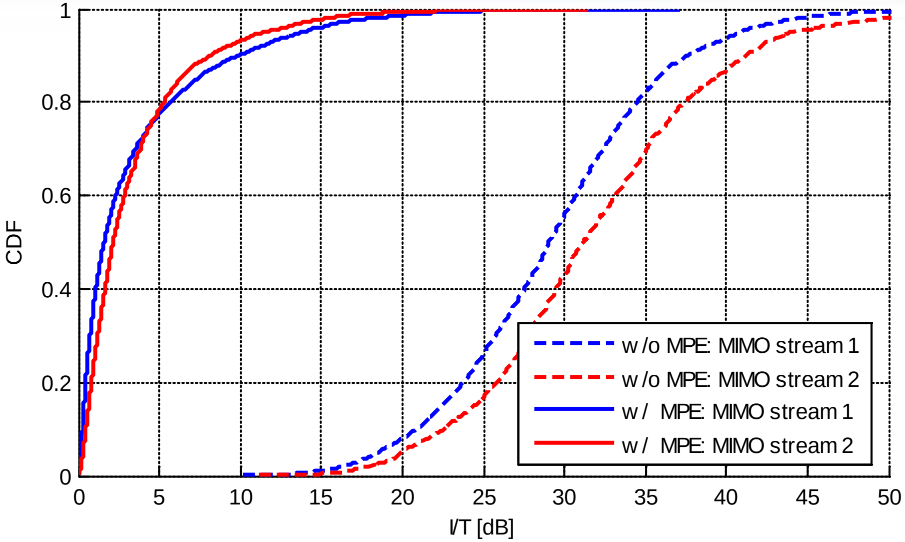

2x4, ISD = 500m, 5 tiers, SU-MIMO, 1 UE/cell, MPE TX order = full

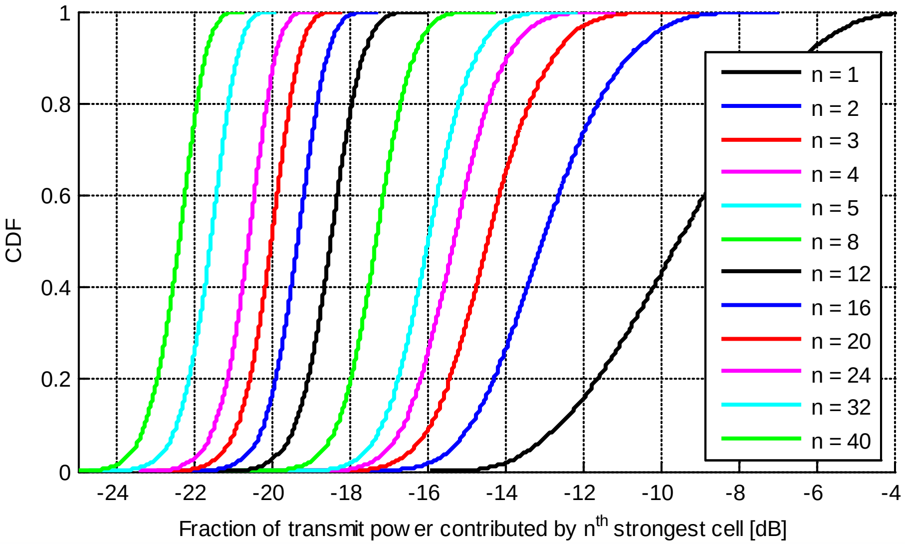

2x4, ISD = 500m, 5 tiers, SU-MIMO, 1 UE/cell, MPE TX order = full

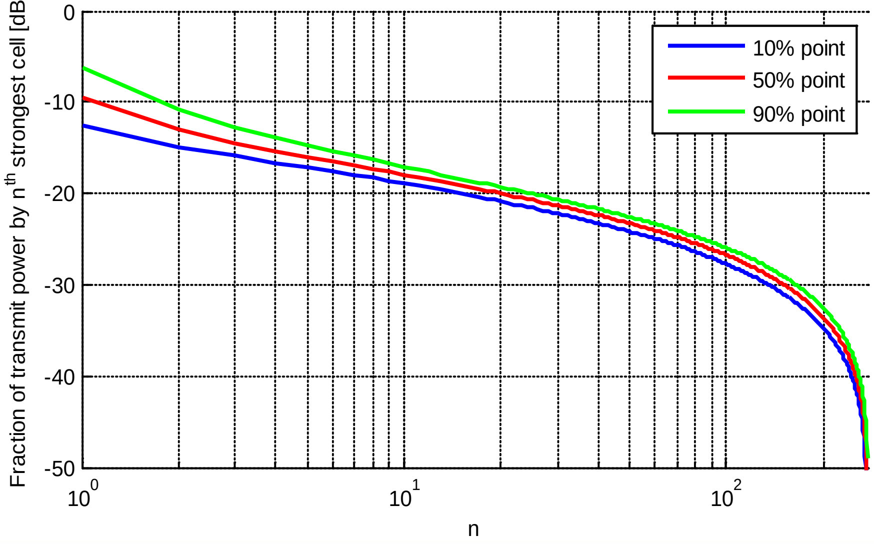

2x4, ISD = 500m, 5 tiers, SU-MIMO, 1 UE/cell, MPE TX order = full

Joint transmission, full coordination: 2x2, ISD 500m


2x2, ISD = 500m, 5 tiers, SU-MIMO, 1 UE/cell, MPE TX order = full


2x2, ISD = 500m, 5 tiers, SU-MIMO, 1 UE/cell, MPE TX order = full


2x2, ISD = 500m, 5 tiers, SU-MIMO, 1 UE/cell, MPE TX order = full


2x2, ISD = 500m, 5 tiers, SU-MIMO, 1 UE/cell, MPE TX order = full

Practical considerations (1/2)

- UE can measure/report channels from a limited number of cells
  - limited measurement set: maintain limited DL reference signal overhead
    - limit based on “un-coordinated” long-term C/I of the cells
  - limited radio reporting set: maintain limited UL feedback overhead
    - limit based on the maximum number of cells fed back by UE
- Any given packet transmitted by a limited number of cells and any given cell can multiplex a limited number of packets
  - overall backhaul loading, total backhaul payload and number of control packets associated w/ a transmitted data packet
  - physical proximity of boxes sharing the data
  - complexity considerations
- Distributed coordination architecture
  - minimize the amount of information entities exchanged across eNodeBs
  - minimize the number of (new) functional units needed to support CoMP

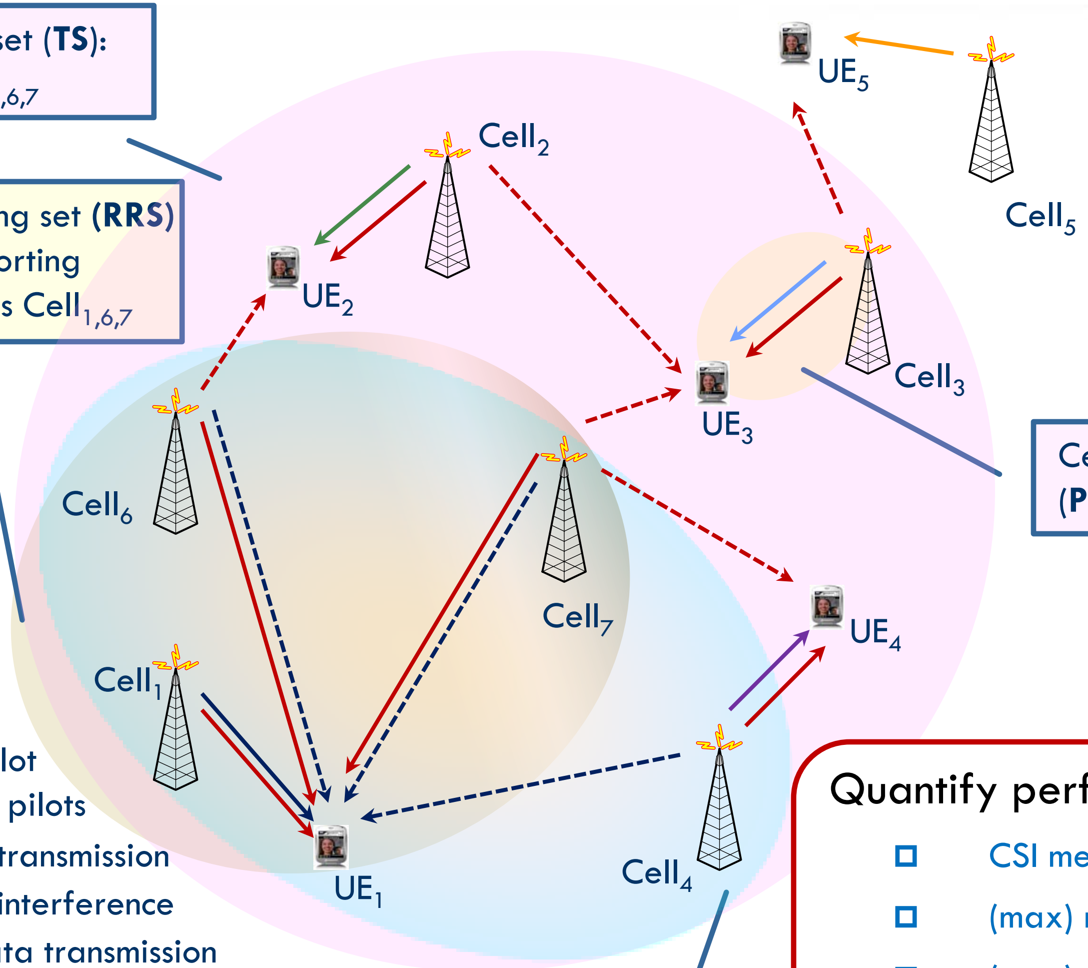
Practical considerations (2/2)

- Backhaul latency
  - minimize the number of exchanges need prior to a scheduling decision
- Total per-cell power constraint
  - need to be met regardless of the number of packets being transmitted
- Distributed MPE scheduler design
  - how to make the right “un-coordinated” scheduling decision(s)
  - sensitivity of scheduling decision(s) to the decisions of neighbor cells
- Impact of propagation delays on MPE performance
  - inter-symbol and inter-carrier interference and cyclic prefix length
- Spatial channel state information
  - channel estimation / truncation rules, CSI-RS overheads
  - time-frequency feedback compression and encoding
  - MPE performance versus UE feedback overhead: tradeoff

MPE operation outline

- **Scheduling step:** each cell selects UE to be served on a given resource (time/frequency), independently from other cells
  - inter-cell interference removal is accounted for in channel quality
  - scheduling decisions exchanged between cells
- **MPE computation step:** serving cell computes multi-cell beam to transmit packet of the scheduled UE
  - beam computation assumes knowledge of all scheduled UEs and their CSI to all relevant cells
    - multi-cell beam chosen according to SLR criterion
  - beam weights and UE data are sent to all cells that have non-zero beam weight ("transmission set of that packet UE")
- **Transmission step:** cells transmit the sum of all beams received from all cells
  - per-cell power capping applied as needed

MPE: sets and parameters



UE$_1$ transmission set (**TS**): includes Cell$_{1,2,3,4,6,7}$

UE$_1$ radio reporting set (**RRS**) limited by UL reporting overhead: includes Cell$_{1,6,7}$

Cell$_3$ packet multiplexing order (**PMO**) = 2: includes UE$_{1,3}$

→ serving pilot
⇢ measured pilots
→ UE$_1$ data transmission
⇢ UE$_1$ data interference
→ UE$_{2,3,4,5}$ data transmission

UE$_1$ measurement set determined by C/I threshold subject to CSI-RS overhead: includes Cell$_{1,4,6,7}$

Quantify performance impact

- ☐ CSI measurement accuracy
- ☐ (max) radio reporting set size (**RRSS**)
- ☐ (max) transmission set size (**TSS**)
- ☐ (max) packet mux order (**PMO**)

Multi-point transmission illustration

Focus on the packet of Cell$_1$ to UE$_{1.1}$

⬭ BRS of Cell$_1$

⬭ serving association (= control attachment point)

◌ ***step #1:*** UEs are scheduled

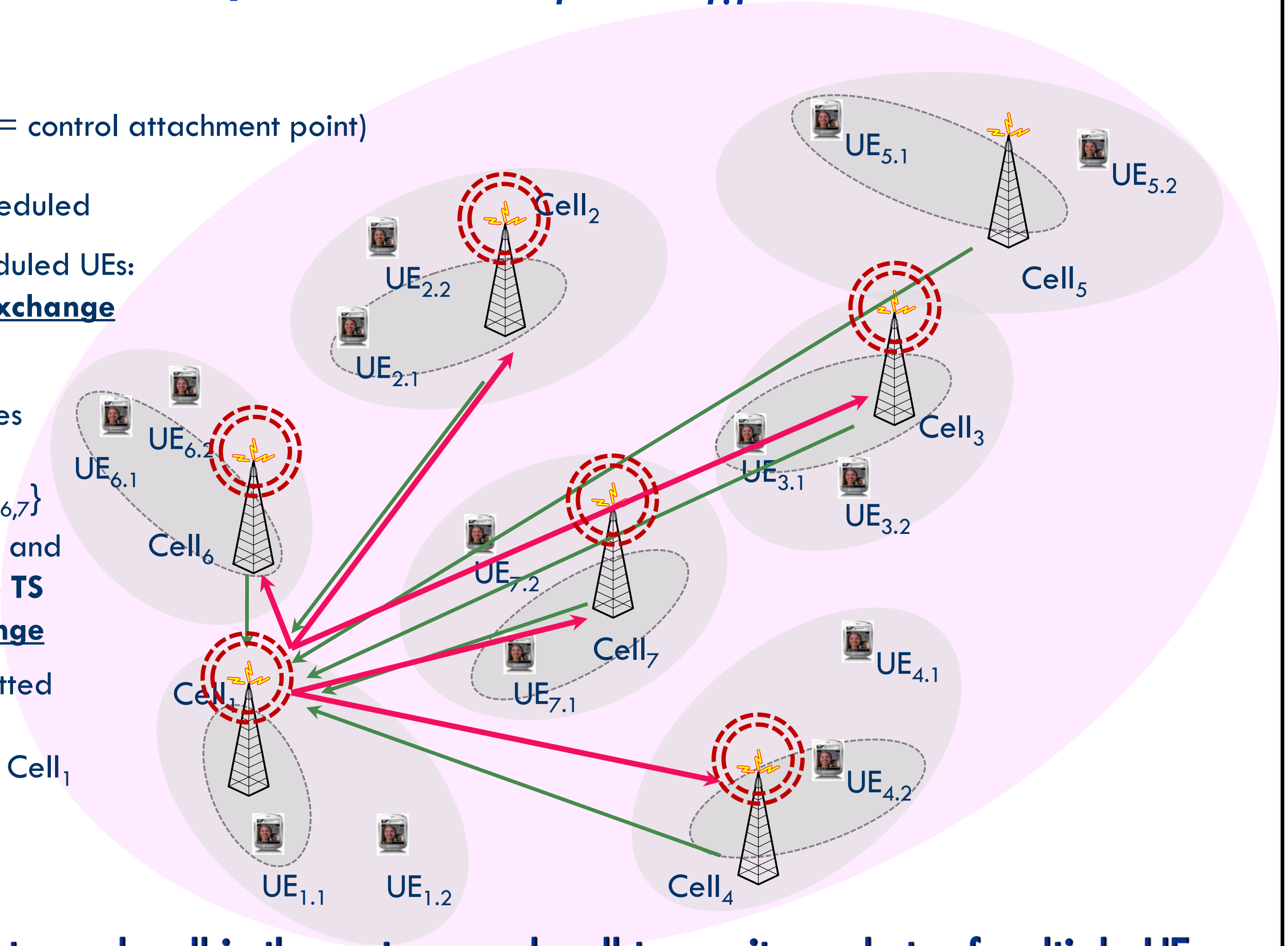
→ ***step #2:*** CSI of scheduled UEs:
1st inter-eNodeB exchange

step #3: Cell$_1$ defined **TS** for the scheduled packet(s) and computes MPE coefficients

in this example **TS**=\{Cell$_{1,2,3,4,6,7}$\}

→ ***step #4:*** MPE coefficients and UE data packet(s) sent to **TS**
2nd inter-eNodeB exchange

◌ ***step #5:*** UE data transmitted by **TS** according to MPE coefficients computed by Cell$_1$



★ **This timeline applies to each cell in the system: each cell transmits packets of multiple UEs**

Performance gains w/ feedback quantization

ISD = 500m, 4 tiers, ½ RB feedback, MST = -20dB & adaptive BRS (MPE)

UEs / cell	RX x TX	Statistics	Finite feedback quantization	
			w/o MPE	w/ MPE
2	2x2	10%	**1.05**	**1.64 (56%)**
		50%	**2.34**	**3.03 (30%)**
		mean	**2.76**	**3.28 (19%)**
	2x4	10%	**1.43**	**2.89 (102%)**
		50%	**3.09**	**4.33 (40%)**
		mean	**3.67**	**4.62 (26%)**
5	2x2	10%	**1.22**	**1.70 (39%)**
		50%	**2.67**	**3.53 (32%)**
		mean	**3.22**	**3.87 (20%)**
	2x4	10%	**1.65**	**3.24 (96%)**
		50%	**3.58**	**4.96 (39%)**
		mean	**4.10**	**5.19 (26%)**

Numbers in the table represent rounded spectral efficiencies [bps/Hz] (percentage gain over "w/o MPE" baseline)

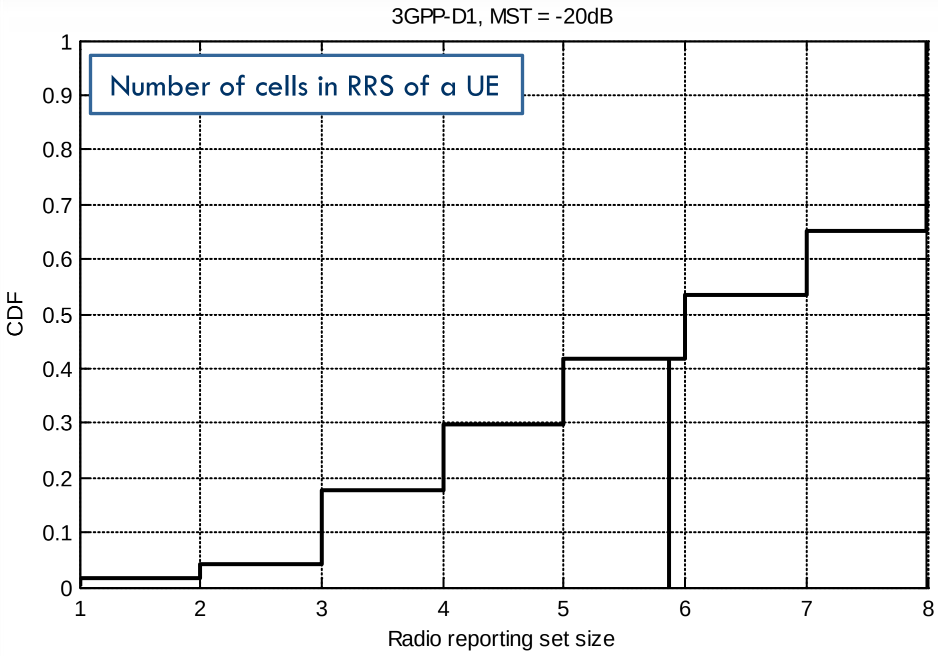
RX x TX	Average normalized feedback rate [bps/Hz/UE]	
	w/o MPE	w/ MPE
2x2	**0.008**	**0.026**
2x4	**0.013**	**0.028**

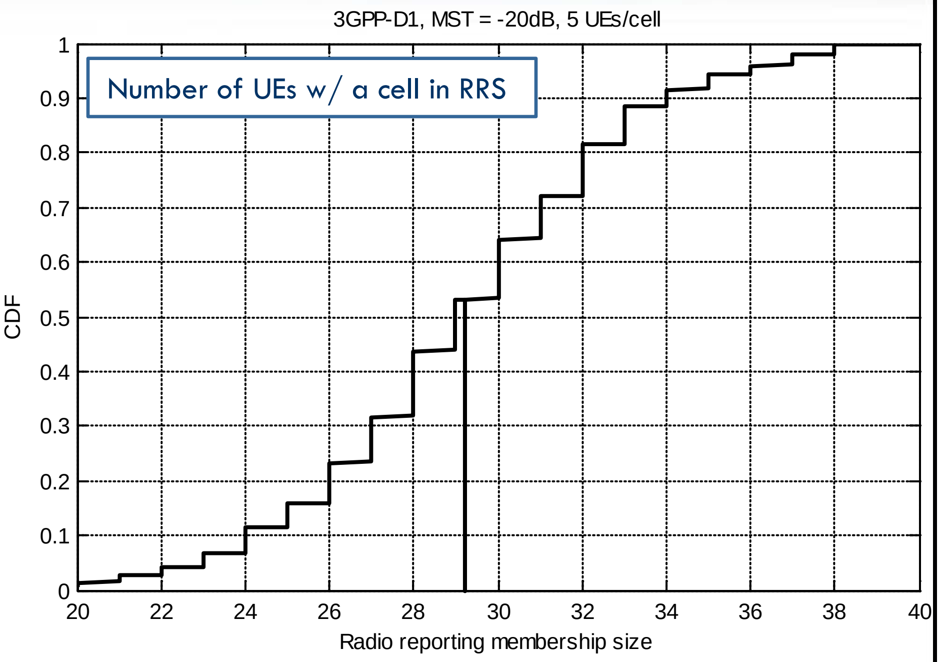
- **Results w/o MPE use dynamic SU-MIMO / MU-MIMO switching while MPE uses MU-MIMO only to reduce overhead**
- **Feedback overhead w/o MPE can be halved w/o much throughput loss**

Highlights

- Joint transmission CoMP can offer moderate throughput gains
  - average throughput gain **≈20%** w/ 2TX and **≈25%** w/ 4TX
  - comparable gains in hexagonal and practical layouts
- Major limiting factors for MPE gain
  - practical ability to detect multiple neighbors claims over **50%** of theoretical MPE throughput thereby limiting gain to **≈100%**
  - limited CSI accuracy claims **over 30%** of the gain achievable w/ perfect CSI: fundamental accuracy ⇔ overhead tradeoff
  - finite subband granularity and quantization payload account for additional **≈8%** loss: controllable via UE feedback overhead
  - excess delay spread w/ normal cyclic prefix (LTE) accounts for additional **≈5-8%** based on practical deployments

Radio reporting set and membership

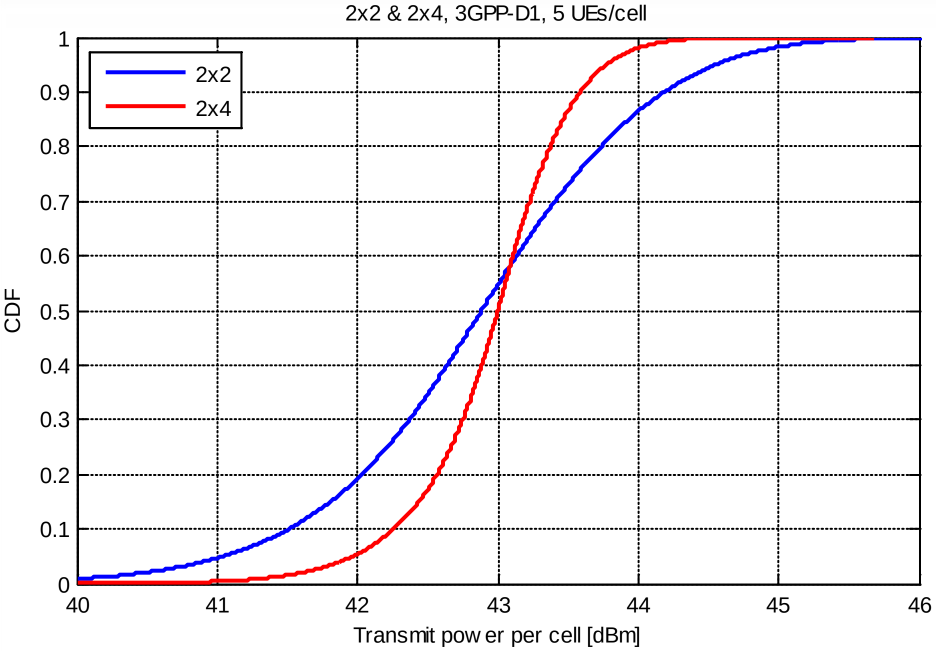


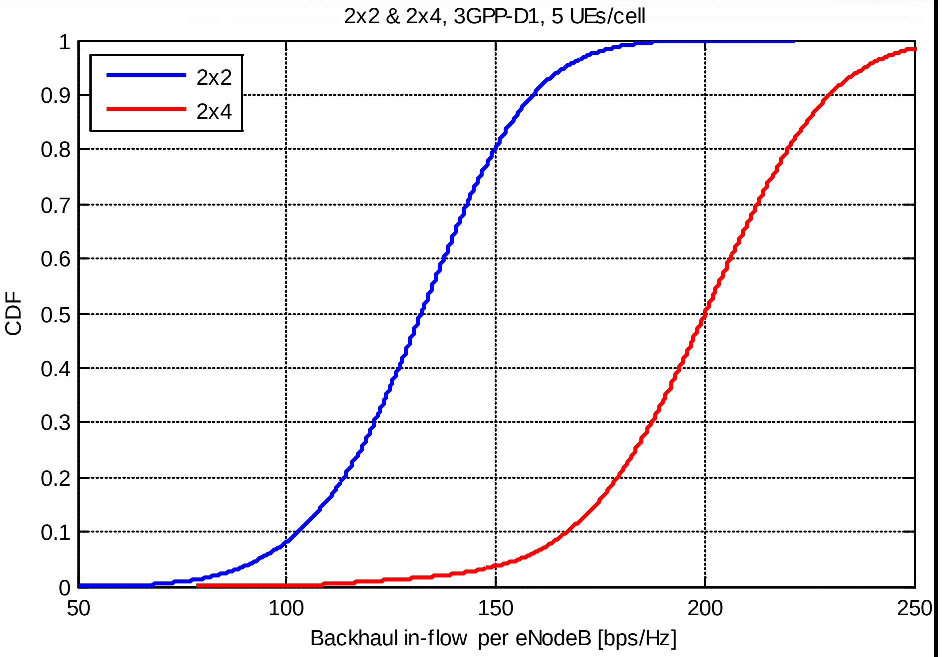


Maximum RRSS seen ≈35% of time

Radio reporting membership ≈ RRSS × UEs/cell

Power headroom and backhaul loading





Maximum power of 46dBm per cell never reached with 3dB backoff

Per eNodeB backhaul in-flow on the order of 1.5 - 2.0 Gbps in a 10MHz system

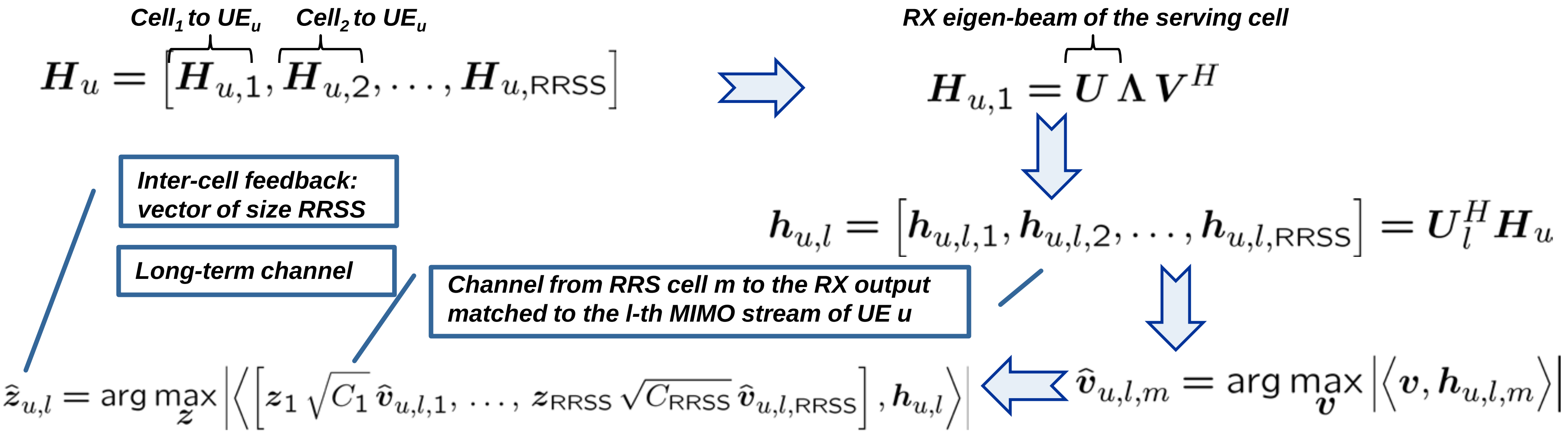
* ≈40% less once account for overheads / losses

Feedback optimizations and gains

- Main steps towards feedback reduction undertaken in this study
  - exploit time-domain CSI correlation to reduce feedback
    - MPE is efficient at pedestrian mobility only: use channel coherence
    - first order differential encoding based on assumed UE mobility
    - around 35% feedback rate reduction
  - scalable feedback to address different accuracy requirements
    - weaker cells within **RRS** of the UE require lower feedback accuracy
    - joint optimization FSB granularity and feedback payload across **RRS**
    - up to 25% feedback rate reduction
  - graceful scaling w/ the number of UEs per cell by rank restriction

Spatial feedback design

- Suggested solution is hierarchical eigen-feedback
  - A. UE decides on RX beam for every MIMO stream
    - example: receive eigen-modes matched to the serving cell
    - result: equivalent MISO channel between network & UE/stream pair
      - additional relative gains across eigen-modes → interference alignment
  - B. resulting channel from multiple cells/antennas to RX broken down into per-cell and inter-cell components
    - per-cell and eventually inter-cell feedback reported upon request



$$\boldsymbol{H}_u = \left[\overbrace{\boldsymbol{H}_{u,1}}^{\textit{Cell}_1\textit{ to UE}_u}, \overbrace{\boldsymbol{H}_{u,2}}^{\textit{Cell}_2\textit{ to UE}_u}, \ldots, \boldsymbol{H}_{u,\mathrm{RRSS}}\right]$$

$$\boldsymbol{H}_{u,1} = \overbrace{\boldsymbol{U}}^{\textit{RX eigen-beam of the serving cell}} \boldsymbol{\Lambda} \boldsymbol{V}^H$$

$$\boldsymbol{h}_{u,l} = \left[\boldsymbol{h}_{u,l,1}, \boldsymbol{h}_{u,l,2}, \ldots, \boldsymbol{h}_{u,l,\mathrm{RRSS}}\right] = \boldsymbol{U}_l^H \boldsymbol{H}_u$$

Channel from RRS cell m to the RX output matched to the l-th MIMO stream of UE u

$$\hat{\boldsymbol{v}}_{u,l,m} = \arg\max_{\boldsymbol{v}} \left|\left\langle \boldsymbol{v}, \boldsymbol{h}_{u,l,m} \right\rangle\right|$$

Inter-cell feedback: vector of size RRSS

Long-term channel

$$\hat{\boldsymbol{z}}_{u,l} = \arg\max_{\boldsymbol{z}} \left|\left\langle \left[z_1 \sqrt{C_1}\, \hat{\boldsymbol{v}}_{u,l,1}, \ \ldots, \ z_{\mathrm{RRSS}} \sqrt{C_{\mathrm{RRSS}}}\, \hat{\boldsymbol{v}}_{u,l,\mathrm{RRSS}}\right], \boldsymbol{h}_{u,l} \right\rangle\right|$$

Methodology of feedback optimization

- Quantify contribution of various error sources to the increase of residual interference level

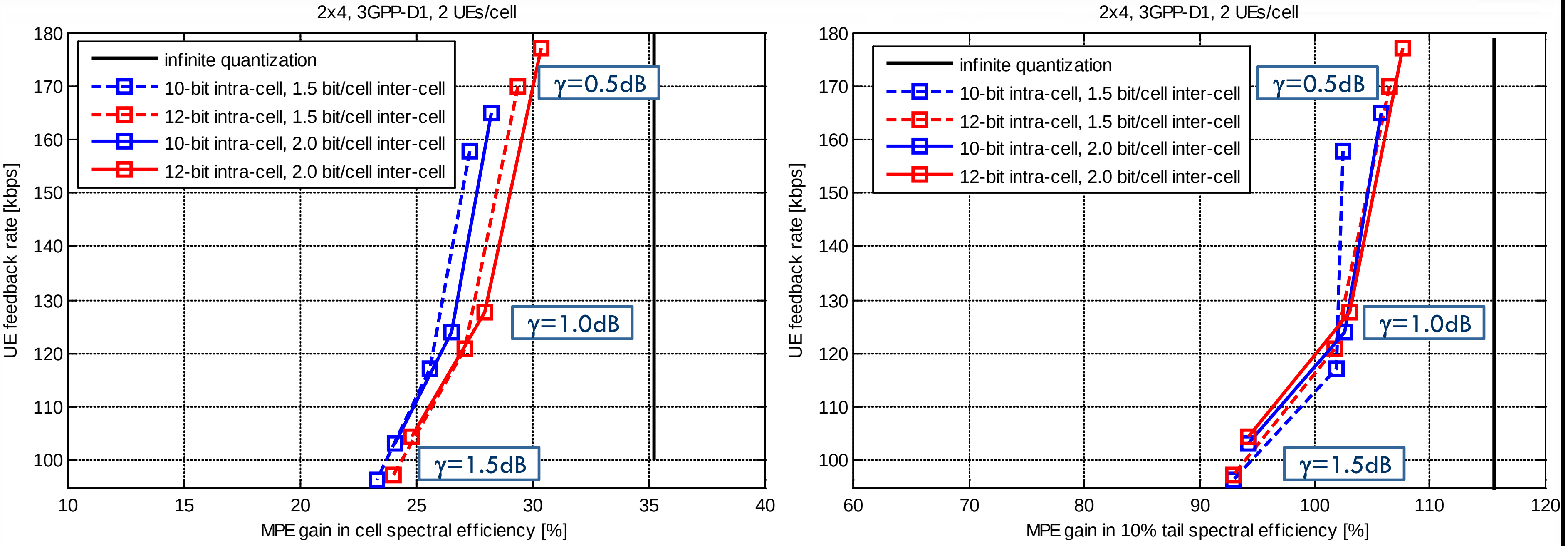
CSI estimation error
depends on C/I of a cell

Frequency response error
depends on FSB size

Differential encoding error
depends on payload

  - express C/I loss as function of the above error sources
  - exponential approximation of frequency & encoding error
    - frequency response error as function of the number of FSBs
    - differential encoding error as function of payload/sub-band
      - applies to per-cell channel component of every spatial stream
  - analytic first order approximation of long-term SINR
- Formulate optimization problem as minimizing the total payload of per-cell codebook feedback subject to maximum SINR loss (γ)
  - bi-convex function of (number of FSBs, payload per sub-band)
  - optimized via alternating minimization

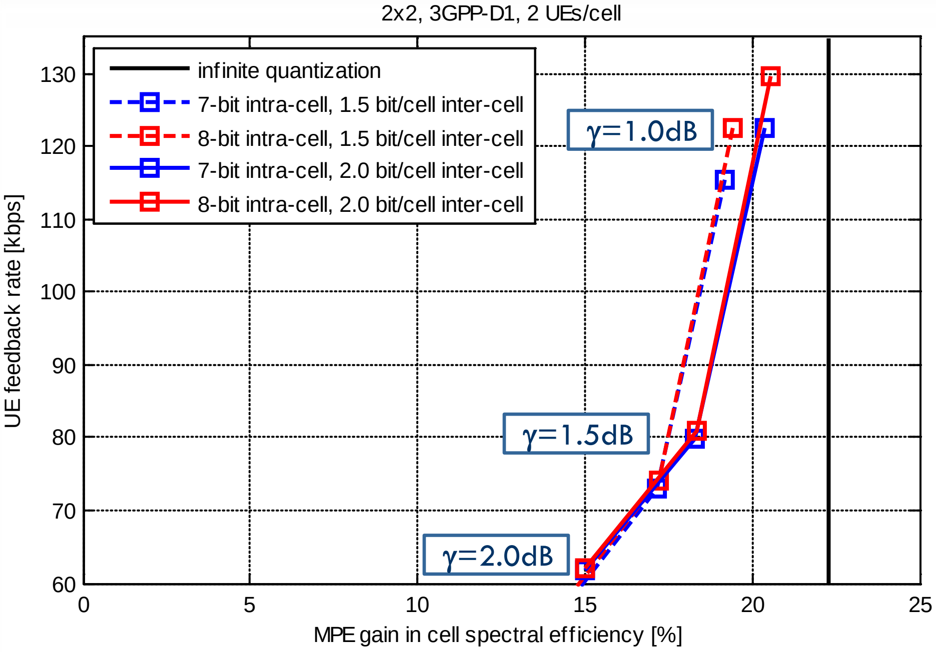
Maximum codebook size & C/I loss (2x4)

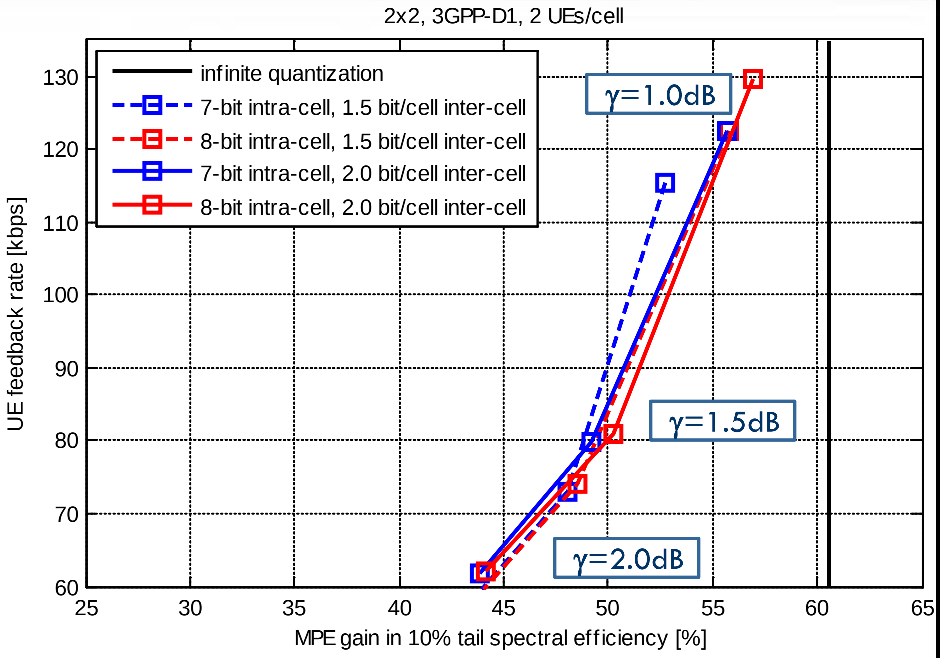


- Recommended feedback encoding parameters
  - maximum intra-cell codebook/stream size: 12 bits
  - inter-cell codebook/stream size: 2 bits/cell
  - allowed C/I degradation: $\gamma = 1.0$dB

★ **This analysis is based on 3-tier system simulations**

Maximum codebook size & C/I loss (2x2)





- Recommended feedback encoding parameters
  - maximum intra-cell codebook/stream size: 7 bits
  - inter-cell codebook/stream size: 2 bits/cell
  - allowed C/I degradation: $\gamma = 1.0$dB

★ **This analysis is based on 3-tier system simulations**

Scheduling for MPE

- Heuristics for channel energy prediction
  - MPE maximizes signal energy under multiple transmit nulling constraints
    - close to projecting the channel vector across all **RRS** antennas onto orthogonal complement of subspace spanned by *many* victim channels
    - can be factored as quasi-deterministic loss w.r.t. MRC transmission?
  - eNodeB maintains **MPE loss**: filtered ratio of the actual post-MPE energy to the energy assuming MRC transmission across **RRS**
  - **MPE loss** applied to the actual channel to predict post-MPE energy
- UE measures residual post-MPE interference based on demodulation reference signals (UE-RS) as part of demodulation process
  - filtered post-MPE interference used to obtain post-MPE CQI at eNodeB
  - (minor) refinement on long-term *residual* interference from outside **RRS**
    - other interference sources kept possibly small compared to residual interference
    - accurate estimate of post-MPE interference due to substantial averaging

Corporate R&D

Annex A: system evaluation parameters

Evaluation methodology and parameter settings

★ **Throughout the document $N_{RX} \times N_{TX}$ is used for a MIMO channel**

System evaluation parameter	3GPP-D1, 4 tiers
eNodeB antenna gain	14dB
UE antenna gain	0dB
TX power per cell	46dBm
Bandwidth (w/ 90% occupancy)	5MHz
UE noise figure	9dB
Inter-site distance	500m
Min drop distance	35m
Log normal standard deviation	8dB
Log normal correlation (inter-site)	0.5
Log normal correlation (intra-site)	1.0
Vertical pattern	omni
Horizontal pattern	IMT
eNodeB antenna height	32m
UE antenna height	1.5m
Path loss exponent	3.76
Path loss constant	15.3
Penetration loss	20dB
Fading model	ped-B, *i.i.d.* spatial
Number of UEs/cell	2,5

CoMP evaluation parameter	Value
MST [dB]	-20
Maximum TSS [cells]	20
Maximum PMO/cell [MIMO streams]	48
Maximum RRSS [cell]	8
Maximum BRSS [cells]	57
UE speed [km/h]	1
Assumed speed @ eNodeB [km/h]	0
CSI reporting interval [ms]	20
Cyclic prefix [us]	4.69
Total power per stream [dBm]	43 for 1 MIMO stream per cell 40 for 2 MIMO streams per cell

CoMP evaluation parameter	w/o MPE	w/ MPE
CSI-RS overhead [%]	2	5
Feedback subband size [kHz]	90 & 900 (0.5 & 5 PRB)	90 (0.5 PRB)
Scheduling subband size [kHz]	180 & 900 (1 & 5 PRB)	180 (1 PRB)

CoMP evaluation parameter	2 x 2	2 x 4
Maximum intra-cell codebook payload [bits/stream]	7	12
Maximum inter-cell codebook payload [bits/stream/cell]	2	2

Spectral efficiencies computed based on 64QAM information rate w/ 3dB gap