Performance Evaluation of a Beam Coordinated LTE-Advanced System

Benedikt Wolz

Communication Networks (ComNets) Research Group
Prof. Dr.-Ing. Bernhard Walke
RWTH Aachen University, Faculty 6, Germany

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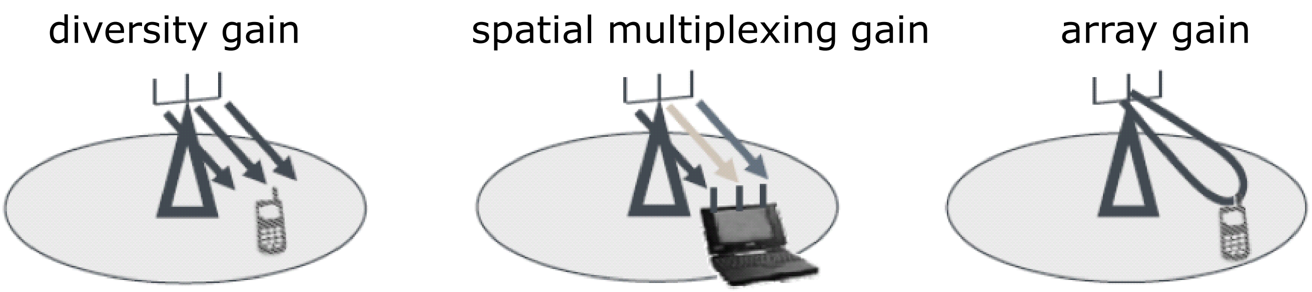
Contents

- Motivation
- Beam Coordination Scheme
- Model
- Results
- Conclusion

Motivation
Beamforming Technique

Fundamental Benefits of Multiple Antennas [Sesia, 2011]



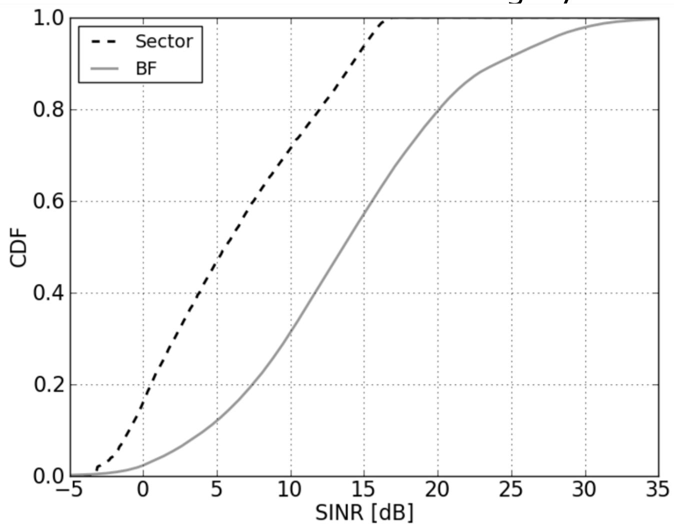
Beamforming vs. other MIMO techniques

- Beneficial in sparse multipath scenarios with increased cell size and high LOS probability
- Extends cell coverage and increases system capacity by one technique (→ simple transceivers)
- Multiple antennas are only required at the BS side (→ simple end-user devices)

Motivation
Coordinated Beamforming

SINR CDF - UMa

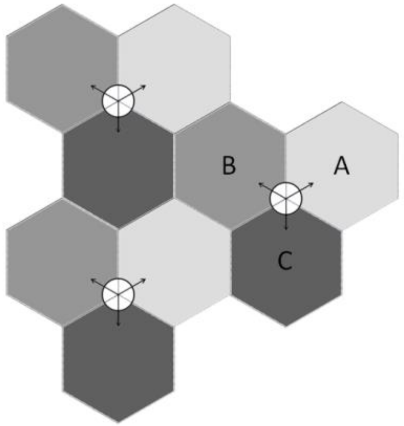
Sector- versus Beamforming System



- Coordination can improves beamforming by reducing "flash light" effect (reduced I-level in general, occasionally increased I within main lobe)
- Coordination schemes can yield gain by
  - Increasing precision of SINR estimations → more efficient link adaptation
  - Mitigating inter-cell interference
- Targeting for Increased Cell Spectral Efficiency (CSE) and Cell Edge User Spectral Efficiency (CE-USE)

Beam Coordination – Synchronised Cycles of Coordinated Beams

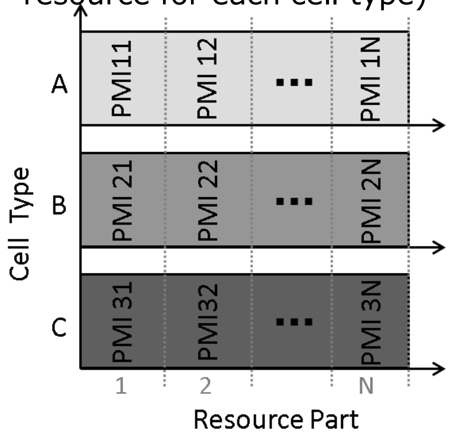
Types of Cells



- Beam coordinated scheduling NP-Hard Problem [van Rensburg, 2009]
  number of beam combinations with 8 beams per sector
  two tiers: $8^{21} \approx 9.2*10^{18}$, one tier $8^{7} \approx 2*10^{6}$
- Split into smaller problems
  - 1) How reduce complexity
  - 2) How find beneficial beam combinations

Coordination Matrix

(defines applied beam in resource for each cell type)



To 1)

- Reduce complexity by introducing cell types
  →Cell types instead of single cells are coordinated
- Cells of same type synchronously apply same beam
- A cell cycles through a set of beams with predefined order
- Coordination matrix defines applied beam in time-frequency resource blocks for each cell type

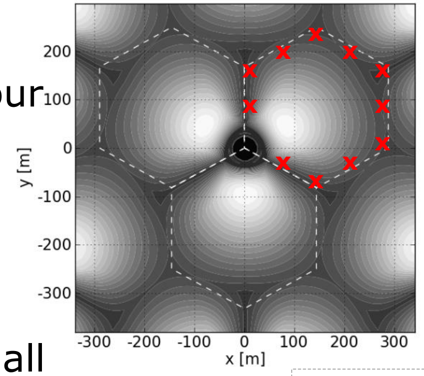
Beam Coordination – Seeking Beneficial Beam Combinations

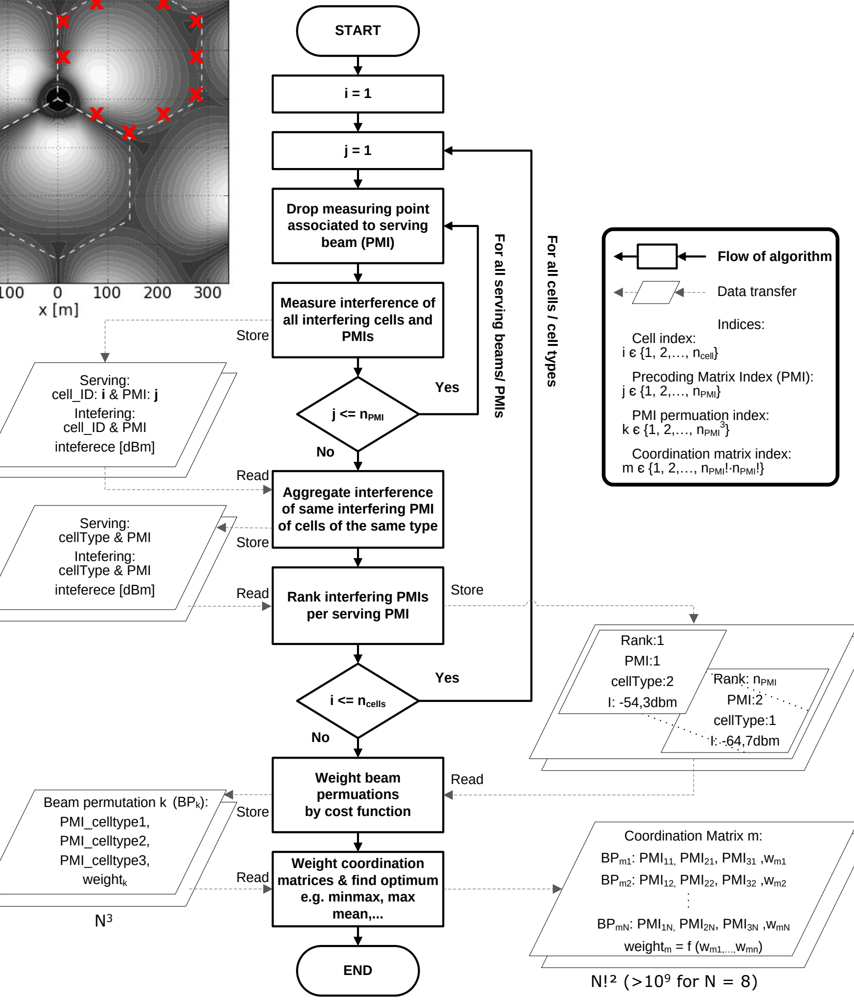
- Goal:

1) beams applied at same time in neighbour cells minimally interfere each other
2) all users are served

- Set measurement points at cell edge
- Measure interference for each beam of all neighbour cells, for each cell type
- Weight all beam combination (defined by three PMI values) by appropriate cost function indicating amount of mutual interference (e.g., mean interference, min. rank of beams)
- Weight all coordination matrix (set of beam combinations) (e.g. mean, deviation, min max interference)
- Search for optimal CM is speed up by only considering beam combination weighted above threshold

SINR Map with Measurment Points at Cell Edge

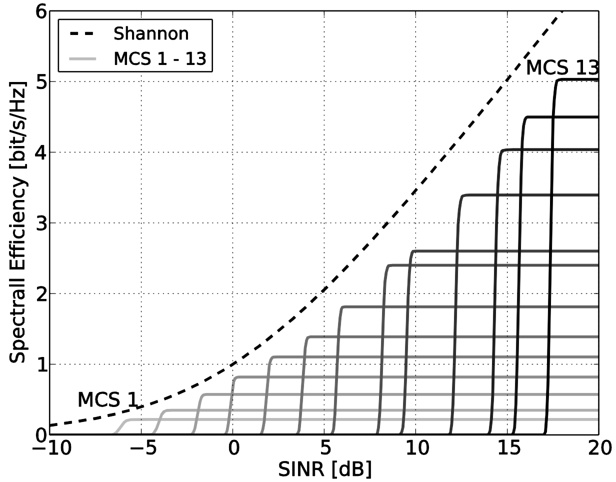




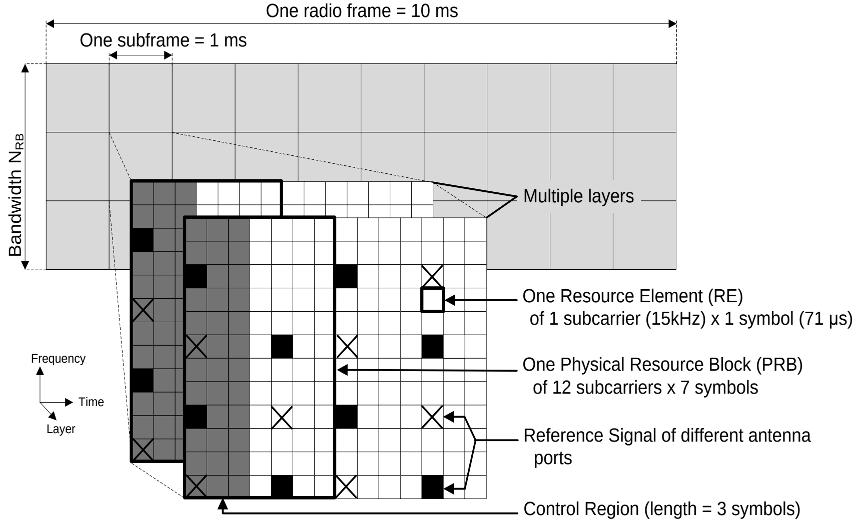
System Model

- System Model comprises
  - 3GPP standard Rel.9 / LTE
    (link adaptation, overhead, interference management (X2-Interface Rel.10))

Net spectral efficiency of LTE – MCS and Shannon bound



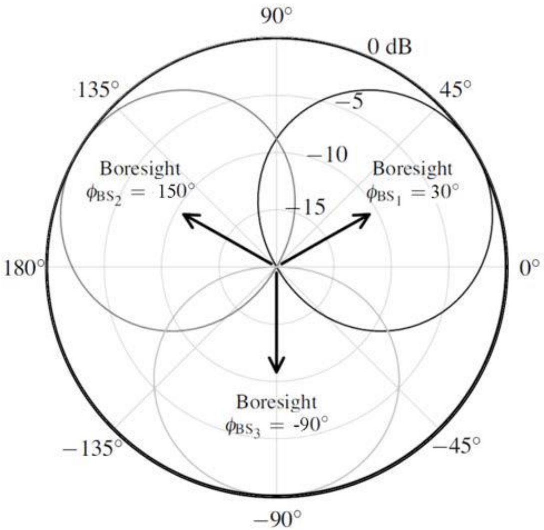
Overhead in the downlink resource grid



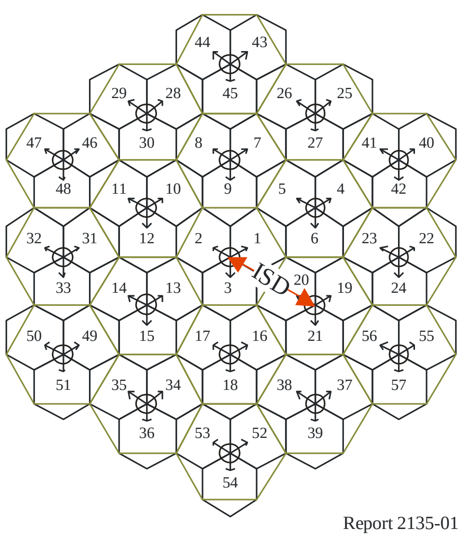
System Model

- System Model comprises
  - 3GPP standard Rel.9 / LTE
    (link adaptation, overhead, interference management (X2-Interface Rel.10))
  - ITU-R Guidelines, IMT-Advanced
    (scenarios, channel- and antenna models)
  - Beamforming Model [Godara, 1997]
    (narrowband signal, correlated antenna elements, narrow angular spread)
  - Approach of permutations [Bueltmann, 2010] extended by beamforming and coordination
    (closed analytical calculation of SINR and user throughput distributions at the transition to an infinite number of drops)

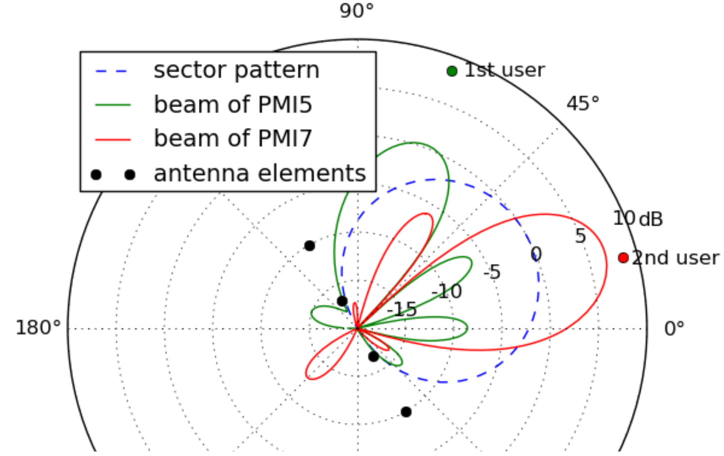
Antenna Gain
Azimuth Sector Pattern



Hexagonal Cell Layout,
[ITU-R M.2135]

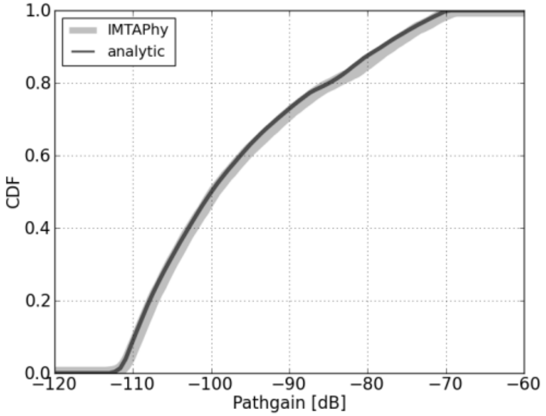


Sector- and example beam patterns
(precoding codebook [3GPP TS36.211],
4 antenna elements, λ/2 spacing)

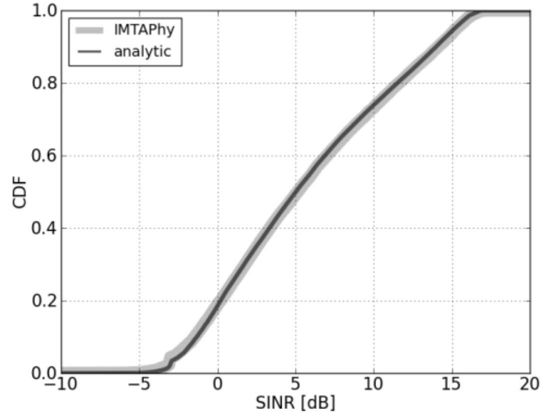


System Model – Validation against IMTAphy

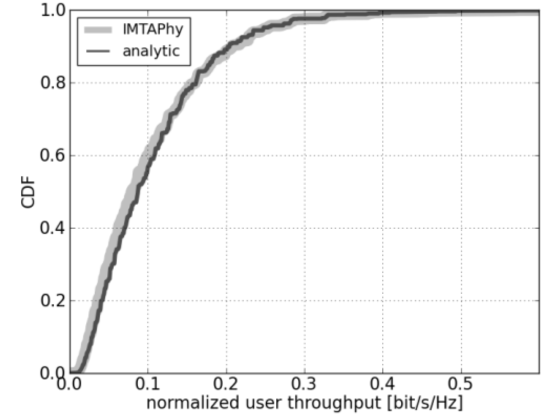
Pathgain CDF
(with constant vehicle penetration loss)



Wideband SINR CDF
(without random component of shadowing)



Normalized User Throughput CDF
(without small-scale fading)



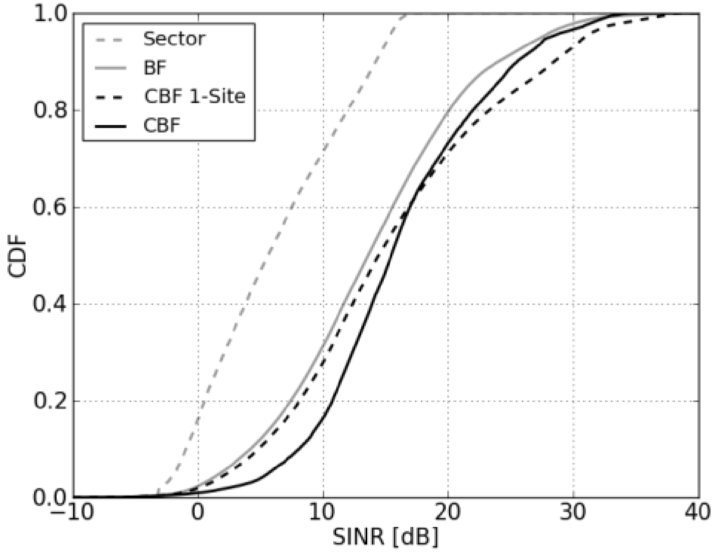
- Validating against well documented & calibrated stochastic simulator IMTAphy [Ellenbeck, 2012]
- Conducted with common parameter set considering features of used model
  small scale fading & shadowing disregarded, constant vehicle penetration loss (9 dB) instead of log-normal distributed loss ($\mathcal{N}(9;\,5)$ in dB); evaluating central site vs. entire scenario with wrap around
- Feeder pathgain is sum of all losses btw. MS and serving BS disregarding fast-fading
  feeder loss, pathloss of feeder link, shadowing, vehicle penetration losses, antenna patterns; CDF indicates issues of association procedure, user placement (such as minimum distances), LOS classification
- Wideband SINR (geometry) is average downlink SINR in a reuse one scenario
  CDF validate correct dependencies between links, e.g. links to same site have same propagation conditions
- Per-user throughput CDF contributed by all aspects of link-to-system model, protocol implementation (Assumptions: UMa Scenario, frequency reuse one, Round-Robin scheduling, sector antennas (without MIMO techniques))
- The curves from analytic tool and from IMTAphy (thicker) are approximately identical

Scenario

Parameter	Value
Environment	UMa
Spatial Resolution	Equidistant grid with 5m distance
eNB antenna	Sector antenna or antenna array with 4 elements
Traffic model	Full buffer model [ITU-R M.2135, Annex 2]
Antenna downtilt	12° [3GPP TR 36.814]
Channel estimation	Instant & accurate SINR estimation
System Type	Sector, Beamforming, Beam Coordinated
Scheduling strategy	Round Robin or Rate Fair
Frequency reuse schemes	Frequency Reuse 1 and 3 , and Soft Frequency Reuse with $\alpha = 2.6$
Number of fixed beams	Sector pattern, 3, 5, or 7 beams

Results - Systems Types

SINR CDFs

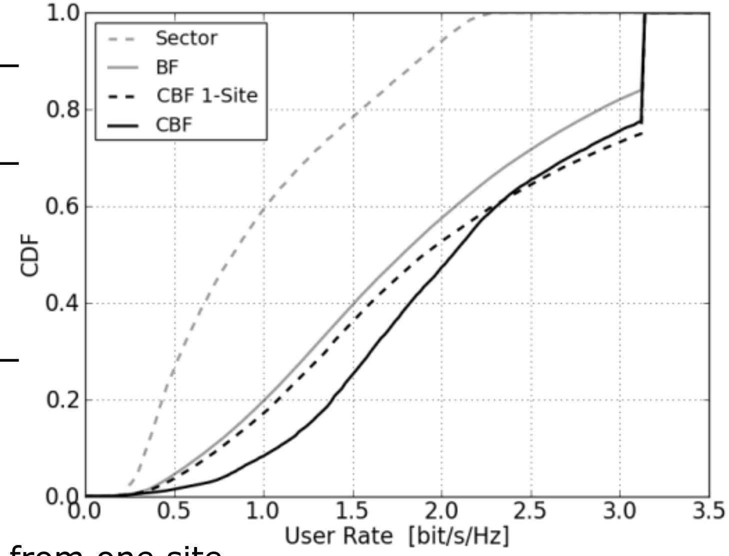


Mean & Standard Deviation (STD)

System Type	Mean in [dB]	STD in [dB]
Sector	6.17	4.78
BF	13.97	6.05
CBF 1-Site	15.60	7.06
CBF	16.16	5.39

BF: Beamforming,
CBF: Coordinated BF
CBF 1-Site: CBF of cells from one site

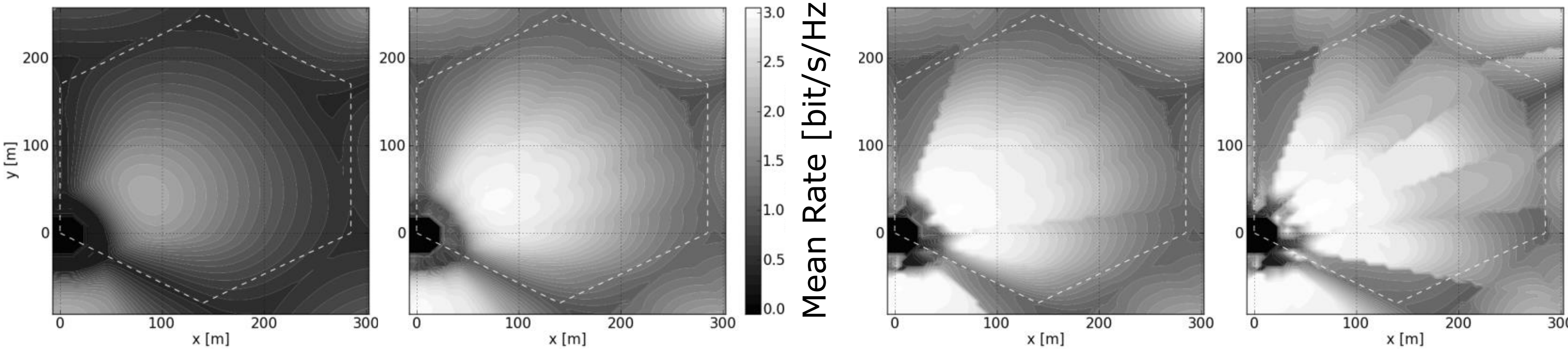
User Rate CDFs



- BF vs. Sector, increases mean SINR by 8 dB, reduce STD by 27%
  flash light effect increases variance of I
- CBF 1-Site vs. BF, improves mean SINR by 1.6 dB, increases STD by 17%
  especially strong users benefit → suboptimal 1-Site coordination
- CBF (all cells) vs. BF, increases mean SINR by 2.2 dB, reduces STD by 11%.
  avoids strong interfering beams in neighbour cells, especially weak users benefit, reduced STD indicates more predictable SINR / more efficient link adaptation
- Rates saturate for SINRs beyond 20 dB (for 20-30% users)
  → higher MCS are required for leveraging MIMO and CoMP schemes

Results - Systems Types
Mean Rate Maps

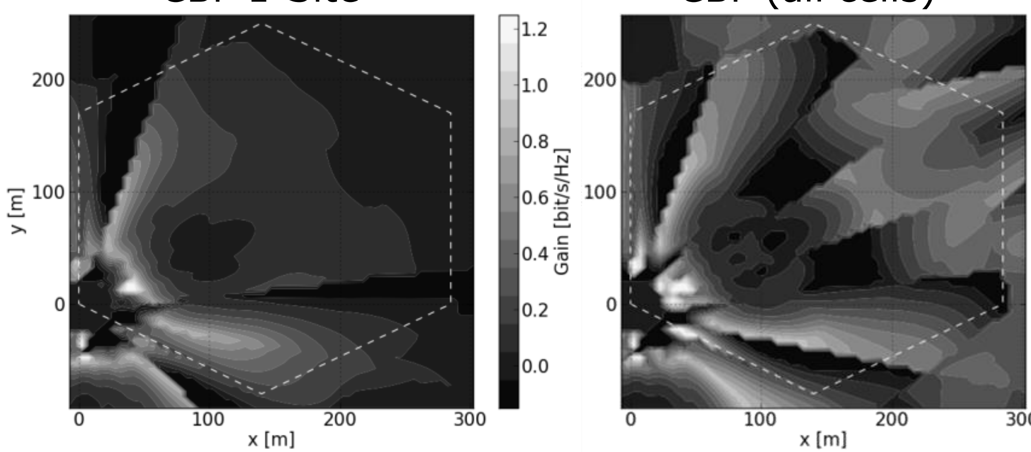
Sector | Beamforming (BF) | Beam Coordination: CBF 1-Site | CBF (all cells)



- BF increases the whole rate level, esp. strong users
- CBF 1-Site additionally increases rates, mainly in centre cell, only slightly at common cell edge
- CBF improves rates in whole cell, areas served by two outer beams are disadvantaged
- Few regions suffer from coordination, perceive lower rates than with BF
- Future scheme improvement: explicitly mitigating interference in the centre cell as well

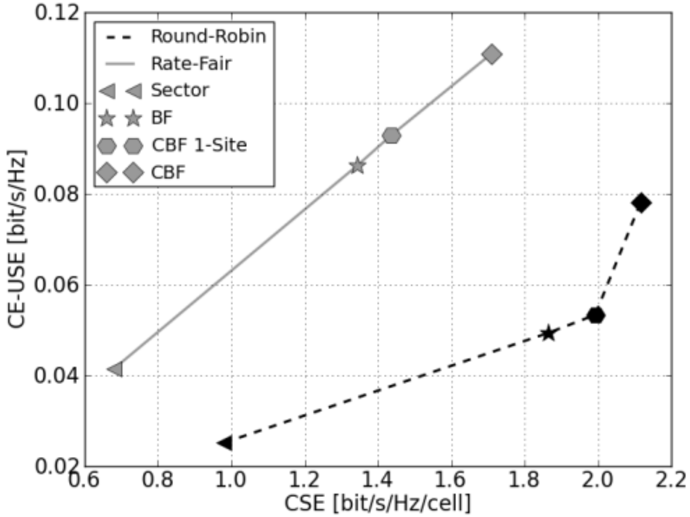
Gain [bit/s/Hz]

CBF 1-Site | CBF (all cells)



Results - Scheduling Schemes

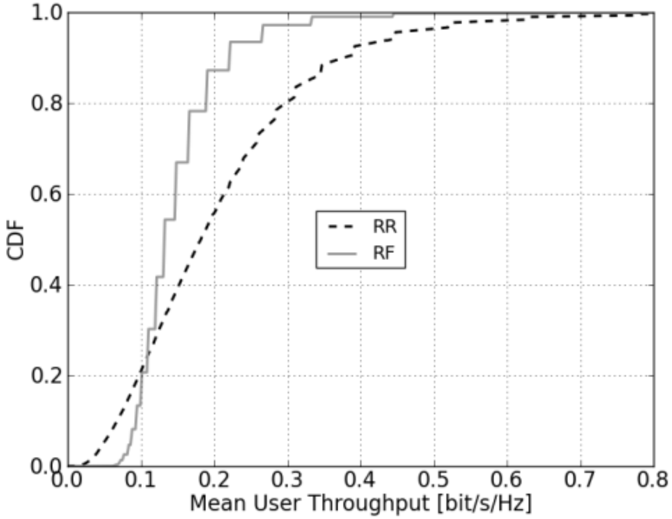
CE-USE vs. CSE



Coordination Gains vs. Beamforming

System Type	CSE	CE-USE
CBF 1-Site		
Round-Robin	7%	8%
Rate-Fair	7%	8%
CBF		
Round-Robin	13%	58%
Rate-Fair	27%	29%

User Throughput CDF

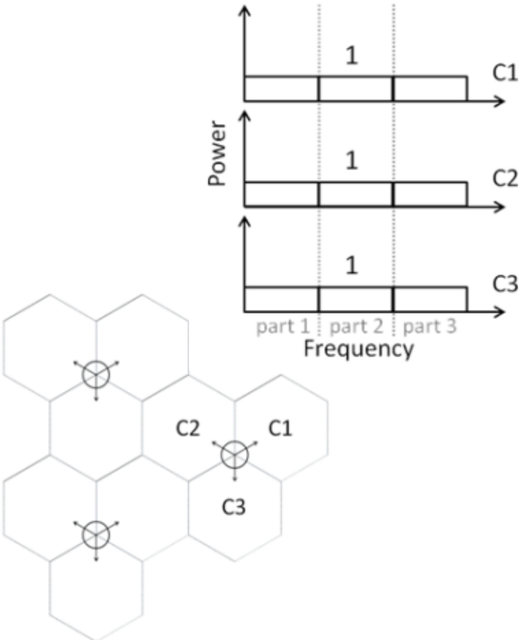


- Coordination produces significant gains with both strategies
- Rate gain reflect interference mitigation, but ignores improved link adaptation by more predictable SINR due to model's perfect SINR estimation
- Round-Robin yields higher cell capacity of 40% within same system type (with CBF gain of 20% for CSE),
- Rate-Fair generates higher fairness of 70% within same system type (with CBF gain of 40% for CE-USE)

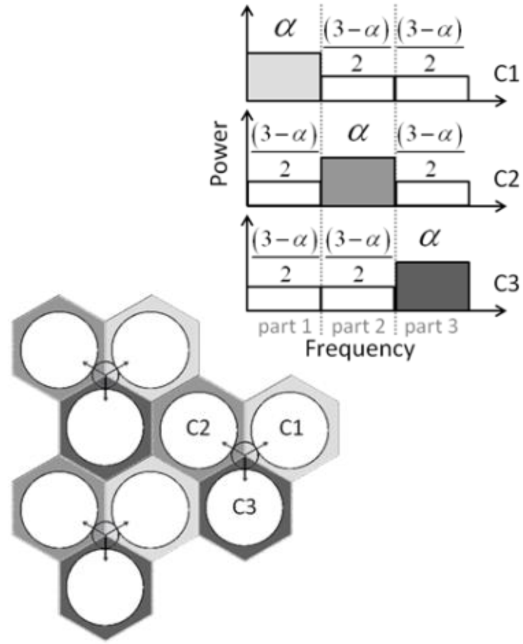
→ Scheduling strategies trade off fairness against cell capacity

Results – Frequency Reuse Schemes

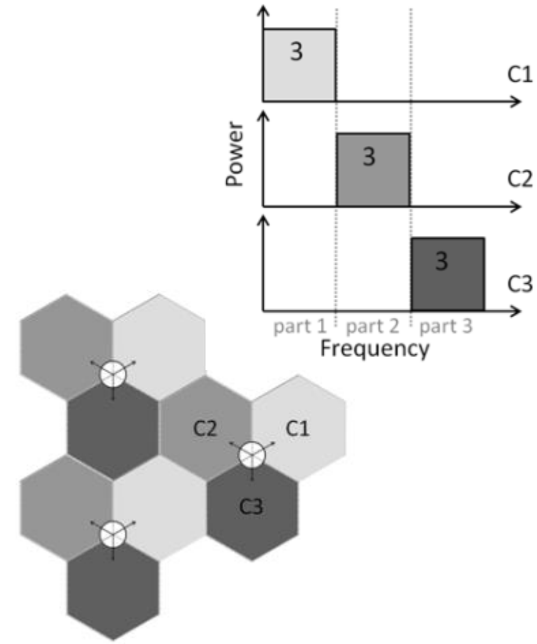
Frequency Reuse One (FR1)



Soft Frequency Reuse (SFR)

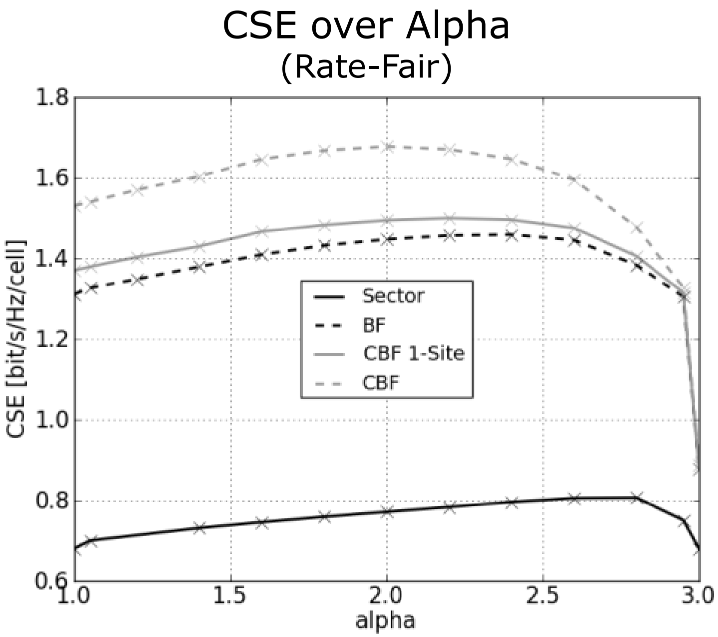


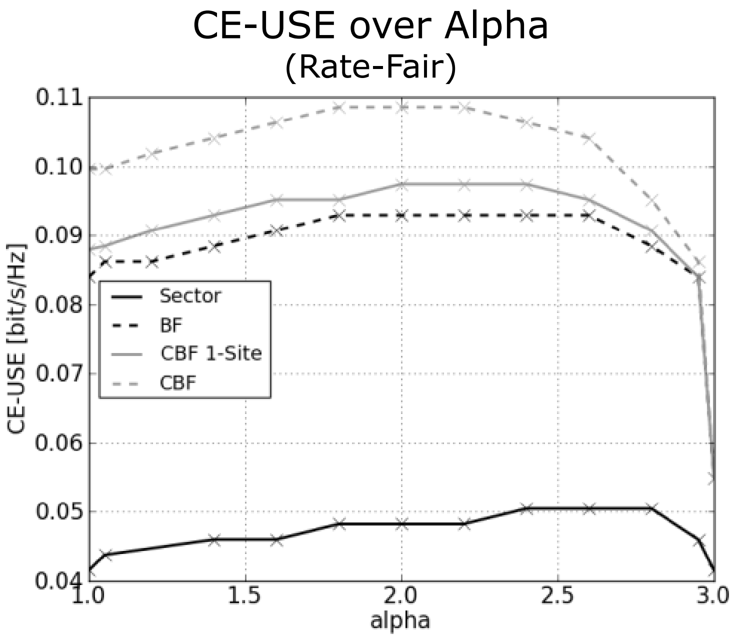
Frequency Reuse Three (FR3)



- Power masks depict max. transmit power in specific spectrum part
- SFR two power levels: α in primary part, $\beta=(3-\alpha)/2$ in two secondary parts, α defines *effective reuse factor (1< α <3)*
- Constant total transmit power, allows fair evaluation
- FR3 & SFR reduce inter-cell interference by increasing reuse distance especially for users at the cell-edge

Results - SFR Operating Point

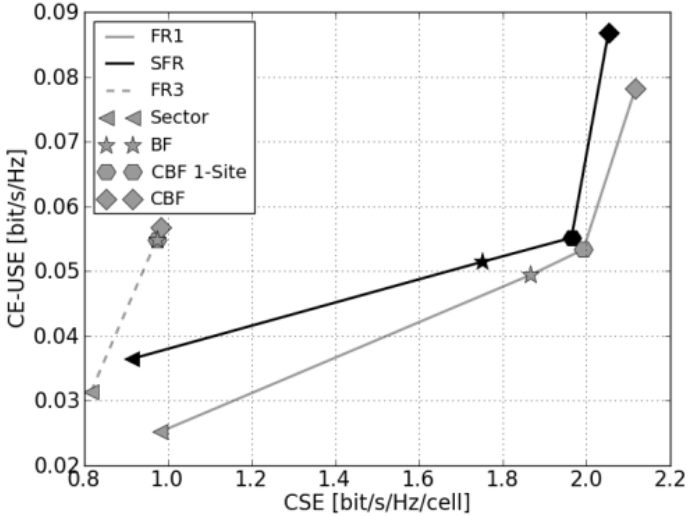




- Operating point $\alpha = 2.6$ yields optimal results for non-coordinated systems and allows still for significant coordination gains
- In the following, the SFR scheme is used with $\alpha = 2.6$

Results – Varying Reuse Schemes
(Round Robin, 7 beams)

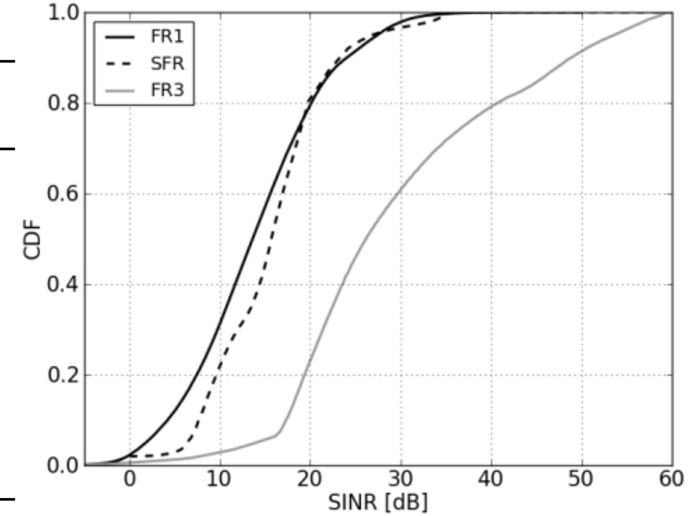
CE-USE versus CSE



Coordination gain vs. Beamforming

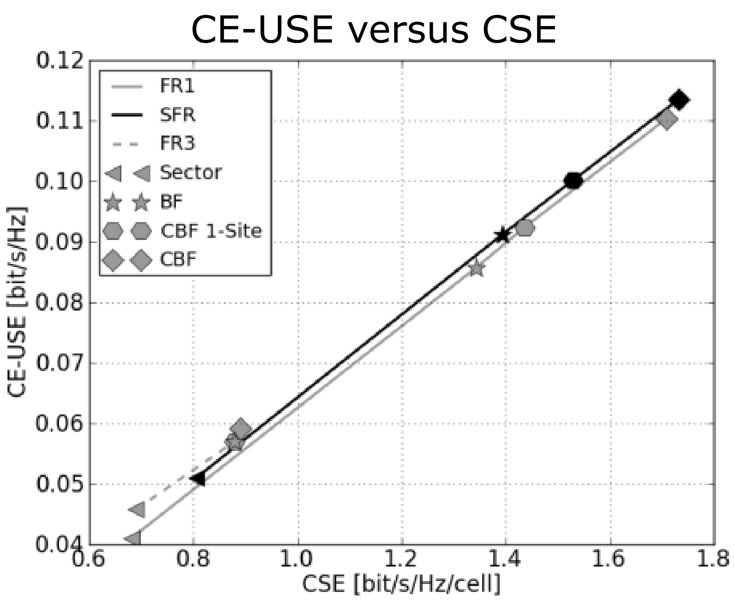
System Type	CSE	CE-USE
CBF 1-Site		
FR1	7%	8%
SFR	12%	8%
FR3	0%	0%
CBF		
FR1	13%	58%
SFR	17%	72%
FR3	1%	3%

SINR CDF with Beamforming



- Both coordination schemes can significantly increase cell capacity and fairness in FR1 and SFR, with higher gains in SFR
- In FR3 marginal coordination gains occur
- CBF improves cell capacity but particularly increases cell edge performance by avoiding most interfering beams at cell edge
- Higher gain in SFR through beneficial impact on secondary part
  these users perceive low signal strength (β = 0.2) and high interference (α = 2.6)
  → higher gain from I mitigation than in FR1
- Reuse schemes tend to trade capacity versus fairness
- Reduced significance of dependency by saturating rates for SINRs >20 dB

Results – Varying Reuse Scheme Rate-Fair



Coordination Gain vs. Beamforming

System Type	CSE	CE-USE
CBF 1-Site		
FR1	7%	8%
SFR	10%	10%
FR3	0%	0%
CBF		
FR1	27%	29%
SFR	24%	25%
FR3	1%	4%

- Similar results to Round-Robin scheduling
- Similar Gain at cell edge and in whole cell, due to scheduling characteristic
- With Rate-Fair scheduling, CBF higher gains in FR1 than in SFR
  In SFR, more users on primary part with RF than with RR
  → I mitigation more effective with FR1 than in primary part with SFR

Conclusions & Outlook

Conclusions

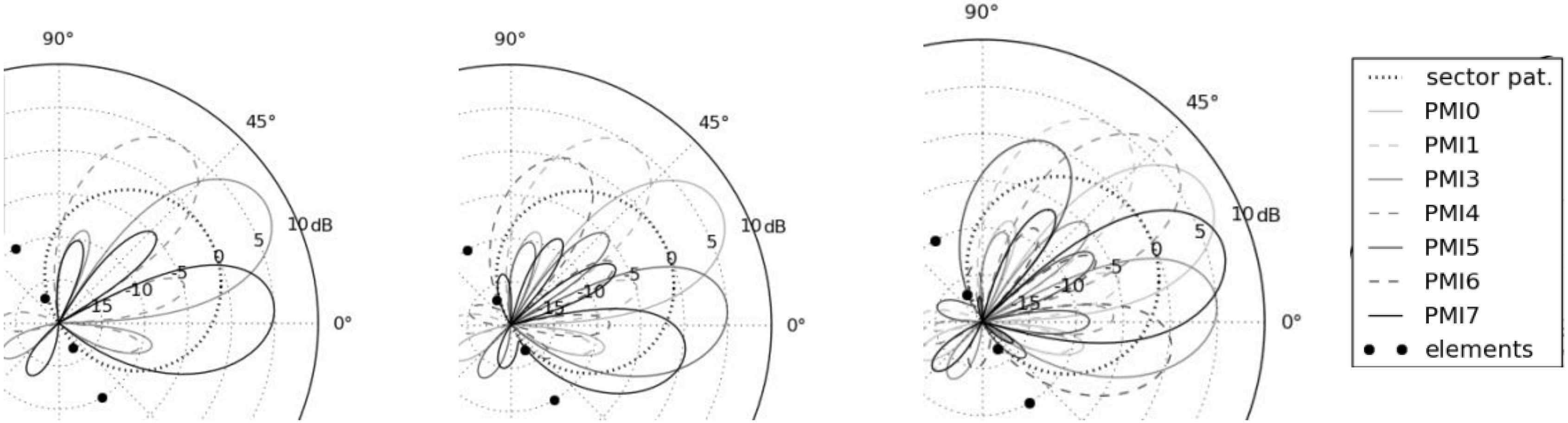
- Designed coordination scheme significantly outperforms ordinary beamforming for all studied parameters (scheduling strategy, reuse scheme, or number of beams, coordination type 1-Site/ system wide)
  - CBF vs. BF improves mean SINR by 2.2 dB & reduces SINR variance by 11% in avoiding harmful beam combination of neighbour cells
  - CBF increases cell edge performance by up to 58% & system capacity up to 29% with FR1. With SFR, cell edge performance improved by up to 72%
  - CBF 1-Site yields gains of up to 12% cell capacity & up to 10% fairness with far lower costs
- With FR3, coordination gains are marginal
- Optimal SFR operating point depends on scheduling, maximum available rate, coordination type
- Scheduling strategies and frequency reuse schemes trade off fairness against cell capacity, beam coordination improves both

Future work

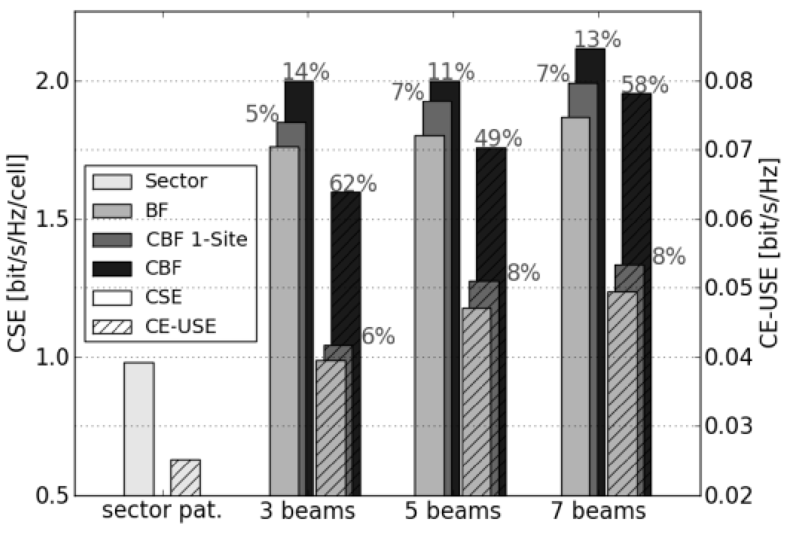
- Study impact of more predictable SINR by coordination
- Study impact of sharper beams by increased number of antenna elements
- Adapt scheme to in flight broadband Direct-Air-to-Ground communications

Backup Slides

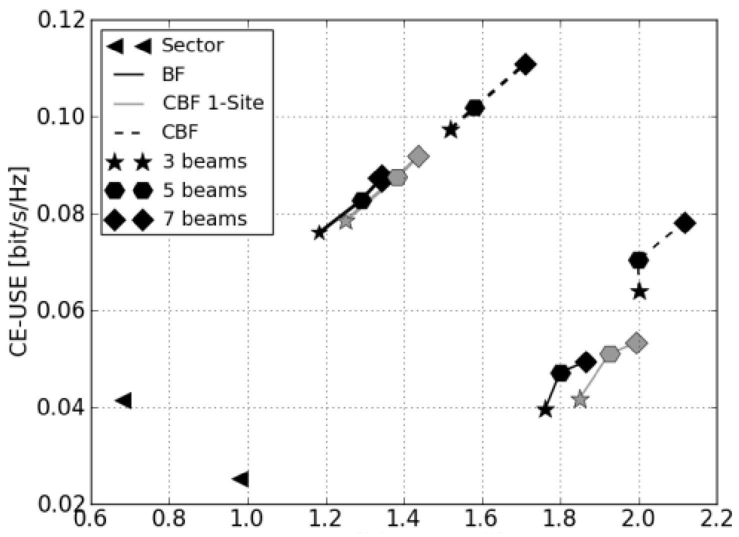
Beams


90°
45°
10 dB
5
0
-5
-10
15
0°
sector pat.
PMI0
PMI1
PMI3
PMI4
PMI5
PMI6
PMI7
elements

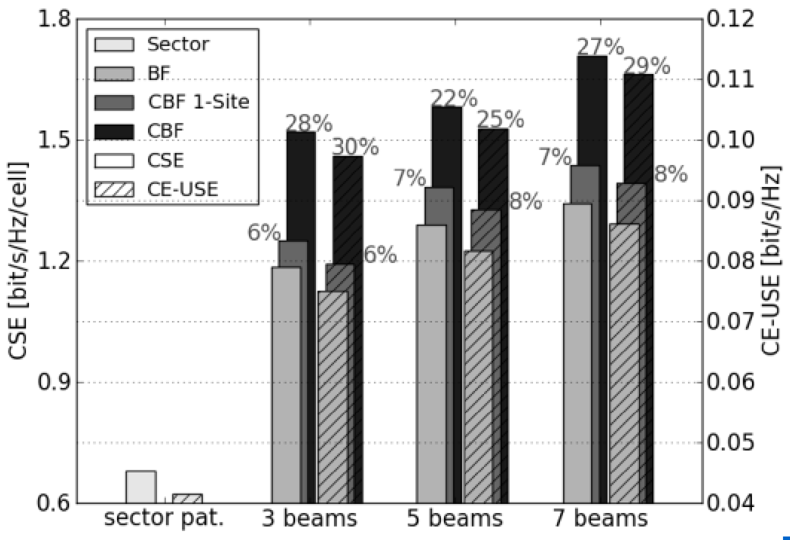
Beams



CSE [bit/s/Hz/cell]
CE-USE [bit/s/Hz]
Sector
BF
CBF 1-Site
CBF
CSE
CE-USE
sector pat.
3 beams
5 beams
7 beams
5%
14%
62%
6%
7%
11%
49%
8%
7%
13%
58%
8%



CE-USE [bit/s/Hz]
Sector
BF
CBF 1-Site
CBF
3 beams
5 beams
7 beams



CSE [bit/s/Hz/cell]
CE-USE [bit/s/Hz]
Sector
BF
CBF 1-Site
CBF
CSE
CE-USE
sector pat.
3 beams
5 beams
7 beams
6%
28%
30%
6%
7%
22%
25%
8%
7%
27%
29%
8%