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Interference management in wireless networks: Practice and Theory

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Outline

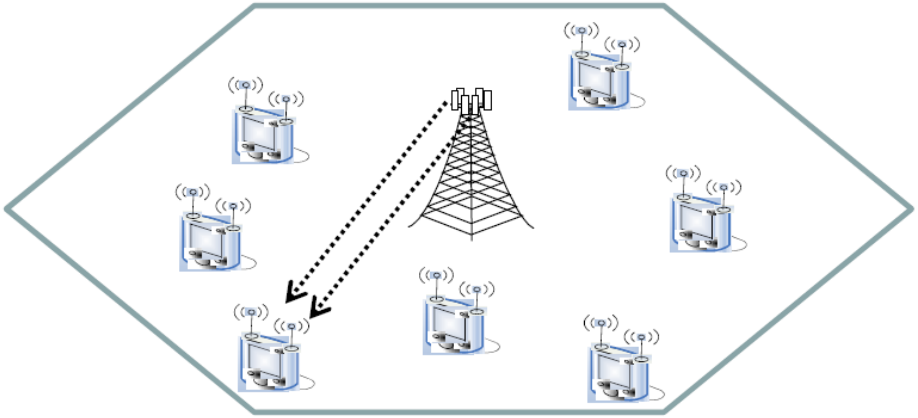
1. Interference Management in MIMO wireless networks

2. **Part 1: An industry perspective – how to make it work?**
    1. LTE-A system level performance evaluations
    2. Practical coordination/cooperation strategies

3. **Part 2: An academic perspective – how to exploit interference?**
    1. MIMO Broadcast Channel with Imperfect CSIT
    2. MIMO Interference Channel with information and energy transfer

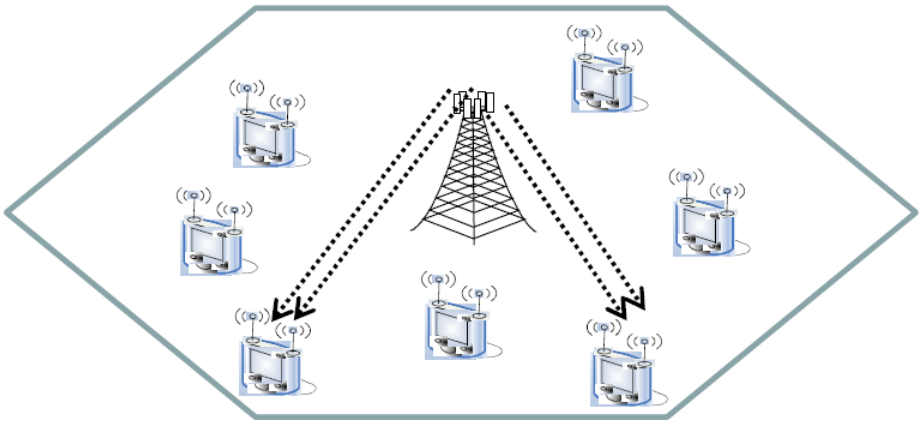
4. Conclusions

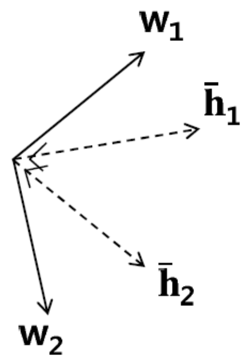
Single-user (SU) MIMO



- One user scheduled in each cell on a given time-frequency resource
- Maximize single-link throughput
- Spatial Multiplexing (with or without CSI at the transmitter)

Multi-User (MU) MIMO [Clerckx2013a]





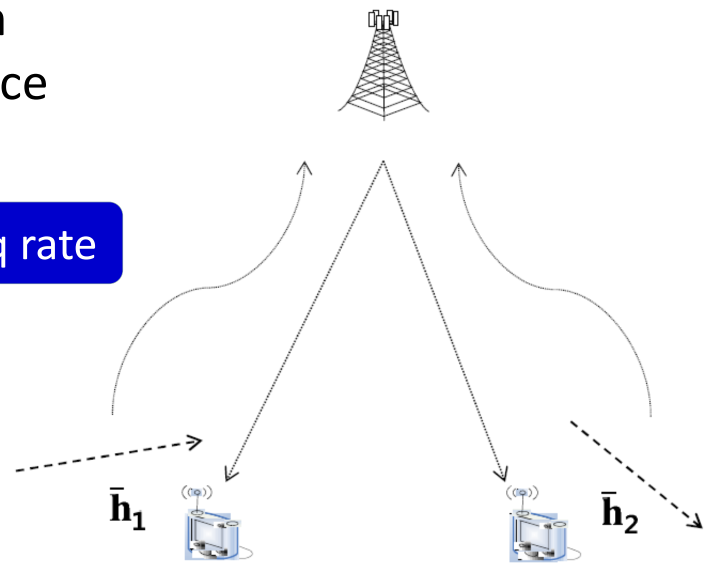
- Multiple users scheduled in each cell on a given time-frequency resource -> intra-cell interference

- Maximize cell throughput

User-q weight
User-q rate

$$\{\mathbf{c}'^{\star}, \mathbf{G}^{\star}, \mathbf{K}^{\star}\} = \arg \max_{\mathbf{c}', \mathbf{G}, \mathbf{K} \subset \mathcal{K}} \sum_{q \in \mathbf{K}} w_q R_q$$

Tx signal
Rx filter
User schedule



- Popular precoding strategy: Zero-Forcing Beamforming (ZFBF)

Multi-Cell (MC) MIMO [Clerckx2013a]

- Denoted as CoMP in LTE-A
- Jointly allocate resources across the whole network (and not for each cell independently) and use the antennas of multiple cells to improve the received signal quality at the mobile terminal and to manage the intra and inter-cell interferences.
- Targets primarily cell edge users
- Paradigm shift: maximize a network utility metric rather than a cell utility metric

$$\{\mathbf{S}^\star, \mathbf{W}^\star, \mathbf{G}^\star, \mathbf{K}^\star\} = \arg \max_{\mathbf{S},\mathbf{W},\mathbf{G},\mathbf{K}\subset\mathcal{K}} \sum_{i=1}^{n_c} \sum_{q\in\mathbf{K}_i} w_q R_{q,i}$$

Tx power
Tx beamformer

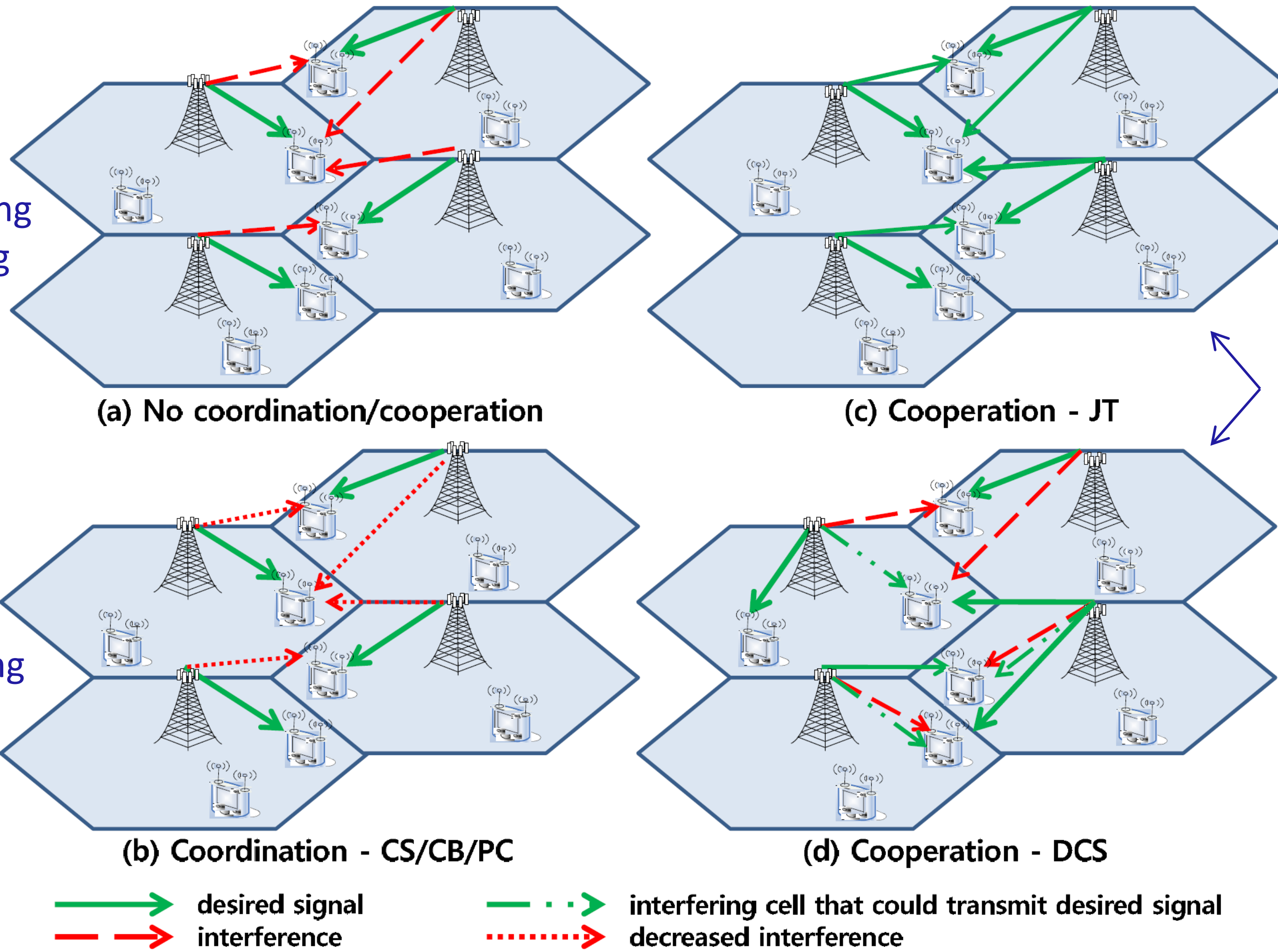
Rx filter

User schedule

Sum over all cells in the network

Multi-Cell (MC) MIMO [Clerckx2013a]

- Two main categories: data sharing (cooperation) and no data sharing (coordination)



No data sharing
No CSI sharing

Interference converted into useful signal

Data sharing
CSI sharing

No data sharing
CSI sharing

Coordination - “no data sharing”

- User data is available at a single transmitter
- Modelled as a MIMO Interference Channel
- Coordinated beamforming - CB (including interference alignment)
  - spatial domain cooperation
  - beamforming design among cells for a predefined set of scheduled users and allocated power
- Coordinated scheduling - CS
  - user domain cooperation
  - identifies users to schedule in the different cells and on the appropriate frequency resources assuming no beamforming and a predefined power allocation
- Coordinated power control - PC
  - power domain cooperation
  - controls the power in each cells and each frequency resource for a predefined set of users and beamformers and a predefined power allocation
- Combination of various coordination methods

A general framework of Coordination

- Iterative Algorithm
  - At iteration-n, each cell refreshes its decisions on the user schedule and the transmit precoders (beamformers and power) based on the decisions made by other cells in iteration n − 1. Scheduling decisions and CSI are shared between cells.
  - Interference pricing: scheduling decisions in a given cell i should also based on the victim users' utility metric. Cell i allocates resources such that

$$\left\{\mathbf{S}_i^{(n)}, \mathbf{W}_i^{(n)}, \mathbf{G}_i^{(n)}, \mathbf{K}_i^{(n)}\right\} = \arg \max_{\substack{\mathbf{K}_i \in \mathcal{K}_i \\ \mathbf{P}_{k,i}\left(\mathcal{K}_i, \mathcal{R}_i^{(n-1)}\right)}} \mathcal{U}_i^{(n)}\left(\mathcal{K}_i, \mathcal{R}_i^{(n-1)}\right)$$

Tx power
Tx beamformer
Rx filter
User schedule
Cell i utility metric (function of its served user set and its victim user set at iteration n-1)

$$\mathcal{U}_i^{(n)} = \frac{1}{T}\sum_{k=0}^{T-1} \sum_{q \in \mathbf{K}_{k,i}^{(n)}} w_q R_{(k),q,i}\left(\mathbf{P}_{k,q,i}^{(n)}, \mathbf{P}_{k,j\in\mathcal{M}_q^{(n-1)}}^{(n-1)}\right) - \Pi_i\left(\mathcal{R}_i^{(n-1)}\right)$$

Single-cell weighted sum-rate
Tax to be paid due to the interference created to victim users in adjacent cells

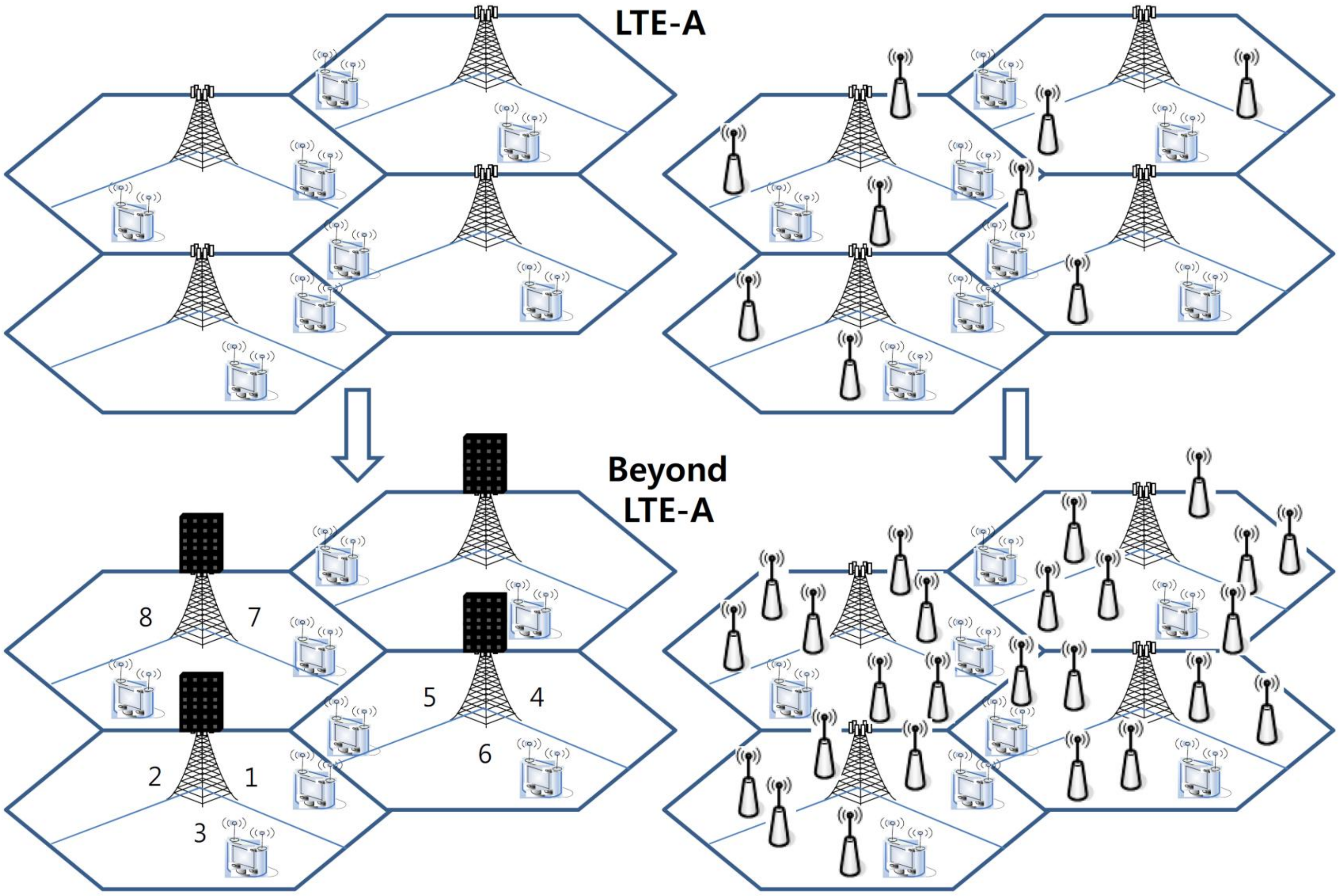
Cooperation - "data sharing"

- User data is available at multiple transmitters

- Modelled as a MIMO Broadcast Channel

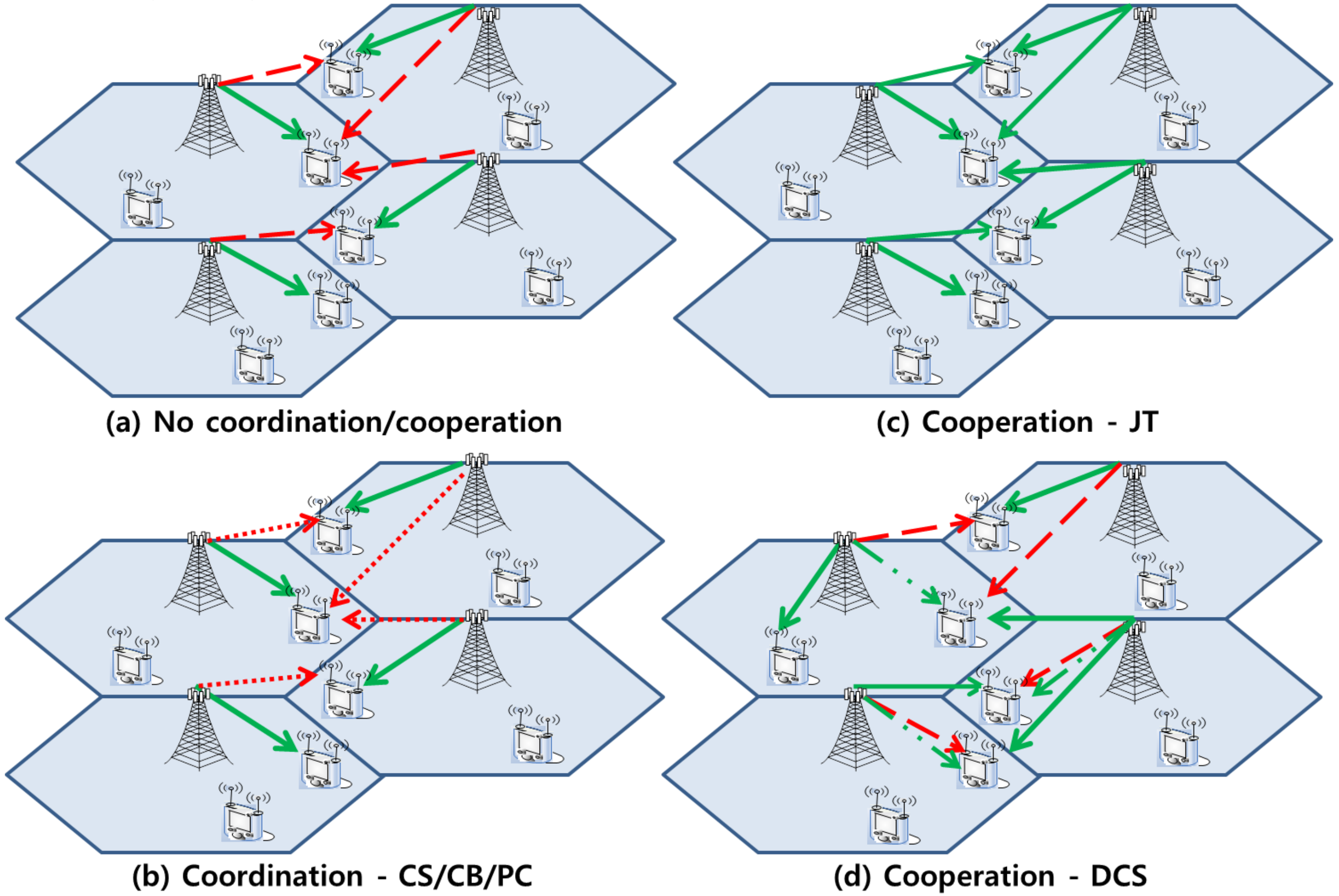
- Joint Transmission (JT) or Network MIMO
  - Similar to MU-MIMO
  - No sum power constraint anymore but per BS power constraint

MIMO Networks: Multi-user, Multi-cell, Massive, Network, Cooperative, Coordinated, …



MIMO Networks: a central problem…the role of CSIT

- MIMO Networks exploit more and more channel state information at the transmitter (CSIT)



- Performance crucially rely on accurate CSIT

Questions

1. How much gain do those techniques provide in realistic scenarios?
2. What are the major impairments?
3. Can we make coordination/cooperation more practical and still get performance benefits?
4. Are the right strategies standardized/implemented? If not, what should we do?
5. Can we exploit interference rather than simply manage it?

Part 1:
An industry perspective – how to make it work?

1. LTE-A system level performance evaluations
2. Practical coordination/cooperation strategies

1. 3GPP LTE and LTE-Advanced

- LTE Rel. 8 (finalized in Dec 2008):
  - Up to 4x4 (up to 4 layers transmission)
  - primary focus on SU-MIMO design
  - Stone-age MU-MIMO based on common reference signals (CRS)

SU-MIMO centric

- LTE Rel. 9 (finalized in Dec 2009):
  - Up to 4x4 (up to 4 layers transmission)
  - Introduction of demodulation reference signals (DM-RS)
  - Enhancement of MU-MIMO to support ZFBF-like precoding
- LTE-A Rel. 10 (finalized mid 2011):
  - Up to 8x8 (up to 8 layers transmission)
  - New channel measurement reference signals (CSI-RS)
  - New feedback mechanisms for 8Tx

MU-MIMO centric

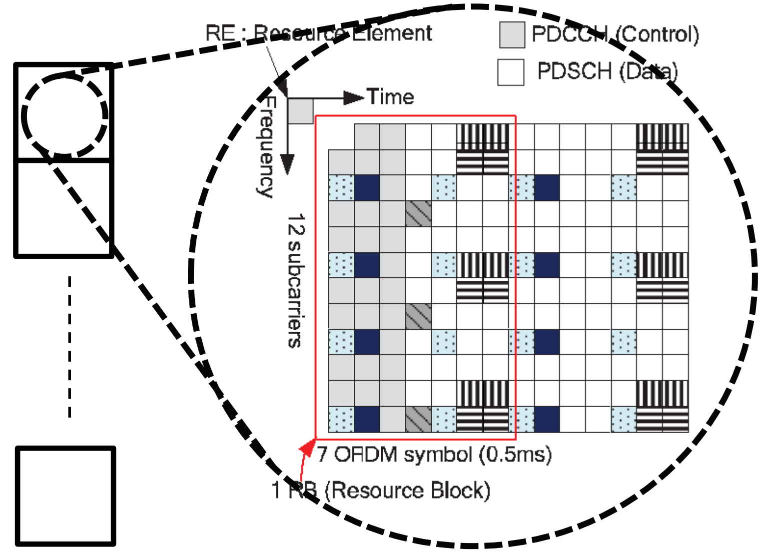
- LTE-A Rel. 11 (finalized in Dec 2012):
  - Coordinated Multi-Point Transmission/Reception (CoMP)
    - Homogeneous (Macro) and heterogeneous (pico, DAS) networks

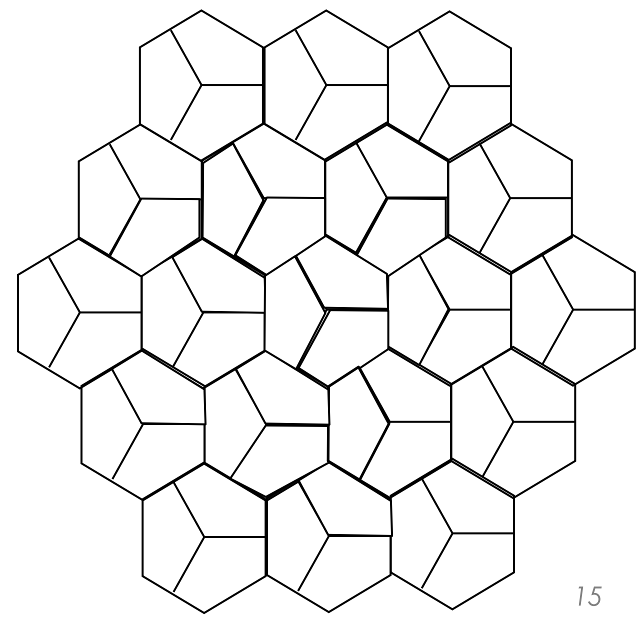
MC-MIMO (CoMP) centric

- LTE-A Rel. 12 on-going

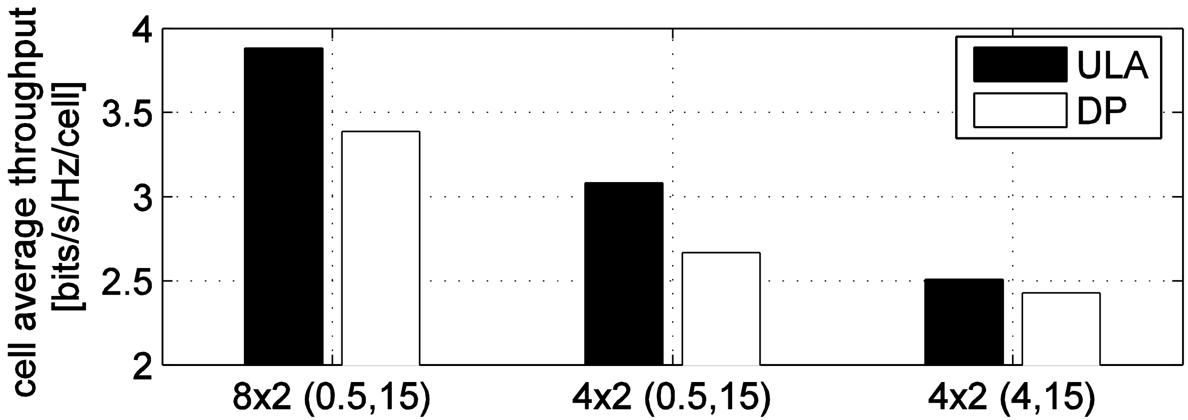
LTE-A Performance Evaluations [Clerckx2013a]

- Assumptions:
  - DL synchronized LTE-Advanced network based on FDD and 10 MHz bandwidth made of 50 resource blocks (RB).
  - 19 hexagonal cell sites with 3 sectors per cell are wrap-around modelled and 10 users are dropped per sector.
  - Full-buffer traffic
  - HARQ based on Chase Combining (target BLER 10%)
  - Proportional Fair scheduling
- Performance gain:
  - SU-MIMO (SM with quantized feedback) vs. MU-MIMO (ZFBF with quantized feedback)
  - SU-MIMO vs. coordinated SU-MIMO
  - Cooperation/coordination in HetNet





MU-MIMO: Antenna deployment



Notations:

$n_t \times n_r$ (d/λ,AS)

Nbr of Tx ant.

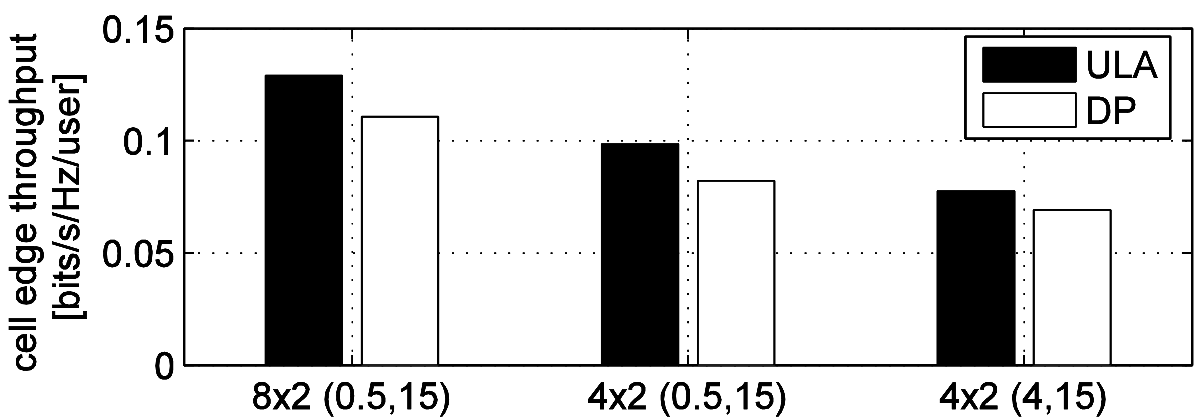
Nbr of Rx ant.

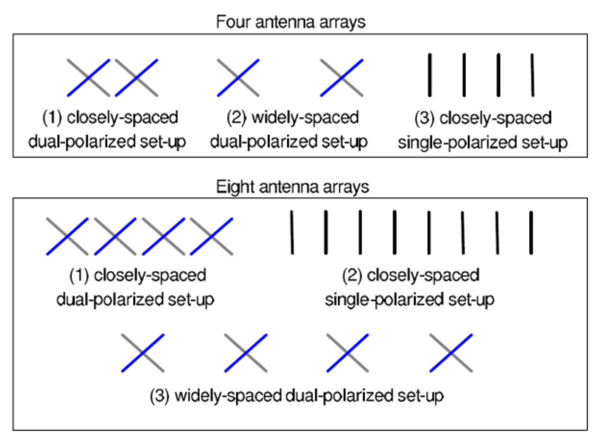
Ant. spacing

Angle spread

ULA: Uniform Linear Array

DP: Dual-polarized



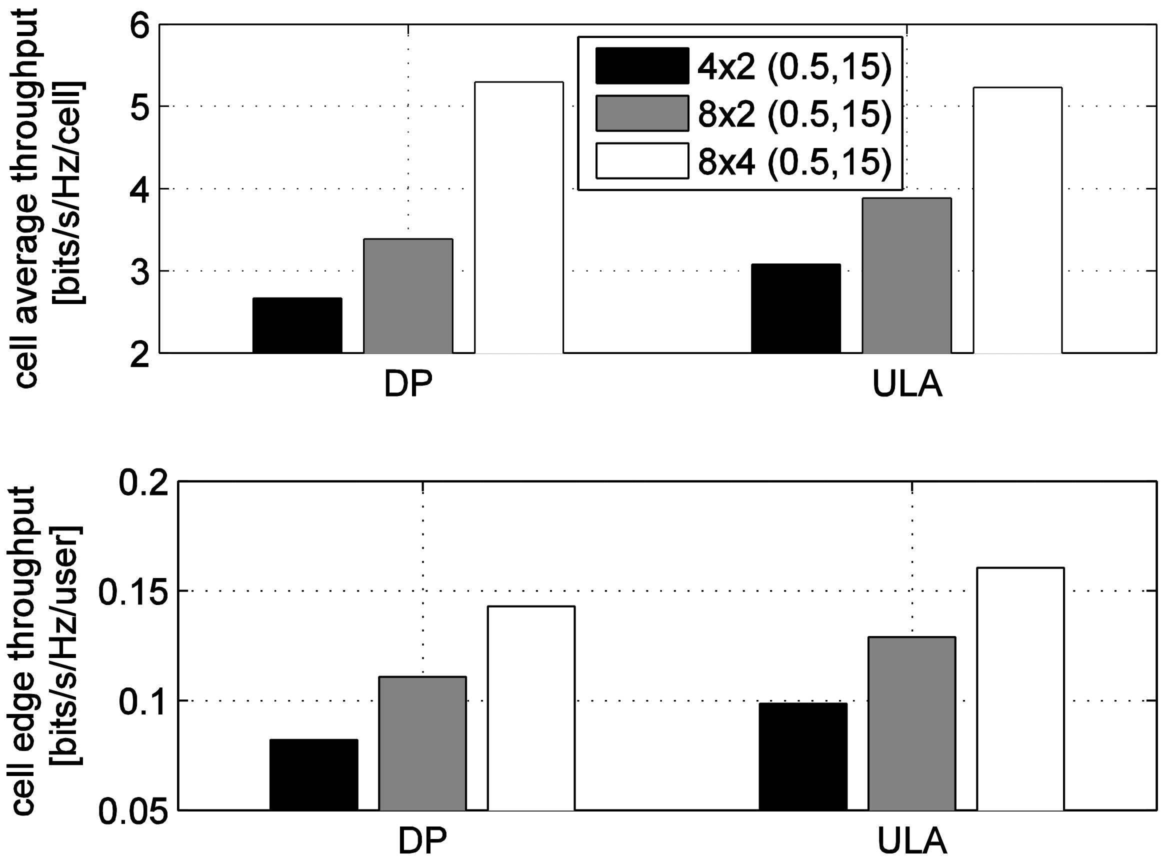


Observations:

- ULA > DP for cell average for any number of Tx
- ULA > DP at the cell edge
- 0.5 λ > 4 λ

… but we deploy DP in practice

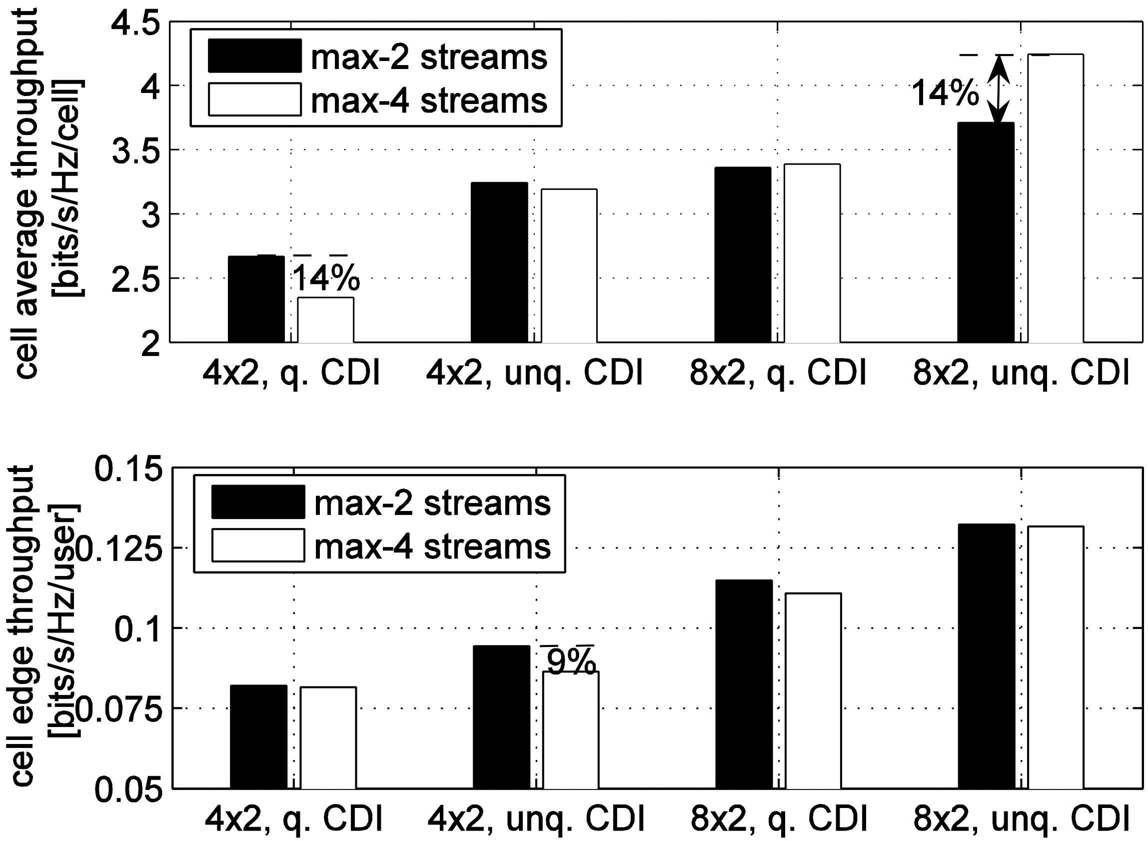
MU-MIMO: Antenna configuration



Observations:

- 8x4 provides significant gain over 8x2
    - 8Tx ZFBF is far from nulling out MU interference
    - more pronounced in DP

MU-MIMO: Dimensioning

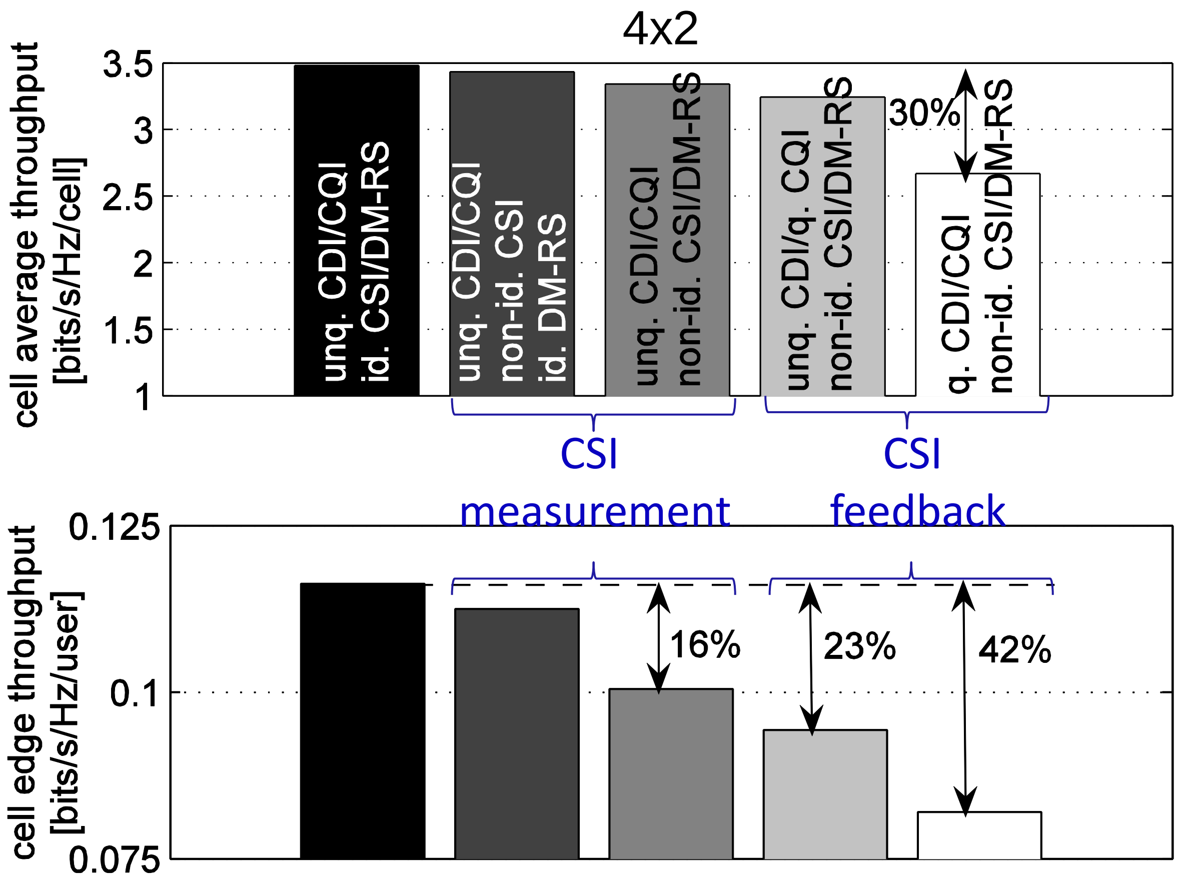


CDI: Channel Direction Information
q.: quantized
unq.: unquantized

Observations (with DL overhead):

- 4x2: 2 streams > 4 streams even with accurate feedback
- 8x2: 4 streams > 2 streams if accurate feedback, 2 streams enough if LTE-A codebook

MU-MIMO: CSI measurement and feedback



Assumptions:

- 6RB subband size
- 5ms feedback delay at 3km/h

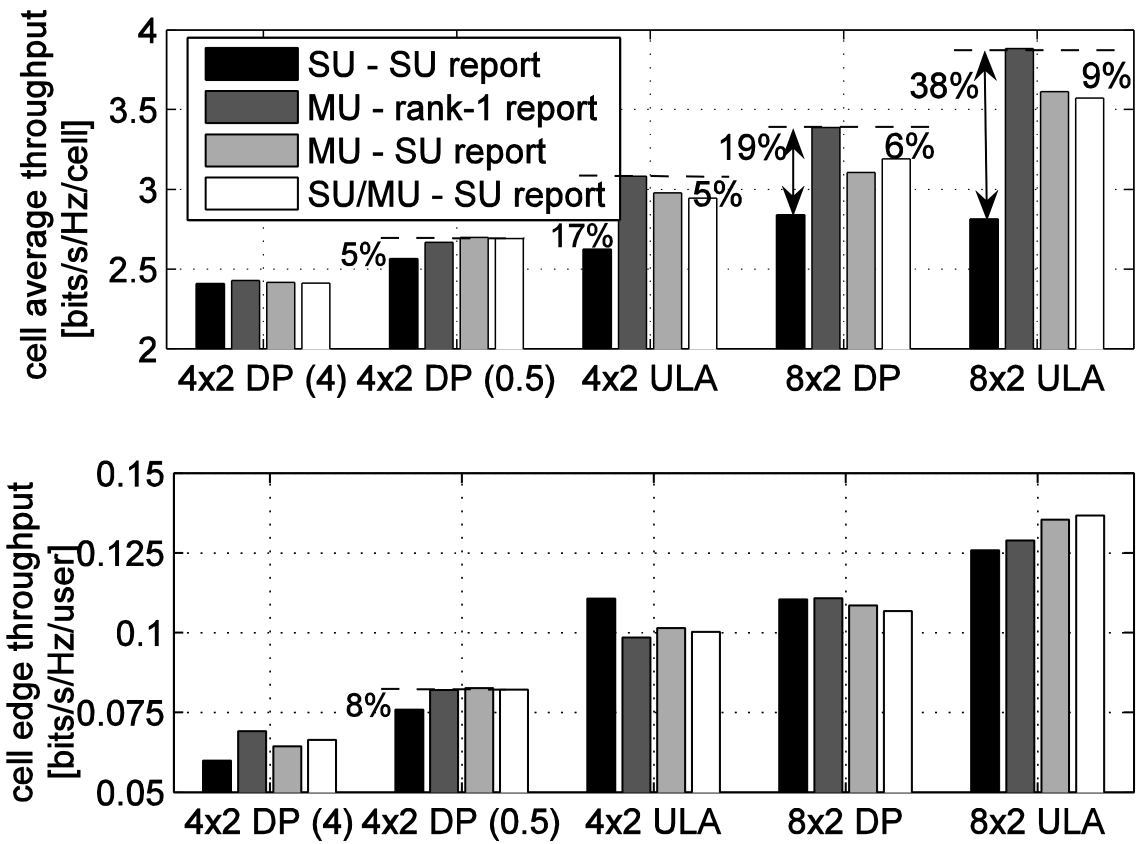
CSI-RS: Reference signals for CSI measurement before feedback

DM-RS: reference signals for demodulation

Observations:

- ranking of losses in increasing order of severity:
  CSI-RS < q. CQI < DM-RS << q. CDI

SU vs. MU vs. SU/MU-MIMO dynamic switching



MU: 1 layer per UE

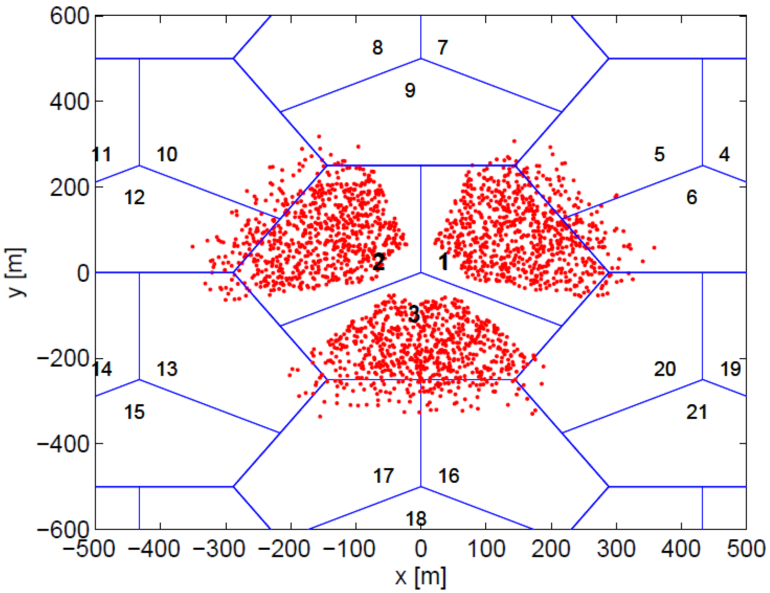
SU/MU: SU or multi-layer MU

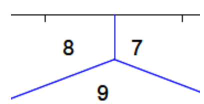
Observations:

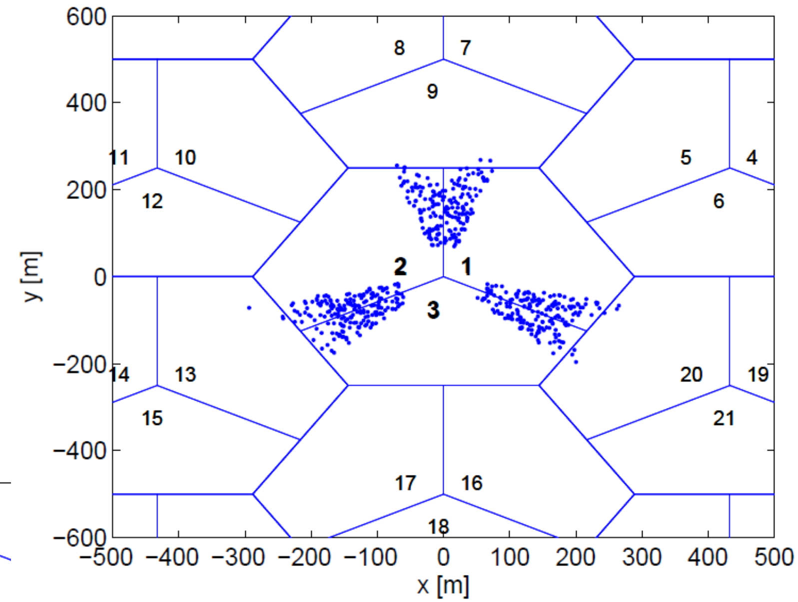
- MU & SU/MU bring negligible gain over SU in 4x2 DP (4,15)
- MU & SU/MU bring only 5-6% gain over SU in 4x2 DP (0.5,15)
- MU – rank-1 report outperforms MU – SU report and SU/MU – SU report
- SU/MU performs the same as MU

Multi-cell MIMO cooperation/coordination

- Which users benefit from cooperation ?



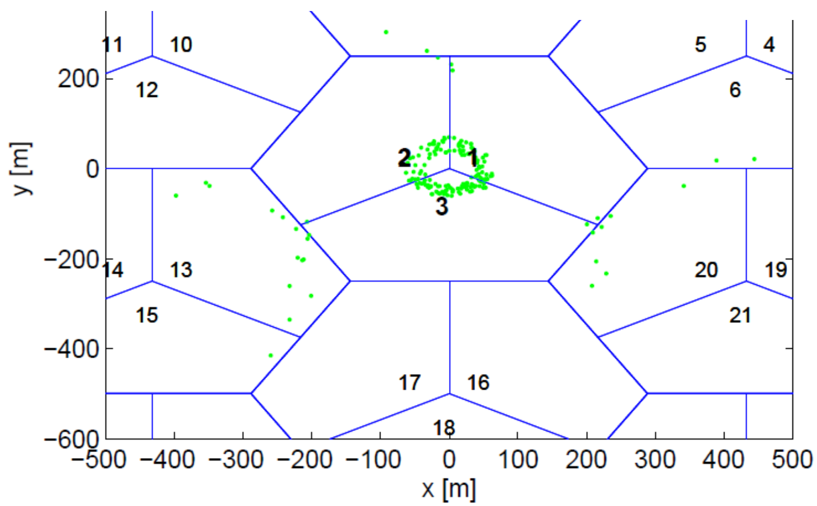




1 BS

2 BS

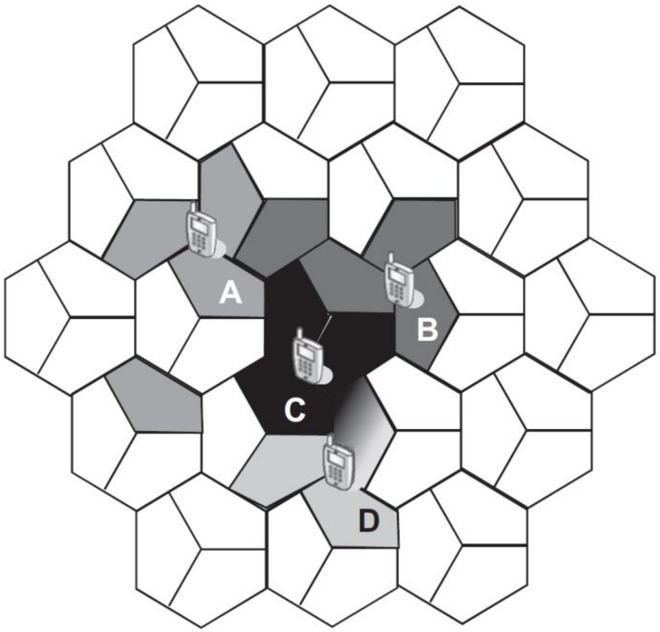
3 BS



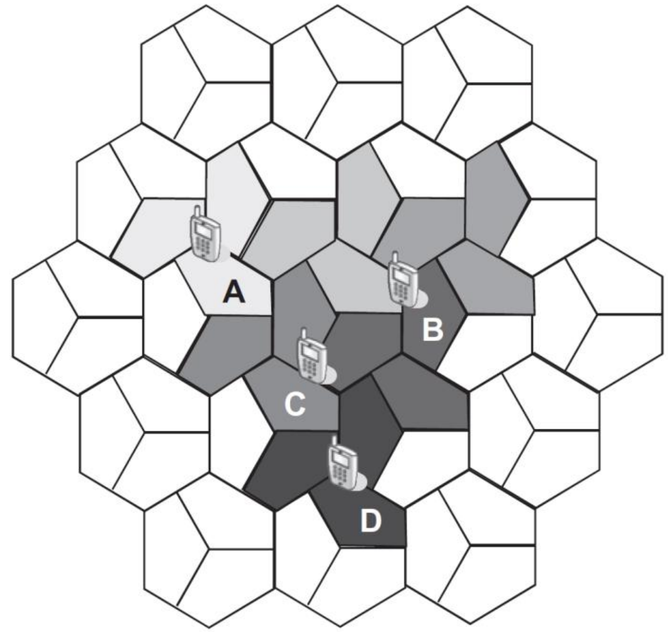
- 3D antenna pattern
- intra-site
- 10 dB triggering threshold

Clustering

- User-centric clustering vs. Network predefined clustering



(a) User-centric clustering



(b) Network predefined clustering

Clustering

- Assume a 10dB triggering threshold for coordination/cooperation

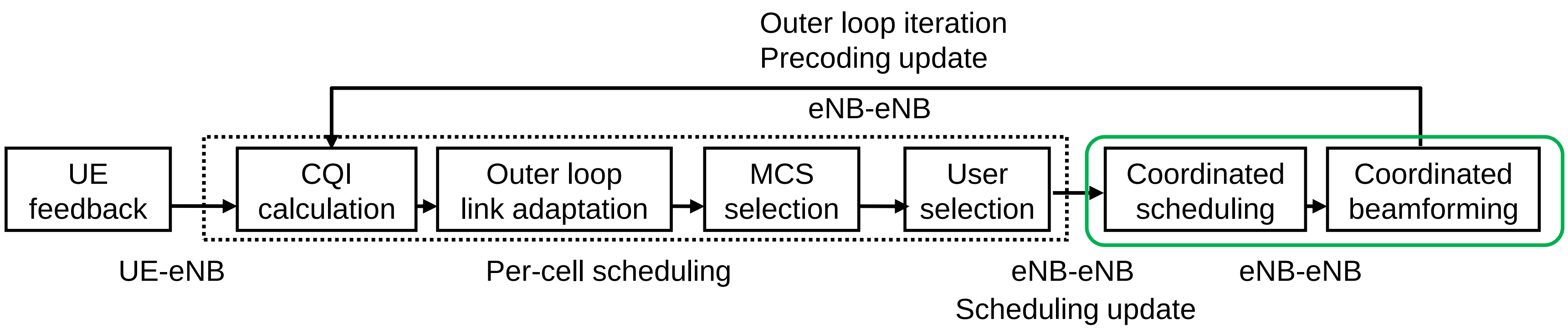
CoMP measurement set size	1	2	3	4	5	6
Inter-eNodeB CoMP	53%	23%	18%	3%	2%	1%
Intra-eNodeB CoMP	75%	19%	6%	0%	0%	0%

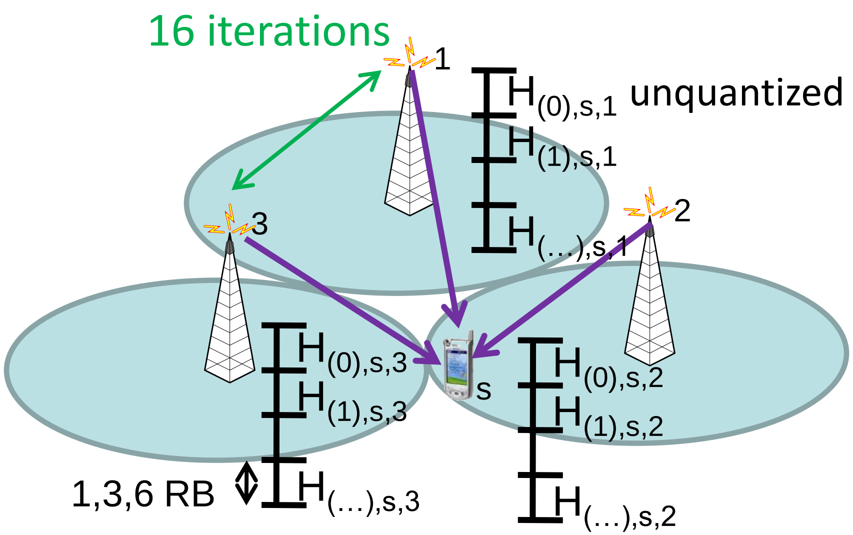
  – network predefined clustering (e.g. intra-site) constraints the number and occurence of CoMP UEs
  – no benefit to have more than three-cell cooperation
  – Feedback overhead for K users (B bits overhead per reported link):

Deployment	Absolute overhead	Overhead increase
Intra-eNodeB	0.75*K*B+0.19*K*2B+ 0.06*K*3B=1.31*K*B	~31% increase
Inter-eNodeB	0.53*K*B+0.23*K*2B+ 0.24*K*3B=1.71*K*B	~71% increase

Coordinated SU-MIMO using CS/CB

- Coordinated SU-MIMO: one user scheduled at a time in each cell on a given time/frequency resource
- network level iterative coordinated scheduling and beamforming

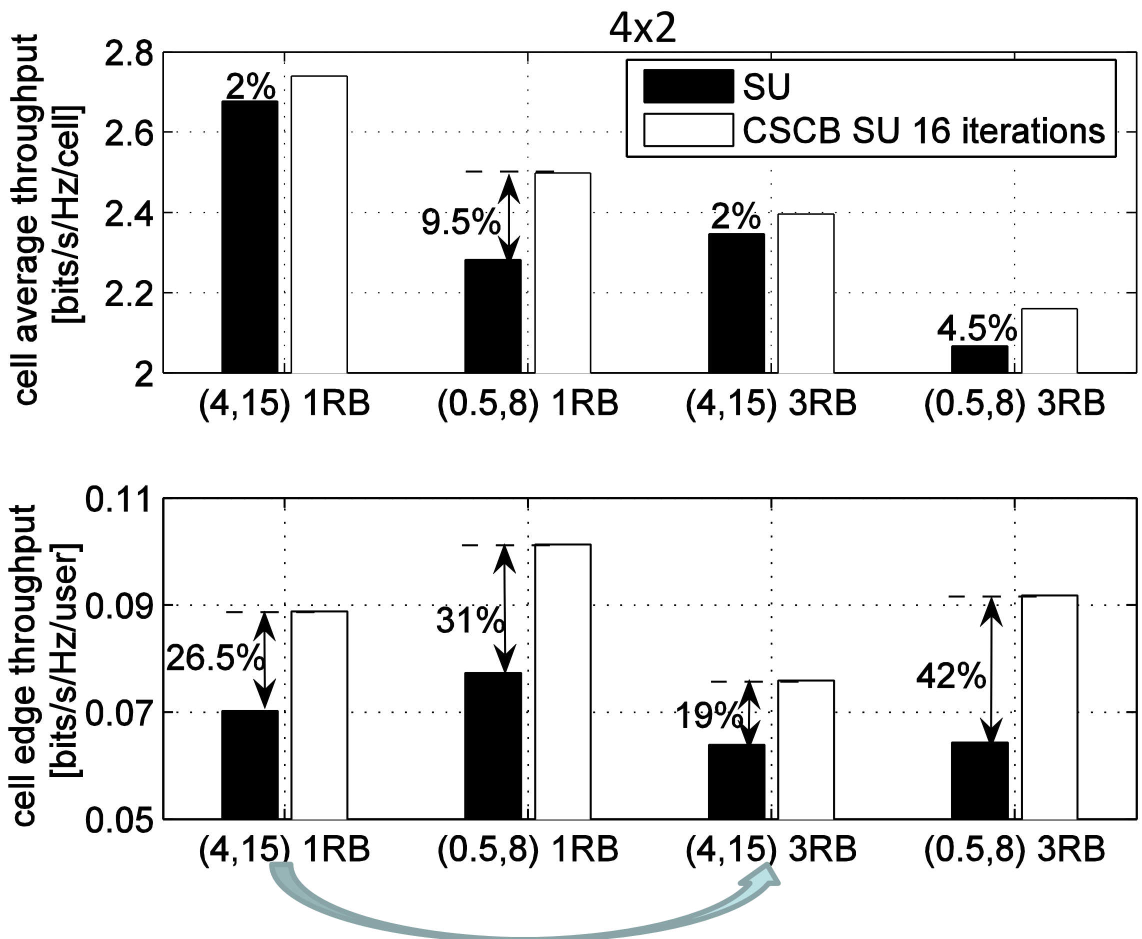




interference pricing, SLNR filter design and user-centric clustering

Signal-to-Leakage-and-Noise-Ratio

SU-MIMO vs. coordinated SU-MIMO (CS/CB)

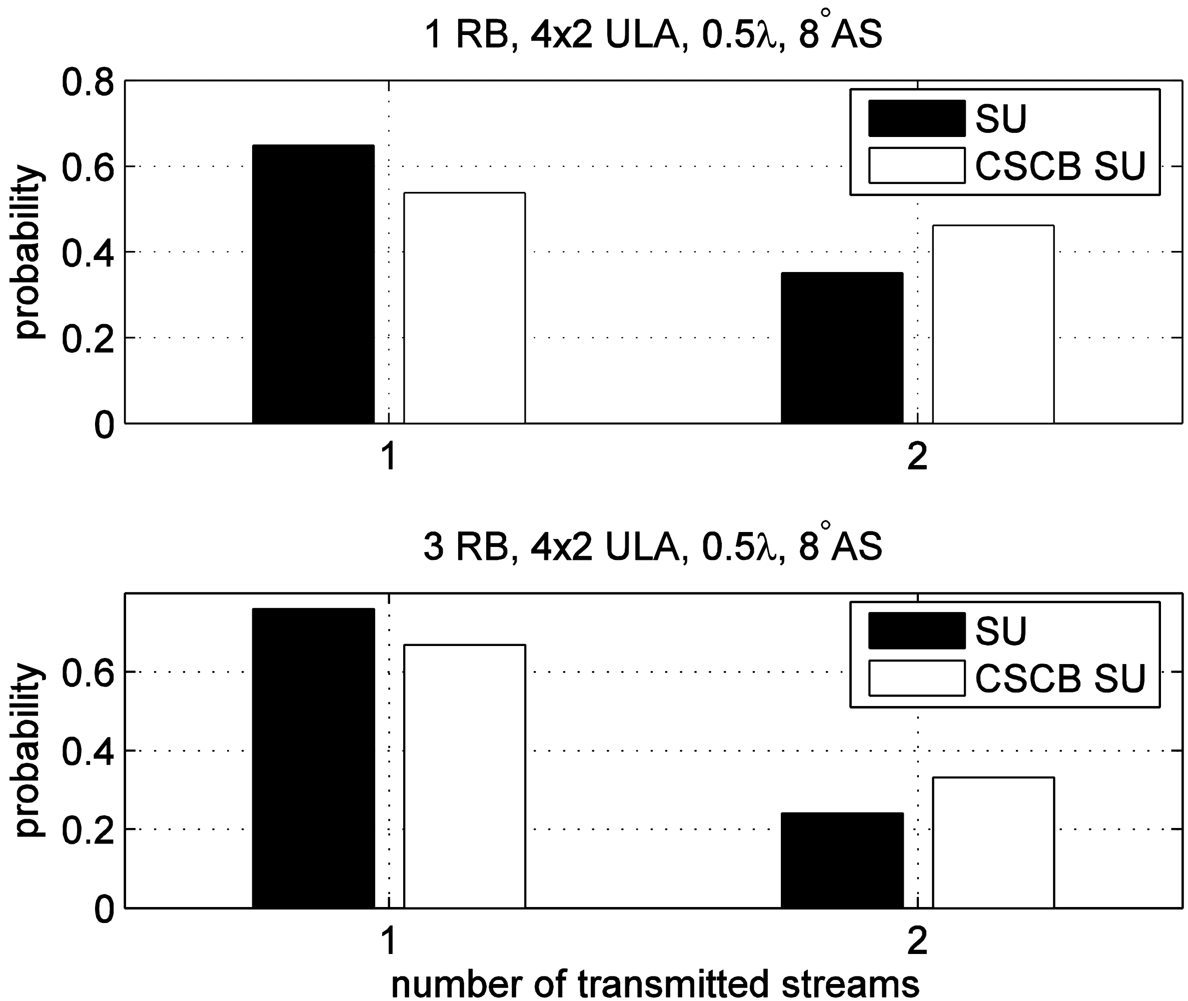


Assumptions:

- unquantized feedback
- user receiver implementation assumed known at the BS
- perfect CSI measurement
- no delay

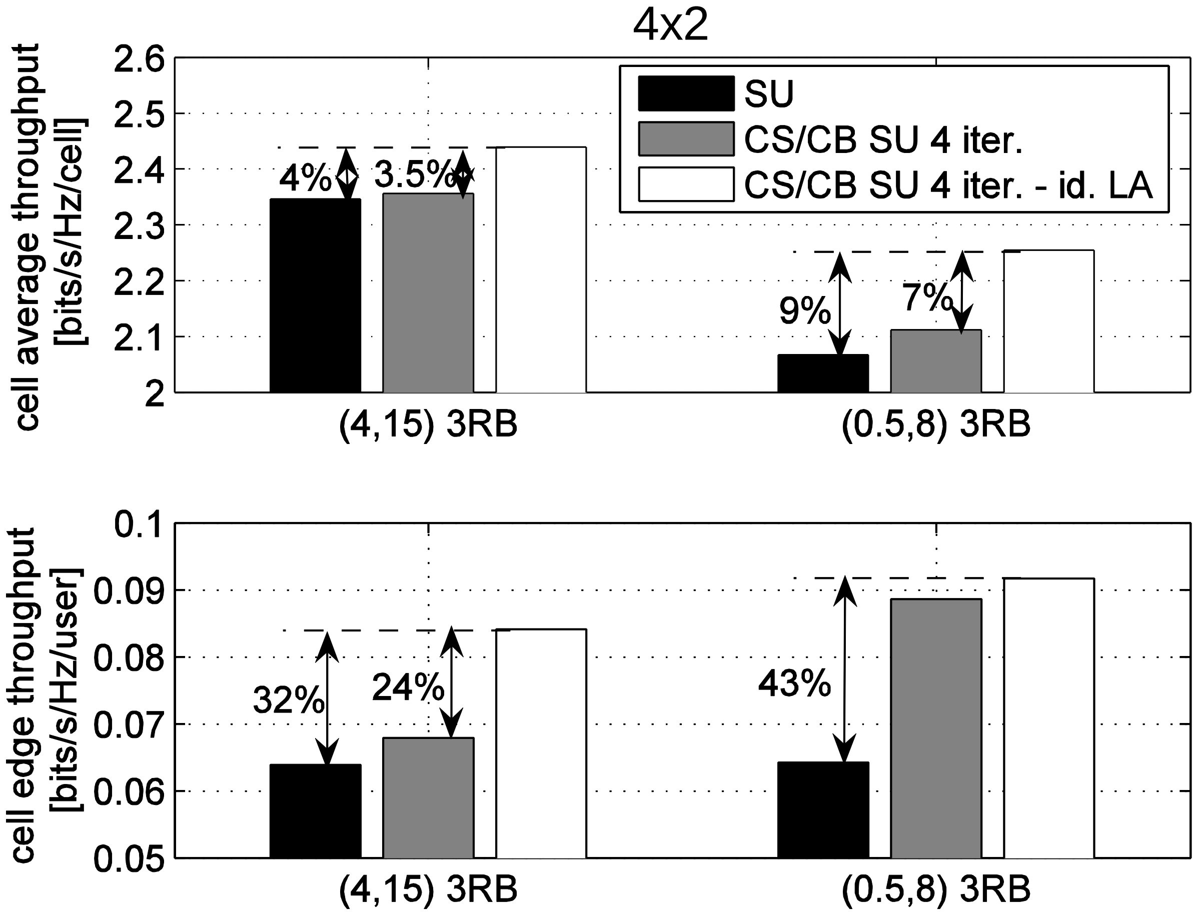
- Gain of coordination of ~30% at the cell edge
    - but overhead increase of 71%
- big loss as the CSI accuracy decreases

SU CS/CB: transmission rank



CS/CB allows cell edge users to benefit from spatial multiplexing gains

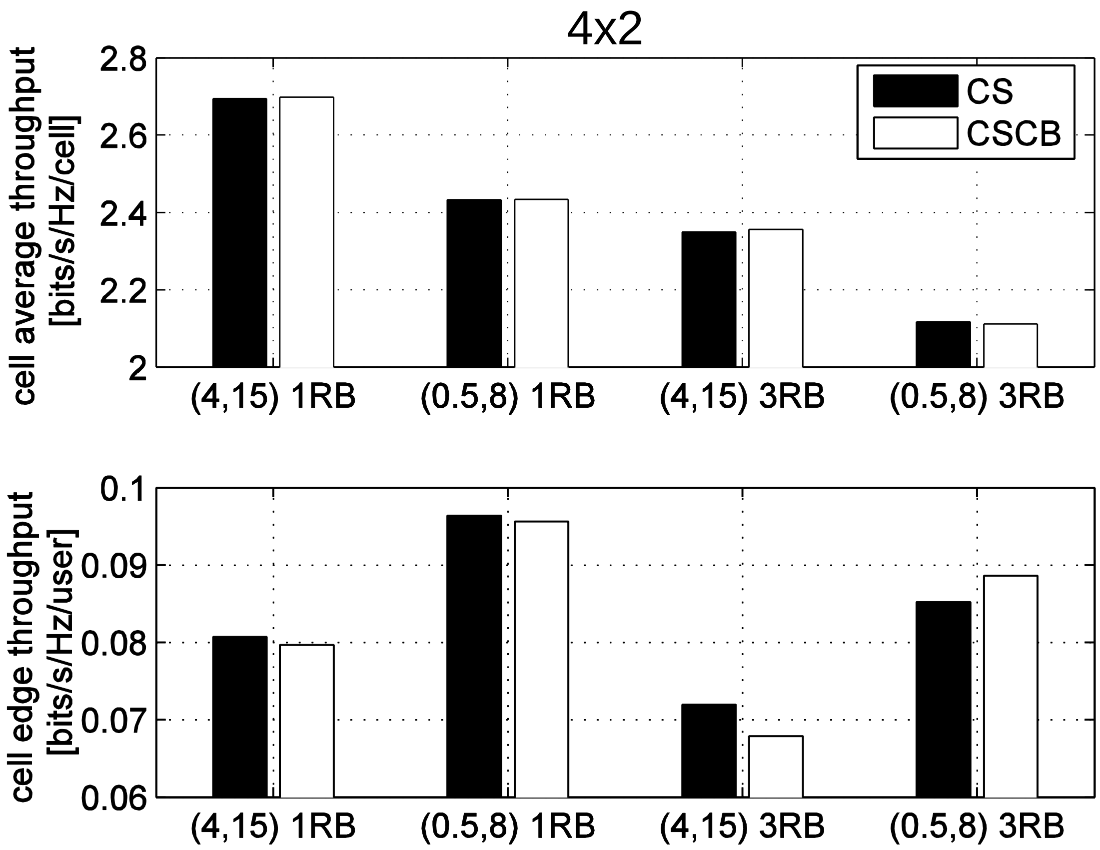
CS/CB: Link adaptation



Most of the potential gain lost due to inaccurate LA.

Inaccurate CQI prediction hampers the appropriate selection of the users, the transmission ranks and the beamformers at every iteration of scheduler and ultimately the whole link adaptation and the convergence of the scheduler

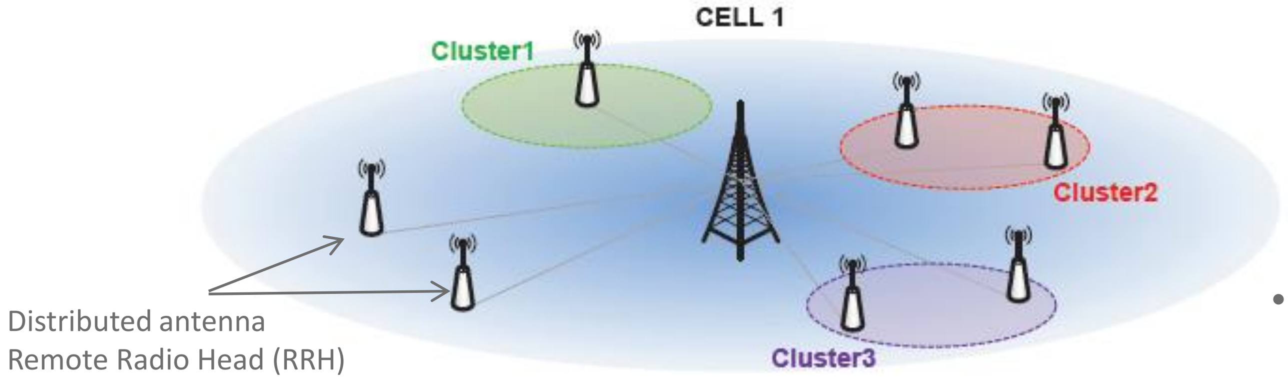
CS vs. CS/CB



CS only brings all the gains

Heterogeneous network (NetNet) - DAS

- Distributed Antenna Systems (DAS)



- In HetNet, the numerous nodes create more cell boundaries, and the overlay of macro and small cells with different transmission powers enlarges the interference zone.
- More UEs become eligible to benefit from CoMP in HetNet

- Dynamic point selection with dynamic blanking (ON/OFF power control)

PERFORMANCE OF DAS IN CLUSTERED HETEROGENEOUS DEPLOYMENTS.

	N	Av. area thrpt	cell edge thrpt
Rel. 10 (0dB RE,no ABSF)	4	16.41	0.0574
Rel. 10 (20dB RE,60% ABSF)	4	16.50 (1%)	0.0668 (16%)
DAS with DS	4	15.55 (-5.2%)	0.0698 (21.6%)
DAS with DS/DB	4	16.68 (1.6%)	0.0840 (46.3%)
Rel. 10 (0dB RE,no ABSF)	10	22.33	0.0708
Rel. 10 (20dB RE,60% ABSF)	10	23.76 (6%)	0.0937 (32%)
DAS with DS	10	22.66 (1.5%)	0.0820 (15.8%)
DAS with DS/DB	10	23.27 (4.2%)	0.1067 (50.7%)

- cooperation/coordination gain larger in heterogeneous than homogeneous

Conclusions (1/3)

- Potential gain of single-cell and multi-cell MIMO in theory but benefits may vanish in practical scenarios

Sensitivity to CSI measurement • Channel estimation errors particularly large for cell edge users	Feedback and message exchange overhead • Target cell edge users
CSI feedback inaccuracy • Limited feedback • Subband feedback with strong frequency selectivity within subband • Particularly problematic in dual-polarized antenna deployments	Inaccurate link adaptation • due to feedback inaccuracy • BS does not know the receiver at the mobile terminal • Traffic model • fast variation of the inter-cell interference
Latency of the feedback and the backhaul	Scheduler convergence and complexity

many other issues left: time/frequency synchronization, antenna calibration, …

- Sensitivity different depending on SU-MIMO, MU-MIMO, Multi-Cell MIMO

Conclusions (2/3)

- Current wireless system design is at the network level
  - Lots of aspects interact with each other
- Network designs become more and more sensitive to impairments

SU MIMO	MU MIMO	Multi-cell MIMO
CSI Feedback measurement	CSI Feedback measurement	CSI Feedback measurement
scheduler	scheduler	scheduler
Link adaptation	Link adaptation	Link adaptation
CSI Feedback accuracy	CSI Feedback accuracy	CSI Feedback accuracy

- Gap between theory and practice gets much bigger as we move from single-cell to (cooperative/coordinated) multi-cell designs
- Account for impairments!

Conclusions (3/3)

- MU-MIMO
  - A mere 5-6% gain over SU-MIMO expected with current systems
  - room left for improvement if CSI further enhanced

- MC-MIMO
  - Gain of cooperation/coordination larger in heterogeneous networks

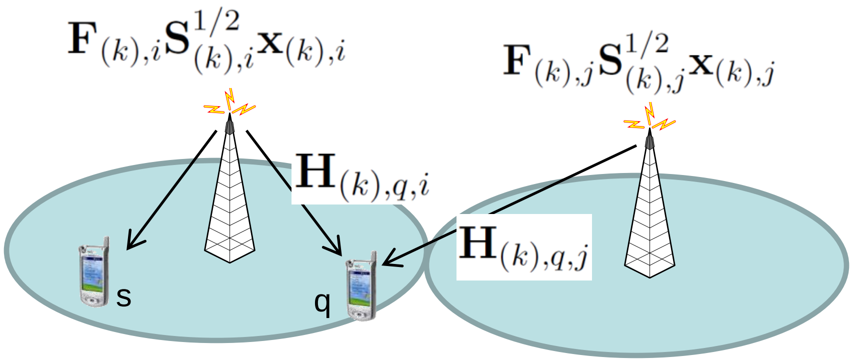
2. How to make coordination/cooperation more practical?

- Observations:
  - Common assumption in both performance and design points of view
    - » DoF analysis, any local CSI available at the base station (BS) with no delay, no measurement error, no constraint on the uplink and backhaul overhead, no dynamic interference, perfect CSI feedback on every subcarrier, perfect link adaptation, receiver implementation assumed perfectly known at the BS.
  - Terminals considered as dumb so far, i.e. the BS takes all the decisions and tells them what to do. All the coordination burden is put on the network side.
- Questions:

1. Can we design impairments-aware (robust) cooperative schemes ?
2. Can we decrease the coordination burden at the network side by bringing the contribution of the receivers into the multi-cell coordination?
3. Can the receivers be smarter and help the network to take appropriate scheduling decisions?
    - » not be helpful in ideal situations because the network possesses all necessary information to make accurate decisions
    - » particularly helpful when the aim is to design multi-cell coordination schemes for scenarios where the network does not have enough information to make accurate decisions

System Model [Clerckx2013b]

- MIMO-OFDMA network with
  - N_t transmit antennas
  - N_r receive antennas
  - n_c cells
  - K_i users in cell *i*
  - T subcarriers



- DL multi-point multiuser MIMO-OFDMA network
  - Received signal of user *q* scheduled in cell *i* on subcarrier *k*

$$\mathbf{y}_{(k),q} = \alpha_{q,i}^{1/2}\mathbf{G}_{(k),q}\mathbf{H}_{(k),q,i}\mathbf{F}_{(k),i}\mathbf{S}_{(k),i}^{1/2}\mathbf{x}_{(k),i} + \sum_{j\neq i}\alpha_{q,j}^{1/2}\mathbf{G}_{(k),q}\mathbf{H}_{(k),q,j}\mathbf{F}_{(k),j}\mathbf{S}_{(k),j}^{1/2}\mathbf{x}_{(k),j} + \mathbf{G}_{(k),q}\mathbf{n}_{(k),q}$$

Path loss + shadowing ($\alpha_{q,i}^{1/2}$); small scale fading ($\mathbf{H}_{(k),q,i}$); Receive filter ($\mathbf{G}_{(k),q}$)

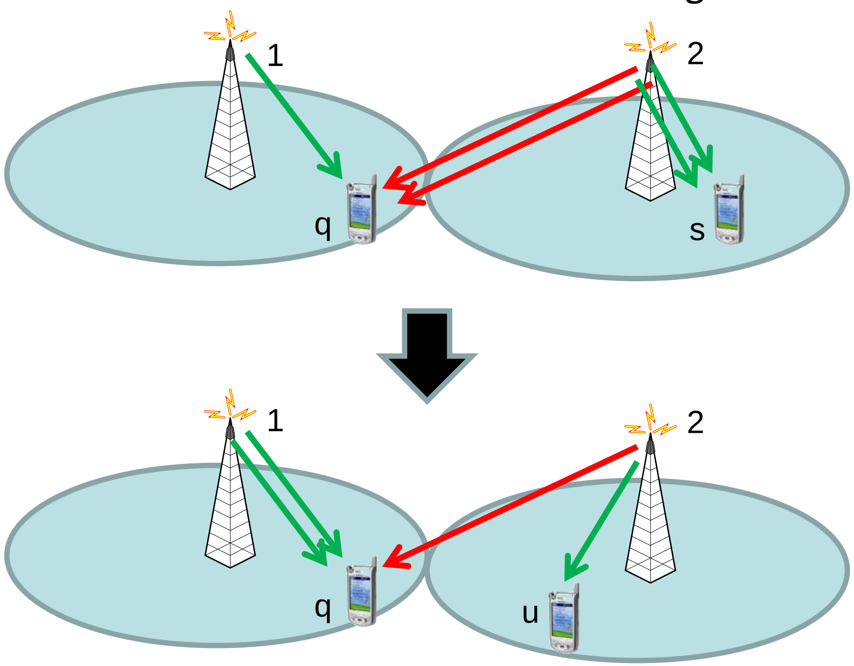
with

$$\mathbf{F}_{(k),i}\mathbf{S}_{(k),i}^{1/2}\mathbf{x}_{(k),i} = \mathbf{F}_{(k),q,i}\mathbf{S}_{(k),q,i}^{1/2}\mathbf{x}_{(k),q,i} + \sum_{s\in \mathcal{K}_{(k),i}, s\neq q}\mathbf{F}_{(k),s,i}\mathbf{S}_{(k),s,i}^{1/2}\mathbf{x}_{(k),s,i}$$

power ($\mathbf{S}_{(k),i}^{1/2}$); Precoder with $L_{(k),i}$ streams ($\mathbf{F}_{(k),i}$)

Joint scheduling and rank coordination [Clerckx2013b]

- Improve cell edge user experience
  - Enable robust multi-streams transmission to cell edge users



Two major issues:
- User scheduling
- Transmission rank (number of transmitted streams in each cell)

  - Directly address the problem of user scheduling and rank coordination using a simple distributed scheduler with limited CSI knowledge and without requiring the heavy machinery of the iterative scheduler for CS/CB/PC.

Joint scheduling and rank coordination [Clerckx2013b]

- Network-level scheduler and rank coordination

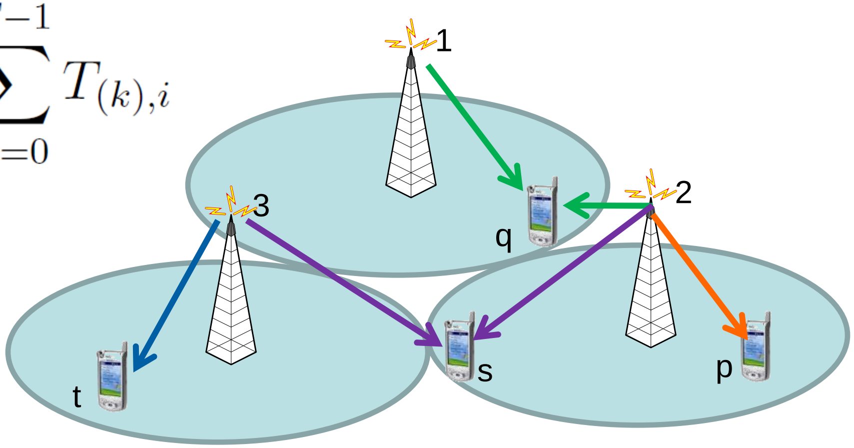
Set of scheduled users in all cells and subcarriers

Set of transmission ranks in all cells and subcarriers

$$\{\mathrm{K}^\star, \mathbf{L}^\star\} = \arg \max_{\mathrm{K} \subset \mathcal{K}, \mathbf{L}} \sum_{i=1}^{n_c} \sum_{k=0}^{T-1} T_{(k),i}$$

Weighted sum-rate in cell *i* on subcarrier *k*

$$T_{(k),i} = \sum_{q \in \mathrm{K}_{(k),i}} w_q T_{(k),q,i}$$



under constraints

$$L_{(k),i} \geq L_{min,i}$$

$$L_{(k),i} \leq L_{max,i}$$

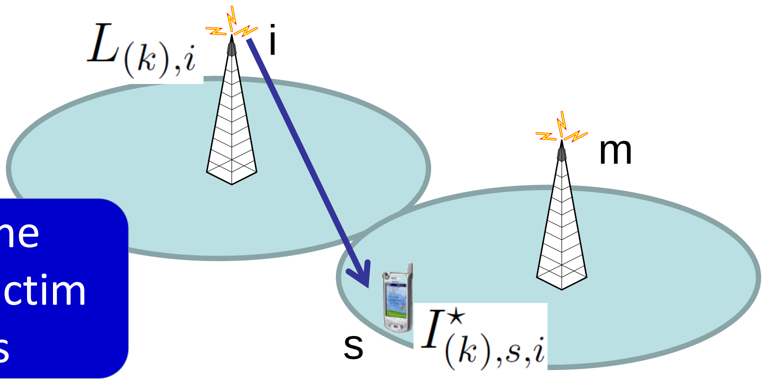
Transmission rank in cell i and subcarrier k

- Scheduler decisions of cell 1 influence cell 2, which will influence cell 3
- scheduler and resource allocation to be done at the network level

Assumption: beamforming directions are fixed and predefined for every transmission rank

Interference pricing

- Interference pricing can be used for rank coordination
- Out of Lagrangian optimization, each cell *i* tries to maximize the following surplus function



$$\Upsilon_{(k),i} = T_{(k),i} - \Pi_{(k),i}$$

Single-cell weighted sum-rate

Tax to be paid due to the interference created to victim users in adjacent cells

$$\Pi_{(k),i} = \sum_{m \neq i} \sum_{s \in \mathrm{K}_{(k),m}} \left(L_{(k),i} - I^{\star}_{(k),s,i} \right) w_s \pi_{(k),s,m,i}$$

$$I^{\star}_{(k),s,i} = \arg\max_{L_{(k),i}} T_{(k),s,m} \left(L_{(k),i}, \left\{ L_{(k),j} \right\}_{j \neq i} \right)$$

preferred interference rank

$$\pi_{(k),s,m,i} = -\frac{\partial T_{(k),s,m}}{\partial L_{(k),i}}$$

price

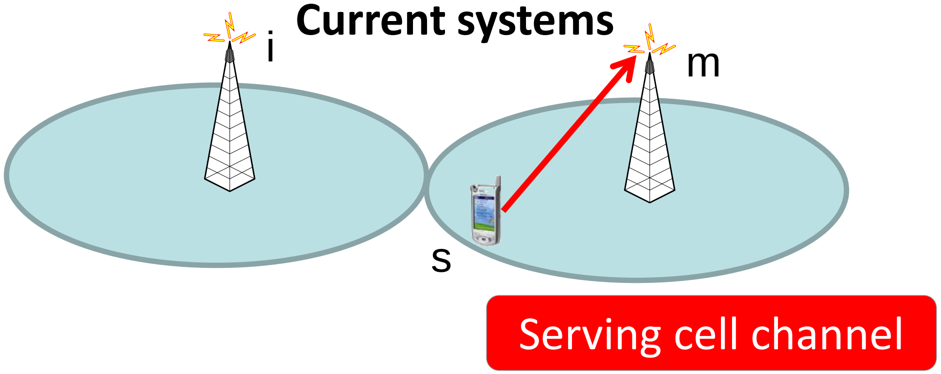
Tax function of
- deviation w.r.t to preferred interference rank
- price (sensitivity of victim UE's throughput to the transmission rank of interfering cells)
- QoS ws of victim UEs

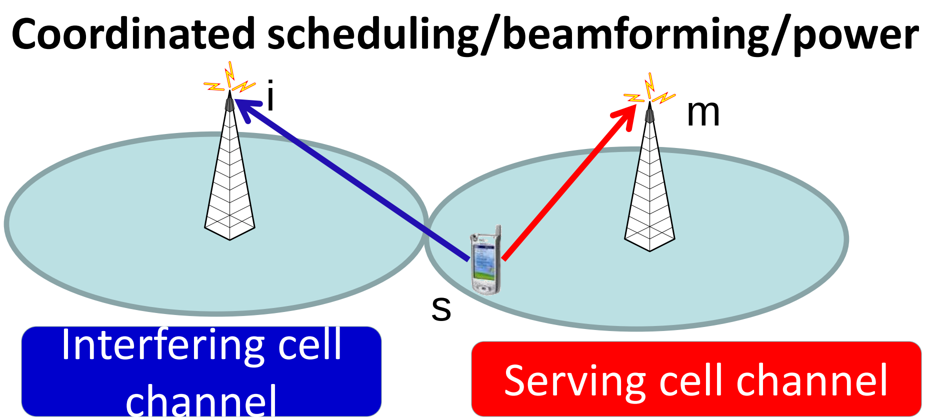
Rank recommendation (RR)

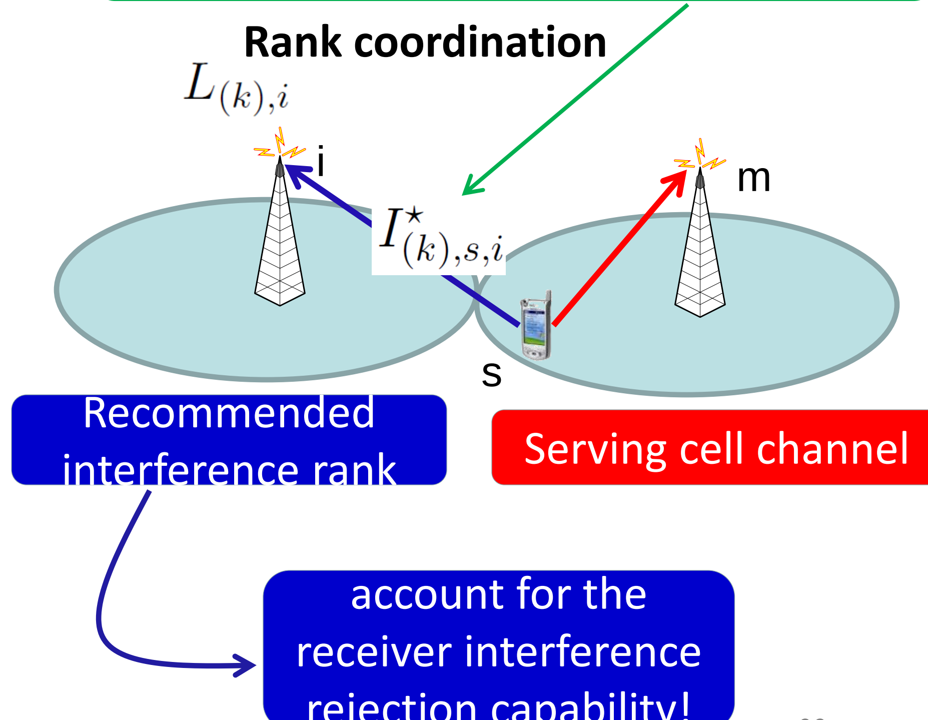
- Each cell edge UE recommends the interfering cells to use a transmission rank that is the most beneficial to its performance
  - user s recommends to choose $L_{(k),i} = I^{\star}_{(k),s,i}$
  - Preferred interference rank computed at the user side

Computed over the throughput average

$$\tilde{T}_{k,q,i}\left(\mathbf{F}_{k,i}, L_{k,i}, \{L_{k,j}\}_{j\in\mathcal{M}_q}\right) \approx \mathcal{E}_{\{\mathbf{F}_{k,j}\in\mathcal{C}\}_{j\in\mathcal{M}_q}}\{T_{k,q,i}\}$$







Master-Slave distributed scheduler

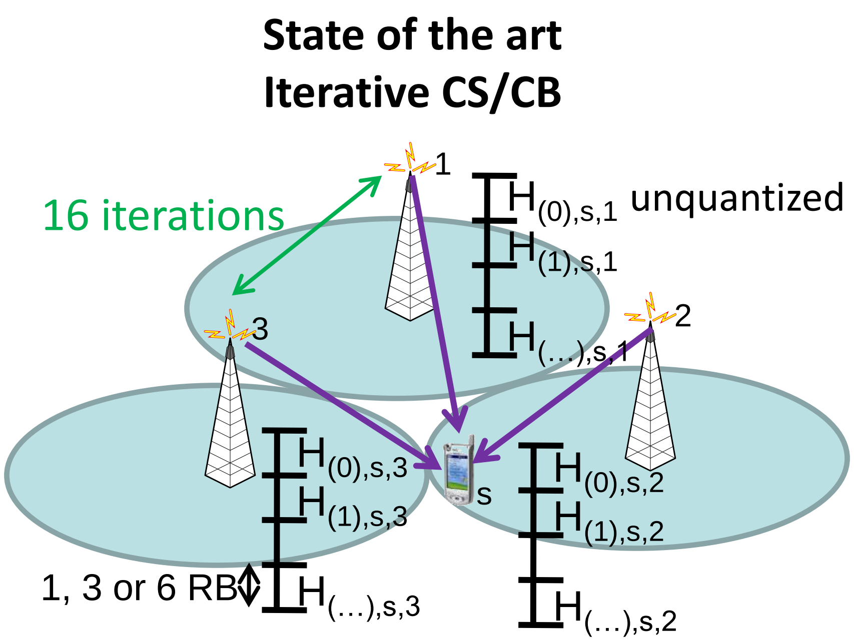
- Goal: strive to guarantee $\Pi_{(k),i} = 0$ (Tax) with a small number of iterations
- Principle:
  - Strive to have $L_{(k),i} - I^{\star}_{(k),s,i} = 0$ on subcarriers where user s is scheduled
  - At each time instant, one cell acts as Master (M) and the rest as Slaves (S_1,S_2)

time	1	2	3	4	5	6	7	8	9
BS_1	M, L_M=2	S_1	S_1	M, L_M=1	S_1	S_1	M, L_M=2	S_1	S_1
BS_2	S_1	M, L_M=1	S_2	S_1	M, L_M=2	S_2	S_1	M, L_M=1	S_2
BS_3	S_2	S_2	M, L_M=3	S_2	S_2	M, L_M=1	S_2	S_2	M, L_M=3

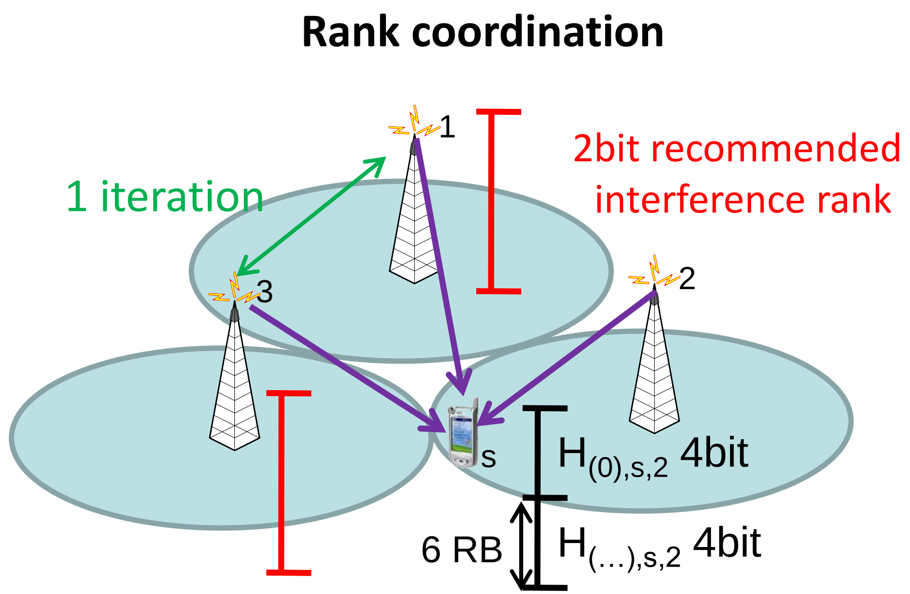
  - Cells take turns to act as Master, having priority for accepting recommended interference rank
  - Based on the rank recommendation, Master decides the value of transmission rank L_{M} (fairness controlled based on price and QoS of users)
  - The slave BSs schedule with highest priority its users whose recommended rank is equal to L_{M}

Performance evaluation

- Assumptions inline with 3GPP LTE-Advanced cellular system
- SU-MIMO with and without coordination

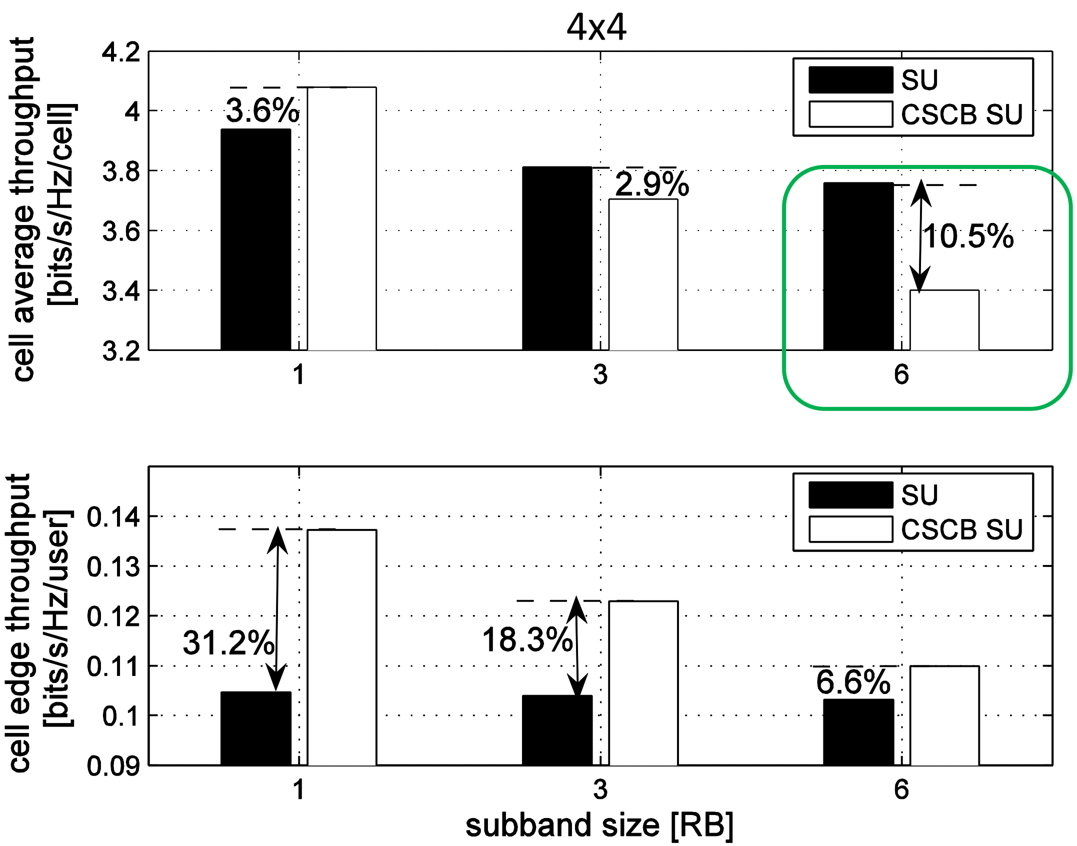


- high feedback overhead
- high scheduler complexity



- low feedback overhead
- low scheduler complexity

iterative coordinated scheduling and beamforming



- big loss as the CSI accuracy decreases
- big loss due to non-ideal link adaptation

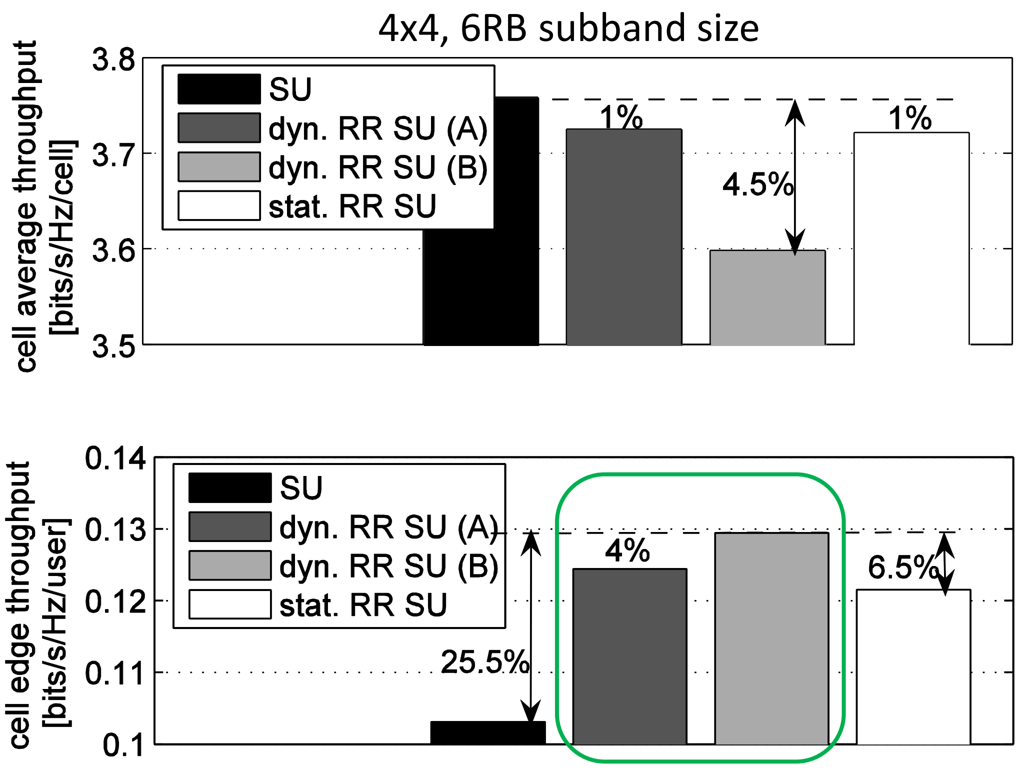
… and still so many idealities

- unquantized feedback
- user receiver implementation assumed known at the BS
- perfect CSI measurement

For 6RB, big loss of SU CS/CB compared to uncoordinated SU-MIMO despite a 71% overhead increase

Joint scheduling and rank coordination

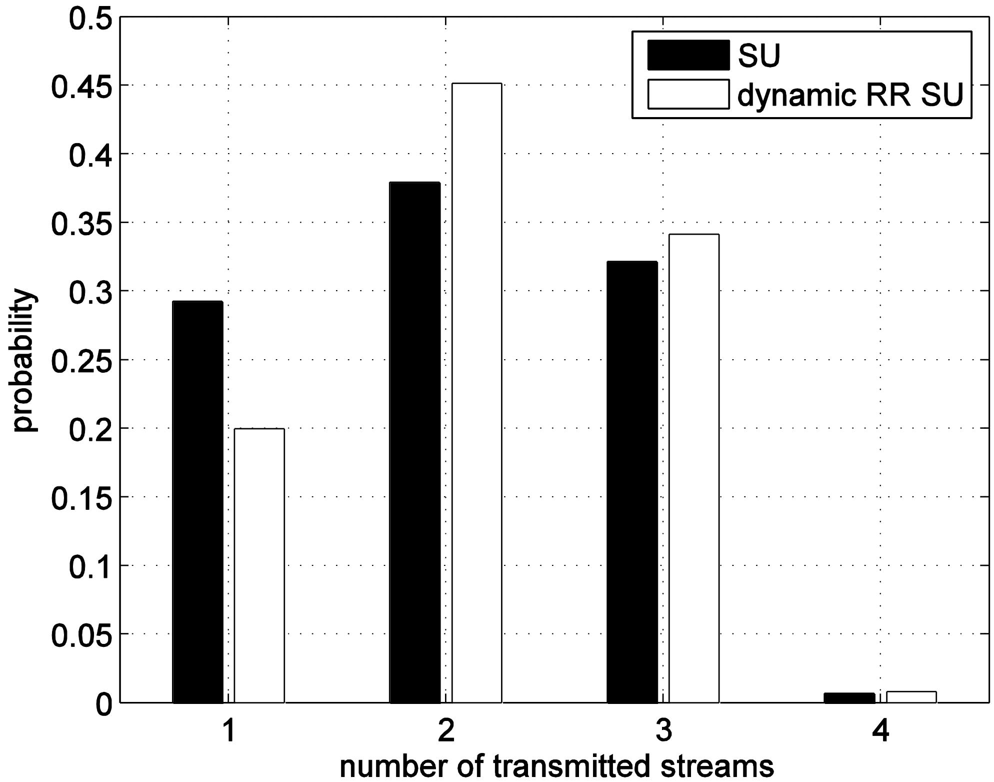
- Better performance gain with a significantly lower feedback overhead and scheduler complexity



About 20% gain at the cell edge with only 2-bit additional feedback compared to uncoordinated SU-MIMO

Joint scheduling and rank coordination

- Distribution of transmission rank after scheduling



Larger transmission rank (i.e. number of data streams) for cell edge users with only 2 bits additional feedback !

Joint scheduling and rank coordination

- Account for impairments
  - Easier convergence of the scheduler despite the low feedback overhead
  - Link adaptation
    - Accurate CQI/MCS because computed at the user side and accounting for cooperation
    - Accounts for receiver implementation
  - Sensitivity to CSI measurement
    - Less sensitive given the wideband properties
  - Low feedback overhead
    - Recommended rank (2 bit additional feedback)
    - No need for additional CSI feedback compared to single-cell
    - Can be applied to both OL (e.g. space-time/frequency coded) and CL MIMO
    - Works also based on statistical recommended interference rank
  - Robustness of control channels
    - recommended interference rank has very low overhead
    - Easy to report for cell edge users
  - Feedback delay and backhaul delay
    - Less sensitive due to wideband feedback

Conclusions

- Impairments-aware (robust) cooperative schemes using a simple joint scheduling and rank coordination

- Decrease the coordination burden at the network side by bringing the contribution of the receivers into the multi-cell coordination

- Make the receivers smarter to help the network in making appropriate scheduling decisions

Part 2:
An academic perspective – how to exploit interference?

1. MIMO Broadcast Channel with Imperfect CSIT
2. MIMO Interference Channel with information and energy transfer

1. MIMO Broadcast Channel with Imperfect CSIT

- Transmission strategies originally designed for perfect CSIT are tested in non-ideal conditions with imperfect CSIT
- Potential large benefits with perfect CSIT but benefits quickly vanish in practical scenarios
- Many sources of inaccurate CSIT

Sensitivity to CSI measurement
- Channel estimation errors particularly large for cell edge users

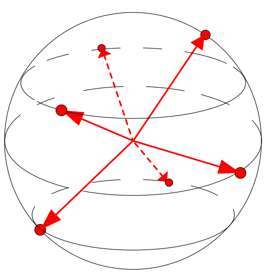
major issue: CSI feedback inaccuracy
- Limited feedback
- Subband feedback with strong frequency selectivity within subband
- Particularly problematic in dual-polarized antenna deployments

Latency of the feedback and the backhaul → Secondary issue as about 80% of the users are indoor/pedestrian

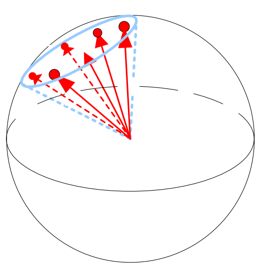
Two Options …

1. Pursue the conventional approach: design MIMO strategies for perfect CSIT and assess performance loss due to imperfect CSIT
    - Approach taken by 3GPP and WiMAX for many years
    - Suitable only for high CSIT accuracy: total DL throughput scales as nt log2(ρ) with nt transmit antennas
    - DL throughput and UL feedback overhead of DL MU-MIMO with quantized CSI [Jindal2006,Clerckx2008]

Grassmannian codebook



Adaptive/dual codebook



Deployment	DL throughput	UL overhead
I.i.d.	$n_t \log_2(\rho)$	$n_t (n_t-1) \log_2(\rho)$
Spatially correlated	$n_t \log_2(\rho)$	$n_t (r-1) \log_2(\rho)$

r: rank of transmit correlation matrix

SNR=10dB, n_t=4, B≈10 in i.i.d. and B≈4 in spatially correlated with r≈2, on every subcarrier vs. B=4 for 72 contiguous subcarriers (as in LTE-A)

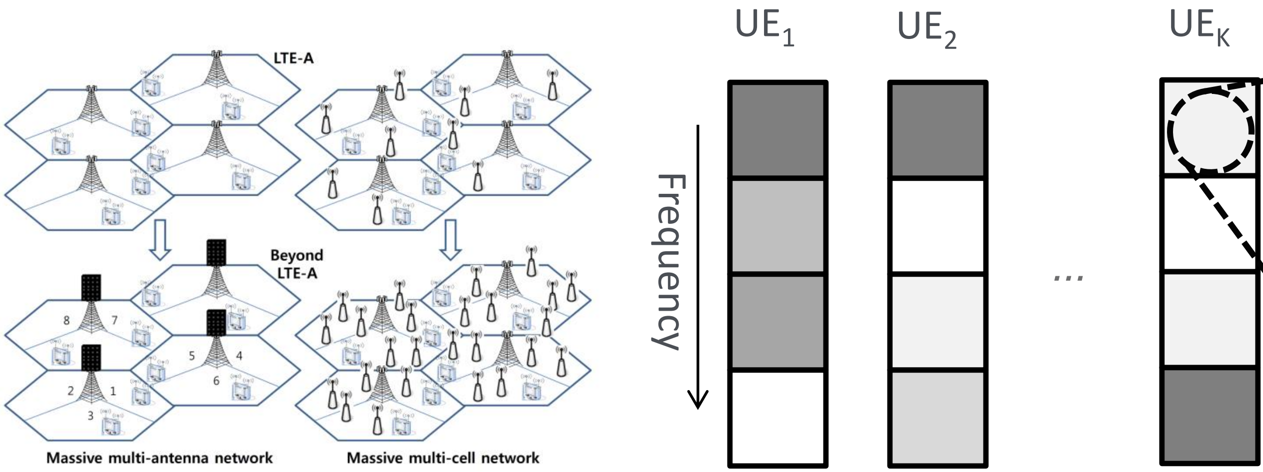
- 3GPP/WiMAX do not provide high enough CSIT accuracy
- Is 3GPP/5G willing to increase CSIT accuracy drastically once for all?

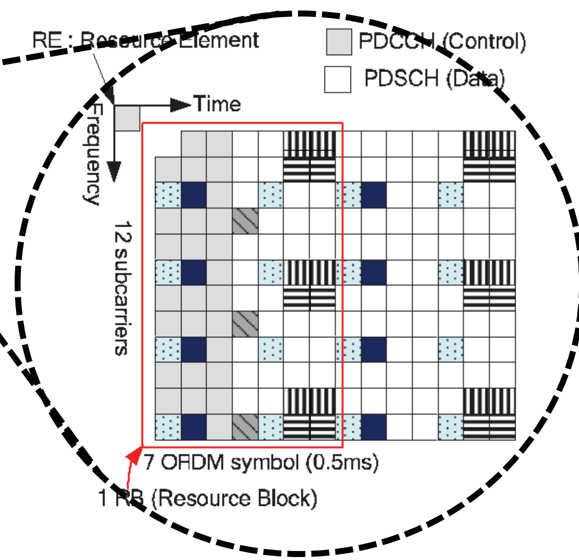
Two Options …

2. Pursue another approach: design MIMO networks for imperfect CSIT
    - New perspective triggered by [MAT2012]
        - completely outdated CSIT is still useful
        - overhear interference and use feedback as a way to exploit the overheard interference.
    - Use Degree of Freedom (DoF) as metric: number of interference-free streams at high SNR
    - Example: 2-user 2 antenna MISO BC
        - If full CSIT, DoF per user of 1
        - If no CSIT, DoF per user of ½
        - If completely delayed (perfect) CSIT, DoF per user of 2/3 > 1/2
    - Triggered much research in the last 12 months to analyze delayed CSIT: outdated CSIT [MAT2012], outdated CSIT + partial current CSIT [Yang2013,Gou 2012]

Problem statement …

- Imperfect CSIT in frequency domain more critical !
- Multi-user/Multi-cell/Massive/Network/Cooperative/Coordinated MIMO-OFDMA for imperfect CSIT





MIMO-OFDMA network with various CSI feedback qualities across subbands and users

- Given imperfect feedback in the frequency domain,
  - what is the maximum achievable rate region?
  - what are the optimal/suboptimal transmission and reception strategies?
  - How to optimally make use of feedback resources?

System Model [Hao2013a,Hao2013b]

- Consider a MISO Broadcast Channel with one 2-antenna transmitter and two single-antenna users over two-subband with imperfect CSIT

	User 1	User 2
Subband A	β	α
Subband B	α	β

Unmatched

	User 1	User 2
Subband A	β	β
Subband B	α	α

Matched

- Transmit signal vector in subband *i* as $\mathbf{s}_i$ subject to a per-subband based power constraint $E\{\|\mathbf{s}_i\|^2\} \sim P$ (P is the SNR).

- Observations at receiver 1 and 2 are respectively (with unit power AWGN noise)

$$y_i = \mathbf{h}_i^H \mathbf{s}_i + \epsilon_{i,y}$$
$$z_i = \mathbf{g}_i^H \mathbf{s}_i + \epsilon_{i,z}$$

System Model

- $\mathbf{h}_i$ and $\mathbf{g}_i$ are the CSI in subband i of user 1 and user 2, respectively. The CSI are i.i.d across users and subbands.

- Imperfect CSIT: $\hat{\mathbf{h}}_i$ of user 1 is and $\hat{\mathbf{g}}_i$ of user 2. Error vectors $\tilde{\mathbf{h}}_i = \mathbf{h}_i - \hat{\mathbf{h}}_i$ and $\tilde{\mathbf{g}}_i = \mathbf{g}_i - \hat{\mathbf{g}}_i$.
  - Unmatched: $E\{\|\tilde{\mathbf{h}}_A\|^2\} = E\{\|\tilde{\mathbf{g}}_B\|^2\} \sim P^{-\beta}$ and $E\{\|\tilde{\mathbf{h}}_B\|^2\} = E\{\|\tilde{\mathbf{g}}_A\|^2\} \sim P^{-\alpha}$
  - Matched: $E\{\|\tilde{\mathbf{h}}_A\|^2\} = E\{\|\tilde{\mathbf{g}}_A\|^2\} \sim P^{-\beta}$ and $E\{\|\tilde{\mathbf{h}}_B\|^2\} = E\{\|\tilde{\mathbf{g}}_B\|^2\} \sim P^{-\alpha}$

  Assume β≥α. β, α ∈ $[0,1]$ represent the quality of the CSIT. 0 represents no CSIT and 1 represents perfect CSIT. [Yang2013]

- Degrees of Freedom per user and per channel use

$$d_k \triangleq \lim_{P\to\infty} \frac{R_k}{S \log P}, \quad k = 1, 2$$

where R_k is the rate achieved by user k over S channel uses.

Achievability: the building blocks

1. ZFBF: designed for perfect CSIT (β=1,α=1)
   - Transmit signal on subband A (similar for subband B) with u_A for user 1 and v_A for user 2

$$\mathbf{s}_A = \hat{\mathbf{g}}_A^{\perp} u_A + \hat{\mathbf{h}}_A^{\perp} v_A$$

	User 1	User 2
A	1	1
B	1	1

   - Received signals on subband A (similar for subband B)

$$y_A = \mathbf{h}_A^H \hat{\mathbf{g}}_A^{\perp} u_A + \mathbf{h}_A^H \hat{\mathbf{h}}_A^{\perp} v_A + \epsilon_{A,y},$$

$$z_A = \mathbf{g}_A^H \hat{\mathbf{g}}_A^{\perp} u_A + \mathbf{g}_A^H \hat{\mathbf{h}}_A^{\perp} v_A + \epsilon_{A,z}.$$

   - Sum DoF: 2
   - If imperfect CSIT (β,α)

$$y_A = \overbrace{\mathbf{h}_A^H \hat{\mathbf{g}}_A^{\perp} u_A}^{P} + \overbrace{\mathbf{h}_A^H \hat{\mathbf{h}}_A^{\perp} v_A}^{P^{1-\beta}} + \epsilon_{A,y},$$

$$z_A = \underbrace{\mathbf{g}_A^H \hat{\mathbf{g}}_A^{\perp} u_A}_{P^{1-\alpha}} + \underbrace{\mathbf{g}_A^H \hat{\mathbf{h}}_A^{\perp} v_A}_{P} + \epsilon_{A,z}.$$

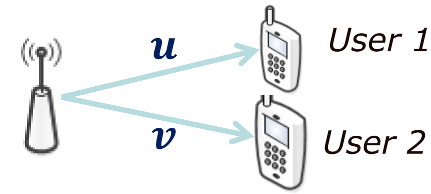
	User 1	User 2
A	β	α
B	α	β

Unmatched

Sum DoF: β (rate of u_A) + α (rate of v_A)

Achievability: the building blocks

2. MAT: designed for delayed CSIT in the time domain



- Broadcast private symbols at slot 1 and 2

Tx $\boldsymbol{s_i}$	$\boldsymbol{v}_1 = [v_{11}, v_{12}]^T$	$\boldsymbol{u}_2 = [u_{21}, u_{22}]^T$
Rx1	$y_1 = \eta_{11} = \boldsymbol{h}_1^H \boldsymbol{v}_1$	$y_2 = \boldsymbol{h}_2^H \boldsymbol{u}_2$
Rx2	$z_1 = \boldsymbol{g}_1^H \boldsymbol{v}_1$	$z_2 = \eta_{22} = \boldsymbol{g}_2^H \boldsymbol{u}_2$

- Broadcast sum of $\eta_{11} + \eta_{22}$ at slot 3

Tx $\boldsymbol{s_i}$	$[\eta_{11}+\eta_{22},0]^T$
Rx1	$y_3 = h_{31}^*(\eta_{11}+\eta_{22})$
Rx2	$z_3 = g_{31}^*(\eta_{11}+\eta_{22})$

$\boldsymbol{u}_2$ is decodable at user 1

$$\begin{cases} y_2 = \boldsymbol{h}_2^H \boldsymbol{u}_2, \\ y_3 - h_{31}^* y_1 = h_{31}^* \eta_{22}(\boldsymbol{u}_2), \end{cases}$$

Remarks:

1. Outdated CSIT- boost the DoF:
   a) Eliminate interference
   b) Provide side information
2. Only $\boldsymbol{h}_1$ and $\boldsymbol{g}_2$ are actually needed at the Tx

MAT in the frequency domain over 3-subbands

$$\mathbf{s}_A = \mathbf{v}_A, \quad \mathbf{s}_B = \mathbf{u}_B, \quad \mathbf{s}_C = [\eta_{A,1} + \eta_{B,2}, 0]^T,$$
$$y_A = \eta_{A,1}, \quad y_B = \mathbf{h}_B^H \mathbf{u}_B, \quad y_C = h_{C,1}^* (\eta_{A,1} + \eta_{B,2}),$$
$$z_A = \mathbf{g}_A^H \mathbf{v}_A, \quad z_B = \eta_{B,2}, \quad z_C = g_{C,1}^* (\eta_{A,1} + \eta_{B,2}),$$

	User 1	User 2
A	1	0
B	0	1
C	0	0

Achievability: the building blocks

3. $S_3^{3/2}$: designed for alternating CSIT, i.e. the transmitter has perfect CSIT of only one user at a time (β=1,α=0) [Tandon2012]

- Transmit signal on subband A and B with u_0 and u_B for user 1 and v_A for user 2

$$\mathbf{s}_A = \begin{bmatrix} u_0 \\ 0 \end{bmatrix} + \hat{\mathbf{h}}_A^{\perp} v_A,$$

$$\mathbf{s}_B = \begin{bmatrix} u_0 \\ 0 \end{bmatrix} + \hat{\mathbf{g}}_B^{\perp} u_B,$$

	User 1	User 2
A	1	0
B	0	1

Unmatched

- Sum DoF: 3/2
- If imperfect CSIT (β,α)

$$\mathbf{s}_A = \overbrace{\begin{bmatrix} u_0 \\ 0 \end{bmatrix}}^{P} + \overbrace{\hat{\mathbf{h}}_A^{\perp} v_A}^{P^{1-\beta}},$$

$$\mathbf{s}_B = \underbrace{\begin{bmatrix} u_0 \\ 0 \end{bmatrix}}_{P} + \underbrace{\hat{\mathbf{g}}_B^{\perp} u_B}_{P^{1-\beta}},$$

	User 1	User 2
A	β	α
B	α	β

Unmatched

Sum DoF: 1/2(β (rate of u_0) + 1 (rate of v_A) + 1 (rate of u_B)) = 1+β/2

Achievability in the unmatched scenario [Chen2013]

	User 1	User 2
Subband A	β	α
Subband B	α	β

Unmatched

- Strategy 1: integrating ZFBF and $S_3^{3/2}$
- Transmit signals in subband A and B

$$\mathbf{s}_A = [x_{c,A}, 0]^T + [\hat{\mathbf{g}}_A^{\perp}, \hat{\mathbf{g}}_A][u_A, u_0]^T + \hat{\mathbf{h}}_A^{\perp} v_A,$$
$$\mathbf{s}_B = [x_{c,B}, 0]^T + [\hat{\mathbf{h}}_B^{\perp}, \hat{\mathbf{h}}_B][v_B, u_0]^T + \hat{\mathbf{g}}_B^{\perp} u_B.$$

FDMA ZFBF $S_3^{3/2}$

where

- $x_{c,A}$ and $x_{c,B}$ are messages to be decoded by both users (intended to user 1 and user 2 respectively or exclusively to user 1 or user 2)
- u_A, u_0 and u_B are symbols sent to user 1
- v_A and v_B are symbols sent to user 2

Achievability in the unmatched scenario

$$\mathbf{s}_A = [x_{c,A}, 0]^T + [\hat{\mathbf{g}}_A^{\perp}, \hat{\mathbf{g}}_A][u_A, u_0]^T + \hat{\mathbf{h}}_A^{\perp} v_A,$$
$$\mathbf{s}_B = [x_{c,B}, 0]^T + [\hat{\mathbf{h}}_B^{\perp}, \hat{\mathbf{h}}_B][v_B, u_0]^T + \hat{\mathbf{g}}_B^{\perp} u_B.$$

- Power and rate allocation

subband A	*subband B*	Power	Rate ($\log P$)
$x_{c,A}$	$x_{c,B}$	$P - P^{\beta}$	$1-\beta$
u_A	v_B	$P^{\alpha}/2$	α
u_0	u_0	$(P^{\beta} - P^{\alpha})/2$	$\beta - \alpha$
v_A	u_B	$P^{\beta}/2$	β

- Received signals in subband A and B

$$y_A = \underbrace{h_{A,1}^* x_{c,A}}_{P} + \underbrace{\mathbf{h}_A^H \hat{\mathbf{g}}_A^{\perp} u_A}_{P^{\alpha}} + \underbrace{\mathbf{h}_A^H \hat{\mathbf{g}}_A u_0}_{P^{\beta}} + \underbrace{\mathbf{h}_A^H \hat{\mathbf{h}}_A^{\perp} v_A}_{P^0},$$

$$z_A = \underbrace{g_{A,1}^* x_{c,A}}_{P} + \underbrace{\mathbf{g}_A^H \hat{\mathbf{g}}_A^{\perp} u_A}_{P^0} + \underbrace{\mathbf{g}_A^H \hat{\mathbf{g}}_A u_0}_{P^{\beta}} + \underbrace{\mathbf{g}_A^H \hat{\mathbf{h}}_A^{\perp} v_A}_{P^{\beta}},$$

$$y_B = \underbrace{h_{B,1}^* x_{c,B}}_{P} + \underbrace{\mathbf{h}_B^H \hat{\mathbf{h}}_B^{\perp} v_B}_{P^0} + \underbrace{\mathbf{h}_B^H \hat{\mathbf{h}}_B u_0}_{P^{\beta}} + \underbrace{\mathbf{h}_B^H \hat{\mathbf{g}}_B^{\perp} u_B}_{P^{\beta}},$$

$$z_B = \underbrace{g_{B,1}^* x_{c,B}}_{P} + \underbrace{\mathbf{g}_B^H \hat{\mathbf{h}}_B^{\perp} v_B}_{P^{\alpha}} + \underbrace{\mathbf{g}_B^H \hat{\mathbf{h}}_B u_0}_{P^{\beta}} + \underbrace{\mathbf{g}_B^H \hat{\mathbf{g}}_B^{\perp} u_B}_{P^0},$$

Decoding strategy (for user 1)

1. Decode $x_{c,A}$ and $x_{c,B}$ by treating all the other terms as noise.
2. Decode u_0 and u_A from y_A using SIC
3. With the knowledge of u_0, decode u_B from y_B

d_{Σ}^{opt}=1/2 (2-2β+2α+β-α+2β) $= 1 + \frac{\beta+\alpha}{2}$

Achievability in the unmatched scenario [Hao2013a]

	User 1	User 2
Subband A	β	α
Subband B	α	β

Unmatched

- Strategy 2: integrating ZFBF and "MAT-like"
- Transmit signals in subband A and B

$$\mathbf{s}_A = [x_{c,A}, 0]^T + [\mu_A, 0]^T + [\hat{\mathbf{h}}_A^{\perp}, \hat{\mathbf{h}}_A][v_{A1}, v_{A2}]^T + \hat{\mathbf{g}}_A^{\perp} u_A,$$
$$\mathbf{s}_B = [x_{c,B}, 0]^T + [\mu_B, 0]^T + [\hat{\mathbf{g}}_B^{\perp}, \hat{\mathbf{g}}_B][u_{B1}, u_{B2}]^T + \hat{\mathbf{h}}_B^{\perp} v_B,$$

FDMA MAT-like transmission ZFBF

Rather than having 1 symbol, we have 2 symbols, leading to the overheard interference re-transmission
-> DoF loss compared to strategy 1

where

- $x_{c,A}$ and $x_{c,B}$ are messages to be decoded by both users (intended to user 1 and user 2 respectively or exclusively to user 1 or user 2)
- u_A, u_{B1} and u_{B2} are symbols sent to user 1
- v_B, v_{A1} and v_{A2} are symbols sent to user 2

Achievability in the matched scenario [Hao2013b]

	User 1	User 2
Subband A	β	β
Subband B	α	α

Matched

- Transmit signals

$$\mathbf{s}_i = [\underbrace{x_{c,i}}_{P-P^j}, 0]^T + \underbrace{\hat{\mathbf{g}}_i^{\perp} u_i}_{P^j/2} + \underbrace{\hat{\mathbf{h}}_i^{\perp} v_i}_{P^j/2}, \ (i,j)=(A,\beta),(B,\alpha)$$

FDMA ZFBF

- Decoding strategy
  1. Decode $x_{c,i}$ by each user with rate $(1-j)\log P$ in subband *i*
  2. Each user decodes respectively its own private symbol with rate $j \log P$

$$d_{\Sigma}^{opt} = 1/2\ (1-\beta+1-\alpha+2\beta+2\alpha) = 1 + \frac{\beta+\alpha}{2}$$

Optimal DoF Region [Hao2013b]

Theorem. *The outer-bound of the DoF region in the frequency correlated Broadcast Channel (for both unmatched and matched scenario) with imperfect CSIT is specified by*

$$d_1 + d_2 \leq 1 + \frac{\beta + \alpha}{2},$$
$$d_1 \leq 1, d_2 \leq 1.$$

Given that the outer-bound is achievable, this is the optimal DOF region.

Both scenarios have the same DoF regions.

$\frac{\beta + \alpha}{2}$ can be viewed as the average quality of CSIT of a user.

Interpretation of the Optimal DoF Region (1/3) [Hao2013b]

- Assume the unmatched scenario
- Virtually decompose subbands into sub-channels
  - $\tilde{A}, \tilde{B}$: no CSIT, each with channel use 1-β;
  - $\hat{A}$ ($\hat{B}$): perfect CSIT of user 1 (2), with channel use β-α;
  - $\bar{A}, \bar{B}$: perfect CSIT of both users, with channel use α.

	User 1	User 2
Subband A	β	α
Subband B	α	β

=

α

	User 1	User 2
$\tilde{A}$	1	1
$\tilde{A}$	1	1

\+ β-α

	User 1	User 2
$\hat{A}$	1	0
$\hat{B}$	0	1

\+ 1-β

	User 1	User 2
$\bar{A}$	0	0
$\bar{B}$	0	0

Interpretation of the Optimal DoF Region (2/3)

The DoF region in the original subbands A and B can be obtained as the weighted sum of the regions of each subchannel:

$$\mathcal{D}_u = (1-\beta)\tilde{\mathcal{D}} + (\beta-\alpha)\hat{\mathcal{D}} + \alpha\bar{\mathcal{D}}$$

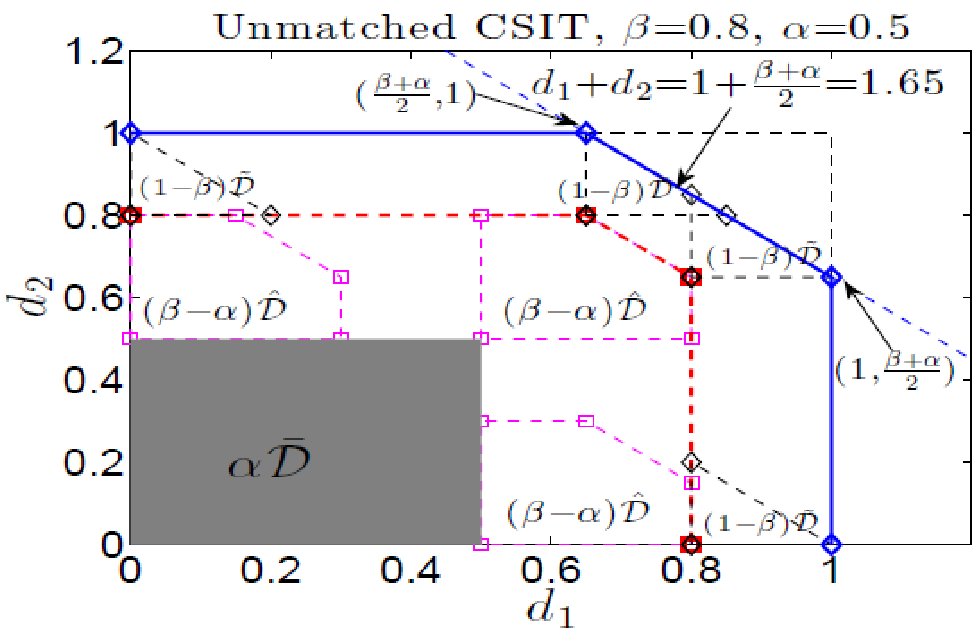
- Subchannel $\tilde{A}, \tilde{B}$ can be categorized as the BC with no CSIT

$$\mathcal{D}^{\tilde{A}} = \mathcal{D}^{\tilde{B}} = \tilde{\mathcal{D}} : d_1 + d_2 \leq 1$$

- Subchannel $\bar{A}$, $\bar{B}$ can be categorized as the BC with perfect CSIT of both users

$$\mathcal{D}^{\bar{A}} = \mathcal{D}^{\bar{B}} = \bar{\mathcal{D}} : d_1 \leq 1, d_2 \leq 1$$

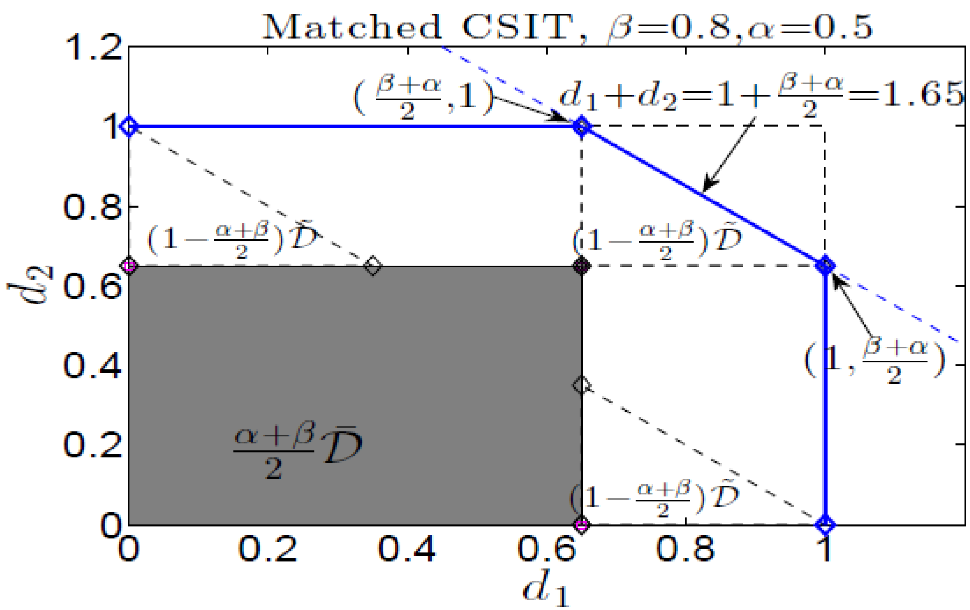
- Subchannel $\hat{A}$, $\hat{B}$ have an alternating CSIT setting with two states: (perfect CSIT, no CSIT) and (no CSIT, perfect CSIT)



$$(\mathcal{D}^{\hat{A}}+\mathcal{D}^{\hat{B}})/2 = \hat{\mathcal{D}} : d_1 + d_2 \leq 1.5, d_1 \leq 1, d_2 \leq 1$$

Interpretation of the Optimal DoF Region (3/3)

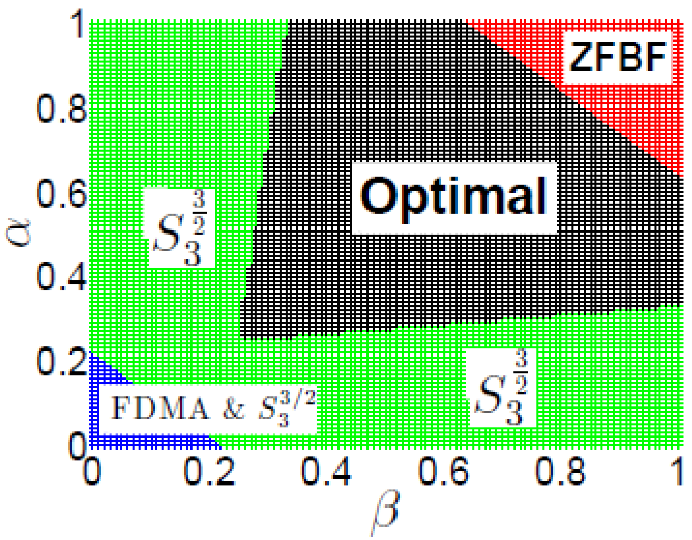
- Assume the matched scenario
- Virtually decompose subbands into sub-channels
  - $\tilde{A}, \tilde{B}$: no CSIT, each with channel use 1-β and 1-α;
  - $\bar{A}, \bar{B}$: perfect CSIT of both users, with channel use β and α.
- Weighted sum of the DoF regions $\mathcal{D}_m = (1 - \frac{\beta+\alpha}{2})\tilde{\mathcal{D}} + \frac{\beta+\alpha}{2}\bar{\mathcal{D}}$



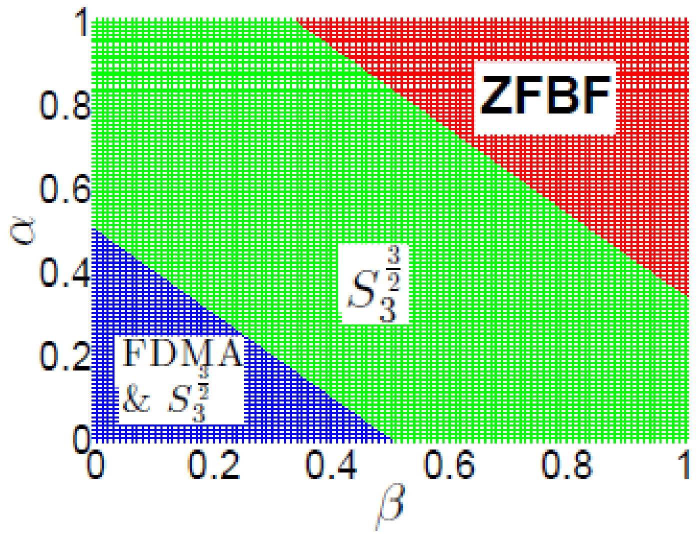
Mode switching among sub-optimal strategies (1/2) [Hao 2013b]

- Optimal scheme integrates FDMA, ZFBF and $S_3^{3/2}$. What about a simple switching strategy?
  - FDMA only: sum DoF $d_\Sigma^F = 1$
  - ZFBF only: sum DoF $d_\Sigma^Z = \beta + \alpha$
  - $S_3^{3/2}$ only (for unmatched case): sum DoF $d_\Sigma^S = 1 + \frac{\beta}{2}$

- For the unmatched scenario, $\max(d_\Sigma^F, d_\Sigma^Z, d_\Sigma^S) \geq 0.8 \times d_\Sigma^{opt}, \forall \beta, \alpha \in [0, 1]$



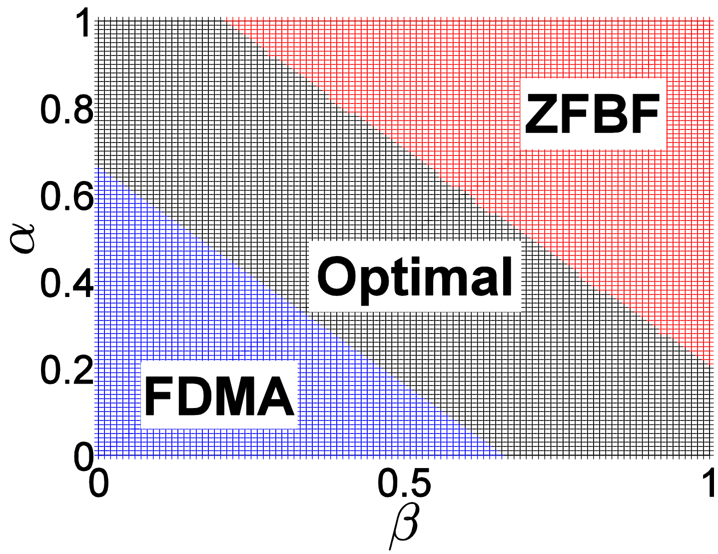
Achieving **90%** of the optimal sum DoF d_Σ^{opt}



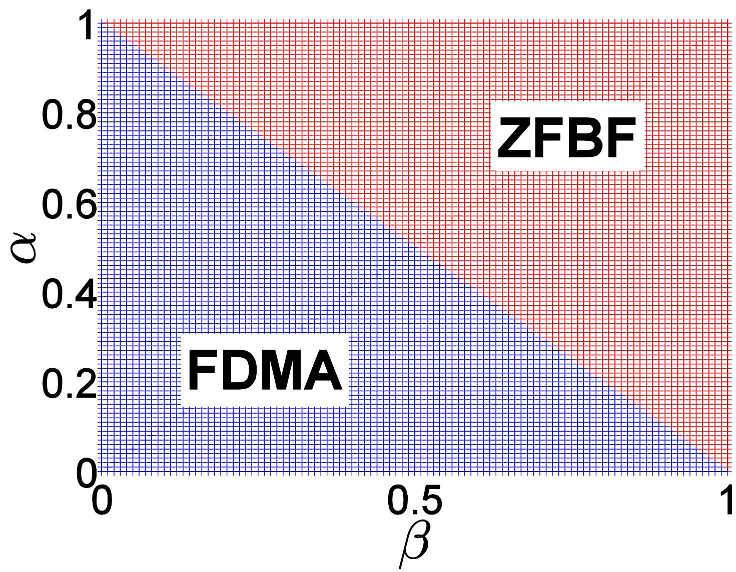
Achieving **80%** of the optimal sum DoF d_Σ^{opt}

Mode switching among sub-optimal strategies (2/2)

- For the matched scenario, $\max(d_\Sigma^F, d_\Sigma^Z) \geq 2/3 \times d_\Sigma^{opt}, \forall \beta, \alpha \in [0,1]$



Achieving **75%** of the optimal sum DoF d_Σ^{opt}



Achieving **66.7%** of the optimal sum DoF d_Σ^{opt}

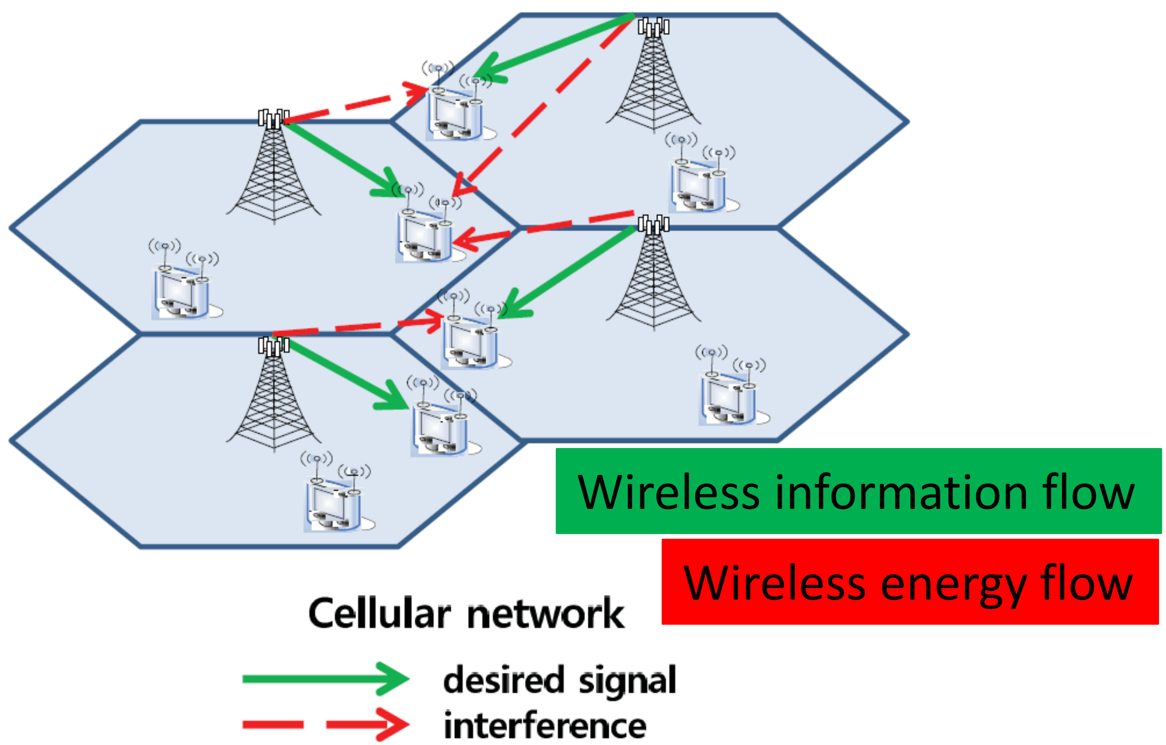
Conclusions

- Time for a proper design of MIMO networks relying on CSIT accounting for imperfect CSIT
- Derive the optimal DoF region of a Two-User frequency correlated MISO Broadcast Channel
- Interpretation as a weighted sum of the DoF regions achieved by FDMA, ZFBF and $S_3^{3/2}$
- Achievable scheme is obtained as an integration of FDMA, ZFBF and $S_3^{3/2}$
- Simple switching strategy can get a big chunk of the sum DoF
  - Unmatched scenario: 80% of the sum DoF achievable by switching between $S_3^{3/2}$ and ZFBF
  - Matched scenario: 66.7% of the sum DoF achievable by switching between FDMA and ZFBF
- To be done: generalization of the two-user two-subbands multi-user MIMO-OFDMA to a general Multi-user/Multi-cell/Massive/Network/Cooperative/Coordinated MIMO-OFDMA

2. MIMO Interference Channel with information and energy transfer [Park2013]

- RF signals carry information as well as energy
  - RF energy harvesting over short (feasible with reasonable efficiency) and long (more challenging but on-going research) distances

- One single wireless network: information network and energy network merged
- If we can exploit (harvest) the energy originating from the interference, would interference be beneficial or detrimental to system performance?



System Model (1/2)

- Two user IC with M antennas at each transmitter/receiver

$$\mathbf{y}_1 = \mathbf{H}_{11}\mathbf{x}_1 + \mathbf{H}_{12}\mathbf{x}_2 + \mathbf{n}_1,$$

$$\mathbf{y}_2 = \mathbf{H}_{21}\mathbf{x}_1 + \mathbf{H}_{22}\mathbf{x}_2 + \mathbf{n}_2,$$

- Each receiver can either decode the information (ID mode) or harvest energy (EH mode) from the received signal but cannot decode information and harvest energy at the same time due to the hardware limitations.
- The transmitters have perfect knowledge of the local CSI (i.e. the links between a transmitter and all receivers) but do not share those CSI between them.
- Interference is assumed not decodable at the receivers
- $\mathbf{Q}_j = E[\mathbf{x}_j\mathbf{x}_j^H]$: covariance matrix of the transmit signal at transmitter *j*
- Transmit power constraint: $tr(\mathbf{Q}_j) \leq P$

System Model (2/2)

- ID mode: achievable rate at receiver *i*

$$R_i = \log\det(\mathbf{I}_M + \mathbf{H}_{ii}^H \mathbf{R}_{-i}^{-1} \mathbf{H}_{ii} \mathbf{Q}_i)$$

Covariance matrix of noise + interference at receiver i

$$\mathbf{R}_{-1} = \mathbf{I}_M + \mathbf{H}_{12}\mathbf{Q}_2\mathbf{H}_{12}^H$$

$$\mathbf{R}_{-2} = \mathbf{I}_M + \mathbf{H}_{21}\mathbf{Q}_1\mathbf{H}_{21}^H$$

- EH mode: harvested energy at receiver *i*

$$\begin{aligned} E_i &= \zeta_i E[\|\mathbf{y}_i\|^2] \\ &= \zeta_i tr\left(\sum_{j=1}^{2} \mathbf{H}_{ij}\mathbf{Q}_j\mathbf{H}_{ij}^H + \mathbf{I}_M\right), \\ &\approx tr\left(\sum_{j=1}^{2} \mathbf{H}_{ij}\mathbf{Q}_j\mathbf{H}_{ij}^H\right) \\ &= tr\left(\mathbf{H}_{i1}\mathbf{Q}_1\mathbf{H}_{i1}^H\right) + tr\left(\mathbf{H}_{i2}\mathbf{Q}_2\mathbf{H}_{i2}^H\right) \\ &= E_{i1} + E_{i2}, \end{aligned}$$

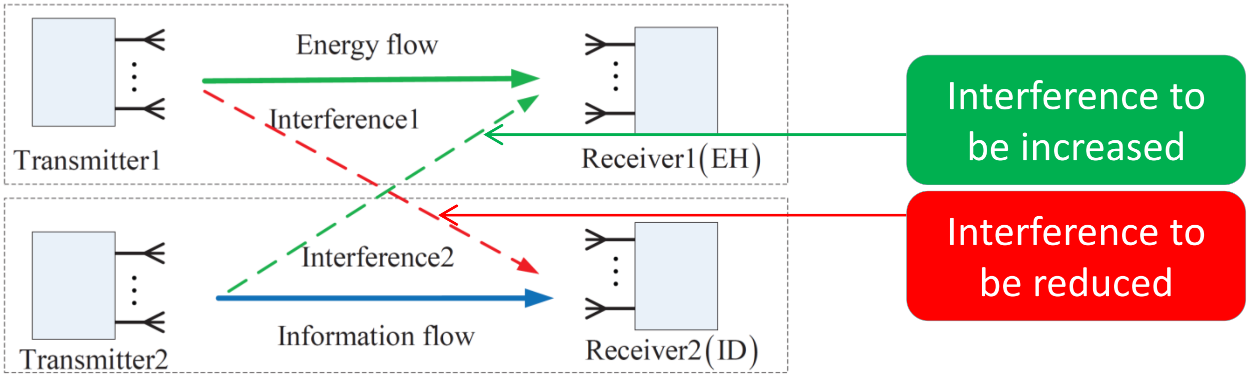
Efficiency assumed equal to 1 (ζ_i)

Noise power negligible compared to transferred energy ($\approx$)

Energy (or interference) transferred from Tx 1 and Tx2 to receiver i (E_{i1}, E_{i2})

- When the receiver decodes the information data from the associated transmitter under the assumption that the interfering signal from the other transmitter is not decodable, the interference is to be mitigated.
- In contrast, when the receiver harvests the energy, the interference becomes a useful energy-transferring source.

- Mitigate or Exploit interference? Interfere or not interfere?



Two receivers on a single mode

- Two ID receivers: maximum achievable sum rate

$$(P1)\ \text{maximize} \quad \sum_{i=1}^{2} R_i$$
$$\text{subject to} \quad tr(\mathbf{Q}_j) \leq P,\ \mathbf{Q}_j \succeq \mathbf{0} \quad \text{for } j = 1, 2,$$

Solution: Iterative water-filling [Scutari2009]

Harvested energy is zero.

- Two EH receivers: maximum harvested sum energy

$$(P2)\ \text{maximize} \quad \sum_{i=1}^{2} E_i$$
$$\text{subject to} \quad tr(\mathbf{Q}_j) \leq P,\ \mathbf{Q}_j \succeq \mathbf{0} \quad \text{for } j = 1, 2,$$

Proposition 1: The optimal $\mathbf{Q}_j$ for (P2) has a rank equal to one and is given as $\mathbf{Q}_j = P[\bar{\mathbf{V}}_j]_1[\bar{\mathbf{V}}_j]_1^H$, where $\bar{\mathbf{V}}_j$ is a $M \times M$ unitary matrix obtained from the SVD of $\bar{\mathbf{H}}_j \triangleq \begin{bmatrix} \mathbf{H}_{1j} \\ \mathbf{H}_{2j} \end{bmatrix}$. That is, $\bar{\mathbf{H}}_j = \bar{\mathbf{U}}_j \bar{\mathbf{\Sigma}}_j \bar{\mathbf{V}}_j^H$, where $\bar{\mathbf{\Sigma}}_j = diag\{\bar{\sigma}_{j,1}, ..., \bar{\sigma}_{j,M}\}$ with $\bar{\sigma}_{j,1} \geq ... \geq \bar{\sigma}_{j,M}$.

Rank-1 beamforming along the dominant singular vector

Achievable rate is zero.

One ID receiver and One EH Receiver (1/4)

- Assume (EH_1, ID_2) - the first receiver harvests the energy and the second d ecodes information: $R=R_2$ and $E=E_1=E_{12}+E_{12}$
- Achievable rate-energy region (characterizes the interfere/not interfere tradeoff)

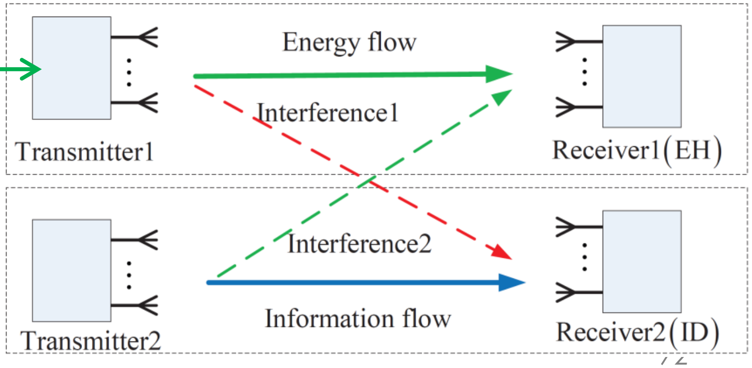
$$C_{R\text{-}E}(P) \triangleq \Big\{(R, E) : R \leq \log\det(\mathbf{I}_M + \mathbf{H}_{22}^H \mathbf{R}_{-2}^{-1} \mathbf{H}_{22} \mathbf{Q}_2),$$

$$E \leq \sum_{j=1}^{2} tr(\mathbf{H}_{1j} \mathbf{Q}_j \mathbf{H}_{1j}^H), tr(\mathbf{Q}_j) \leq P, \mathbf{Q}_j \succeq \mathbf{0}, j = 1,2 \Big\}.$$

- A necessary condition for the optimal transmission strategy

Proposition 2: In the high SNR regime, the optimal $\mathbf{Q}_1$ at the boundary of the achievable rate-energy region has a rank one at most. That is, $rank(\mathbf{Q}_1) \leq 1$.

Rank-1 at most



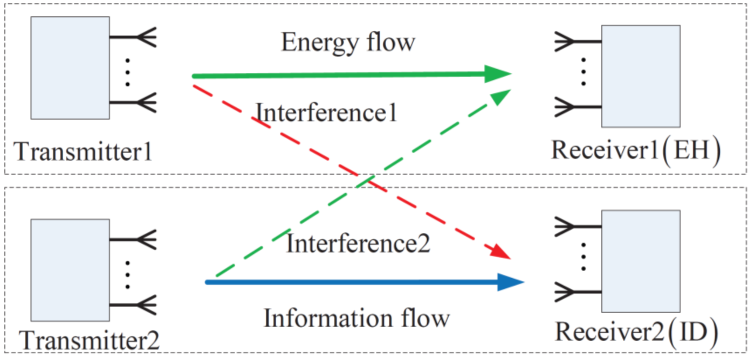
Assume a boundary point $(\bar{R}, \bar{E})$,

If $\bar{E} \leq tr(\mathbf{H}_{12} \mathbf{Q}_2 \mathbf{H}_{12}^H)$, turn off Tx1 ($\mathbf{Q}_1 = \mathbf{0}$)

If $\bar{E} > tr(\mathbf{H}_{12} \mathbf{Q}_2 \mathbf{H}_{12}^H)$, turn on Tx1 with $rank(\mathbf{Q}_1)$=1

One ID receiver and One EH Receiver (2/4)

- Even though the identification of the optimal achievable R-E boundary is an open problem, it can be found that the first transmitter will opt for a rank-one beamforming scheme.



- Rank-one Beamforming Design?
  - Maximum-energy beamforming (MEB):

$$\mathbf{Q}_1 = P_1[\mathbf{V}_{11}]_1[\mathbf{V}_{11}]_1^H$$

$0 \leq P_1 \leq P$

Rank-1 beamforming along the dominant singular vector of H_{11}

$$\mathbf{H}_{11} = \mathbf{U}_{11}\mathbf{\Sigma}_{11}\mathbf{V}_{11}^H$$

  - Minimum-leakage beamforming (MLB):

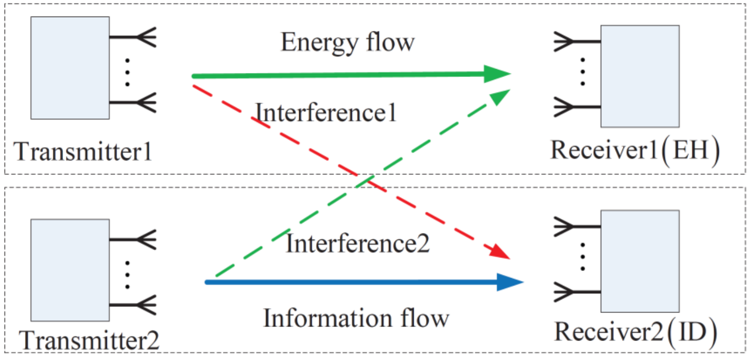
$$\mathbf{Q}_1 = P_1[\mathbf{V}_{21}]_M[\mathbf{V}_{21}]_M^H$$

Rank-1 beamforming along the weakest singular vector of H_{21}

$$\mathbf{H}_{21} = \mathbf{U}_{21}\mathbf{\Sigma}_{21}\mathbf{V}_{21}^H$$

One ID receiver and One EH Receiver (3/4)

- Achievable R-E region



Energy harvested from the first transmitter. It can be computed for MEB and MLB

$$C_{R-E}(P) = \Big\{(R,E) : R = R_2, E = E_{11} + E_{12},$$

$$R_2 \leq \log\det(\mathbf{I}_M + \mathbf{H}_{22}^H \mathbf{R}_{-2}^{-1} \mathbf{H}_{22} \mathbf{Q}_2), E_{12} \leq tr(\mathbf{H}_{12}\mathbf{Q}_2\mathbf{H}_{12}^H),$$

$$tr(\mathbf{Q}_2) \leq P, \mathbf{Q}_2 \succeq \mathbf{0}\Big\},$$

Covariance matrix of noise + interference. It can be computed for MEB and MLB

function of P_1

$$\tilde{\mathbf{H}}_{22} = \mathbf{R}_{-2}^{-1/2}\mathbf{H}_{22}$$

$$(P3)\ \underset{\mathbf{Q}_2}{\text{maximize}}\quad \log\det(\mathbf{I}_M + \tilde{\mathbf{H}}_{22}\mathbf{Q}_2\tilde{\mathbf{H}}_{22}^H)$$

$$\text{subject to}\ \ tr(\mathbf{H}_{12}\mathbf{Q}_2\mathbf{H}_{12}^H) \geq \max(\bar{E} - E_{11}, 0)$$

$$tr(\mathbf{Q}_2) \leq P,\ \ \mathbf{Q}_2 \succeq \mathbf{0},$$

Remaining energy to be harvested from interference to reach boundary point $\bar{E}$

One ID receiver and One EH Receiver (4/4)

- Iterative identification of the achievable R-E region
  1. n=0, $P_1^{(0)} = P$, compute $E_{11}^{(0)}$ and $\mathbf{R}_{-2}^{(0)}$ for either MEB or MLB.
  2. For n= 0: Nmax, solve the optimization problem (P3) for $\mathbf{Q}_2^{(n)}$ as a function of $E_{11}^{(n)}$ and $\mathbf{R}_{-2}^{(n)}$.

     "water-filling-like" approach

     If $tr(\mathbf{H}_{12}\mathbf{Q}_2^{(n)}\mathbf{H}_{12}^H) + E_{11}^{(n)} > \bar{E}$,

     i.e. total harvested energy is larger than the required harvested energy

     $$P_1^{(n+1)} = max\left(\frac{\bar{E} - tr(\mathbf{H}_{12}\mathbf{Q}_2^{(n)}\mathbf{H}_{12}^H)}{\kappa}, 0\right)$$

     If < 0, P_1=0, i.e. rank($\mathbf{Q}_1$)=0

     P_1 is reduced to lower the interference to ID receiver

     Parameter than depends on beamforming strategy (MEB, MLB)

     Then, $P_1^{(n+1)} = min(P, P_1^{(n+1)})$ and update $E_{11}^{(n+1)}$ and $\mathbf{R}_{-2}^{(n+1)}$ with $P_1^{(n+1)}$.
  3. The boundary point on the achievable R-E region is given as

$$(R, E) = (\log\det(\mathbf{I}_M + \tilde{\mathbf{H}}_{22}\mathbf{Q}_2^{(N_{max}+1)}\tilde{\mathbf{H}}_{22}^H),\ E_{11}^{(N_{max}+1)} + tr(\mathbf{H}_{12}\mathbf{Q}_2^{(N_{max}+1)}\mathbf{H}_{12}^H)).$$

Energy-Regularized SLER-Maximizing Beamforming

- Signal-to-Leakage-and-Noise-Ratio (SLNR): maximization of the ratio of the desired signal power to leakage of the desired signal on other users plus noise
- Signal-to-Leakage-and-harvested Energy Ratio (SLER):

$$SLER = \frac{\|\mathbf{H}_{11}\mathbf{v}\|^2}{\|\mathbf{H}_{21}\mathbf{v}\|^2 + max(\bar{E} - P_1\|\mathbf{H}_{11}\|^2, 0)}$$

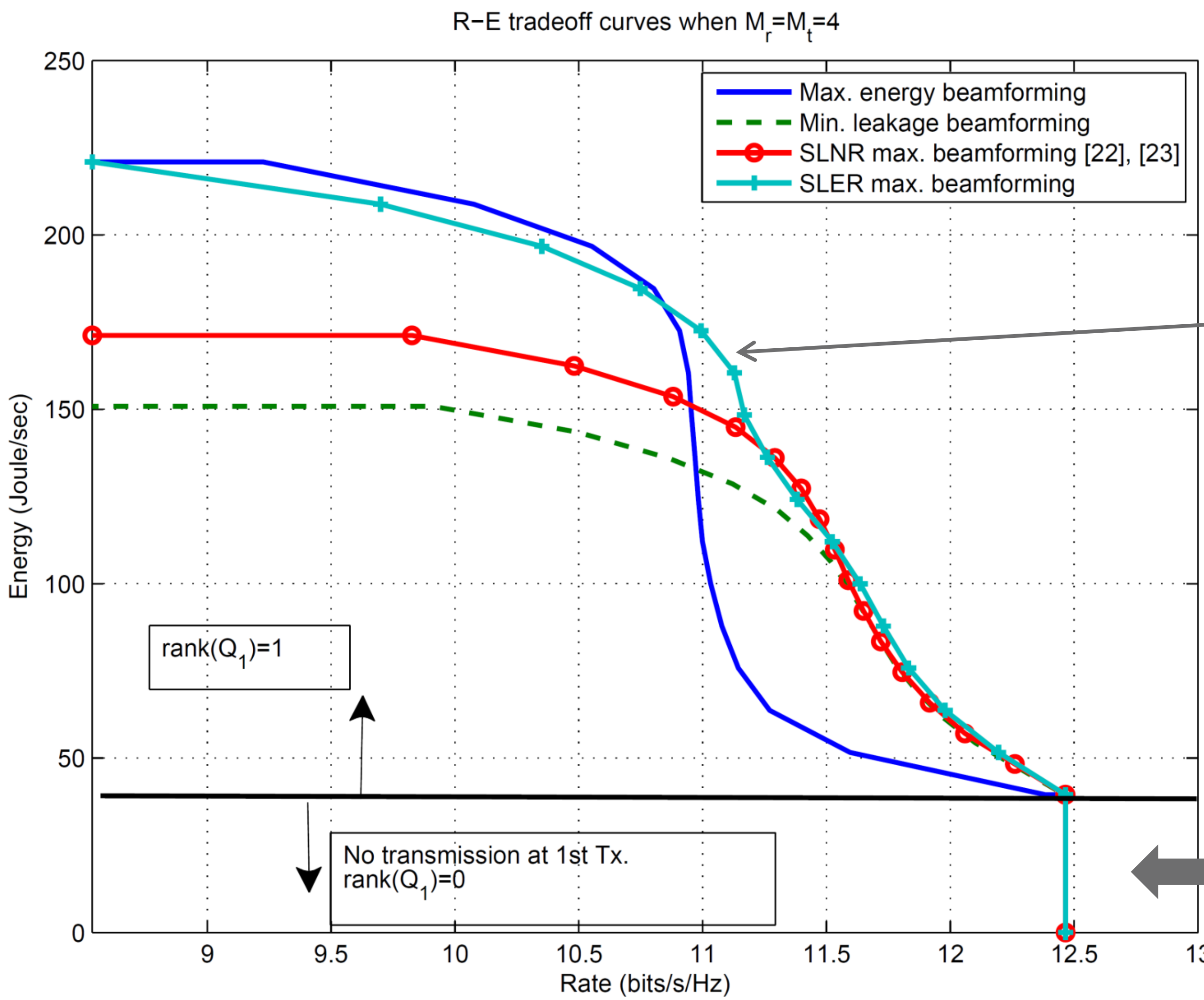
  - replace noise by the minimum required harvested energy
  - the required harvested energy minus the energy directly harvested from the first transmitter is the main performance barrier of the EH receiver
  - Softly evolves between MEB and MLB.
- Mode switching between (EH_1,ID_2) or (ID_1,EH_2):
  - higher SLER implies that the transmitter can transfer more energy to its associated EH receiver incurring less interference to the ID receiver
  - If $SLER_1 > SLER_2$, (EH_1,ID_2) is selected.

Massive MIMO Interference Channel

- When nodes have a large number of antennas, the transmit signal for energy transfer can be designed by caring about its own link (using MEB), not caring about the interference link to the ID receiver.

- massive MIMO effect makes the joint information and energy transfer in the MIMO IFC naturally split into disjoint information and energy transfer in two non-interfering links.

Evaluations (1/3)

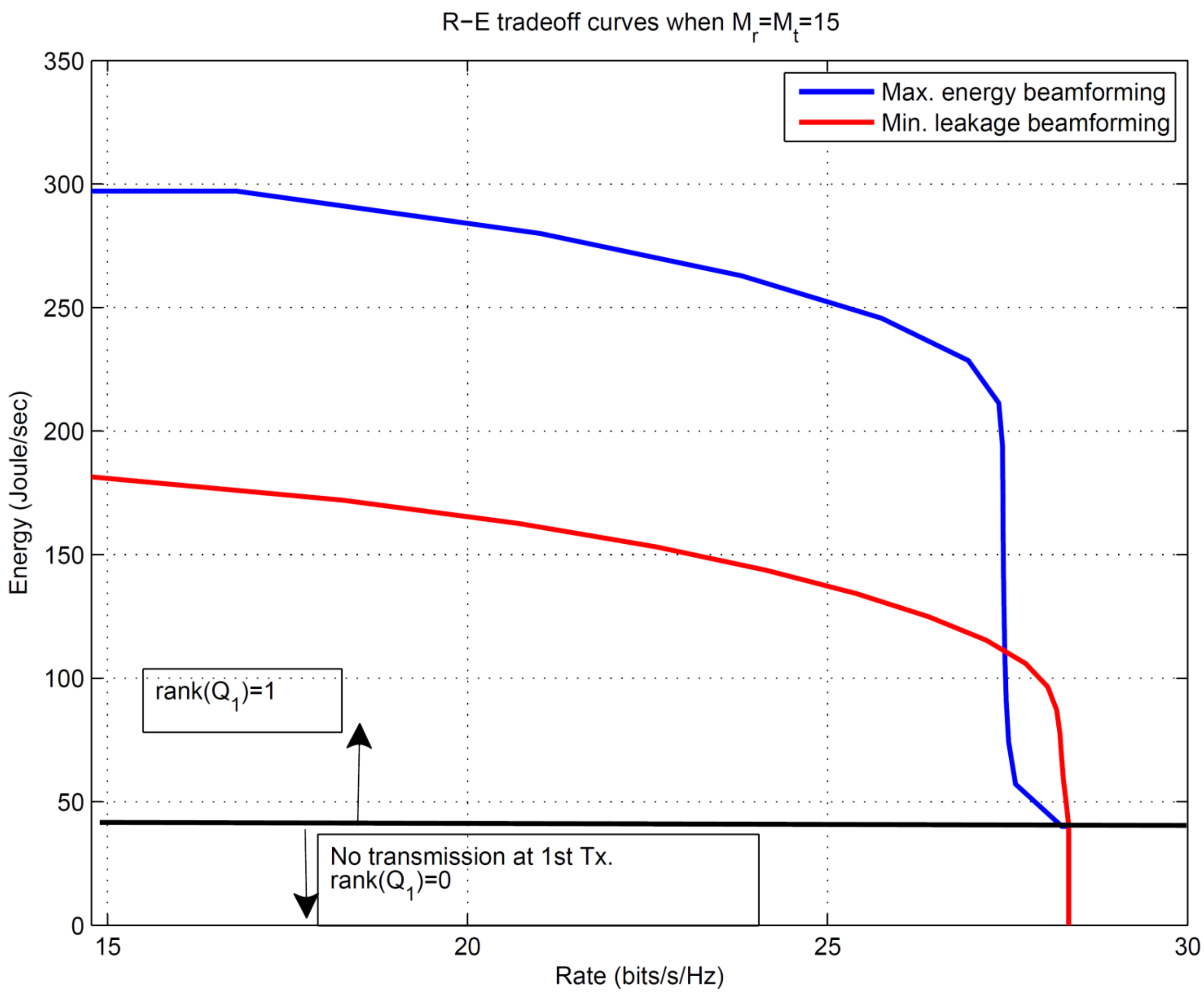


(EH_1, ID_2)

The R-E region of the proposed SLER maximizing beamforming covers most of those of both MEB and MLB

No need to turn on the 1st Tx.
Energy harvested from interference is sufficient.
No interference to the ID receiver.

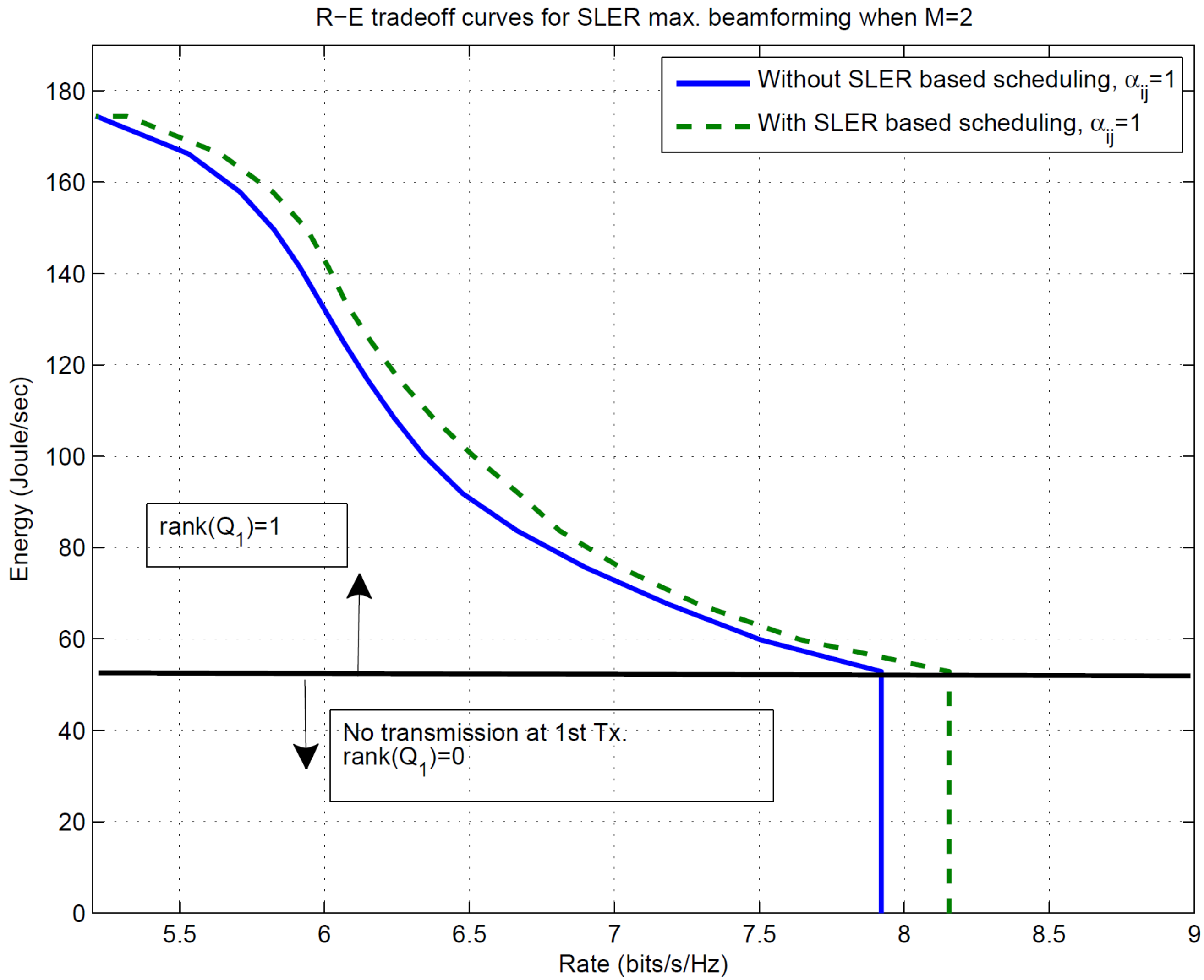
Evaluations (2/3)

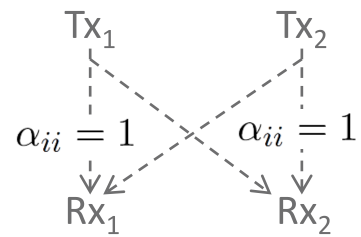


As MIMO gets massive,

- the gap between the achievable rates of MEB and MLB is less apparent
- MEB exhibits wider R-E region

Evaluations (3/3)





SLER-based scheduling, i.e. switching between (EH_1,ID_2) and (ID_1,EH_2), extends the achievable R-E region

Note: shape of rate region function of path loss α_{ij}

Conclusions

- Joint wireless information and energy transfer in a two-user MIMO IC
- 4 different operation modes:
  - (ID_1, ID_2): iterative water-filling
  - (EH_1, EH_2): energy-maximizing beamforming
  - (EH_1, ID_2) and (ID_1, EH_2):
    - necessary condition for optimality: one of the transmitters should take a rank-one beamforming (combined with power control)
    - Achievable R-E tradeoff region for MEB and MLB
    - MEB (MLB) exhibits larger harvested energy (achievable rate)
    - when the SNR decreases or the number of antennas increases, the joint information and energy transfer in the MIMO IC can be naturally split into disjoint information and energy transfer in two non-interfering links.
    - new transmission strategy satisfying the necessary condition - signal-to-leakage-and-energy ratio (SLER) - shows wider R-E region, i.e. effectively exploits the interference to harvest energy without compromising ID performance.
    - Optimal R-E boundary still unknown

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Propagation and techniques for Single-user, Multi-user, Multi-cell, Massive, Network, Cooperative, Coordinated MIMO

MIMO LTE/LTE-A, WiMAX

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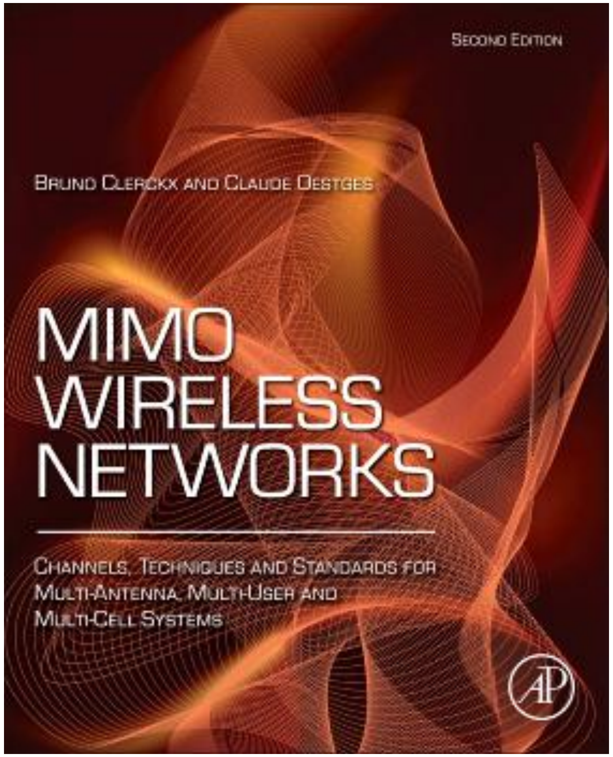

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