one6G work item on next generation MIMO: **Multiuser strategies for user-centric cell free MIMO**

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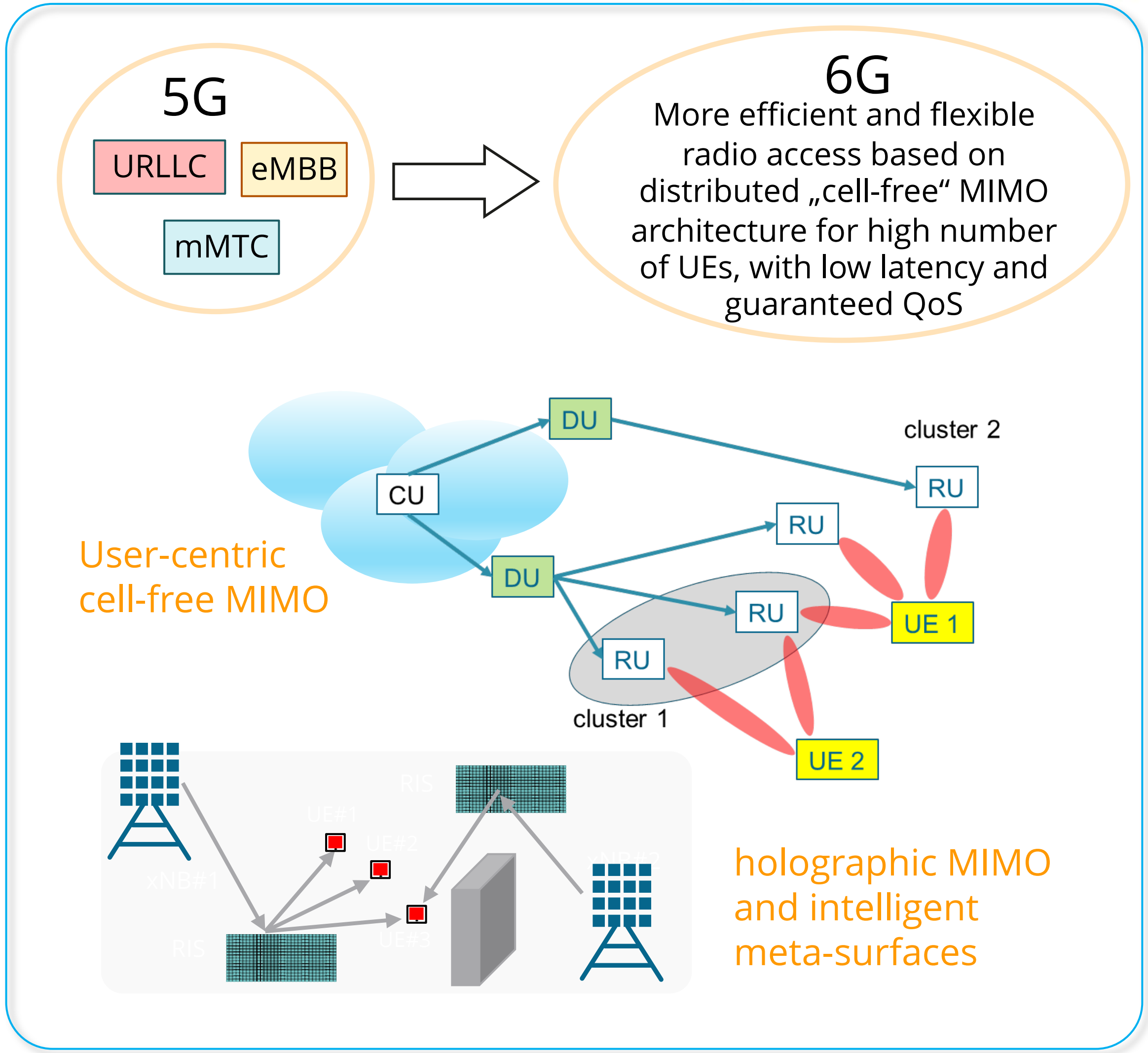
ONE6G WORK ITEM “NEXT GENERATION MIMO”

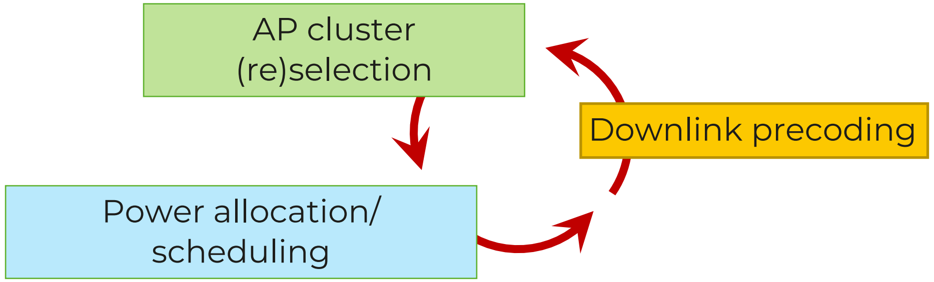
- MIMO is a cornerstone technology for 6G and beyond [1]. Our WI aims to gain a better understanding of some **new, emerging MIMO technologies**
  - Holographic MIMO and intelligent meta-surfaces, ISAC, AI/ML, …
  - New architecture: User-centric cell-free mMIMO, aka (distributed) D-MIMO
- Also, we take a **fresh look at some old MIMO results**
  - New types of resource constraints (fronthaul, computing, etc)
  - Coherent joint transmission under realistic time/frequency synchronization, possibly IP-based
  - Need for flexible UE-RU association (clustering), dynamically route fronthaul traffic, resource allocation
  - Towards distributed, flexible, and efficient multiple access based on MIMO networks



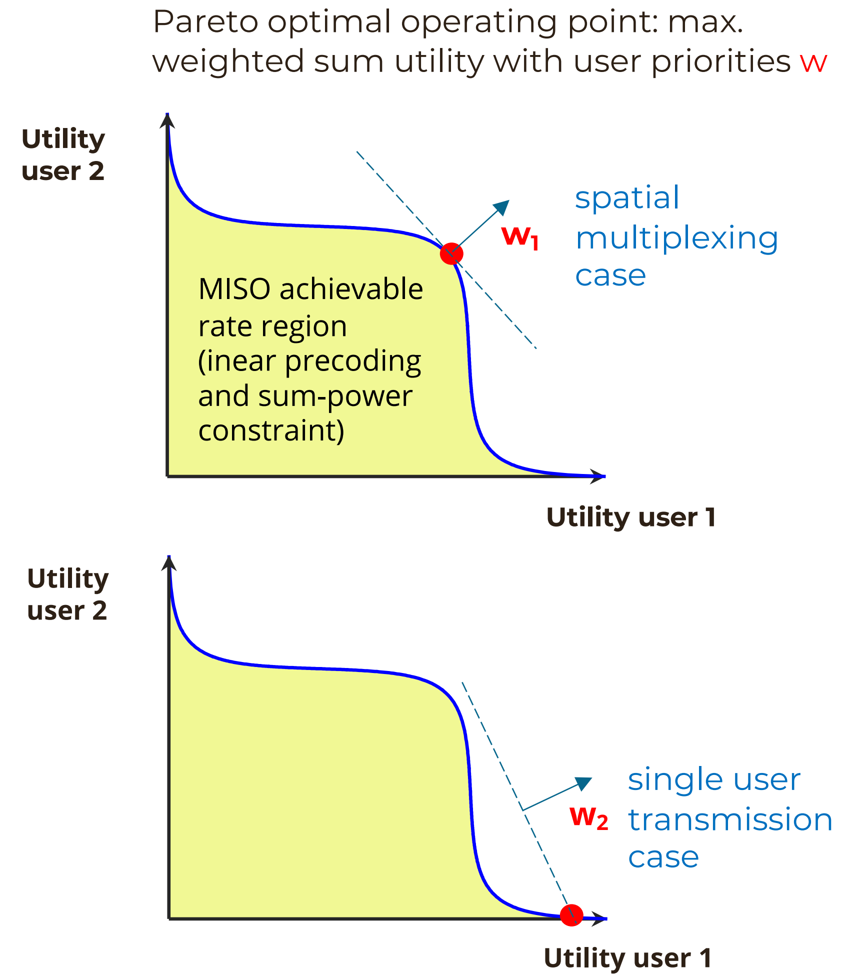
[1] Orange „Mobile Network Technology Evolutions Beyond 2030“, White Paper, April 2024

Multiuser transmission over coupled MIMO channels

- User utilities are coupled by mutual interference and limited resources → multi-objective optimization over achievable region
- Find a suitable operating point for K coupled utility functions (e.g. data rates)
  - We can focus on linear MIMO processing, which is nearly optimal for systems with many antennas and scheduling
  - What is the optimal transmission strategy for the cell-free DL?



  - Only partial solutions to this problem are known



THE IMPORTANCE OF MIMO SCHEDULING

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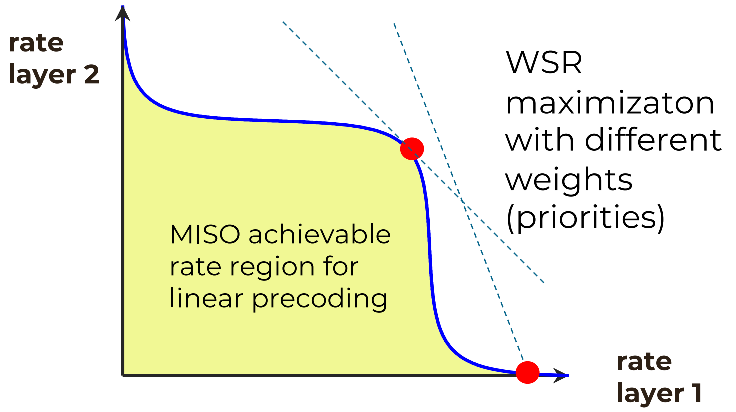
- **Scheduling**: how to select, precode, and distribute data streams over users/MIMO layers, sub-bands, time slots, and RU-clusters?
  - Infrastructure is costly, and in the future we will possibly have more active UEs/layers than antennas (→ the common assumption M>>K may not apply), but only a few of them are scheduled at any given time
  - Wireless channel is time/frequency/space selective, thus need to sort out the "bad apples" for every realization of the block fading channel
- **Proportional fairness:** solve a weighted sum rate (WSR) optimization problem for every channel realization [1, 2].
  - maximize $\sum_k w_k$ rate$_k$(CSI) over all data streams *k (users or MIMO layers)*
  - The weights w_k depend on the past data rates (moving average window)
  - CSI can be obtained, e.g., by uplink channel sounding, exploiting UL/DL reciprocity

Some special cases:
- Single Tx antenna [3] / low SNR:
  - only serve the strongest layer at any given time
- High SNR / orthogonal channels
  - spatial multiplexing/SDMA

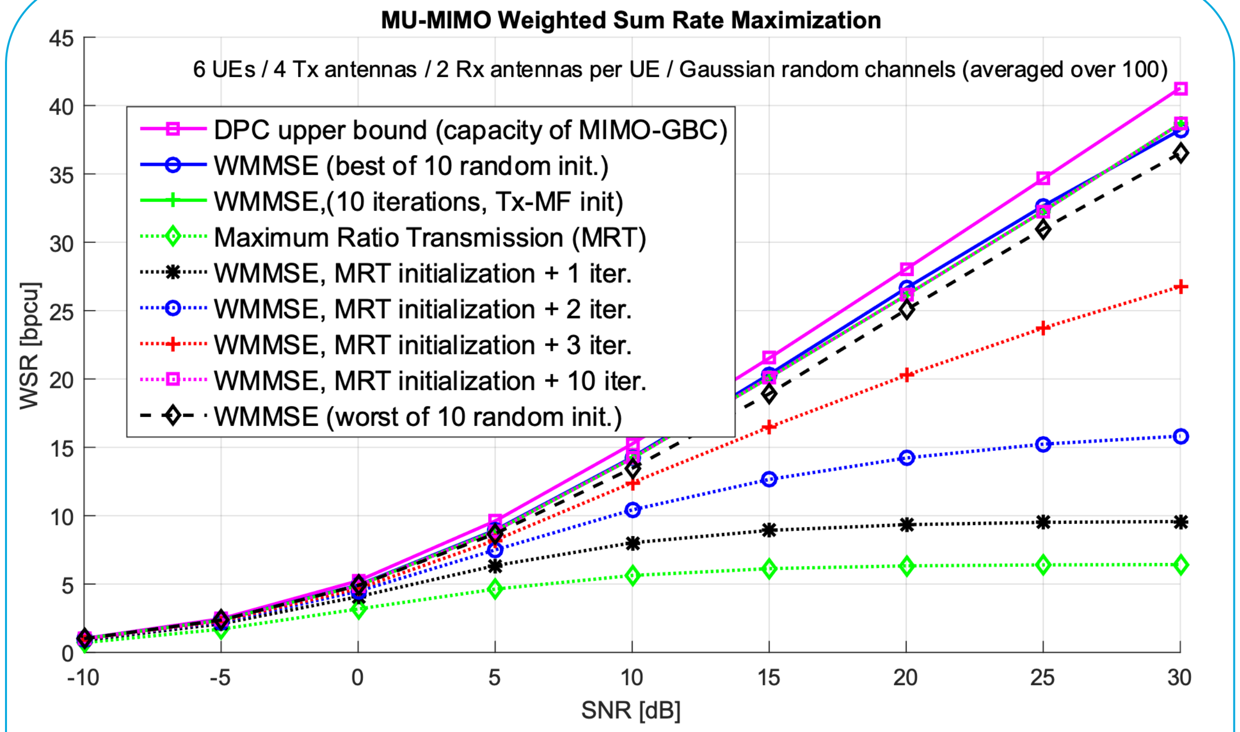
How to deal with the medium SNR regime and semi-orthogonal channels? In this case, the rate region with linear precoding is non-convex.

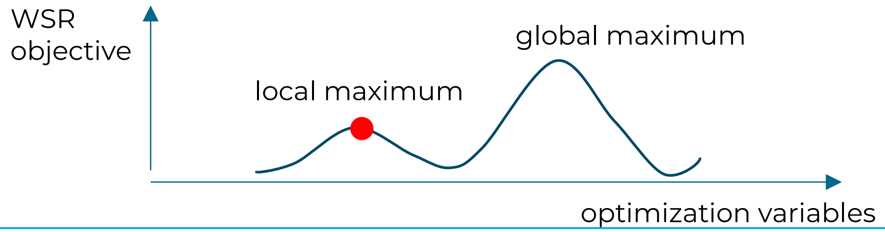


[1] P. Viswanath, D. N. C. Tse, and R. Laroia, "Opportunistic Beamforming using Dumb Antennas," IEEE Trans. Info. Theory, vol. 48, June 2002
[2] Kushner , Whiting, „Convergence of Proportional-Fair Sharing Algorithms Under General Conditions", 2004
[3] Knopp, Raymond / Humblet, Pierre A., "Information capacity and power control in single-cell multiuser communications", 1995

ALGORITHMS FOR WSR

- The WSR problem is non-convex for linear MIMO systems, but efficient solutions exist
- Weighted (W)MMSE algor. [1, 2]: converges to a stationary point of the WSR-objective function
  - Iteratively update Tx and Rx filters
  - Performance depends on the initializaton
- Many other algorithms have been proposed, e.g. based on greedy strategies with partial orthogonalizations [3]
- Extensively researched topic. But do the conclusions still hold under new system constraints in a cell-free MIMO context?





[1] Christensen / Agarwal / De Carvalho / Cioffi, Weighted sum-rate maximization using weighted MMSE for MIMO-BC beamforming design, IEEE Trans. WC, 2008.
[2] Zhao / Lu / Shi / Luo, Rethinking WMMSE: Can Its Complexity Scale Linearly With the Number of BS Antennas?, IEEE Trans. Signal Proc. , Vol. 71, 2023.
[3] Guthy / Utschick / Hunger / Joham, Efficient Weighted Sum Rate Maximization With Linear Precoding IEEE Trans. Signal Proc. , Vol. 58, No. 4, 2010

FLEXIBEL RU-UE ASSOCIATION (CLUSTERING)

- User-centricity: each UE is served flexibly by a cluster of Radio Units (RU) [1]. The cluster selection has impact on
  - The multiuser interference (and thus precoding/scheduling)
  - The constumption of limited resources at each distributed RU (Tx power, fronthaul load, etc)

→ Optimize the cluster selection jointly with precoding and scheduling, subject to distributed resource constraints

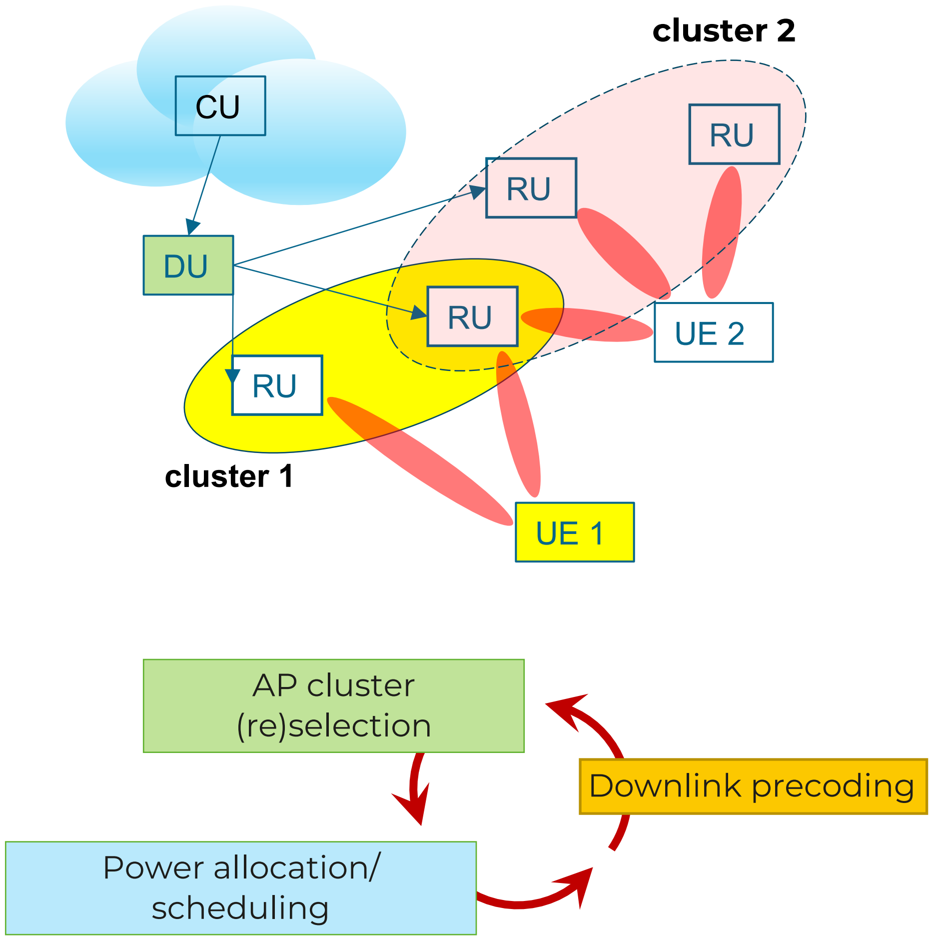
- The clustering variables in the DL are coupled

→ mixed-integer nonlinear optimization problems, where the discrete search increases exponentially with the number of UEs

→ intractable even for moderately sized systems

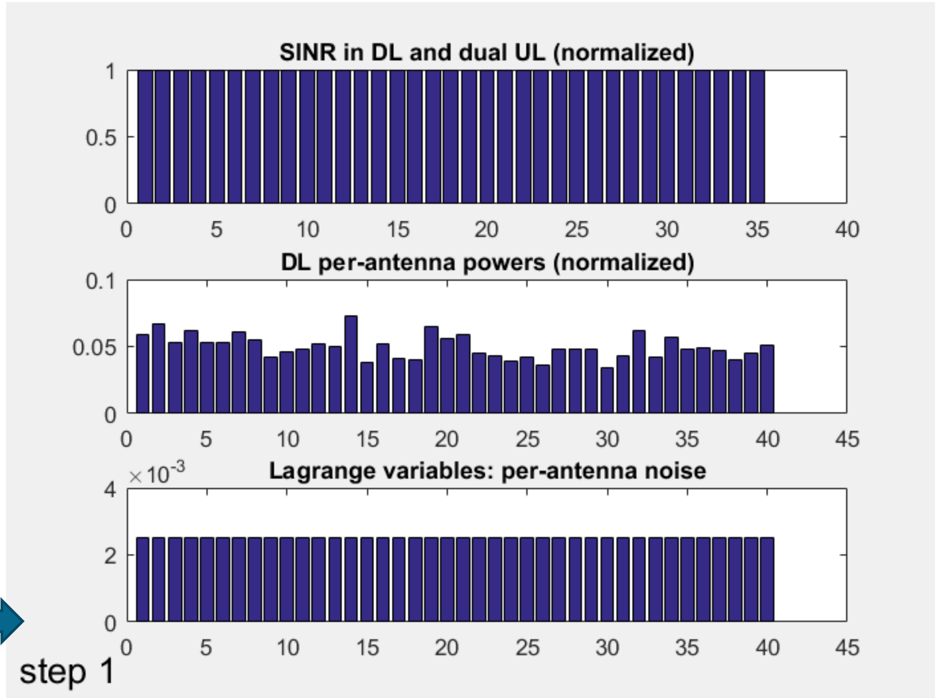
→ Exploit UL/DL duality: in the dual domain, the discrete search complexity scales linearly in the number of UEs [2]

[1] Prado-Alvarez, / Calabuig / Monserrat / Bazzi / Xu, Study of Clustering Solutions for Scalable Cell-Free Massive MIMO, 2023
[2] Schubert / Böhnke / Xu, "Duality-Based Joint Clustering and Precoding for Cell-Free Distributed MIMO," WSA 2024



Uplink/downlink Duality

- For many DL MU-MIMO problems it is easier to solve the Lagrangian dual problem instead. This has the advantage that optimization variables decouple, which enables more efficient algorithms. The dual problem has a similar structure as the uplink (transposed channel, reversed Tx and Rx)
- Conventional UL-DL duality [1, 2, 3] holds under a sum-power constraint:
  - Rate tuple **r** is achievable in the DL ⇔ **r** is achievable in the UL, and $\sum_k^K q_k = \sum_k^K p_k$ (same sum power)
  - The optimal DL precoders are scaled versions of the optimal UL combiners
- This was extended to a duality under per-antenna/TRP power constraints [4]
  - The noise powers of the dual channel are unknown variables
  - $\sum_{k=1}^K q_k = \sum_{m=1}^M n_m p_m$ (UL sum power = weighted DL per-antenna powers p_m)
  - Dual noise powers n_m can be found via projected sub-gradient [4]



[1] G. Caire / S. Shamai, “On achievable rates in a multi-antenna broadcast downlink,” Allerton Conf., 2000
[2] A. Goldsmith / S. A. Jafar / N. Jindal / S. Vishwanath, “Capacity Limits of MIMO Channels,” IEEE JSAC, 2003.
[3] H. Weingarten, Y. Steinberg and S. Shamai, "The capacity region of the Gaussian MIMO broadcast channel," ISIT 2004
[4] Yu, Wei / Lan, Tian, Transmitter Optimization for the Multi-Antenna Downlink with Per-Antenna Power Constraints, IEEE Trans SP, 2007

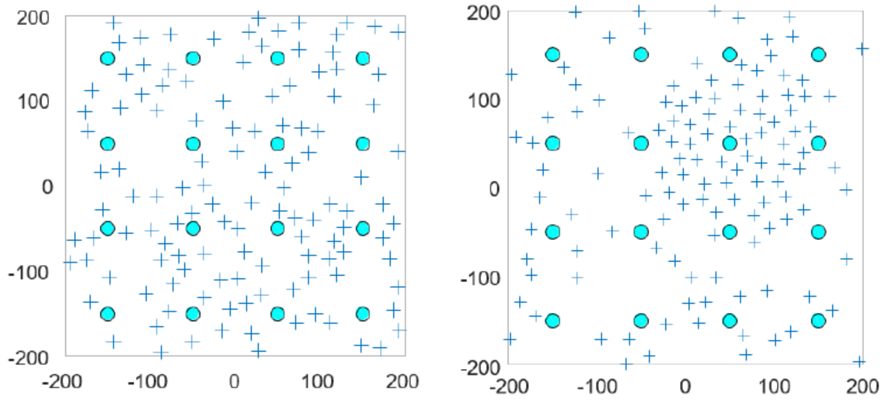
Simulation Scenario

- With the help of these duality results, we can jointly optimize precoders, clusters, and the power allocation in the dual domain [1]
  - → Cluster selection complexity scales linearly in the number of UEs
- We focus on the power minimization problem (MU-MISO) :

  Minimize the maximal antenna/TRP power subject to SINR constraints

  - Extension to the WSR problem is under preparation
- Some interesting questions:
  - What is the benefit of optimal clustering compared to heuristic selection based on the strongest coupling gains between TRP/UE pairs?
  - What is the loss compared to the case where per-antenna constraints are ignored and the optimization is based on the less restrictive assumption of a sum-power constraint?

[1] Schubert / Böhnke / Xu, "Duality-Based Joint Clustering and Precoding for Cell-Free Distributed MIMO," WSA 2024

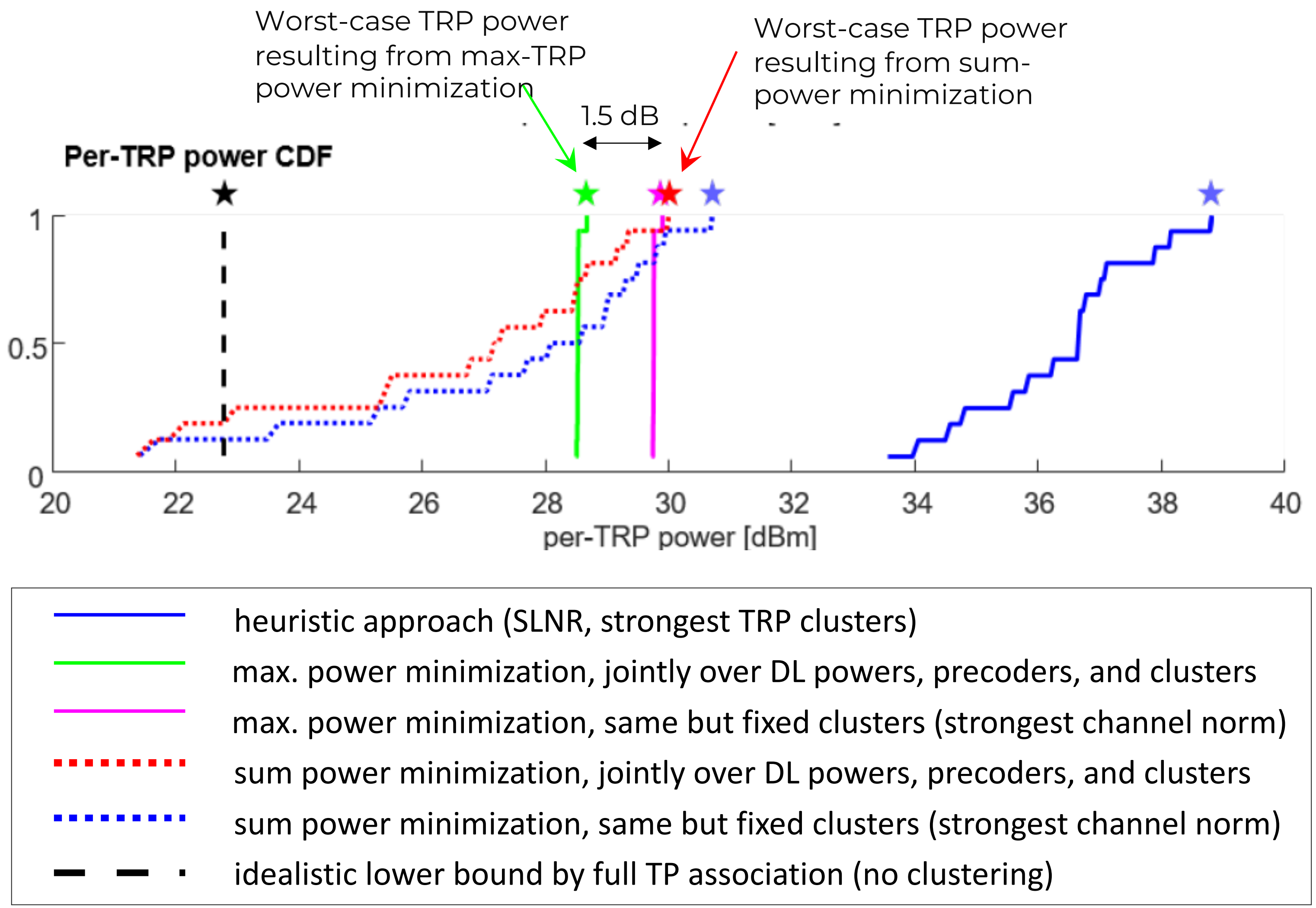


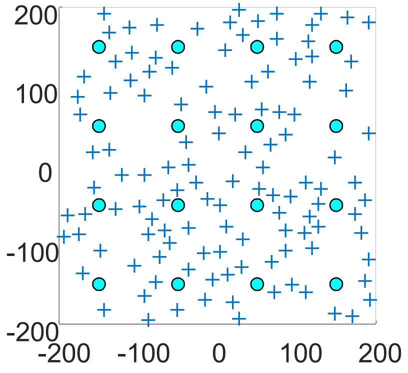
a) uniform distribution b) hotspot scenario

Direction	downlink
Bandwidth	100 MHz
Carrier freq.	10 GHz
MIMO channel	LoS steering vector, azimuth only
Antenna type	Uniform Circular Array (UCA)
Pathloss model (LOS+NLOS)	UMi Street Canyon [13]
ISD	100 m
Max. Tx power per TP	40 dBm
UEs per resource	120
Number of TPs	16
Antennas per TP	8
Antennas per UE	1
CSI	perfect
TP combining	coherent
clustering strategy	best 3 out of 4 strongest

Simulations: evenly distributed UEs

- Per-TRP optimization compared to sum-power minimization:
  - More even distribution of Tx powers over all TRPs
  - We can reduce the worst-case TRP power by ~1.5 dB
- Optimal scheduling compared to heuristic scheduling:
  - Connecting to the TRP(s) with largest channel norm is mostly optimal (~1.5 dB loss)





SIMULATIONS: HOTSPOT UE DISTRIBUTION

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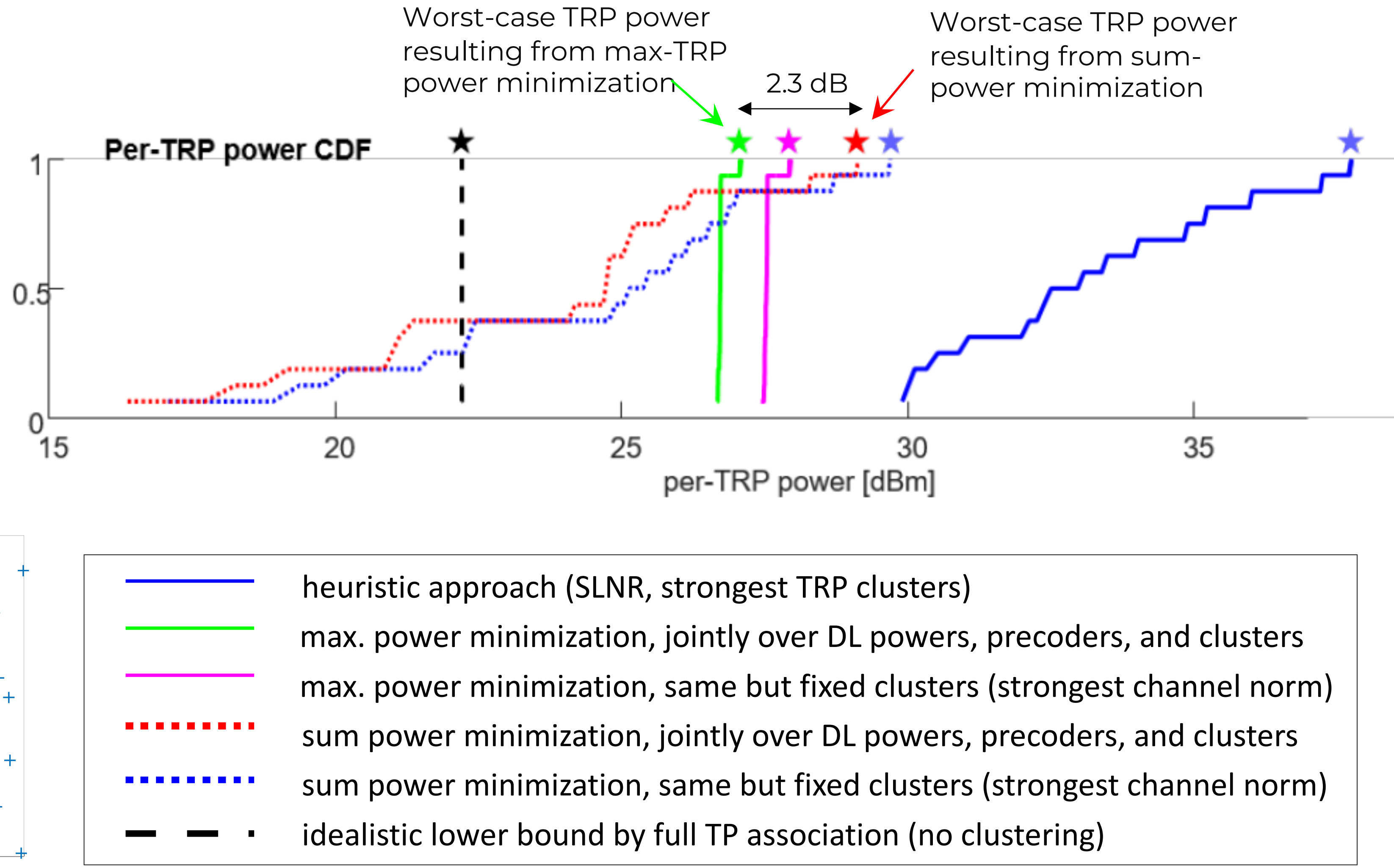
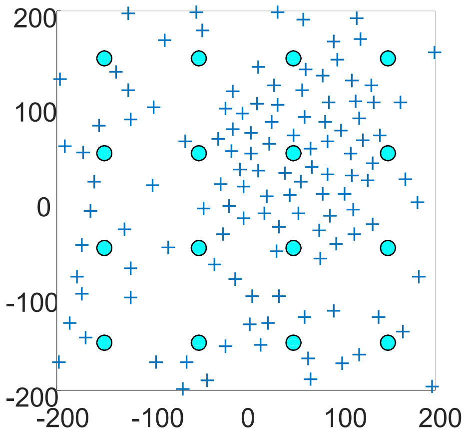
For a hotspot scenario, the gain of per-TRP optimization is a little more pronounced (~2.3 dB reduction of worst-case TRP power)

- Explanation: TRPs with excessive Tx power are avoided to a certain extent by re-allocating some UEs to neighboring TPs
- However, this strategy has its limits, as the increased path loss has a detrimental effect





Discussion

- The one6G work item „Next Generation MIMO“ aims to increase our understanding of the implementations of next-generation MIMO technologies.
  - Not limited to the topics discussed here. Other MIMO-related topics (RIS enhancement, ISAC, NTN) are being studied in the context of this WI
  - Open for new members
- The development towards new architectures and technologies means that old certainties may have to be reassessed. Remaining challenges include (just a few examples)
  - Clustering and per-TRP constraints require new optimization strategies and algorithms
  - More antennas, higher frequencies and bandwidths, multi-band, etc, create new challenges for hardware implementations (nonlinear power amplifiers, low-resolution ADC/DAC [1], hybrid beamforming with RIS, …)
  - CSI acquisition is a challenge for distributed MIMO. Transceiver designs under imperfect CSI are required, e.g. the team MMSE approach [2]
  - Next-generation distributed grant-free access, e.g. unsourced random access [3]

[1] F. Askerbeyli, W. Xu and J. A. Nossek, "Sum Rate Maximization for Regularized Zero-Forcing Precoder in 1-Bit MIMO," 2023 IEEE 98th Vehicular Technology Conference (VTC2023-Fall)
[2] Miretti / Cavalcante / Björnson / Stańczak, UL-DL duality for cell-free massive MIMO with per-AP power and information constraints, 2023
[3] Çakmak / Gkiouzepi / Opper / Caire, “Joint Message Detection and Channel Estimation for Unsourced Random Access in Cell-Free User-Centric Wireless Networks”, arXiv:2304.12290, 2024

THANK YOU FOR YOUR ATTENTION

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