Optimization algorithms for physical layer in 5G and beyond wireless networks

Fabio Saggese

Dipartimento di Ingegneria dell'Informazione

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Università di Pisa

Outline

1. Resource allocation in presence of interference
   - Spectrum and power allocation for NOMA-FD systems
   - A quasi-optimal clustering algorithm for MIMO-NOMA downlink systems

2. Radio Access Network Slicing
   - Power Minimization of Downlink Spectrum Slicing for eMBB and URLLC

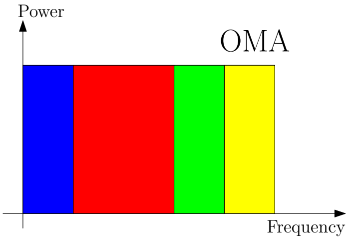
Resource allocation in presence of interference

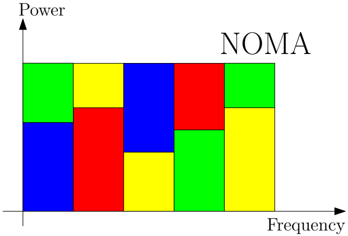
Pros

- higher degrees of freedom
- possibly better performance

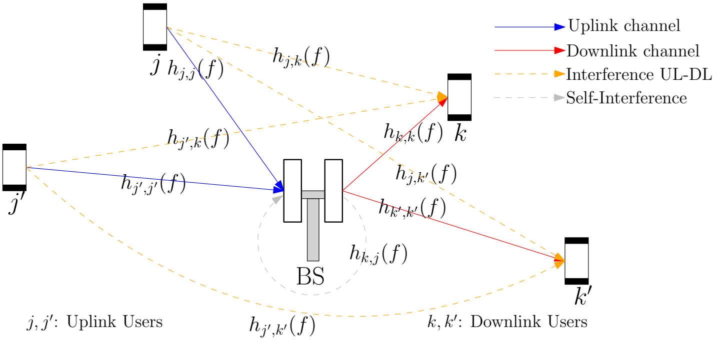
Cons

- Interference must be managed
- Increased receiver and signal processing complexity





NOMA-FD SYSTEM



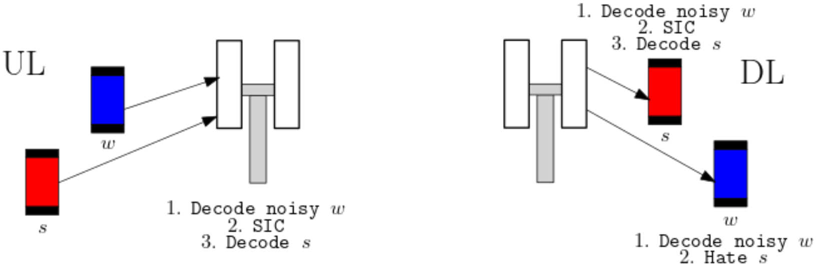
- *Full-Duplex* enables the simultaneous transmission and reception of different signals onto the same frequency band (needs specific hardware)
- *Power-domain NOMA* allocates more than one user of the same direction to the same resource (needs specific signal processing)

Full-Duplex

The BS has with hardware able to cancel most of the self-interference.

NOMA

Data signal associated to the *strong* user is decoded without interference from the *weak* data.



The weak transmission rate must be achievable on the strong receiver.

Optimization problem

$$\max_{\mathbf{P}\succeq 0, \boldsymbol{\rho}\in\mathcal{X}} u(\boldsymbol{\rho},\mathbf{P}) = \sum_{f\in\mathcal{F}}\sum_{i\in\mathcal{A}(f)} \left(\rho_{i,s}(f)+\rho_{i,w}(f)\right)\alpha_i r_i(f)$$

subject to

$$\sum_{f\in\mathcal{F}} \big(\rho_{i,s}(f)+\rho_{i,w}(f)\big) P_i(f) \le P_U, \quad \forall i \in \mathcal{U}$$

$$\sum_{f\in\mathcal{F}}\sum_{i\in\mathcal{D}} \big(\rho_{i,s}(f)+\rho_{i,w}(f)\big) P_i(f) \le P_D$$

$$\Upsilon_{k',k}(f) \ge 0, \begin{array}{r} \forall k', k \in \mathcal{D} \\ \forall f \in \mathcal{F} \end{array} \Big| \begin{array}{l} \rho_{k',w}(f) = \rho_{k,s}(f) = 1, \\ P_{k'}(f) > 0, P_k(f) > 0. \end{array}$$

Strategy

Split the problem into strong and weak allocations:

1. solve strong allocation keeping weak fixed
2. solve weak allocation keeping strong fixed
3. iterate...

Optimization problem

$$\max_{\mathbf{P}\succeq 0, \boldsymbol{\rho}\in\mathcal{X}} u(\boldsymbol{\rho}, \mathbf{P}) = \sum_{f\in\mathcal{F}} \sum_{i\in\mathcal{A}(f)} (\rho_{i,s}(f) + \rho_{i,w}(f)) \alpha_i r_i(f)$$

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$$\Upsilon_{k',k}(f) \geq 0, \begin{matrix} \forall k', k \in \mathcal{D} \\ \forall f \in \mathcal{F} \end{matrix} \Bigg| \begin{matrix} \rho_{k',w}(f) = \rho_{k,s}(f) = 1, \\ P_{k'}(f) > 0, P_k(f) > 0. \end{matrix}$$

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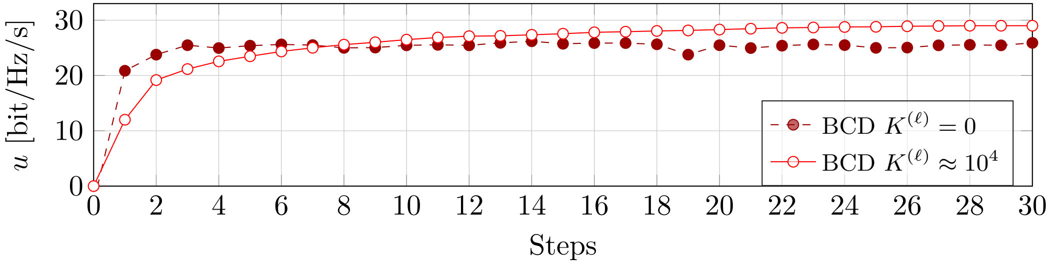
$$\begin{cases} \boldsymbol{\rho}_s^{(\ell)}, \mathbf{P}_s^{(\ell)} = \underset{\boldsymbol{\rho}\in\mathcal{X}_s^{(\ell)}, \mathbf{P}\succeq 0}{\arg\max} \left\{ u\left(\boldsymbol{\rho}, \mathbf{P}; \boldsymbol{\rho}_w^{(\ell-1)}, \mathbf{P}_w^{(\ell-1)}\right) - K^{(\ell)} ||\mathbf{P} - \mathbf{P}_s^{(\ell-1)}||^2 \right\}, \\ \boldsymbol{\rho}_w^{(\ell)}, \mathbf{P}_w^{(\ell)} = \underset{\boldsymbol{\rho}\in\mathcal{X}_w^{(\ell)}, \mathbf{P}\succeq 0}{\arg\max} \left\{ u\left(\boldsymbol{\rho}_s^{(\ell)}, \mathbf{P}_s^{(\ell)}; \boldsymbol{\rho}, \mathbf{P}\right) - K^{(\ell)} ||\mathbf{P} - \mathbf{P}_w^{(\ell-1)}||^2 \right\}, \\ \text{subject to power budget and SIC requirement} \end{cases}$$



BCD-low complexity (BLC)

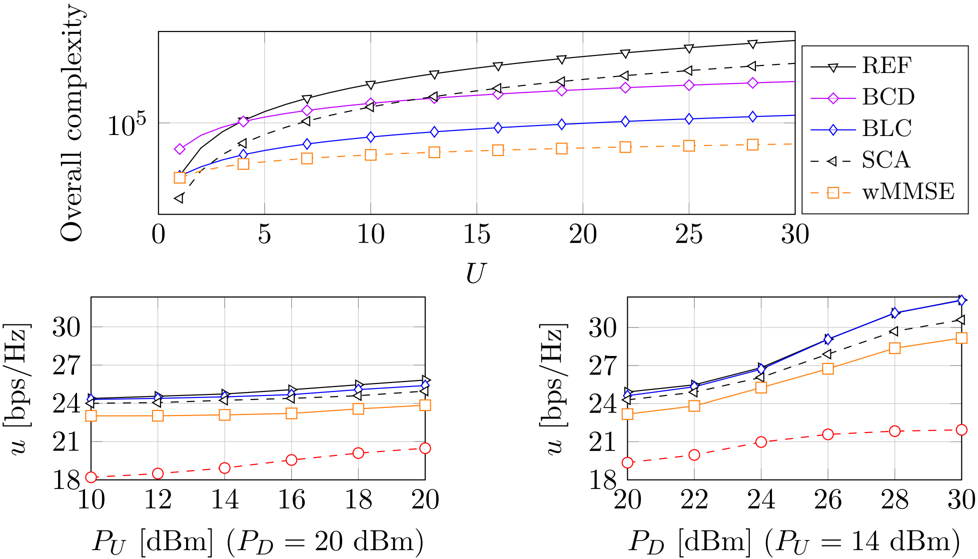
BCD complexity depends on the (unknown) number of iterations needed for convergence.

To speed up the convergence, we employ a heuristic strategy

1. Perform Strong allocation
2. Perform Weak allocation
3. Redistribute power in an optimal way $\max_{\mathbf{P}_U, \mathbf{P}_D} u(\boldsymbol{\rho}, \mathbf{P}_U, \mathbf{P}_D)$

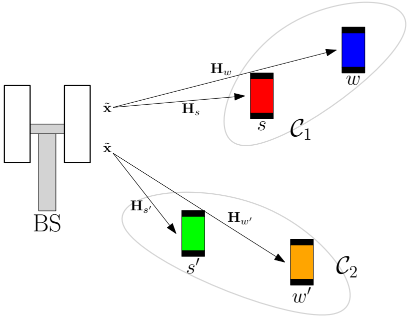
Decoupling for each frequency and for uplink and downlink can be beneficial

Numerical results



MIMO-NOMA SYSTEM

Exploit space and power domain at the same time may achieve even better results.



AIMING TO MINIMUM POWER

- MIMO to spatially divide the users
- NOMA is performed in each cluster

STRATEGY

1. BS precoder to nullify the inter-cluster interference
   → SVD of the stack channel matrix.
2. optimal beamformer and power to meet the rate constraints
   → SVD + waterfilling
3. $\mathcal{C}$: Minimum power clusterization selection
   → bi-partite matching MILP problem

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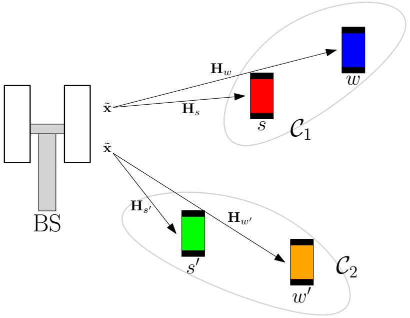

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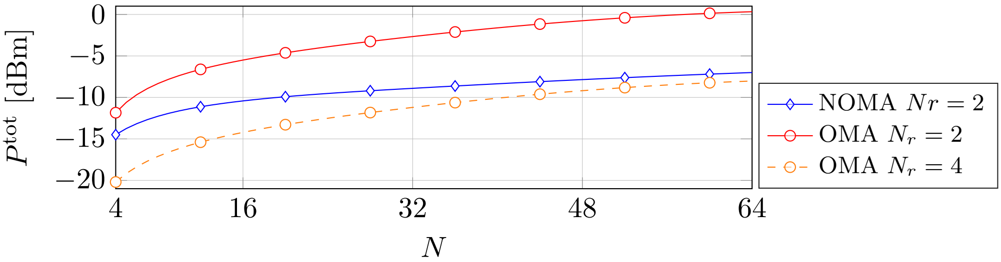
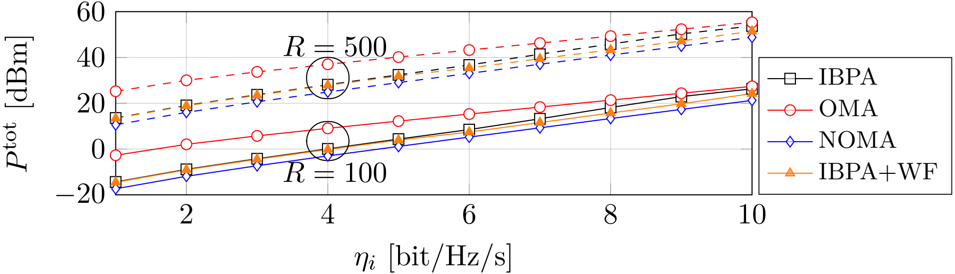




Summary

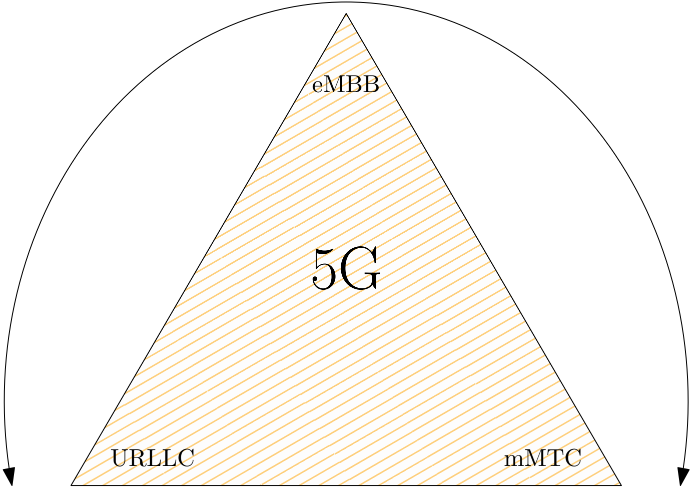
- High interference translates into high non-convex problem
- we decompose it into simpler sub-problems
- proposed methods reach outstanding performance with reduced computational complexity
- NOMA might outperforms OMA

Related publications

- A. Abrardo, M. Moretti and **F. Saggese**, "Power and Subcarrier Allocation in 5G NOMA-FD Systems," in IEEE Transactions on Wireless Communications, vol. 19, no. 12, pp. 8246-8260, Dec. 2020, doi: 10.1109/TWC.2020.3021036.
- A. Abrardo, M. Moretti and **F. Saggese**, "WMMSE resource allocation for FD-NOMA," in IEEE Communications Letters, 2022, doi: 10.1109/LCOMM.2022.3197701.
- **F. Saggese**, M. Moretti and A. Abrardo, "A Quasi-Optimal Clustering Algorithm for MIMO-NOMA Downlink Systems," in IEEE Wireless Communications Letters, vol. 9, no. 2, pp. 152-156, Feb. 2020, doi: 10.1109/LWC.2019.2946548.

Radio Access Network Slicing

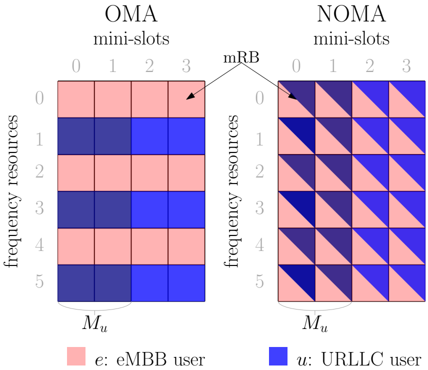
Heterogeneous services



Spectrum slicing

Network slicing:
partitioning the physical network infrastructure in different end-to-end isolated virtual networks, i.e. *slices*, each one able to support a different service requirement for different use cases

Spectrum slicing:
how to utilize a given chunk of spectrum to serve users with heterogeneous requirements



eMBB

- allocated on a time slot basis
- spectral efficiency $\geq \eta_e$ [bps/Hz]
- knowledge of the CSI available

URLLC

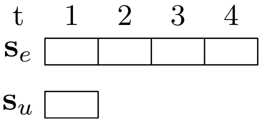
- allocated on a mini-slot basis
- packets having rate $\eta_u \ll \eta_e$ [bps/Hz]
- outage probability $\leq \epsilon_u$
- max latency is $M^{\max}$ mini-slot (wlog)
- knowledge of statistical CSI only (Γ_u)

NOMA: TRANSMITTED SIGNAL AND SIC CONSIDERATIONS

The BS transmits both eMBB and URLLC data streams using superposition coding:

$$\mathbf{x}(t,f) = \sqrt{P_e(t,f)}\mathbf{s}_e(t,f) + \sqrt{P_u(t,f)}\mathbf{s}_u(t,f)$$

- NOMA rely on SIC
- but URLLC cannot wait for an entire e codeword
- hence, **SIC is employed by the eMBB user only**



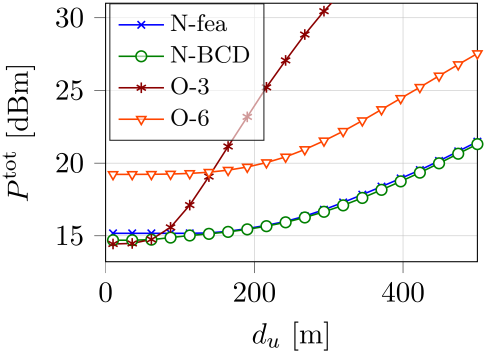
Minimum power scheduling

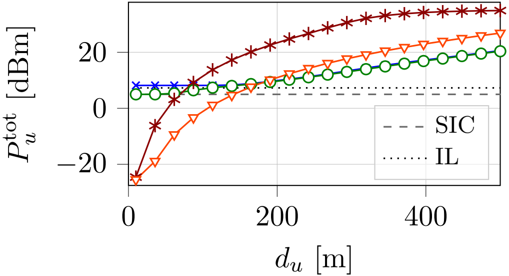
$$\min_{\substack{\mathbf{P}_e \succeq 0 \\ \mathbf{P}_u \succeq 0}} P^{\text{tot}} \begin{cases} p_e = 0, & \text{(eMBB outage)} \\ p_{u,e} = 0, & \text{(SIC failure)} \\ p_u \leq \epsilon_u, & \text{(URLLC outage)} \end{cases} \Lleftarrow$$

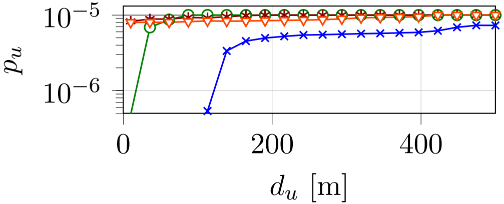
- not convex
- URLLC outage has no closed form

Strategy

1. using the eMBB CSI to find eMBB and SIC power requirements
   → `waterfilling` × `2`
2. find URLLC power through look-up table solution
   → `Monte Carlo + BCD (optional)`







d_e [m]	NOMA	O-3	O-6	O-9
464.56	33.21	34.18	38.89	58.27
261.2	23.36	24.32	29.09	48.54
146.9	14.21	14.44	19.23	38.74
82.6	5.84	5.84	9.05	28.44
46.5	-1.87	-1.87	-0.64	18.79
26.1	-9.67	-9.67	-9.67	8.65

eMBB power spent [dBm]

Summary

- The problem is complex even in a simple setting, and finding a feasible allocation strategy is difficult
- We provide a practical solution for the minimum power coefficients
- NOMA can play a fundamental role in multiplexing heterogeneous users

Related publications

- **F. Saggese**, M. Moretti and P. Popovski, "NOMA Power Minimization of Downlink Spectrum Slicing for eMBB and URLLC Users," 2022 IEEE Wireless Communications and Networking Conference (WCNC), 2022, pp. 1725-1730
- **F. Saggese**, M. Moretti and P. Popovski, "Power Minimization of Downlink Spectrum Slicing for eMBB and URLLC Users," in IEEE Transactions on Wireless Communications, 2022
- **F. Saggese**, L. Pasqualini, M. Moretti and A. Abrardo, "Deep Reinforcement Learning for URLLC data management on top of scheduled eMBB traffic," 2021 IEEE Global Communications Conference (GLOBECOM), 2021, pp. 1-6

Open questions?

- Is spectral efficiency a good way of optimizing NOMA systems? [1]
- How much is the overhead for informing the downlink strong user to act accordingly?
- How to use the analytical findings to multiplex multiple users?
- What about the model of the incoming URLLC traffic?
- How to train a DRL agent for multi-carrier reliable transmission?
- How to tackle the trade-off between eMBB and URLLC requirements? [2]

[1] Wang et al. "A Minimum Error Probability NOMA Design". 2021.

[2] Tian et al. "Successive Convex Approximation Based Off-Policy Optimization for Constrained Reinforcement Learning". 2022.

Thank you for the attention.

About Me

Fabio Saggese, fasa@es.aau.dk
PhD in Information Engineering, University of Pisa
Research Assistant, Electronic System Department, Aalborg University