From Skopje to Ilmenau, from Linear to Multilinear Signal Processing

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Outline

- Origins
- Master in Communications and Signal Processing
- Tensor Algebra
- Application to Biomedical Signal Processing
- Application to Wireless Communication Systems

Origins

- Born in **Skopje, Macedonia**
  - ⇒ At that time was actually Yugoslavia
  - ⇒ In 1991 Macedonia declared independence.

[W] Wikipadia, Republic of Macedonia, https://en.wikipedia.org/wiki/Republic_of_Macedonia

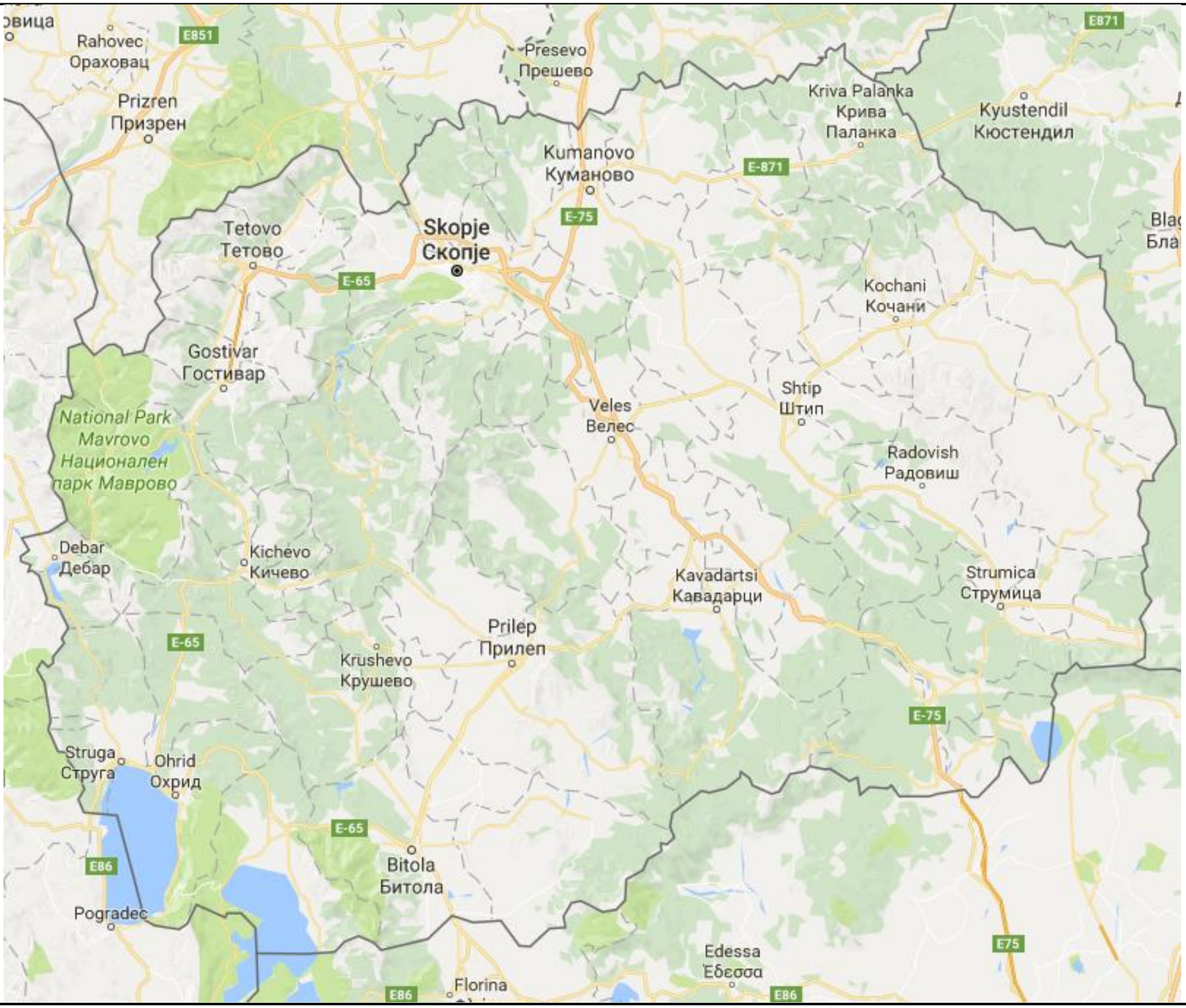
Macedonia

- Capital – **Skopje**
- Official Language – **Macedonian**
  - ⇒ Alphabet – Cyrillic
- Population – 2 Million
  - ⇒ Many ethnic groups, Albanians, Turks, Romani, Serbs, etc.

- Politic Situation – Very Complicated (almost impossible to keep track of)
- Macedonia is
  - ⇒ small, beautiful, with a lot of history, different cultures, friendly people and has delicious food.

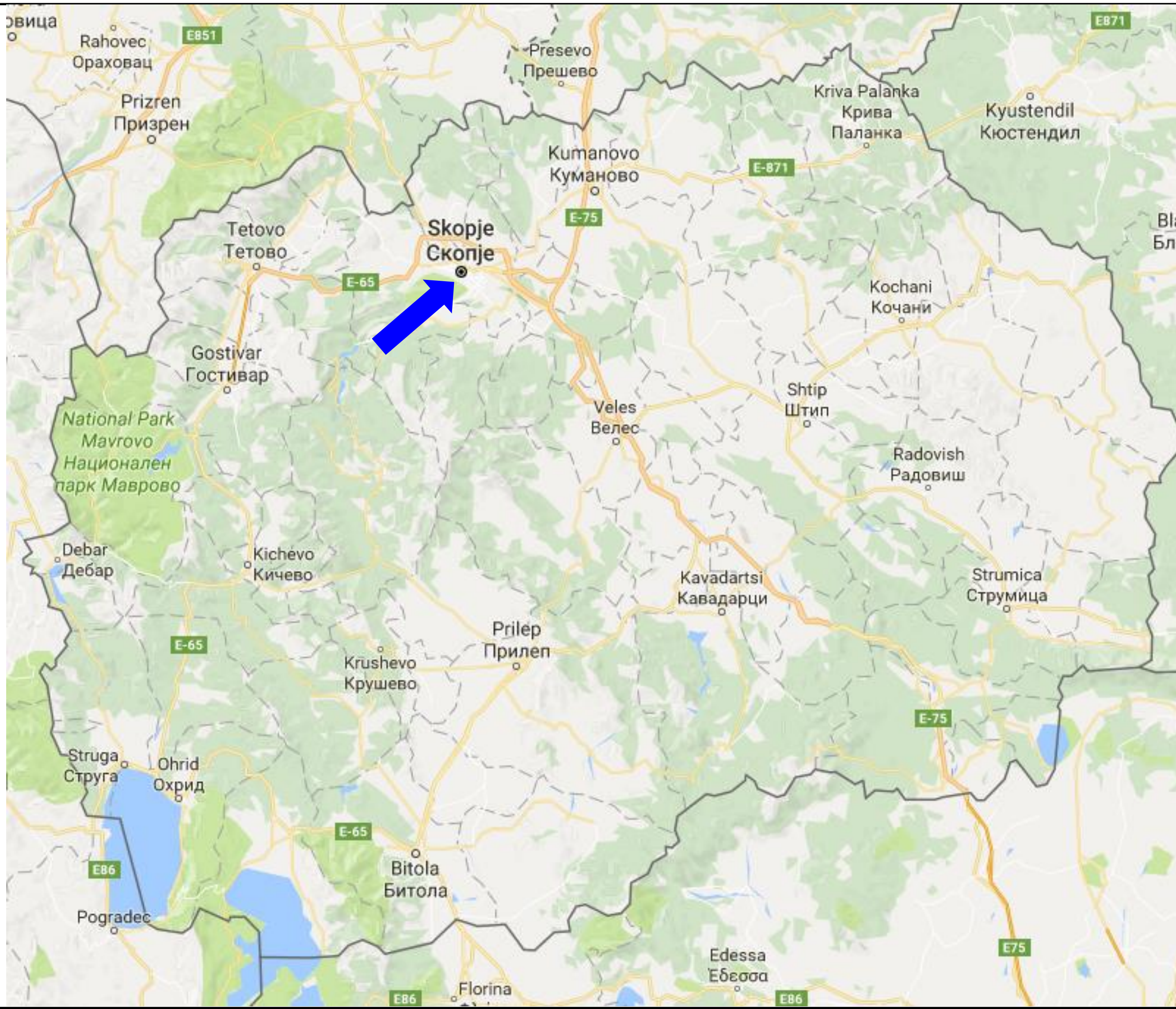
[W] Wikipadia, Republic of Macedonia, https://en.wikipedia.org/wiki/Republic_of_Macedonia

Around Macedonia



[GM] Google Maps, Republic of Macedonia, https://www.google.de/maps/@41.5777291,21.5884824,8.75z

Around Macedonia



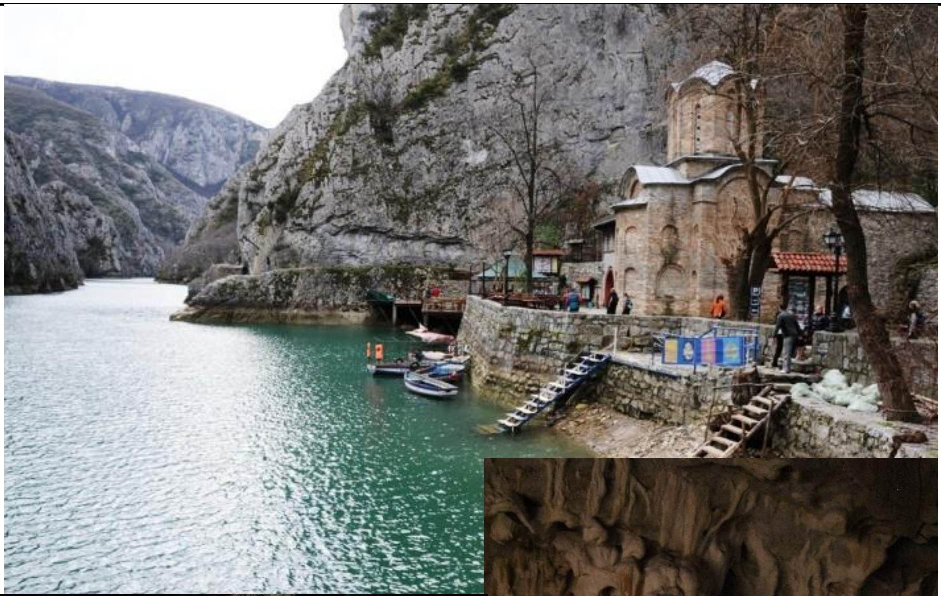
[GM] Google Maps, Republic of Macedonia, https://www.google.de/maps/@41.5777291,21.5884824,8.75z

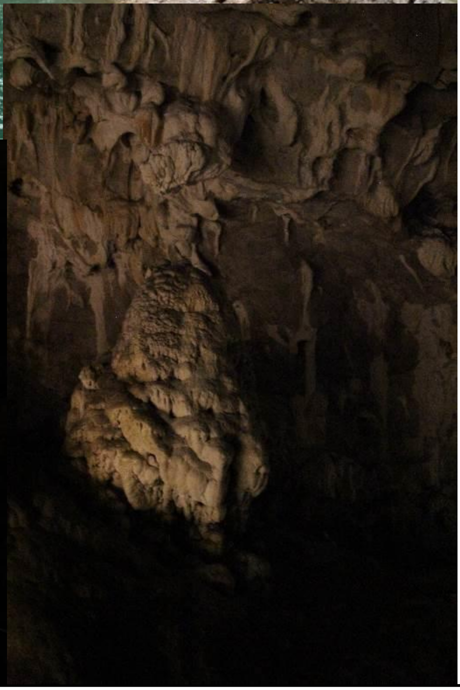
Skopje


HERE WAS THE HOUSE WHERE ON 26-08-1910 WAS BORN GONDZA BOJADZIU MOTHER THEREZA
ГОНЏА БОЈАЏИУ
МАЈКА ТЕРЕЗА

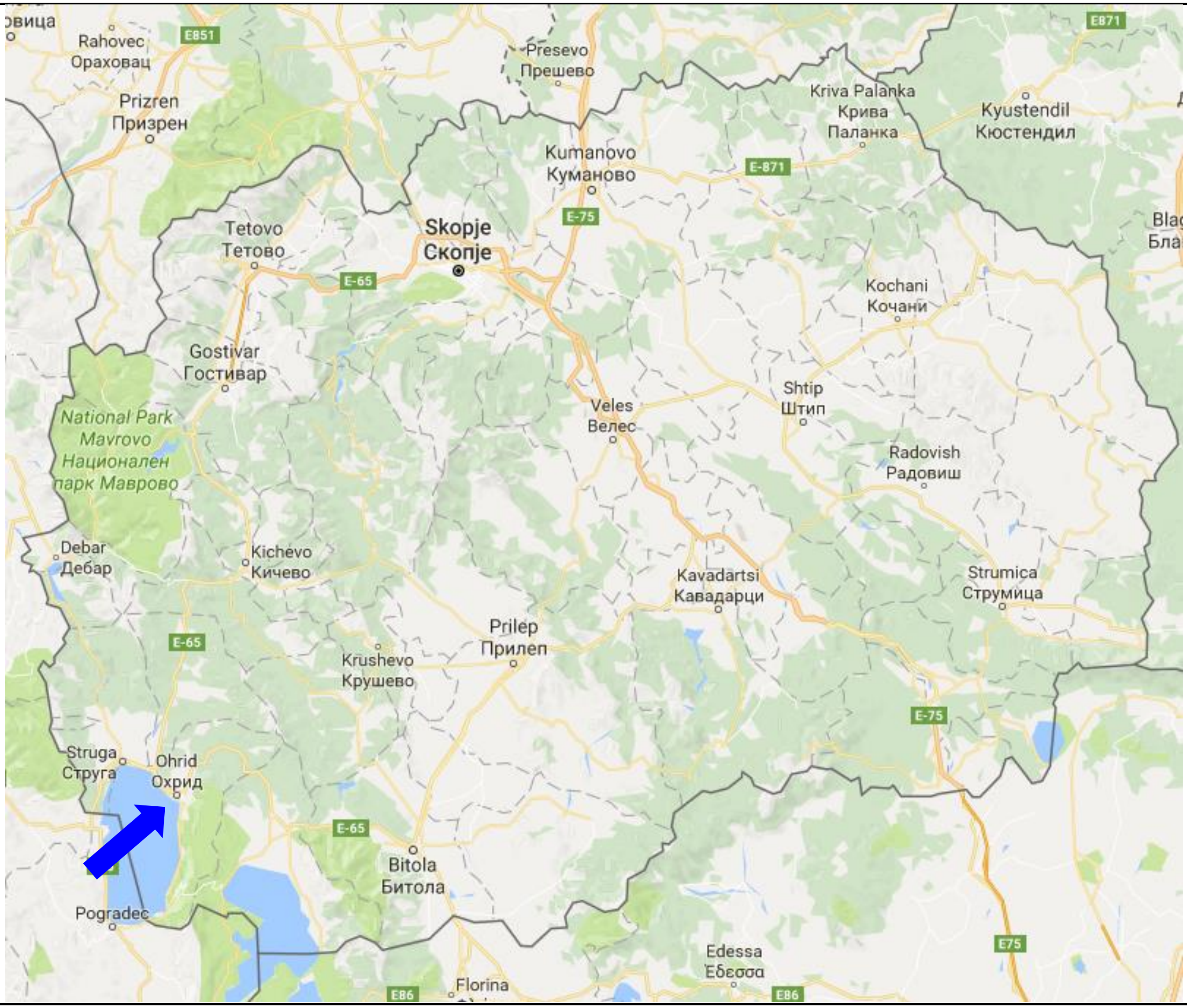
Canyon Matka

- Along the river Treska
- Vrelo Cave
  - ⇒ There are two lakes in the cave
  - ⇒ The exact depth of the cave is unknown. In could be the deepest underwater cave in the world. An international diving team has reached 205 meters.
  - ⇒ Many Stalactites



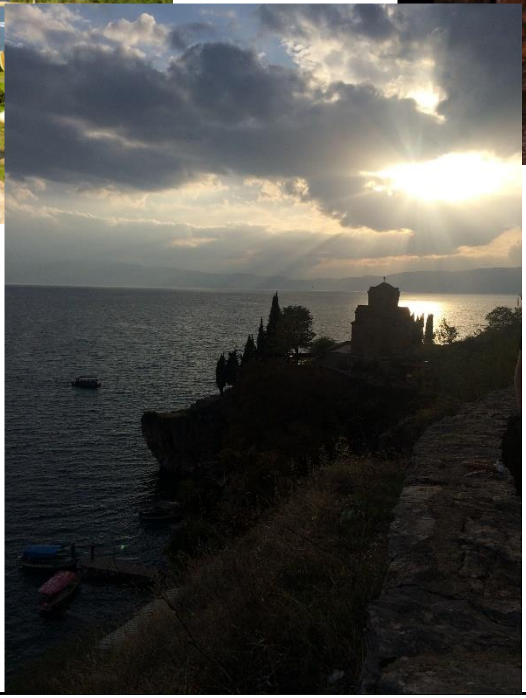


Around Macedonia



[GM] Google Maps, Republic of Macedonia, https://www.google.de/maps/@41.5777291,21.5884824,8.75z

Ohrid



Macedonian Food

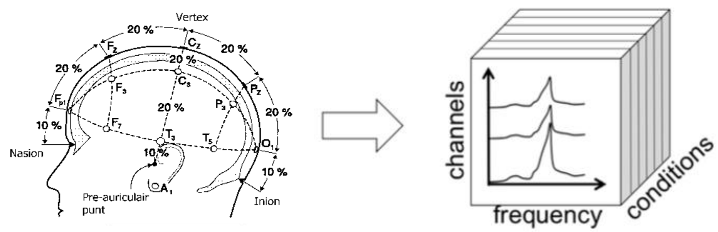
Masters in Communications and Signal Processing

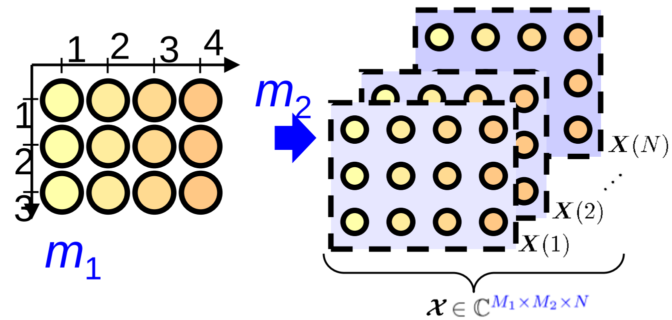
- Bachelor’s degree from Ss. Cyril and Methodius University in Skopje, Faculty of Electrical Engineering and Information Technologies.
  - ⇒ study program: Telecommunications.

- October, 2011 joint Master of Science in Communication and Signal Processing at Ilmenau University of Technology, Germany.
- DAAD scholarship holder.
- Master Thesis: “Multi-linear Algebra and its Application in Wireless Communication and Signal Processing”.
  - ⇒ channel estimation for two-way relaying networks
  - ⇒ several matrix and tenors based channel estimation schemes ware investigated
  - ⇒ including two different system models, one with multiple relays and another with multiple nodes

Tensor Algebra

- Tensor Algebra
  - ⇒ preserves the structure of multidimensional signals



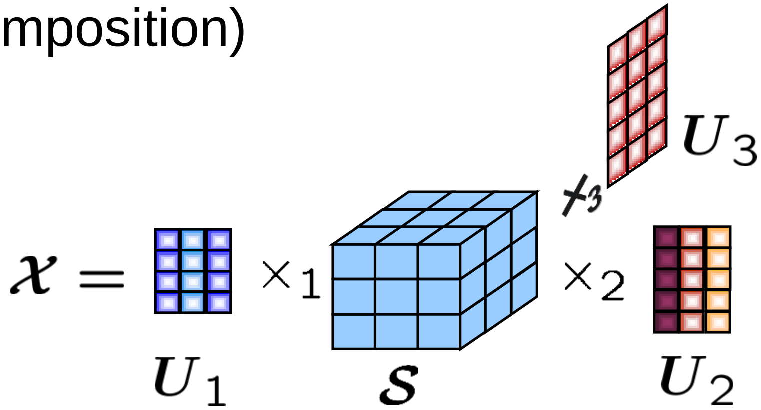


  - ⇒ provides improved identifiability
    - the tensor **rank** can largely **exceed** its **dimensions**
  - ⇒ **Uniqueness**
    - bilinear (matrix) decomposition: requires constraints for uniqueness, such as orthogonality (SVD)
    - trilinear/multilinear (tensor) decomposition: **essentially unique** up to permutation and scaling
      - columns of mixing matrix can be identified individually
      - blind source separation

Tensor Decompositions

HOSVD (Higher Order Singular Value Decomposition)

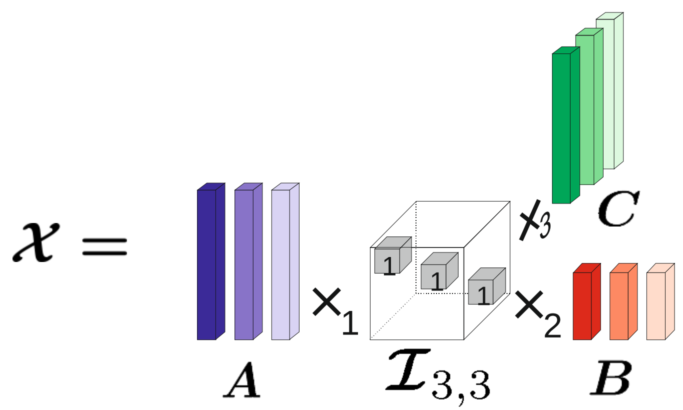
$$\mathcal{X} = \mathcal{S} \times_1 \boldsymbol{U}_1 \times_2 \boldsymbol{U}_2 \times_3 \boldsymbol{U}_3$$



- Direct, easy computation via matrix-SVDs
- Often used for "compressing" data

CP (Canonical Polyadic)

$$\mathcal{X} = \sum_{i=1}^{R} \boldsymbol{a}_i \circ \boldsymbol{b}_i \circ \boldsymbol{c}_i = \mathcal{I}_{3,R} \times_1 \boldsymbol{A} \times_2 \boldsymbol{B} \times_3 \boldsymbol{C}$$



- Often used for analyzing data
- Not easy to find the factor matrices
- Factor matrices may be flat and have a "physical significance"

Computation of CP and Coupled CP decomposition

- The **SECSI** (Semi-Algebraic framework for approximate CP decomposition via SImultaneaous matrix diagonalization) framework
  - $\Rightarrow$ efficiently estimates the factor matrices
  - $\Rightarrow$ even in ill-posed scenarios
  - $\Rightarrow$ with adjustable complexity-accuracy trade-offs.

[RH13] F. Roemer and M. Haardt, "A semi-algebraic framework for approximate CP decompositions via simultaneous matrix diagonalizations (SECSI)," *Elsevier Signal Processing*, vol. 93 , pp. 2722–2738, Sep. 2013.

- Two tensors of order three denoted by $\mathcal{X}^{(i)}, i = 1, 2$, which have the **first factor matrix in common** have **coupled** CP decomposition

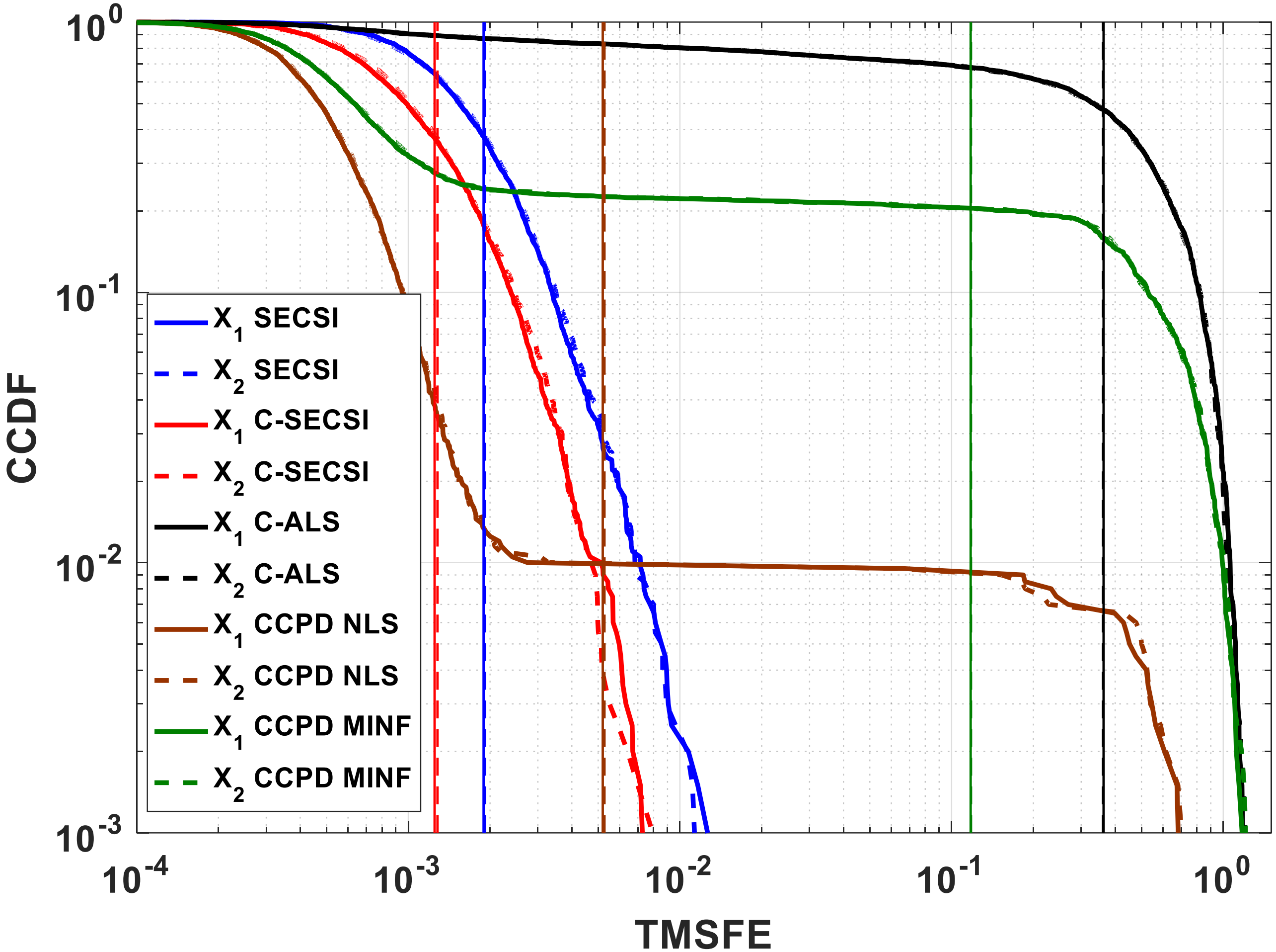
$$\mathcal{X}^{(1)} = \mathcal{I}_{3,R} \times_1 \boldsymbol{A} \times_2 \boldsymbol{B}^{(1)} \times_3 \boldsymbol{C}^{(1)}$$

$$\mathcal{X}^{(2)} = \mathcal{I}_{3,R} \times_1 \boldsymbol{A} \times_2 \boldsymbol{B}^{(2)} \times_3 \boldsymbol{C}^{(2)}$$

- Extension of the SECSI fremework to the **Coupled** SECSI (C-SECSI) framework.

[NH16] K. Naskovska and M. Haardt, "Extension of the semi-algebraic framework for approximate CP decompositions via simultaneous matrix diagonalization to the efficient calculation of coupled CP decompositions", in Proc. of 50th Asilomar Conf. on Signals, Systems, and Computers, pp. 1728–1732, Nov. 2016.

Complex-valued tensors, correlated



$7 \times 8 \times 4$

$R = 3$

$\text{SNR} = 45 \text{ dB}$

$\boldsymbol{A}, \boldsymbol{B}^{(i)}$,

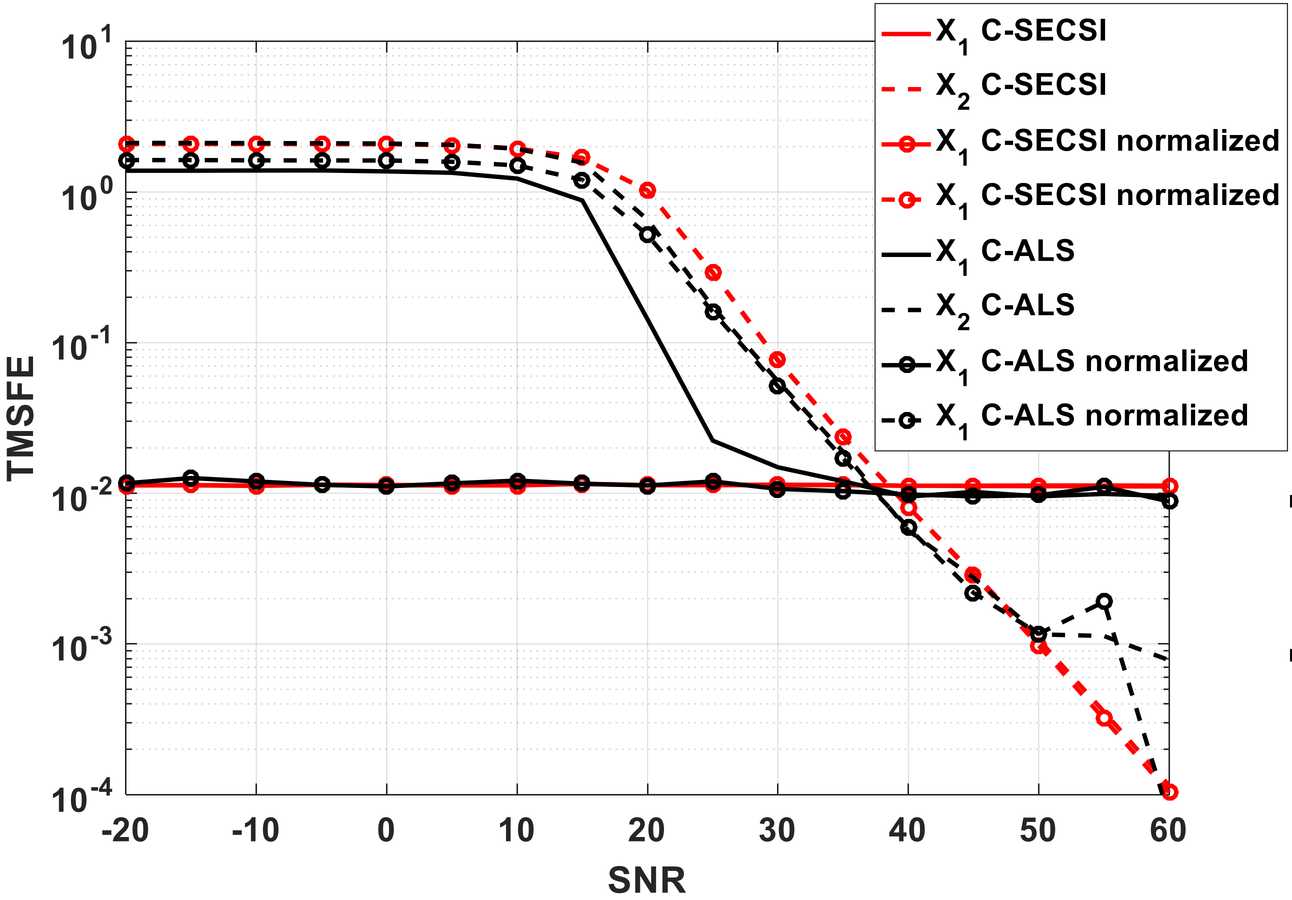
random, complex

$$\boldsymbol{C}^{(1)} = \begin{bmatrix} 1 & 1 & 1 \\ 1 & 0.95 & 0.95 \\ 1 & 0.95 & 1 \\ 1 & 1 & 0.95 \end{bmatrix}$$

$$\boldsymbol{C}^{(2)} = \begin{bmatrix} 0.95 & 1 & 0.95 \\ 1 & 1 & 1 \\ 0.95 & 1 & 1 \\ 1 & 1 & 0.95 \end{bmatrix}$$

- C-SECSI has improved performance since the correlation is not in the common mode.

Complex valued tensors, different SNRs



$3 \times 8 \times 7$

$R = 3$

$\mathrm{SNR}_1 = 40$ dB

$\mathrm{SNR}_2 = -20 : 60$ dB

$\rho_n = [0, 0, 0]$

2000 realizations

- C-ALS requires normalization of the noise variance
- C-SECSI does not require normalization of the noise variance

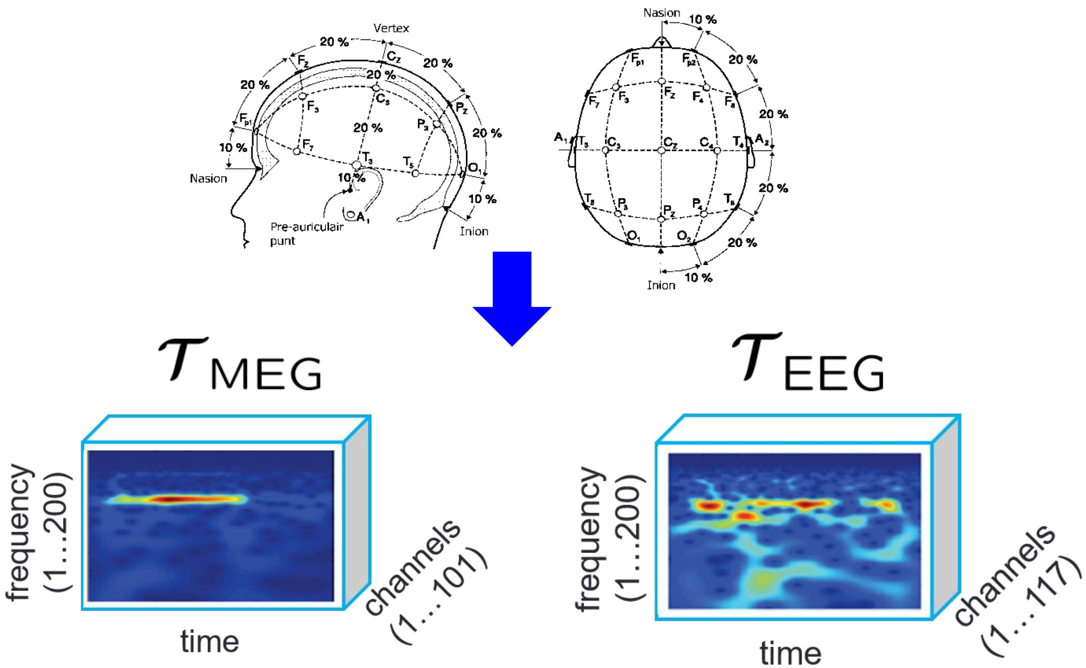
Application to Biomedical Signal Processing

- Joint EEG-MEG signal analysis using coupled CP decomposition

- **IPS** (Intermittent Photic Stimulation) is a stimulation of the brain by repetitive light flashes that can induce the **PD** (Photic Driving) effect.
- The resonance effect is characterized by enlarged response amplitudes for the photic stimulation with frequencies at or close to the individual **alpha frequency** or half the individual **alpha frequency** for our study.
- The PD effect is widely used to assess effects of medicaments and for diagnosis.
- Moreover, the PD effect is also used to study several neurophysiological diseases like
  - ⇒ Alzheimer,
  - ⇒ schizophrenia,
  - ⇒ and some forms of epilepsy.

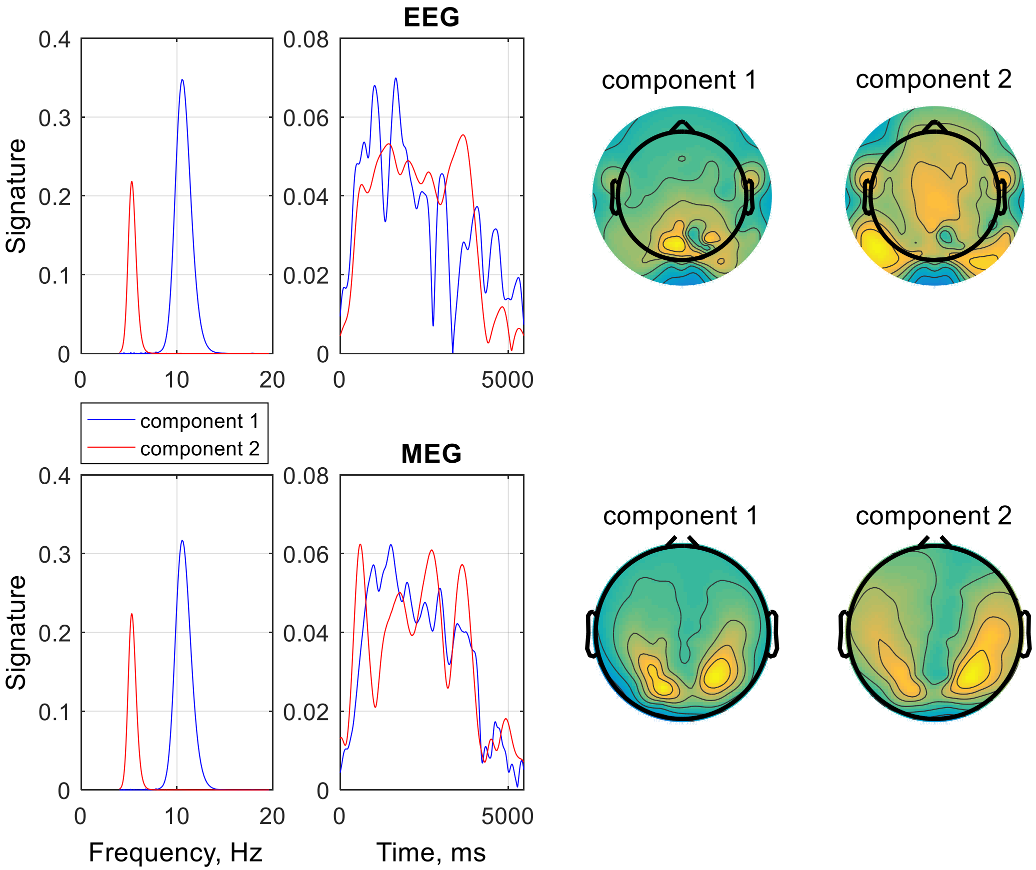
Application of the C-SECSI to the joint EEG-MEG signal analysis

- Measurement data
  - ⇒ simultaneously recorded from 128 EEG channels and 102 MEG magnetometer channels
  - ⇒ at the Biomagnetic Center of the University Hospital in Jena, Germany.



Application of the C-SECSI to the joint EEG-MEG signal analysis

- Using the C-SECSI framework the coupled CP decompostion of the EEG and MEG signal tensor was estimated
  - ⇒ assuming that the frequency mode is common



[NKHH17] K. Naskovska, A. A. Korobkov, M. Haardt, and J. Haueisen, “Analysis of the photic driving effect via joint EEG and MEG data processing based on the coupled CP decomposition,” in Proc. 25-th European Signal Processing Conference (EUSIPCO 2017) (Accepted), pp. –, 2017.

Application to Wireless Communication Systems

- **GFDM** (Generalized Frequency Division Multiplexing) is One of the candidate waveforms that fulfils the 5G requirements.
  - ⇒ flexible multi-carrier scheme that spreads the data symbols in a **time-frequency** block.
  - ⇒ not all symbols are transmitted on orthogonal subcarriers

- GFDM **transmit block** for one transmit antenna

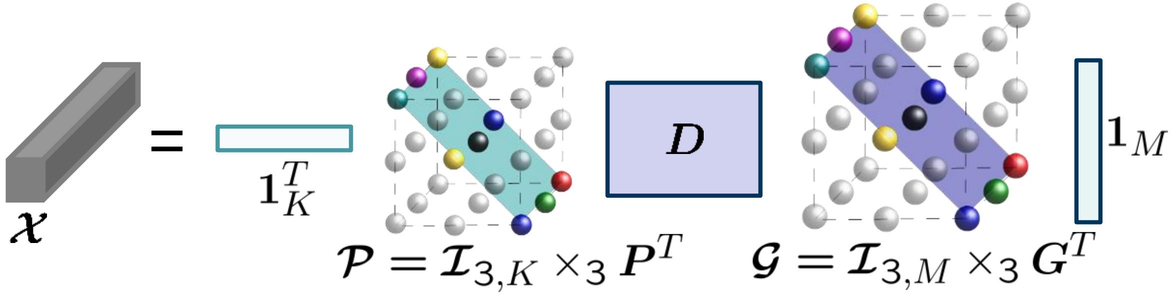
$$x_n = \sum_{k=1}^{K} \sum_{m=1}^{M} d_{k,m} p_{k,n} g_{m,n}, \quad \forall \ n = 1, \ldots, N,$$

  - K **subcarriers** denoted by $p_{k,n} = \exp\left(j2\pi \frac{k}{N} n\right)$
  - M complex time **subsymbols** filtered with the filter coefficients $g_{m,n}$
  - $N = M \cdot K$ GFDM **block** length

[NCH+17] K. Naskovska, S. A. Cheema, M. Haardt, B. Valeev, and Y. Evdokimov, "Iterative GFDM receiver based on the PARATUCK2 tensor decomposition," in Proc. 21-st International ITG Workshop on Smart Antennas, 2017.

Application to Wireless Communication Systems

- Tensor model



$$\boldsymbol{\mathcal{X}} \in \mathbb{C}^{1\times 1\times N}$$
$$\boldsymbol{P} \in \mathbb{C}^{K\times N}$$
$$\boldsymbol{D} \in \mathbb{C}^{K\times M}$$
$$\boldsymbol{G} \in \mathbb{C}^{M\times N}$$

- **PARATUCK 2** tensor decompostion
- Exploiting the tensors model, we have

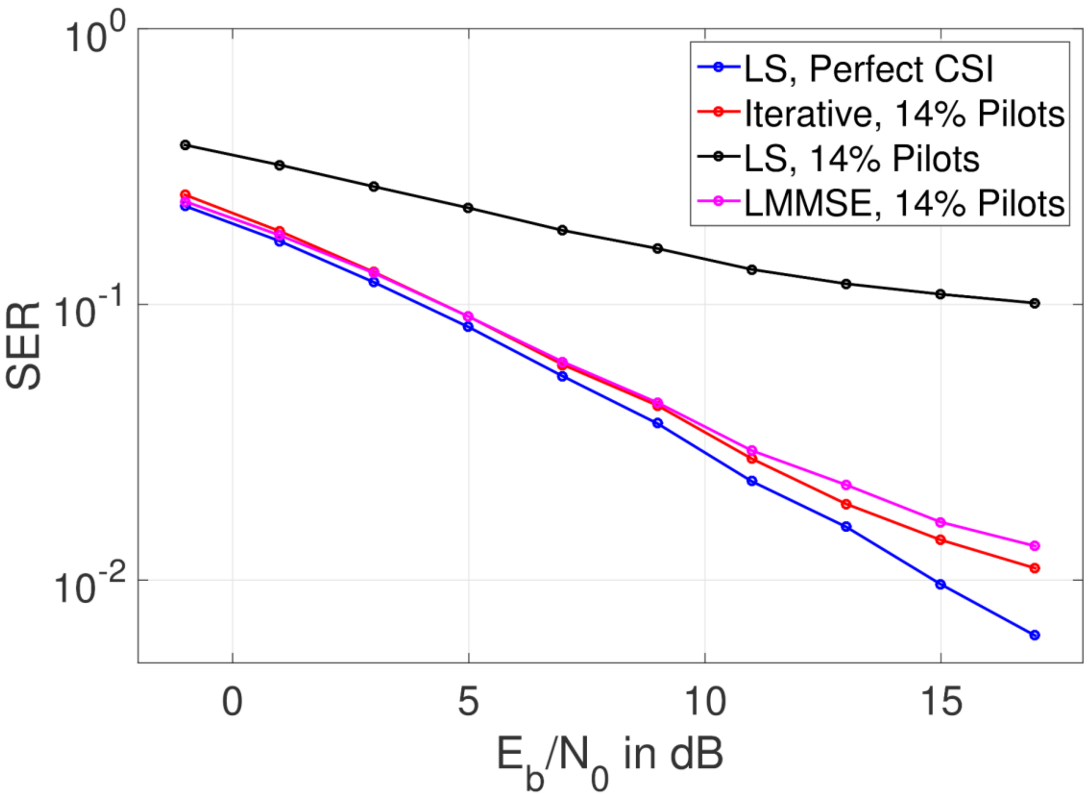
$$\boldsymbol{x} = \underbrace{(\boldsymbol{G} \diamond \boldsymbol{P})^T}_{\text{GFDM modulation matrix}} \mathrm{vec}(\boldsymbol{D})$$

GFDM modulation matrix

- The extension to the MIMO systems, leads to an iterative reciever.

[NCH+17] K. Naskovska, S. A. Cheema, M. Haardt, B. Valeev, and Y. Evdokimov, “Iterative GFDM receiver based on the PARATUCK2 tensor decomposition,” in Proc. 21-st International ITG Workshop on Smart Antennas, 2017.

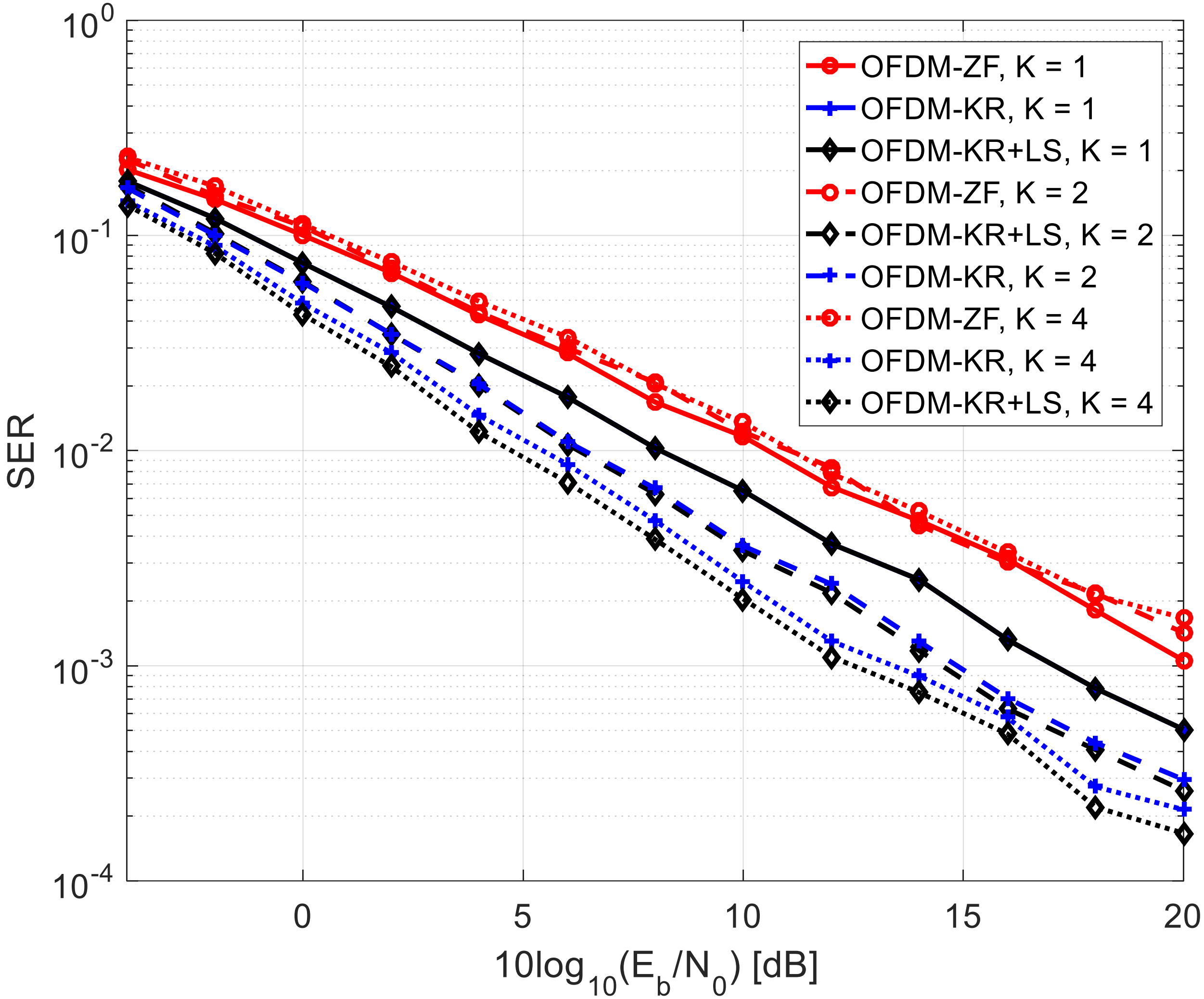
Iterative GFDM Receiver based on the PARATUCK2 Tensor Decomposition



- 2 x 2 MIMO system
- 3GPP Pedestrian A channel
- QPSK
- Maximum number of iteration is five.
- Root-raised cosine
- Roll-off factor 0.3
- 32 subcarriers
- 15 subsymbols
- 2000 realizations

[NCH+17] K. Naskovska, S. A. Cheema, M. Haardt, B. Valeev, and Y. Evdokimov, "Iterative GFDM receiver based on the PARATUCK2 tensor decomposition," in Proc. 21-st International ITG Workshop on Smart Antennas, 2017.

Application to MIMO OFDM Systems



- Soon to be published
- Tensor based receiver
- 2x2 MIMO
- QPSK
- 128 subcarriers

Thank you!