Development of a Single-Carrier SM-MIMO Transceiver for Broadband Large-Scale Antenna Systems

System Model & Analysis
Channel Estimation & Synchronization

Communications Engineering Lab
Prof. Dr.rer.nat. Friedrich K. Jondral

System Model: Spatial Modulation

- Use antenna index information as additional modulation dimension.
- Apply information in specific SM-symbol modulation algorithm.

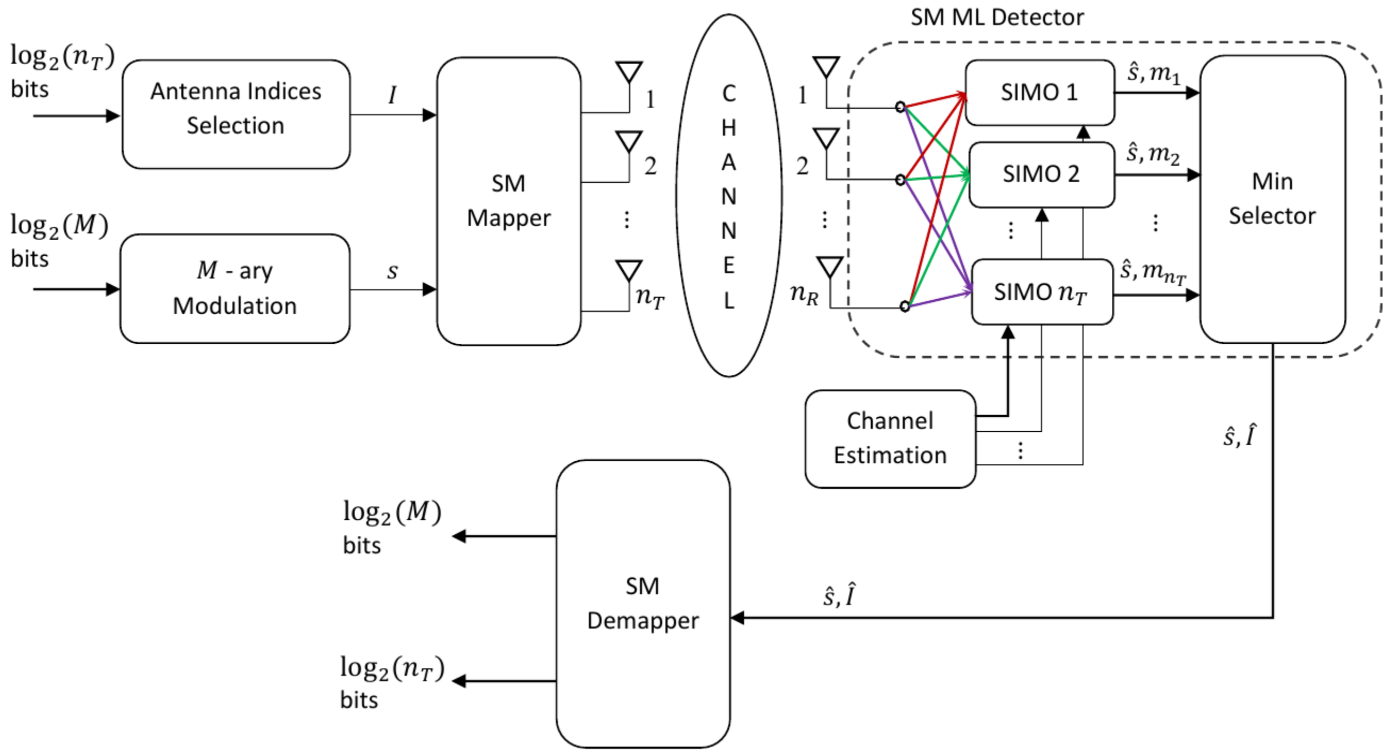

Figure 1: General structure of Spatial Modulation systems [**0**].

System Model: Large-Scale Single-Carrier

- Spatial Modulation predominantly investigated in flat fading channels.
- In frequency-selective channels: OFDM is assumed.
- Disadvantages of OFDM-SM:
  - Usage of various transmit antennas in one frame jeopardizes single-RF benefits of SM-MIMO.
  - Low power amplifier efficiency due to PAPR.
  - Computational burden of DFTs increases with number of transmit antennas
- Frequency-selective channel may be converted into frequency flat fading channels by carefully designed receive filters.

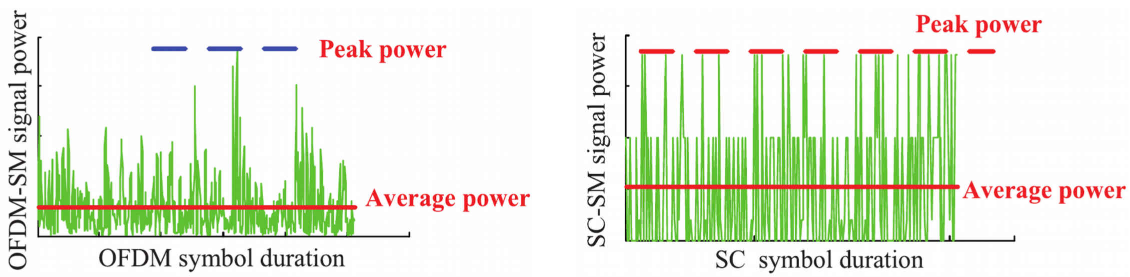

Figure 2: Comparison of PAPR of OFDM-SM and SC-SM [**1**].

Single-Carrier Spatial Modulation (1)

SM with N_t=2, BPSK

Bits-to-Symbol Mapping		
Input bits	Active antenna	BPSK symbol
00	1	-1
01	1	+1
10	2	-1
11	2	+1

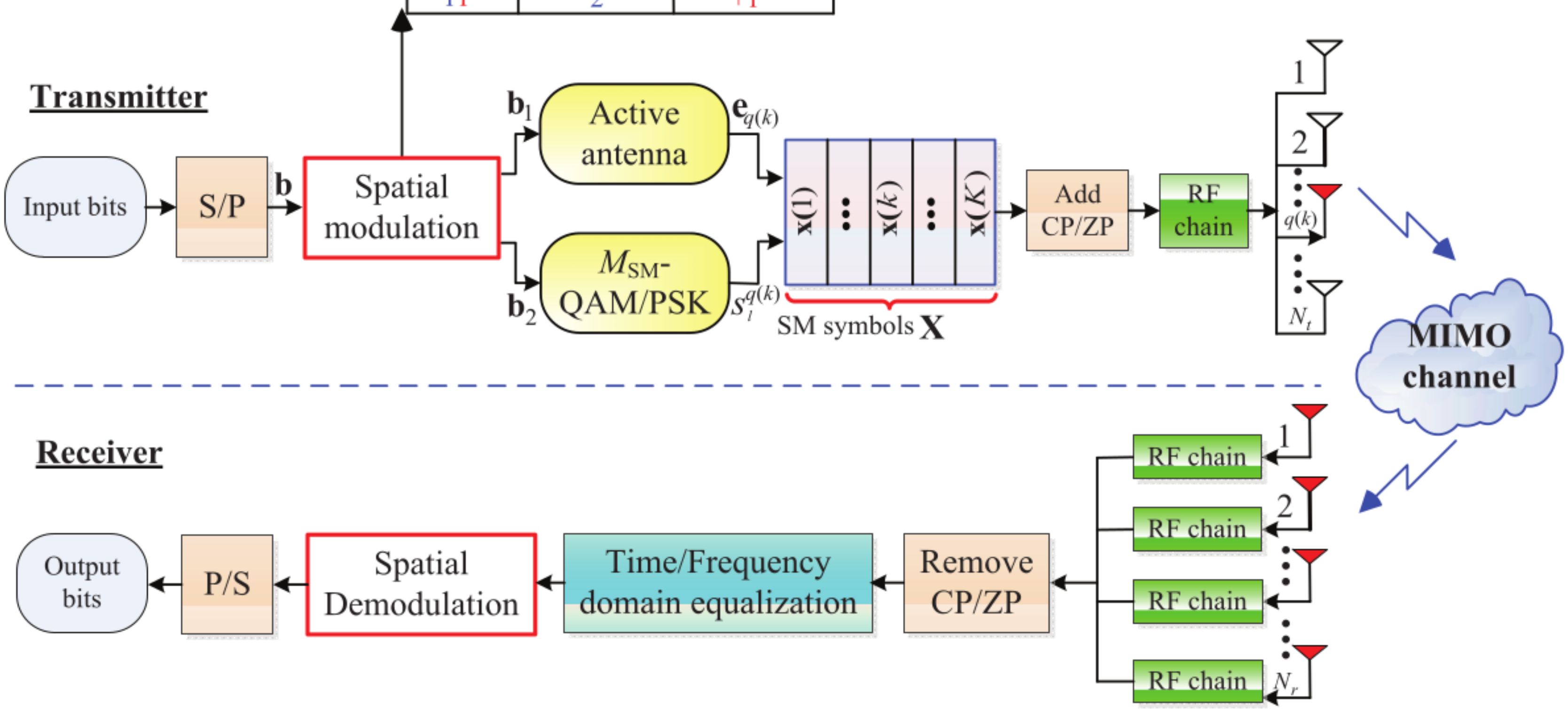

Figure 3: General transceiver structure of SC-SM systems [**1**].

Single-Carrier Spatial Modulation (2)

- Use ZP-aided SC-SM:
  - Promising BER performance.
  - Only one RF-chain at transmission.
- Channel matrix might be rank deficient.
- Attractive trade-off amongst detection complexity, BER, achievable transmission rate and power efficiency.

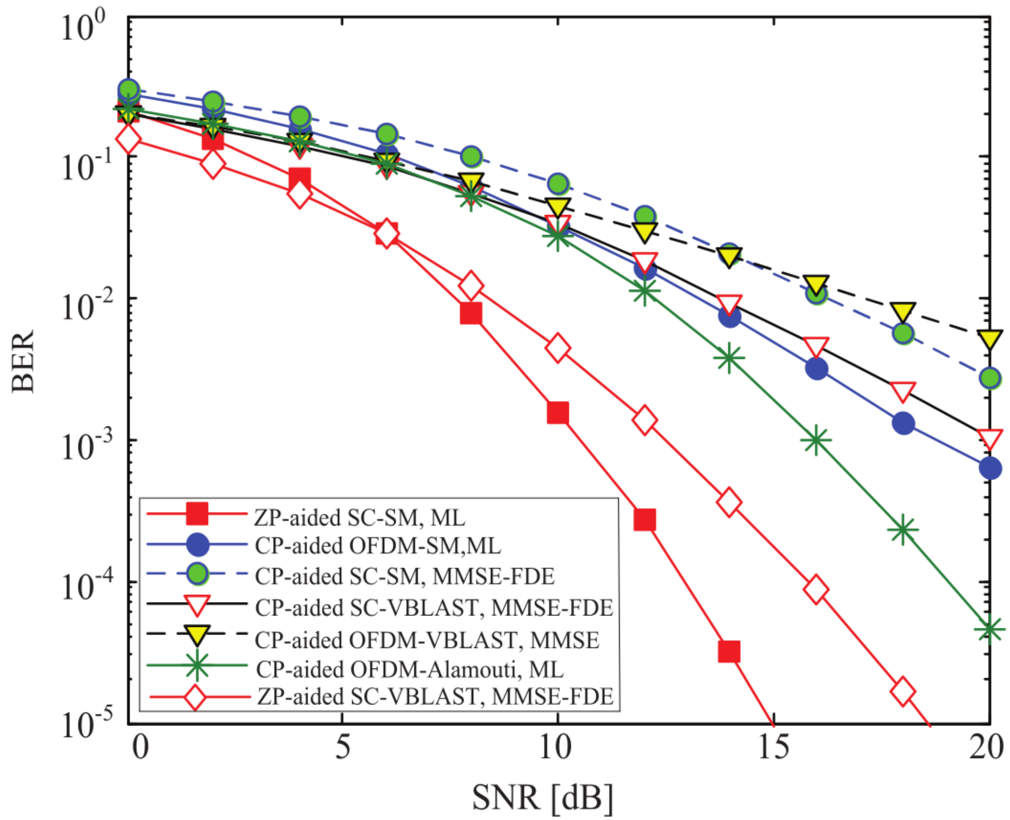

Figure 4: BER comparison of the ZP-aided SC-SM scheme over its CP-aided counterpart and various CP-aided classic MIMO transmission schemes [**1**].

Advantages & Disadvantages

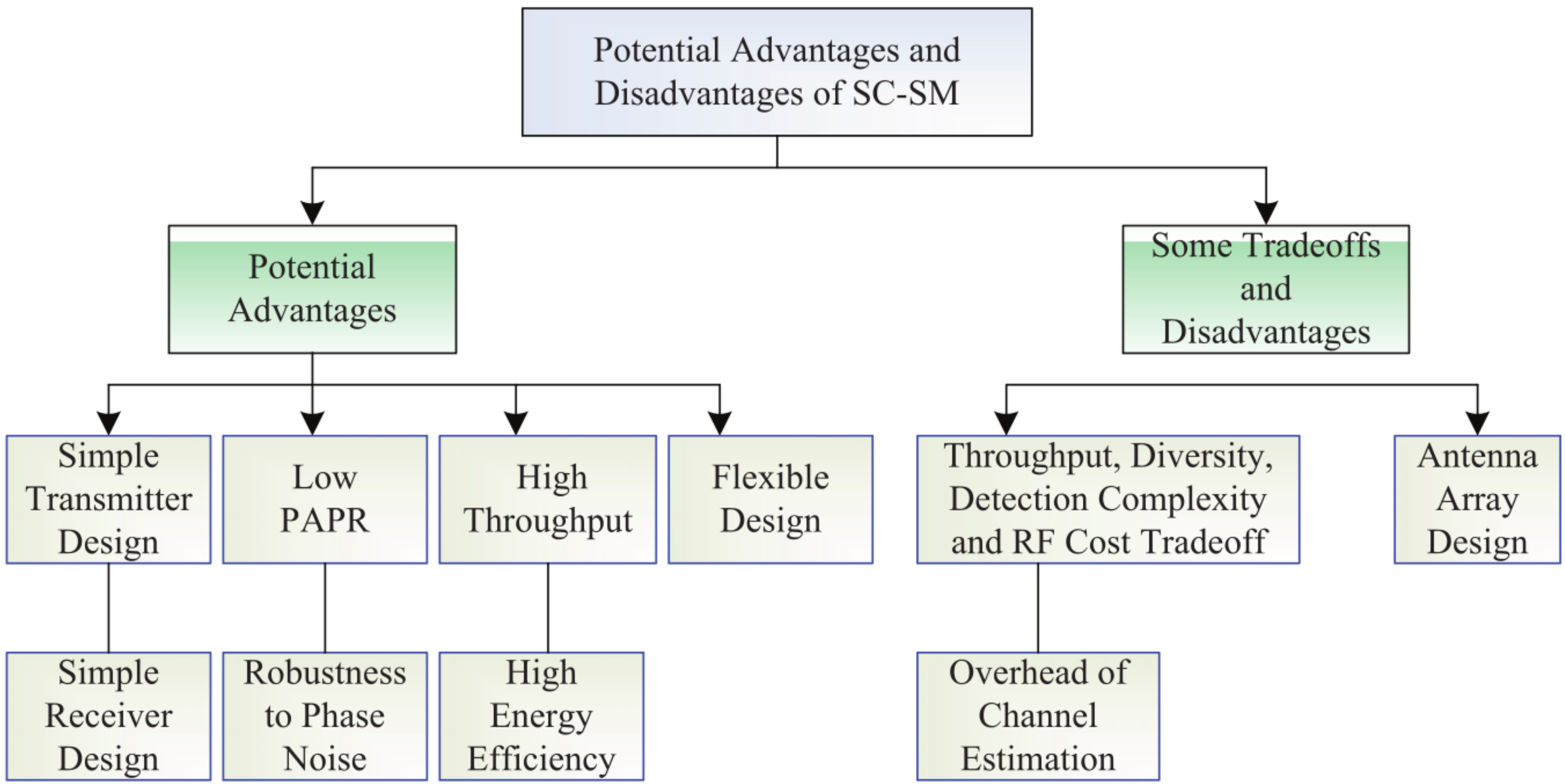

Figure 5: A summary of main advantages and disadvantages of the SC-SM scheme [**1**].

Low-Complexity Detection Scheme for GSM-SC

- Based on M-algorithm
- Single stream ML detection
- Avoids QR-decomposition
- Balanced trade-off: performance & complexity
- Scheme approaches ML detector with increasing M
- Efficient operation even in rank-deficient channel scenarios

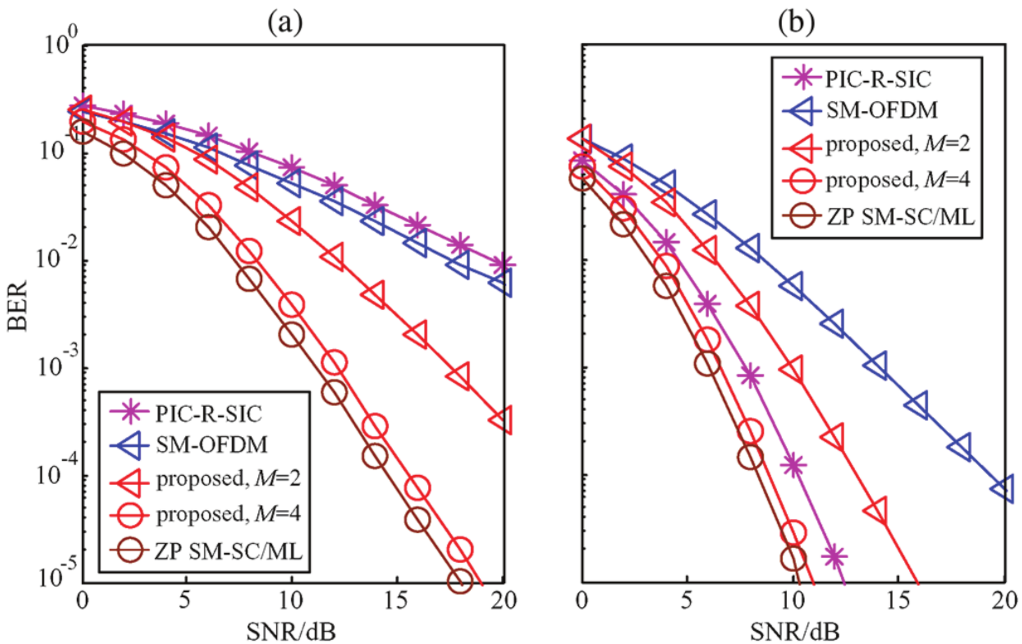

Figure 6: BER of ZP-aided SM-SC and SM-OFDM with different receiver antennas: (a) N_r = 1; (b) N_r = 2 [**2**].

Specific Detector Design

- Transmission system model:

$$\underbrace{\begin{bmatrix} \mathbf{Y}_1 \\ \mathbf{Y}_2 \\ \vdots \\ \mathbf{Y}_{K+P-1} \end{bmatrix}}_{\mathbf{Y}\text{ of size}(K+P-1)N_r\times 1} = \underbrace{\begin{bmatrix} \mathbf{H}_0 & \mathbf{O} & \dots & \mathbf{O} & \mathbf{O} \\ \mathbf{H}_1 & \mathbf{H}_0 & \dots & \mathbf{O} & \mathbf{O} \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{H}_{P-1} & \mathbf{H}_{P-2} & \dots & \mathbf{H}_0 & \mathbf{O} \\ \mathbf{O} & \mathbf{H}_{P-1} & \dots & \mathbf{H}_1 & \mathbf{H}_0 \\ \vdots & \vdots & \ddots & \vdots & \vdots \\ \mathbf{O} & \mathbf{O} & \dots & \mathbf{H}_{P-1} & \mathbf{H}_{P-2} \\ \mathbf{O} & \mathbf{O} & \dots & \mathbf{O} & \mathbf{H}_{P-1} \end{bmatrix}}_{\mathbf{H}\text{ of size }(K+P-1)N_r\times KN_t} \underbrace{\begin{bmatrix} \mathbf{x}_1 \\ \mathbf{x}_2 \\ \vdots \\ \mathbf{x}_K \end{bmatrix}}_{\mathbf{x}\text{ of size }KN_t\times 1} + \underbrace{\begin{bmatrix} \mathbf{n}_1 \\ \mathbf{n}_2 \\ \vdots \\ \mathbf{n}_{K+P-1} \end{bmatrix}}_{\mathbf{n}\text{ of size }(K+P-1)N_r\times 1}$$

- For each step: compute and choose M best metrics.

$$\mathbf{e}_1 = ||\hat{\mathbf{Y}}_1 - \mathbf{H}_0\mathbf{x}_1||_F^2, \mathbf{x}_1 \in C_{GSM}.$$

$$\begin{aligned} \mathbf{e}_2^m &= \left\| \hat{\mathbf{Y}}_2 - \begin{pmatrix} \mathbf{H}_0 & 0 \\ \mathbf{H}_1 & \mathbf{H}_0 \end{pmatrix} \begin{pmatrix} \mathbf{x}_1^m \\ \mathbf{x}_2 \end{pmatrix} \right\|_F^2 \\ &= \tilde{\mathbf{e}}_1^m + \left\| \mathbf{Y}_2 - (\mathbf{H}_1 \quad \mathbf{H}_0) \begin{pmatrix} \mathbf{x}_1^m \\ \mathbf{x}_2 \end{pmatrix} \right\|_F^2, \mathbf{x}_2 \in C_{GSM} \end{aligned}$$

- Final detection after K steps:

$$\hat{\mathbf{x}}_{proposed} = \underset{m\in(1,2,\dots,\hat{M})}{\arg\min} ||\mathbf{Y} - \mathbf{H}\mathbf{D}_K^m||_F^2$$

Communications Engineering Lab
Prof. Dr.rer.nat. Friedrich K. Jondral

Potential Design Issues

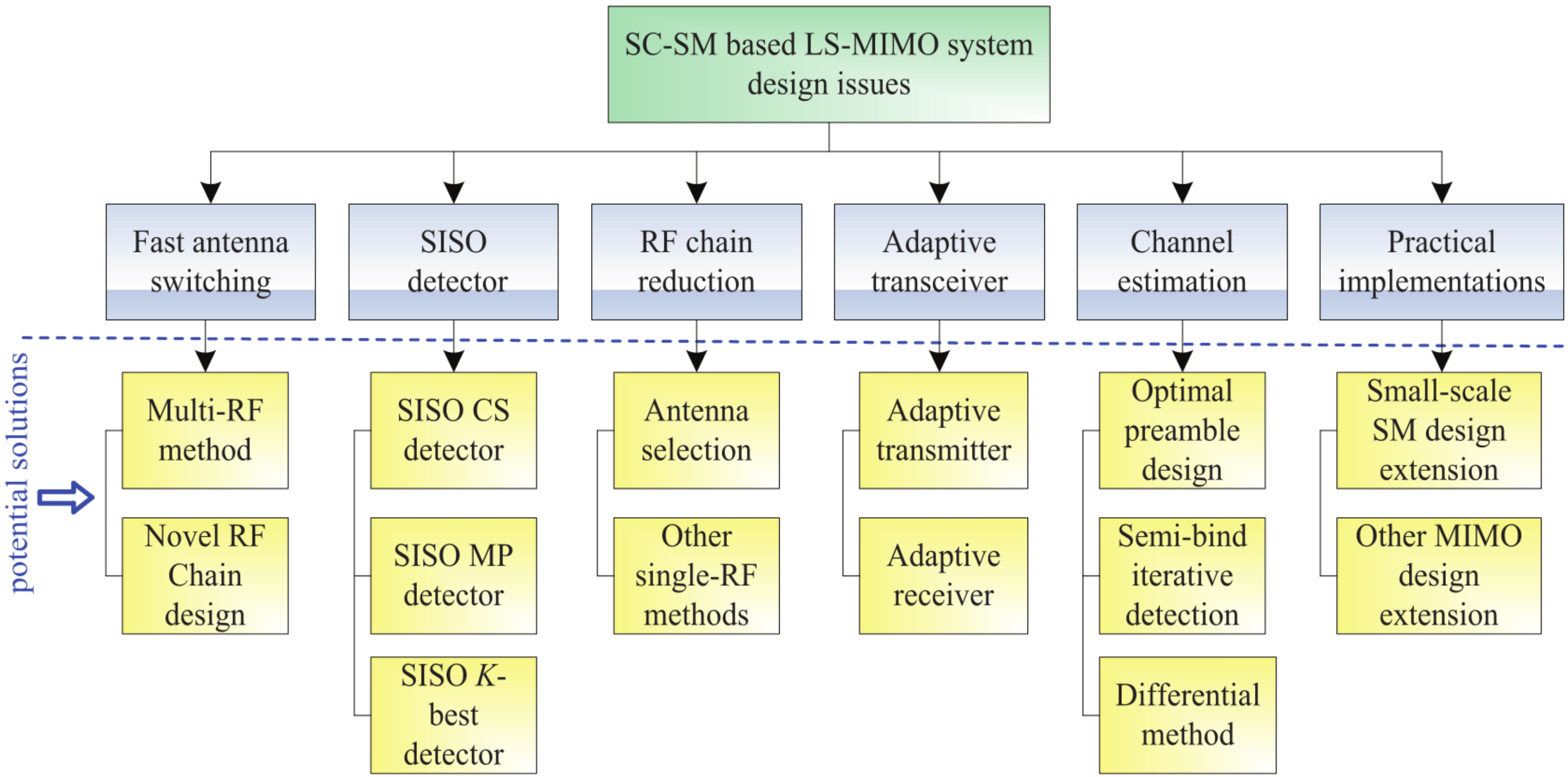

Figure 7: Potential future design issues and potential solutions [**1**].

Classic Channel Estimation scheme

- For each transmission antenna: send training sequence.
- Using Gold Sequences: no multi-path effects for different antennas.
  - A frame can contain multiple antenna sequences.
- Correlate with the corresponding sequence at the receiver.
  - Channel Impulse Response for each transmit antenna.
- Reconstruct channel matrix with impulse responses.

- Performance trade-offs:
  - Longer sequences → lower threshold for reconstruction & more overhead.
  - More N_t → more index information & more overhead.
  - More N_r → lower channel estimation SNR needed.

Simulation Results: Classic Approach (1)

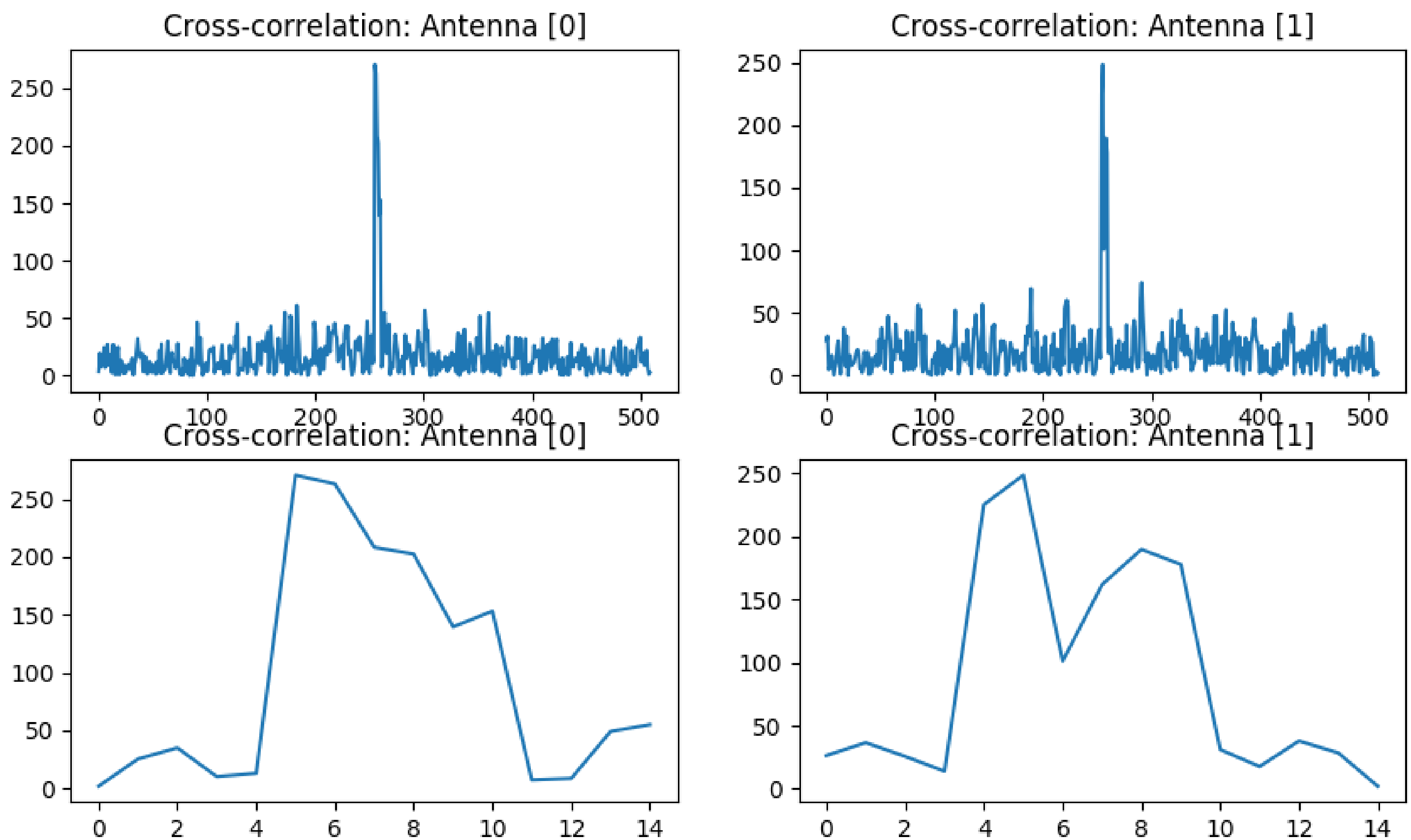

Figure 8: Results of correlation: Channel Impulse Response
for different sending antennas [N_r =2; N_r = 2; hard coded].

Simultaneous Frame Synchronization and Channel Estimation scheme

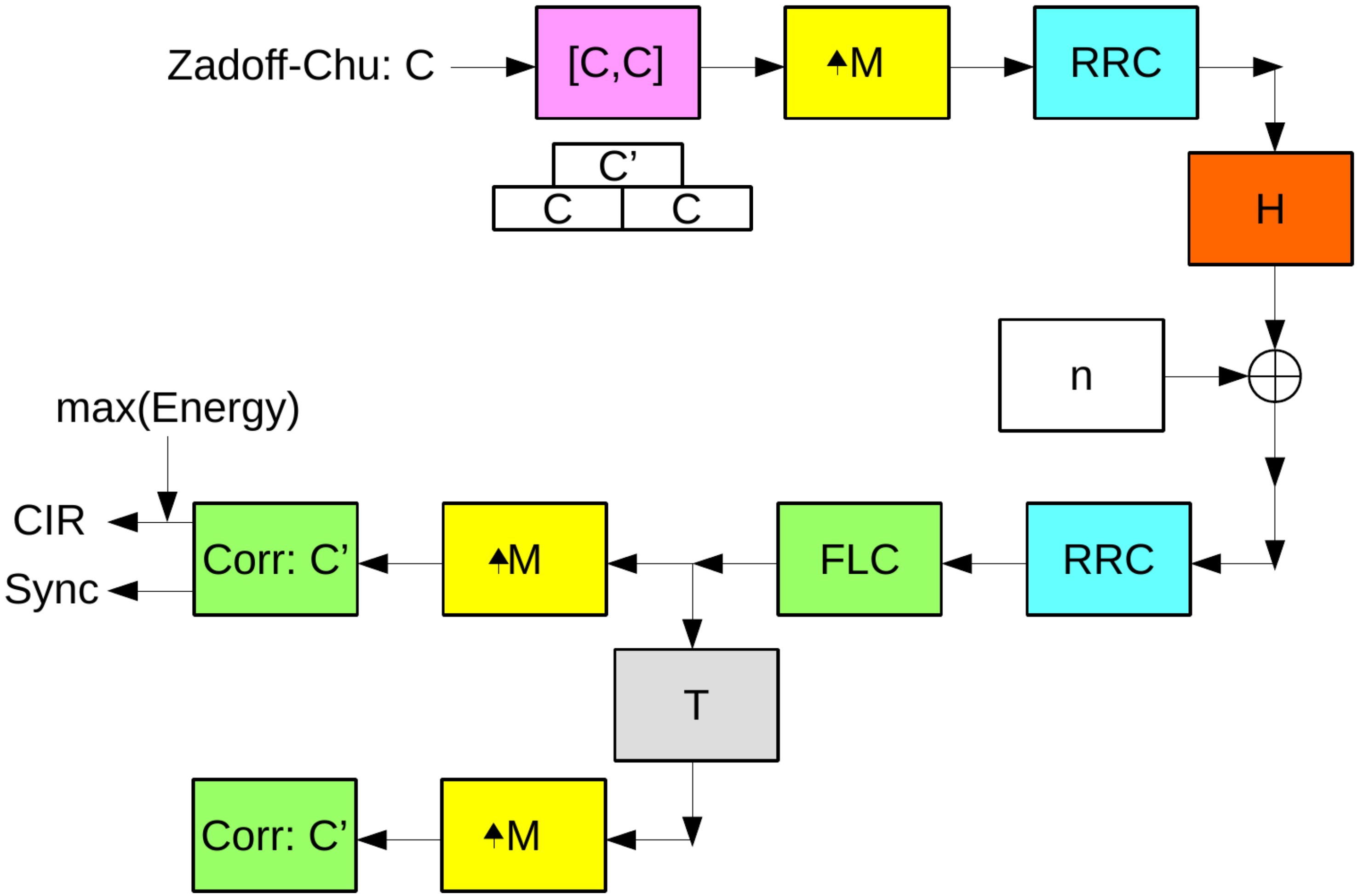

Figure 9: Proposed Synchronization & Channel Estimation scheme.

Simulation Results: Pulse shaped chirp

Karlsruher Institut für Technologie

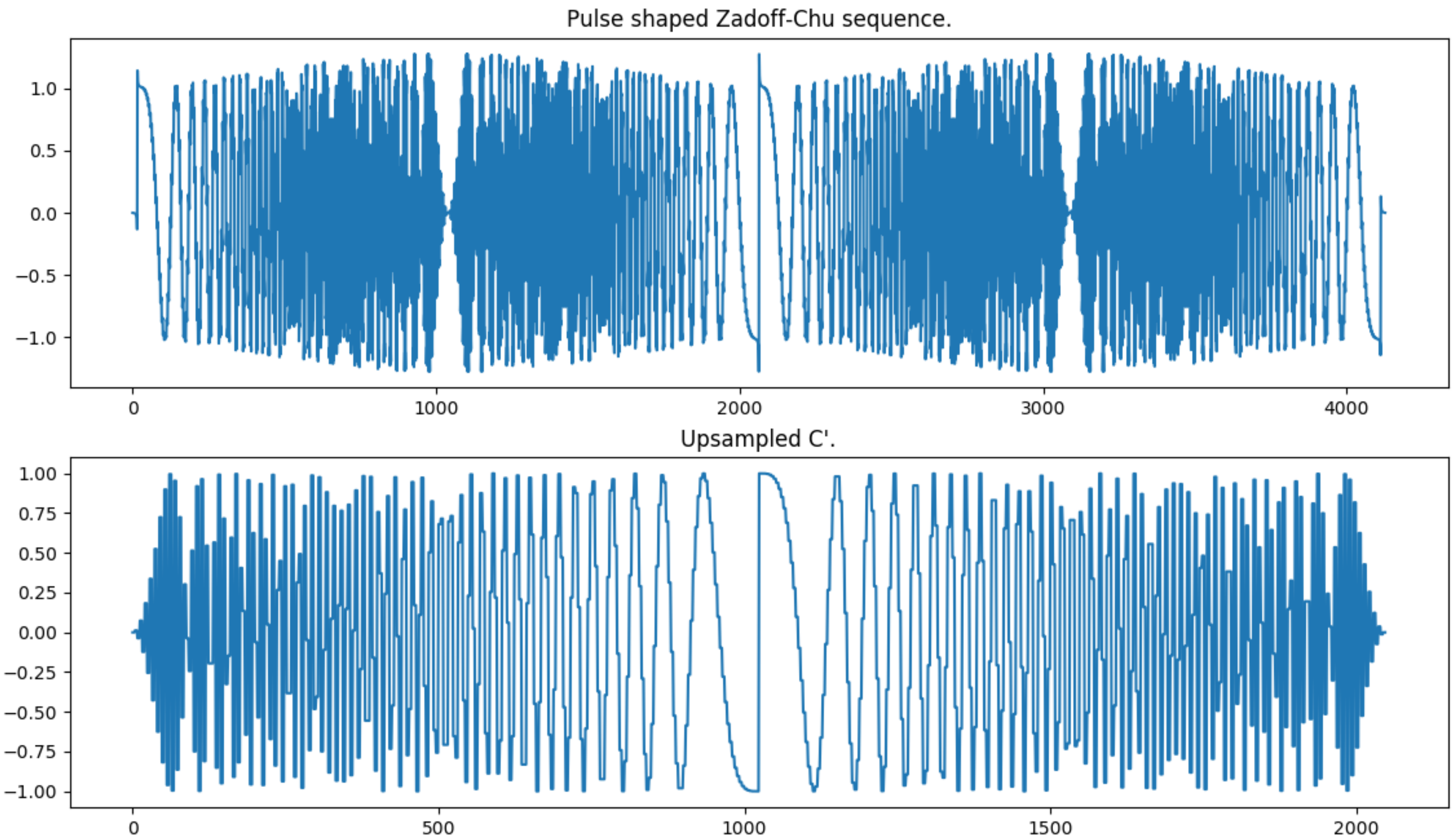

Figure 10: Upsampled frames: C and C'.

Simulation Results: SIMO / Split (1)

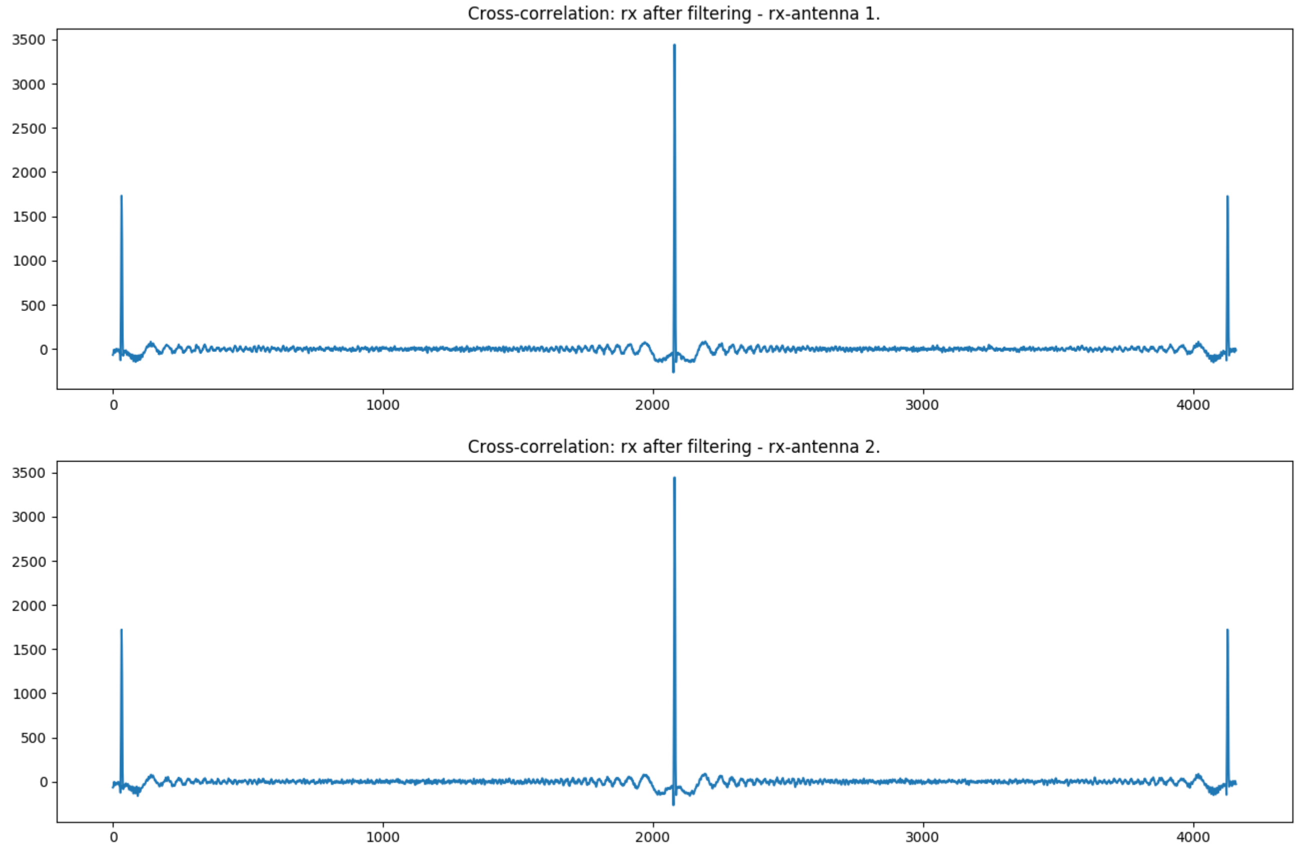

Figure 11: Cross-correlation of the received frame with C' - split reception antennas.

Simulation Results: SIMO / Split (2)

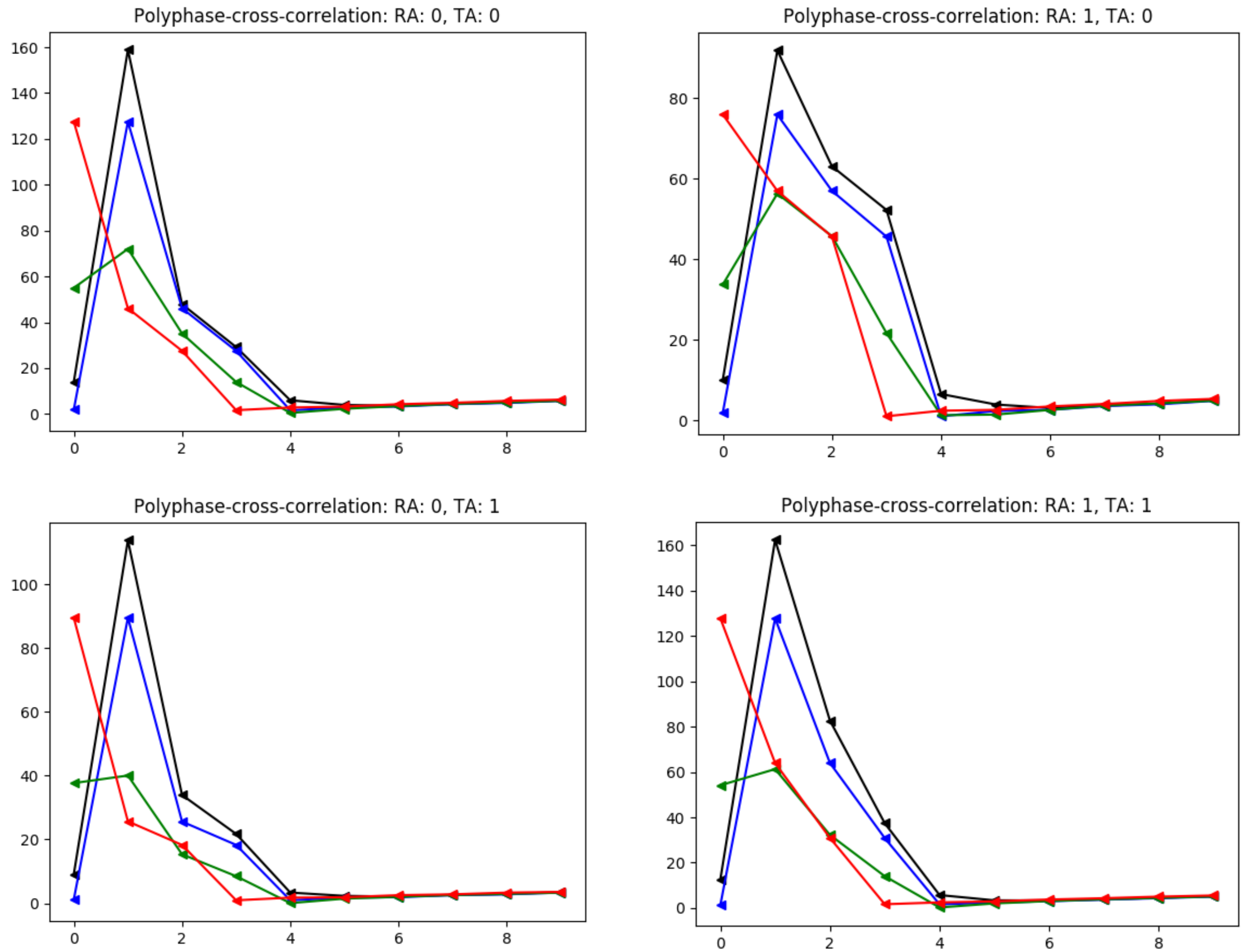

Figure 12: Polyphase-cross-correlation of the received frame with C' - split reception antennas – split transmit antennas.

Frequency & Phase Synchronization

- Estimate frequency-offset by multiplying the identical values of the training frame halves:
  - Resulting phase-offset over time between points is frequency offset.
- Frame offset is estimated by energy of channel impulse response.
- Phase-offset is phase of frame begin of correlation.

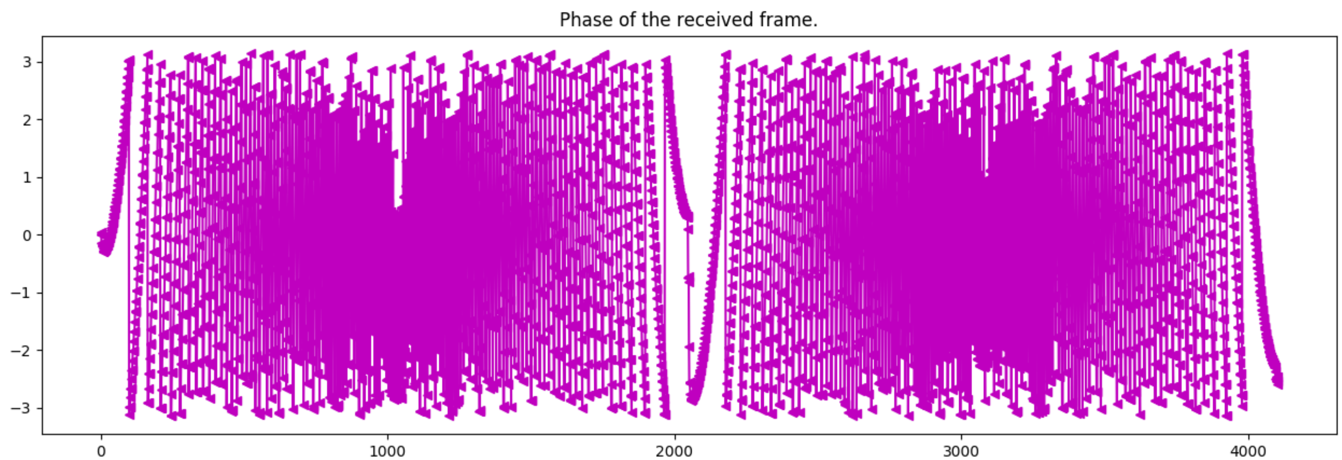

Figure 13: Phase of the received frame.

Results

- Single-carrier SM and detector scheme:
  - System scales well.
  - Relatively low complexity.
  - Robust even in demanding scenarios.
  - Promising candidate for large-scale MIMO aided multiuser uplink and downlink design.

- Channel estimation and synchronization scheme:
  - Works well in most scenarios.
  - Overhead trade-off: frame length and coherence time.
  - Scheme might be published in a paper.

Prospects

- Current work:
  - Exhaustive tests and comparisons.
  - Test different channel models (COST, LTE).
  - Compare to other Spatial Modulation approaches.
  - Generalize, optimize and improve code base.

- In future works:
  - Proof of concept with GNU Radio.
  - Tests on hardware.

Any questions?

- Sources
  - [0] E. Basar, M. Wen, R. Mesleh, M. Di Renzo, Y. Xiao, H. Haas, "**Index Modulation Techniques for Next-Generation Wireless Networks**," *IEEE Access*, vol. 5, August 2017
  - [1] P. Yang, Y. Xiao, Y. L. Guan, K. V. S. Hari, A. Chockalingam, S. Sugiura, H. Haas, M. Di Renzo, C. Masouros, Z. Liu, L. Xiao, S. Li and L. Hanzo, "**Single-Carrier SM-MIMO: A Promising Design for Broadband Large-Scale Antenna Systems**," *IEEE Commun. Surveys & Tutorials*, vol. 18, no. 3, pp. 1687-1716, August 2016
  - [2] L. Xiao, D. Lilin, Y. Zhang, Y. Xiao, P. Yang and S. Li, "**A low-complexity detection scheme for generalized spatial modulation aided single carrier systems**," *IEEE Commun. Lett.*, vol. 19, no. 6, pp. 1069-1072, Jun. 2015