Sequential Closed-Form Semiblind Receiver for Space-Time Coded Multihop Relaying Systems

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Agenda

- Introduction
- System model
- Proposed closed-form semiblind receiver
- Simulation assumptions and results
- Conclusions and perspective
- References

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- The generalized nested PARAFAC model can be decomposed into $K+1$ third-order PARAFAC models

Introduction

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- Assuming a simplified KRST coding scheme, the signals received at destination satisfy a $(K+3)$th-order generalized nested PARAFAC tensor model
- The generalized nested PARAFAC model can be decomposed into $K+1$ third-order PARAFAC models
- Assuming the coding matrices known, a closed-form semiblind receiver based on rank-one matrix approximations is derived for jointly estimating the information symbols and the individual channels

System Model

One-way MIMO Multihop Relay Cooperative System

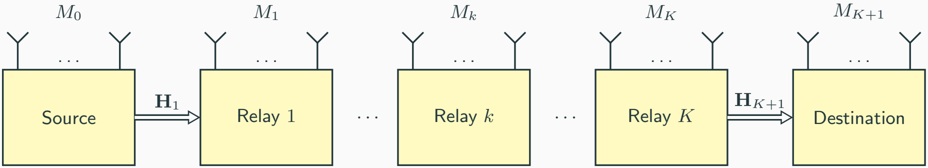

Figure 1: System model with K relays.

- M_k denotes the number of antennas at node k

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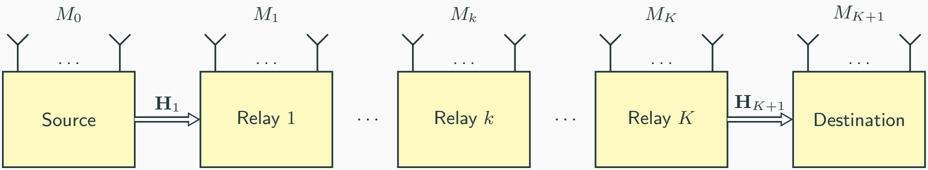

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- M_k denotes the number of antennas at node k
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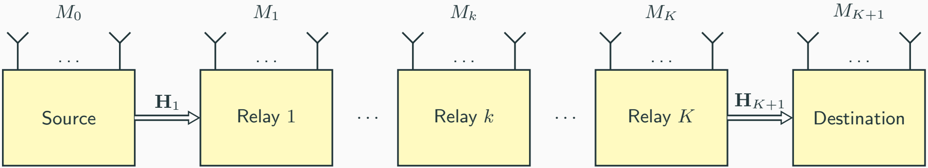

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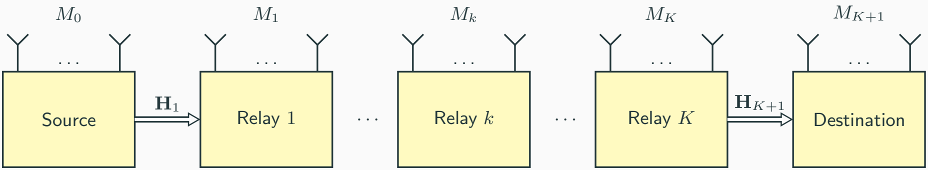

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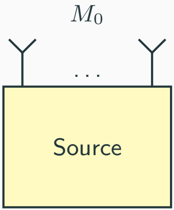
- Source and relay nodes encodes the received signal with a KRST following the AF protocol
- $\tilde{\mathcal{X}} = \mathcal{X} + \mathcal{N}$ is the noisy received signal tensor

System Model: Two Relays Scenario



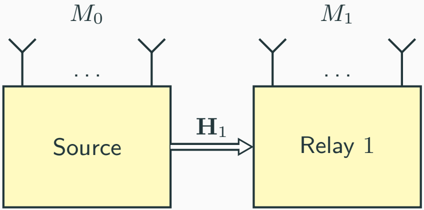
Encoded symbols

$$\boxed{\mathbf{X}^{(0)}_{M_0 \times P_0 N} = (\mathbf{G}_0 \diamond \mathbf{S})^T} \tag{1}$$

- The symbol matrix $\mathbf{S} \in \mathbb{C}^{N \times M_0}$ containing N data-streams composed of M_0 symbols is multiplexed by M_0 transmit antennas at the source
- Source and relays encode the signals with a KRST coding matrix $\mathbf{G}_k \in \mathbb{C}^{P_k \times M_k}$, chosen as a truncated DFT matrix $\mathbf{G}_k^T \mathbf{G}_k^* = \mathbf{I}_{M_k}$, $(k = 0, \cdots, K)$

System Model: Two Relays Scenario

First Hop



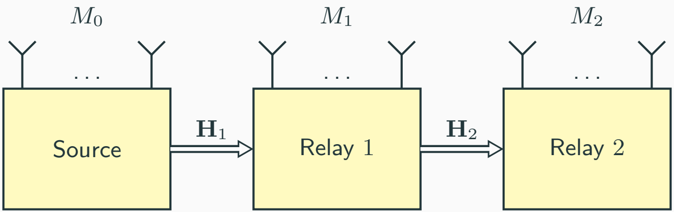
Received signal at Relay-1

$$\boxed{\tilde{\mathbf{X}}^{(1)}_{M_1 \times P_0 N} = \mathbf{H}_1 \left(\mathbf{G}_0 \diamond \mathbf{S}\right)^T + \mathbf{N}^{(1)}_{M_1 \times P_0 N}}$$

- Signals received at relay-1 define a third-order tensor $\tilde{\mathcal{X}}^{(1)} \in \mathbb{C}^{M_1 \times P_0 \times N}$ satisfying a PARAFAC model $\|\mathbf{H}_1, \mathbf{G}_0, \mathbf{S}; M_0\|$
- $\tilde{\mathbf{X}}^{(1)}_{M_1 \times P_0 N}$ represents the flat mode-1 unfolding of $\tilde{\mathcal{X}}^{(1)}$

System Model: Two Relays Scenario

Second Hop



Received signal at Relay-2

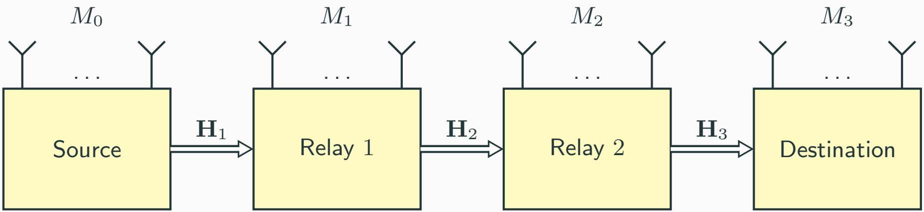
$$\tilde{\mathbf{X}}^{(2)}_{M_2 \times P_1 P_0 N} = \mathbf{H}_2 \left(\mathbf{G}_1 \diamond \tilde{\mathbf{X}}^{(1)}_{P_0 N \times M_1} \right)^T + \mathbf{H}_2 \left(\mathbf{G}_1 \diamond \mathbf{N}^{(1)}_{P_0 N \times M_1} \right)^T + \mathbf{N}^{(2)}_{M_2 \times P_1 P_0 N}$$ [1]

- The signals received at relay-2 define a fourth-order tensor $\tilde{\mathcal{X}}^{(2)} \in \mathbb{C}^{M_2 \times P_1 \times P_0 \times N}$
- $\tilde{\mathbf{X}}^{(2)}_{M_2 \times P_1 P_0 N}$ represents the flat mode-1 unfolding of $\tilde{\mathcal{X}}^{(2)}$

[1] From now on, a noiseless formulation

System Model: Two Relays Scenario

Third Hop



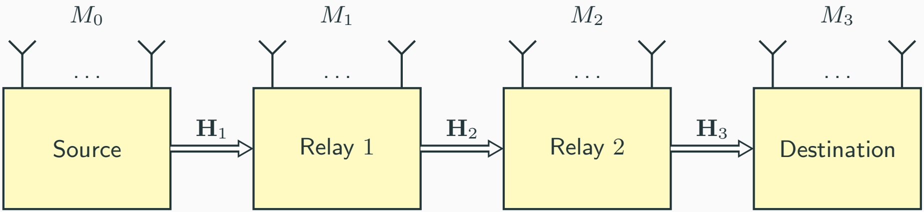
Received signal at Destination

$$\mathbf{X}^{(3)}_{M_3 \times P_2 P_1 P_0 N} = \mathbf{H}_3 \left(\mathbf{G}_2 \diamond \mathbf{X}^{(2)}_{P_1 P_0 N \times M_2} \right)^T$$

- The signals received at the destination define a fifth-order tensor $\mathcal{X}^{(3)} \in \mathbb{C}^{M_3 \times P_2 \times P_1 \times P_0 \times N}$
- $\mathbf{X}^{(3)}_{M_3 \times P_2 P_1 P_0 N}$ is the flat mode-1 unfolding of tensor $\mathcal{X}^{(3)}$ following a PARAFAC decomposition

System Model: Two Relays Scenario

Third Hop

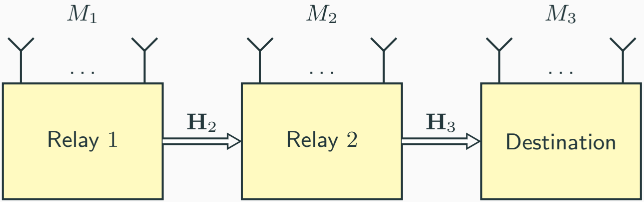


Received Signal at Destination

- Replacing $\mathbf{X}^{(2)}_{P_1 P_0 N \times M_2}$ and then $\mathbf{X}^{(1)}_{P_0 N \times M_1}$, tensor $\mathcal{X}^{(3)}$ also satisfies a generalized nested PARAFAC decomposition

$$\mathbf{X}^{(3)}_{M_3 \times P_2 P_1 P_0 N} = \mathbf{H}_3 \left[\mathbf{G}_2 \diamond \left(\mathbf{G}_1 \diamond \left(\mathbf{G}_0 \diamond \mathbf{S} \right) \mathbf{H}_1^T \right) \mathbf{H}_2^T \right]^T$$

Received Signal at Destination



- Another unfolding of the PARAFAC model $\mathcal{X}^{(3)} \in \mathbb{C}^{M_3 \times P_2 \times P_1 \times P_0 \times N}$ is

$$\mathbf{X}^{(3)}_{M_3 P_2 \times P_1 P_0 N} = (\mathbf{H}_3 \diamond \mathbf{G}_2)\, \mathbf{X}^{(2)}_{M_2 \times P_1 P_0 N}.$$

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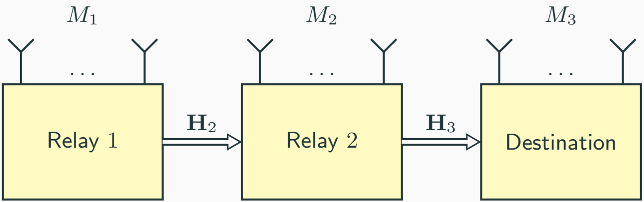

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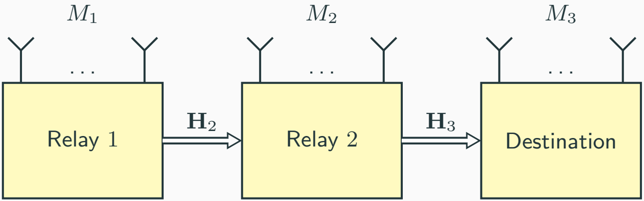

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$$\mathbf{X}^{(3)}_{M_3 P_2 \times P_1 P_0 N} = \underbrace{(\mathbf{H}_3 \diamond \mathbf{G}_2)\, \mathbf{H}_2}_{\mathbf{H}^{(1 \mapsto 3)}_{M_3 P_2 \times M_1}} \left(\mathbf{G}_1 \diamond \mathbf{X}^{(1)}_{P_0 N \times M_1} \right)^T$$

Received Signal at Destination

- $\mathbf{H}^{(1\mapsto 3)}_{M_3P_2\times M_1}$ is a unfolding of the third-order effective channel tensor $\mathcal{H}^{(1\mapsto 3)} \in \mathbb{C}^{M_3\times P_2\times M_1}$ linking the relay-1 and the destination (node-3)

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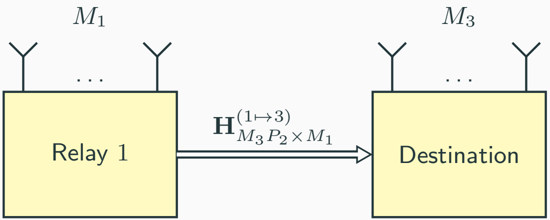

Received Signal at Destination

Equivalent Channel

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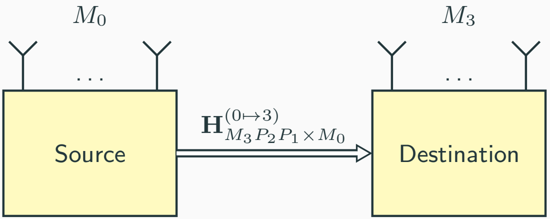

Closed-Form Semiblind Receiver

Receiver Equations

- The fifth-order nested PARAFAC model is decomposed into three third-order PARAFAC models from $\mathcal{X}^{(3)}$, $\mathcal{H}^{(0\mapsto 3)}$, and $\mathcal{H}^{(1\mapsto 3)}$ as

$$\begin{aligned}
\mathbf{X}^{(3)}_{NM_3P_2P_1\times P_0} &= \left(\mathbf{S}\diamond\mathbf{H}^{(0\mapsto 3)}_{M_3P_2P_1\times M_0}\right)\mathbf{G}_0^T = \mathbf{R}\mathbf{G}_0^T \\
\mathbf{H}^{(0\mapsto 3)}_{M_3P_2M_0\times P_1} &= \left(\mathbf{H}^{(1\mapsto 3)}_{M_3P_2\times M_1}\diamond\mathbf{H}_1^T\right)\mathbf{G}_1^T = \mathbf{Q}\mathbf{G}_1^T \\
\mathbf{H}^{(1\mapsto 3)}_{M_3M_1\times P_2} &= \left(\mathbf{H}_3\diamond\mathbf{H}_2^T\right)\mathbf{G}_2^T = \mathbf{Z}\mathbf{G}_2^T
\end{aligned} \tag{1}$$

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\end{aligned} \qquad (1)$$

- As $\mathbf{G}_k^T\mathbf{G}_k^* = \mathbf{I}_{M_k}$ for $k = 0, \cdots, K$ allows us to derive a three-step closed-form semiblind receiver to estimate the symbol matrix $\mathbf{S}$ and the channel matrices $\mathbf{H}_k$, $k = 1, 2, 3$

Closed-Form Semiblind Receiver

Receiver Equations

- Using the column orthonormality of $\mathbf{G}_k$, $k = 0, 1, 2$, the least squares (LS) estimates of $(\mathbf{R}, \mathbf{Q}, \mathbf{Z})$ can be successively calculated as

$$\hat{\mathbf{R}} = \mathbf{X}^{(3)}_{NM_3P_2P_1 \times P_0}\mathbf{G}_0^* \cong \left(\mathbf{S} \diamond \mathbf{H}^{(0\mapsto 3)}_{M_3P_2P_1 \times M_0}\right), \quad (2)$$

$$\hat{\mathbf{Q}} = \hat{\mathbf{H}}^{(0\mapsto 3)}_{M_3P_2M_0 \times P_1}\mathbf{G}_1^* \cong \left(\mathbf{H}^{(1\mapsto 3)}_{M_3P_2 \times M_1} \diamond \mathbf{H}_1^T\right), \quad (3)$$

$$\hat{\mathbf{Z}} = \hat{\mathbf{H}}^{(1\mapsto 3)}_{M_3M_1 \times P_2}\mathbf{G}_2^* \cong \left(\mathbf{H}_3 \diamond \mathbf{H}_2^T\right), \quad (4)$$

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$$\begin{aligned}
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\hat{\mathbf{Q}} &= \hat{\mathbf{H}}^{(0\mapsto 3)}_{M_3P_2M_0\times P_1}\mathbf{G}_1^* \cong \left(\mathbf{H}^{(1\mapsto 3)}_{M_3P_2\times M_1}\diamond\mathbf{H}_1^T\right), && (3)\\
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\end{aligned}$$

- From the LS estimate $\hat{\mathbf{R}}$, the factors $\mathbf{S}$ and $\mathbf{H}^{(0\mapsto 3)}_{M_3P_2P_1\times M_0}$ are found by the Khatri-Rao factorization (KRF) algorithm

Closed-Form Semiblind Receiver

Receiver Equations

- Using the column orthonormality of $\mathbf{G}_k$, $k = 0, 1, 2$, the least squares (LS) estimates of $(\mathbf{R}, \mathbf{Q}, \mathbf{Z})$ can be successively calculated as

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$$\hat{\mathbf{Z}} = \hat{\mathbf{H}}^{(1 \mapsto 3)}_{M_3M_1 \times P_2}\mathbf{G}_2^* \cong \left(\mathbf{H}_3 \diamond \mathbf{H}_2^T\right), \tag{4}$$

- From the LS estimate $\hat{\mathbf{R}}$, the factors $\mathbf{S}$ and $\mathbf{H}^{(0 \mapsto 3)}_{M_3P_2P_1 \times M_0}$ are found by the Khatri-Rao factorization (KRF) algorithm
- Then, the estimate $\hat{\mathbf{H}}^{(0 \mapsto 3)}_{M_3P_2P_1 \times M_0}$ is reshaped as $\hat{\mathbf{H}}^{(0 \mapsto 3)}_{M_3P_2M_0 \times P_1}$ to compute $\hat{\mathbf{Q}}$, from which the factors $\mathbf{H}_1$ and $\mathbf{H}^{(1 \mapsto 3)}_{M_3P_2 \times M_1}$ are extracted by applying the KRF algorithm

Closed-Form Semiblind Receiver

Receiver Equations

- Using the column orthonormality of $\mathbf{G}_k$, $k = 0, 1, 2$, the least squares (LS) estimates of $(\mathbf{R}, \mathbf{Q}, \mathbf{Z})$ can be successively calculated as

$$\hat{\mathbf{R}} = \mathbf{X}^{(3)}_{NM_3P_2P_1 \times P_0} \mathbf{G}_0^* \cong \left(\mathbf{S} \diamond \mathbf{H}^{(0 \mapsto 3)}_{M_3P_2P_1 \times M_0} \right), \quad (2)$$

$$\hat{\mathbf{Q}} = \hat{\mathbf{H}}^{(0 \mapsto 3)}_{M_3P_2M_0 \times P_1} \mathbf{G}_1^* \cong \left(\mathbf{H}^{(1 \mapsto 3)}_{M_3P_2 \times M_1} \diamond \mathbf{H}_1^T \right), \quad (3)$$

$$\hat{\mathbf{Z}} = \hat{\mathbf{H}}^{(1 \mapsto 3)}_{M_3M_1 \times P_2} \mathbf{G}_2^* \cong \left(\mathbf{H}_3 \diamond \mathbf{H}_2^T \right), \quad (4)$$

- From the LS estimate $\hat{\mathbf{R}}$, the factors $\mathbf{S}$ and $\mathbf{H}^{(0 \mapsto 3)}_{M_3P_2P_1 \times M_0}$ are found by the Khatri-Rao factorization (KRF) algorithm
- Then, the estimate $\hat{\mathbf{H}}^{(0 \mapsto 3)}_{M_3P_2P_1 \times M_0}$ is reshaped as $\hat{\mathbf{H}}^{(0 \mapsto 3)}_{M_3P_2M_0 \times P_1}$ to compute $\hat{\mathbf{Q}}$, from which the factors $\mathbf{H}_1$ and $\mathbf{H}^{(1 \mapsto 3)}_{M_3P_2 \times M_1}$ are extracted by applying the KRF algorithm
- Finally, $\hat{\mathbf{H}}^{(1 \mapsto 3)}_{M_3P_2 \times M_1}$ is reshaped as $\hat{\mathbf{H}}^{(1 \mapsto 3)}_{M_3M_1 \times P_2}$ to compute $\hat{\mathbf{Z}}$, from which the channels $(\mathbf{H}_2, \mathbf{H}_3)$ are extracted using again the KRF algorithm

General Case K relays

- The signals received at the destination defines a $(K+3)th$-order tensor $\tilde{\mathcal{X}}^{(K+1)} \in \mathbb{C}^{M_{K+1} \times P_K \times P_{K-1} \times \cdots \times P_0 \times N}$, with flat mode-1 unfolding as

$$\boxed{\mathbf{X}^{(K+1)}_{M_{K+1} \times P_K P_{K-1} \cdots P_0 N} = \mathbf{H}_{K+1} \left(\mathbf{G}_K \diamond \mathbf{X}^{(K)}_{P_{K-1} \cdots P_0 N \times M_K} \right)^T}$$

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$$\boxed{\mathbf{X}^{(K+1)}_{M_{K+1} \times P_K P_{K-1} \cdots P_0 N} = \mathbf{H}_{K+1} \left(\mathbf{G}_K \diamond \mathbf{X}^{(K)}_{P_{K-1} \cdots P_0 N \times M_K} \right)^T}$$

- The equivalent third-order PARAFAC model $\|\mathbf{H}^{(0 \mapsto K+1)}_{M_{K+1} P_K \cdots P_1 \times M_0}, \mathbf{G}_0, \mathbf{S}; M_0\|$ for $\mathcal{X}^{(K+1)}$ is

$$\boxed{\mathbf{X}^{(K+1)}_{N M_{K+1} P_K \cdots P_1 \times P_0} = \left(\mathbf{S} \diamond \mathbf{H}^{(0 \mapsto K+1)}_{M_{K+1} P_K \cdots P_1 \times M_0} \right) \mathbf{G}_0^T}$$

General Case K relays

- The signals received at the destination defines a $(K+3)th$-order tensor $\tilde{\mathcal{X}}^{(K+1)} \in \mathbb{C}^{M_{K+1}\times P_K \times P_{K-1}\times\cdots\times P_0\times N}$, with flat mode-1 unfolding as

$$\boxed{\mathbf{X}^{(K+1)}_{M_{K+1}\times P_K P_{K-1}\cdots P_0 N} = \mathbf{H}_{K+1}\left(\mathbf{G}_K \diamond \mathbf{X}^{(K)}_{P_{K-1}\cdots P_0 N\times M_K}\right)^T}$$

- The equivalent third-order PARAFAC model $\|\mathbf{H}^{(0\mapsto K+1)}_{M_{K+1}P_K\cdots P_1\times M_0}, \mathbf{G}_0, \mathbf{S}; M_0\|$ for $\mathcal{X}^{(K+1)}$ is

$$\boxed{\mathbf{X}^{(K+1)}_{NM_{K+1}P_K\cdots P_1\times P_0} = \left(\mathbf{S}\diamond\mathbf{H}^{(0\mapsto K+1)}_{M_{K+1}P_K\cdots P_1\times M_0}\right)\mathbf{G}_0^T}$$

- From $\mathbf{H}^{(0\mapsto K+1)}_{M_{K+1}P_K\cdots P_1\times M_0}$ we can define other K third-order PARAFAC models to estimate the individual channel hops as

$$\boxed{\mathbf{H}^{(k\mapsto K+1)}_{M_{K+1}P_K\cdots P_{k+2}M_k\times P_{k+1}} = (\mathbf{H}^{(k+1\mapsto K+1)}_{M_{K+1}P_K\cdots P_{k+2}\times M_{k+1}} \diamond \mathbf{H}^T_{k+1})\mathbf{G}^T_{k+1}}$$

Simulation Assumptions

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- The transmitted symbols are randomly drawn from a unit energy QAM symbol alphabet
- We assume $\mathbf{H}_{k+1}$, $k = 0, \cdots, K$, i.i.d. zero-mean circularly-symmetric complex Gaussian entries with variances given by $1/\eta^{\beta} M_k$, where $\eta = d/d_0 = 1/(K+1)$ and $\beta = 3$, d denoting the distance between two consecutive nodes, and d_0 the distance between the source and the destination

SER: 4-QAM, $K = 1:3$ relays

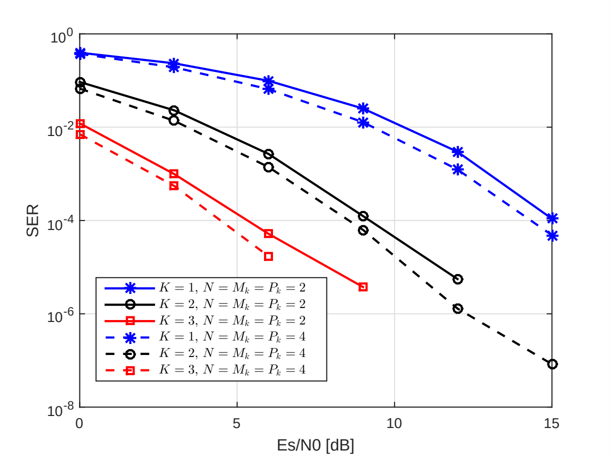

Figure 2: SER for three different numbers of relays and two system configurations.

NMSE: 4-QAM, $K = 2$ relays, $P_k = M_k = N = 3$

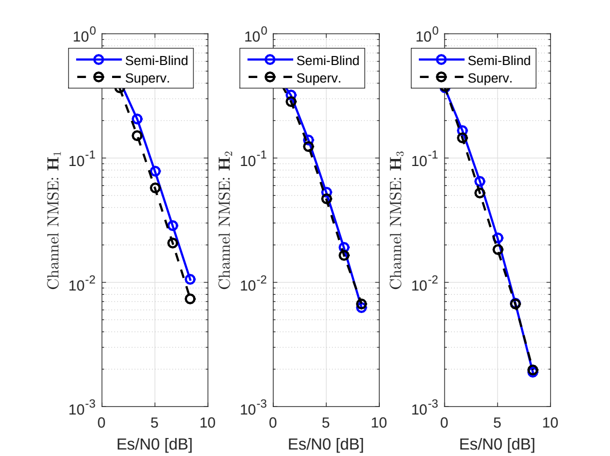

Figure 3: NMSE of the individual channels with $K = 2$.

Conclusions and Perspectives

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- Extensions of this work include the exploitation of the noise structure to develop a tensor-based receiver using a minimum-mean-square-error (MMSE) algorithm, and the case of orthogonal frequency division multiplexing (OFDM) relay systems

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Thank you for your attention.