FREQUENCY-DOMAIN DECOUPLING FOR MIMO-GFDM SPATIAL MULTIPLEXING

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Introduction

Generalized Frequency Division Multiplexing (GFDM)

- Generalization of traditional OFDM
- Low out-of-band (OOB) emissions
- Relaxed time-frequency synchronization requirements
- Potential inter subcarrier interference (ICI) w/ most prototype filters
- ICI-free ↔ frequency-domain (FD) decoupling

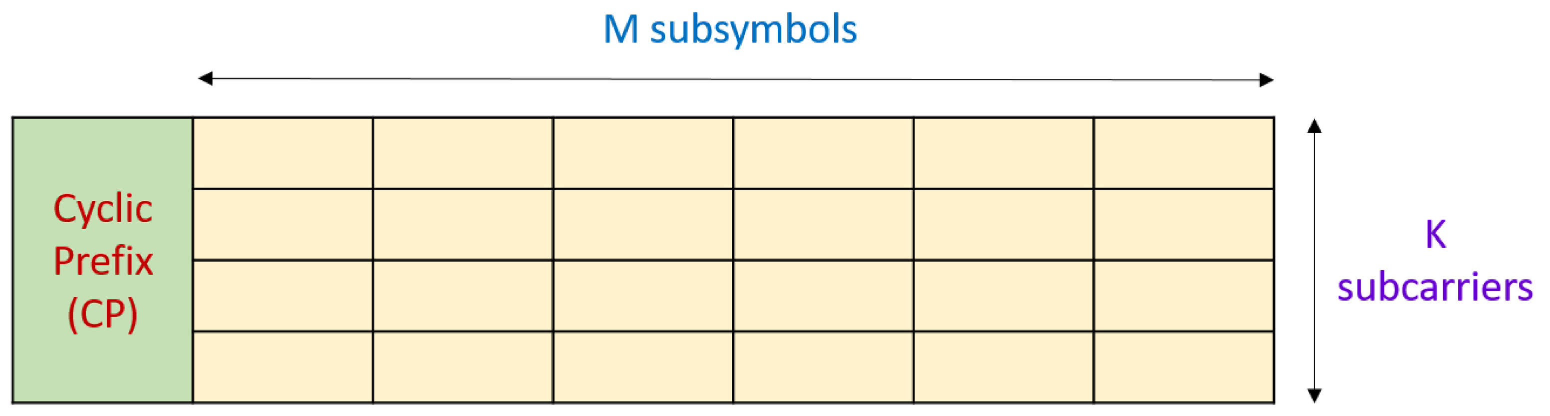


Figure 1: GFDM block

Contribution

- Propose a class of ICI-free prototype filters for MIMO-GFDM.
- Evaluate the depth-first sphere decoding (DFSD) with this class of prototype filters for MIMO-GFDM spatial multiplexing (SM).

System Model & Problem Formulation

MIMO-GFDM SM (w/ T Tx and R Rx antennas)

- GFDM transmitter matrix ($D = K \times M$)

$$\mathbf{A} = [\mathbf{g}_{0,0} \cdots \mathbf{g}_{K-1,0} \quad \mathbf{g}_{0,1} \cdots \mathbf{g}_{K-1,1} \cdots \mathbf{g}_{K-1,M-1}]$$

  – GFDM prototype filter: $\mathbf{g} \in \mathbb{C}^D$ (FD prototype filter: $\mathbf{g}_f = \sqrt{D}\mathbf{W}_D\mathbf{g}$)

  – Pulse-shaping: $[\mathbf{g}_{k,m}]_n = [\mathbf{g}]_{\langle n-mK \rangle_D} e^{j2\pi kn/K}$, $n = 0, 1, ..., D-1$, $m = 0, 1, ..., M-1, k = 0, 1, ..., K-1$

- The signal at receive antennas

$$\underbrace{\begin{bmatrix} \mathbf{y}_1 \\ \vdots \\ \mathbf{y}_R \end{bmatrix}}_{\mathbf{y}} = \underbrace{\begin{bmatrix} \mathbf{H}_{1,1}\mathbf{A} & \cdots & \mathbf{H}_{1,T}\mathbf{A} \\ \vdots & \ddots & \vdots \\ \mathbf{H}_{R,1}\mathbf{A} & \cdots & \mathbf{H}_{R,T}\mathbf{A} \end{bmatrix}}_{\tilde{\mathbf{H}}} \underbrace{\begin{bmatrix} \mathbf{d}_1 \\ \vdots \\ \mathbf{d}_T \end{bmatrix}}_{\mathbf{d}} + \mathbf{n} \qquad (1)$$

  – Maximum likelihood (ML) solution to (1): $\hat{\mathbf{d}} = \arg\min_{\mathbf{d} \in \mathcal{D}} \|\mathbf{y} - \tilde{\mathbf{H}}\mathbf{d}\|^2$ [4]

    * Exhaustive search is infeasible due to the huge size of $\mathcal{D}$.
    * FD decoupling splits the original problem into K subproblems.

Proposed Method

MIMO-GFDM Detection

Theorem (FD Decoupling)

Let $\mathbf{A}$ be a GFDM matrix derived from its FD prototype filter $\mathbf{g}_f$ and assume that $\mathbf{g}_f$ contains at most M consecutive nonzero entries (i.e., there exist $\mathbf{g}_1 \in \mathbb{C}^M$ and an integer l, $0 < l \leq D$) such that

$$\mathbf{g}_f = \mathbf{\Pi}_D^l \left[\mathbf{g}_1^T \; \mathbf{0}_{(K-1)M}^T \right]^T.$$

Consequently, the matrix $\tilde{\mathbf{H}}$ as defined in (1) can be decomposed into the form

$$\tilde{\mathbf{H}} = \mathbf{U}^H \text{blkdiag}(\{\mathbf{F}_k\}_{k=0}^{K-1})\mathbf{P},$$

where $\mathbf{U} = (\mathbf{\Pi}_{KR} \otimes \mathbf{I}_M)(\mathbf{I}_R \otimes \mathbf{\Pi}_D^{-l}\mathbf{W}_D)$, $\mathbf{P} = (\mathbf{\Pi}_{KT} \otimes \mathbf{I}_M)(\mathbf{I}_T \otimes \mathbf{\Pi}_{KM})$, and $\mathbf{F}_k$, $k = 0, ..., K-1$, are some $MR \times MT$ matrices.

- Notations: $\mathbf{\Pi}_A = \begin{bmatrix} \mathbf{0}^T & 1 \\ \mathbf{I}_{A-1} & \mathbf{0} \end{bmatrix}$, $[\mathbf{\Pi}_{AB}]_{mB+p,qA+n} = \delta_{mn}\delta_{pq}, \forall m, n \in \{0, 1, ..., A-1\}, \forall p, q \in \{0, 1, ..., B-1\}$.

  – MIMO-GFDM w/ Dirichlet filter: $\mathbf{g}_1 = \sqrt{K} \times \mathbf{1}_M$ and $l = D - \lfloor M/2 \rfloor$

  – MIMO-OFDM: $M = 1$

- Step 1: Multiply both sides of (1) with $\mathbf{U}$.

$$\bar{\mathbf{y}} = \mathbf{U}\mathbf{y} = \text{blkdiag}(\{\mathbf{F}_k\}_{k=0}^{K-1})\bar{\mathbf{d}} + \bar{\mathbf{n}}$$

- Step 2: Split into K subproblems and apply sorted QR decomposition (SQRD).

$$\bar{\mathbf{y}}_k = \mathbf{F}_k\bar{\mathbf{d}}_k + \bar{\mathbf{n}}_k = \mathbf{Q}_k\mathbf{R}_k\mathbf{P}_k^T\bar{\mathbf{d}}_k + \bar{\mathbf{n}}_k, k = 0, 1, ..., K-1 \qquad (2)$$

- Step 3: Multiply both sides of (2) with $\mathbf{Q}_k^H$.

$$\tilde{\bar{\mathbf{y}}}_k = \mathbf{Q}_k^H\bar{\mathbf{y}}_k = \mathbf{R}_k\tilde{\bar{\mathbf{d}}}_k + \tilde{\bar{\mathbf{n}}}_k, k = 0, 1, ..., K-1 \qquad (3)$$

- Step 4: Find the ML solution $\hat{\tilde{\bar{\mathbf{d}}}}_k$ to (3) with DFSD.

Complexity Analysis

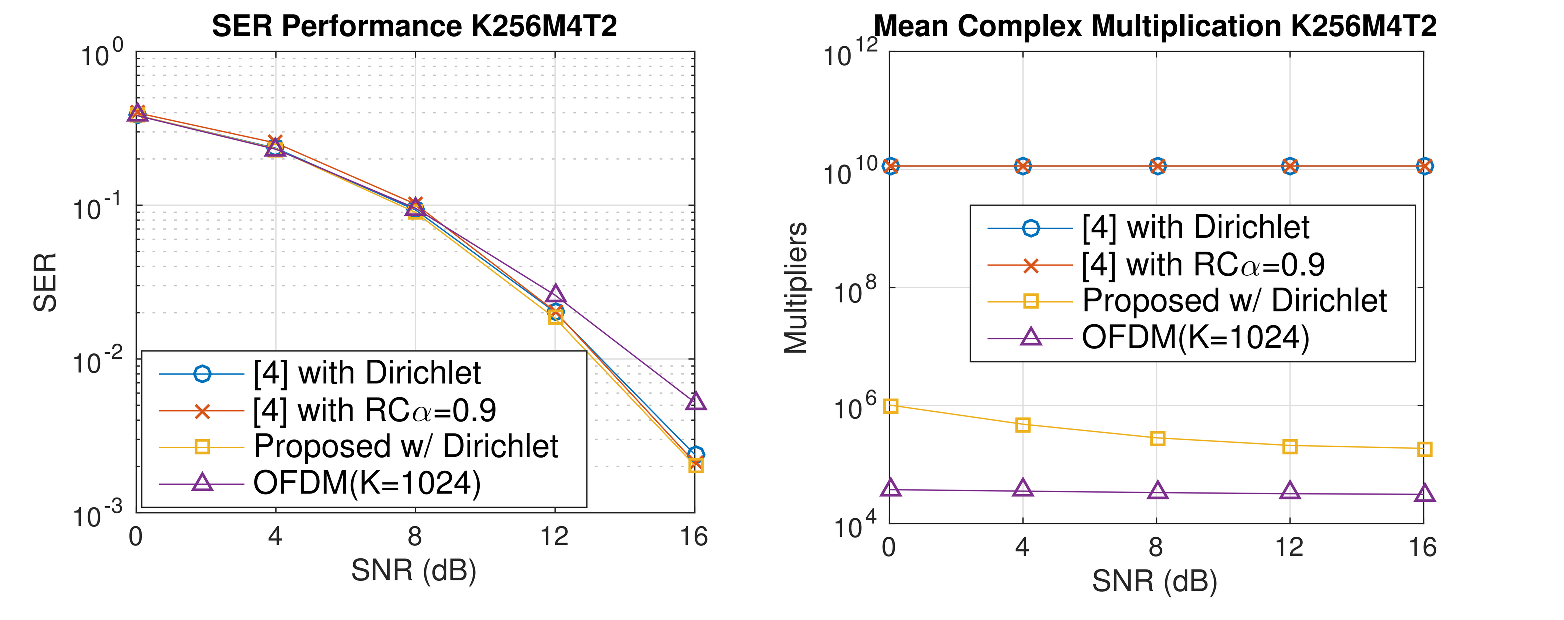
- Complexity: # of complex multiplications (CMs) required to detect KMT symbols at the receiver

Table 1: Computational Complexity of SQRD and successive interference cancellation (SIC)

Scheme	SQRD	SIC
OFDM	$KMT^2R + KMTR + (KMT^2 - KMT)/2$ (Using SQRD)	0
Near-ML MIMO-GFDM [4]	$K^3M^3T^2R + K^2M^2TR + (2K^3M^3T^3 + 3K^2M^2T^2 + KMT)/6$ (Using MMSE-SQRD)	$K^2T^2M^2$
Proposed	$KM^3T^2R + KM^2TR + (KM^2T^2 - KMT)/2$ (Using SQRD)	0

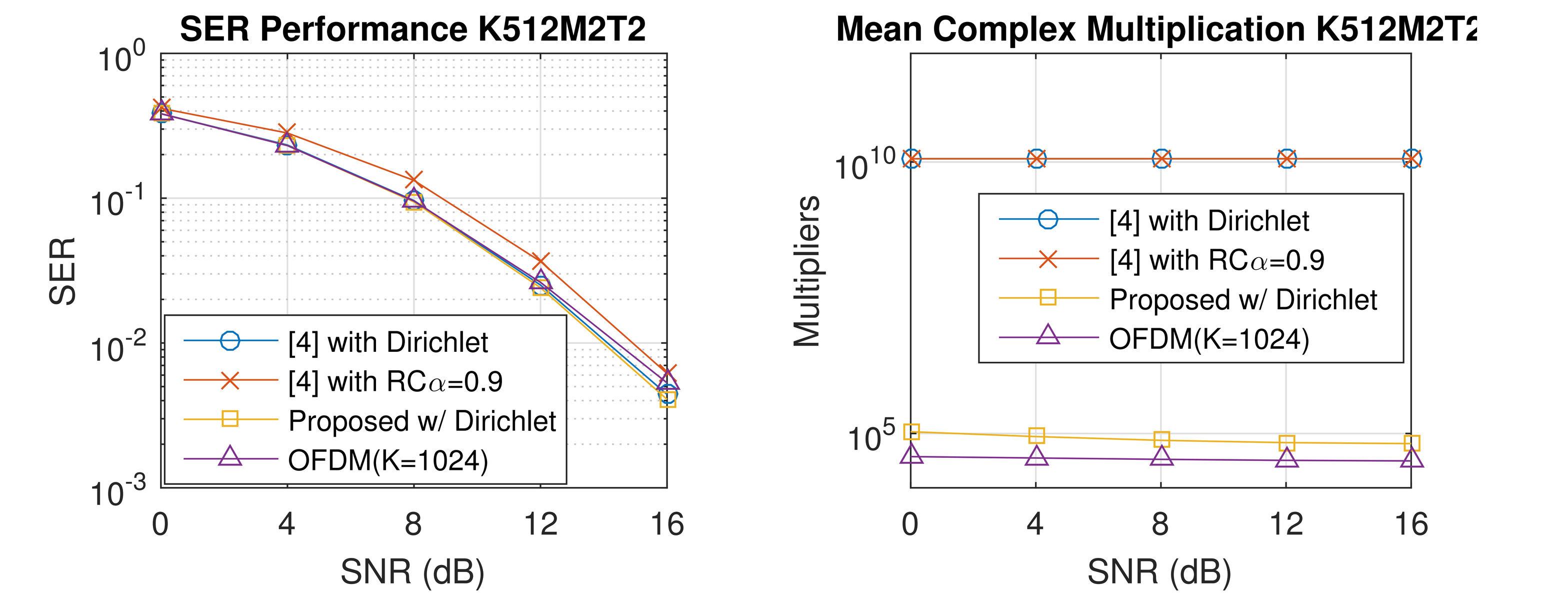
Simulation

- Modulation: QPSK, symbol energy: $E_s = 1$, and CP length: $L = D/8$
- # of SM-mode MIMO spatially uncorrelated Rayleigh-fading multipath channel realizations: 500
- Chan. power delay profile: exponential from 0 to -10 dB with L taps
- # of independent data blocks for each channel realization: 100
- $(T, R) = (2, 2)$



(a) SER (b) Complexity

Figure 2: Performances for $K = 256, M = 4, T = 2$



(a) SER (b) Complexity

Figure 3: Performances for $K = 512, M = 2, T = 2$

- Symbol error rate (SER): MIMO-GFDM (FD decoup.) > MIMO-GFDM ([4]) > MIMO-OFDM (subcarrier spacing ↔ frequency diversity)
- Complexity: MIMO-GFDM significantly improves via FD decoupling.

Conclusion

- MIMO-GFDM achieves FD decoupling w/ proposed prototype filters.
- Dirichlet filter w/ proposed scheme outperforms widely-applied RC filter in terms of SER and complexity performances for MIMO-GFDM.

References

[4] M. Matthé, I. Gaspar, D. Zhang, and G. Fettweis, "Near-ML Detection for MIMO-GFDM," in *Veh. Technol. Conf. (VTC Fall), 2015 IEEE 82nd*, Sept. 2015, pp. 1–2.

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