Uplink Symbol Detection in Dynamic TDD MIMO Systems with AP-AP Interference

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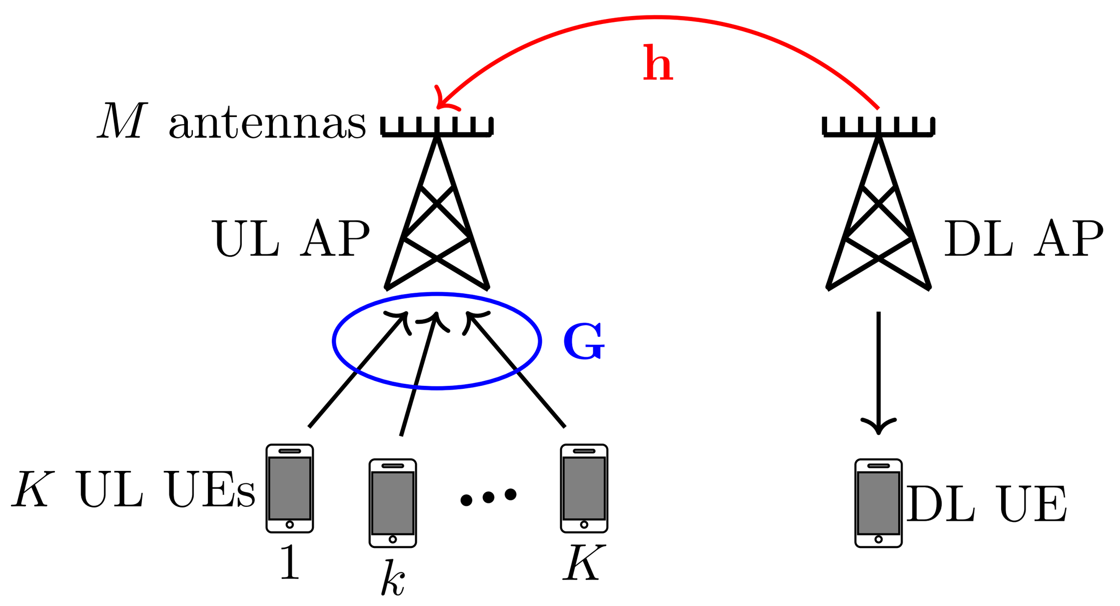
Abstract

We consider a MIMO communication system operating in dynamic TDD, where one uplink (UL) access point (AP) detects data symbols transmitted from UL users (UEs) in the presence of AP-AP interference caused by the signal a downlink (DL) AP transmits to a DL UE. We propose to jointly estimate the UL symbols and the interference channel, but show that this problem is not uniquely solvable in the least-squares sense, and propose two methods for symbol detection that overcome this issue.

System Model



- $\tau_c \in \mathbb{N}$: Coherence block length (number of samples).
- $\mathbf{G} \in \mathbb{C}^{M\times K}$: Channel from UL UEs to UL AP.
- $\mathbf{X} \in \mathbb{C}^{K\times \tau_c}$: Data transmitted from UL UEs.
- $\mathbf{h} \in \mathbb{C}^{M\times 1}$: Effective (single-layer) AP-AP interference channel.
- $\mathbf{s} \in \mathbb{C}^{\tau_c\times 1}$: Data transmitted from DL AP.
- $\mathbf{W} \in \mathbb{C}^{M\times \tau_c}$: Receiver noise at UL AP.

The UL AP receives (on equivalent matrix and vector forms):

$$\boxed{\mathbf{Y} = \mathbf{G}\,\mathbf{X} + \mathbf{h}\,\mathbf{s}^T + \mathbf{W} \in \mathbb{C}^{M\times\tau_c} \quad \text{or} \quad \mathbf{y} = \mathbf{A}\,\mathbf{z} + \mathbf{w} \in \mathbb{C}^{M\tau_c\times 1}.}$$

To derive the second expression, recall $\mathrm{vec}(\mathbf{B}\,\mathbf{C}\,\mathbf{D}) = (\mathbf{D}^T \otimes \mathbf{B})\,\mathrm{vec}(\mathbf{C})$, and define $\mathbf{x} \triangleq \mathrm{vec}(\mathbf{X})$, $\mathbf{y} \triangleq \mathrm{vec}(\mathbf{Y})$, and $\mathbf{w} \triangleq \mathrm{vec}(\mathbf{W})$, to write:

$$\begin{aligned} \mathbf{y} &= (\mathbf{I}_{\tau_c} \otimes \mathbf{G})\,\mathbf{x} + (\mathbf{s} \otimes \mathbf{I}_M)\,\mathbf{h} + \mathbf{w} \\ &= \underbrace{[(\mathbf{I}_{\tau_c} \otimes \mathbf{G}) \quad (\mathbf{s} \otimes \mathbf{I}_M)]}_{\triangleq \mathbf{A}} \underbrace{\begin{bmatrix}\mathbf{x} \\ \mathbf{h}\end{bmatrix}}_{\triangleq \mathbf{z}} + \mathbf{w} = \mathbf{A}\,\mathbf{z} + \mathbf{w}. \end{aligned}$$

Problem Formulation

We propose to jointly estimate $\mathbf{X}$ and $\mathbf{h}$ with the least-squares method:

$$\min_{\mathbf{X},\mathbf{h}} \|\,\mathbf{Y} - \mathbf{G}\,\mathbf{X} - \mathbf{h}\,\mathbf{s}^T\,\|^2 \qquad \text{or} \qquad \min_{\mathbf{z}} \|\,\mathbf{y} - \mathbf{A}\,\mathbf{z}\,\|^2.$$

However, this problem is not uniquely solvable. In fact, the solution space is K-dimensional:

Theorem 1. *The nullspace of $\mathbf{A}$ is K-dimensional, i.e., so is the solution space to the least-squares problem.*

Proof. See [1, Appendix A]. □

Solution

We solve this by forcing the UL UEs to be silent in their first sample:

$$\mathbf{X} = [\mathbf{0}_{K\times 1}, \bar{\mathbf{X}}].$$

Then, the received signal at the UL AP can be partitioned as

$$[\mathbf{y}_1, \bar{\mathbf{Y}}] = \mathbf{G}[\mathbf{0}_{K\times 1}, \bar{\mathbf{X}}] + \mathbf{h}[s_1, \bar{\mathbf{s}}^T] + [\mathbf{w}_1, \bar{\mathbf{W}}].$$

We propose two methods for symbol estimation:

- **Method 1**: Joint estimation of data $\bar{\mathbf{X}}$ and interference channel $\mathbf{h}$.
- **Method 2**: Estimate $\mathbf{h}$ with the first sample and subtract interference.

Method 1: Joint Estimation

Disregarding the first sample, the UL AP receives:

$$\bar{\mathbf{Y}} = \mathbf{G}\,\bar{\mathbf{X}} + \mathbf{h}\,\bar{\mathbf{s}}^T + \bar{\mathbf{W}} \qquad \text{or} \qquad \bar{\mathbf{y}} = \bar{\mathbf{A}}\bar{\mathbf{z}} + \bar{\mathbf{w}},$$

where $\bar{\mathbf{A}}$ is full rank and is obtained by removing the first K columns of $\mathbf{A}$. We propose to jointly estimate the remaining UL data $\bar{\mathbf{X}}$ and $\mathbf{h}$:

$$\min_{\bar{\mathbf{X}},\mathbf{h}} \|\bar{\mathbf{Y}} - \mathbf{G}\,\bar{\mathbf{X}} - \mathbf{h}\,\bar{\mathbf{s}}^T\|^2 \qquad \text{or} \qquad \min_{\bar{\mathbf{z}}} \|\bar{\mathbf{y}} - \bar{\mathbf{A}}\bar{\mathbf{z}}\|^2,$$

with the unique solution

$$\hat{\bar{\mathbf{z}}} = (\bar{\mathbf{A}}^H\bar{\mathbf{A}})^{-1}\bar{\mathbf{A}}^H\bar{\mathbf{y}}.$$

Extract $\hat{\bar{\mathbf{x}}}$ from $\hat{\bar{\mathbf{z}}}$ and reshape to obtain the estimate $\hat{\bar{\mathbf{X}}}$ of $\bar{\mathbf{X}}$.

Method 2: Interference Subtraction

The first sample is used to obtain the least-squares estimate $\hat{\mathbf{h}}$ of $\mathbf{h}$:

$$\mathbf{y}_1 = \mathbf{h}\,s_1 + \mathbf{w}_1 \qquad \Rightarrow \qquad \hat{\mathbf{h}} = \frac{s_1^*}{|s_1|^2}\,\mathbf{y}_1\,.$$

Subtract the known part $\hat{\mathbf{h}}\bar{\mathbf{s}}^T$ of the interference before estimating $\bar{\mathbf{X}}$:

$$\hat{\bar{\mathbf{X}}} = (\mathbf{G}^H\,\mathbf{G})^{-1}\,\mathbf{G}^H(\bar{\mathbf{Y}} - \hat{\mathbf{h}}\bar{\mathbf{s}}^T).$$

Baseline Algorithms

Define the interference-free signal:

$$\dot{\mathbf{Y}} \triangleq \mathbf{Y} - \mathbf{h}\,\mathbf{s}^T = \mathbf{G}\,\mathbf{X} + \mathbf{W} \quad \text{or} \quad \dot{\mathbf{y}} = \underbrace{(\mathbf{I}_{\tau_c} \otimes \mathbf{G})}_{\triangleq \dot{\mathbf{A}}}\,\mathbf{x} + \mathbf{w} = \dot{\mathbf{A}}\,\mathbf{x} + \mathbf{w}\,.$$

We consider one best-case (genie) and one worst-case (naive) baseline:

- **Genie** (full interference mitigation): $\hat{\bar{\mathbf{X}}} = (\dot{\mathbf{A}}^H\dot{\mathbf{A}})^{-1}\dot{\mathbf{A}}^H\dot{\mathbf{y}}$.
- **Naive** (no interference mitigation): $\hat{\bar{\mathbf{X}}} = (\dot{\mathbf{A}}^H\dot{\mathbf{A}})^{-1}\dot{\mathbf{A}}^H\,\mathbf{y}$.

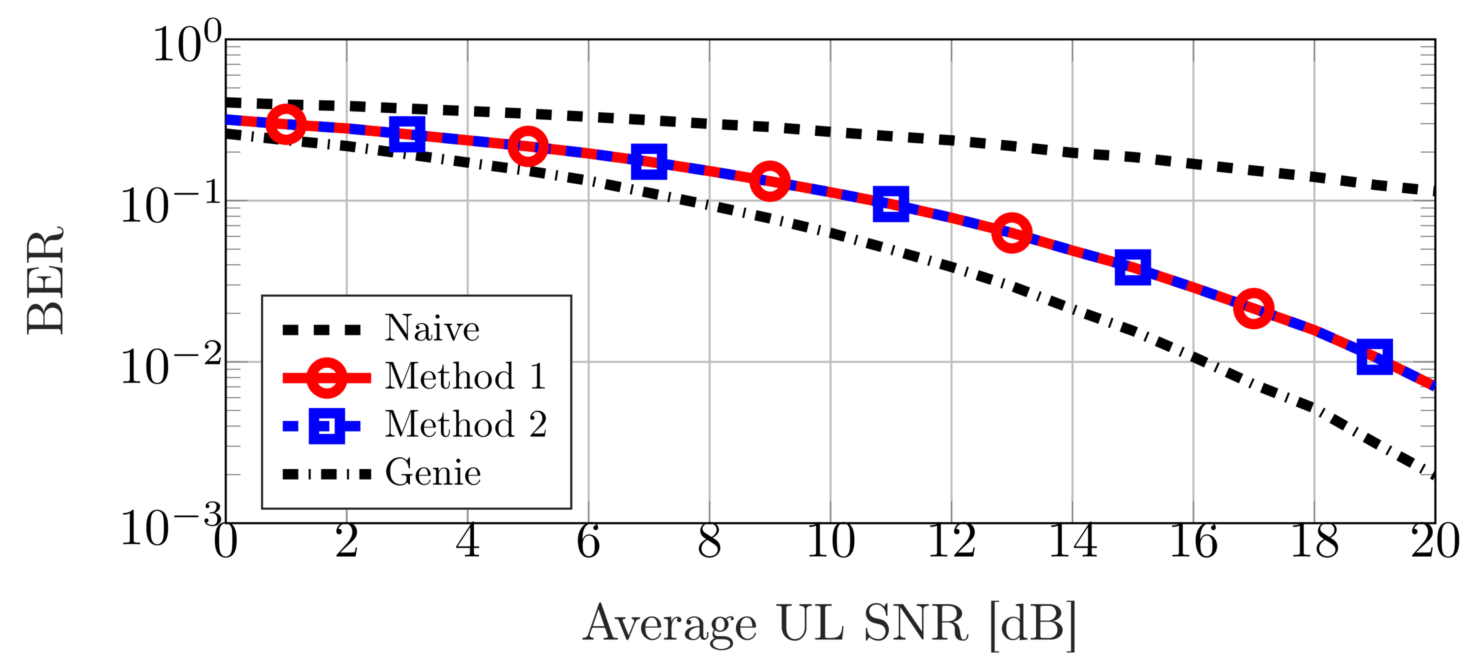
Performance Comparison

Interestingly, our two methods turn out to be equivalent:

Theorem 2. *Method 1 and Method 2 are equivalent.*

Proof. See [1, Appendix D]. □

We compare our two methods to the genie and naive baseline algorithms. With $M = 10$, $K = 3$, $\tau_c = 50$ and APs/UEs randomly distributed in a 250×250 m^2 square, we get the following bit-error rates (BERs):



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