Massive Unsourced Random Access Based on Bilinear Vector Approximate Message Passing

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1 Summary

- New algorithmic solution to the massive unsourced random access (mURA) problem.
- Relies on slotted transmissions framework.
- Takes advantage of the inherent coupling provided by the users' spatial signatures in the form of channel correlations across slots.
- Eliminates the need for concatenated coding.
- Combines the steps of activity detection, channel estimation, and data decoding into a unified mURA framework.
- Uses the bilinear vector approximate message passing (Bi-VAMP) algorithm, tailored to fit the inherent constraints of mURA.
- The modified Bi-VAMP algorithm uses a probabilistic observation model to jointly recover the two unknown matrices from their noise-corrupted product.
- **Idea**:
  - We can model the mURA problem in the adequate matrix way that can be tackled by Bi-VAMP.

3 Bi-VAMP

The Bi-VAMP algorithm can jointly recovers two matrices **X** = **AΔ** and **H** from their noisy product through a probabilistic observation model.

$$\mathbf{Y} = \mathbf{XH} + \mathbf{W}.$$

In principle, the standard Bi-VAMP algorithm enables the use of different priors on the columns of **H** as well as on the rows of **X**. however, the specific structure of **Δ** enforces a prior on the columns of each slot.

The prior on slots of **Δ** is assumed to be column-wise separable and expressed as follow:

$$p_{\boldsymbol{\delta}_{k,l}}(\boldsymbol{\delta}_{k,l}) = \frac{1}{2^J}\sum_{j=1}^{2^J}\delta(\boldsymbol{\delta}_{k,l} - \mathbf{u}_j),$$

We assume a column-wise separable prior on **H:**

$$p_{\mathrm{H}}(\mathrm{H}) = \prod_{i=1}^{M_r} p_{\mathrm{h}_i}(\mathrm{h}_i) \text{ with } p_{\mathrm{h}_i}(\mathrm{h}_i) = \mathcal{N}(\mathrm{h}_i; 0, \sigma^2\mathrm{I}).$$

2 System Model

Base station (BS) containing Mr receiving antennas serving a network consisting of Ka active devices. The uplink received signal at the BS antenna m in the l slot is expressed as follow:

$$\mathbf{y}_{m,l} = \sum_{k=1}^{K}\sum_{j=1}^{2^J}\sqrt{\beta_k}\, g_{k,m}\delta_{j,k,l}\mathbf{a}_j + \mathbf{w}_{m,l}.$$

Where :

- β_k is the large scale fading,
- $g_{k,m} \sim \mathcal{CN}(\mathbf{0}, \mathbf{I})$ is small scale fading,
- $\mathbf{w}_{m,l} \sim \mathcal{CN}(\mathbf{0}, \sigma_w^2\mathbf{I})$ is the white additive Gaussian noise,
- $\delta_{j,k,l} = \begin{cases} 1 & \text{if user } k \text{ transmits codeword } \mathbf{a}_j \text{ in the } l^{th} \text{ slot} \\ 0 & \text{otherwise} \end{cases}$

The input-output relationship of the system is expressed as matrices equations:

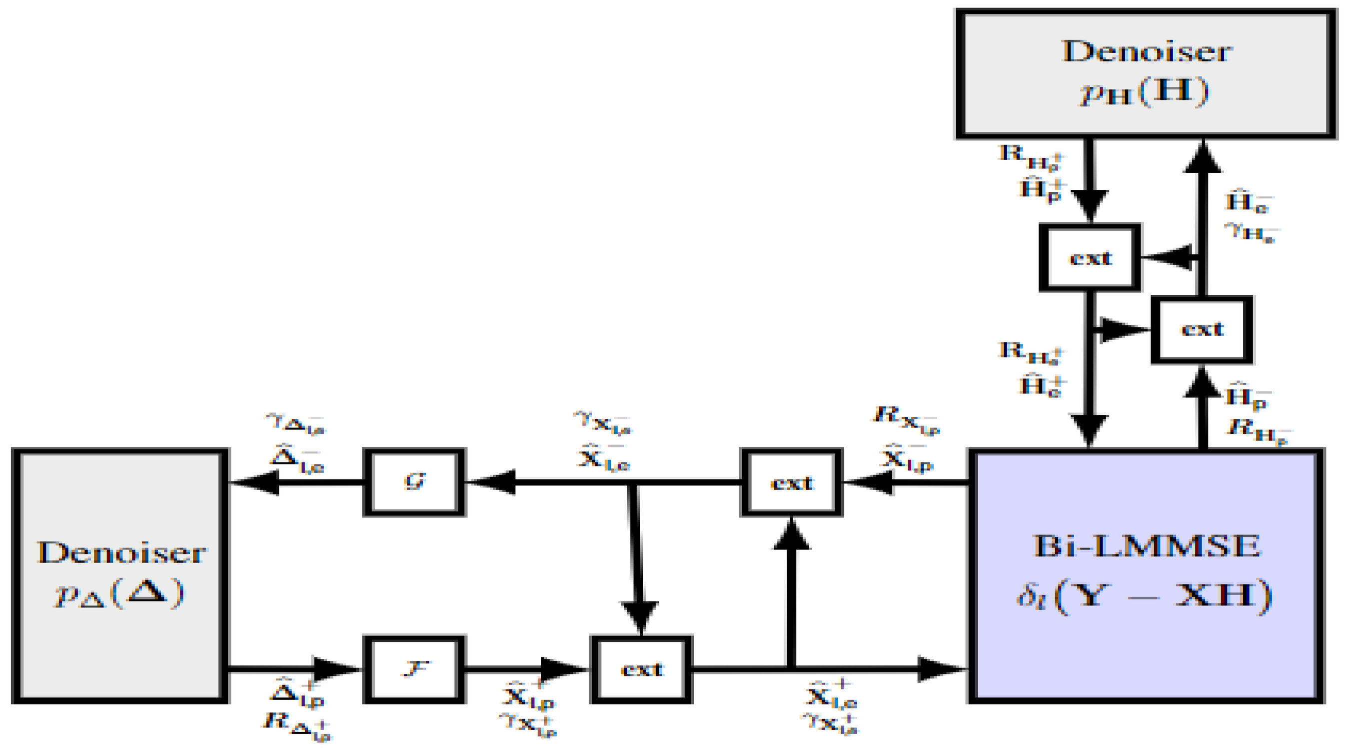
$$\mathrm{Y}_l = \mathcal{A}\Delta_l\mathrm{H} + \mathrm{W}_l \quad \text{for} \quad l = 1, \ldots, L.$$

H the unknown channel matrix common to all slots. The structure of the **Δ** matrices are imposed the following constraints:

- **Constraint 1:** The number of codewords sent in each slot must be equal to Ka.
- **Constraint 2:** Different users can transmit the same codeword in the same slot.
- **Constraint 3:** Every user transmits exactly L codewords over the whole transmission period.

The Bi-VAMP algorithm should be tailored to fit the inherent constraints of mURA.

4 Block diagram



Block diagram of the adapted Bi-VAMP algorithm with its three modules: two denoising modules and the approximate bi-LMMSE module.

The messages calculated by the denoising blocks is calculated as follow:

$$\widehat{\boldsymbol{h}}^{+}_{\mathrm{m,p}} = \mathrm{g_h}\left(\widehat{\boldsymbol{h}}^{-}_{\mathrm{m,e}}, \gamma_{\boldsymbol{H}^{-}_{\mathrm{e}}}\right), \mathbf{R}_{\boldsymbol{H}^{+}_{\mathrm{p}}} = \frac{\gamma^{-1}_{\boldsymbol{H}^{-}_{\mathrm{e}}}}{M_r}\sum_{m=1}^{M_r}\mathrm{g}'_{\mathrm{h}}\left(\widehat{\boldsymbol{h}}^{-}_{\mathrm{m,e}}, \gamma_{\boldsymbol{H}^{-}_{\mathrm{e}}}\right)$$

$$\widehat{\boldsymbol{\delta}}^{l,+}_{\mathrm{k,p}} = \mathrm{g}_{\delta}\left(\widehat{\boldsymbol{\delta}}^{l,-}_{\mathrm{k,e}}, \gamma_{\boldsymbol{\Delta}^{-}_{\mathrm{l,e}}}\right), \mathbf{R}_{\boldsymbol{\Delta}^{+}_{\mathrm{l,p}}} = \frac{\gamma^{-1}_{\boldsymbol{\Delta}^{-}_{\mathrm{l,e}}}}{K_a}\sum_{k=1}^{K_a}\mathrm{g}'_{\delta}\left(\widehat{\boldsymbol{\delta}}^{-}_{\mathrm{k,l,e}}, \gamma_{\boldsymbol{\Delta}^{-}_{\mathrm{l,e}}}\right)$$

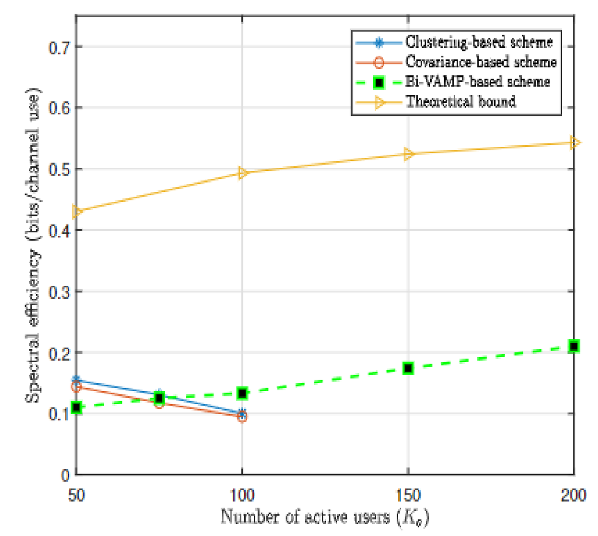
Where:

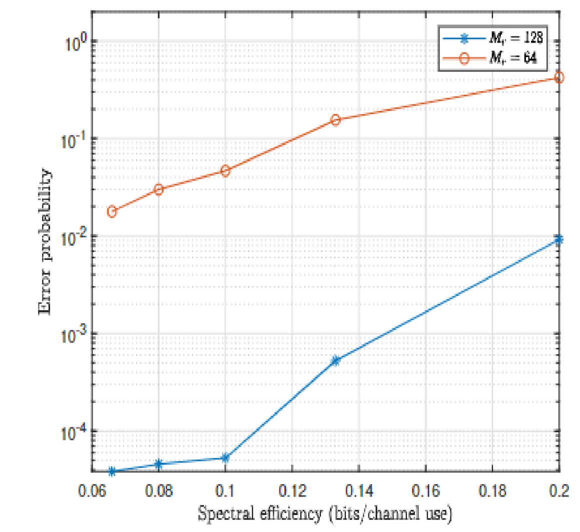
$$\mathrm{g_h}\left(\widehat{h}, \gamma_{H}^{-1}\right) = \frac{\int h p_{\mathrm{h}}(h)\mathcal{N}\left(h; \widehat{h}, \gamma_{H}^{-1}\boldsymbol{I}\right) dh}{\int p_{\mathrm{h}}(h)\mathcal{N}\left(h; \widehat{h}, \gamma_{H}^{-1}\boldsymbol{I}\right) dh}, \quad \mathrm{g}'_{\mathrm{h}}\left(\widehat{h}, \gamma_{H}^{-1}\right) = \frac{\partial \mathrm{g_h}\left(\widehat{h}, \gamma_{H}^{-1}\right)}{\partial \widehat{h}}$$

$$\mathrm{g}_{\delta}\left(\widehat{\delta}, \gamma_{\Delta}^{-1}\right) = \frac{\int \delta p_{\delta}(\delta)\mathcal{N}\left(\delta; \widehat{\delta}, \gamma_{\Delta}^{-1}\boldsymbol{I}\right) d\delta}{\int p_{\delta}(\delta)\mathcal{N}\left(\delta; \widehat{\delta}, \gamma_{\Delta}^{-1}\boldsymbol{I}\right) d\delta}, \quad \mathrm{g}'_{\delta}\left(\widehat{\delta}, \gamma_{\Delta}^{-1}\right) = \frac{\partial \mathrm{g}_{\delta}\left(\widehat{\delta}, \gamma_{\Delta}^{-1}\right)}{\partial \widehat{\delta}}$$

5 Results

Simulation 1: Covariance based scheme (CCS) / Clustering-based scheme / Bi-VAMP based scheme. We determine the largest per-user spectral efficiency which leads to a target error probability of 0.01 with fixing the ratio of number of receiving antennas per active user to 0.6. $K_a \in \{50, 75, 100, 150, 200\}$, $M_r \in \{30, 45, 60, 90, 120\}$





Simulation 2: we fix the number of active users to 200 and the SNR to 30 dB while varying the spectral efficiency from 0.065 to 0.2 for Mr=64 and Mr= 128.

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