FASURA: A Scheme for Quasi-Static Unsourced Random Access Channels

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International Symposium on Topics in Coding (ISTC) Workshop

August 2022

This material is based upon work supported, in part, by NSF under Grants CNS-2148354, CCF-2131106, and CCF-1619085

This material is also based upon work support, in part, by Qualcomm Technologies, Inc., through their University Relations Program

Presentation Outline and Objectives

Unsourced random access

1. Motivation
2. Uncoordinated & unsourced
3. Single-antenna setting
4. Spread architecture
5. Multi-antenna setting
6. FASURA

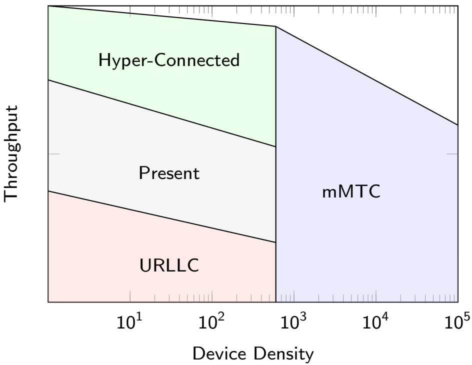
Tools for complexity

- Signal from message alone
- Activity detection
- Gaussian linear form
- LMMSE estimation
- Successive interference cancellation

Additional Resources

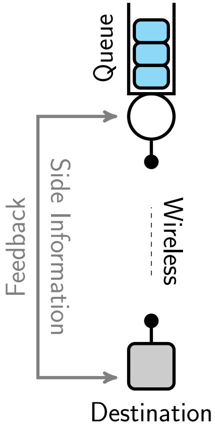
- Source code
- `https://engprojects.github.io/mMTC/`

6G Envisioned Traffic Types



- Hyper-Connected Experience: XR, Hologram, Digital Replica
- Ultra-Reliable and Low Latency Communications (URLLC)
- massive Machine Type Communications (mMTC) – Uplink

An Evolving Wireless Landscape



Conventional systems

- Human operators, sustained connections
- Scheduling decisions based on channel quality & queue length
- Acquisition of side information amortized over long connections

Envisioned IoT environments

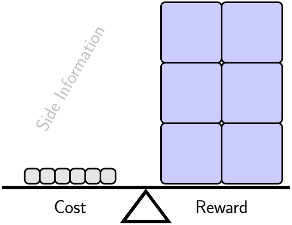
- Machine-to-machine communications
- Sporadic single transmissions from large number of devices
- Minute payloads

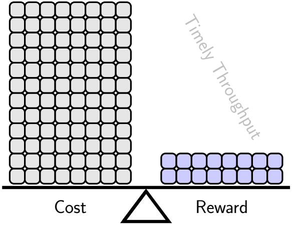
Losing Connections

Emerging M2M traffic characteristics

- Device density – Massive versus small
- Connectivity profile – Sporadic versus sustained
- Packet payloads – Minuscule versus moderate-to-long

Anticipated traffic characteristics invalidate the acquisition-estimation-scheduling paradigm!





Leveraging Sparsity in mMTC Uplink Traffic

Revival of Uncoordinated Access

- Must address sporadic nature of machine-driven communications
- Transfer of small payloads without ability to amortize cost of acquiring channel and buffer states over long connections
- Preclude use of opportunistic scheduling

Communication and Identity

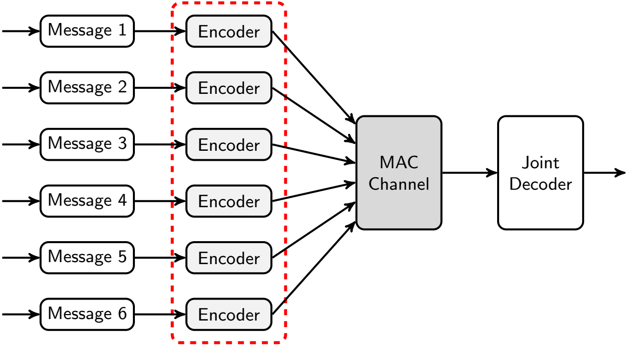
When number of devices is massive, with only subset of them active, problem of allocating resources (e.g., codebook, subcarriers, signature sequences) to every user as to manage interference becomes complex

Unsourced Random Access

Part I

One Antenna at Receiver: Spread Unsourced Random Access with Tensor/Hadamard Constructions

Uncoordinated and Unsourced MAC



No personalized feedback

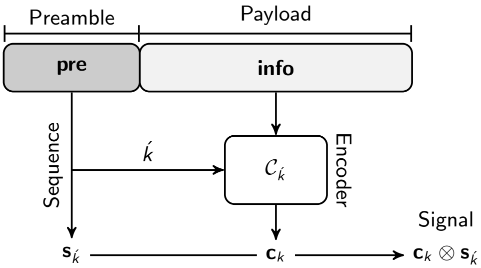
- All devices use same codebook
- No explicit knowledge of identities
- Decoder returns unordered list

Mathematical model

$$\mathbf{y} = \sum_i \mathbf{x}_i + \mathbf{z}$$

where $\mathbf{x}_i$ depends on message

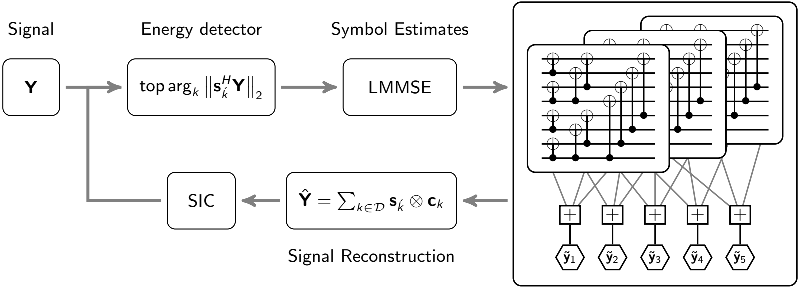
Spreading Unsourced Random Access



- Message is partitioned into two parts (**pre**, **info**)
- Preamble **pre** selects spreading sequence
- Payload **info** is encoded using traditional code: Polar/LDPC

Remark: Presentation adopts tensor product $\mathbf{c}_k \otimes \mathbf{s}_{\acute{k}}$ for simplicity.
In reality, signal is created using Hadamard product $(\mathbf{c}_k \otimes \mathbf{1}) \circ \mathbf{s}_{\acute{k}}$

Joint Decoding Architecture



Signal

$\mathbf{Y}$

Energy detector

$\text{top}\,\text{arg}_k \left\|\mathbf{s}_{\acute{k}}^H \mathbf{Y}\right\|_2$

Symbol Estimates

LMMSE

SIC

$\hat{\mathbf{Y}} = \sum_{k\in\mathcal{D}} \mathbf{s}_{\acute{k}} \otimes \mathbf{c}_k$

Signal Reconstruction

1. Sequence identification
2. Symbol estimation
3. Bank of single-user decoders
4. Signal reconstruction
5. Successive interference cancellation

Signal Structure and Energy Detector

- Outer product representation of sent signal

$$\mathbf{X}_k = \mathbf{s}_{\acute{k}} \cdot \mathbf{c}_k^{\mathsf{T}} = \begin{bmatrix} | & | & & | \\ c_1\,\mathbf{s}_{\acute{k}} & c_2\,\mathbf{s}_{\acute{k}} & \cdots & c_n\,\mathbf{s}_{\acute{k}} \\ | & | & & | \end{bmatrix}$$

- Outer product representation of received signal

$$\mathbf{Y} = \sum_k \mathbf{X}_k + \mathbf{Z}$$

- Energy detector for sequence identification

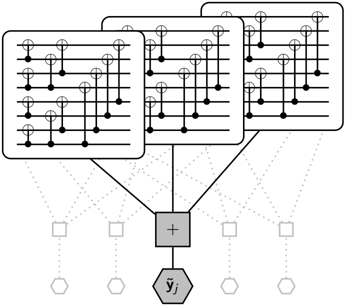
$$\mathbf{s}_{\acute{k}}^H \mathbf{Y} = \left\|\mathbf{s}_{\acute{k}}\right\|_2^2 \mathbf{c}_k^{\mathsf{T}} + \underbrace{\sum_{\ell \neq k} \left\langle \mathbf{s}_{\acute{k}}, \mathbf{s}_{\acute{\ell}} \right\rangle \mathbf{c}_\ell^{\mathsf{T}}}_{\text{Noise like}} + \mathbf{s}_{\acute{k}}^H \mathbf{Z}$$

$$\text{Set of active sequences} = \operatorname*{top\,arg}_{\acute{k}} \left\|\mathbf{s}_{\acute{k}}^H \mathbf{Y}\right\|_2$$

Intuition Behind Symbol Estimation

Measurement structure
(w/o collisions)

$$\mathbf{Y} = \sum_k \begin{bmatrix} | \\ \mathbf{s}_{\acute{k}} \\ | \end{bmatrix} \begin{bmatrix} -\mathbf{c}_k- \end{bmatrix} + \mathbf{Z}$$



Rearranging terms, we get

$$\mathbf{Y} = \begin{bmatrix} \sum_k \begin{matrix} | \\ \mathbf{s}_{\acute{k}} \\ | \end{matrix} c_{k,1} & \sum_k \begin{matrix} | \\ \mathbf{s}_{\acute{k}} \\ | \end{matrix} c_{k,2} & \cdots & \sum_k \begin{matrix} | \\ \mathbf{s}_{\acute{k}} \\ | \end{matrix} c_{k,n} \end{bmatrix} + \mathbf{Z}$$

$$= \begin{bmatrix} \mathbf{S} \begin{bmatrix} c_{1,1} \\ \vdots \\ c_{K,1} \end{bmatrix} & \mathbf{S} \begin{bmatrix} c_{1,2} \\ \vdots \\ c_{K,2} \end{bmatrix} & \cdots & \mathbf{S} \begin{bmatrix} c_{1,n} \\ \vdots \\ c_{K,n} \end{bmatrix} \end{bmatrix} + \mathbf{Z}$$

Intuition Behind Symbol Estimation

Active sequences known

- Gaussian linear form

$$\mathbf{Y} = \mathbf{S}\mathbf{C} + \mathbf{Z}$$

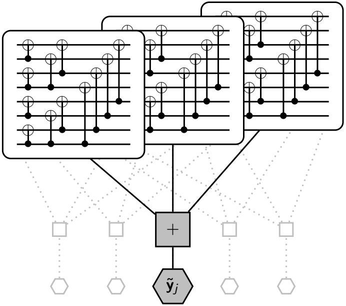
- MMSE estimator is

$$\hat{\mathbf{C}} = \mathbf{S}^H \left(\mathbf{S}\mathbf{S}^H + \mathbf{I}\right)^{-1} \mathbf{Y}$$

With activity detection

- Estimated sequences $\mathcal{D}$
- Approx. Gaussian linear form

$$\mathbf{Y} \approx \mathbf{S}_{\mathcal{D}}\mathbf{C} + \mathbf{Z}$$



- Approximate MMSE estimator

$$\hat{\mathbf{C}} = \mathbf{S}_{\mathcal{D}}^H \underbrace{\left(\mathbf{S}_{\mathcal{D}}\mathbf{S}_{\mathcal{D}}^H + \mathbf{I}\right)}^{-1} \mathbf{Y}$$

Spreading URA

Single-user code

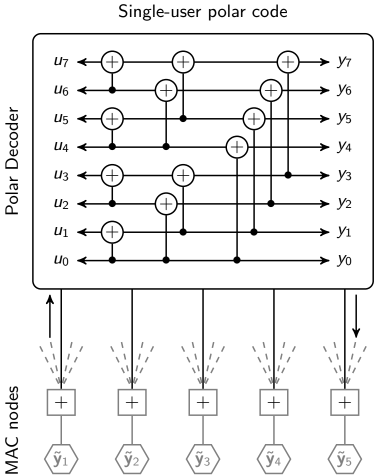
- Polar code & CRC
- Likelihoods derived from symbol estimate

$$\hat{\mathbf{C}} \approx \mathbf{S}_{\mathcal{D}}^{H} \left(\mathbf{S}_{\mathcal{D}} \mathbf{S}_{\mathcal{D}}^{H} + \mathbf{I} \right)^{-1} \mathbf{Y}$$

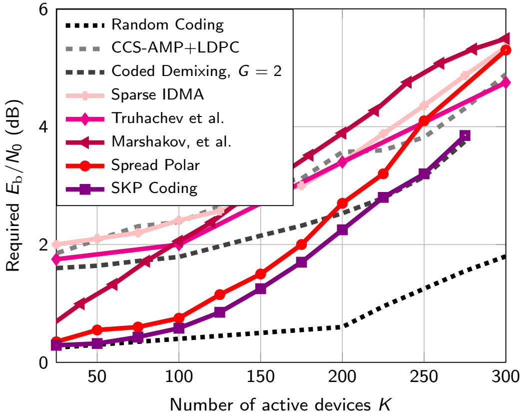
- CRC added to information

Decoding approach

- Joint successive cancellation within decoding loop
- Sequences dictate frozen bits
- LMMSE can be tuned to account for collisions



Spread URA Single-Antenna



- 100 bits
- 30,000 uses
- 1 antenna
- $P_e \leq 0.05$
- 2^9–2^{12} sequences
- 29–117 lengths
- 1024-256 coded bits
- BSK

- *Spread polar* outperforms Irregular Repetition Slotted ALOHA (IRSA) polar by E. Marshakov, G. Balitskiy, K. Andreev, A. Frolov
- Low complexity scheme by D. Truhachev, M. Bashir, A. Karami, E. Nassaji performs well for large population
- *SKP* – Sparse Kronecker-Product Coding for Unsourced Multiple Access by Z. Han, X. Yuan, C. Xu, S. Jiang and X. Wang

Signal Structure Revisited

$\mathbf{c} \otimes \mathbf{s}$ versus $(\mathbf{c} \otimes \mathbf{1}) \circ \mathbf{s}^{+}$

- One random realization for every symbol period
- New representation of sent signal

$$\mathbf{X} = (\mathbf{c} \otimes \mathbf{1}) \circ \mathbf{s}^{+} \Rightarrow \begin{bmatrix} | & | & & | \\ \mathbf{s}^{+}(1)\, c_1 & \mathbf{s}^{+}(2)\, c_2 & \cdots & \mathbf{s}^{+}(n)\, c_n \\ | & | & & | \end{bmatrix}$$

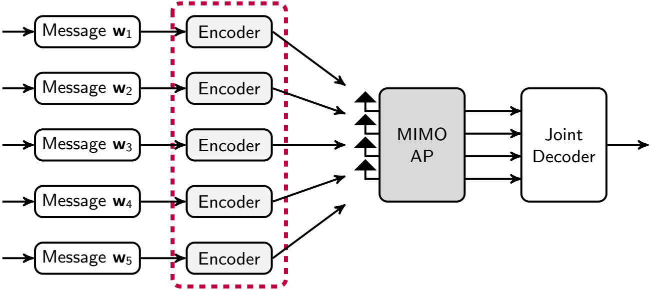
with a different spreading column for every coded symbol

- One LMMSE matrix inversion per coded symbol period j
- Match filter versus LMMSE
  - Buying performance at expense of complexity
  - Model becomes more brittle to fine synchronization
- Random subset of sequence set precludes CDMA-style designs

Part II

Multiple Antennas at Receiver: FASURA: Fading Spread Unsourced Random Access

Quasi-Static (Massive) MIMO Channel



Signal model

- Signal observed with multiple antennas at receiver and fading

$$\mathbf{Y} = \sum_i \mathbf{x}_i \cdot \mathbf{h}_i^T + \mathbf{Z}$$

- Number of antennas is large $M \gg 1$
- Fading does NOT change within URA frame

Quasi-Static (Massive) MIMO Channel

Problem Formulation

- Noisy MMV support recovery

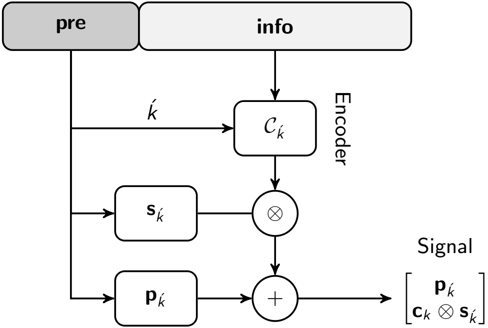
$$\mathbf{Y} = \sum_i \mathbf{x}_i \cdot \mathbf{h}_i^{\mathsf{T}} + \mathbf{Z}$$

- Signal $\mathbf{x}_i$ is function of message alone
- Channel is quasi-static
- Coefficients are not known

Possible URA design strategies

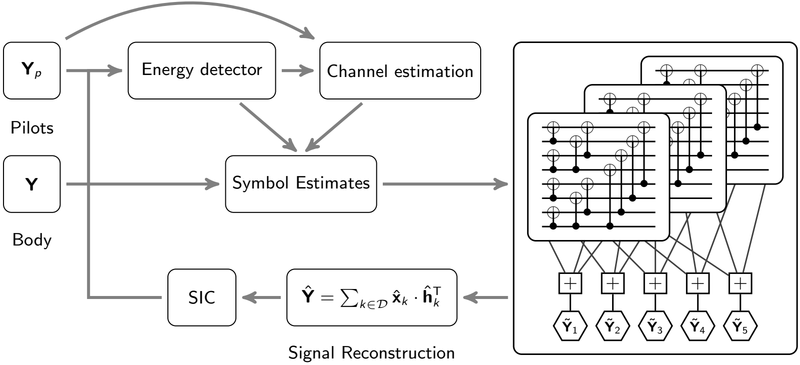
- Collisions may not be as much of an issue
- Complexity must be managed
- Strategies with pilots seem advantageous

FASURA Encoding – Pilot plus Spreading



- Encoding similar to spread URA, albeit with pilots ($\mathbf{p}_{\acute{k}}$'s)
- Pilot sequence used for activity detection and channel estimation
- Payload **info** is encoded with traditional code: Polar & CRC

Joint Decoding Architecture MIMO



$\mathbf{Y}_p$

Pilots

$\mathbf{Y}$

Body

Energy detector

Channel estimation

Symbol Estimates

SIC

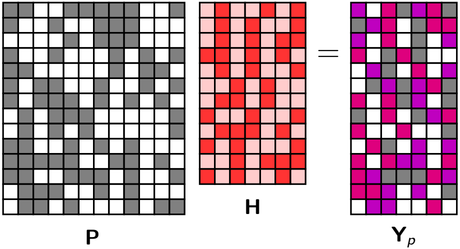
$\hat{\mathbf{Y}} = \sum_{k \in \mathcal{D}} \hat{\mathbf{x}}_k \cdot \hat{\mathbf{h}}_k^{\mathrm{T}}$

Signal Reconstruction

Energy Detector

$$\text{Pilot set} = \underset{k}{\text{top arg}} \left\| \mathbf{p}_{\acute{k}}^{H} \mathbf{Y}_p \right\|_2$$

Channel Estimation Block



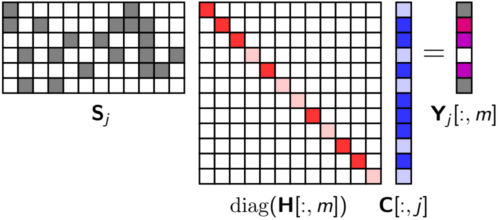
- Observations from preambles

$$\mathbf{Y}_p = \mathbf{P}\mathbf{H} + \mathbf{Z}_p$$

- $\mathbf{H}$ has entries drawn i.i.d. from $\mathcal{CN}(0,1)$
- Channel estimates

$$\hat{\mathbf{H}} = \left(\hat{\mathbf{P}}^H \hat{\mathbf{P}} + \mathbf{I}\right)^{-1} \hat{\mathbf{P}}^H \mathbf{Y}_p$$

Intuition Behind MIMO Symbol Estimation



Measurement Structure

Observation $\tilde{\mathbf{Y}}_j$ for jth symbols

$$\mathbf{Y}[\mathbf{n}_j, m] \quad (\text{Spreading} \times \text{Antenna}_m)$$

$$\approx \mathbf{S}_j \,\mathrm{diag}\left(\hat{\mathbf{H}}[:, m]\right) \begin{bmatrix} c_{1,j} \\ \vdots \\ c_{K,j} \end{bmatrix} + \mathbf{Z}[\mathbf{n}_j, m]$$

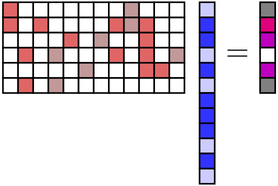
where $\mathbf{n}_j$ spread sequence slice

Structure of Multiple Measurement Vector

Received signal

- Period j
- Antenna m

$$\mathbf{Y}_j[:,m] = \mathbf{S}_j \operatorname{diag}(\mathbf{H}[:,m])\mathbf{C}[:,j] + \mathbf{Z}_j[:,m]$$



Stacked version

- Period j
- All antennas

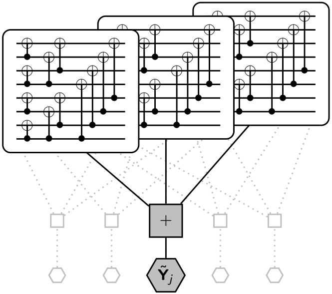
$$\underbrace{\begin{bmatrix} \mathbf{Y}[\mathbf{n}_j,1] \\ \vdots \\ \mathbf{Y}[\mathbf{n}_j,M] \end{bmatrix}}_{\overline{\mathbf{Y}}_j} = \underbrace{\begin{bmatrix} \mathbf{S}_j \operatorname{diag}\left(\hat{\mathbf{H}}[:,1]\right) \\ \vdots \\ \mathbf{S}_j \operatorname{diag}\left(\hat{\mathbf{H}}[:,M]\right) \end{bmatrix}}_{\overline{\mathbf{SH}}_j} \mathbf{C}[:,j] + \begin{bmatrix} \mathbf{Z}[\mathbf{n}_j,1] \\ \vdots \\ \mathbf{Z}[\mathbf{n}_j,M] \end{bmatrix}$$

MIMO Symbol Estimation Block

LMMSE estimate

$$\hat{\mathbf{C}}[:,j] = \overline{\mathbf{SH}}_j^H \left(\overline{\mathbf{SH}}_j \overline{\mathbf{SH}}_j^H + \mathbf{I} \right)^{-1} \overline{\mathbf{Y}}_j$$

- $\overline{\mathbf{SH}}_j$ has size $n_j M \times n_j$
- Invert many matrices
- Loop over SIC



? Truncated Neumann series

? AMP iteration

NOPICE: Noisy Pilot Channel Estimation

Channel Structure and Pilots

$$\mathbf{Y}_p = \underbrace{\begin{bmatrix} | & | & & | \\ \mathbf{p}_1 & \mathbf{p}_2 & \cdots & \mathbf{p}_K \\ | & | & & | \end{bmatrix}}_{\mathbf{P}} \underbrace{\begin{bmatrix} - & \mathbf{h}_1^T & - \\ & \vdots & \\ - & \mathbf{h}_M^T & - \end{bmatrix}}_{\mathbf{H}} + \mathbf{Z}_p = \mathbf{PH} + \mathbf{Z}_p$$

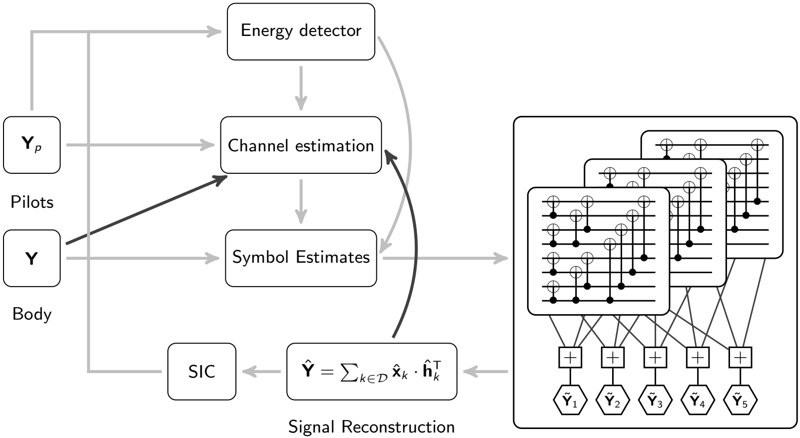
with estimate $\hat{\mathbf{H}} = \left(\mathbf{P}^H\mathbf{P} + \sigma^2\mathbf{I}\right)^{-1}\mathbf{P}^H\mathbf{Y}_p$

Noisy Pilot Channel Estimation

$$\underbrace{\begin{bmatrix} \mathbf{Y}_p \\ \mathbf{Y} \end{bmatrix}}_{\check{\mathbf{Y}}} = \underbrace{\begin{bmatrix} | & | & & | \\ \mathbf{p}_1 & \mathbf{p}_2 & \cdots & \mathbf{p}_K \\ \hat{\mathbf{c}}_1 \otimes \mathbf{s}_1 & \hat{\mathbf{c}}_2 \otimes \mathbf{s}_2 & \cdots & \hat{\mathbf{c}}_K \otimes \mathbf{s}_K \\ | & | & & | \end{bmatrix}}_{\check{\mathbf{P}}} \begin{bmatrix} - & \mathbf{h}_1^T & - \\ & \vdots & \\ - & \mathbf{h}_M^T & - \end{bmatrix} + \begin{bmatrix} \mathbf{Z}_p \\ \mathbf{Z} \end{bmatrix}$$

with estimate $\check{\mathbf{H}} = \left(\check{\mathbf{P}}^H\check{\mathbf{P}} + \sigma^2\mathbf{I}\right)^{-1}\check{\mathbf{P}}^H\check{\mathbf{Y}}$

FASURA with NOPICE



Remark:

New arrows improve performance at expense of computational complexity

Alternate Scheme – Tensor-Based Modulation

Code Construction

Codebook is created based on tensors

$$\{\mathbf{x}_1 \otimes \mathbf{x}_2 \otimes \cdots \otimes \mathbf{x}_d : \mathbf{x}_1 \in \mathcal{C}_1, \mathbf{x}_2 \in\in \mathcal{C}_2, \ldots \mathbf{x}_d \in \mathcal{C}_d\}$$

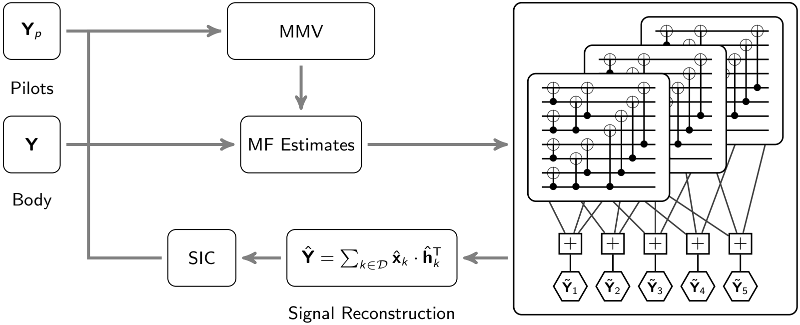
Received signal is sum of K rank-1 tensors plus noise

$$\sum_k \mathbf{x}_{1,k} \otimes \mathbf{x}_{2,k} \otimes \cdots \otimes \mathbf{x}_{d,k} \otimes \mathbf{h}_k + \mathbf{z}$$

- Decode with canonical polyadic decomposition (CPD)
- Iterative nonlinear least square algorithm on flattened outer products
- Pilots are not used in this scheme

A. Decurninge, I. Land, and M. Guillaud. *Tensor-based modulation for unsourced massive random access*. IEEE Wireless Communications Letters, 2021.

Alternate Scheme – Pilot-Based Approach



$\mathbf{Y}_p$

Pilots

$\mathbf{Y}$

Body

MMV

MF Estimates

SIC

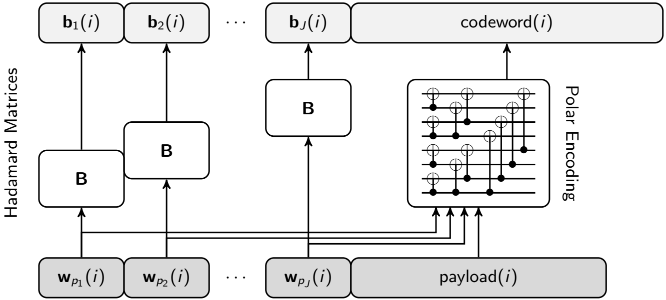
$\hat{\mathbf{Y}} = \sum_{k \in \mathcal{D}} \hat{\mathbf{x}}_k \cdot \hat{\mathbf{h}}_k^{T}$

Signal Reconstruction

- Advocated for pilot-based approach
- MMV-AMP and match filtering estimation
- Polar code plus cyclic redundancy check (CRC)

A. Fengler, O. Musa, P. Jung, and G. Caire. *Pilot-based unsourced random access with a massive MIMO receiver, interference cancellation, and power control*. IEEE Jour. Selected Areas in Comm., 2022.

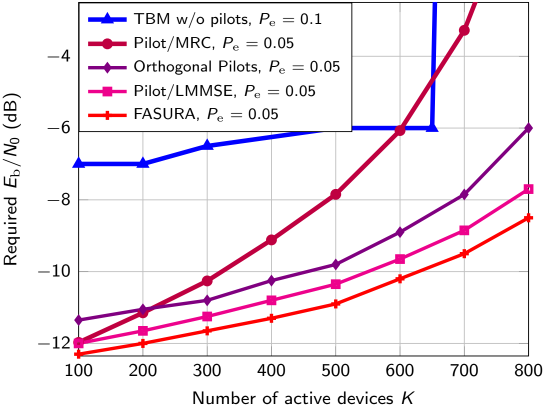
Alternate Scheme – Orthogonal Pilots



- Hadamard pilots for fast processing: detection and estimation
- Polar code plus cyclic redundancy check (CRC)
- Excellent performance versus complexity tradeoff

M. J. Ahmadi and T. M. Duman. *Unsourced random access with a massive MIMO receiver using multiple stages of orthogonal pilots*. ISIT, 2022.

Spread URA Single-Antenna



- 100 bits
- 3200 uses
- 50 antennas
- $P_e \leq 0.05$
- 896 pilots
- 9-bit sequences
- 256 sequences
- 512 coded bits
- QPSK
- 12–16 CRC

- Tensor-Based Modulation by A. Decurninge, I. Land, & M. Guillaud
- Orthogonal Pilots by M. J. Ahmadi & T. M. Duman
- Pilot/MRC by A. Fengler, O. Musa, P. Jung, & G. Caire
- FASURA by M. Gkagkos, K. R. Narayanan, JFC, and C. N. Georghiades

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