

Blind asynchronous Goal-Oriented Detection (BaGOD) for Massive Connectivity

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Outline

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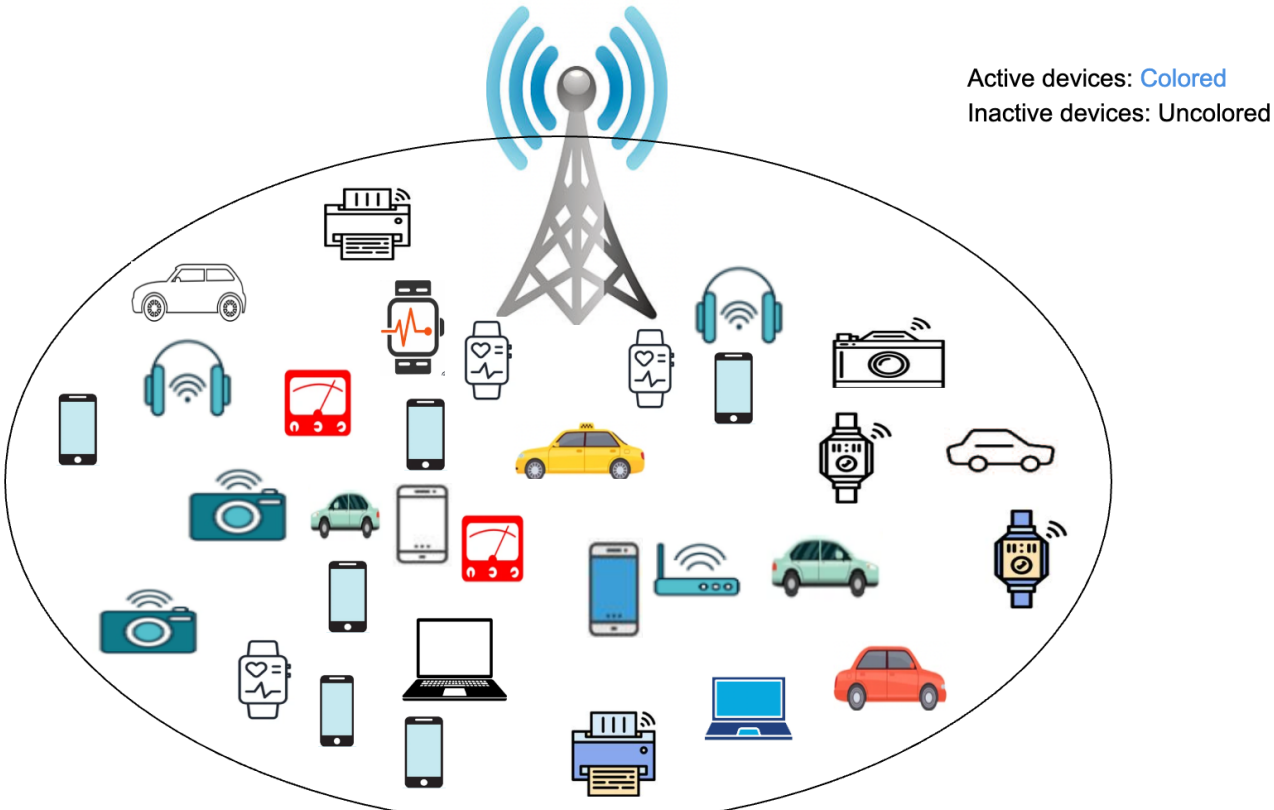
Introduction

- Random access (RA) is the key component of the communications between users and the BS in wireless networks.
- Various applications of IoT demand for massive machine machine-type communications (MTC).
- Uplink transmission of massive IoT devices with short packets
- Sporadic traffic of IoT devices



RA frameworks

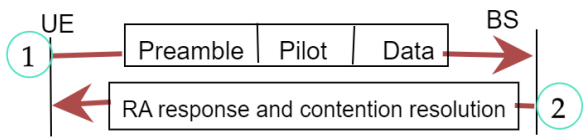
- Each active device transmits a preamble along with the data payload in a time division manner.
- At each time slot, the BS first detects the active devices by detecting which preamble sequences are used.

Sourced RA (S-RA)

- BS is interested in both the messages and the identities of the devices.
- Each device is preassigned to a unique signature (preamble) sequence for identification.
- Applications in Device-Oriented Communications

Unsourced RA (U-RA)

- BS is interested in the transmitted messages only and not the identity of the devices.
- Each user selects a B bit message from a shared codebook and transmit it.
- Applications in Content-Oriented Communications



Two-step S-RA

System Model

- Uniform linear array BS with N receive antennas serving $K = K_M + K_S$ single antenna users
- Only $K_a = K_{a,M} + K_{a,S} \ll K$ are active, which use the same time-freq. resource.
- We assume a flat-fading model in which the channel is considered to be fixed during T signal dimensions in a channel of time-freq. coherence block:

$$\boldsymbol{h}_k = \rho_k \sum_{l=1}^{L_k} \alpha_l^k \boldsymbol{a}(\theta_l^k) \in \mathbb{C}^{N\times 1}$$

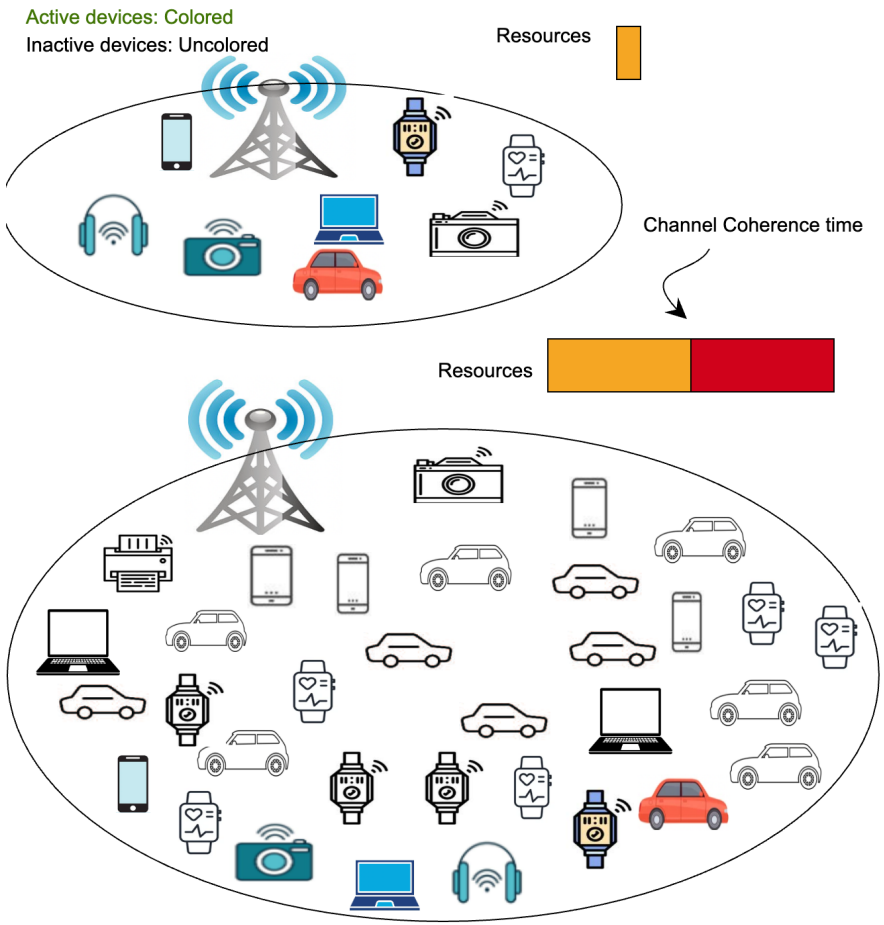
- The signal received at the BS can be given as:

$$\boldsymbol{Y}_\Omega = \sum_{k\in\mathcal{S}_{\mathrm{AU}}} \mathcal{P}_\Omega(\boldsymbol{h}_k \boldsymbol{\varphi}_k^{\mathsf{H}} \boldsymbol{E}_k) + \boldsymbol{N}$$

where $\boldsymbol{E}_k$ is the delay-gain matrix of user k and $\boldsymbol{\varphi}_k := \boldsymbol{F}_k \boldsymbol{\phi}_k \in \mathbb{C}^{T\times 1}$.

Massive Connectivity challenges

- How many active devices can get a grant to access the BS?
- The number of inactive users ↑ → the amount of required resources ↑ → prices of the available resources ↑



Massive Connectivity Challenges

Sourced RA

- The number of active users that can access the BS in sourced RA is severely limited in massive access scenario ($K_a = \mathcal{O}(\frac{T^2}{\log^2(\frac{K}{T^2})})$).
- The detection accuracy directly depends on the total number of inactive users.
- **Massive connectivity** requires massive **communication costs** at the user side.
- Due to the limited channel coherence time and massive users, it is not possible to assign orthogonal pilots to all of the devices.

Massive Connectivity Challenges

Unsourced RA

- Users are forced to use the same and shared codebook
- Impossible to use individually different codebooks
- The number of active messages that can be transmitted in U-RA is severely limited in massive access scenario $(K_a = \mathcal{O}(\frac{T^2}{\log^2(\frac{2^B}{T^2})}))$
- **Arbitrary data transmission** needs **massive communication costs** at the user side.

BaGOD idea

searching-based detection

- Search for active components among a large number of components
- The required resources (time or frequency) for detection directly depends on the number of inactive components
- The searching item is either the identity of active components or some features (like sparsity) related to these active components
- Any methods from compressed sensing community belongs to searching-based such as approximate message passing, OMP, Basis Pursuit, ...
- The well-known maximum likelihood method is also from searching-based family and searches for active components that maximizes log-likelihood.

Goal-oriented detection

- It is fully independent of the number of inactive components
- Indirectly reveals the information of active components through dual-polynomial functions without searching
- A subset of a generally complicated problem that is destroyed enough to reach specific goals
- The goal in our problem is active user identification.

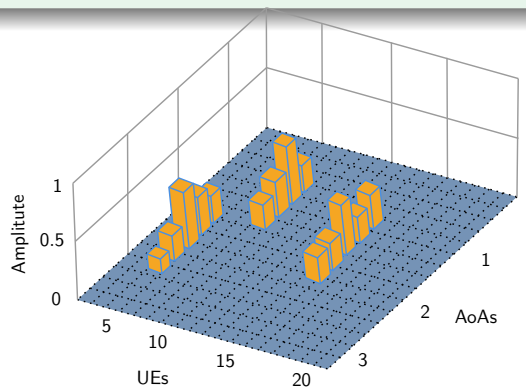
BaGOD strategy

Expensive optimization problem

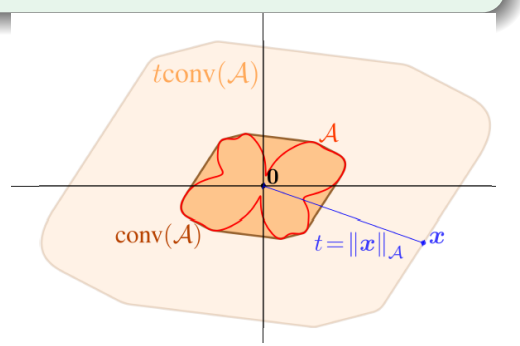
$$\min_{\substack{\boldsymbol{Z}_k \in \mathbb{C}^{N\times T} \\ k=1,\dots,K \\ \boldsymbol{Y}^\star \in \mathbb{C}^{M\times T}}} \sum_{k=1}^{K} \beta_k \|\boldsymbol{Z}_k\|_{\tilde{\mathcal{A}}_k} + \frac{\gamma}{2}\|\boldsymbol{Y} - \boldsymbol{Y}^\star\|_{\mathrm{F}}^2 \; s.t. \quad \boldsymbol{Y}^\star = \sum_{k=1}^{K} \mathcal{P}_\Omega(\boldsymbol{Z}_k), \quad (1)$$

$$\|\boldsymbol{Z}_k\|_{\tilde{\mathcal{A}}_k} := \inf\{t > 0 : \boldsymbol{Z}_k \in t\mathrm{conv}(\tilde{\mathcal{A}}_k)\} = \inf\{\sum_{l=1}^{L_k} c_l^k : \boldsymbol{Z}_k$$

$$= \sum_{l=1}^{L_k} c_l^k \boldsymbol{a}(\theta_l^k)\boldsymbol{\varphi}_k^{\mathsf{H}} \boldsymbol{E}_k, \; c_l^k > 0, \|\boldsymbol{E}_k\|_{2\to 2} \leqslant C_e, \|\boldsymbol{\varphi}_k\|_2 = 1\}, \quad (2)$$



Angular continuous group-sparsity in the uplink channel



Atomic norm

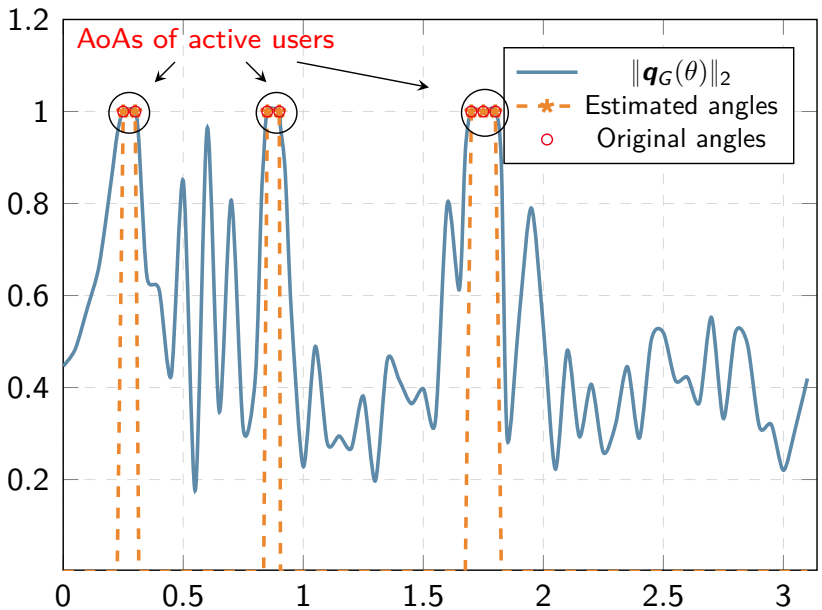
BaGOD strategy

Goal-oriented Optimization problem

$$\min_{\substack{\boldsymbol{v}\in\mathbb{C}^N,\boldsymbol{Z}\in\mathbb{C}^{N\times T}\\ \boldsymbol{Y}^\star\in\mathbb{C}^{M\times T},\boldsymbol{W}\in\mathbb{C}^{T\times T}}} \quad \mathrm{Re}(v_1)+\mathrm{Re}(\mathrm{tr}(\boldsymbol{W}))+\frac{\gamma}{2}\|\boldsymbol{Y}-\boldsymbol{Y}^\star\|_F^2$$

$$\text{s.t.} \quad \begin{bmatrix}\mathcal{T}(\boldsymbol{v}) & \boldsymbol{Z}\\ \boldsymbol{Z}^H & \boldsymbol{W}\end{bmatrix}\succeq \boldsymbol{0} \quad , \boldsymbol{Y}^\star=-2c_1\mathcal{P}_\Omega(\boldsymbol{Z}). \tag{3}$$

$K=100, K_a=3, L_{\max}=3, N=32, T=1$



ℓ_2 norm of the goal-oriented dual polynomial function

Recovery of preambles, channel gains and delay-gain matrices

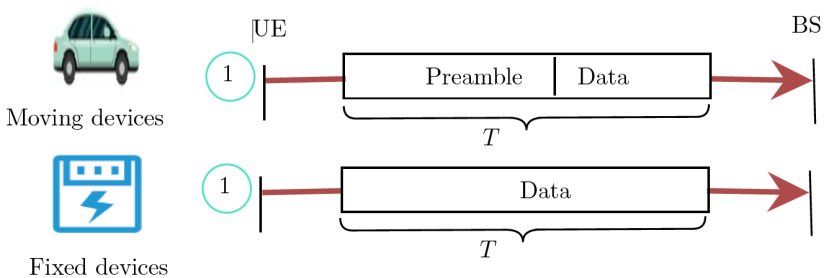
$$\min_{\substack{\boldsymbol{\alpha}^k:=[\alpha_1^k,\ldots,\alpha_{L_k}^k],\\ \boldsymbol{E}_k,\boldsymbol{\phi}_k}} \|\boldsymbol{Y}-\sum_{k\in\widehat{\mathcal{S}}_{\mathrm{AU}}}\sum_{l=1}^{\widehat{L}_k}\alpha_l^k\mathcal{P}_{\Omega}(\boldsymbol{a}(\widehat{\theta}_l^k)\boldsymbol{\phi}_k^{\mathsf{H}}\boldsymbol{F}^{\mathsf{H}}\boldsymbol{E}_k)\|_{\mathrm{F}}$$

$$\text{s.t.}\quad \|\boldsymbol{E}_k\|_{2\to 2}\leqslant C_e,\boldsymbol{\phi}_k\geqslant\boldsymbol{0},\|\boldsymbol{\phi}_k\|_2=1,k=1,\ldots,\widehat{K}_a, \qquad (4)$$

BaGOD strategy

Motivations and Ideas

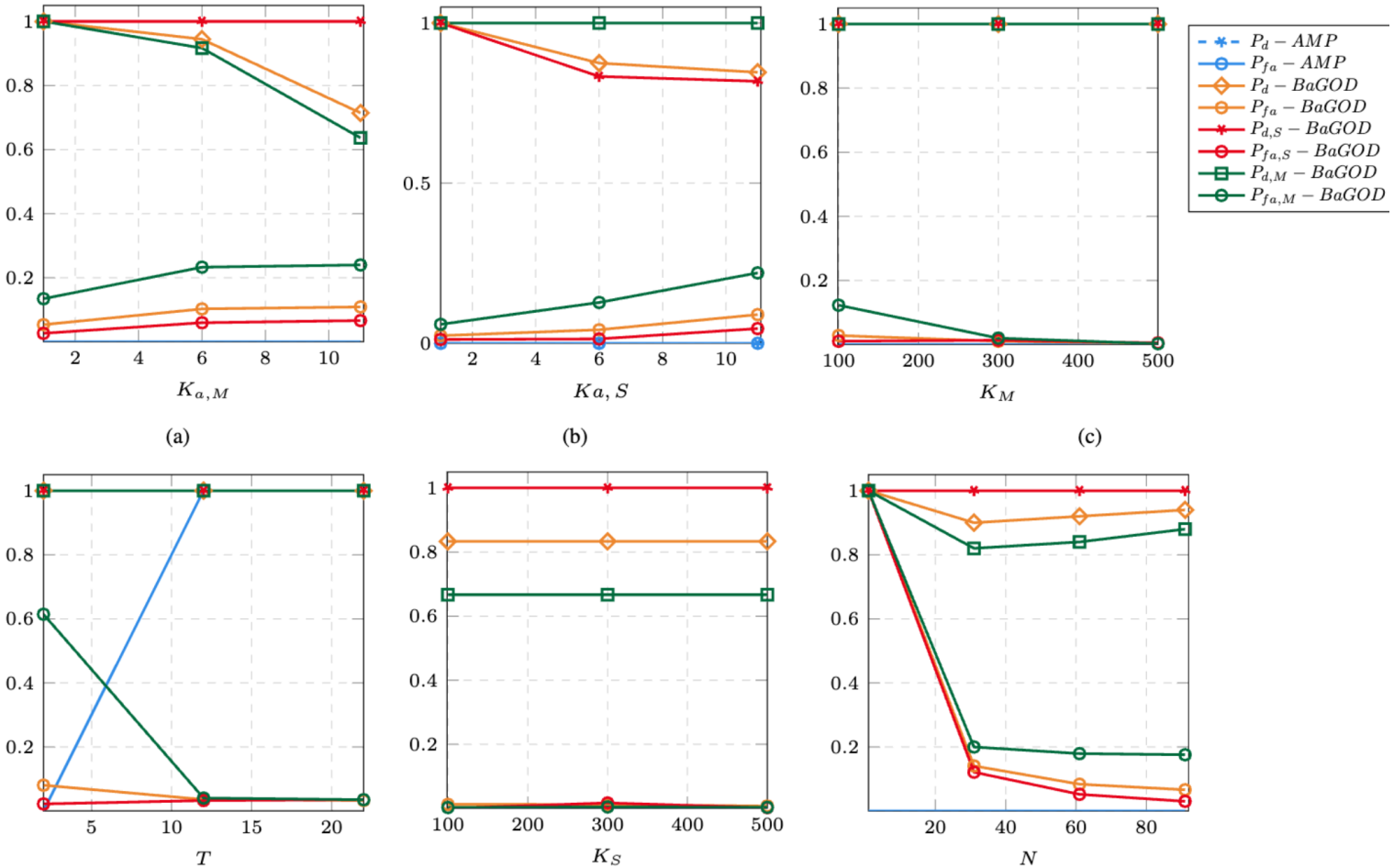
- The expensive optimization problem is computationally intractable in massive access scenarios
- Design a reconstruction-free optimization problem with the goal of active user detection in mind
- The information of channel gains and messages corresponding to all of the devices is completely lost and destroyed.
- **Big discovery:** The maximum of ℓ_2 norm of the dual polynomial functions occurs at the **same** locations for the expensive and goal-oriented problems.
- This shared information between the expensive and goal-oriented optimization problems is sufficient to find out the angles of all active devices.



BaGOD features

- Channel distribution is arbitrary
- Noise distribution is arbitrary
- The first Sourced RA strategy that is fully independent of the total number of inactive devices.
- Communications costs at the users' side for RA are somehow transferred to the computational complexity at the BS.
- Separate the stationary active users by their LoS angles
- Separate the mobile active users by both their angles and preambles
- Stationary users do not have to spend any resources for RA
- Mobile active users have to include a preamble before their data payload
- The first blind unsourced RA
- The users in U-RA are free to transmit any arbitrary messages from individually different codebooks
- Users do not need to be synchronized for data transmission. (in U-RA)
- The messages can have different lengths (in U-RA)

Simulation results



Thank you for your attention!

Questions?