Type-based unsourced multiple access

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Chalmers, Sweden

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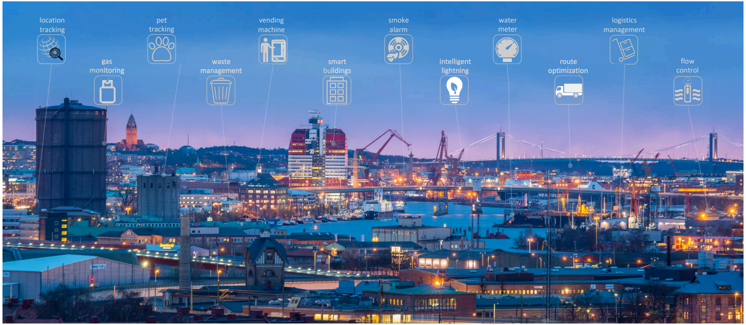
Joint work with Khac-Hoang Ngo, Deekshith Pathayappilly Krishnan, Kaan Okumus, Erik G. Ström

CHALMERS

Wireless-communication-enabled massive connectivity



source: IoTpool

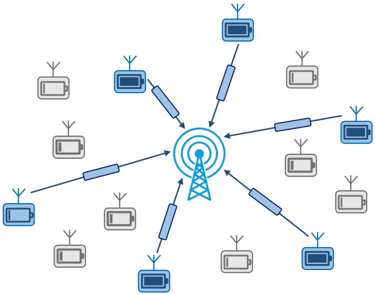
Challenge

- Collect in an energy efficient way data from a massive number of low-cost sensors

Massive wireless connectivity

Massive machine-type communication (mMTC)

- Mostly uplink
- Small information payload (100 bits)
- High user density (10^7 devices per Km^2)
- Sporadic transmission (less than once per minute)



Challenging problem

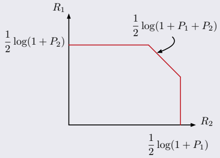
Around 120 complex degrees of freedom per user for a $20\,\mathrm{MHz}$ system

Key design question

How to transmit around 100 bits in around 100 d.o.f. per user over a MAC, under stringent energy-efficiency requirements

Traditional multiple access models and their limitations [Gallager '85]

Multiaccess IT [Cover '75, Wyner '74]



- ✗ All users active (no sporadicity)
- Each user is given a different codebook
- ✗ Not feasible for mMTC (overhead too large)

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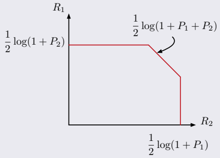

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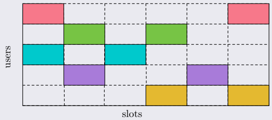
Collision resolution [Abramson '70, Roberts '72, Liva '11]



- ✓ Infinitely many, sporadically active users
- ✗ Crude modeling of communication aspects
- De-facto standard for mMTC

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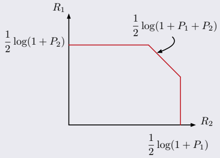

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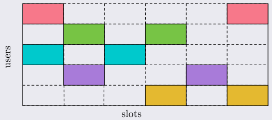

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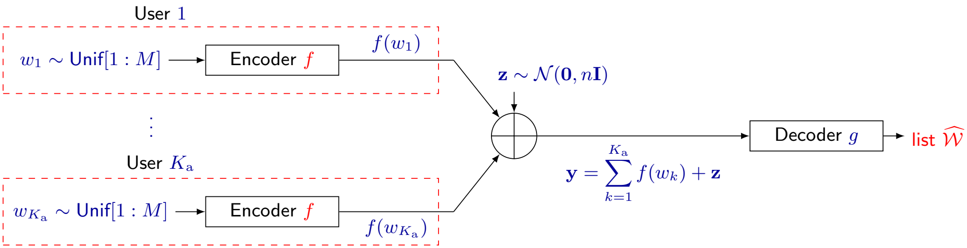
- De-facto standard for mMTC

Addressing these limitations

- Noiseless adder channel (e.g., [Bar-David et al., '97])
- More general information-theoretic perspective [Polyanskiy '17]

Unsourced Gaussian MAC model [Polyanskiy '17]



- $f(w) \in \mathbb{R}^n, \quad \|f(w)\|^2 \leq nP, \quad w = 1, \dots, M$

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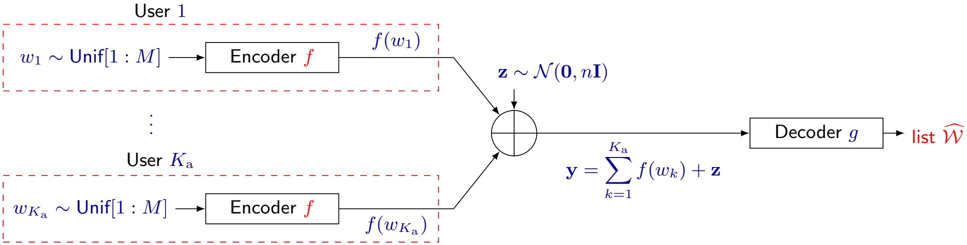

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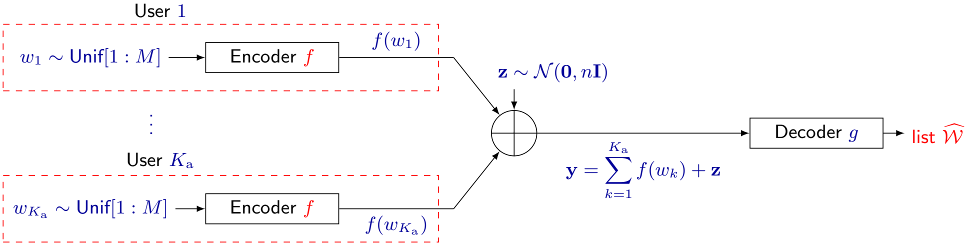

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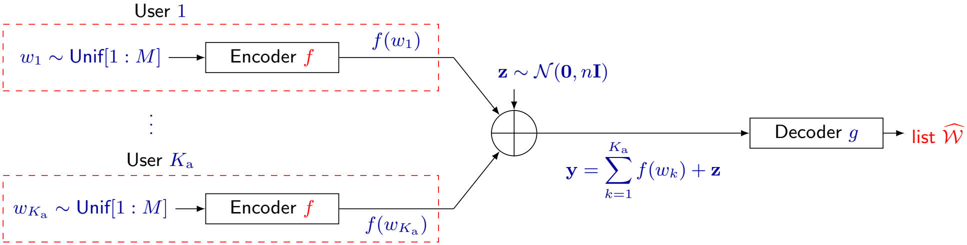

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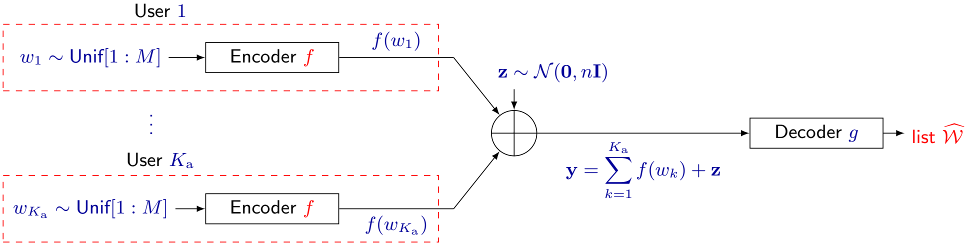

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[Polyanskiy '17]: achievability bound on $E_\mathrm{b}/N_0 = \frac{nP}{\log_2 M}$ required to achieve $P_\mathrm{e} \le \epsilon$

Random coding achievability bound for UMA

Random-coding achievability bound (K_a known) [Polyanskiy '17]

For every $P' < P$, there exists an (M, n, ϵ) code for the K_a-user unsourced GMAC with power constraint P satisfying

$$\epsilon \le \sum_{k=1}^{K_\mathrm{a}} \frac{k}{K_\mathrm{a}} \min\{p_k, q_k\} + p_0, \quad \text{where}$$

$$p_0 = \frac{\binom{K_\mathrm{a}}{2}}{M} + K_\mathrm{a}\,\mathbb{P}\left[\frac{1}{n}\sum_{j=1}^{n} z_j^2 > \frac{P}{P'}\right]$$

$$p_k = e^{-E(t)}$$

$$E(t) = \max_{0 \le \rho_1, \rho_2 \le 1} -\rho_1\rho_2 k R_1 - \rho_2 R_2 + E_0(\rho_1, \rho_2)$$

$E_0(\rho_1, \rho_2)$: complicated expression in ρ_1, ρ_2, k, P'

$$q_k = \inf_\gamma \mathbb{P}[I_k \le \gamma] + e^{n(kR_1+R_2)-\gamma}$$

I_k : related to inf. dens.

$$R_1 = \frac{1}{n}\log M - \frac{1}{nk}\log k!$$

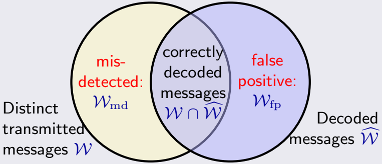
$$R_2 = \frac{1}{n}\log\binom{K_\mathrm{a}}{k}$$

Key ideas in the proof

- Gaussian codebook
- Message collisions or power-constraint violations treated as error
- Decoder: unordered list $\widehat{\mathcal{W}}$ of decoded messages obtained by solving

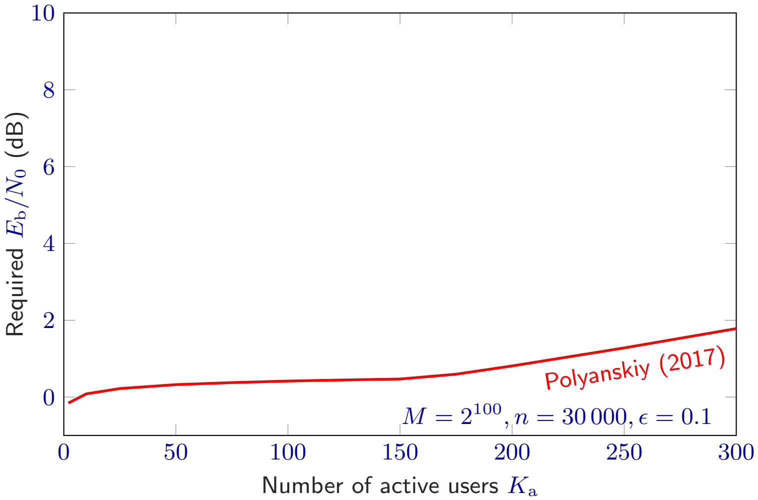
$$\widehat{\mathcal{W}} = \underset{\mathcal{W}' \subset [1:M], |\mathcal{W}'| = K_{\mathrm{a}}}{\arg\min} \|\mathbf{y} - \mathbf{c}(\mathcal{W}')\|, \quad \text{with} \quad \mathbf{c}(\mathcal{W}') = \sum_{w \in \mathcal{W}'} \mathbf{c}_w$$

- Space of error events parameterized by number of misdetected/false-positive messages



- Error exponent analysis

Numerical evaluation of the bound



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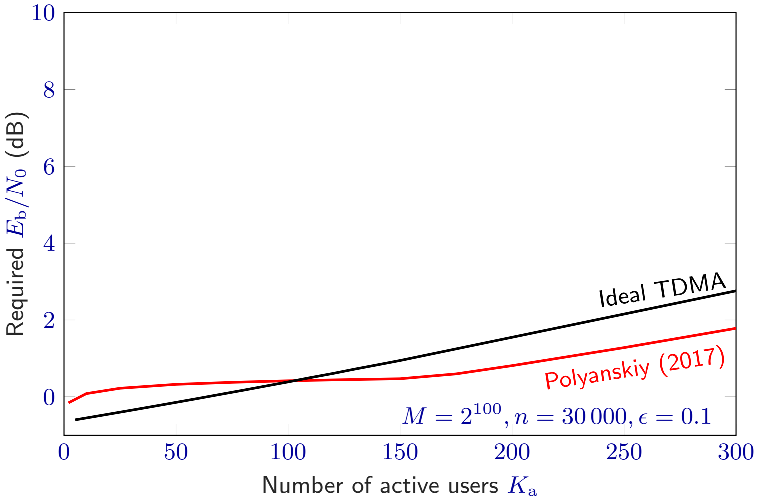

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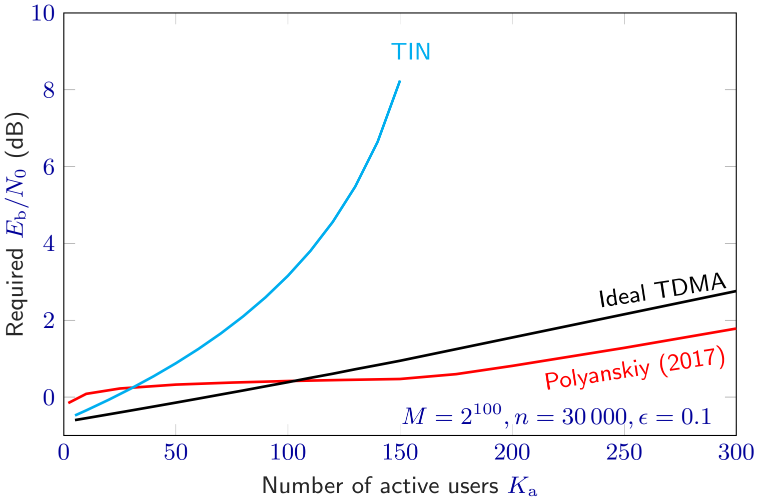

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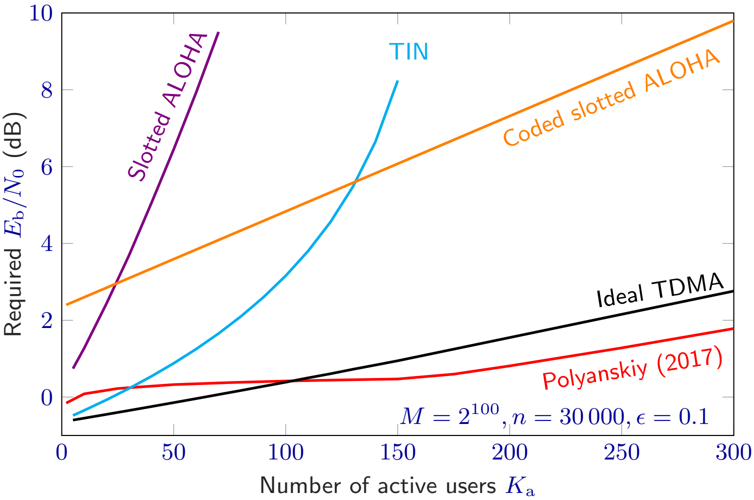
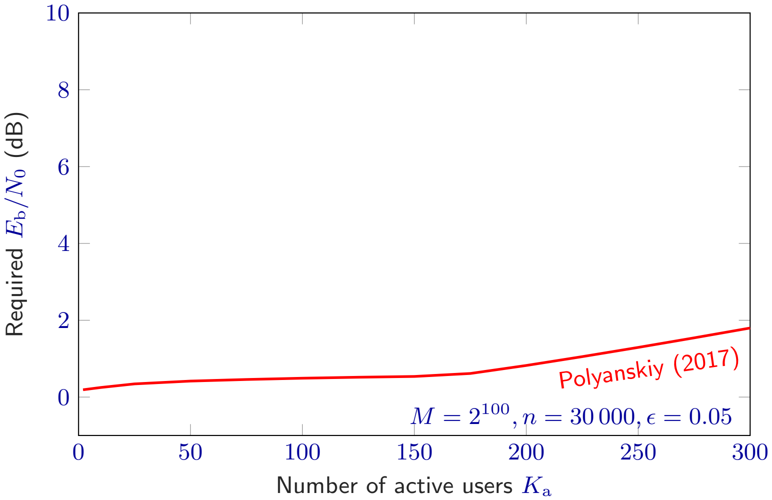


Novel coding schemes (2017–2022)



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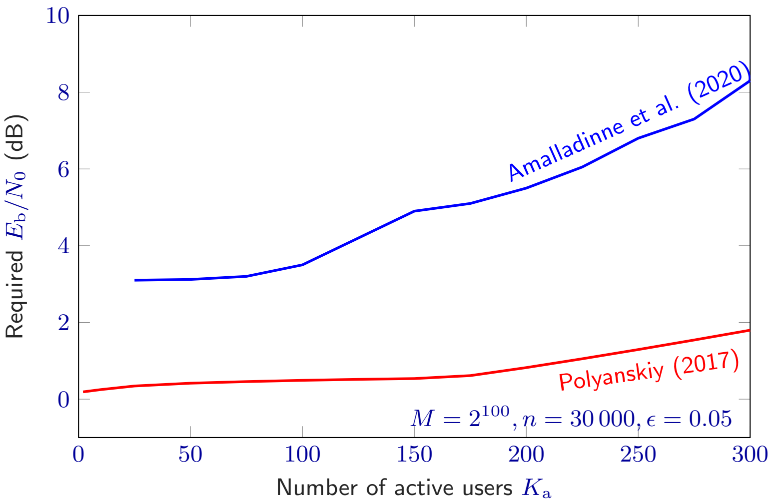

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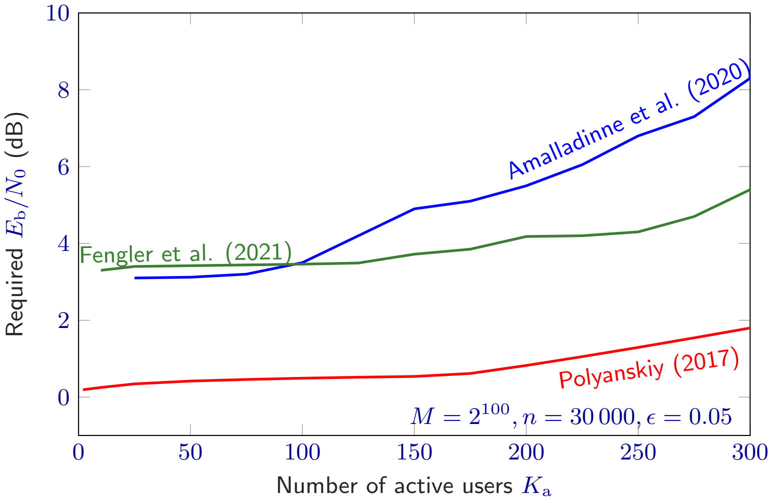

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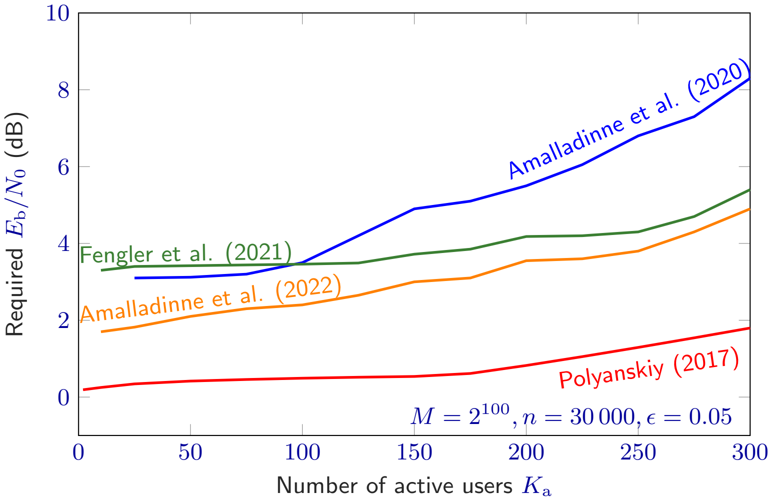

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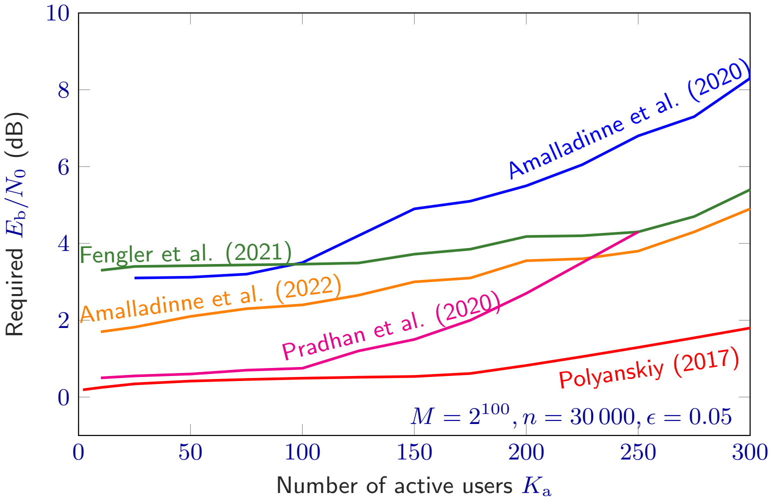

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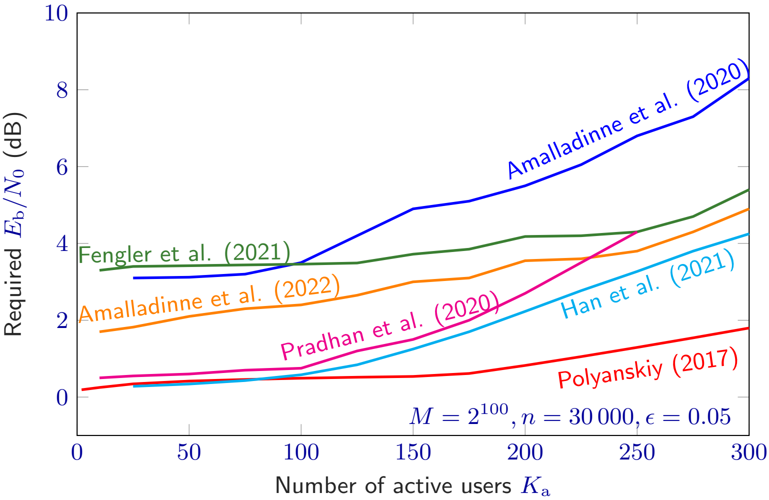
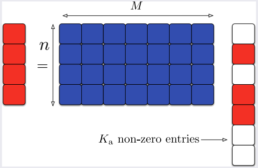


The coded compressive sensing approach

Message detection is a compressive sensing problem

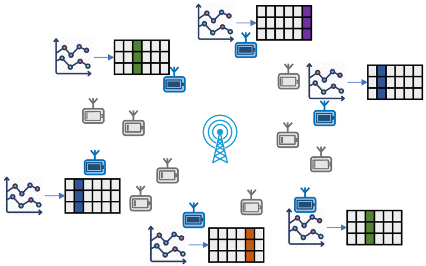


- ✔ We could use compressive sensing solvers such as AMP...
- ✘ ...but the width of the matrix is huge ($M = 2^{100}$)!

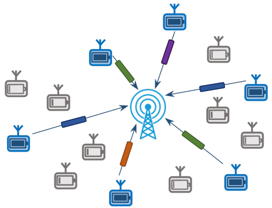
Solution

- Fragment message into smaller sub-blocks (e.g., 16 bits each), transmit one sub-block at a time, and use AMP to decode
- Add outer tree code to stitch together sub- blocks

From UMA to TUMA



Sampling and quantization

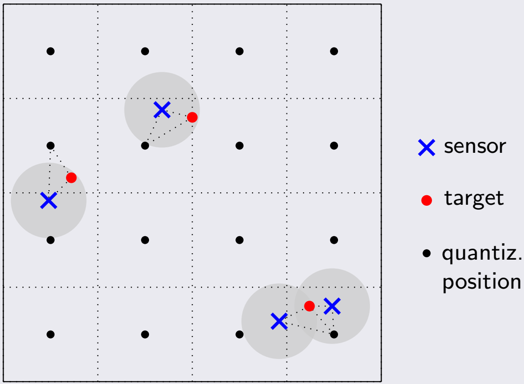


Data transmission

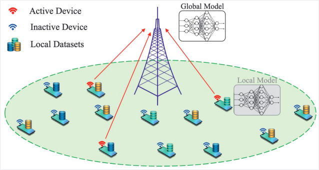
- Users may transmit the same quantized information
- Interested in both the set if transmitted messages and their multiplicities
- Goal: estimate empirical message distribution (type)

Two examples

Multi-target position tracking

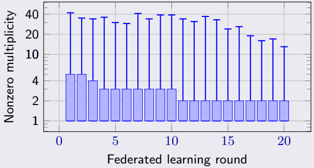


Over-the-air aggregation in federated learning



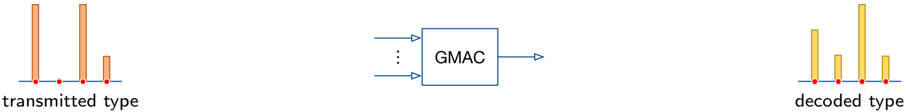
source: Qiao, Gao, Li, and Gündüz (2023)

Message multiplicity: 10th-90th percentile box with full range whiskers



50 clients with 80% random activation

Type-based estimation over multiple access channel



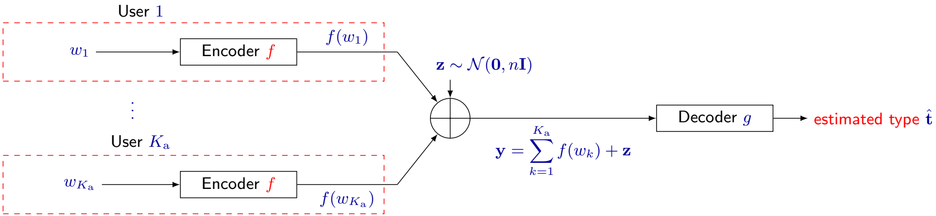
Considered by [Mergen & Tong, 2006], however...

- Assumed that each message can be associated to an orthogonal codeword
- Multiuser interference over a Gaussian MAC can be eliminated via matched filtering

Our scenario—type-based unsourced multiple access (TUMA)

- Number of possible messages (2^{100}) $\gg$ frame length ($30\,000$): orthogonalization not possible
- Only few messages are active (still a compressive sensing problem)

TUMA over a Gaussian MAC



Key differences with respect to UMA

- Messages $w_1, \dots, w_{K_\mathrm{a}}$ forming type $\mathbf{t} = [t_1, \dots, t_M]$ where $t_m = \frac{1}{K_\mathrm{a}} \sum_{k=1}^{K_\mathrm{a}} 1\{w_k = m\}$
- Decoder returns a type estimate $\hat{\mathbf{t}}$
- (Communication) performance metric: total variation distance

$$\mathbb{TV}(\mathbf{t}, \hat{\mathbf{t}}) = \frac{1}{2} \sum_{m=1}^{M} \left| t_m - \hat{t}_m \right|$$

Random coding achievability bound for TUMA [Krishnan et al. 2025]

Random-coding achievability bound (K_{a} and M_{a} known)

For every $P' < P$, there exists an (M, n, ϵ) TUMA code satisfying

$$\epsilon \leq \sum_{k=1}^{K_{\mathrm{a}}} \frac{k}{K_{\mathrm{a}}} p_k + p_0 + p_1, \quad \text{where}$$

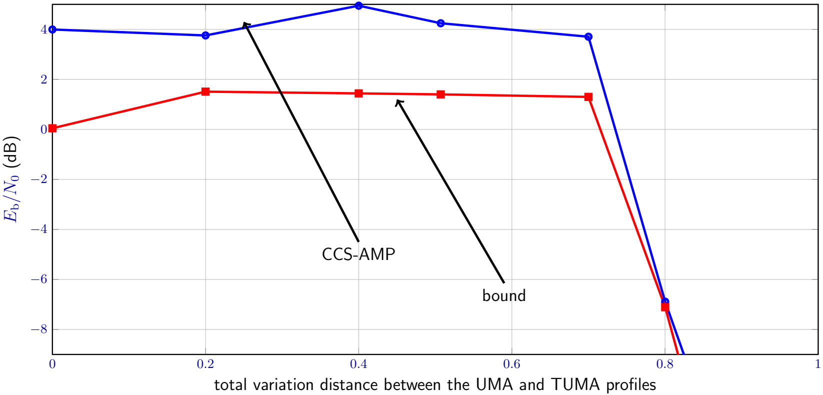
$$p_0 = M_{\mathrm{a}}\, \mathbb{P}\left[\frac{1}{n}\sum_{j=1}^{n} z_j^2 > \frac{P}{P'}\right]$$

$$p_1 = e^{-N\delta^2/8}$$

$\delta =$ complicated expression

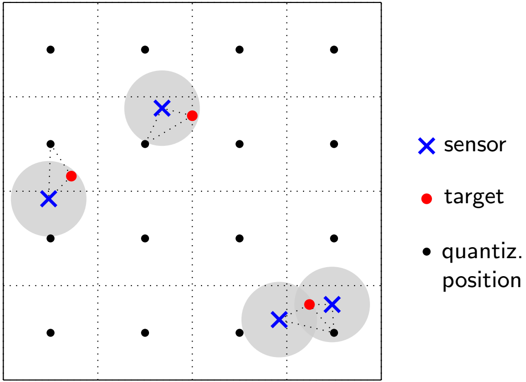
$p_k =$ even more complicated expession...

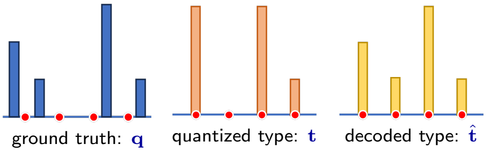
Example: UMA vs TUMA and CCS performance



$$n = 38\,400, \epsilon = 0.05, K_a = 100, M_a \in [2, 100]$$

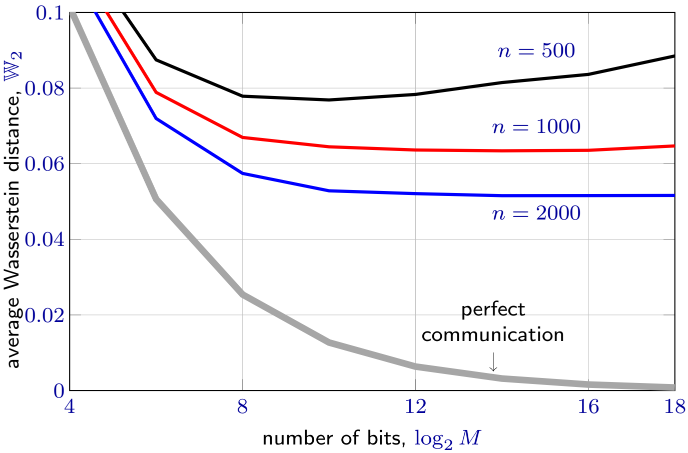
Application example: multi-target position tracking over AWGN channel





- $\mathbb{TV}(\mathbf{t}, \hat{\mathbf{t}})$ captures only communication performance
- Overall performance: Wasserstein distance $\mathbb{W}_2(\mathbf{q}, \hat{\mathbf{t}})$

Tradeoff between communication and quantization [Ngo et al., 2024]



$K_{\mathrm{a}} = 100$ sensors, $M_{\mathrm{a}} = 10$ targets; AMP detection algorithm

Beyond Gaussian MAC: TUMA over fading channels

So far Gaussian MAC...

- Perfect power control: $\mathbf{y} = \sum_{k=1}^{K_\mathrm{a}} f(w_k) + \mathbf{z}$
- Multiplicity can be estimated from power of received codeword
- Over a fading channel, this would require channel inversion [Qiao et al., 2024]

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The benefits of cell-free architectures in UMA

- [Gkiouzepi et al., 2024]: UMA within cell-free massive MIMO architectures
  - Message recovery + channel estimation + estimation of position
  - Perfect knowledge of large-scale fading coefficients
  - Location-based codeword partition
  - Multi-source AMP

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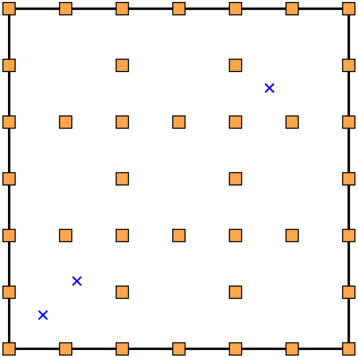
The same ingredients can be used to perform TUMA over a cell-free massive

TUMA over a cell-free massive MIMO architecture



Activity detection

- ✔ Perfect knowledge of large scale fading coefficients (LSFC) of each user
- ✔ Each user has its own signature
- ✔ Association between users and LSFC

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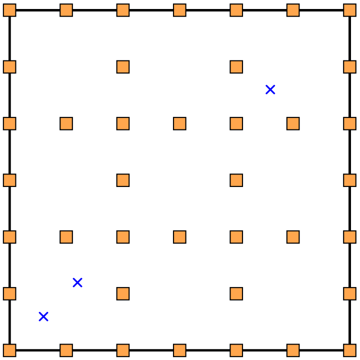

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- ✓ Solution: location-based codeword partitioning

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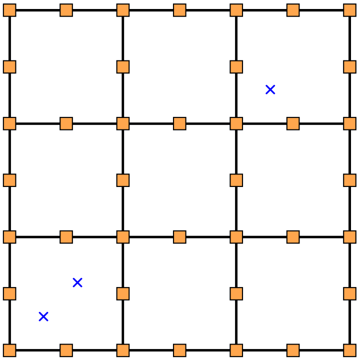

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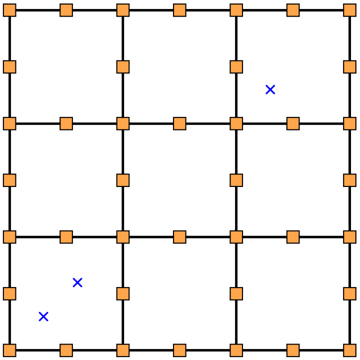

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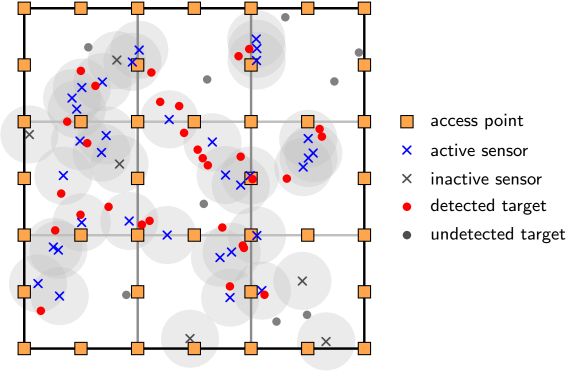
TUMA

- ✔ Possible to estimate multiplicities

TUMA over a cell-free massive MIMO architecture [Okumus et al., 2025]

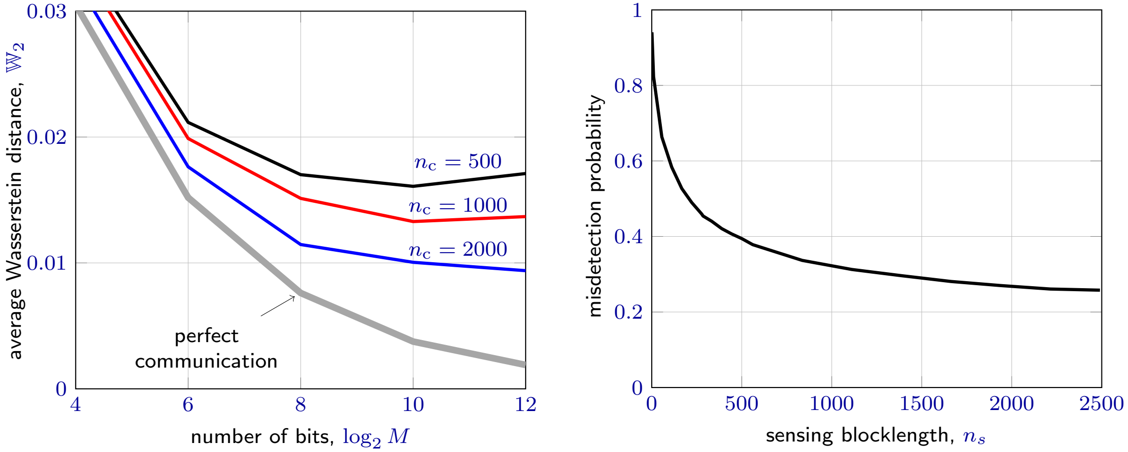


Multi-target tracking example

- 40 access points with 4 antennas each
- 100 sensors, 50 targets
- Sensing phase followed by communication phase: $n = n_{\mathrm{s}} + n_{\mathrm{c}} = 2500$

TUMA over a cell-free massive MIMO architecture [Okumus et al., 2025]

100 sensors, 50 targets, $n = n_\mathrm{s} + n_\mathrm{c} = 2500$, multi-source AMP detection algorithm

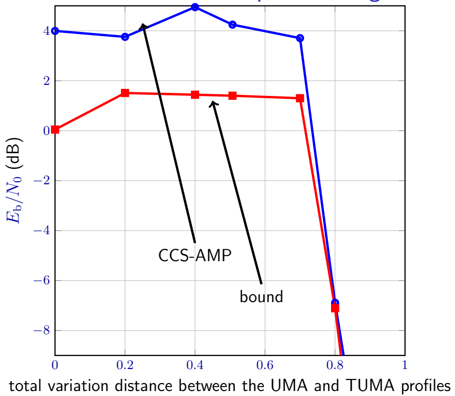


Conclusion

Type-based unsourced multiple access (TUMA)

A framework to collect in an efficient way data from a massive population of sporadically active sensors

Theoretical bounds and practical algorithms



Applications