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Framework for Message Detection, Channel Estimation, and User Positioning for Unsourced Random Access in User-Centric Cell-Free Networks

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Joint work with Eleni Gkiouzepi and Giuseppe Caire

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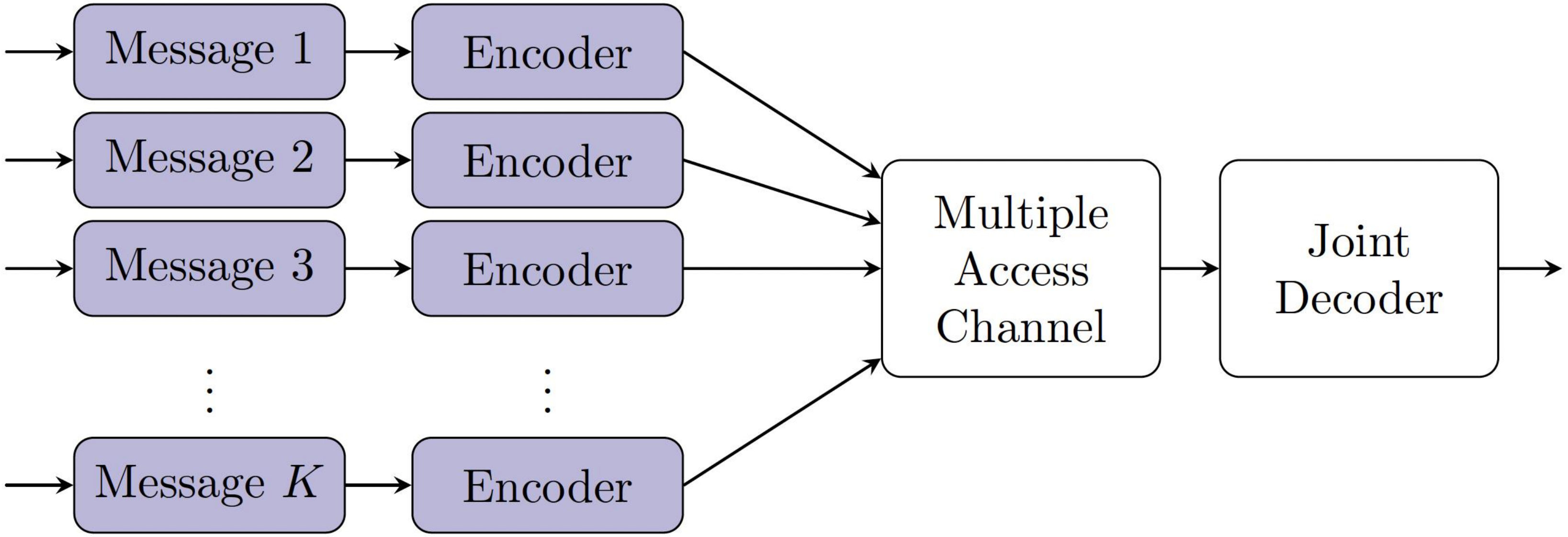
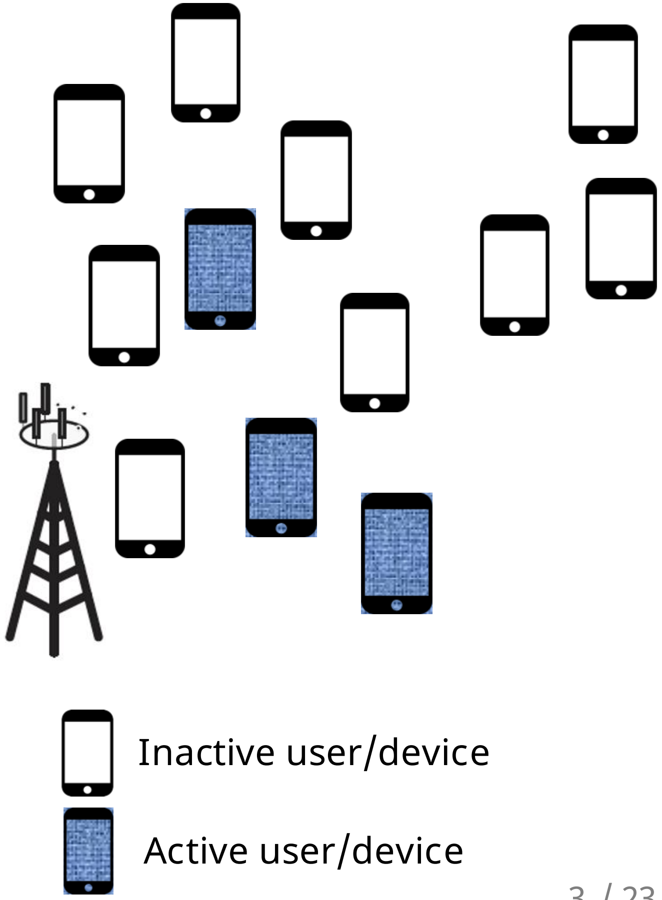
Outlines

- ❑ Motivation
- ❑ Problem Formulation
- ❑ Location-based codebooks and multisource-AMP
- ❑ Frequency-domain approach for uRA user-centric cell-free networks
- ❑ Time-domain approach for uRA user-centric cell-free networks
- ❑ Simulation Results
- ❑ Conclusion

Motivation

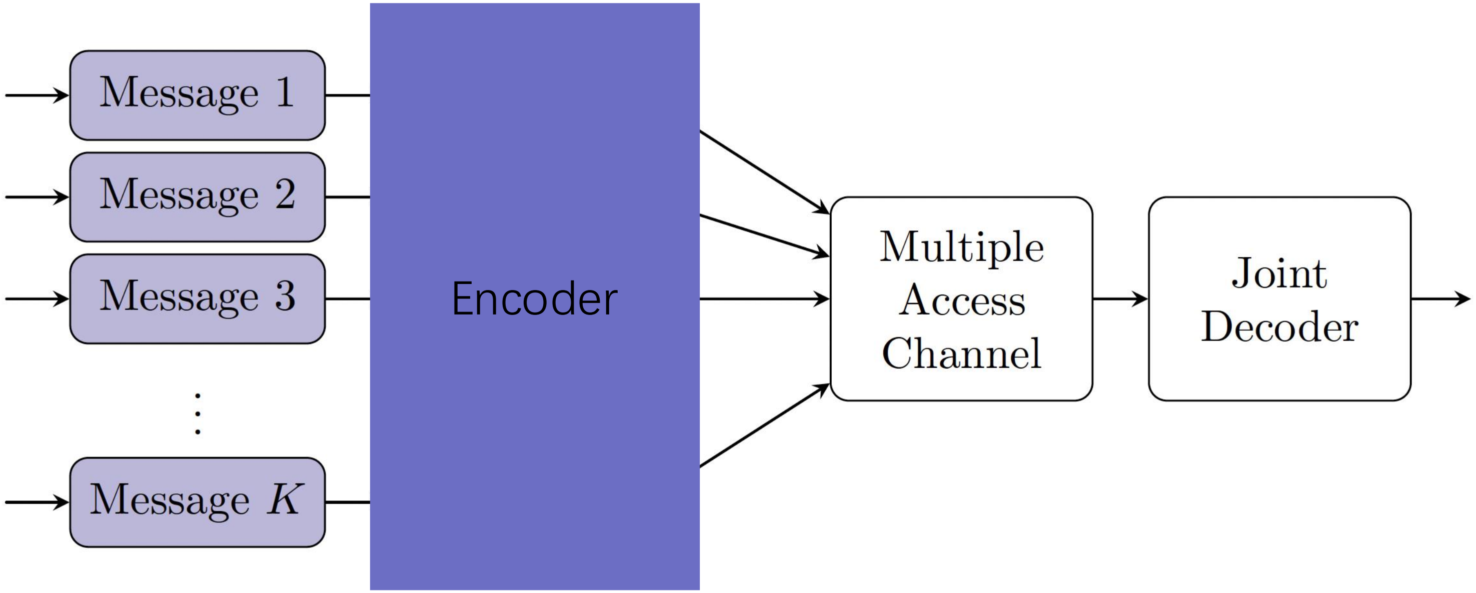
- Target scenarios: applications with a large number of users, sporadic traffic, and intermittent user activities, with emphasis on high spectral and energy efficiencies.
- Next-generation systems must meet stringent requirements on latency, scalability, sensing capabilities, and positioning accuracy.
- Existing multiple access techniques require coordination and/or allocation of available resources to all users.

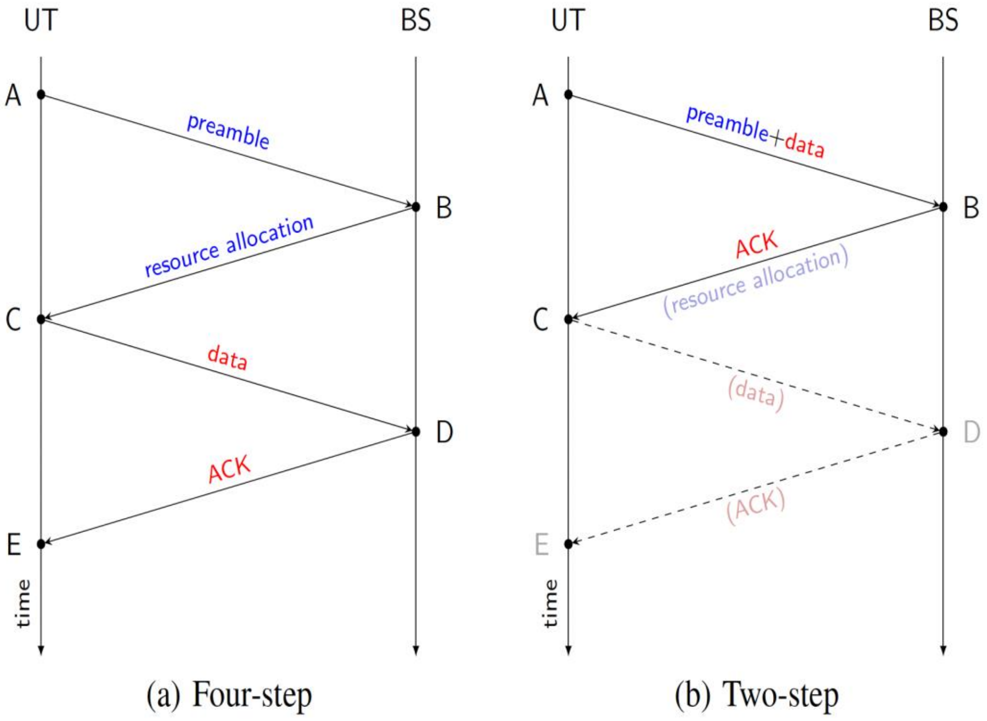




Motivation

- In current networks, each user has a unique access code (e.g., Zadoff-Chu sequences used in 4G LTE and 5G NR)
- For unsourced random access (uRA) [1], when active, the users transmit a randomly chosen codeword of the same codebook
- The goal of the receiver is to detect the list of active messages

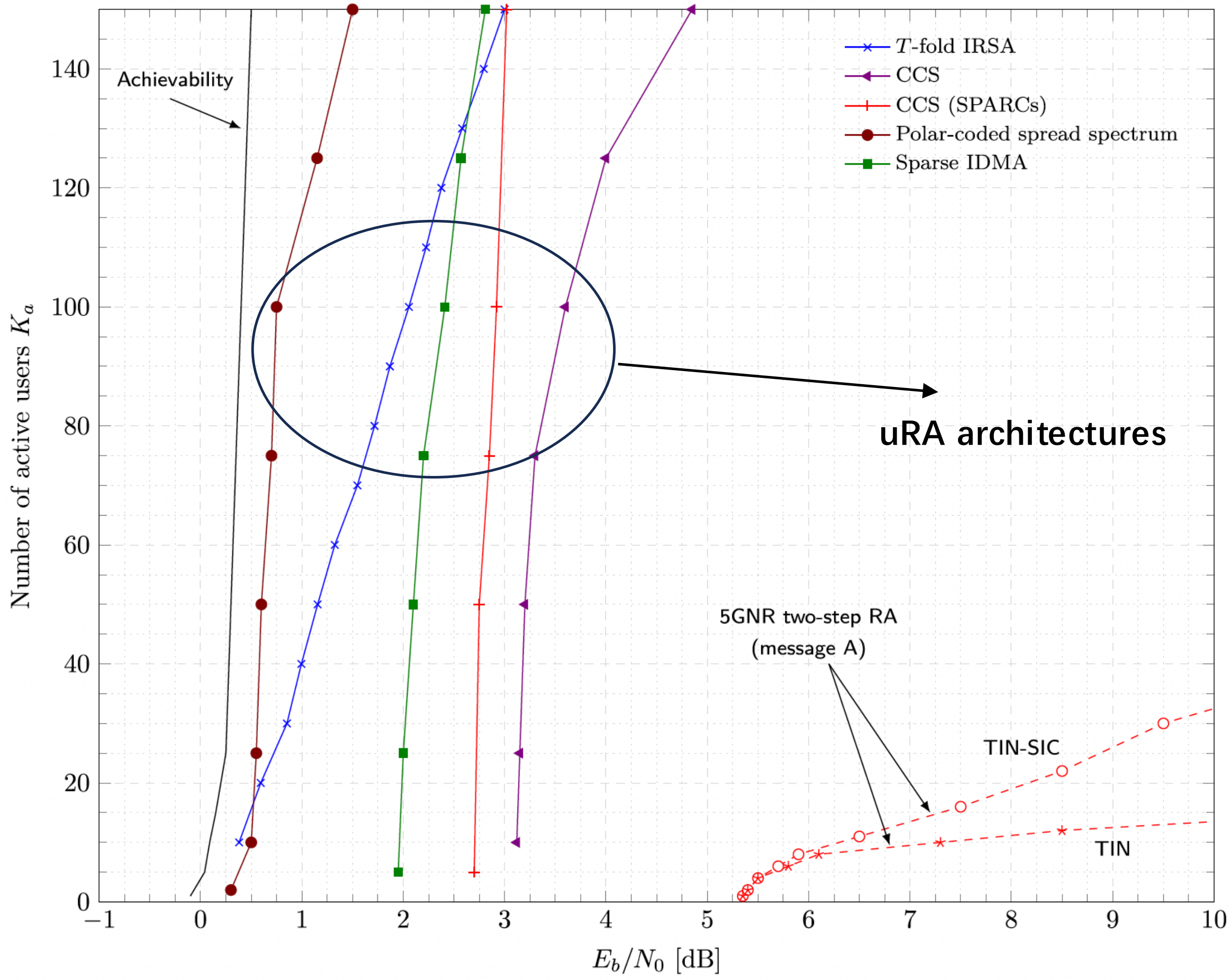




Random access procedures employed by LTE/5GNR standards. (a) Four-step random access, (b) Two-step random access (Release 16 of the 5G-NR standard) [2].

[1] Y. Polyanskiy, “A perspective on massive random-access,” in Proc. IEEE Int. Symp. Inf. Theory (ISIT), Jun. 2017, pp. 2523–2527.
[2] G. Liva and Y. Polyanskiy, “Unsourced multiple access: A coding paradigm for massive random access,” Proc. IEEE, vol. 112, no. 9, pp. 1214–1229, Sep. 2024.

Motivation



Performance comparison of conventional random-access techniques with multiple uRA architectures [1].

[1] G. Liva and Y. Polyanskiy, "Unsourced multiple access: A coding paradigm for massive random access," Proc. IEEE, vol. 112, no. 9, pp. 1214–1229, Sep. 2024.

Compressed sensing formulation (activity detection)

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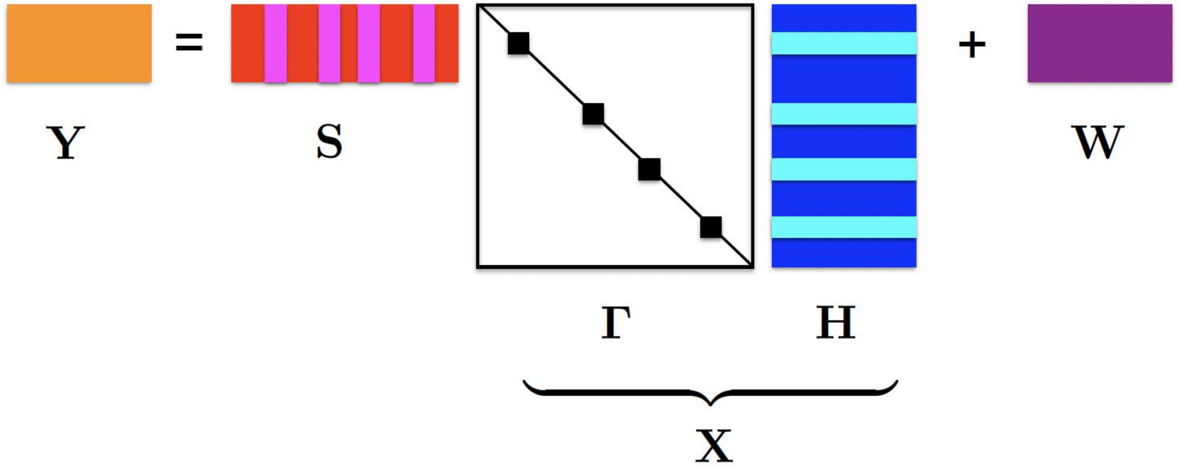
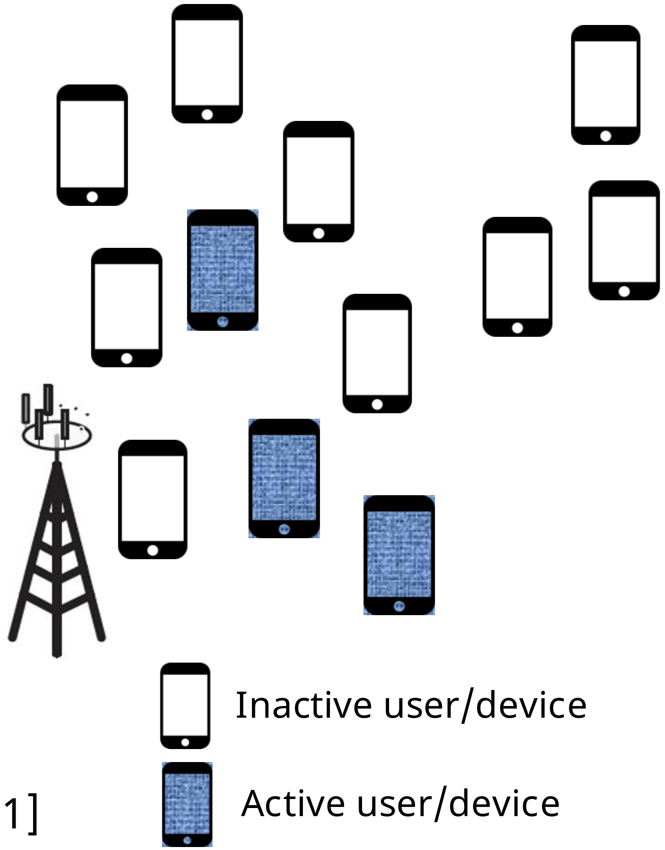
For a single-cell system, the received signal (with signature of length L) is



$\mathbf{\Gamma} = \mathbf{A}\mathbf{G} = \text{diag}(\boldsymbol{\gamma})$, where $\gamma_k = a_k g_k$ for user k with LSFC g_k

$\mathbf{X} = \mathbf{\Gamma}\mathbf{H}$ contains Bernoulli-Gaussian rows

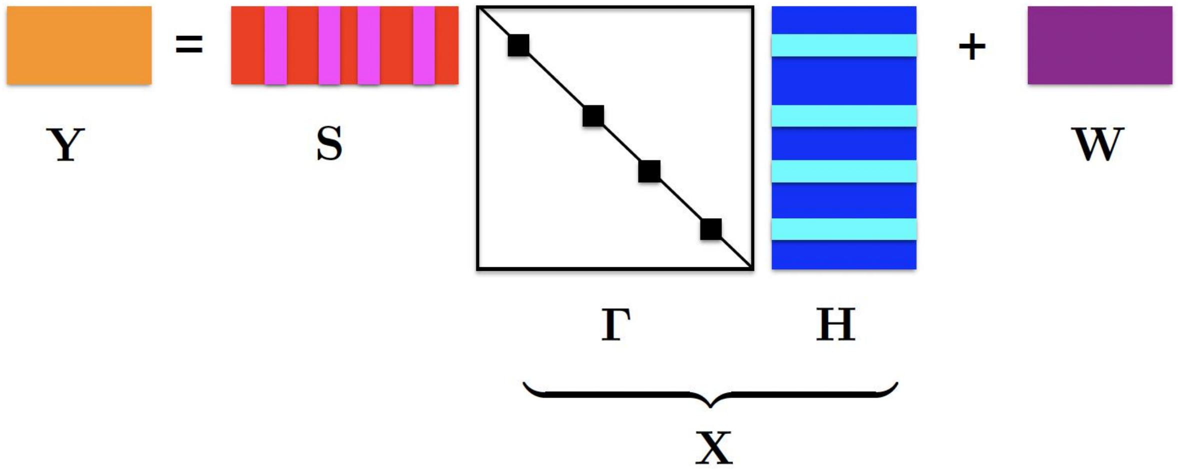


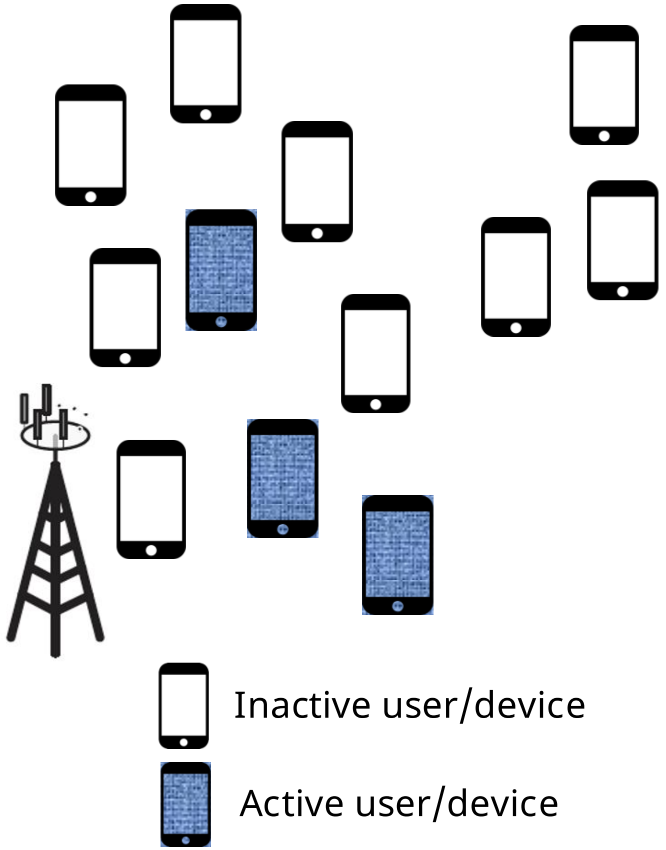
- The columns of **X** share the same sparsity pattern (common activity for a user), i.e., row sparsity [1]
- Can be seen as a multiple measurement vector (MMV) problem in compressed sensing [1]
- This problem can be solved with standard CS techniques, such as approximate message passing (AMP) and its variants (vector-AMP) [2], and Bayesian estimation is possible.

[1] L. Liu and W. Yu, "Massive connectivity with massive MIMO—Part I: Device activity detection and channel estimation," IEEE Trans. Signal Process., vol. 66, no. 11, pp. 2933–2946, Jun. 2018.
[2] Z. Chen, F. Sohrabi, and W. Yu, "Sparse activity detection for massive connectivity," IEEE Trans. Signal Process., vol. 66, no. 7, pp. 1890–1904, Apr. 2018.

Compressed sensing formulation (unsourced RA)

For a single-cell system, the received signal (with signature of length L) is





$\mathbf{\Gamma} = \mathbf{A}\mathbf{G} = \mathrm{diag}(\boldsymbol{\gamma})$, where $\gamma_k = a_k g_k$ for user k with LSFC g_k

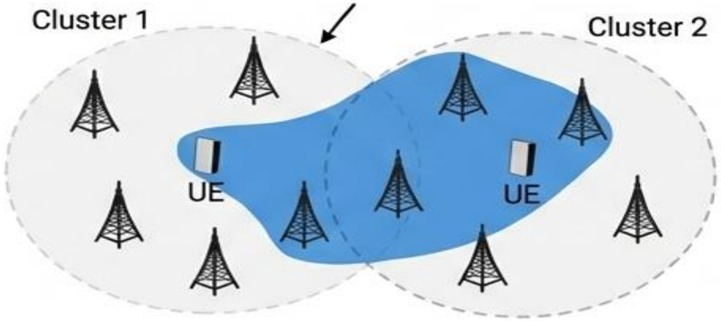
$\mathbf{X} = \mathbf{\Gamma}\mathbf{H}$ contains Bernoulli-Gaussian rows

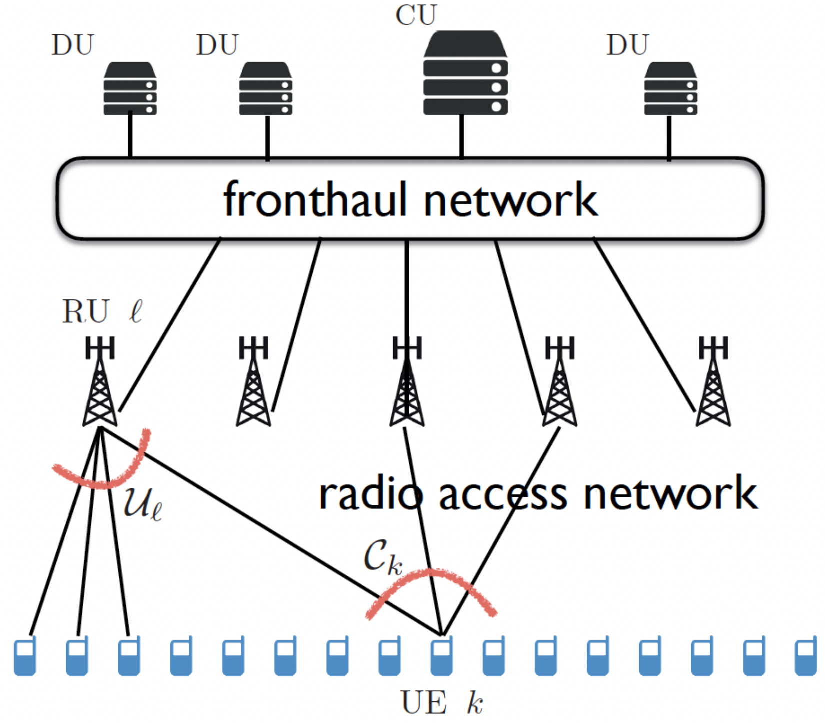
- In uRA, any active user can pick any codeword [1]
- Then, a fixed identification between the columns of **S** and the LSFCs is not possible.
- Then **X** can not be treated as Ber-Gauss. Bayesian estimation is challenging [2]

[1] Y. Polyanskiy, "A perspective on massive random-access," in Proc. IEEE Int. Symp. Inf. Theory (ISIT), Jun. 2017, pp. 2523–2527.
[2] A. Fengler, S. Haghighatshoar, P. Jung, and G. Caire, "Non-Bayesian activity detection, large-scale fading coefficient estimation, and unsourced random access with a massive MIMO receiver," IEEE Trans. Inf. Theory, vol. 67, no. 5, pp. 2925–2951, May 2021.

User-centric Cell-free Networks

- We adopt user-centric cell-free networks [1,2]
- Each user is served by a user-centric cluster of RUs
- The cells will be dynamically determined depending on user locations [3], and the boundary effect can be mitigated
- Centralized units also exist and implement centralized processing

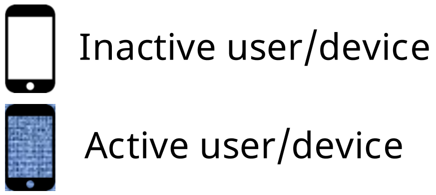


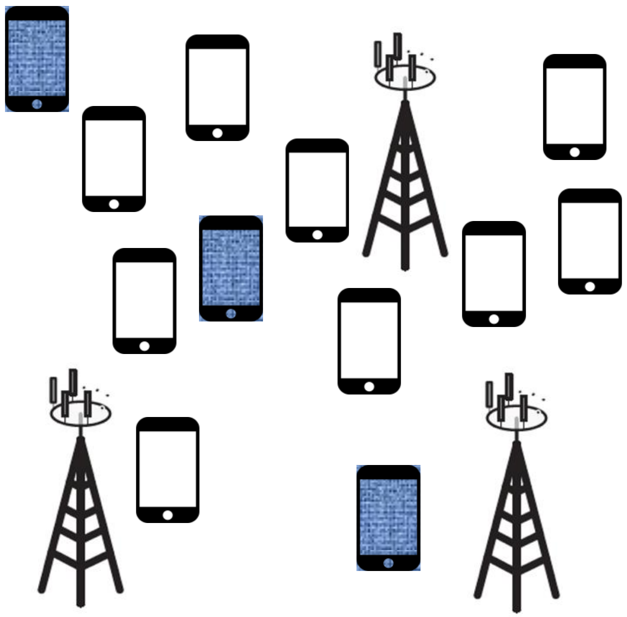


User-Centric Cell-Free Wireless Networks [4]

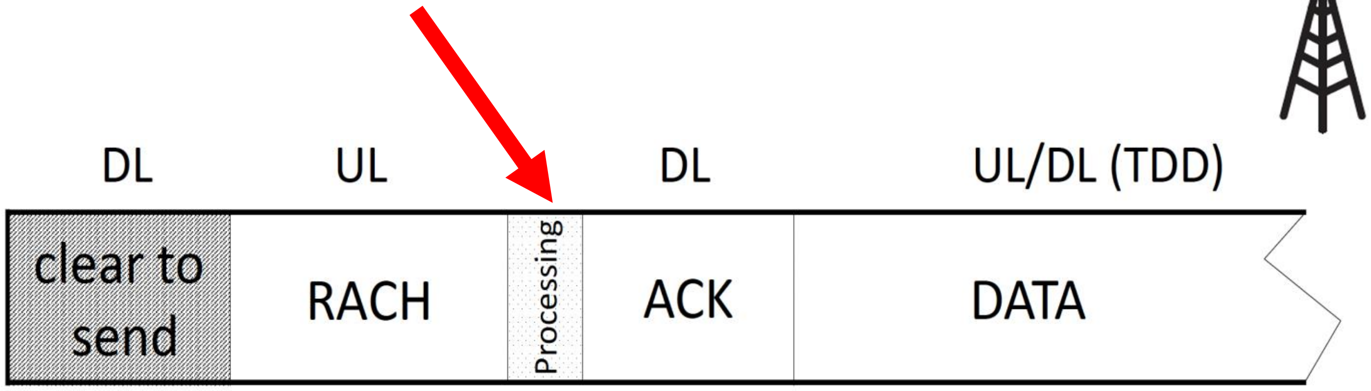
[1] H. Q. Ngo and A. E. Ashikhmin and H. Yang and E. G. Larsson and T. L. Marzetta, ”Cell-free Massive MIMO: Uniformly great service for everyone," IEEE SPAWC 2015.
[2] O . T. Demir, E. Bjornson, and L. Sanguinetti, “Foundations of user-centric cell-free massive MIMO,” Found. Trends Signal Process., vol. 14, nos. 3–4, pp. 162–472, 2021.
[3] H. Q. Ngo et al., “Ultradense cell-free massive MIMO for 6G: Technical overview and open questions,” Proc. IEEE, vol. 112, no. 7, pp. 805–831, 2024.
[4] F. Göttsch, O. Noboru, K. Issei, O. Takeo, and G. Caire, "Fairness scheduling in user-centric cell-free massive MIMO wireless networks." IEEE Transactions on Wireless Communications 23, no. 9 (2024): 11942-11957.

System Model and Problem Formulation

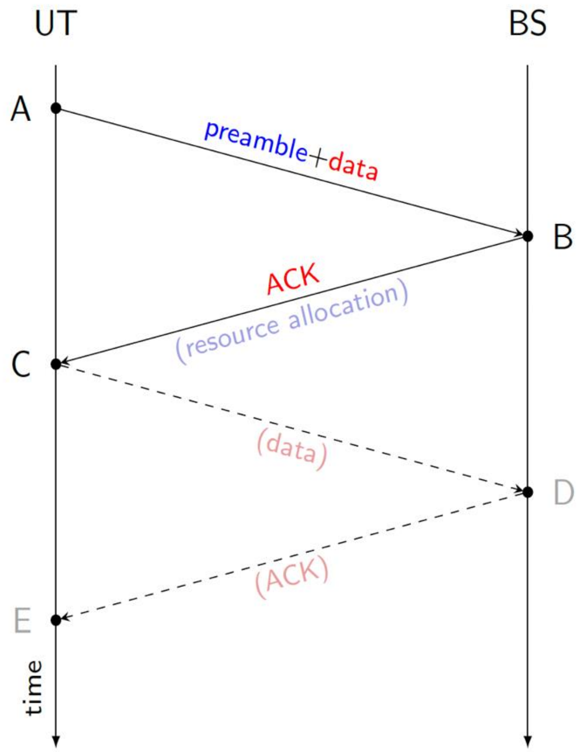




- *uRA message decoding/detection*
- *Channel Estimation*
- *Positioning*
- *User Cluster Formation*



A schematic of the RACH slot, followed by a downlink packet [2].



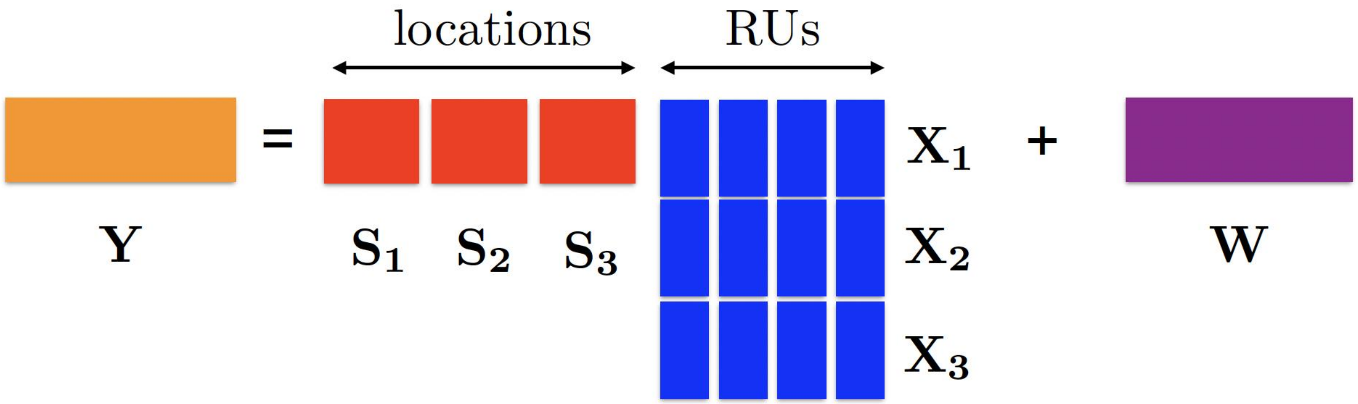
Random access procedures employed by LTE/5GNR standards. Two-step random access (Release 16 of the 5G-NR standard) [1].

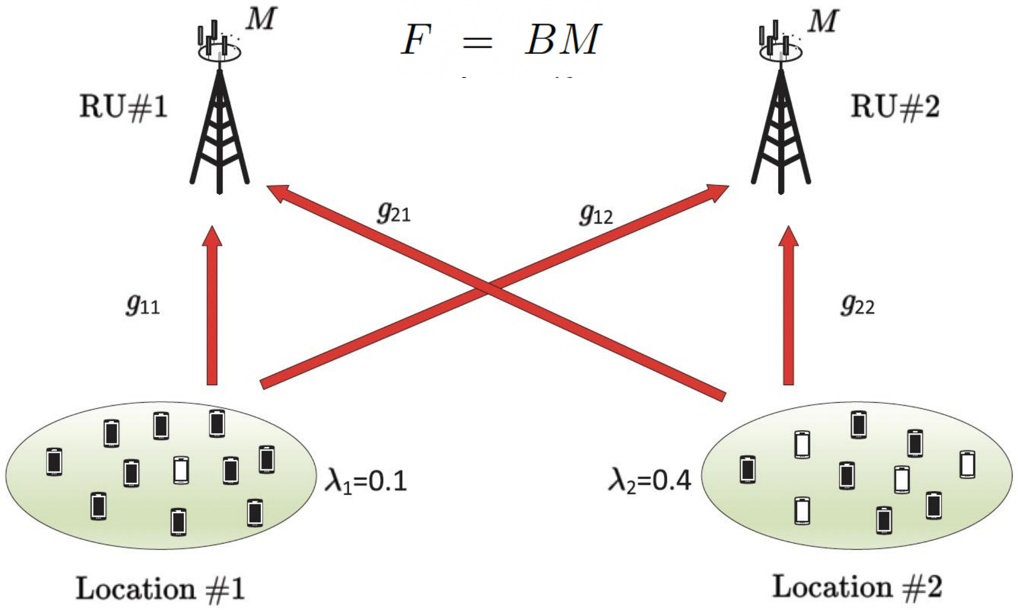
[1] G. Liva and Y. Polyanskiy, “Unsourced multiple access: A coding paradigm for massive random access,” Proc. IEEE, vol. 112, no. 9, pp. 1214–1229, Sep. 2024.

[2] B. Cakmak, E. Gkiouzepi, M. Opper, and G. Caire, “Joint message detection and channel estimation for unsourced random access in cell-free user-centric wireless networks”, IEEE Trans. Inf. Theory, vol. 71, no. 5, pp. 3614-3643, May 2025.

Location-based codebooks

$$\mathbf{Y} = \sum_{u=1}^{U} \mathbf{S}_u \mathbf{X}_u + \mathbf{W}$$





The coverage area $\mathcal{D}$ is partitioned into U disjoint zones $\mathcal{D}_u : u \in [U]$, referred to as "*locations*", such that $\mathcal{D}_u \cap \mathcal{D}_{u'} = \varnothing\ \forall u \neq u'$ and $\bigcup_{u\in[U]} \mathcal{D}_u = \mathcal{D}$.

$$\mathbf{x}_u \sim \mathrm{a}_u \mathbf{h}_u$$

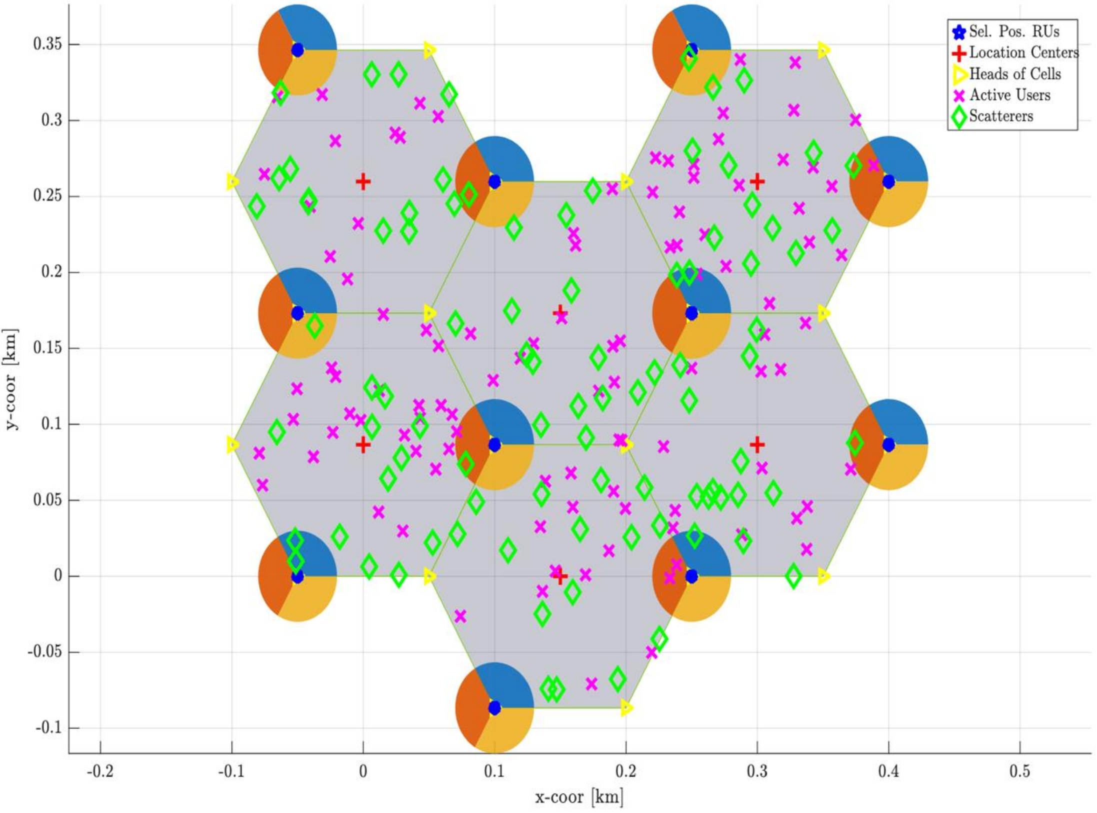
$$\mathbf{h}_u = [\mathbf{h}_{u,1}, \mathbf{h}_{u,2}, \ldots, \mathbf{h}_{u,B}] \sim \mathcal{CN}(\mathbf{0}, \boldsymbol{\Sigma}_u)$$

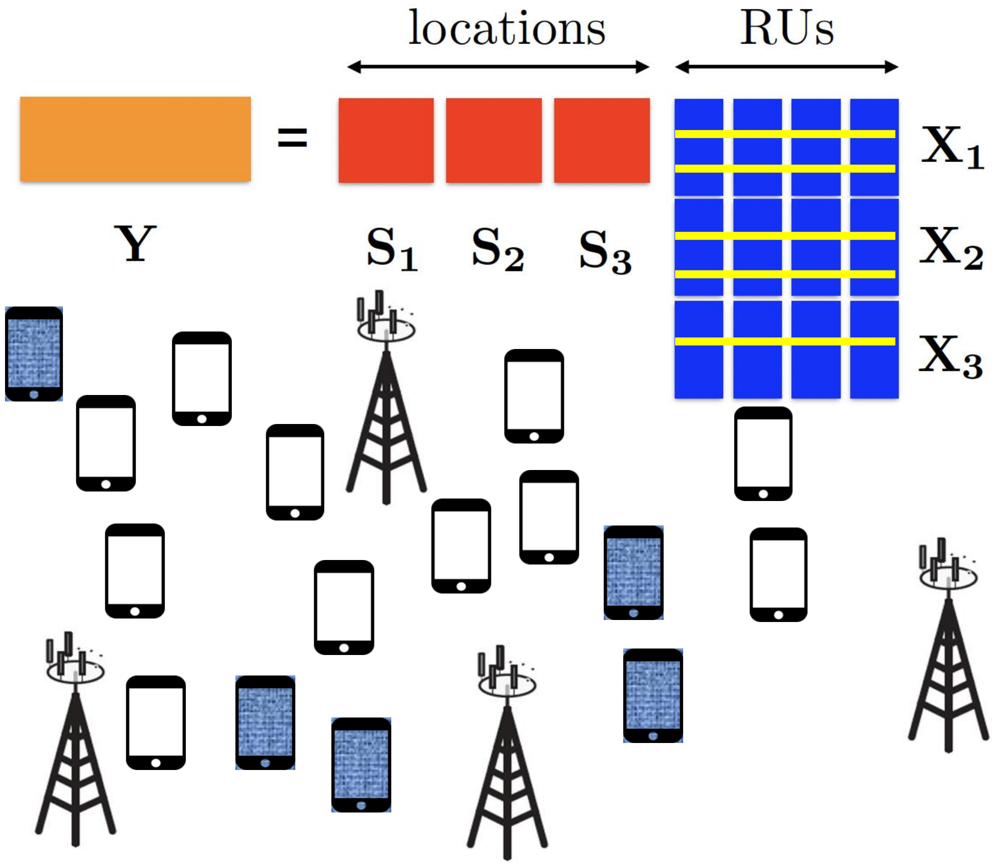
$$\boldsymbol{\Sigma}_u \triangleq \mathrm{diag}(g_{u,1}, g_{u,2}, \cdots, g_{u,B}) \otimes \mathbf{I}_M$$

In [1], the location-dependent LSFC profile for a given zone is defined such that the users in any given location have a statistically identical LSFC profile to all the RUs.

[1] B. Cakmak, E. Gkiouzepi, M. Opper, and G. Caire, "Joint message detection and channel estimation for unsourced random access in cell-free user-centric wireless networks", IEEE Trans. Inf. Theory, vol. 71, no. 5, pp. 3614-3643, May 2025.

Location-based codebooks





[1] B. Cakmak, E. Gkiouzepi, M. Opper, and G. Caire, "Joint message detection and channel estimation for unsourced random access in cell-free user-centric wireless networks", IEEE Trans. Inf. Theory, vol. 71, no. 5, pp. 3614-3643, May 2025.

[2] E. Gkiouzepi, B. Cakmak, M. Opper, and G. Caire, "Joint message detection, channel, and user position estimation for unsourced random access in cell-free networks," in Proc. IEEE Workshop Signal Process. Adv. Wireless Commun. (SPAWC), Lucca, Italy, pp. 151-155, Sep. 2024.

Multisource AMP

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Iterative Algorithm with t=1,2, …, T iterations:

$$\mathbf{\Gamma}_u^{(t)} = \mathbf{S}_u \mathbf{X}_u^{(t)} - \alpha_u \mathbf{Z}^{(t-1)} \mathbf{Q}_u^{(t)} \tag{1a}$$

$$\mathbf{Z}^{(t)} = \mathbf{Y} - \sum_{u=1}^{U} \mathbf{\Gamma}_u^{(t)} \tag{1b}$$

$$\mathbf{R}_u^{(t)} = \mathbf{S}_u^{\mathsf{H}} \mathbf{Z}^{(t)} + \mathbf{X}_u^{(t)} \tag{1c}$$

$$\mathbf{X}_u^{(t+1)} = \eta_{u,t}(\mathbf{R}_u^{(t)}) \tag{1d}$$

Denoiser function (row-wise)

$$\eta_{u,t}(\cdot) : \mathbb{C}^F \to \mathbb{C}^F \qquad \eta_{u,t}(\mathbf{R}) = [\eta_{u,t}(\mathbf{r}_1)^\top, \eta_{u,t}(\mathbf{r}_2)^\top, \cdots, \eta_{u,t}(\mathbf{r}_N)^\top]^\top$$

Using the Jacobian matrix of the denoiser, we can update

$$\mathbf{Q}_u^{(t+1)} = \mathbb{E}[\eta'_{u,t}(\mathbf{x}_u + \boldsymbol{\phi}^{(t)})] \quad \forall t \in [T],$$

[1] B. Cakmak, E. Gkiouzepi, M. Opper, and G. Caire, “Joint message detection and channel estimation for unsourced random access in cell-free user-centric wireless networks”, IEEE Trans. Inf. Theory, vol. 71, no. 5, pp. 3614-3643, May 2025.

Decoupled Model

The decoupling principle with the noise statistics described in [Th1, 1]

$$\underline{\mathbf{r}}_u^{(t)} = \underline{\mathbf{x}}_u + \underline{\boldsymbol{\phi}}^{(t)}$$

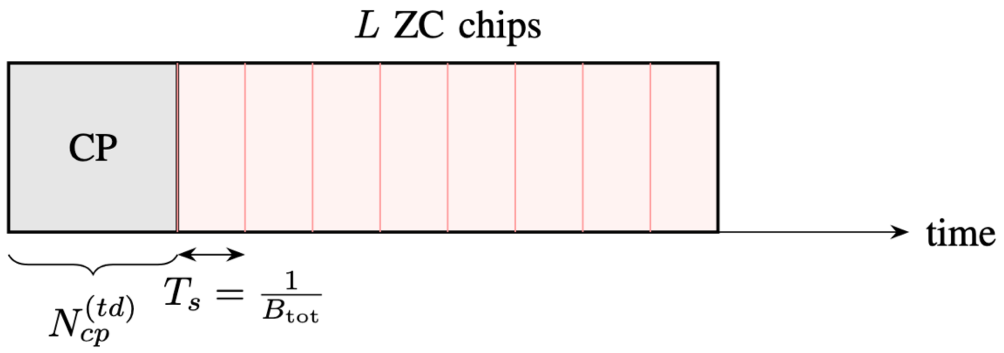
$\{\underline{\boldsymbol{\phi}}^{(t)}\}_{t\in[T]} \in \mathbb{C}^{1\times F}$ is a zero-mean vector-valued Gaussian process with covariance matrix recursively computed by the *state evolution (SE)* in [Def. 1, 1]

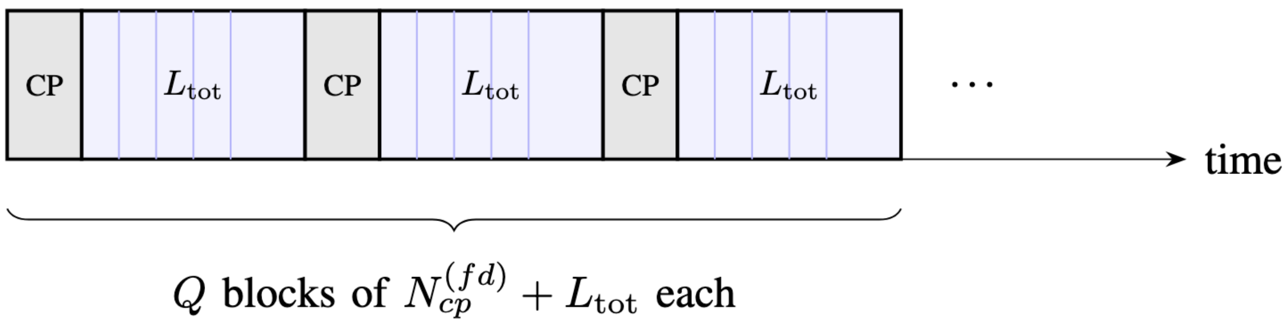
To design the denoiser, one can utilize the posterior mean estimator

$$\eta_{u,t}(\mathbf{r}) = \mathbb{E}[\mathbf{x}_u|\mathbf{r}_u^{(t)}]$$

[1] B. Cakmak, E. Gkiouzepi, M. Opper, and G. Caire, “Joint message detection and channel estimation for unsourced random access in cell-free user-centric wireless networks”, IEEE Trans. Inf. Theory, vol. 71, no. 5, pp. 3614-3643, May 2025.

FD and TD pipelines for uRA user-centric CF





FD and TD pipelines for uRA user-centric CF

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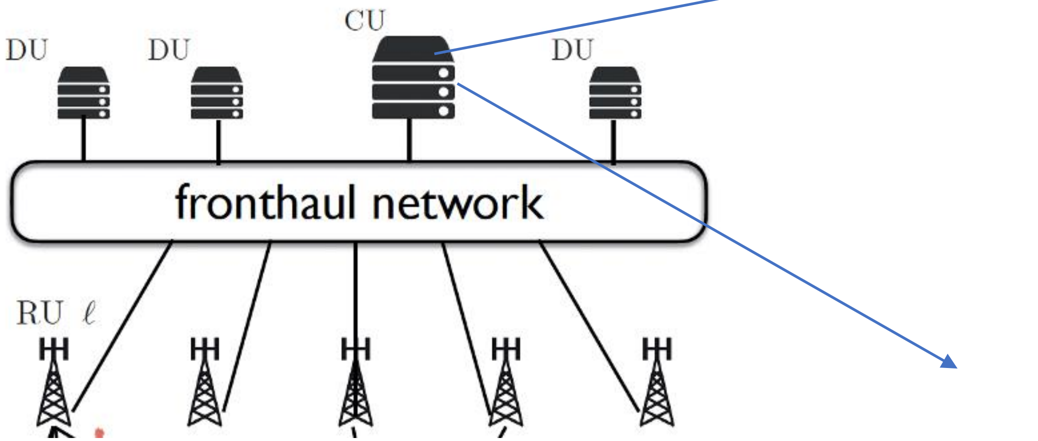
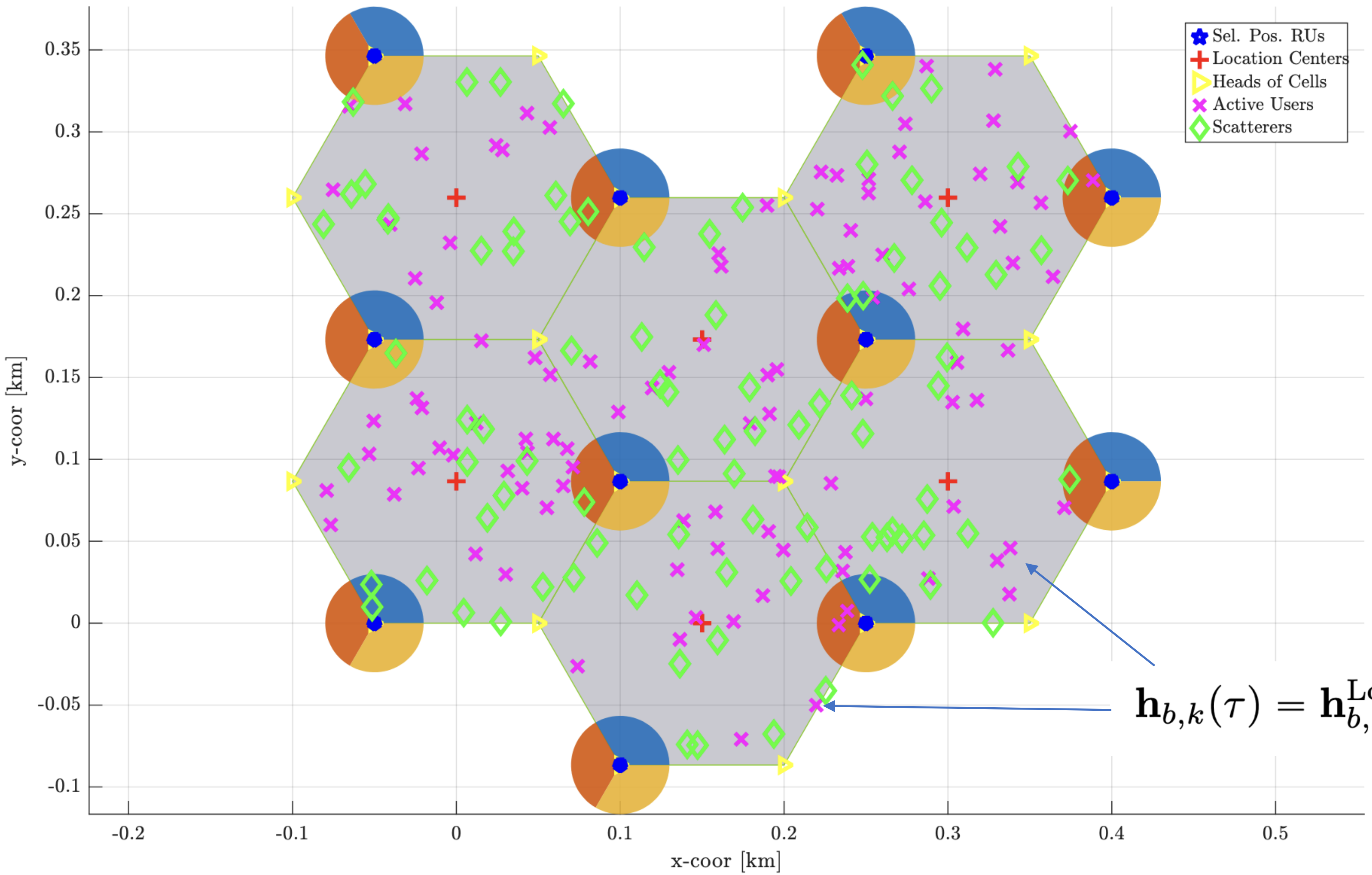


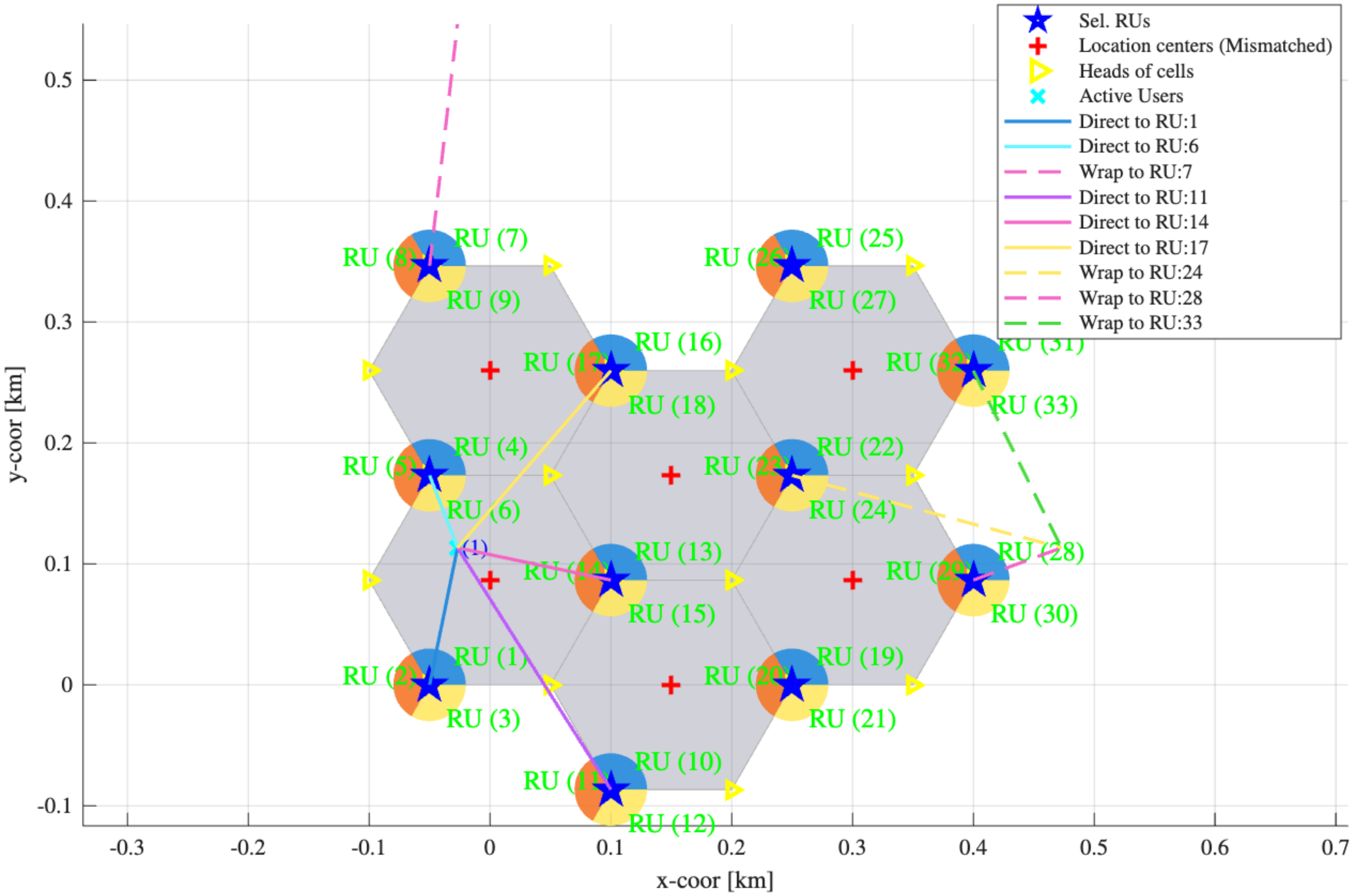
Matched Filter	generalized likelihood ratio test (GLRT)	MMLE Direct Localization
MS-AMP per subcarrier + Mismatched Denoiser	Neyman Pearson	MMLE Direct Localization

Spatially-consistent frequency-selective channel model



$$\mathbf{h}_{b,k}(\tau) = \mathbf{h}_{b,k}^{\mathrm{LoS}}(\tau) + \mathbf{h}_{b,k}^{\mathrm{Spec}}(\tau)$$

Spatially-consistent frequency-selective channel model



Spatially-consistent frequency-selective channel model

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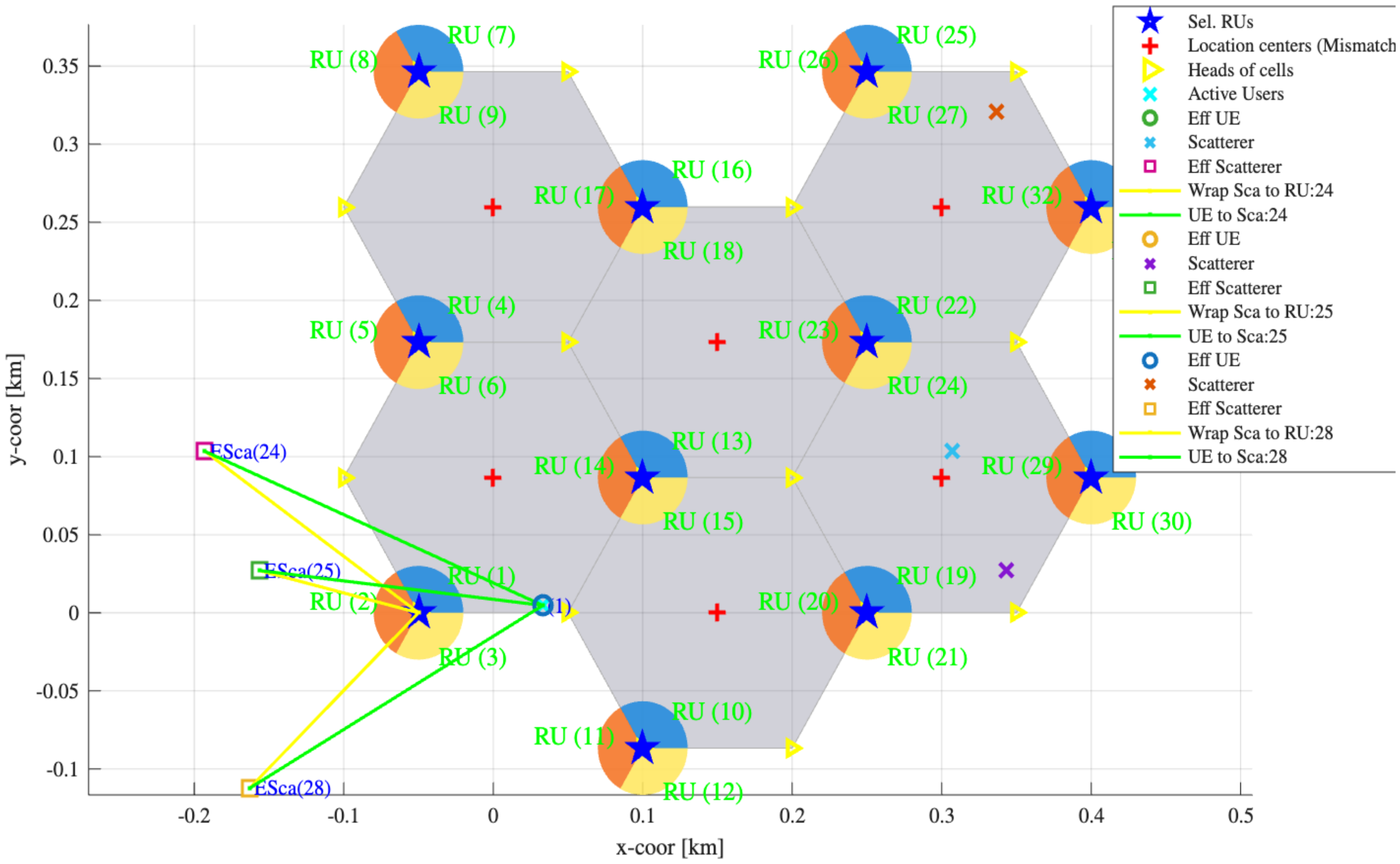

Spatially-consistent frequency-selective channel model

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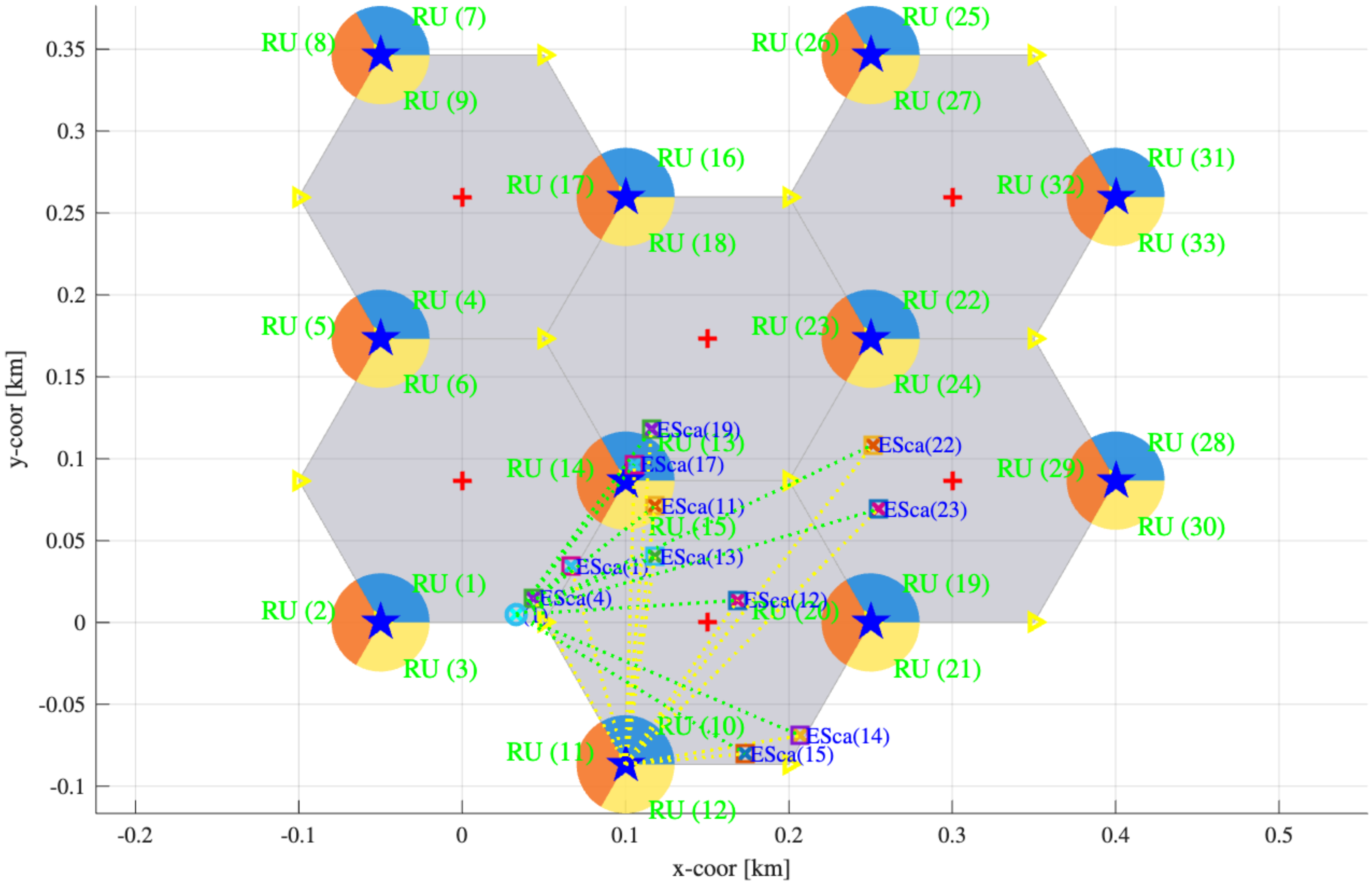

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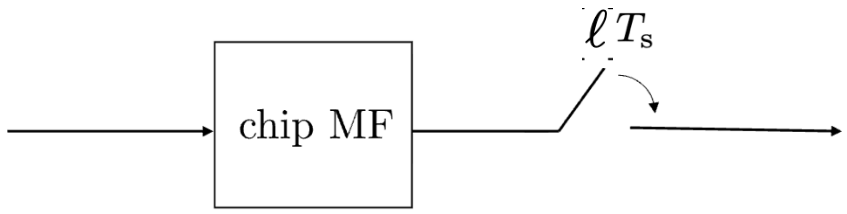
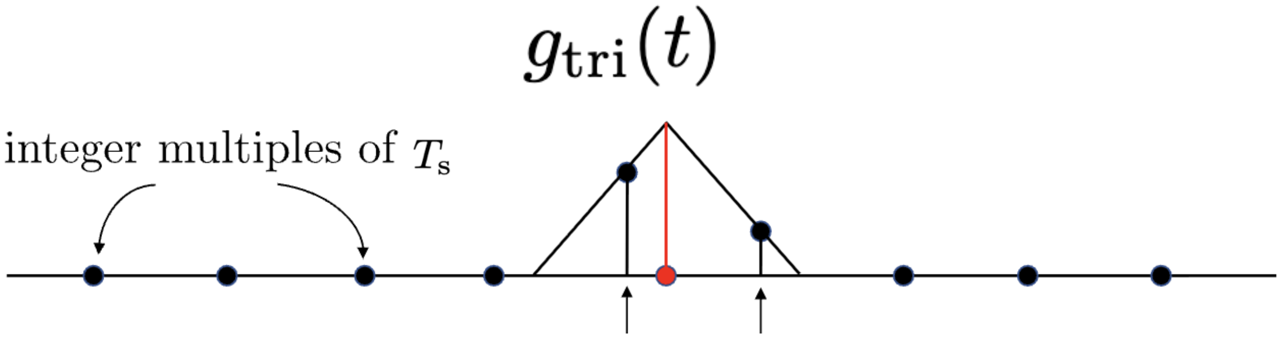




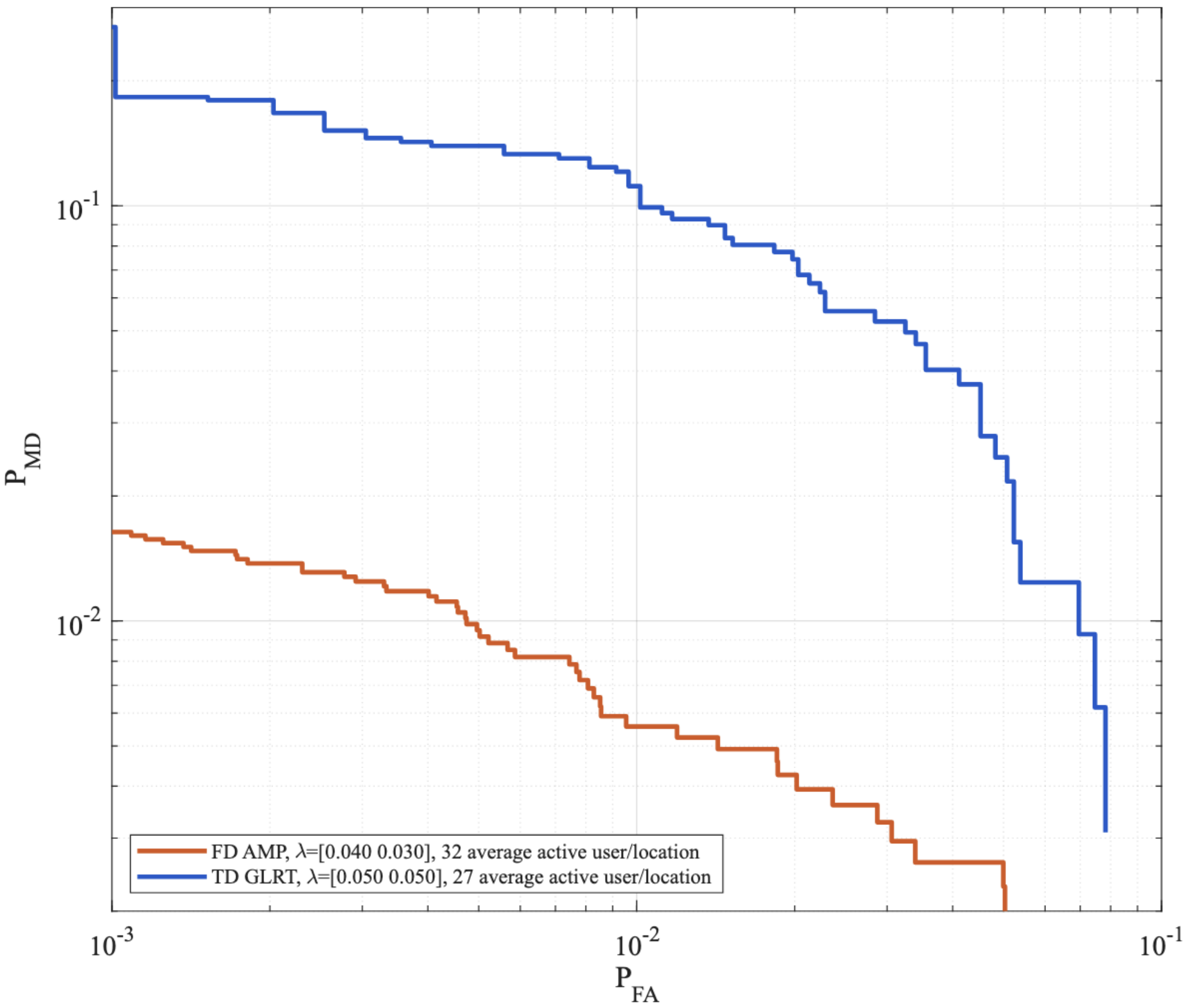
$$\tau_{b,k}^{(p)} = (\ell_{b,k}^{(p)} + \bar{\ell}_{b,k}^{(p)})T_{\text{s}}, \; \bar{\ell}_{b,k}^{(p)} \in [0,1)$$

Frequency domain channel

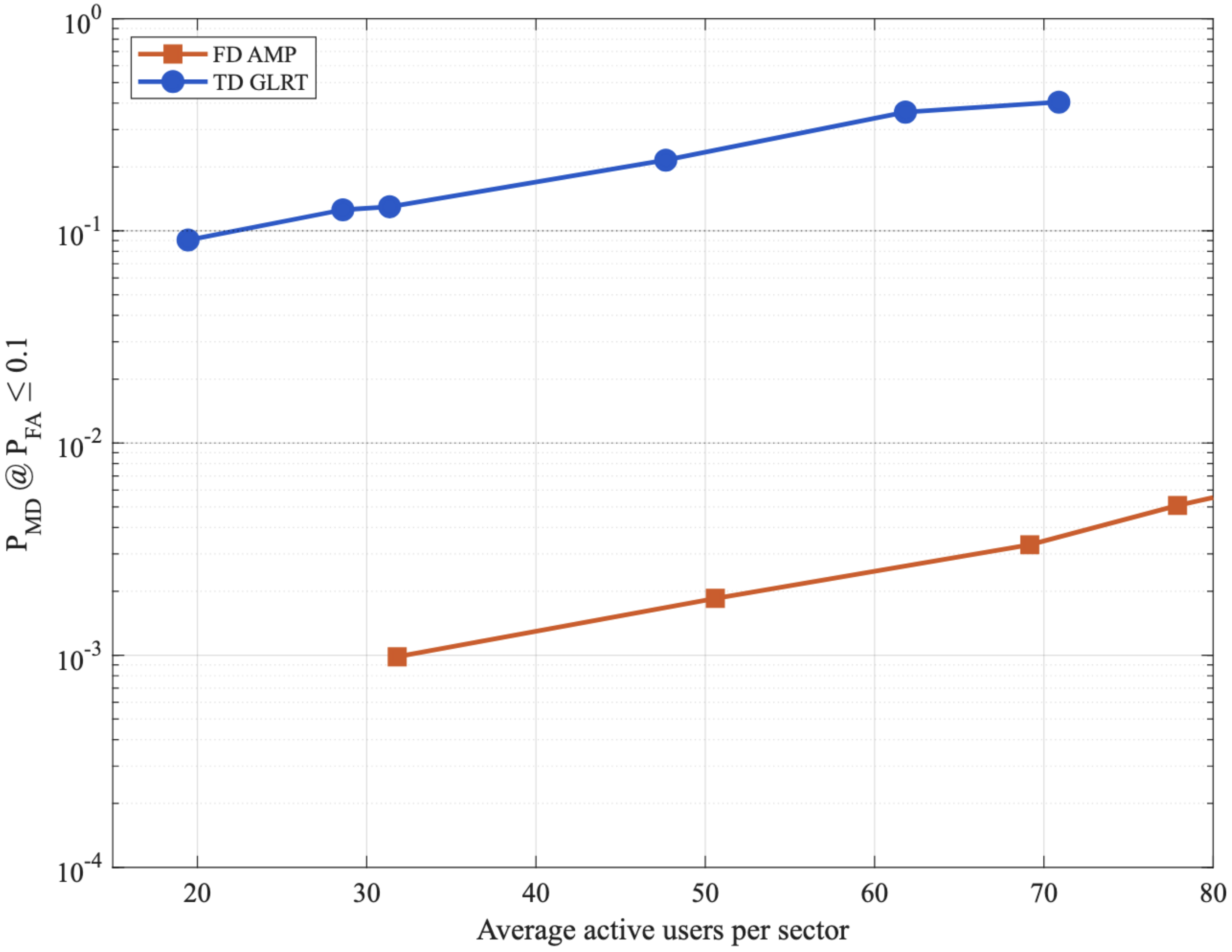
$$\tilde{\mathbf{h}}_{b,k}[\xi] = \sum_{\ell=0}^{L-1} \mathbf{h}_{b,k}[\ell] e^{-j\frac{2\pi\xi}{L_{\text{tot}}}\ell}.$$

Time-delay domain channel

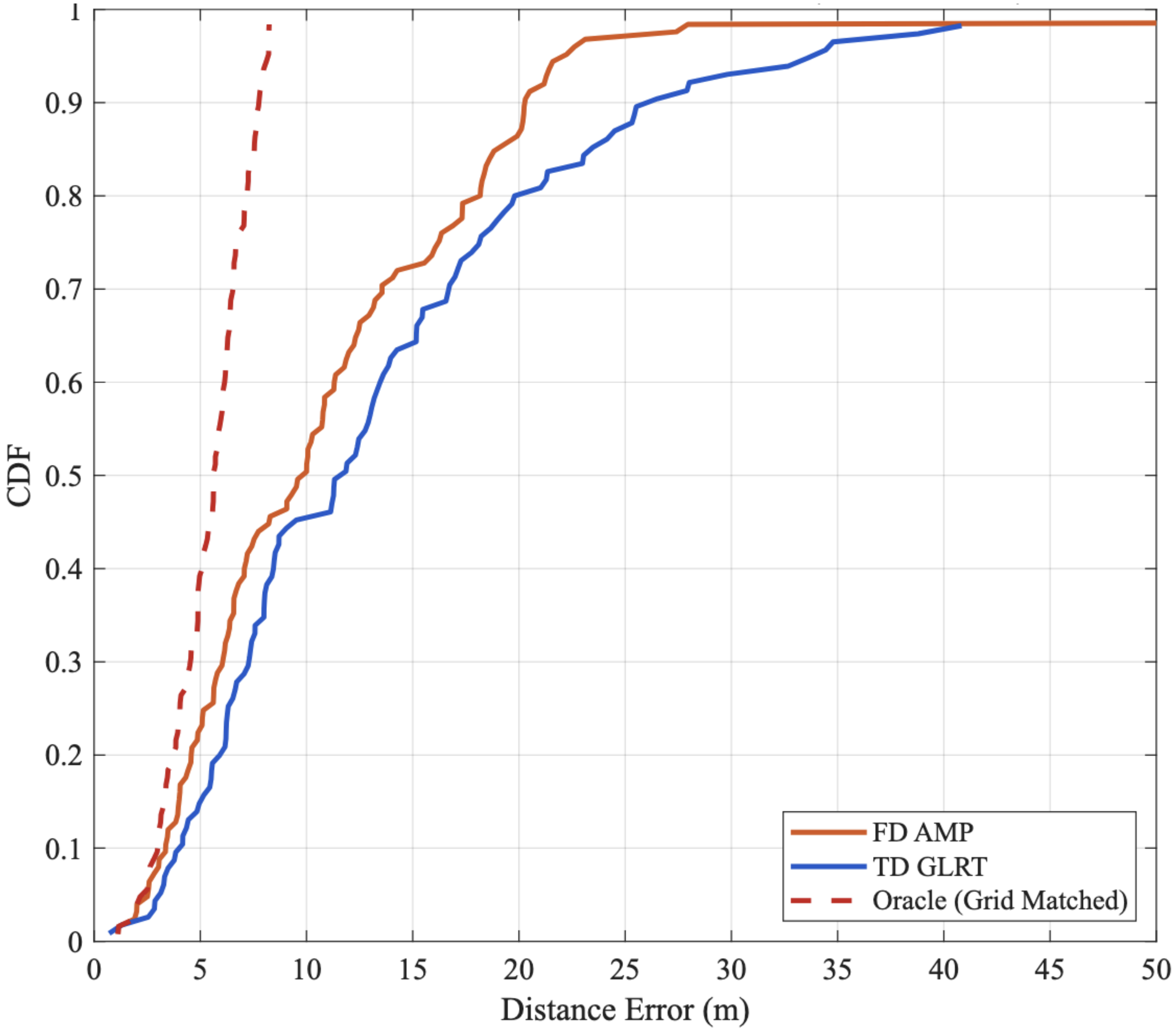
Simulation Results



Simulation Results



Simulation Results



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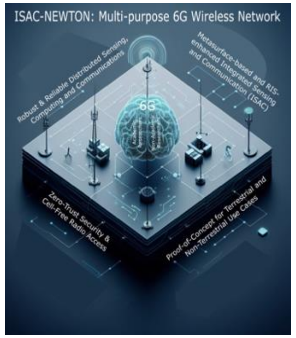

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