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One-Shot Near-Field Localization with AI-Optimized Hybrid Beamformer Design

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Introduction

- Is it possible to localize a user in the near-field with a **hybrid beamformer**?
- **How many** RF chains do we need to achieve reasonable localization accuracy?
- What is the **performance gap** compared to the **fully-digital** scheme?

mmWave, XL-MIMO → **Near-field** up to 100 meters → Is fully-digital feasible? → **Hybrid beamforming**: which combining matrix? → AI-optimized beamformer for near-field localization

System Model

Received signal: $$\mathbf{y} = \sqrt{\rho}\,\mathbf{a}(\theta, r) + \mathbf{n}$$

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SNR

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SNR

Near-field array response vector

$$\mathbf{a}(\theta, r) = [e^{-j\frac{2\pi}{\lambda}(r_1 - r)}, \ldots, e^{-j\frac{2\pi}{\lambda}(r_N - r)}]^T$$

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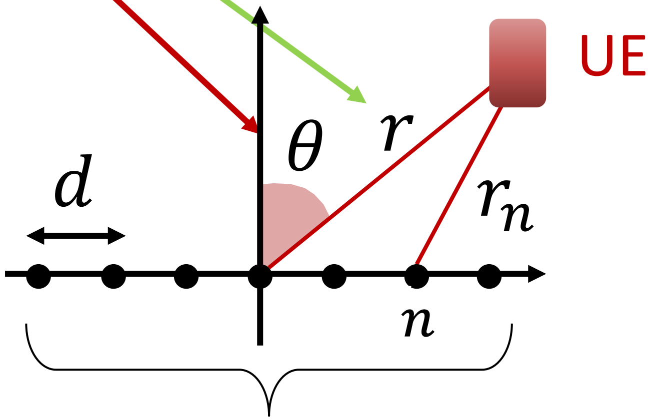
r Distance from the center of the array

θ Angle from the center of the array



Uniform Linear Array

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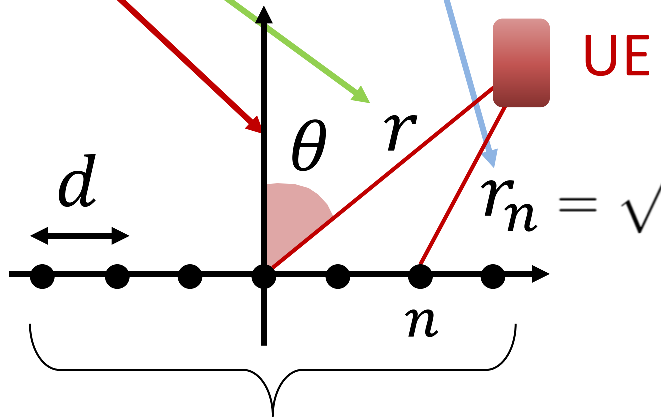


$$r_n = \sqrt{r^2 + \delta_n^2 d^2 - 2r \sin\theta \delta_n d}$$

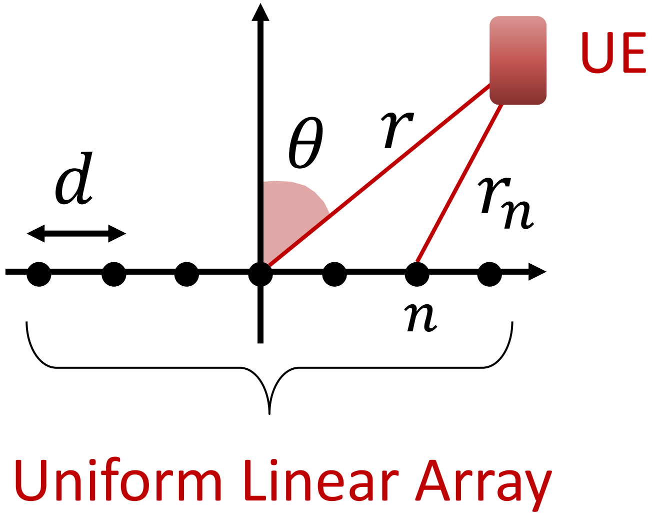
Uniform Linear Array

- r Distance from the center of the array
- θ Angle from the center of the array
- r_n Angle from the *n*-th antenna element

System Model

Received signal: $\mathbf{y} = \sqrt{\rho}\,\mathbf{a}(\theta, r) + \mathbf{n}$

Combined signal: $\bar{\mathbf{y}} = \mathbf{V}\mathbf{y} = \sqrt{\rho}\mathbf{V}\mathbf{a}(\theta, r) + \mathbf{V}\mathbf{n}$



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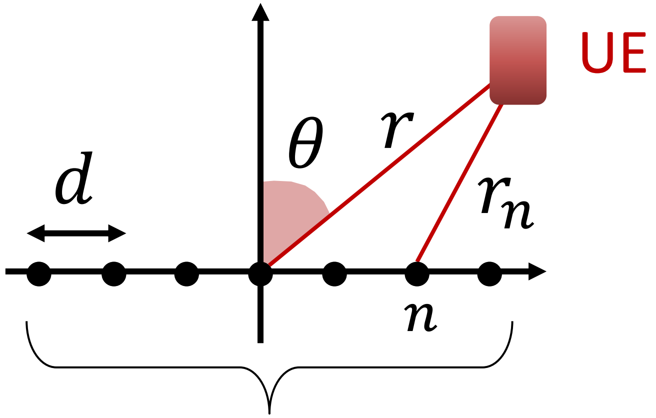
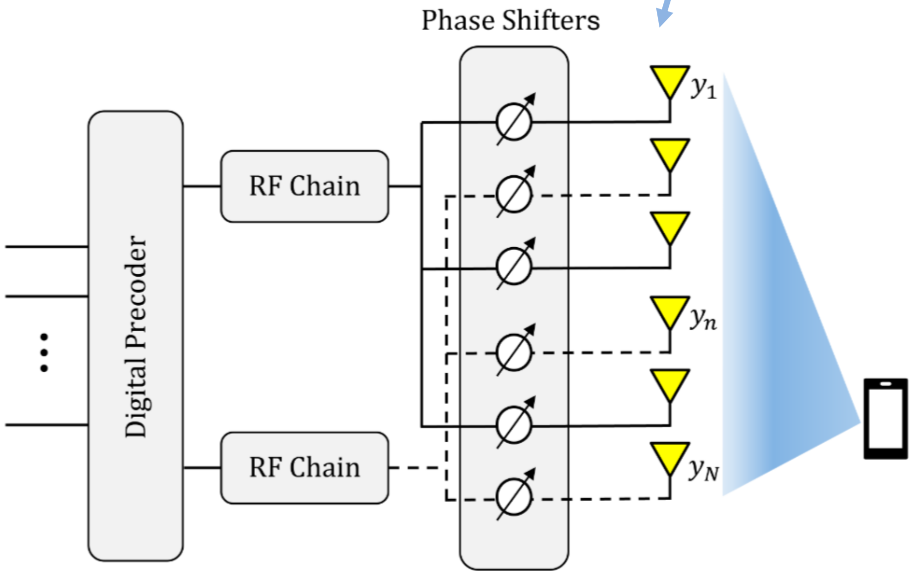
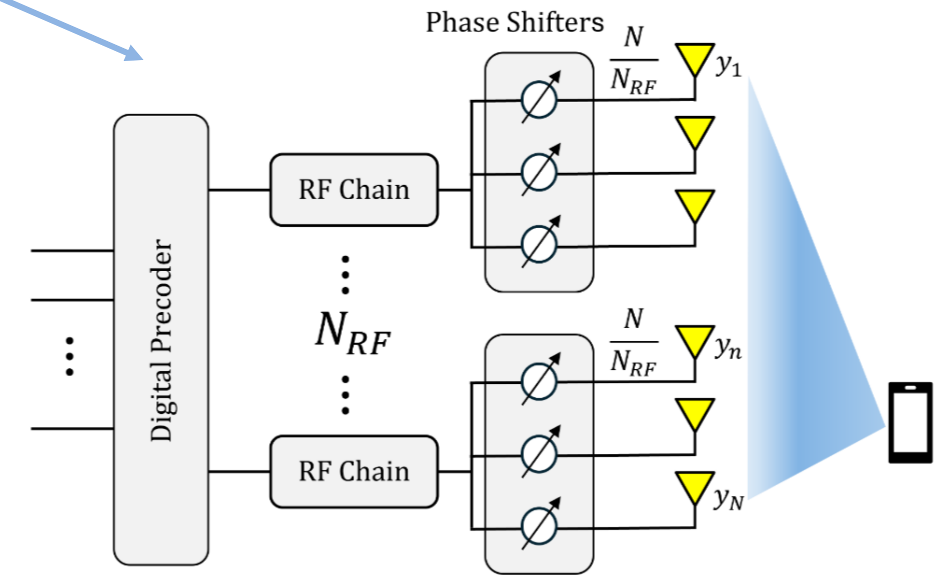


Uniform Linear Array



(b) Inter-connected



(a) Sub-array

Near-Field Localization with Hybrid Beamforming

Methodology

The analog combiner phase shifters are tuned through a set of **constrained** learnable parameters.

Then, a localizing network maps the features into range and angle.

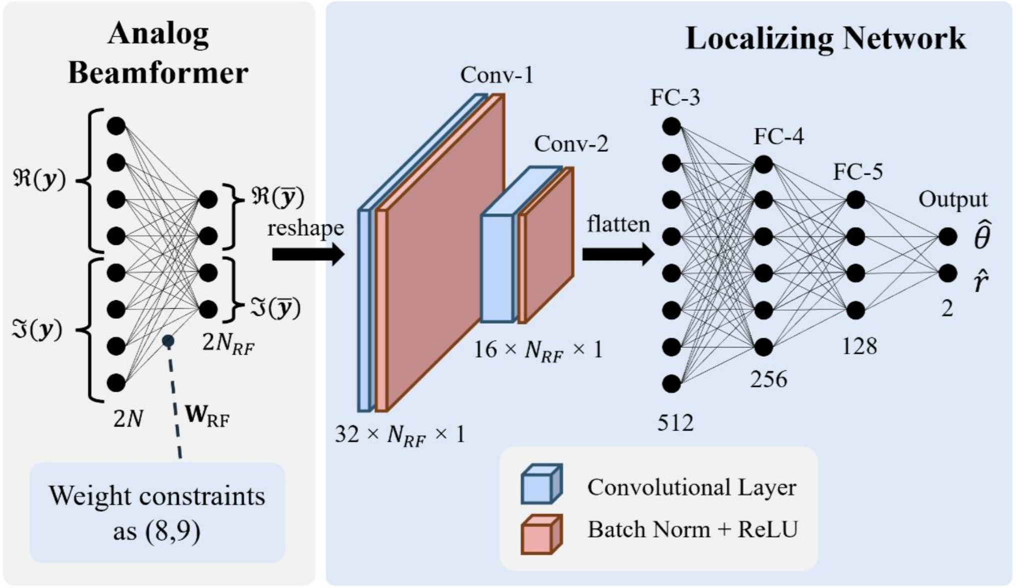


Fig. 2: Structure of the developed DNN, divided into two parts: analog beamformer and localizing function.

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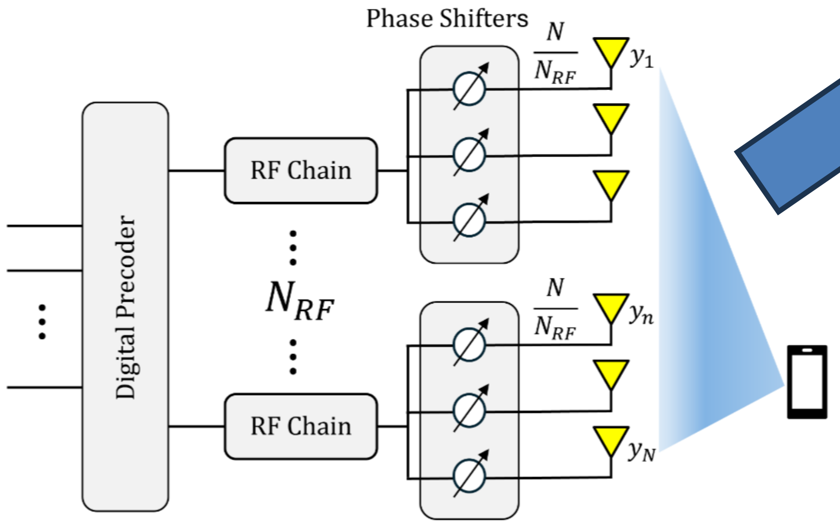
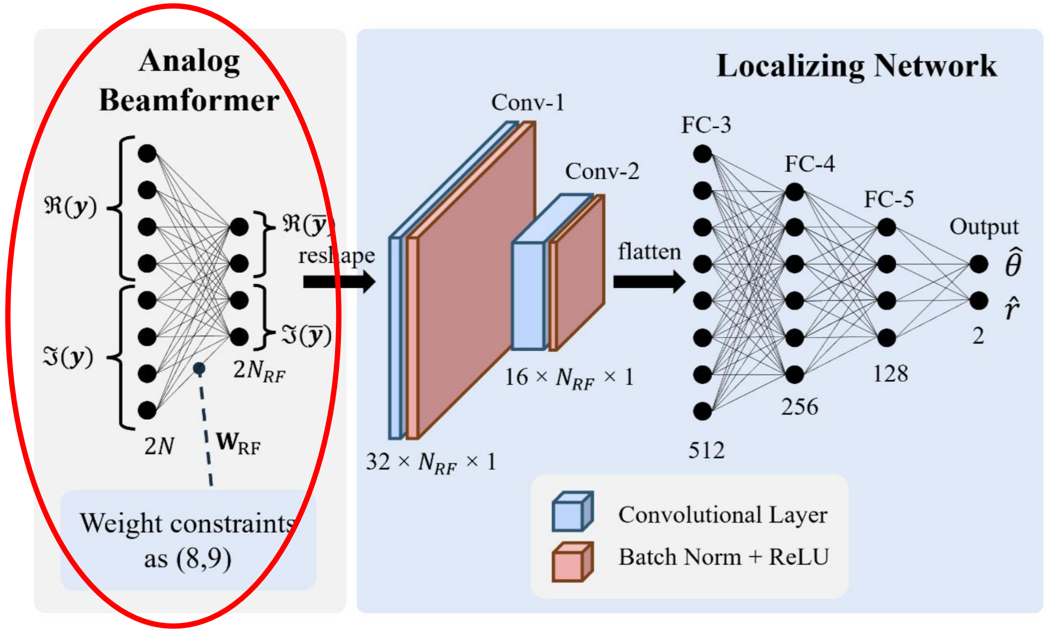


(a) Sub-array



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Near-Field Localization with Hybrid Beamforming

Objective function: find the optimal weights and biases to minimize the position error.

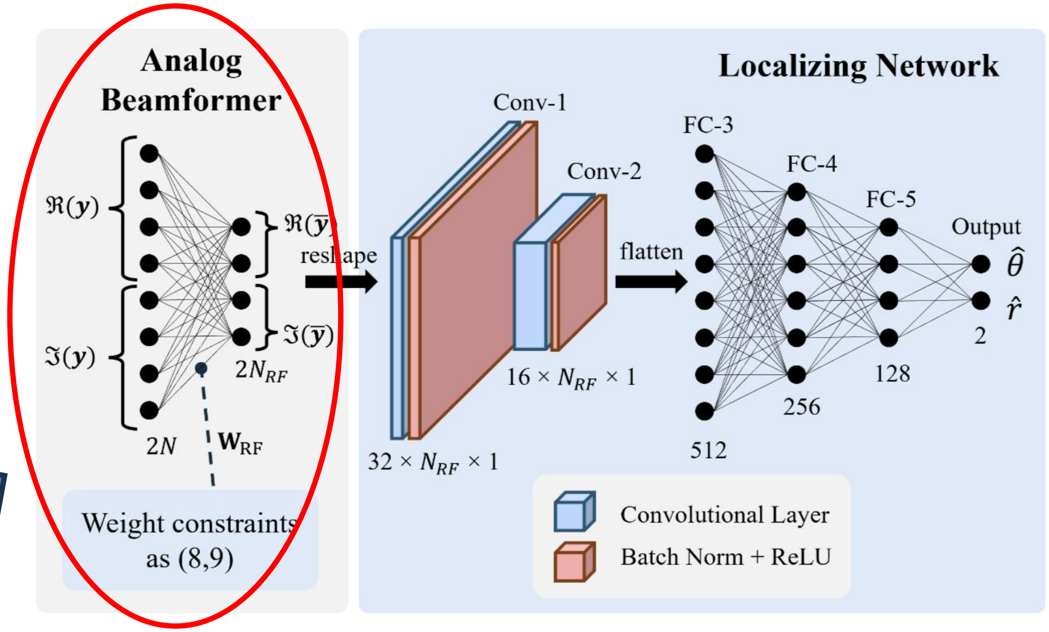
$$(\widetilde{\mathbf{W}}, \widetilde{\mathbf{b}}) = \arg\min_{\mathbf{W},\mathbf{b}} \mathbb{E}\left\{ \left\| \gamma^{(i)} - f^{(\text{train})}(\mathbf{y}^{(i)}) \right\|_2^2 \right\}$$

Weight constraints ensure consistency with the hybrid beamforming structure.

$$f^{(\text{train})}(\mathbf{y}^{(i)}) = f^{(\text{out})}(\dots(f^{(1)}(\mathbf{b}^{(\text{in})} + \mathbf{W}^{(\text{in})}\mathcal{F}(\mathbf{y}^{(i)})))),$$

$$\mathbf{W}^{(\text{in})} = \begin{bmatrix} \mathbf{W}_1^{(\text{in})} & -\mathbf{W}_2^{(\text{in})} \\ \mathbf{W}_2^{(\text{in})} & \mathbf{W}_1^{(\text{in})} \end{bmatrix} \quad (8)$$

$$\left(\left[\mathbf{W}_1^{(\text{in})}\right]_{m,n}\right)^2 + \left(\left[\mathbf{W}_2^{(\text{in})}\right]_{m,n}\right)^2 = \frac{1}{N}, \quad (9)$$
$$\forall n \in \{1, \dots, N\}, \forall m \in \{1, \dots, M\}$$



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Numerical Results

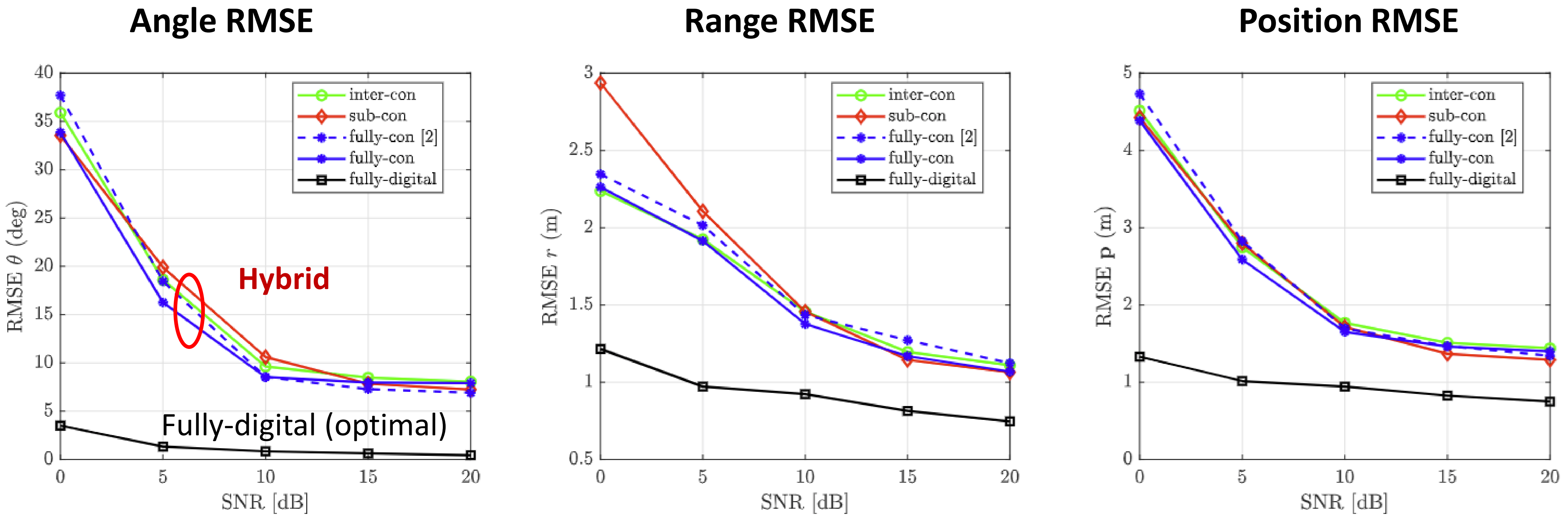

Fig. 3: RMSE of angle, range, and position versus SNR with different hybrid beamforming configurations, when $M = 16$ and $N = 128$.

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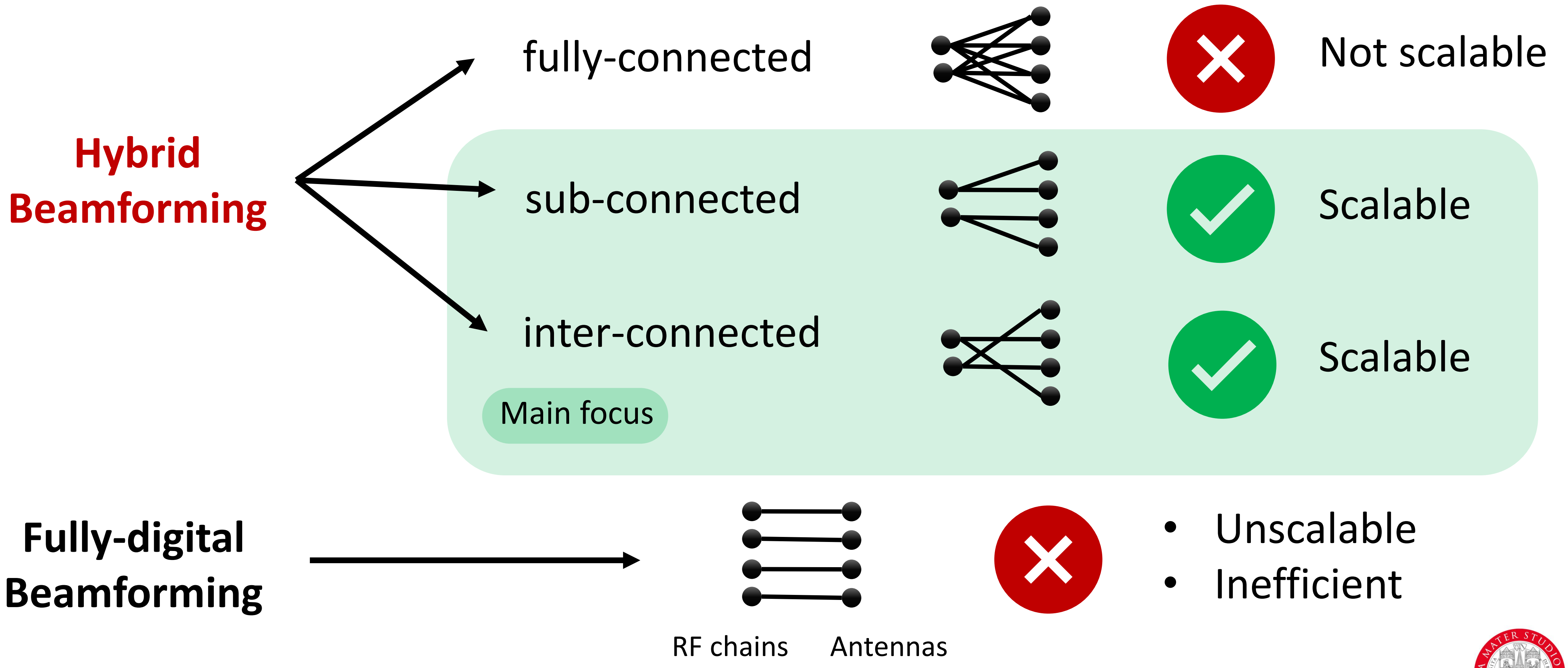
Numerical Results



Numerical Results

Angle RMSE **Range RMSE** **Position RMSE**

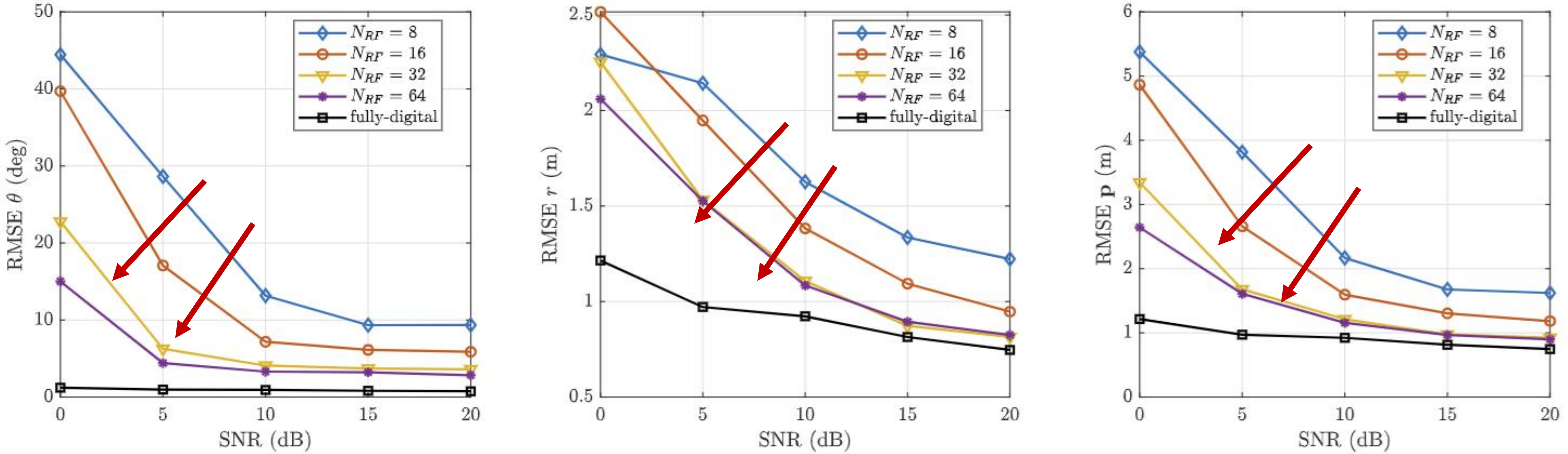


Fig. 4: RMSE of angle, range, and position versus SNR when the number of RF chains varies in a sub-array beamformer configuration with $M = 16$ and $N = 128$.

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Numerical Results

Is the proposed scheme robust to **multipath effects**?

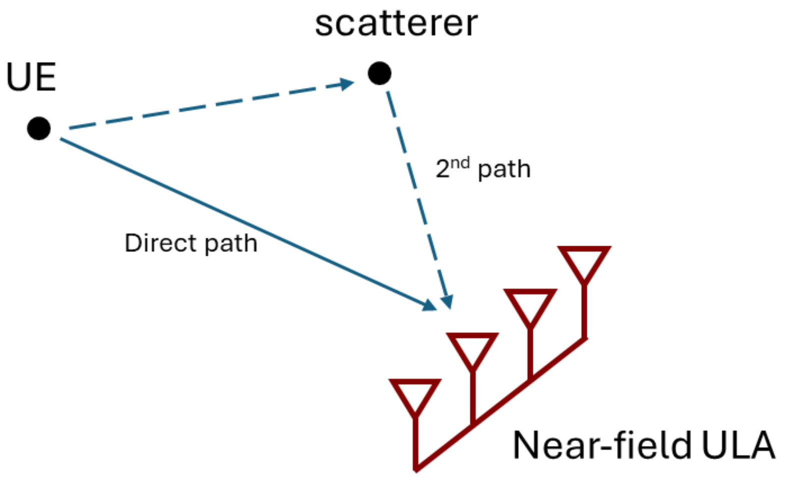
Hypothesis:

- A **point-like scatterer** is randomly placed in the strong near-field region of the ULA

Objective:

- **Localize** both the **user** and a **scatterer** in a single snapshot

$$\begin{cases} \mathbf{h}_{\mathrm{LoS}} = \sqrt{\rho}\,\mathbf{a}(\theta, r) \\ \mathbf{h}_{\mathrm{NLoS}} = \sum_{i=1}^{P} \sqrt{\rho_i} e^{j\phi_i} \mathbf{a}(\theta_i, r_i) \end{cases}$$



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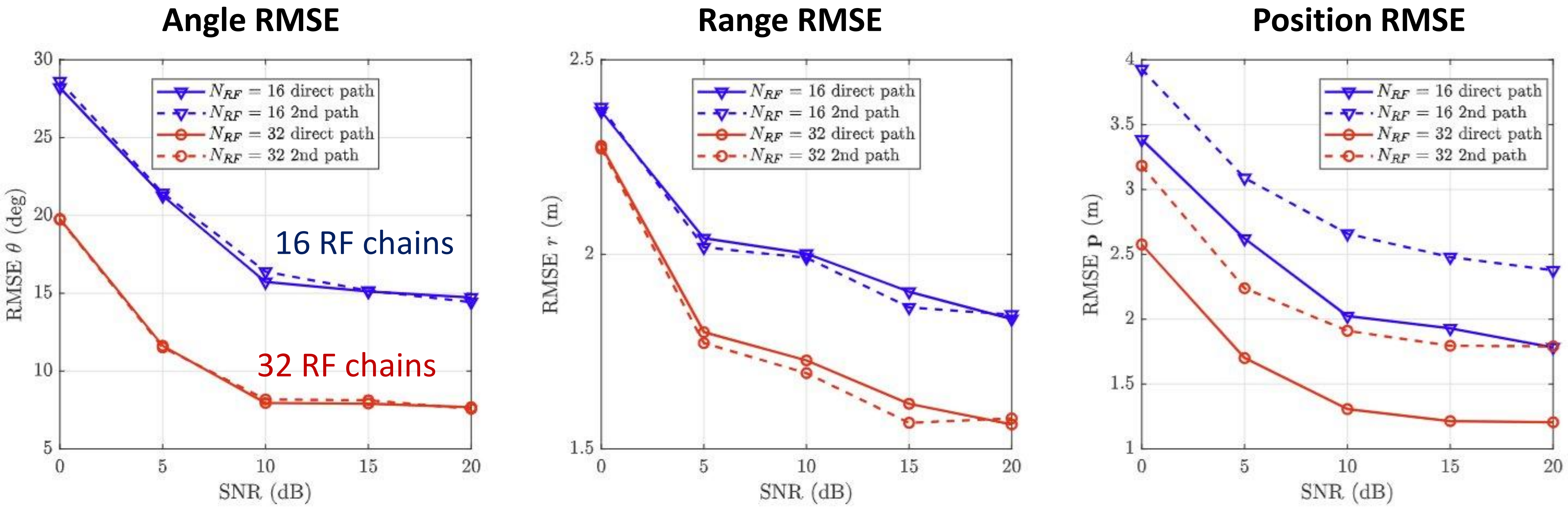

Fig. 5: RMSE of angle, range, and position versus SNR when the number of RF chains varies in a sub-array configuration with multipath.

Conclusions

- The proposed CNN-based framework achieves sub-meter localization accuracy from a single snapshot.
- It reduces phase shifter requirements by a factor of M compared to fully-connected architectures, improving scalability.
- Robustness against multipath effects.

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Thanks for your attention!

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