Paper ID: 4115

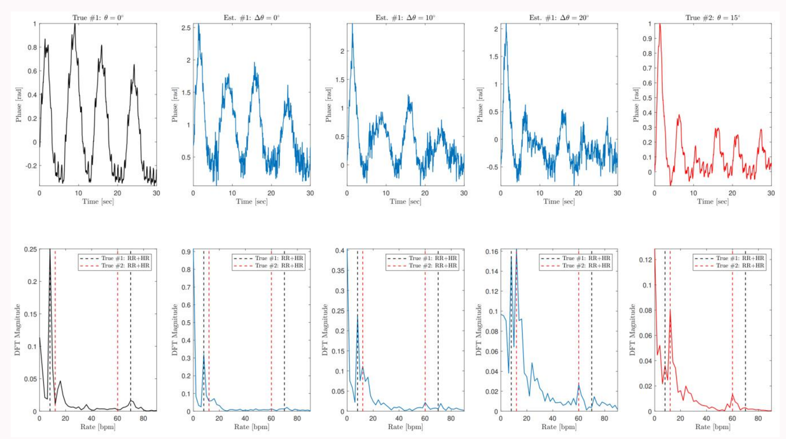
RaLU-Net: Deep Unfolded Radar Localization of Humans for Precise Multi-Person Non-Contact Vital Signs Monitoring

Yonathan Eder, Yhonatan Kvich, Rui Guo, and Yonina C. Eldar
Faculty of Math and Computer Science, Weizmann Institute of Science, Rehovot, Israel
E-mail: yoni.eder@weizmann.ac.il

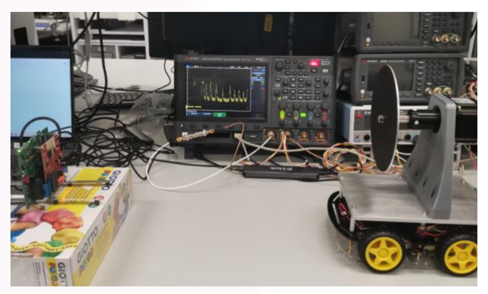
Motivation and Contributions

- SIMO FMCW radars enable multi-object localization, which is crucial for multi-person NCVSM. However, detecting and positioning humans in crowded scenarios is challenging and highly affected by resolution limitations
- This work first provides an iterative localization method (RaLU-JSR) which exploits joint sparsity and cardiopulmonary properties
- Then, it is unfolded into a neural network (RaLU-Net) that utilizes the unique structure of the data to enhance accuracy and reduce computational cost
- Simulations containing real-world data showed the network's superior performance in detecting and positioning multiple humans in thousands of close proximity scenarios outperforming existing techniques via key metrics

- Example of extracted thoracic motions of two adjacent humans. As the beamforming deviation increases, the vital information becomes distorted due to deflection noise and mutual interference



- Hardware phantom for monitoring both static and moving people



Signal Model

- We adopt the bilinear model of [1] for a SIMO FMCW radar signal

$$\mathbf{Y}_l = \mathbf{A}\mathbf{X}_l\mathbf{B} + \mathbf{N}_l, \quad l = 1,\ldots,L \text{ frames}$$

$\mathbf{A} \in \mathbb{C}^{N\times M} : \mathbf{A}(n,m) \triangleq e^{j2\pi f_m n T_f}$ (range-related matrix)

$\mathbf{B} \in \mathbb{C}^{P\times K} : \mathbf{B}(p,k) \triangleq e^{j\phi_p[k]}$ (angle-related matrix)

$\mathbf{X}_l \in \mathbb{C}^{M\times P} : \mathbf{X}_l(m,p) \triangleq x_{m,p} e^{j\psi_{m,p}[l]}$ (complex amplitudes)

$\mathbf{N}_l \in \mathbb{C}^{N\times K} : \mathbf{N}_l(n,k) \triangleq w[n,k,l]$ (noise matrix)

- A-1: The humans are stationary. This means that the $\{m,p\}$ coordinates of $\{\mathbf{X}_l\}_{l=1}^{L}$, corresponding to the thoracic locations, are fixed and joint across all L frames.
- A-2: $U \ll MP$ objects, meaning that $\{\mathbf{X}_l\}_{l=1}^{L}$ are U-sparse matrices
- Goal: Estimate # of humans Z and their $\{d^{(z)}, \theta^{(z)}\}_{z=1}^{Z}$ coordinates

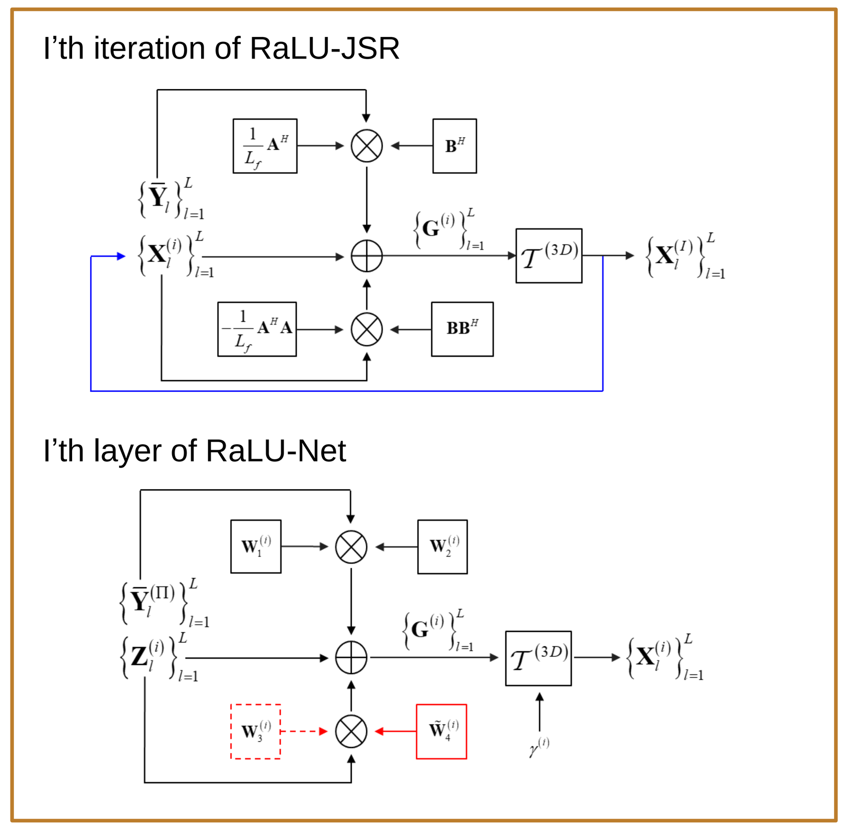
Iterative and Deep Unfolding Strategies

- Estimating $\{\mathbf{X}_l\}_{l=1}^{L}$ by promoting joint sparsity via the 3D $l_{2,1}$ LS problem:

$$\hat{\mathbb{X}} = \arg\min_{\mathbb{X}\in\mathbb{C}^{M\times P\times L}} \frac{1}{2L}\sum_{l=1}^{L}\left\|\mathbf{Y}_l - \mathbf{A}\mathbf{X}_l\mathbf{B}\right\|_F^2 + \gamma\left\|\mathbb{X}\right\|_{2,1}$$

- RaLU-JSR (ISTA)

$$\begin{cases} \mathbf{G}_l^{(i)} = \frac{1}{L_f}\mathbf{A}^H\mathbf{Y}_l\mathbf{B}^H - \frac{1}{L_f}\mathbf{A}^H\mathbf{A}\mathbf{X}_l^{(i)}\mathbf{B}\mathbf{B}^H + \mathbf{X}_l^{(i)}, \ l = 1,\ldots,L \\ \left\{\mathbf{X}_l^{(i)}\right\}_{l=1}^{L} = \mathcal{T}_{\frac{\gamma}{L_f}}^{(3D)}\left(\left\{\mathbf{G}_l^{(i)}\right\}_{l=1}^{L}\right) \end{cases}$$



- Deep Unfolding

$$\begin{cases} \mathbf{G}_l^{(i)} = \mathbf{W}_1^{(i)}\mathbf{Y}_l\mathbf{W}_2^{(i)} + \mathbf{W}_3^{(i)}\mathbf{X}_l^{(i)}\mathbf{W}_4^{(i)} + \mathbf{X}_l^{(i)}, \ l = 1,\ldots,L \\ \left\{\mathbf{X}_l^{(i)}\right\}_{l=1}^{L} = \mathcal{T}_{\gamma^{(i)}}^{(3D)}\left(\left\{\mathbf{G}_l^{(i)}\right\}_{l=1}^{L}\right) \end{cases}$$

Incorporating knowledge for multi-person NCVSM

- RaLU-Net

$$\begin{cases} \mathbf{G}_l^{(i)} = \mathbf{W}_1^{(i)}\bar{\mathbf{Y}}_l^{(\Pi)}\mathbf{W}_2^{(i)} + \mathbf{Z}_l^{(i)}\tilde{\mathbf{W}}_4^{(i)} + \mathbf{Z}_l^{(i)}, \ l = 1,\ldots,L \\ \left\{\mathbf{X}_l^{(i)}\right\}_{l=1}^{L} = \mathcal{T}_{\gamma^{(i)}}^{(3D)}\left(\left\{\mathbf{G}_l^{(i)}\right\}_{l=1}^{L}\right) \\ \mathbf{Z}_l^{(i+1)} = \mathbf{X}_l^{(i)} + \rho^{(i)}\left(\mathbf{X}_l^{(i)} - \mathbf{X}_l^{(i-1)}\right), \ l = 1,\ldots,L \end{cases}$$

Learnable parameters:

$$\Theta = \{\{\mathbf{W}_1^{(i)}, \mathbf{W}_2^{(i)}, \tilde{\mathbf{W}}_4^{(i)}, \gamma^{(i)}, \rho^{(i)}\}_{i=1}^{I}, \Pi\}$$

Mask loss:

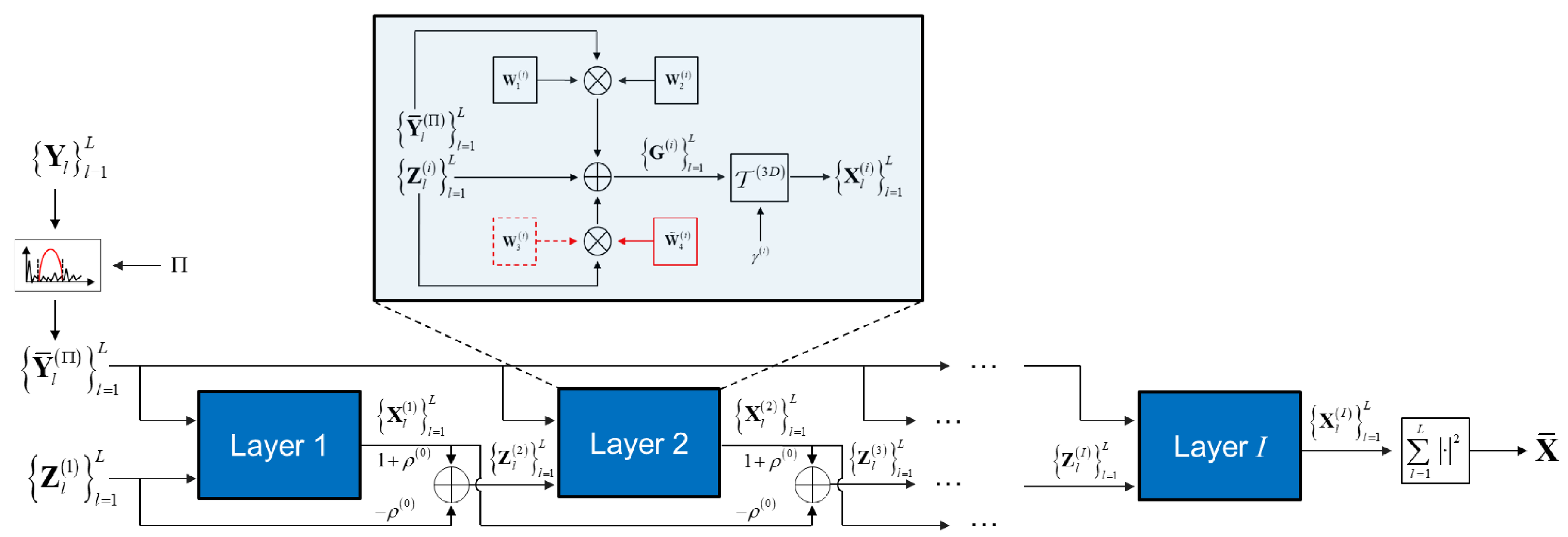
$$\mathcal{L}_{\text{mask}}\left(\bar{\mathbf{X}}, \bar{\mathbf{X}}_{GT}\right) = \mathcal{L}_{\text{MSE}}^{(\mathcal{S})} + \mu\mathcal{L}_{l_1}^{(\mathcal{S}^c)}$$

$$\mathcal{L}_{\text{MSE}}^{(\mathcal{S})} = \frac{1}{|\mathcal{S}|}\sum_{\{m,p\}\in\mathcal{S}}\left(\bar{\mathbf{X}}(m,p) - \bar{\mathbf{X}}_{GT}(m,p)\right)^2$$

$$\mathcal{L}_{l_1}^{(\mathcal{S}^c)} = \frac{1}{|\mathcal{S}^c|}\sum_{\{m,p\}\in\mathcal{S}^c}\left|\bar{\mathbf{X}}(m,p)\right|$$

$$\Rightarrow \mathcal{L}(\Theta) = \frac{1}{N_{tr}}\sum_{n_{tr}=1}^{N_{tr}}\mathcal{L}_{\text{mask}}\left(f\left(\left\{\mathbf{Y}_{l,n_{tr}}\right\}_{l=1}^{L}, \Theta\right), \bar{\mathbf{X}}_{GT,n_{tr}}\right)$$

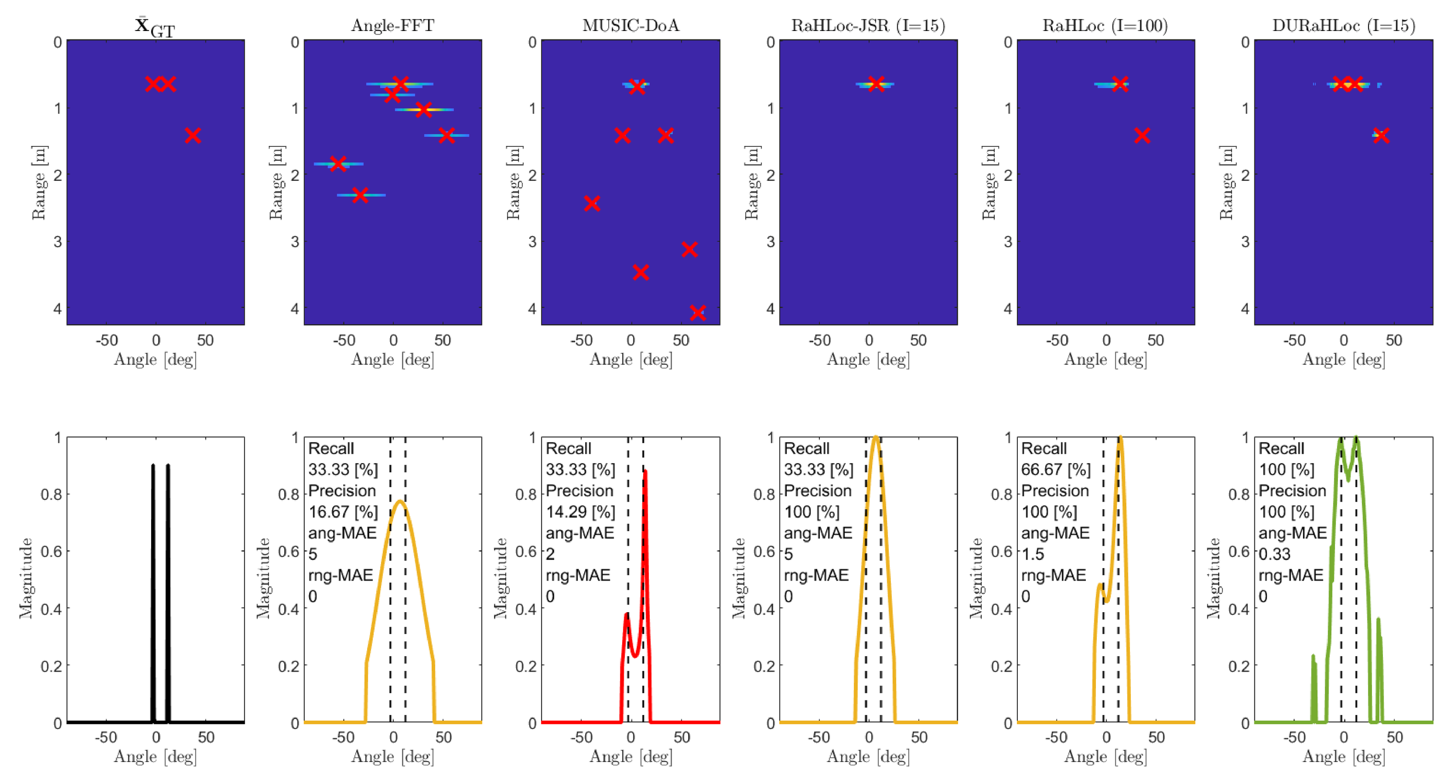
RaLU-Net Architecture



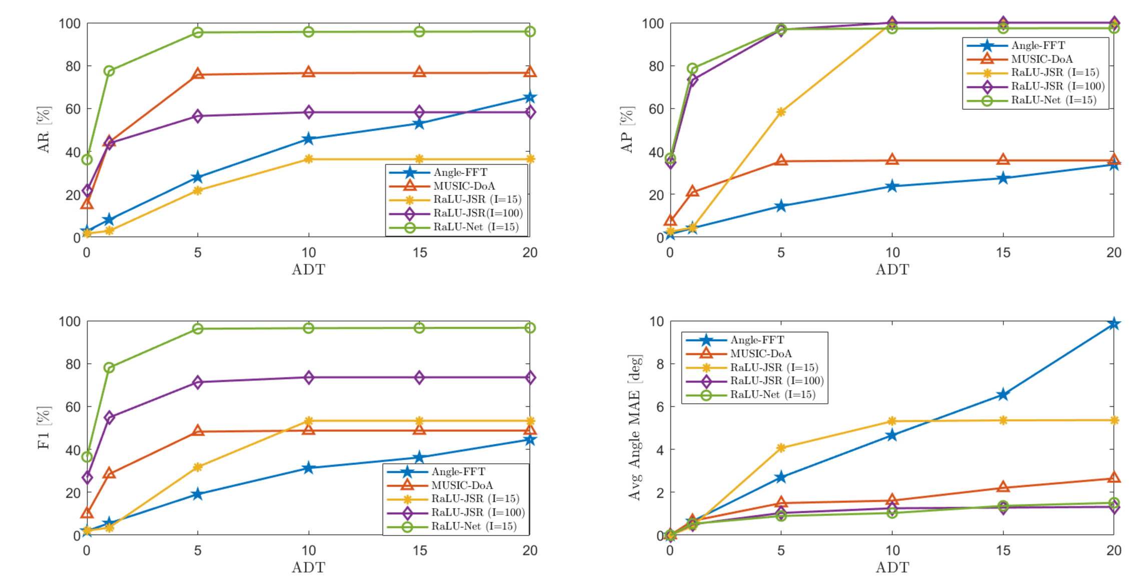
[1] Eder, Y., Zagoury, E., Savariego, S., Namer, M., Cohen, O., & Eldar, Y. C. (2025). Robust Phantom-Assisted Framework for Multi-Person Localization and Vital Signs Monitoring Using MIMO FMCW Radar. arXiv preprint

Results

- Validation example: predicted localization maps of all compared methods relative to ground-truth (GT) map for angle deviation threshold (ADT) of 5°
- The proposed RaLU-Net achieves the best performance:
  1. Detects exactly 3/3 humans (without any misses of false detections)
  2. Exhibits the most distinct separation by both power and angular pattern
  3. Positions the humans with the lowest average angle-MAE
  4. Reduced computational cost compared to the iterative RaLU-JSR



- Average scores for the entire validation set vs. ADT
  1. F1 score of the RaLU-Net outperforms all other methods and passes 96% for any ADT above 5° (here the theoretical angle resolution is ~30°)
  2. Both RaLU-JSR and RaLU-Net achieved a small average angle-MAE< 1.5° for every ADT. However, whereas the accelerated iterative method requires 100 iterations, the unfolded network employs about 7 times lower number of layers



Achieving high performance with minimal computation in thousands of close-proximity scenarios