Resilient and Low-Latency Networks for Situation Awareness in the Factory of the Future

Moe Z. Win (PI), Dimitri P. Bertsekas, and Victor B. Lawrence
Massachusetts Institute of Technology and Stevens Institute of Technology

Project Overview

Motivation: Factory of the Future (FoF)

- FoF is inherently a multi-agent system composed of heterogeneous nodes: machines, workers, workpieces, etc.
- Coordination (communication and control) among heterogeneous nodes facilitates operational resiliency: adaptability, autonomy, and reliability
- Dense and dynamically-changing factory environments create harsh conditions for communication and control of networked systems

Technical Gaps

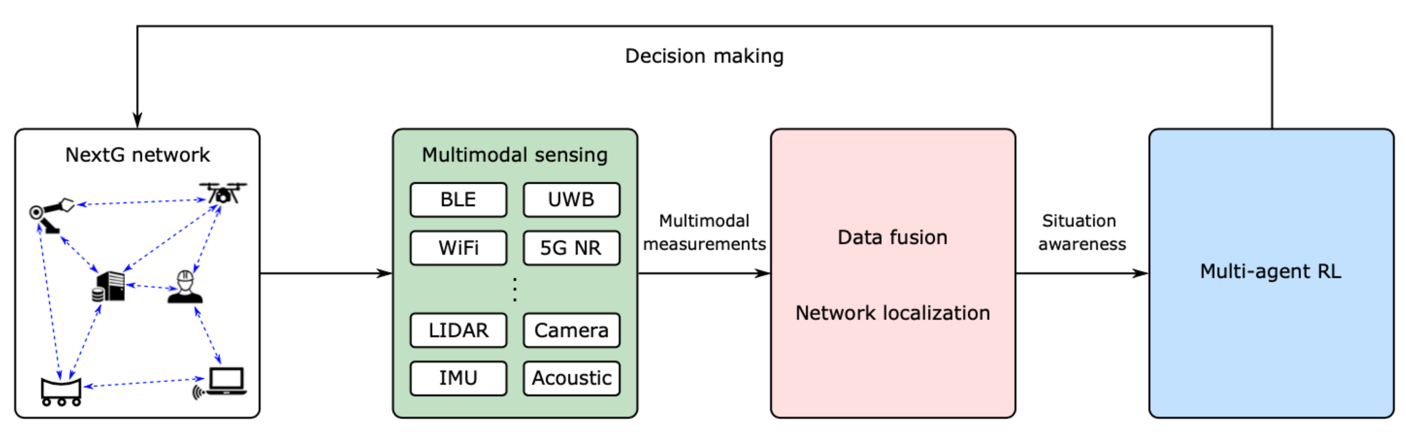
- Limited availability of results in standardized scenarios, such as those defined by 3GPP and included in technical specifications of beyond 5G networks towards 6G
- Existing works on localization do not account for sensing latency and may lead to poor performance when data packets are not readily available
- A systematic design of localization and decision-making accounting for the latency in sensing, communication, and computation is still lacking

Research Objective

- Develop latency-resilient algorithms for network localization, inference, and control to facilitate situational awareness and decision-making in FoF
  - design efficient algorithms for high-accuracy localization by fusing sensed data obtained from heterogeneous devices in FoF
  - develop a framework for location inference in the presence of network latency

Inference and Control Loop for FoF

- Node-level constituents of FoF:
  - physical layer: FoF agents
  - sensing layer: multimodal sensors
- Network-level constituents of FoF:
  - inference layer: processor nodes for localization and navigation
  - control layer: processor nodes for action generations



Physical, sensing, inference, and control layers for FOF

Contributions

- Our contributions to NextG resiliency, network intelligence, performance, and security are as follows:
  - developed localization algorithms for xG networks according to 3GPP specifications, in particular indoor factory (InF) scenarios
  - disseminated results in publications/tutorials
  - https://rings.winslab.lids.mit.edu/

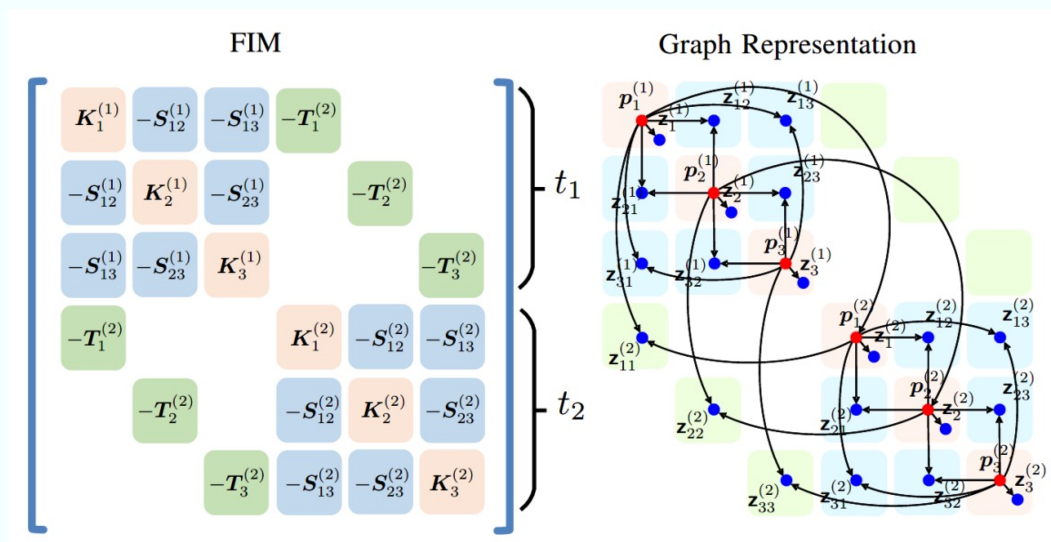
Theoretical Foundation

Fundamental limits of localization accuracy

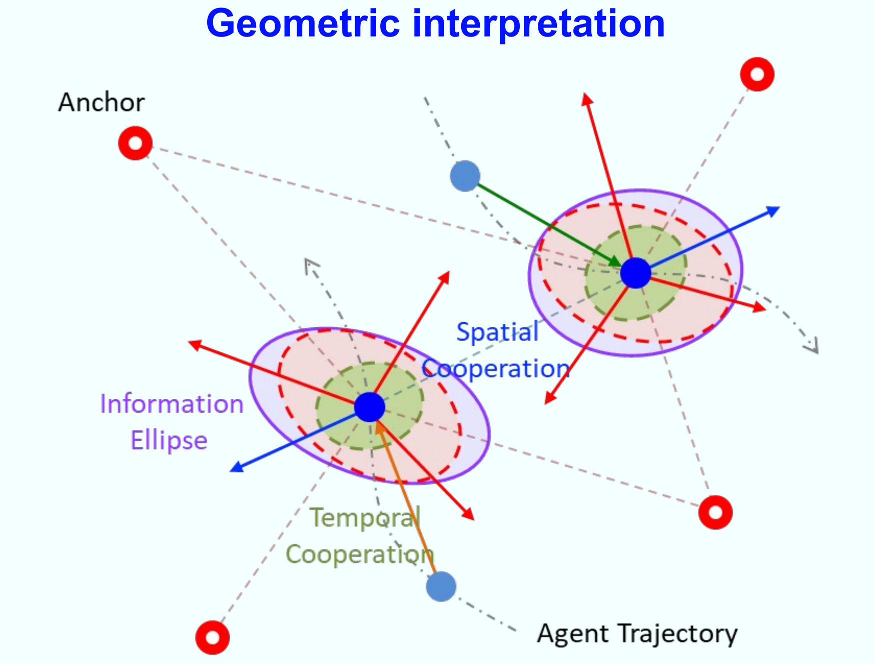
$$J_e(p_1) = \sum_{j\in\mathcal{N}_{b,\mathrm{LOS}}} \lambda_{1j}\, J_r(\phi_{1j}) \qquad \lambda_{1j} = \frac{8\pi^2\beta^2}{c^2}(1-\chi_{1j})\,\mathrm{SNR}_{1j}$$

- **NLOS conditions:** NLOS signals do not contribute since their delays are corrupted by the unknown biases
- **Bandwidth:** RII λ_{1j} is proportional to the SNR and the squared effective bandwidth of the transmitted signal. Large bandwidth also improves multipath resolvability (i.e., reduce χ_{1j})
- **Network geometry:** EFIM is the weighted sum of the RDM from individual anchors. Anchors provide one-dimensional RI along the direction ϕ_{1j} with λ_{1j} intensity

Spatiotemporal cooperation



Geometric interpretation

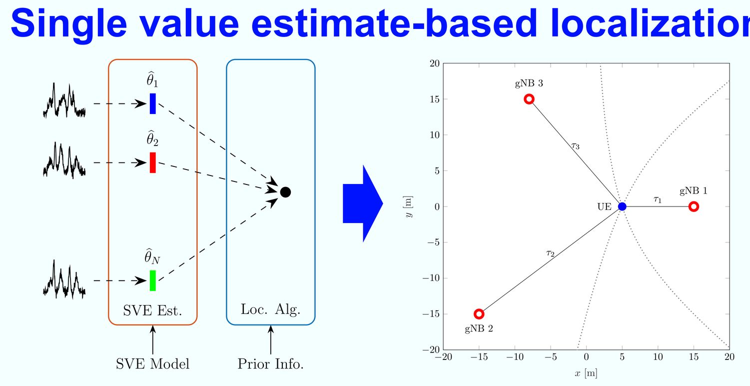


Algorithms

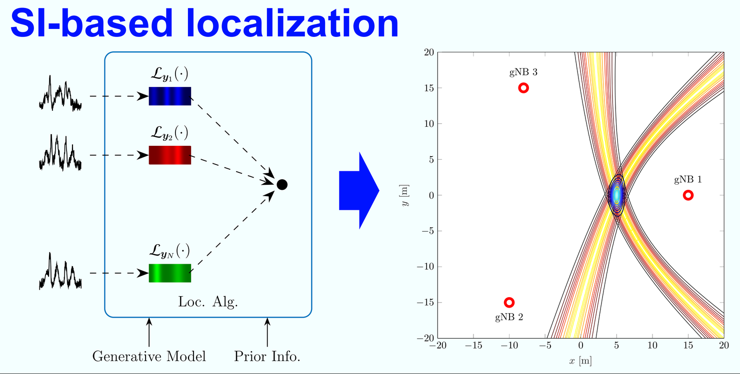
Soft information (SI)-based localization algorithms

- **Measurement vector**
  $y_i = \hat{\tau}_{i,1}$
- **Feature vector**
  $\theta_i(p) = d_{i,1}(p)\,, \quad d_{i,1}(p) = \|p - p_{\mathrm{BS}}^{(i)}\|_2 - \|p - p_{\mathrm{BS}}^{(1)}\|_2$
- **Soft information**
  $\mathcal{L}_{y_i}(\theta_i(p)) = \mathcal{L}_{\hat{\tau}_{i,1}}(d_{i,1}(p))$
- **Estimated position**
  $\hat{p} = \arg\max_{p} \prod_{i=2}^{N_{\mathrm{BS}}} \mathcal{L}_{\hat{\tau}_{i,1}^{(\mathrm{new})}}(d_{i,1}(p))$
- **Machine learning approaches**: determine the relation among measurements and positional features in complex wireless environments

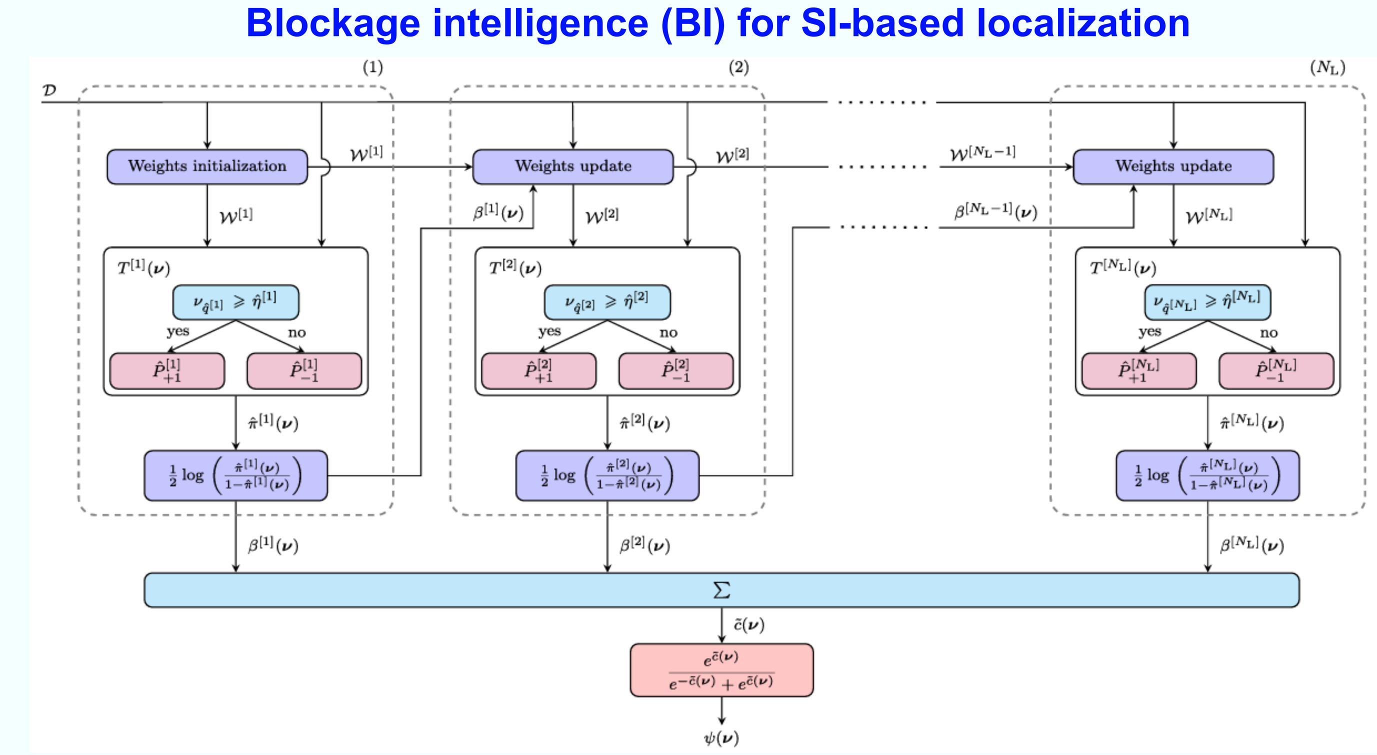
Single value estimate-based localization



SI-based localization



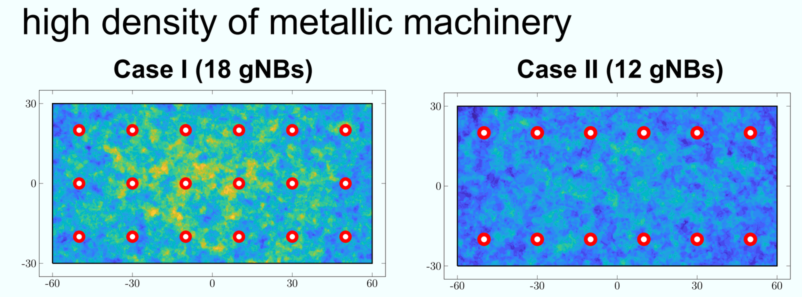
Blockage intelligence (BI) for SI-based localization



Results

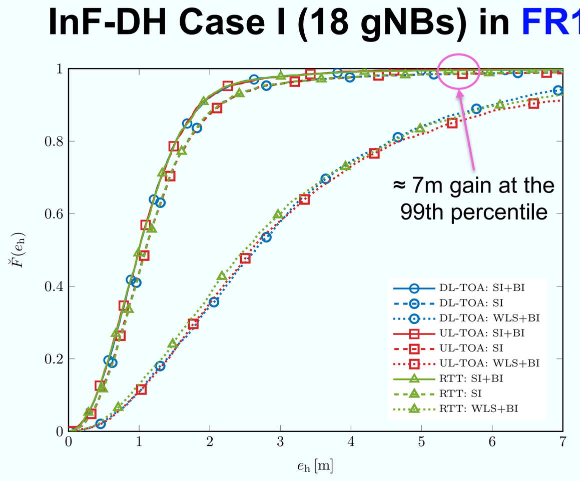
Case studies in 3GPP scenarios

- **Two InF scenarios:** cluttered environments with high density of metallic machinery

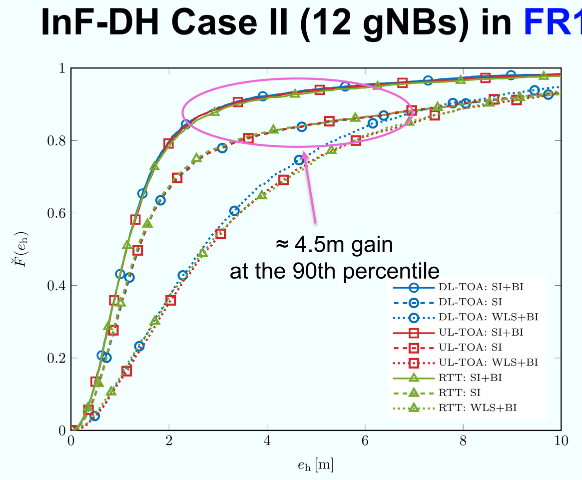


- **Simulation parameters:** 3GPP 38.901 and 38.857 with channels simulated via QuaDRiGa
  - FR1 results (3.5GHz, 100MHz BW)
  - FR2 results (28GHz, 400MHz BW)
- **Localization results** using DL-TOA, UL-TOA, RTT, and AOD (in FR2) measurements

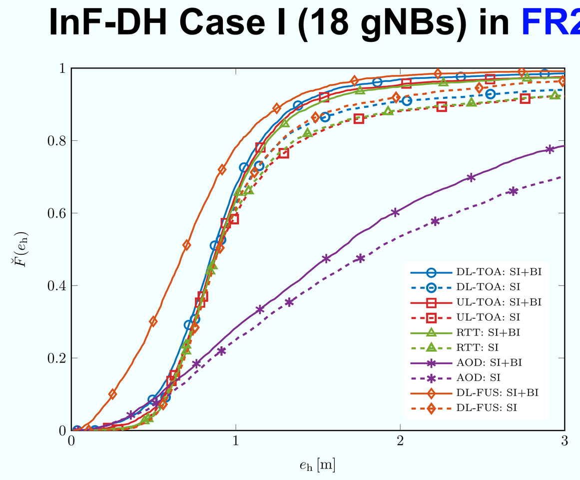
InF-DH Case I (18 gNBs) in FR1



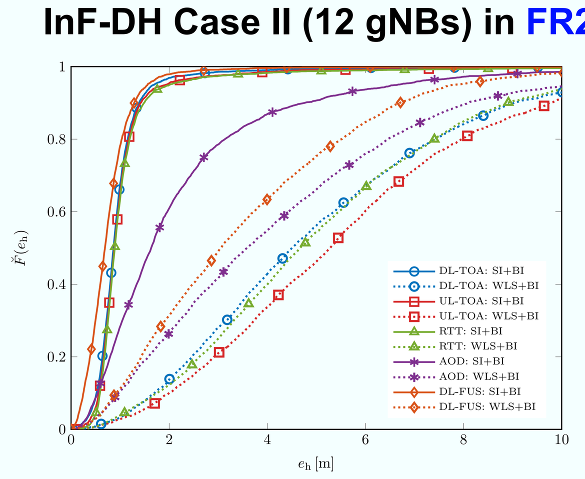
InF-DH Case II (12 gNBs) in FR1



InF-DH Case I (18 gNBs) in FR2



InF-DH Case II (12 gNBs) in FR2



- SI and BI can provide a significant performance gain, especially in Case II with less infrastructure
- SI-based localization always outperforms WLS-based and WLS+BI-based localization