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

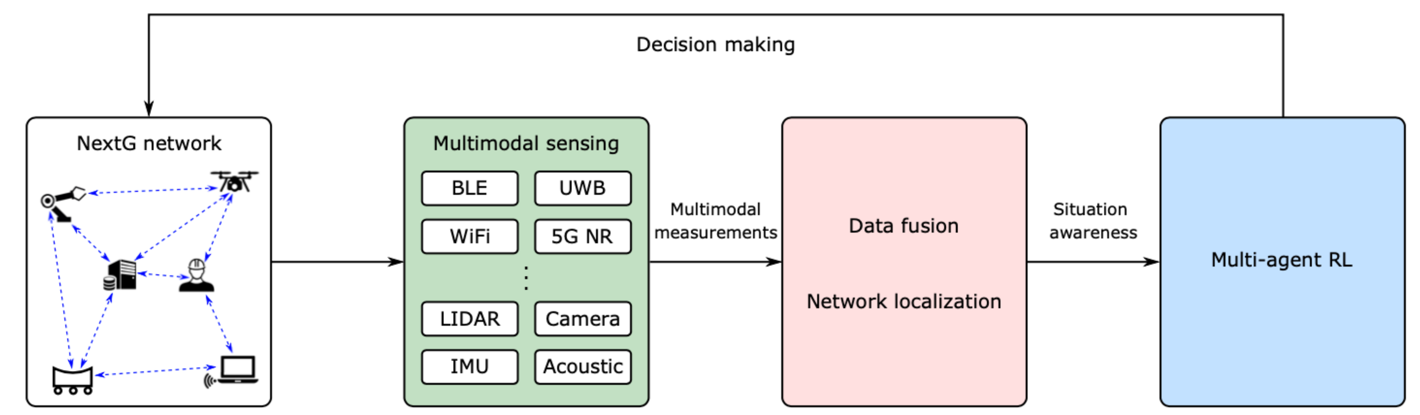
- Limited availability of results in standardized scenarios, such as those defined by 3GPP and included in technical specifications of beyond 5G networks towards 6G
- Existing works on localization do not account for sensing latency and may lead to poor performance when data packets are not readily available
- 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/

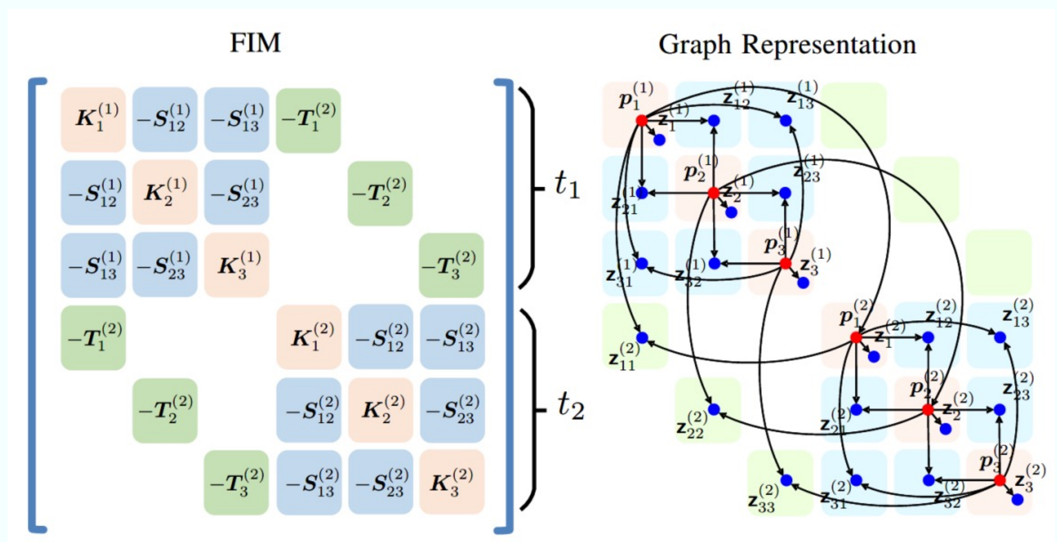
Theoretical Foundation

Fundamental limits of localization accuracy

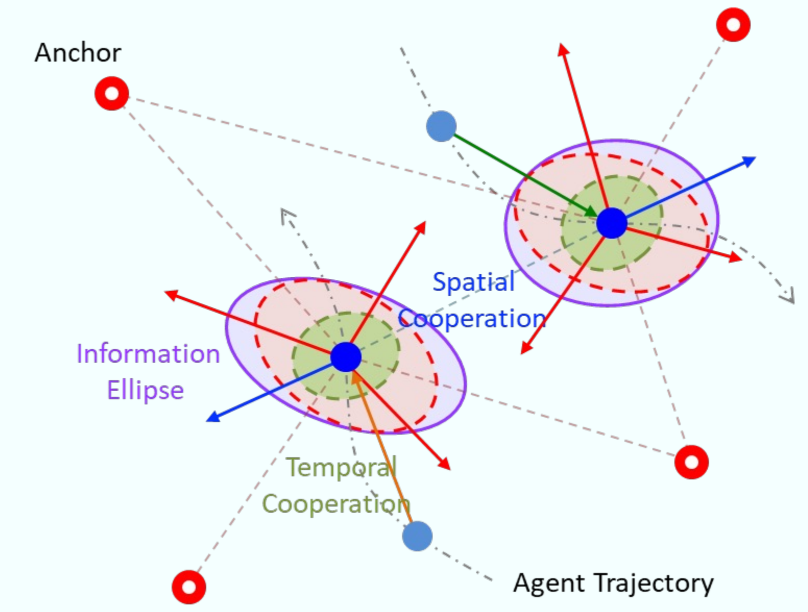
$$\boldsymbol{J}_{\mathrm{e}}(\boldsymbol{p}_1) = \sum_{j \in \mathcal{N}_{\mathrm{b,\,LOS}}} \lambda_{1j}\, \boldsymbol{J}_{\mathrm{r}}(\phi_{1j}) \qquad \lambda_{1j} = \frac{8\pi^2\beta^2}{c^2}(1-\chi_{1j})\,\mathrm{SNR}_{1j}$$

- **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

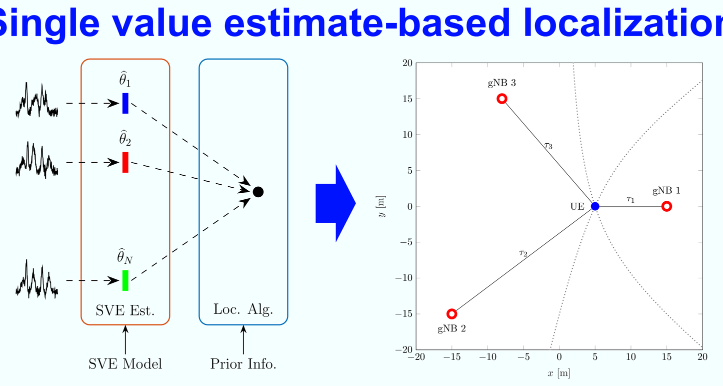


Algorithms and Methods

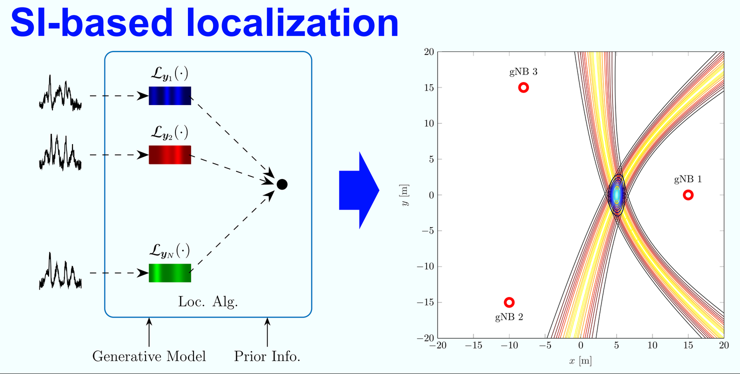
Soft information (SI)-based localization algorithms

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

Single value estimate-based localization

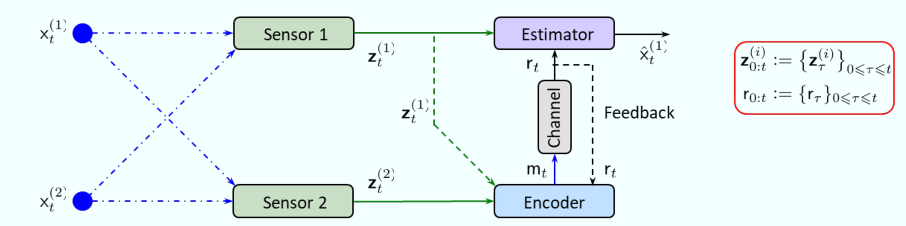


SI-based localization

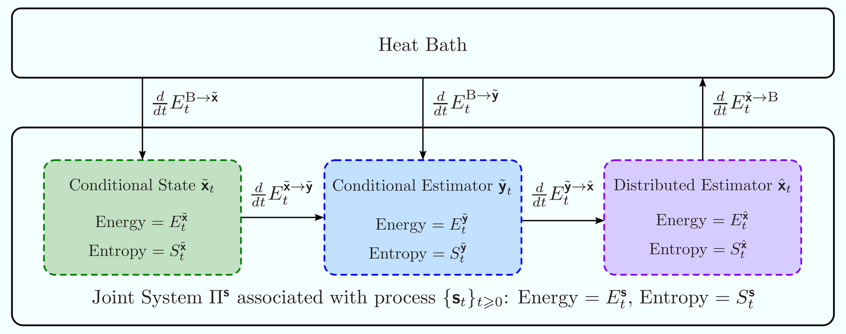


Distributed filtering with sensing and communication constraints

- **Filtering system model**



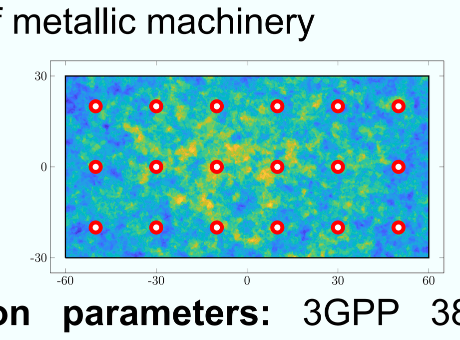
- **Analogy of distributed filtering to a statistical mechanical system**



Results

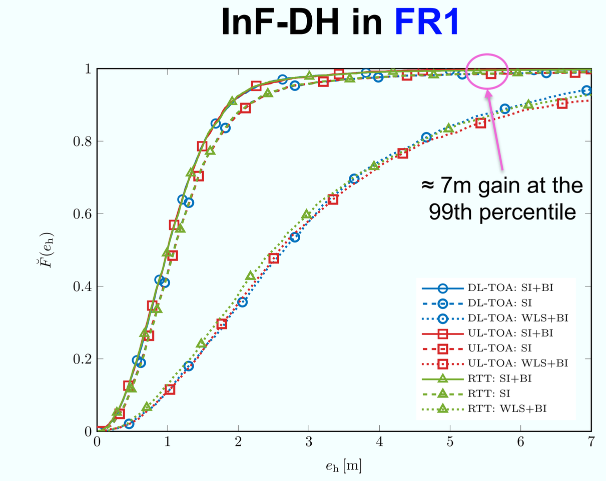
Case studies in 3GPP scenarios

- **InF scenario** cluttered environment with high density of metallic machinery

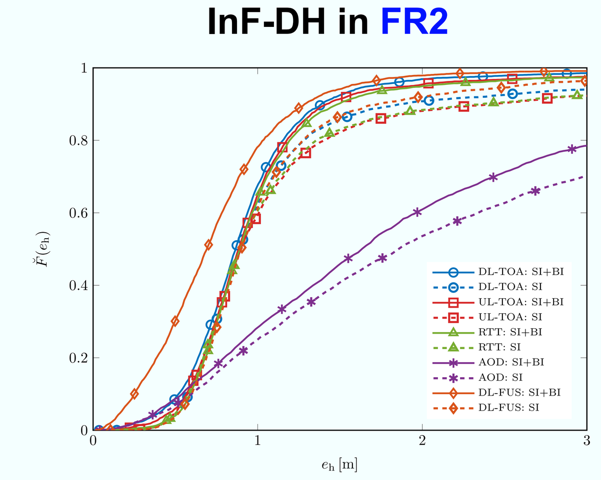


- **Simulation parameters:** 3GPP 38.901 and 38.857 with channels simulated via QuaDRiGa
  - FR1 results (3.5GHz, 100MHz BW)
  - FR2 results (28GHz, 400MHz BW)
- **Localization results** using DL-TOA, UL-TOA, RTT, and AOD (in FR2) measurements

InF-DH in FR1



InF-DH in FR2



- SI and BI can provide a significant performance gain
- SI-based localization always outperforms WLS-based and WLS+BI-based localization

3GPP-compliant datasets for xG location-aware networks

- xG-Loc is the first open dataset for evaluating localization algorithms and location-based services fully compliant with 3GPP technical specifications

	Dataset Name	f_c [GHz]	B [MHz]		Dataset Name	f_c [GHz]	B [MHz]
InF-DH	infdh_5_3.5	3.5	5	IOO	ioo_5_2	2	5
	infdh_20_3.5	3.5	20		ioo_20_2	2	20
	infdh_50_3.5	3.5	50		ioo_50_4	4	50
	infdh_100_3.5	3.5	100		ioo_100_4	4	100
	infdh_100_28	28	100		ioo_100_30	30	100
	infdh_200_28	28	200		ioo_200_30	30	200
	infdh_400_28	28	400		ioo_400_30	30	400
InF-SH	infsh_5_3.5	3.5	5	UMi	umi_5_2	2	5
	infsh_20_3.5	3.5	20		umi_20_2	2	20
	infsh_50_3.5	3.5	50		umi_50_4	4	50
	infsh_100_3.5	3.5	100		umi_100_4	4	100
	infsh_100_28	28	100		umi_100_30	30	100
	infsh_200_28	28	200		umi_200_30	30	200
	infsh_400_28	28	400		umi_400_30	30	400

- The data available in xG-Loc include: received and transmitted PRSs/SRSs, distance/AOD/position estimates, and others.