

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



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# **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**

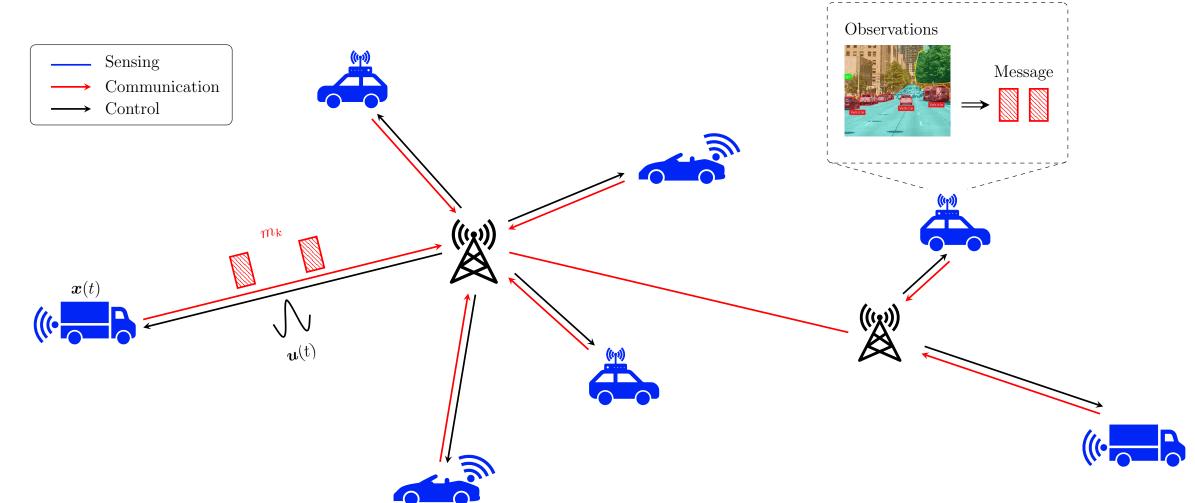
- Limited availability of results in standardized scenarios, such as those defined by 3GPP and included in technical specifications of beyond 5G networks towards 6G
- Existing works on localization do not account for sensing latency and may lead to poor performance when data packets are not readily available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



Network-level location-awareness in FOF

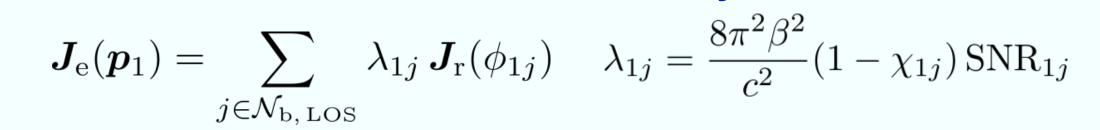
#### **Contributions**

 Our contributions to NextG resiliency, network intelligence, performance, and security are as follows:

- developed localization algorithms for xG networks according to 3GPP specifications and communication algorithms leveraging location information

- disseminated results in publications/tutorials
- https://rings.winslab.lids.mit.edu/

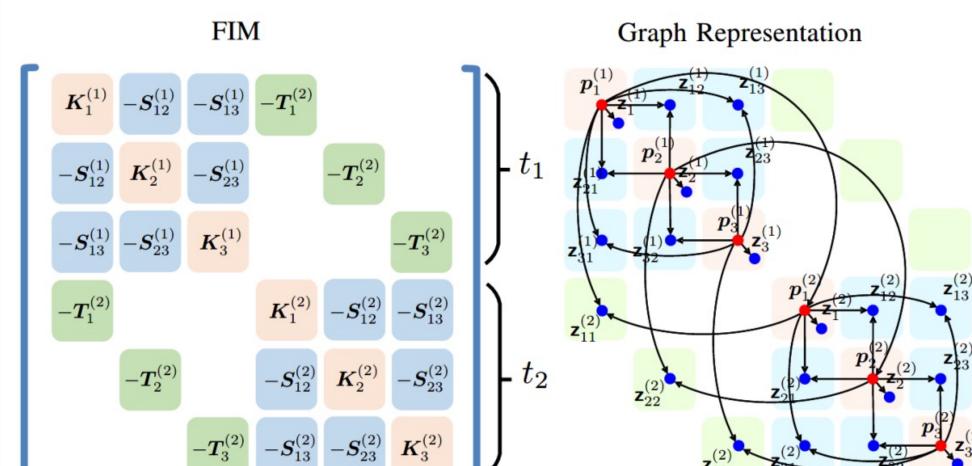
# Fundamental limits of localization accuracy

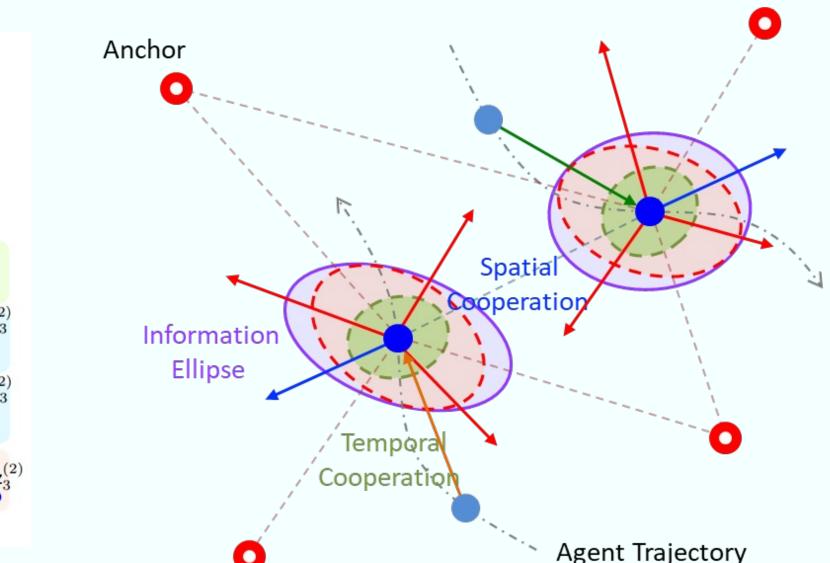


- NLOS conditions: NLOS signals do not contribute since their delays are corrupted by the unknown biases
- **Bandwidth:** RII  $\lambda_{1j}$  is proportional to the SNR and the squared effective bandwidth of the transmitted signal. Large bandwidth also improves multipath resolvability (i.e., reduce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

## **Theoretical Foundation**

## Spatiotemporal cooperation





**Geometric interpretation** 

# **Algorithms and Methods**

#### Soft information (SI)-based localization algorithms

 Measurement vector  $oldsymbol{y}_i = \widehat{ au}_{i.1}$ 

Feature vector

$$m{ heta}_i(m{p}) = d_{i,1}(m{p})$$
 ,  $d_{i,1}(m{p}) = ||m{p} - m{p}_{\mathrm{BS}}^{(i)}||_2 - ||m{p} - m{p}_{\mathrm{BS}}^{(1)}||_2$ 

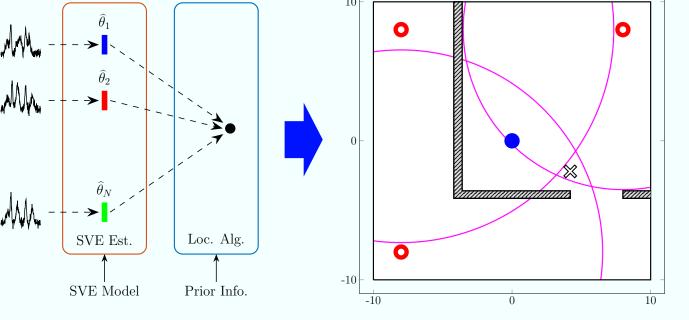
 Soft information  $\mathcal{L}_{oldsymbol{y}_i}\left(oldsymbol{ heta}_i(oldsymbol{p})
ight) = \mathcal{L}_{\hat{ au}_{i,1}}(d_{i,1}\left(oldsymbol{p}
ight)
ight)$ 

Estimated position

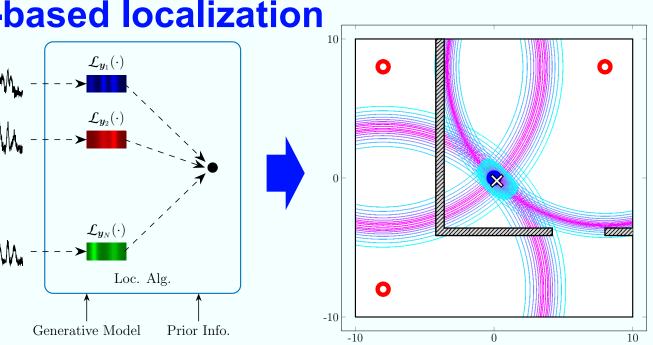
$$\hat{m{p}} = rg \max_{m{p}} \prod^{N_{ ext{BS}}} \mathcal{L}_{\hat{ au}_{i,1}^{( ext{new})}}(d_{i,1}(m{p}))$$

 Machine learning approaches: determine the relation among measurements and positional features in complex wireless environments

## Single value estimate-based localization

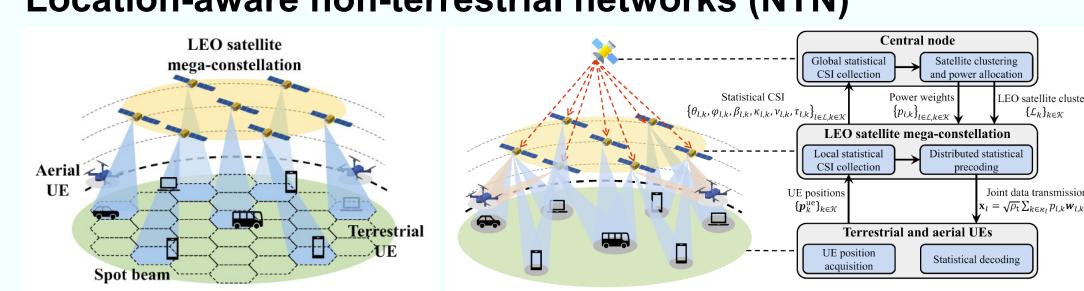


## **SI-based localization**

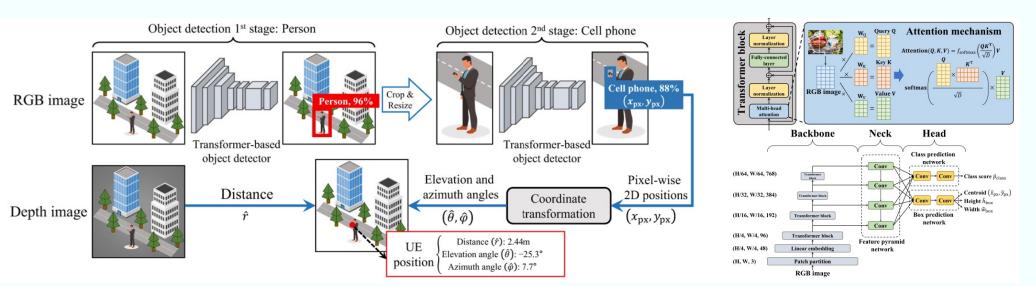


## Location-aware algorithms for communication enhancements

Location-aware non-terrestrial networks (NTN)



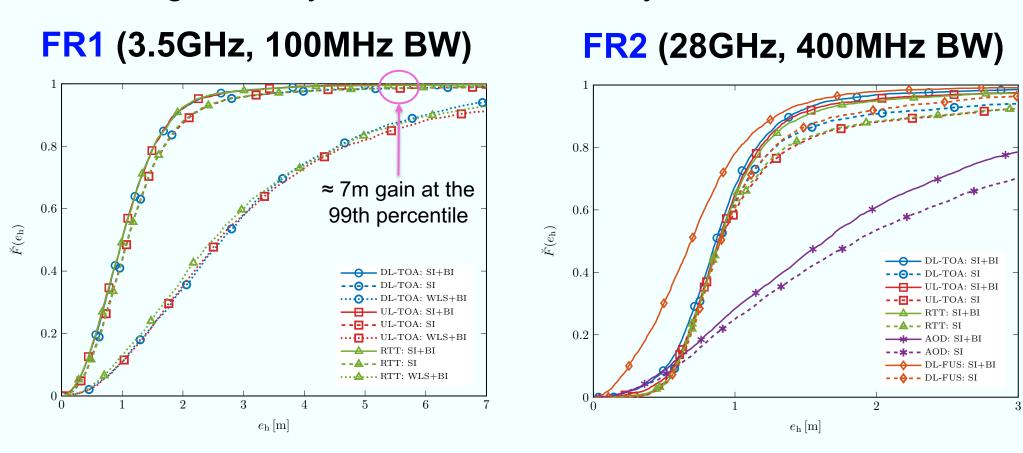
Vision-aided localization and communication



# Results

## Case studies in 3GPP scenarios

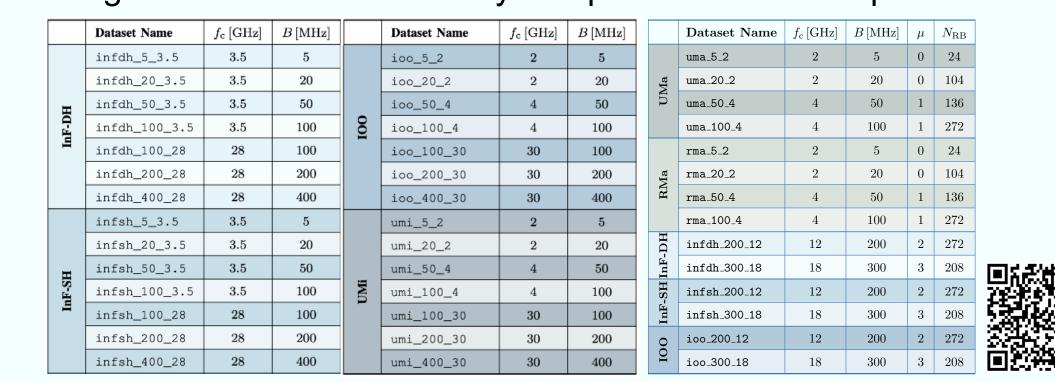
• Tested under InF scenario, which is cluttered environment with high density of metallic machinery



SI and BI can provide a significant performance gain

## 3GPP-compliant datasets for xG location-aware networks

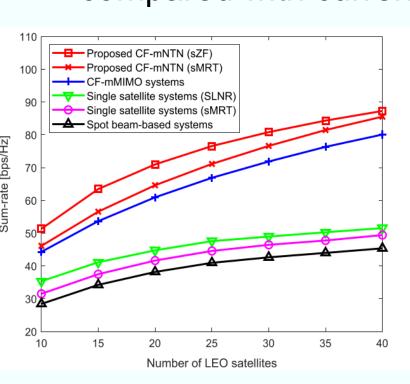
 xG-Loc is the first open dataset for evaluating localization algorithms and services fully compliant with 3GPP specifications

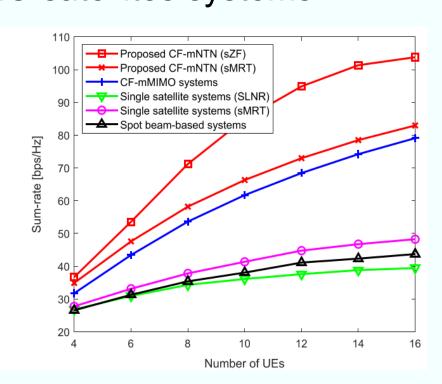


- The data available in xG-Loc include: received and transmitted PRSs/SRSs, distance/AOD/position estimates, and others.
- New scenarios and frequency bands are added in Nov. 2024

## Performance analysis of location-aware networks

• The performance of the location-aware NTN is compared with current LEO satellites systems





 Leveraging location information and cooperation among satellites can bring significant performance gain in NTN















