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

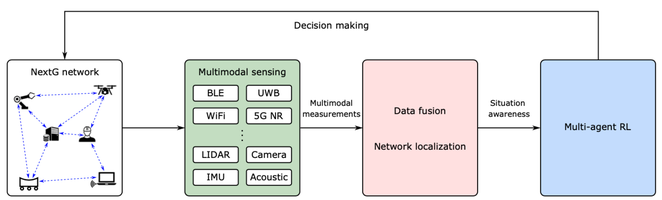
Technical Gaps:

- 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 inference and control to facilitate situational awareness and decision-making in FoF

FoF: Inference and Control Loop

- FoF has the following constituents:
  - Physical layer: FoF agents
  - Sensing layer: multimodal sensors
  - 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:

- Operational resilience under latency
- High-accuracy localization and near-optimal control action generation
- Intelligent network resource coordination

Adaptive Low-Latency Network Localization

Introduction:

- Localization and tracking is important for FoF
- Multiple nodes infer the system state via sensing and inter-node communication

Goals:

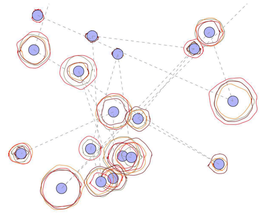
- Design efficient algorithms for high-accuracy localization by fusing sensed data obtained from heterogeneous devices in FoF
- Develop a framework for inference in the presence of network latency

Challenges:

- Heterogeneity of sensors used in FoF
- Communication and computing latency in the network
- Uncertainty in temporal association of sensed data with measurement time

Approaches:

- **Soft Information (SI)**
  - Extraction methods of soft feature information and soft context information
  - Fusion of soft information from heterogenous observations using statistical inference theory



Localization based on soft information

- **Belief Propagation**
  - Iterative evaluation of an approximate posterior distribution for the target positions
  - Tractable association of sensing data with the time instants at which they are measured

Latency-Resilient Decision Making

Introduction:

- Resilient decision-making and the ability to adapt and coordinate agent resources is crucial for NextG networks
- FoF requires the network to efficiently use its limited energy, communication, and sensing resources for inferring and controlling the states of FoF agents

Goals:

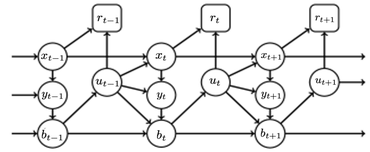
- Design system-wide control policies for partially observable target nodes in the factory
- Develop efficient coordination strategies for sensing and communication

Challenges:

- Performance of the decision layer is limited by the inference layer
- Partial observability of target states is complicated by network-wide latency
- Multi-agent decision problems are difficult to solve

Approaches:

- **Partially observable Markov decision processes (POMDPs)**
  - Formulate the decision-making problem as a POMDP
  - Compute belief state using proposed latency-resilient localization algorithms
  - Employ dynamic programming for obtaining near-optimal policies



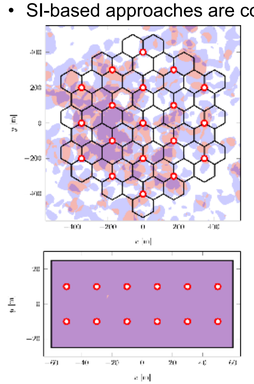
Representation of a POMDP

- **Rollout**
  - Approximate the reward-to-go using a heuristic policy
  - Obtain a sequence of controls for the lookahead horizon using nonlinear programming or optimal control techniques

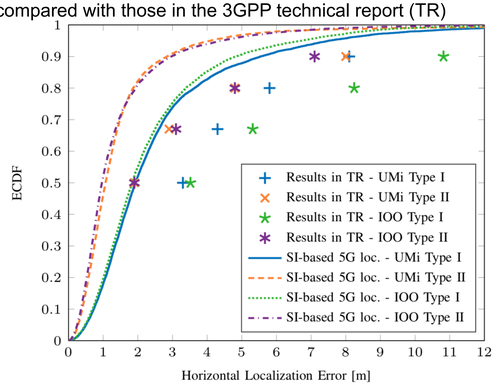
Preliminary Works

Network localization and navigation for beyond 5G networks:

- Numerical results are obtained for ETSI 3GPP standardized scenarios
  - urban microcell (Umi)
  - indoor open office (IOO)
- Channel instantiations are generated accounting for spatially correlated fading
- SI-based approaches are compared with those in the 3GPP technical report (TR)



Line-of-sight map in Umi (top) and IOO (bottom) scenarios



Empirical cumulative distribution function (ECDF) of localization error in different scenarios