SafeT-Net: Situational Awareness for Emergencies through Network-Enabled Technologies

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Project Overview

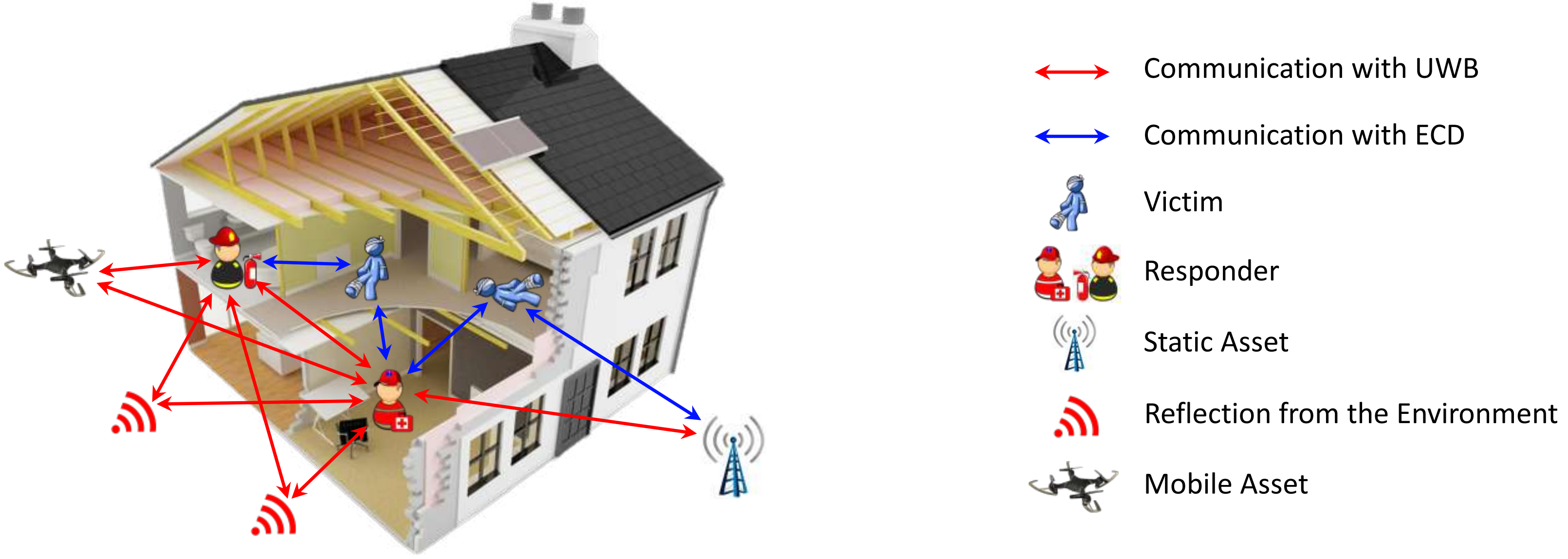
- Goal: raise situational awareness in first responder operations by introducing timely localization and deployment capabilities

- Challenges:
  - infeasibility of optical localization techniques
  - unattainability of environment knowledge
  - inaccessibility of certain regions for asset deployment

- Objectives:
  - robust localization: develop algorithms to localize responders, their assets, and victims accurately and timely using different radio technologies
  - resource management and asset deployment: design context-aware optimization and control strategies for efficient use of resources and assets

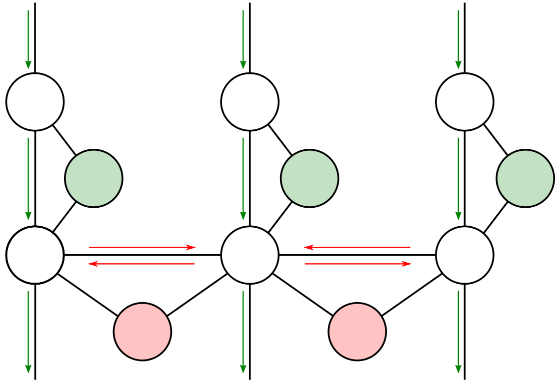
Network-Enabled Technologies

- Utilize different radio technologies, including ultra-wideband (UWB) and end-user communication devices (ECDs)
- Exploit reflections from the environment to improve accuracy and robustness
- Perform efficient resource management and asset deployment



Robust Localization

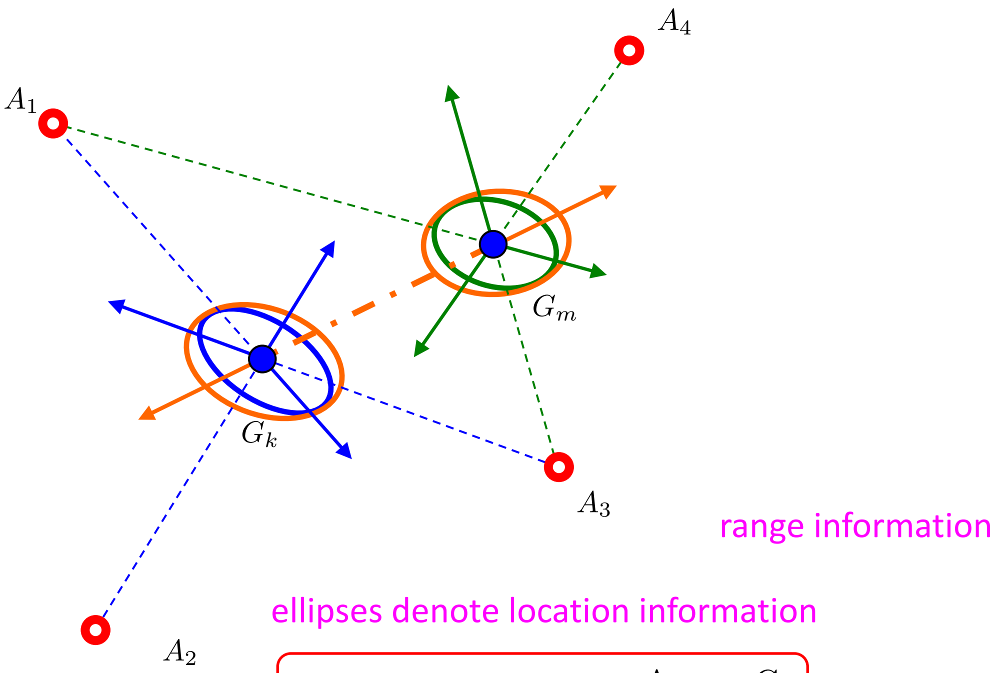
- Research objective: develop algorithms to localize responders, their assets, and victims accurately and timely using different radio technologies
- Methodologies:
  - exploit measurements obtained from devices with different hardware capabilities
  - develop Bayesian inference algorithms based on message passing (MP)
  - design algorithms that can exploit multipath propagation for localization



Asset Management and Deployment

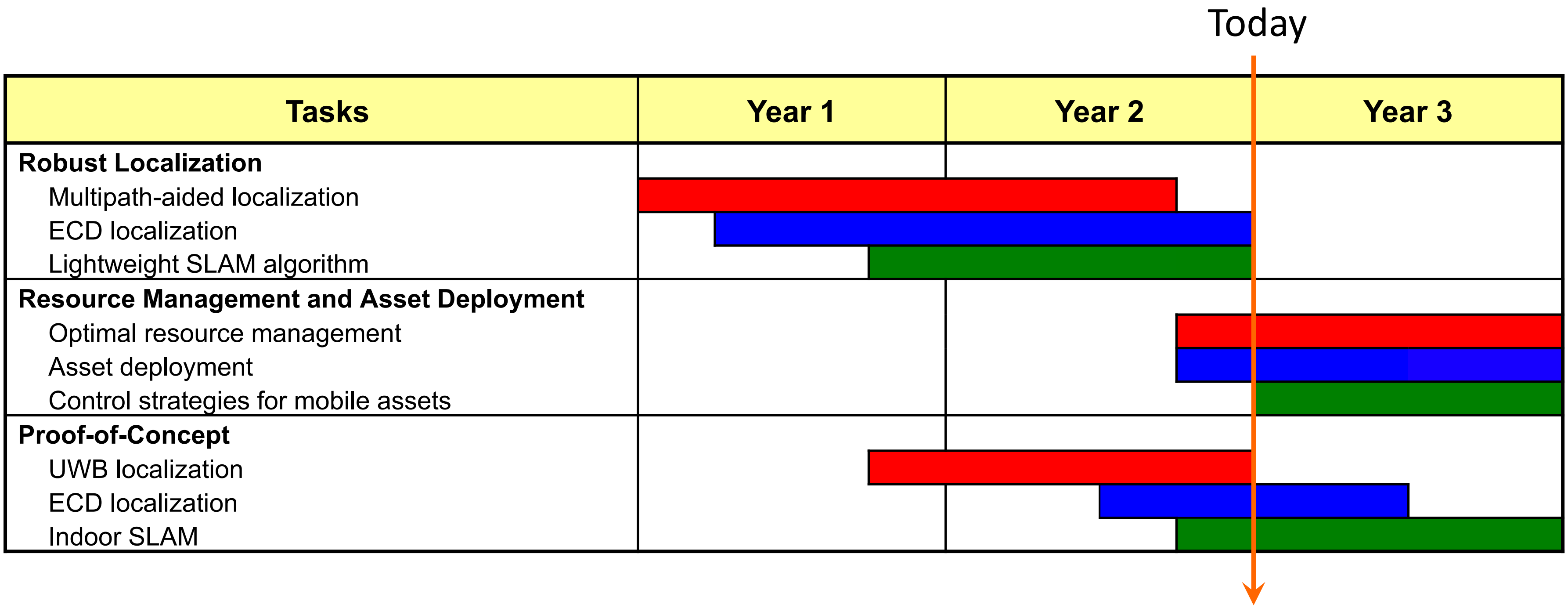
- Research objective: design context-aware optimization and control strategies for efficient use of resources and assets

- Methodologies:
  - adopt concepts from information theory for asset management and deployment design
  - develop information-seeking control strategies for efficient resource utilization and asset deployment



Overall EFIM $\boldsymbol{J}_{\mathrm{e}} = \boldsymbol{J}_{\mathrm{e}}^{\mathrm{A}} + \boldsymbol{J}_{\mathrm{e}}^{\mathrm{C}}$

Timeline and Milestones



Localization with ECDs

- Goal: achieve accurate ranging and localization with ECDs (e.g., devices employing OFDM waveforms)
- Localization with ECDs is challenging due to
  - processing impairments
  - insufficient bandwidth
  - inaccessibility of physical layer information
- Localization with ECDs requires
  - band stitching techniques to increase effective bandwidth for accurate ranging
  - ranging algorithms with processing impairment mitigation capability based on channel state information (CSI)
  - localization methods that can provide accurate position information in the presence of multipath

Localization with ECDs

- Accomplishments:
  - established the theoretical foundation for OFDM ranging systems using the framework of equivalent Fisher information matrix (EFIM)
  - designed fast channel switching protocol in the WiFi driver, enabling CSI measurements for all 37 channels within the channel coherence time
  - modelled CSI processing impairments and implemented impairment mitigation strategies
  - introduced an algorithm to estimate channel impulse response (CIR) based on CSI
  - developed a localization algorithm to infer the positions of ECDs based on CIRs

Channel State Information

- Transmission model in the frequency domain (channel i)

CSI of frequency f_i noise

$$\boxed{y_i} = \boxed{h_i} \cdot \boxed{x_i} + \boxed{n_i}$$

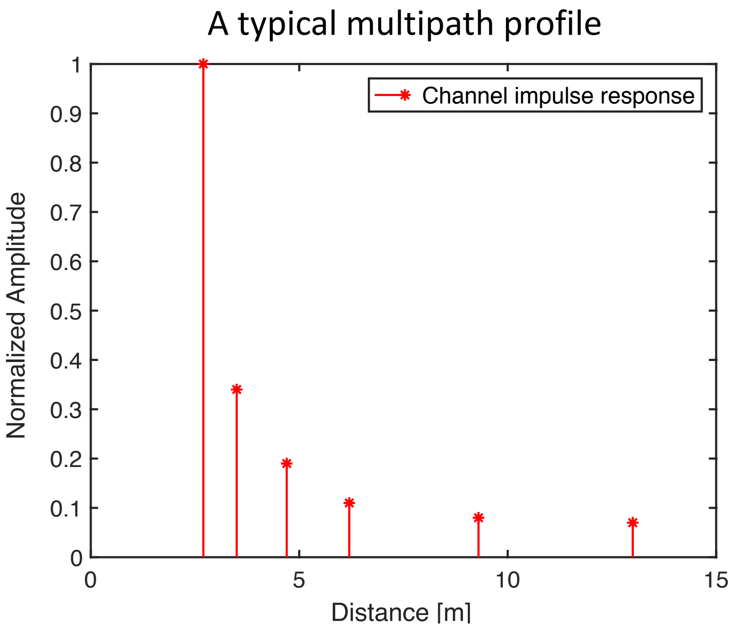
received training symbol transmitted training symbol

- CSI in the multipath environment

number of different paths

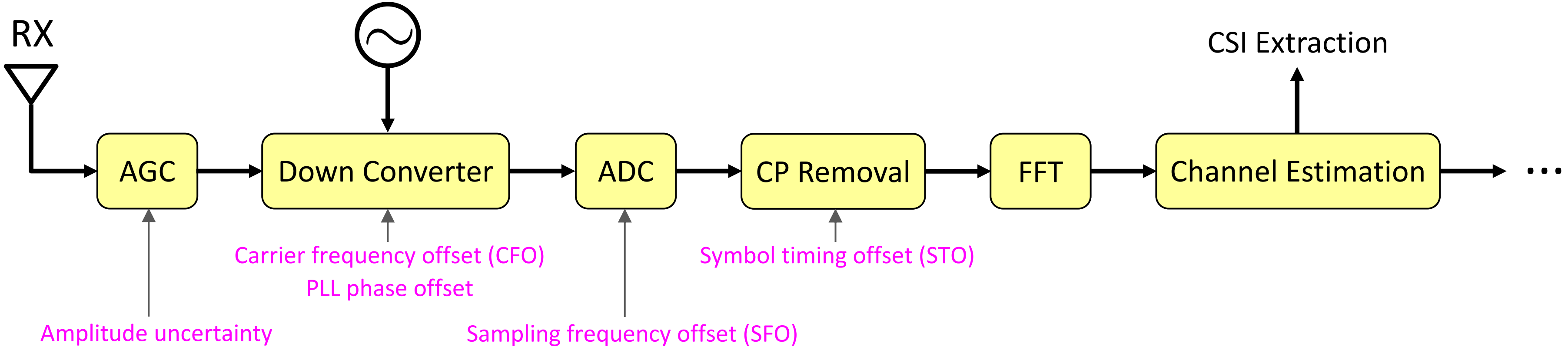
$$h_i = \sum_{l=1}^{\boxed{L}} \boxed{\alpha_l} e^{-j2\pi f_i \boxed{\tau_l}}$$

amplitude of path l propagation delay of path l



CSI Processing Impairments Mitigation

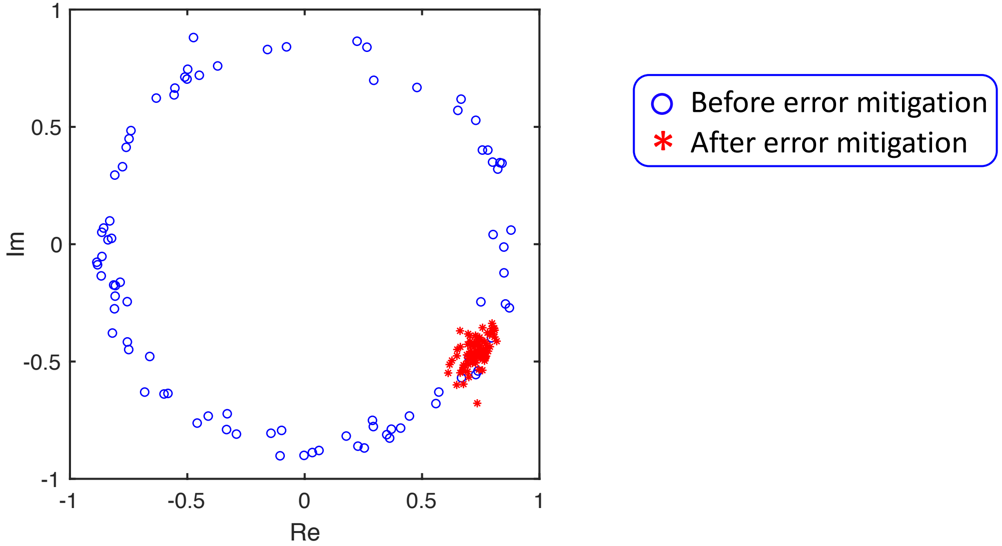
- CSI measured by WiFi cards is affected by processing impairments



- Impairments are challenging to compensate since they are time-varying and different across WiFi channels

CSI Processing Impairments Mitigation

- Mitigate channel impairments based on transmission of several packets for each channel



Normalized CSI before and after impairments mitigation

- Develop fast channel switching, enabling CSI measurements for all 37 channels within the channel coherence time

CIR Estimation Based on Mitigated CSI

- Detect the number of multipath L, and estimate the associated α_l and τ_l of each path based on CSI measurements

- CSI after impairments mitigation:

$$\boxed{\widetilde{\mathsf{h}}_i} = \sum_{l=1}^{L} \alpha_l e^{-j2\pi f_i \tau_l} + \widetilde{\mathsf{n}}_i$$

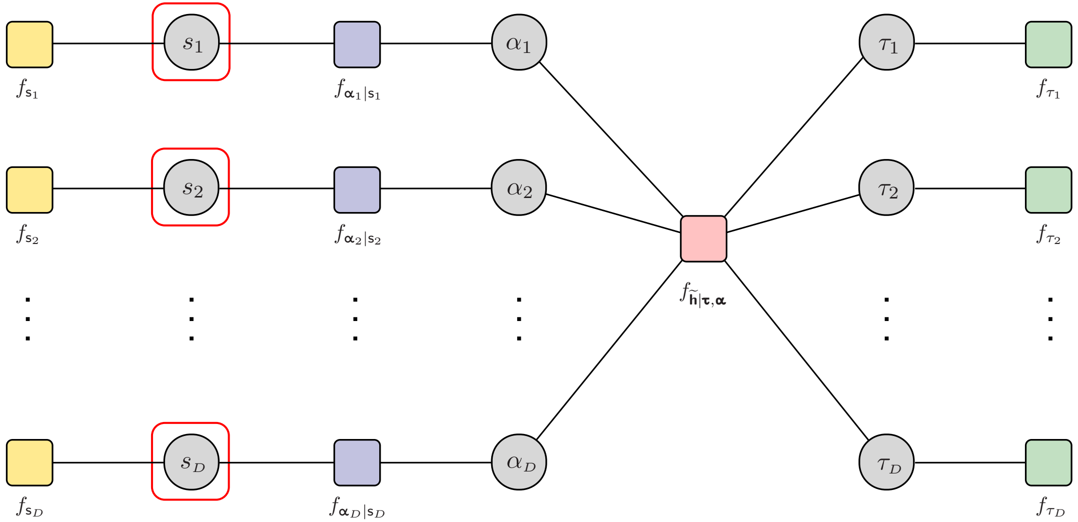
CSI after error mitigation

- Challenge:
  – the number of multipath L is unknown

- Solution:
  – replace L by constant D which is larger than the maximum possible L
  – introduce auxiliary variable $\mathbf{s}$ that determines whether each path exists

The Factor Graph Representation

- The relations between the random variables can be represented by a factor graph



- For $d \in \{1, 2, \ldots, D\}$, the Bernoulli variable s_d determines whether α_d is zero or not

MP Algorithm

- We run an MP algorithm on the factor graph to obtain the distribution of unknown variables

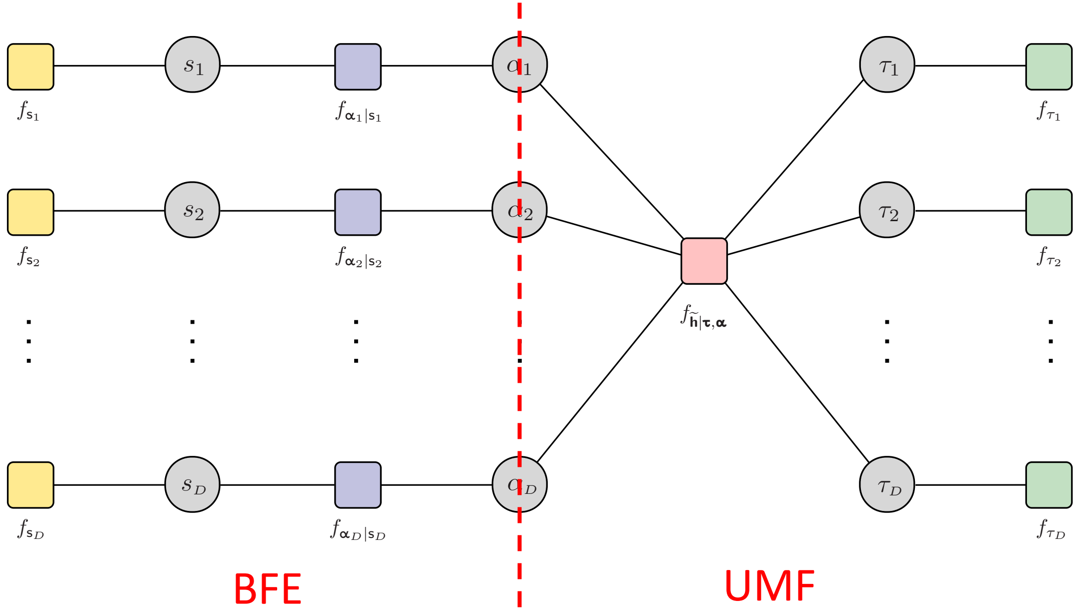
- The MP algorithm aims to find the distribution q^* which minimizes the Kullback-Leibler (KL)-divergence between q and the desired distribution p from a given family $\mathcal{Q}$

$$q^* = \arg\min_{q \in \mathcal{Q}} \mathcal{D}_{\mathrm{KL}}(q||p), \qquad \mathcal{D}_{\mathrm{KL}}(q||p) = \int_{\mathcal{X}} \ln q(x) \frac{q(x)}{p(x)} \mathrm{d}x$$

- Different choice of family $\mathcal{Q}$ results in a different MP algorithm
  - Bethe free energy (BFE) approximation: BFE-based MP algorithm
  - Unstructured mean field (UMF) approximation: UMF-based MP algorithm

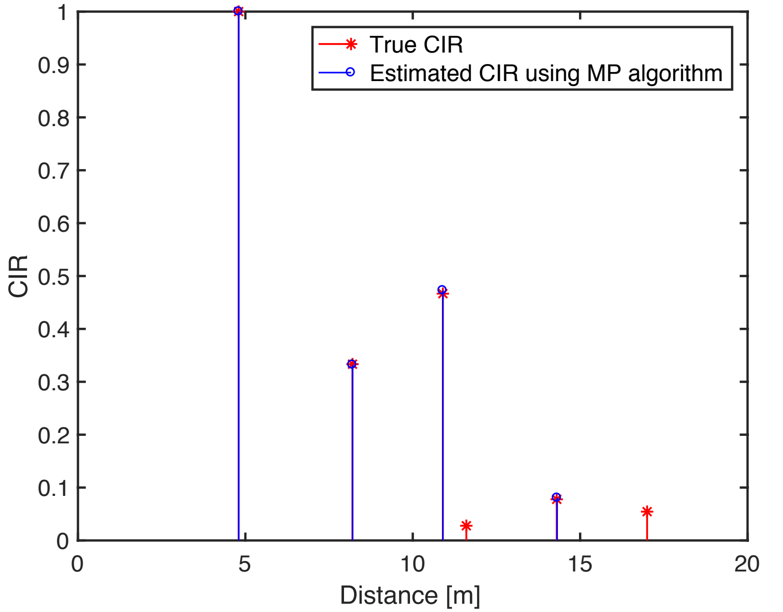
Proposed MP Algorithm

- Exact messages are intractable to calculate in general
- We obtain closed-form expressions of messages by partitioning the graph to BFE and UMF parts



Evaluation of the Proposed MP Algorithm

- Advantages of the proposed MP algorithm
  - no parameter tuning is required
  - it is completely gridless, i.e., there is no spatial discretization



Position Inference Based on CIR Estimates

- Consider a network of 1 agent and N_b anchors
- Each anchor k has the estimates of delays $\hat{\boldsymbol{\tau}}_k = [\hat{\tau}_{k1}, \hat{\tau}_{k2}, \ldots, \hat{\tau}_{k\hat{L}_k}]^\mathrm{T}$
- Goal: infer the position $\mathbf{p}$ of the agent from delays $\hat{\boldsymbol{\tau}}_k, \; k = 1, 2, \ldots, N_\mathrm{b}$
- Consider the posterior distribution of the agent position

$$f(\boldsymbol{p}|\hat{\boldsymbol{\tau}}_1, \hat{\boldsymbol{\tau}}_2, \ldots, \hat{\boldsymbol{\tau}}_{N_\mathrm{b}}) \propto f(\boldsymbol{p}) \prod_{k=1}^{N_\mathrm{b}} f(\hat{\boldsymbol{\tau}}_k|\boldsymbol{p})$$

- Use ideas from probabilistic data association (DA) to model likelihood $f(\hat{\boldsymbol{\tau}}_k|\boldsymbol{p})$

Likelihood Model Inspired by DA

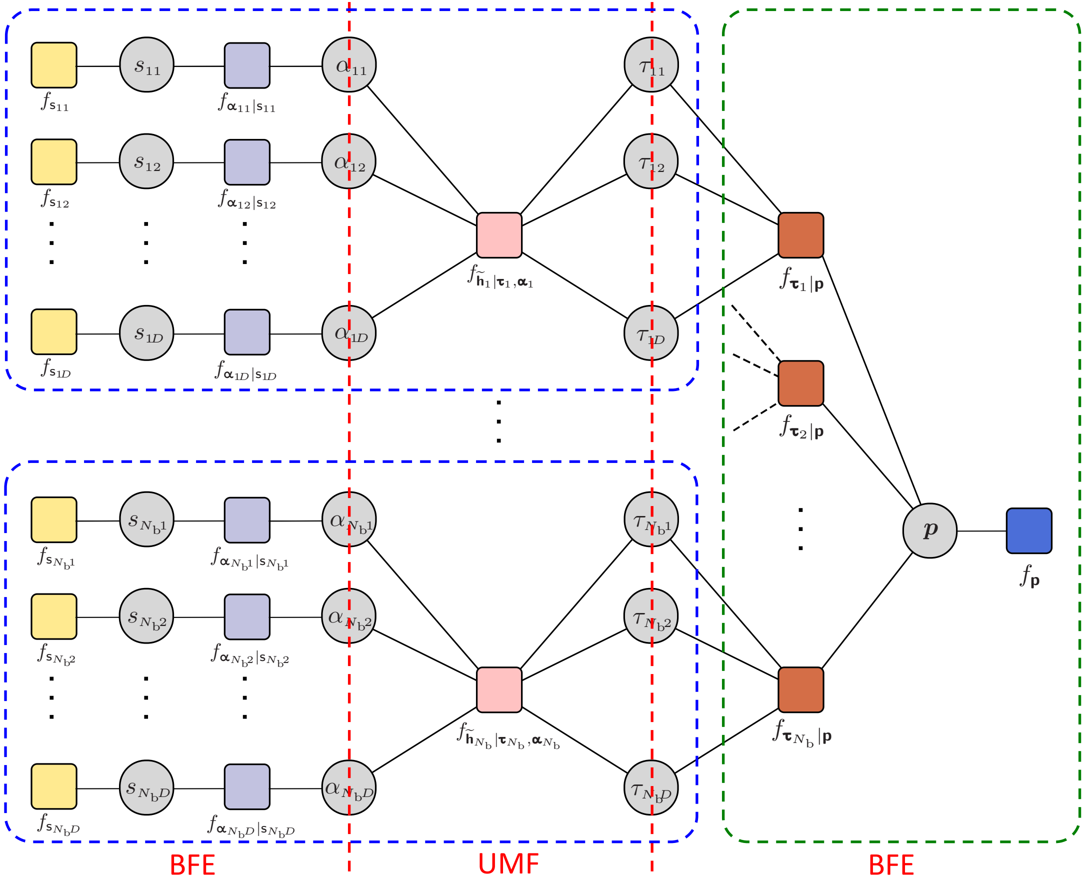
- The DA problem:
  - each anchor receives several measurements from the agent
  - at most one measurement is the true measurement; others are false alarms
  - there is a chance that no true measurement is made

- Analogy to our problem:
  - each anchor estimates a CIR that consists of several delays w.r.t. the agent
  - at most one such delay represents the LOS path; others are NLOS paths
  - there is a chance that there is no LOS path in the CIR

- Inspired by probabilistic DA, the likelihood function $f(\hat{\boldsymbol{\tau}}_k|\boldsymbol{p})$ is a sum of $\hat{L}_k$ terms, where the term $l \in \{1, 2, \ldots, \hat{L}_k\}$ represents the hypothesis that $\hat{\tau}_{kl}$ is the LOS delay

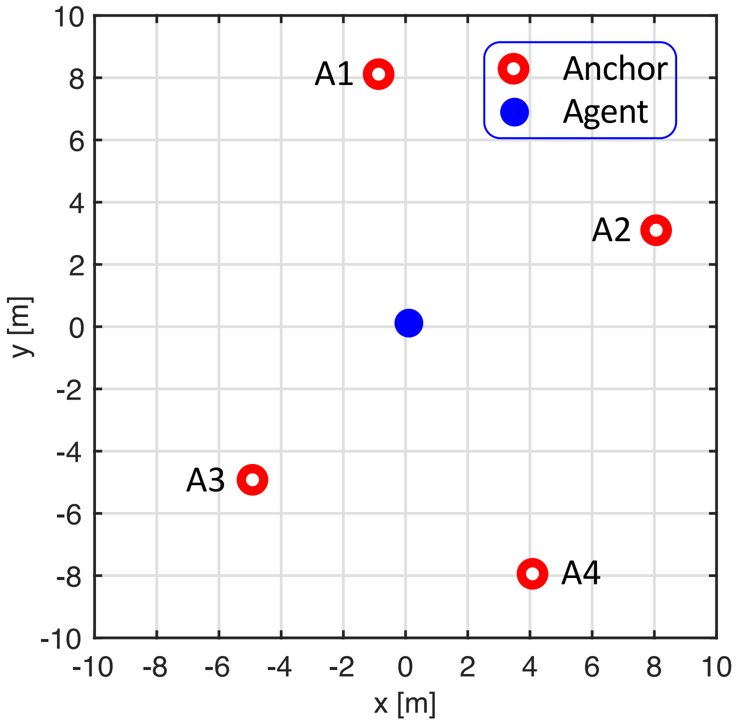
The Integrated Factor Graph

- Combine ranging and localization factor graphs
- Run MP algorithm for each anchor to estimate the CIRs between anchors and agent
- Perform probabilistic DA to infer the agent position from estimated CIRs

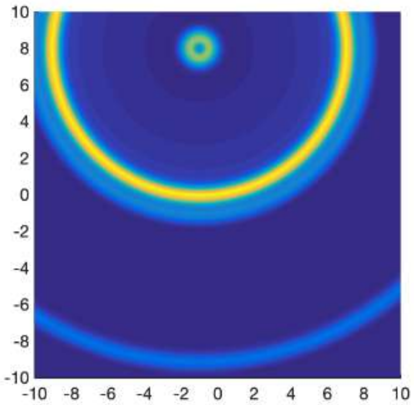


Simulation Settings

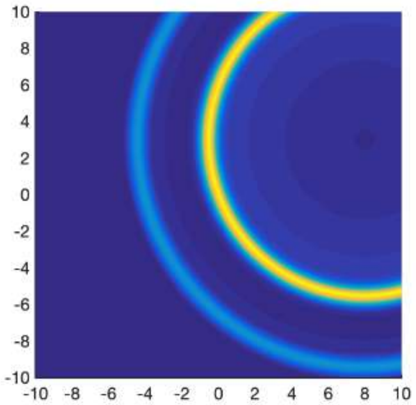
- Perform simulation in indoor environment
- Consider 4 anchors (red) and 1 agent (blue)
- Generate the channels using QuaDRiGa according to
  - WINNER II indoor channel model
  - 3 LOS links (A1, A2, A4) and 1 NLOS link (A3)



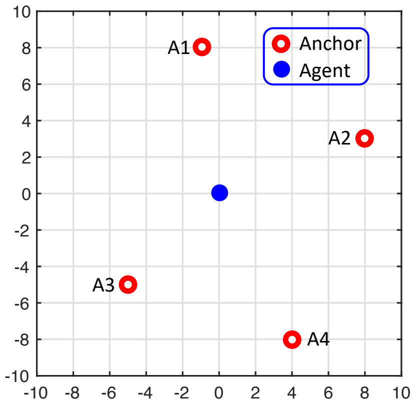
Case Study (Indoor Simulation)



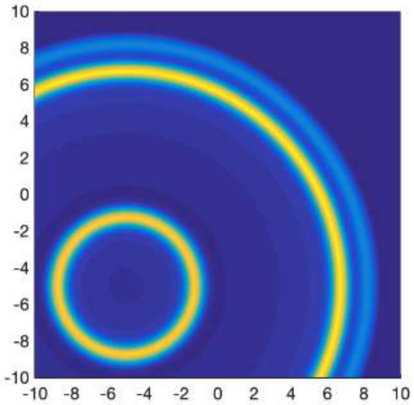
Likelihood function $f(\hat{\boldsymbol{\tau}}_1|\boldsymbol{p})$



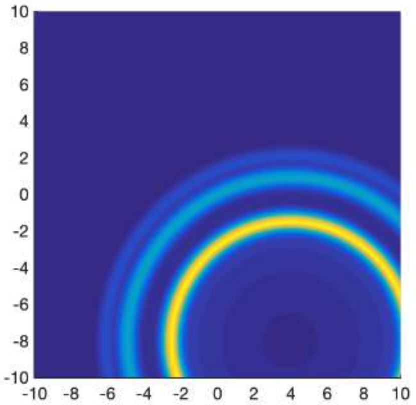
Likelihood function $f(\hat{\boldsymbol{\tau}}_2|\boldsymbol{p})$



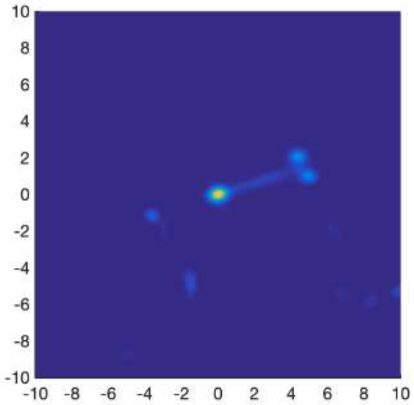
Topology



Likelihood function $f(\hat{\boldsymbol{\tau}}_3|\boldsymbol{p})$



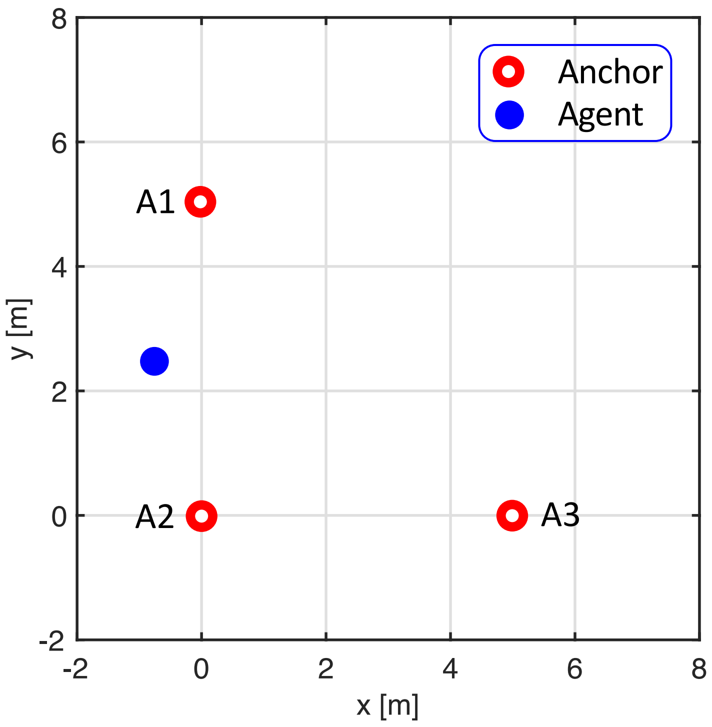
Likelihood function $f(\hat{\boldsymbol{\tau}}_4|\boldsymbol{p})$



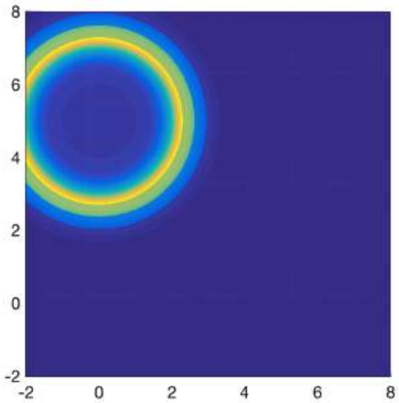
Posterior distribution $f(\boldsymbol{p}|\hat{\boldsymbol{\tau}}_1, \hat{\boldsymbol{\tau}}_2, \hat{\boldsymbol{\tau}}_3, \hat{\boldsymbol{\tau}}_4)$

Experiment Settings

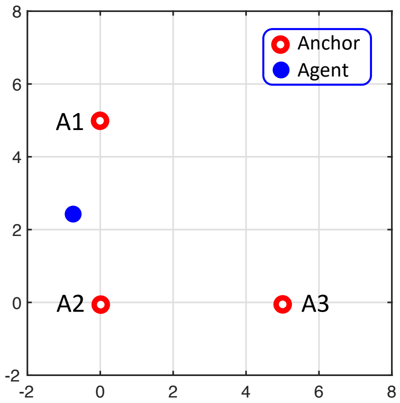
- Perform the experiment in outdoor environment
- Consider 3 anchors (red) and 1 agent (blue)
- All the 3 channels are LOS channels



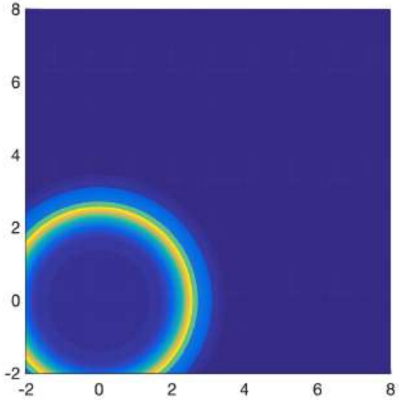
Case Study (Outdoor Experiment)



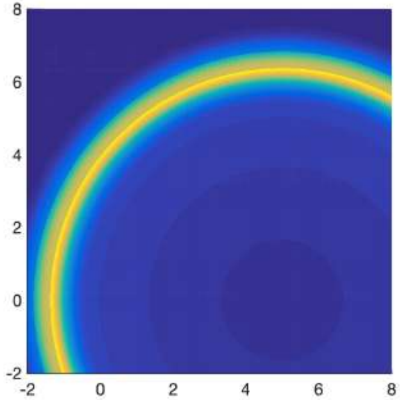
Likelihood function $f(\hat{\boldsymbol{\tau}}_1|\boldsymbol{p})$



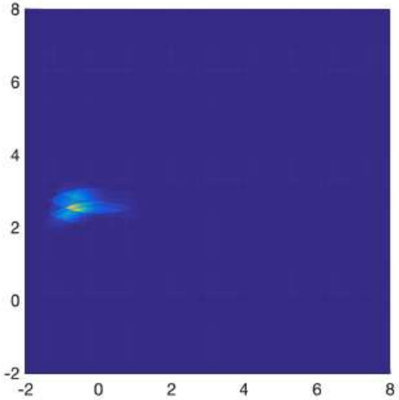
Topology



Likelihood function $f(\hat{\boldsymbol{\tau}}_2|\boldsymbol{p})$



Likelihood function $f(\hat{\boldsymbol{\tau}}_3|\boldsymbol{p})$



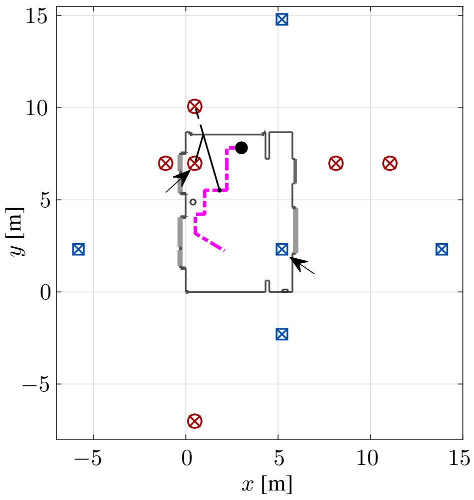
Posterior distribution $f(\boldsymbol{p}|\hat{\boldsymbol{\tau}}_1, \hat{\boldsymbol{\tau}}_2, \hat{\boldsymbol{\tau}}_3)$

Multipath-Aided Localization

- Multipath propagation degrades the performance of conventional localization techniques based on UWB radio signals

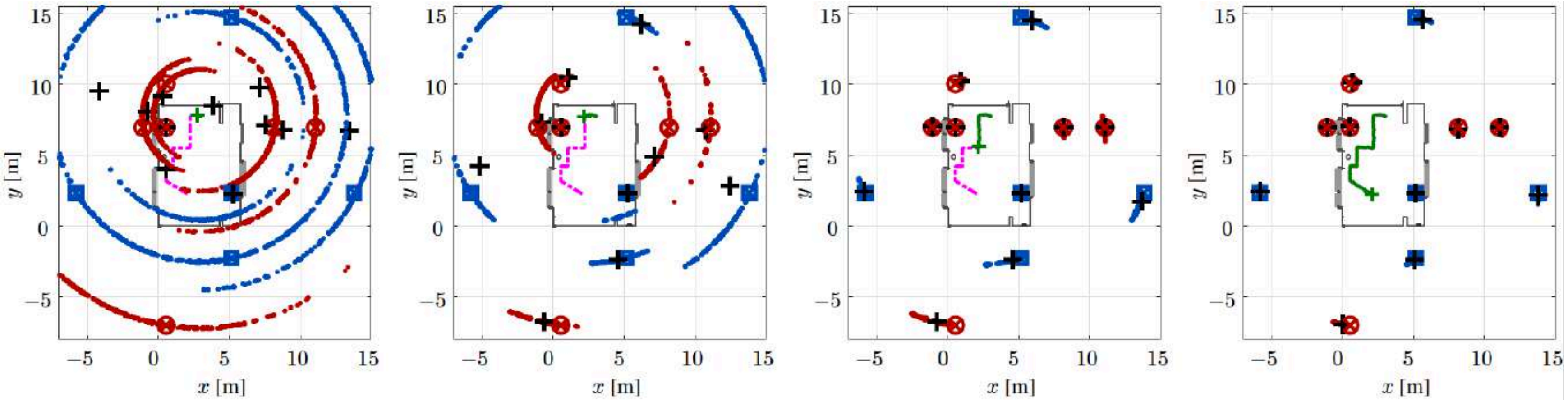
- We aim to exploit multipaths of the received UWB signals to increase robustness and localization accuracy

- Developed an MP algorithm for simultaneous localization and mapping (SLAM) that can
  - determine the positions of virtual sources (VSs) “generated” by specular reflections at flat surfaces
  - associate range measurements related to multipath delays with VSs
  - localize a mobile agent accurately and reliably



Multipath-Aided Localization

- Convergence demonstration of SLAM algorithm using simulated measurement
  - particles represent the posterior pdfs of the mobile agent position and of the detected VSs positions
  - black crosses represent the estimated positions of the detected VSs
- Despite range-only measurements, the mobile agent can be accurately and reliably tracked and VSs can be detected and localized



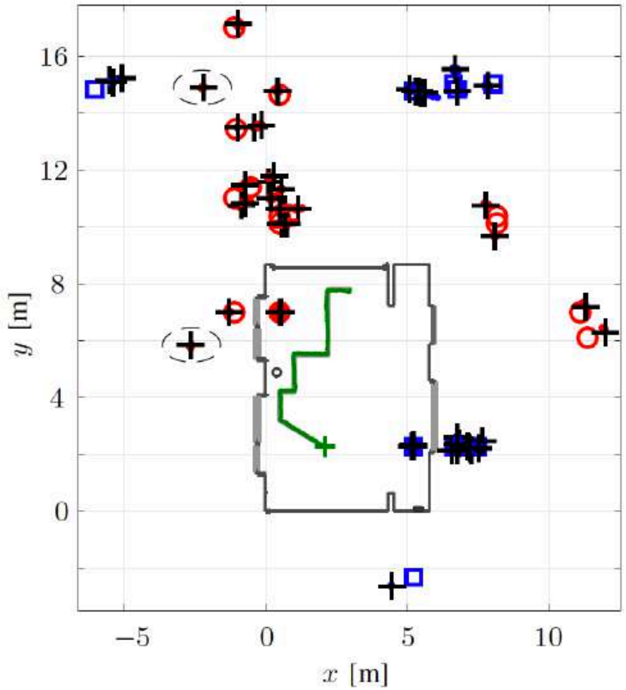
Experimental Results

- We evaluated the proposed SLAM algorithm using UWB measurements collected in a seminar room

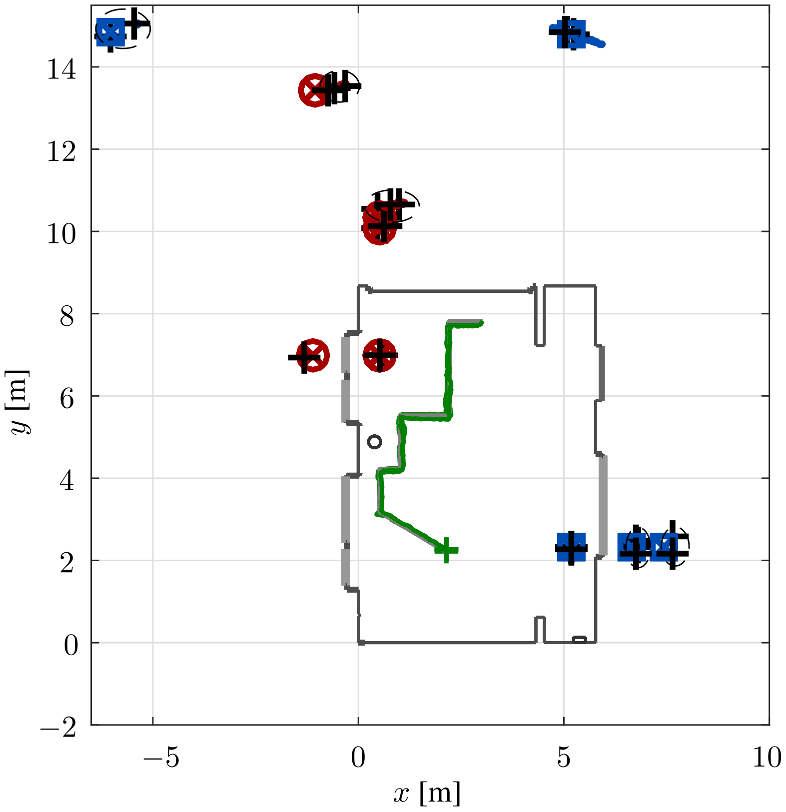
- The proposed algorithm is able to exploit multipath components for localization

- The mobile agent can be accurately and reliably tracked and VSs can be detected and localized

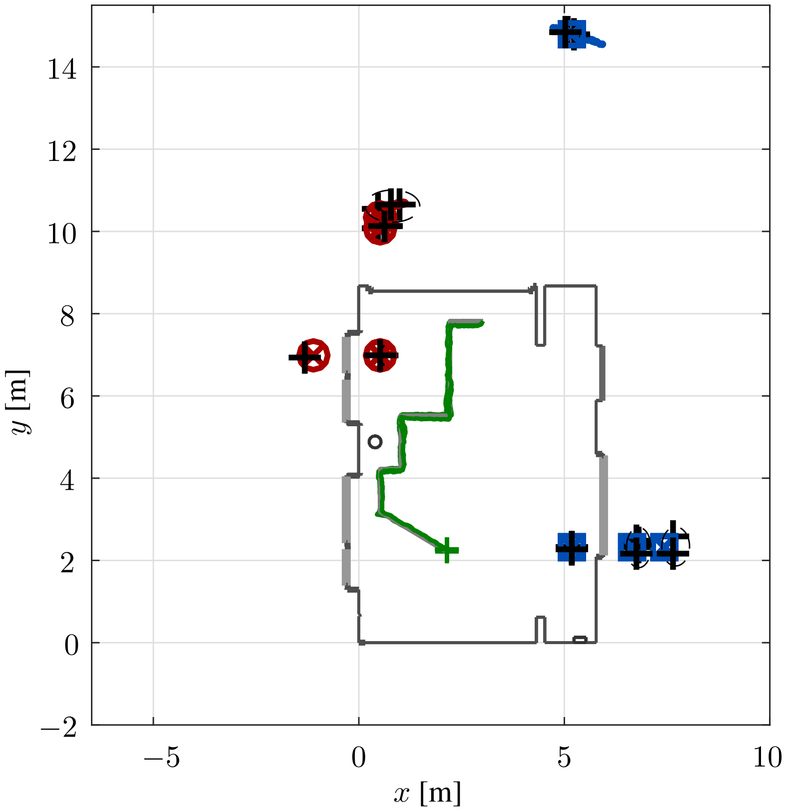
- Estimated VS positions can be associated with geometrically expected VS positions



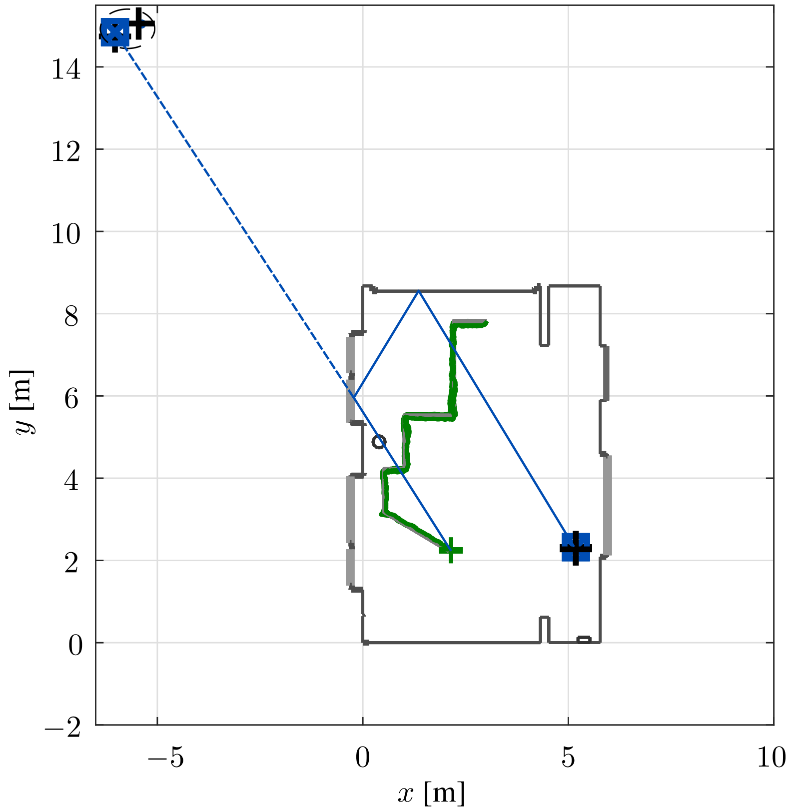
Experimental Results – All VSs at Final Position



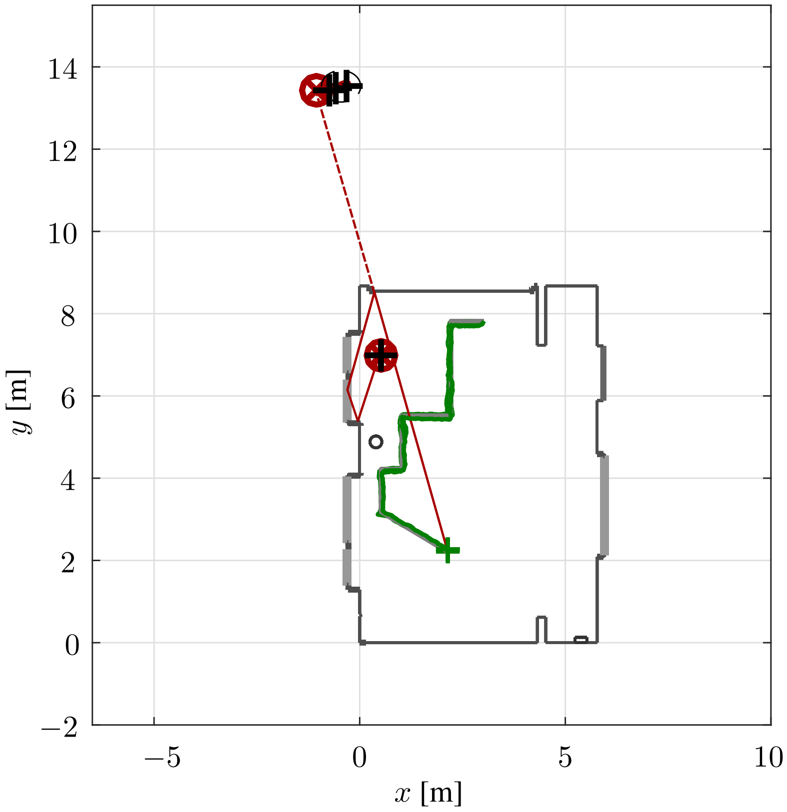
Experimental Results – 1st Order VSs at Final Position



Experimental Results – 2nd Order VS at Final Position

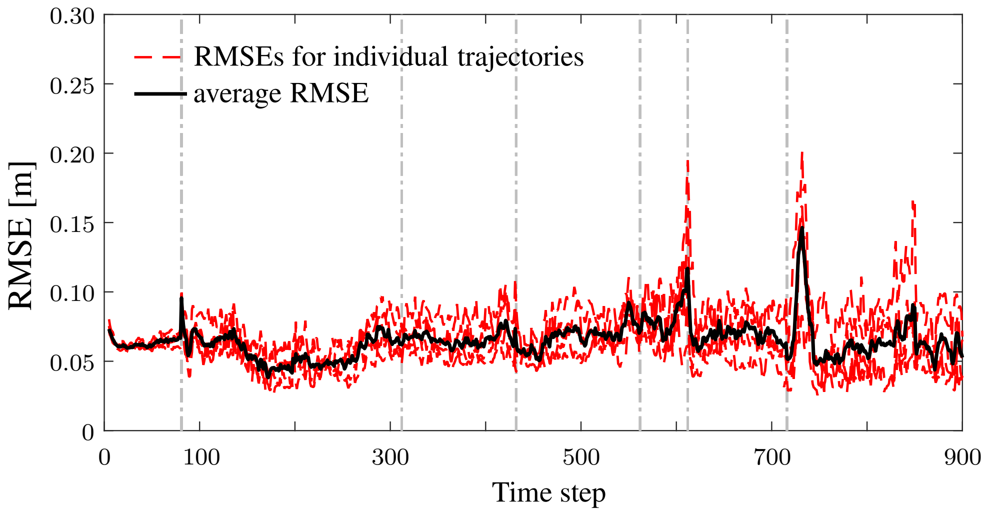


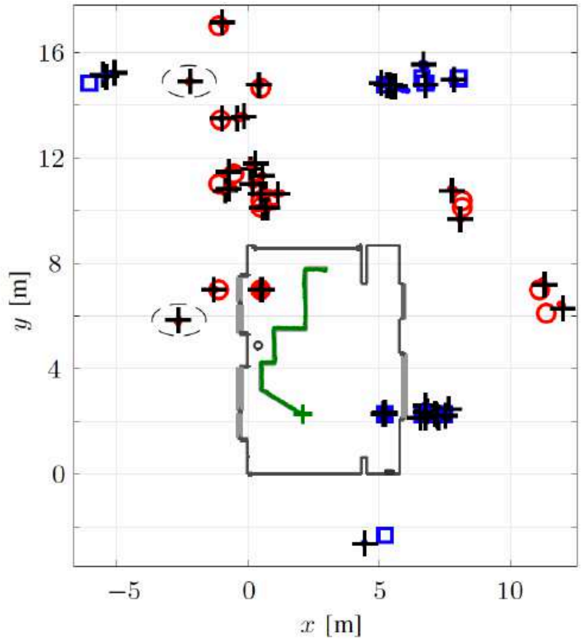
Experimental Results – 3rd Order VS at Final Position



Multipath-Aided Localization Experiment

- Localization and mapping results of developed SLAM algorithm using real measurements
- Accurate and robust indoor localization performance



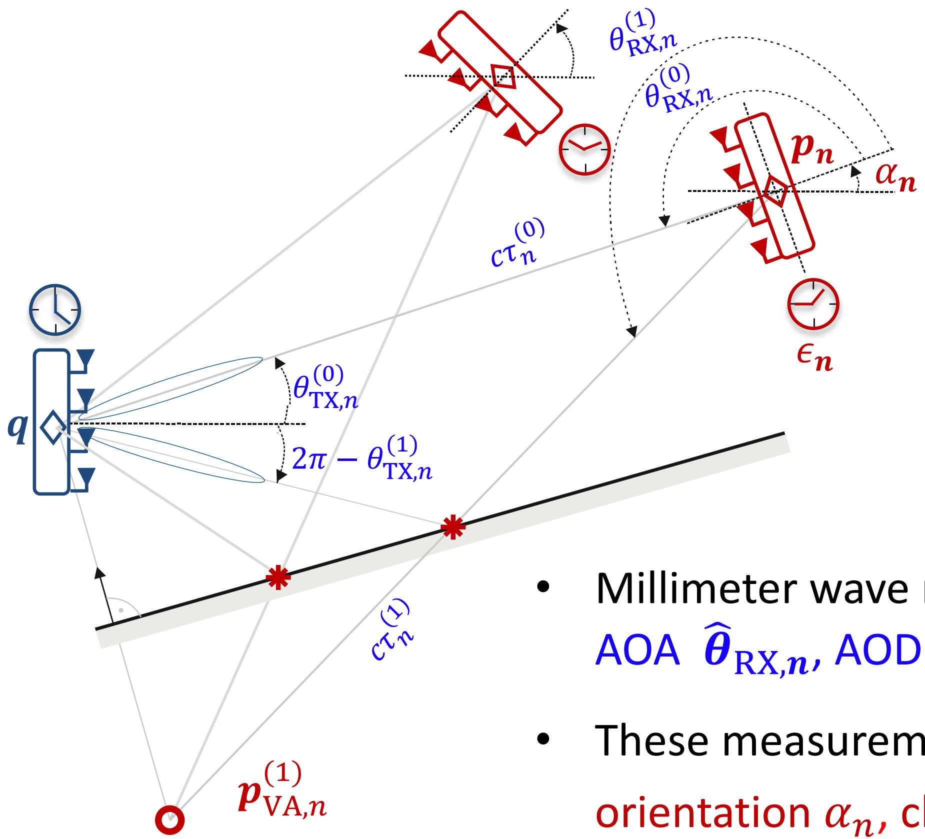


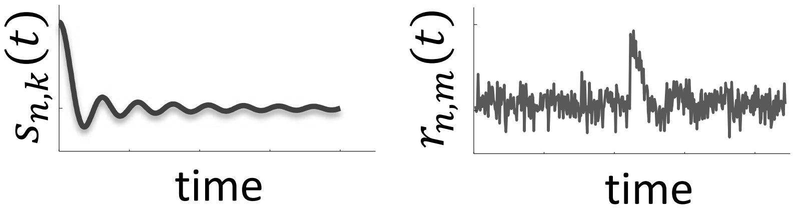
E. Leitinger, F. Meyer, F. Hlawatsch, K. Witrisal, F. Tufvesson, and M. Z. Win, “A belief propagation algorithm for multipath-based SLAM,” *IEEE Trans. Wireless Commun.*, 2019, submitted.

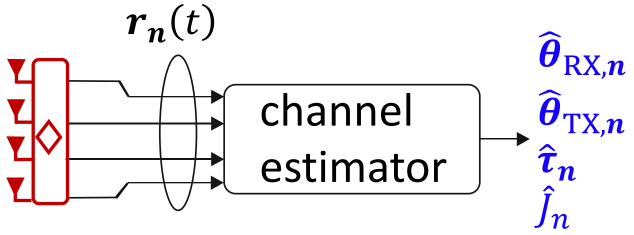
Millimeter Wave Massive MIMO SLAM

- Millimeter wave massive MIMO systems have excellent localization capabilities due to
  - the large number of antennas that can be packed on a small area due to short wavelengths; and
  - the large bandwidth that is available in millimeter wave frequency bands
- Multipath components can be accurately and reliably resolved due to high spatial-temporal resolution
- As a result, a single anchor is sufficient for agent localization and no motion is needed to map VS positions

Millimeter Wave Massive MIMO SLAM







- Millimeter wave massive MIMO systems enable accurate AOA $\widehat{\boldsymbol{\theta}}_{\mathrm{RX},\boldsymbol{n}}$, AOD $\widehat{\boldsymbol{\theta}}_{\mathrm{TX},\boldsymbol{n}}$, and delay $\hat{\boldsymbol{\tau}}_{\boldsymbol{n}}$ measuments of all paths
- These measurements can be used to obtain position $\boldsymbol{p_n}$, orientation α_n, clock offset ϵ_n and map $\boldsymbol{p}_{\mathrm{VA},n}^{(1)}$ estimates

Conclusion

- Localization with ECDs
  - designed an MP algorithm to estimate channel impulse response from CSI extracted from the WiFi driver of an ECD
  - developed an MP algorithm for inferring the positions of ECDs
  - demonstrated that ranging is possible with ubiquitous wireless communication technology (this will enable localization of victims in public safety emergencies)
- Multipath-aided localization and mapping
  - evaluated the localization performance of the developed range-only SLAM method (both by simulations and experimentation) in indoor environments
  - extended the system model of multipath-aided SLAM to account for angle-of-arrival and angle-of-departure measurements
  - showed that reflections from the environment can increase localization capabilities (in contrast to conventional belief that it degrades localization performance)

Way Forward

- Localization with ECDs
  - deploy the system and collect CSI from the network of ECDs
  - improve and evaluate indoor localization performance
- Multipath-aided localization and mapping for massive MIMO
  - develop an inference algorithm for SLAM in millimeter wave systems provided by future 5G massive MIMO communication systems
- Resource management and asset deployment
  - design context-aware optimization and control strategies for efficient resource utilization and deployment of mobile assets