

# CPS: Breakthrough: Selective Listening: Control for Connected Autonomous Vehicles in Data-Rich Environments

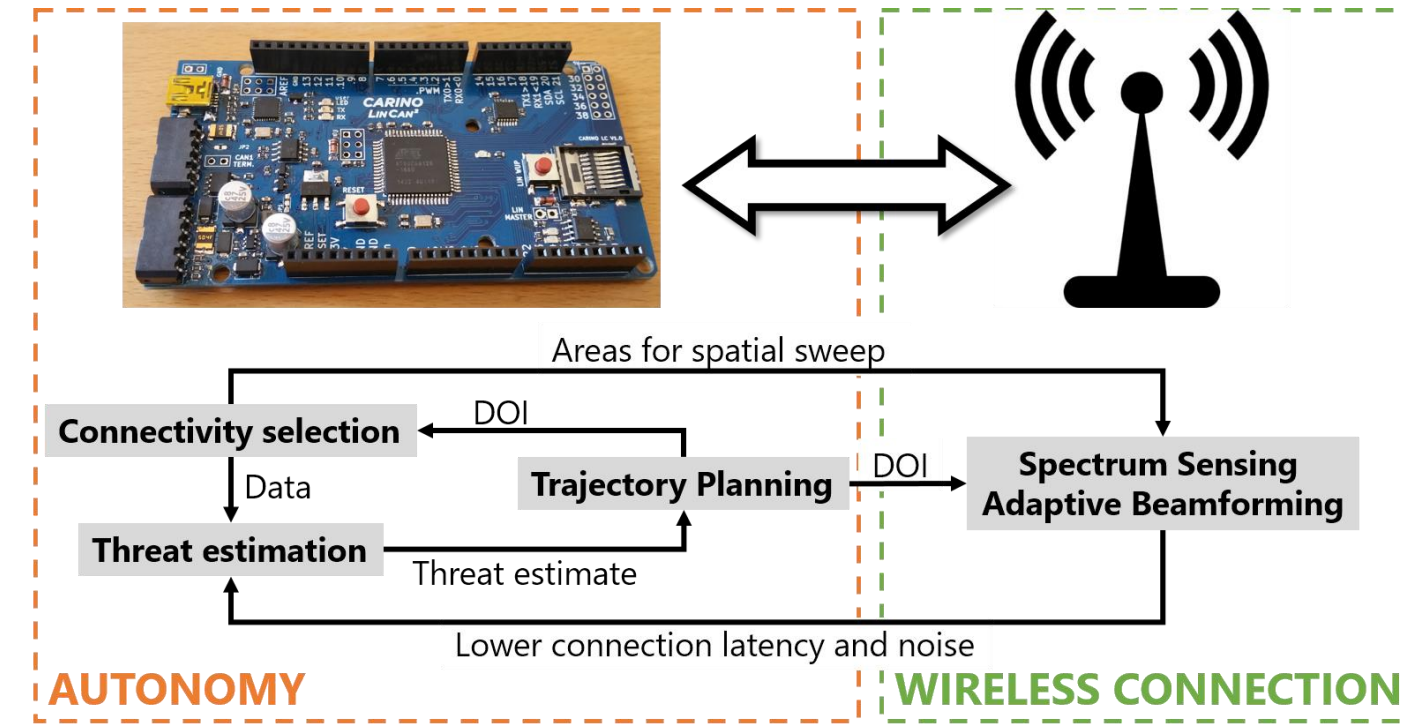
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## Research Objectives

The goal of this project is to study how estimation and control algorithms in connected autonomous cars affect – and are affected by – software-defined radio communications in spectrum-scarce, data-rich environments.



Objective	Anticipated Outcome
<b>Scientific objectives</b> – To characterize the following:	
V2V connectivity requirements.	Size and shape of a minimal region within which V2V connectivity is required to guarantee safety.
Performance limitations due to latencies in connections.	Maximum permissible latencies in connections to remain within desired safety risk levels.
Safety guarantees vis-à-vis uncertainties about other vehicles and pedestrians.	Dependence of safety risk level on the uncertainty in location and velocity of other vehicles.
<b>Engineering objectives</b> – To develop algorithms for the following:	
Connectivity selection and control-driven cognitive radio comms.	Minimal set of vehicles and infrastructure devices to commence V2V and V2I connections, respectively. Reliable radio comms. via spatial wireless filtering.
Analyze and quantify possibility of potential collisions.	Spatiotemporal field signifying the threat of collisions; uncertainty quantification of this field given uncertainties in connection latencies and noise.
Fast trajectory planning.	Trajectory with minimum threat exposure.
<b>Experimental objective</b> – Demonstrate principal features of scientific and engineering outcomes	Connected autonomous golf cart with onboard implementations of aforesaid algorithms; simulated traffic conditions and potential collision environments.

## Technical Approach

### Connectivity selection and collision threat estimation

- Threat field:** spatiotemporal scalar field indicating possibility of collisions with other vehicles.
  - Finitely parametrized using spatial basis functions
- Construct model of threat field evolution using models of other vehicles' motion and ego vehicle's planned trajectory.
- Use data from V2V comms and from ego vehicle's onboard sensors to provide indirect measurements of threat.
- Construct Bayesian estimator to estimate threat field parameters  $q_n$ .

$$c(\mathbf{p}, t) := \exp\left(\frac{-(\ln(\delta_{ix}) - \beta_{ix})^2}{2\alpha_{ix}^2}\right) \exp\left(\frac{-(\ln(\delta_{iy}) - \beta_{iy})^2}{2\alpha_{iy}^2}\right)$$

- Select and rank “best” data nodes.
  - Select data nodes that can be most informative in reducing ego vehicle's safety risk level.
  - Possible method: rank data nodes according to sensitivity of trace of Fisher information matrix.
- Safety risk level:** expected threat exposure over the planned trajectory..
- Determine a spatiotemporal domain of interest where high-ranked data nodes lie.

$$\begin{aligned}\alpha_{ix}(t) &:= \varepsilon_1 \ln\left(\frac{v_0 + |v_{ix}(t)| + \varepsilon_2}{v_0 - |v_{ix}(t)| + \varepsilon_2}\right), & \delta_{ix}(\mathbf{p}, t) &:= (\text{sgn } v_{ix}(t))(x - p_{ix}(t)) + \exp(\beta_{ix}(t)), \\ \alpha_{iy}(t) &:= \varepsilon_1 \ln\left(\frac{\varepsilon_3 + |v_{iy}(t)| + \varepsilon_4}{\varepsilon_3 - |v_{iy}(t)| + \varepsilon_4}\right), & \delta_{iy}(\mathbf{p}, t) &:= (\text{sgn } v_{iy}(t))(y - p_{iy}(t)) + \exp(\beta_{iy}(t)), \\ \beta_{ix}(t) &:= \ln\left(\frac{d_{ix} - |v_{ix}(t)| - \varepsilon_2}{2(|v_{ix}(t)| + \varepsilon_2)}\right), \\ \beta_{iy}(t) &:= \ln\left(\frac{d_{iy} - |v_{iy}(t)| - \varepsilon_4}{2(|v_{iy}(t)| + \varepsilon_4)}\right),\end{aligned}$$

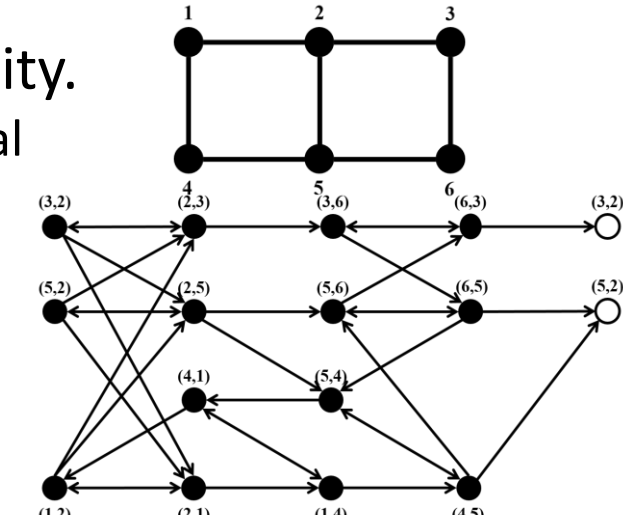
### Trajectory planning

Halfcar dynamical model for ego vehicle

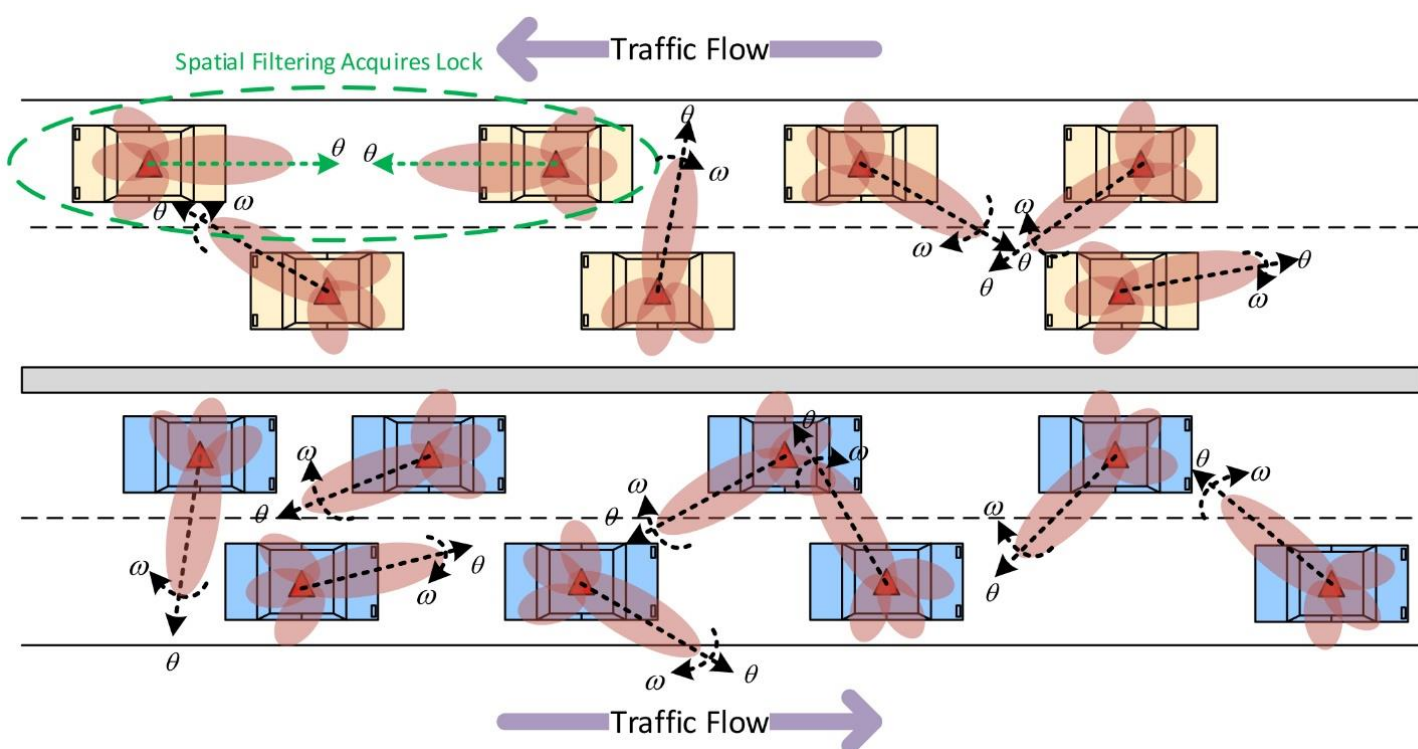
$$\begin{aligned}m\ddot{x} &= (F_{ix} \cos \delta - F_{iy} \sin \delta + F_{rx}) + m\dot{v}_x \dot{\psi}, \\ m\ddot{y} &= (F_{ix} \sin \delta + F_{iy} \cos \delta + F_{ry}) - m\dot{v}_y \dot{\psi}, \\ I_z \ddot{\psi} &= \ell_t (F_{ix} \sin \delta + F_{iy} \cos \delta) - \ell_r F_{ry},\end{aligned}$$

Method of lifted graphs

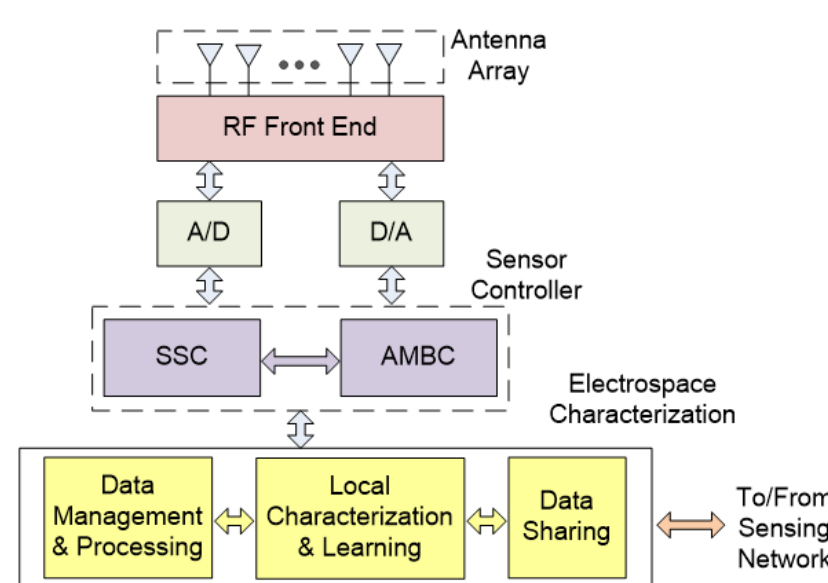
- Incorporate vehicle dynamical constraints in fast graph-based geometric path-planning algorithm.
- Objective is to find path with minimum expected threat.
- Edge transition costs in lifted graph: threat intensity.
  - Feasibility of edge traversal determined by analyzing dynamical model.
- Differential flatness used to determine dynamically feasible traversals in the  $(x, y)$  plane.



### Software-defined radio for threat reduction

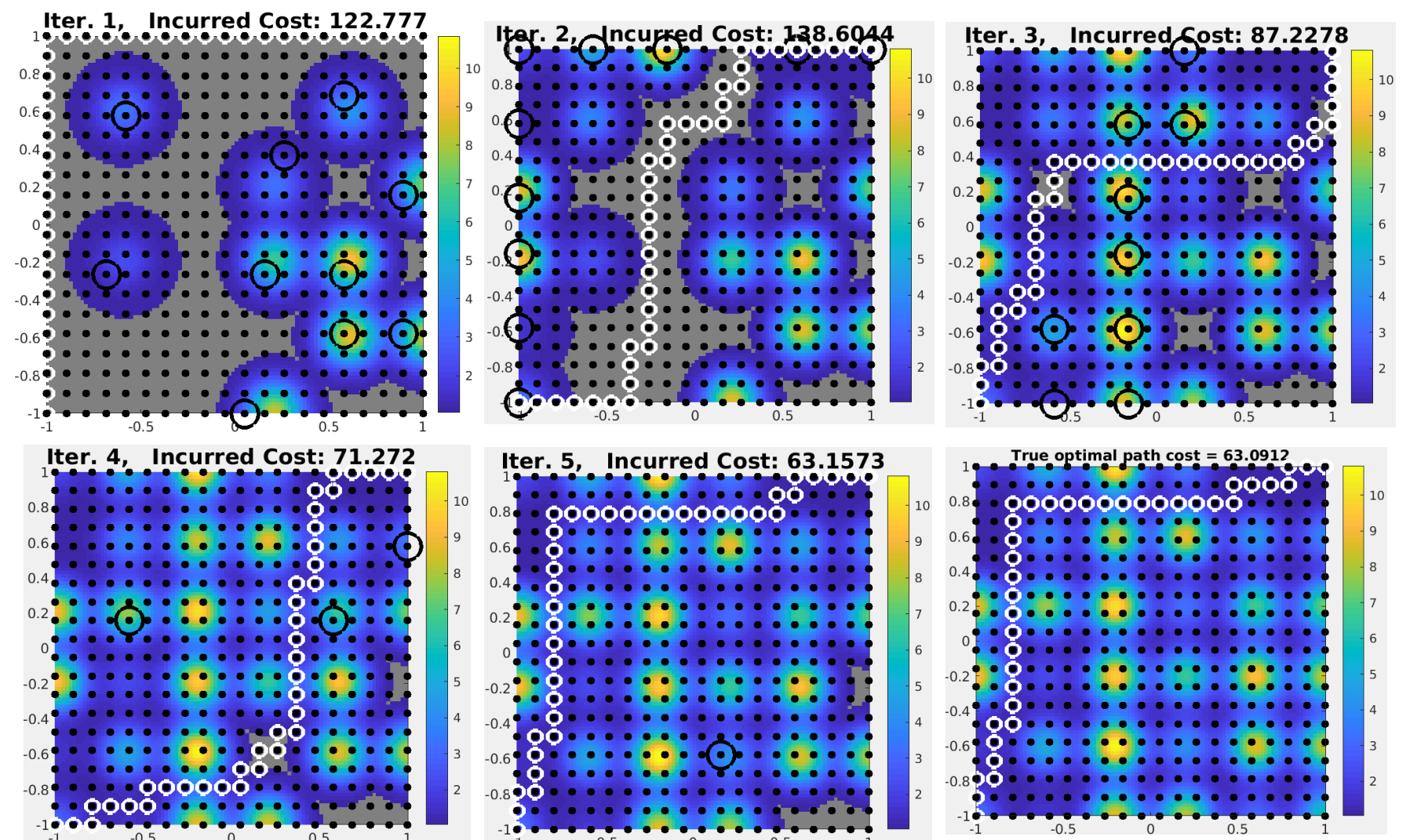
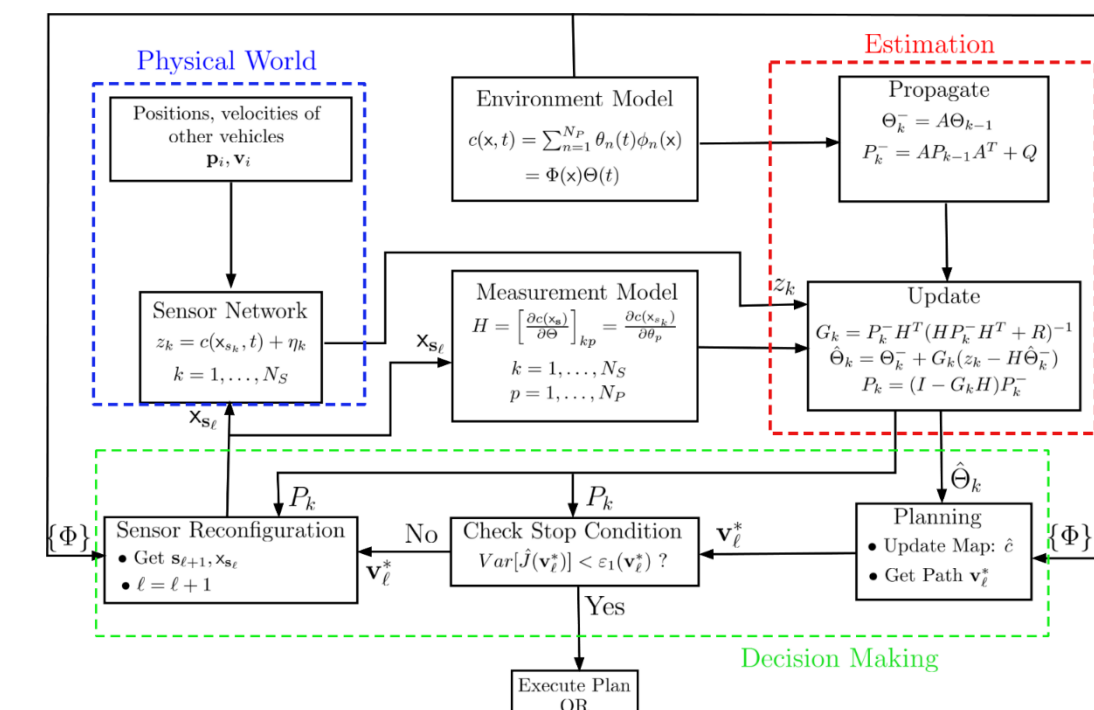


- Spectrum-sensing controller (SSC): coarse-resolution wideband frequency scanning.
- Adaptive multi-beam controller (AMBC): fine-resolution scanning in areas of interest; related to domains of interest identified by trajectory planner.
- Beamforming** will enable faster spectrum sensing and also spatial filtering to increase comms. capacity within the network.
  - Spatial filtering technique to reduce noise power and interference from other connections.

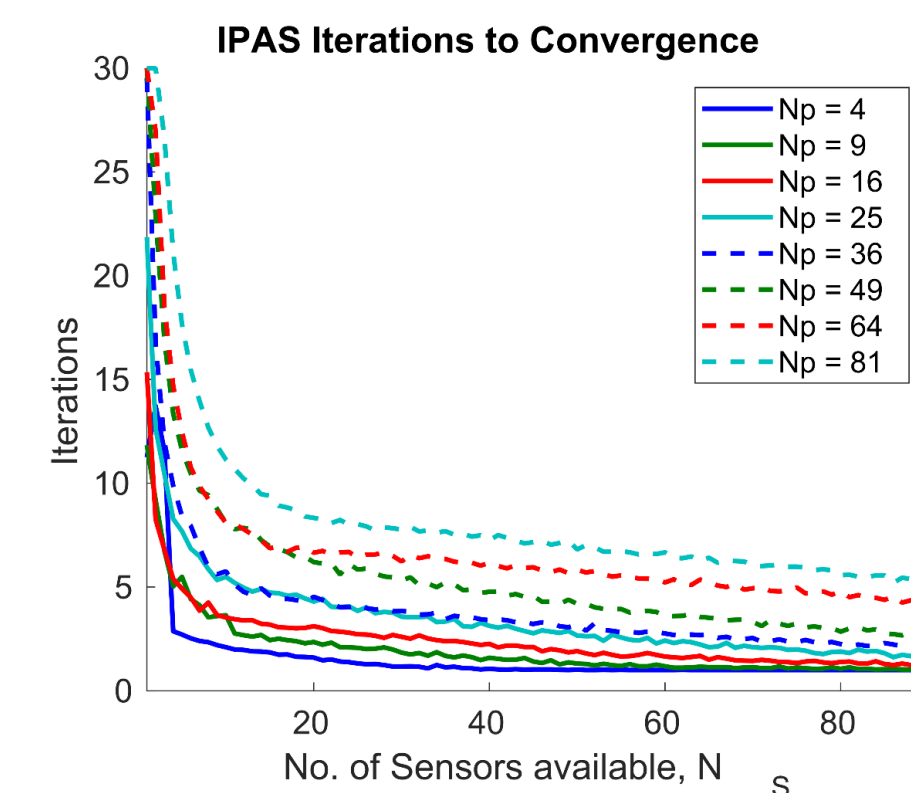


## Findings

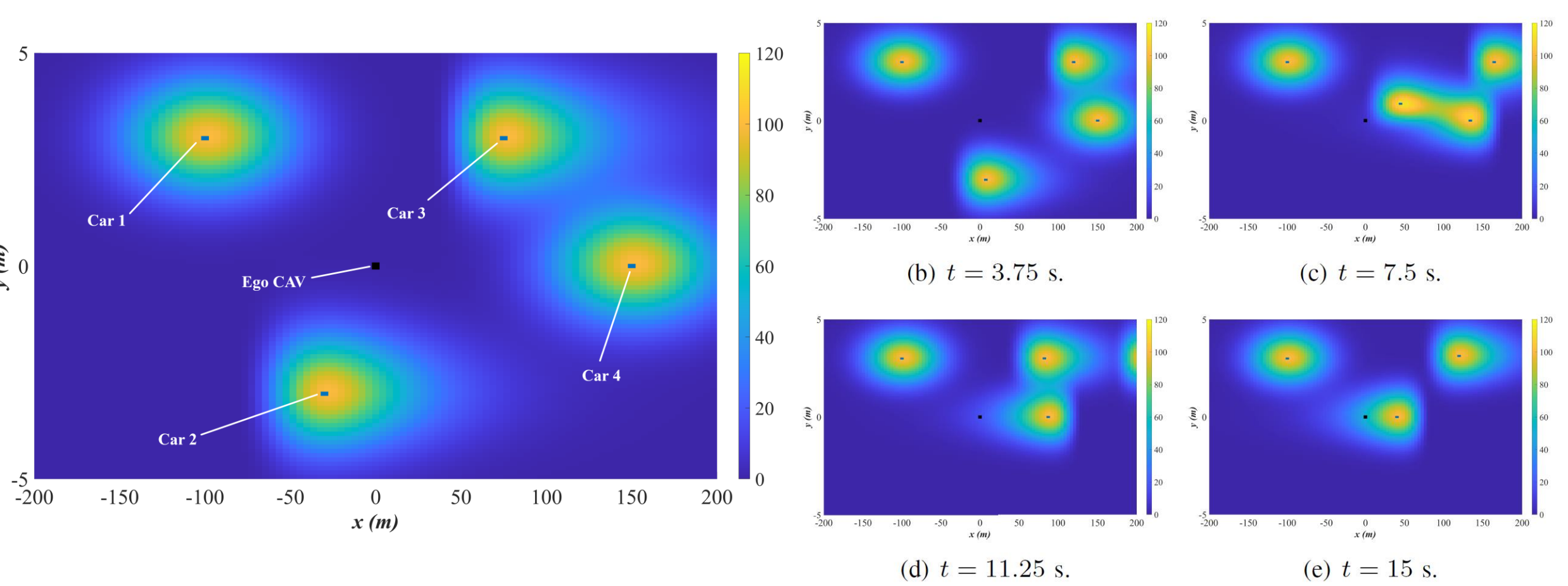
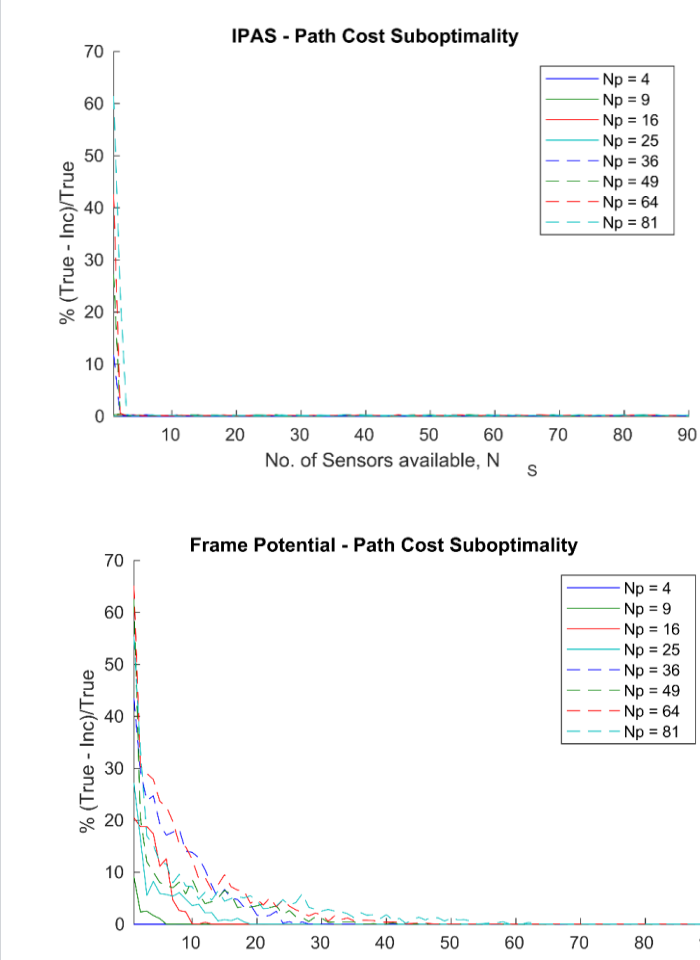
### Interactive path planning and sensor placement in an unknown spatiotemporal field



- Place sensors where most relevant to path planning; bootstrapping algorithm
- Stopping criterion: path cost variance reduces below specified threshold
- V2V links are “sensors”
- Proven to converge and obtain near-optimal solutions for path-planning
- Numerical simulation results below



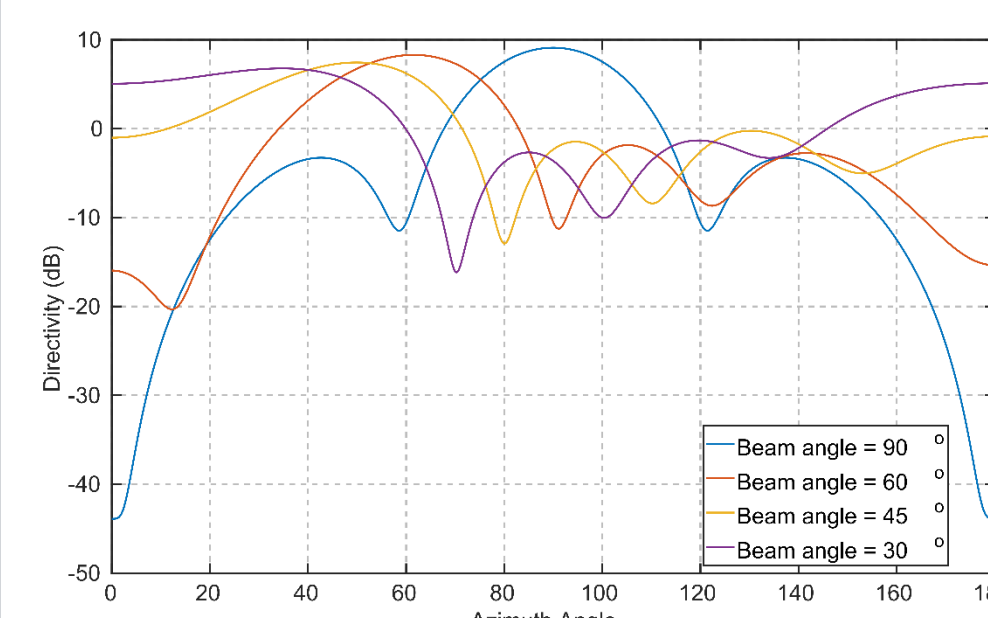
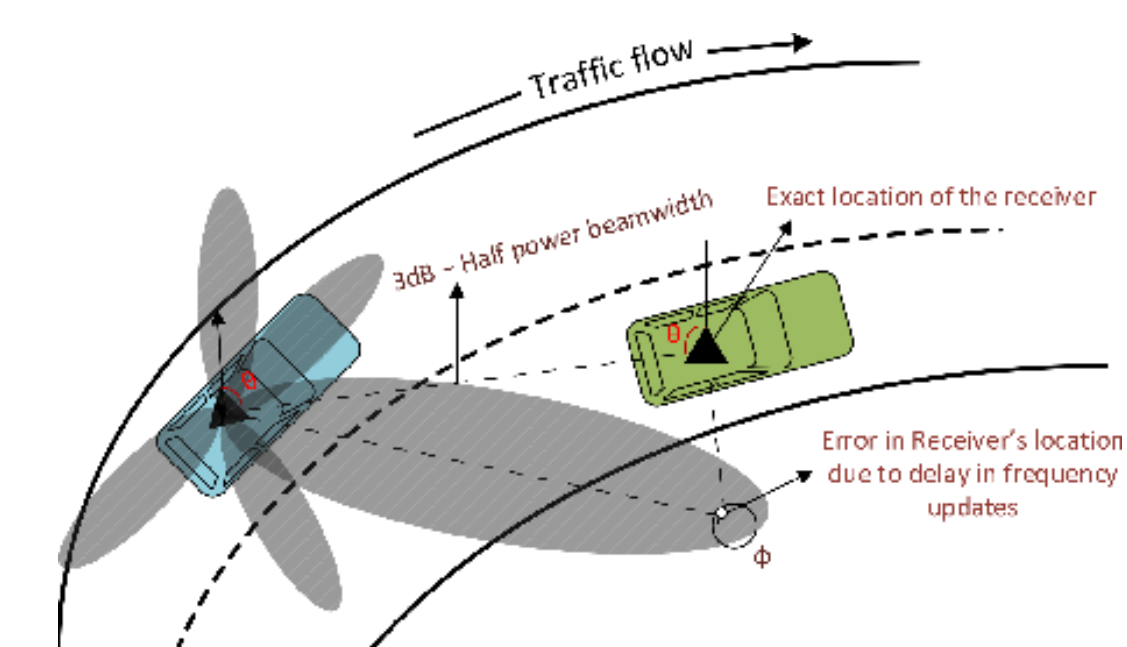
The proposed iterative sensor placement approach enables the path planner to find optimal solutions with fewer measurements



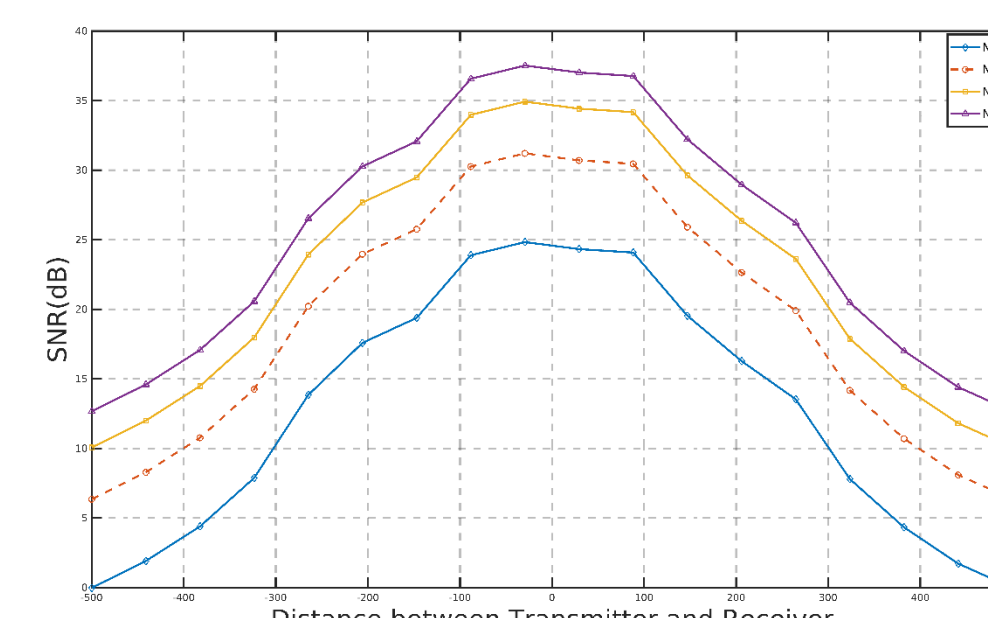
Snapshots of “threat” field in a traffic situation at different time instants

### Adaptive beamforming for V2V communications

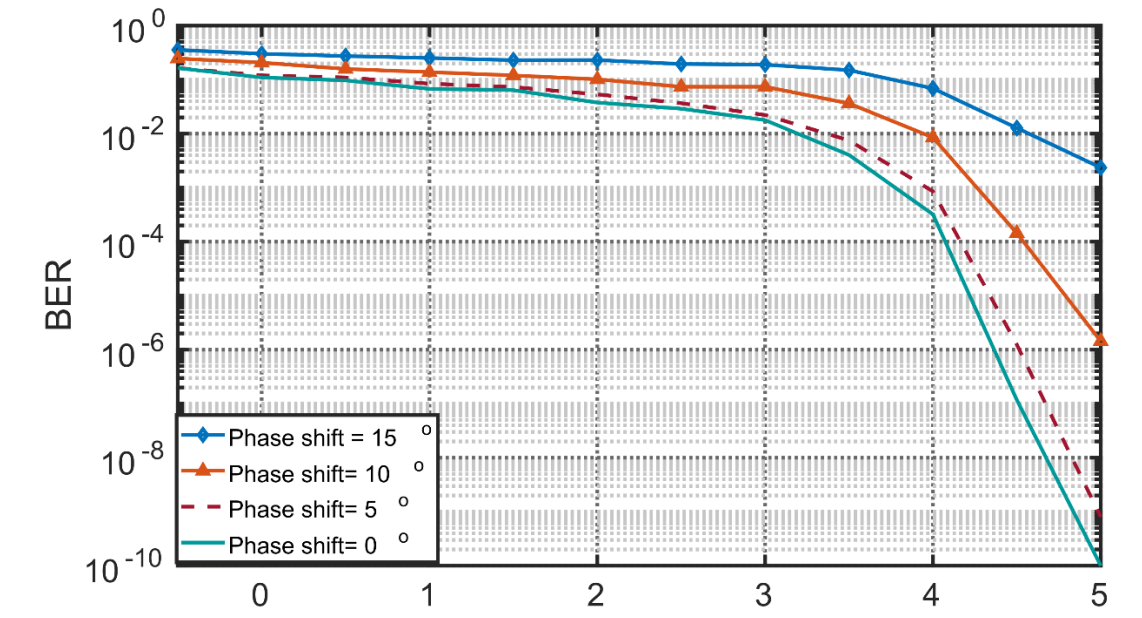
- Beamforming using phased-array antenna is a promising method to establish low-latency reliable V2V links in congested environments
- Localization errors can significantly affect link quality
- Coupled state-estimation (with measurements from an overhead channel) and beamforming can mitigate the impact of localization errors



Beam orientation for 4-element dipole antenna on a vehicular system when the beam angles

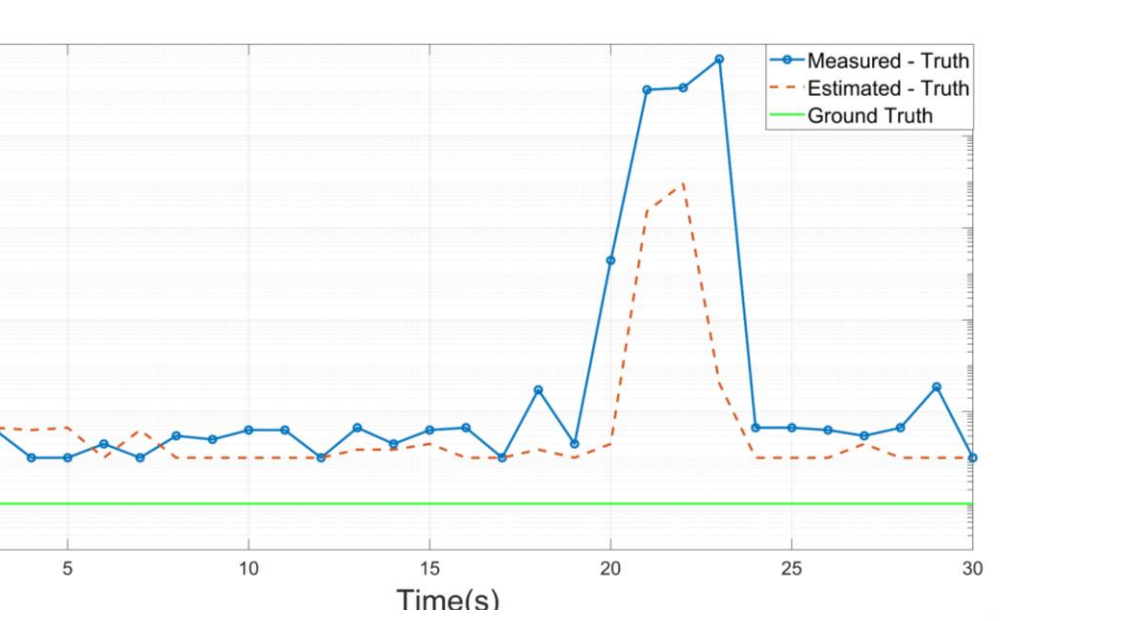
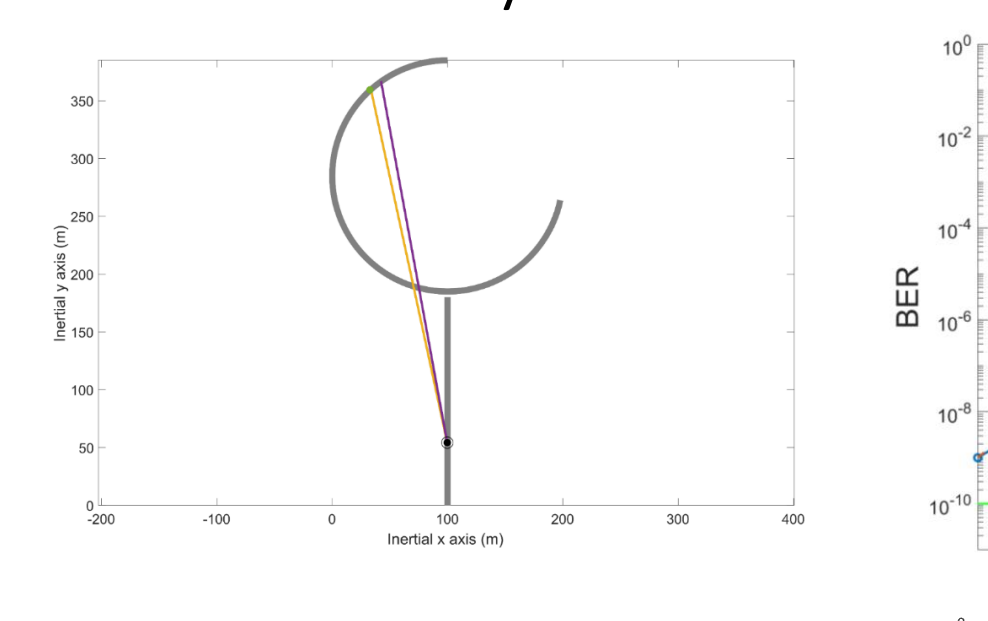


SNR change with respect to different distances between tx and rx with the number of array elements varied



BER change with increasing GPS errors in the receiver's location

- BER changes in a V2V link in typical traffic situations: (1) roundabout, and (2) intersection
- GPS localization errors can lead to high BER depending on road geometry (blue curves)
- State estimation can significantly mitigate this BER (red curves)



## Publications

- C. L. St. Laurent and R. V. Cowlagi, “Depth-first coupled sensor configuration and path-planning in unknown static environments,” in Proceedings of the 2021 European Control Conference, July 2021.
- R. V. Cowlagi, R. C. Debski, and A. M. Wyglinski, “Risk quantification for automated driving using information from V2V basic safety messages,” in 2021 IEEE 93rd Vehicular Technology Conference (VTC2021-Spring), 25–28 April 2021.
- N. Kanthasamy, A. M. Wyglinski, and R. V. Cowlagi, “Effects of interference on beamforming-enabled vehicular networks in multipath propagation environments,” in 2020 IEEE 91st Vehicular Technology Conference (VTC2020-Spring), Antwerp, Belgium, 25–28 May 2020.
- N. Kanthasamy, R. Du, K. S. Gill, A. M. Wyglinski, and R. V. Cowlagi, “Assessment of positioning errors on V2V networks employing dual beamforming,” in Proceedings of the 2018 IEEE 88th Vehicular Technology Conference: VTC2018-Fall, Chicago, IL, USA, 27–30 August 2018.
- N. Kanthasamy, R. V. Cowlagi, and A. M. Wyglinski, “State estimation for mitigating positioning errors in v2v networks employing dual beamforming,” in Proceedings of the IEEE Connected and Autonomous Vehicles Symposium 2018, Chicago, IL, USA, 27–30 August 2018.

