

# Advanced Vehicle Tracking at Uncontrolled Intersection: Integrated Sensing and Communication Strategy

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## Abstract

In modern urban environments, effective vehicle tracking at intersections is paramount for enhancing traffic flow, safety, and overall transportation efficiency. This study presents an approach to vehicle tracking at uncontrolled intersections, leveraging the Integrated Sensing and Communication (ISAC) environment. Building upon previous research in the field, this paper focuses on the integration of advanced sensing and communication strategy to accurately track vehicles and estimate their positions in real-time. Drawing inspiration from beam forming prediction techniques, we propose methodology tailored to the unique challenges posed by intersection environments. The approach combines data from diverse sensors and communication nodes to provide robust tracking capabilities, enabling precise localization and trajectory estimation of vehicles navigating complex junctions. Through scenario-based simulation, we demonstrate the effectiveness of the integrated approach, highlighting its potential to significantly improve intersection management and traffic coordination. This research contributes to the advancement of intelligent transportation systems, paving the way for safer and more efficient urban mobility solutions.

## I. Introduction

In urban transportation systems, intersections serve as critical nodes where the paths of multiple vehicles intersect, presenting unique challenges for traffic management and safety [1][2]. As vehicular traffic continues to grow in urban areas, effective monitoring and control of vehicles at intersections becomes increasingly essential to ensure smooth traffic flow, reduce congestion, and minimize the risk of accidents. Traditional intersection management approaches often rely on static traffic signals and basic vehicle detection systems, which may not fully address the complexities of dynamic traffic conditions and diverse vehicle behaviors [3].

Recent advancements in sensing and communication technologies, particularly Vehicle-to-Infrastructure (V2I) communication, have paved the way for sophisticated intersection management [4][5]. Integrated Sensing and Communication (ISAC) environments, enhanced by V2I, enable real-time monitoring and tracking of vehicles with high accuracy. By integrating sensors such as cameras, radar, LiDAR, and V2I communication, ISAC provides a comprehensive view of intersection dynamics, facilitating proactive traffic control and adaptive signal management [4]. This paper introduces advanced vehicle tracking techniques for uncontrolled intersections, which pose unique challenges due to complex vehicle trajectories. These intersections are typically located in residential neighborhoods or rural areas, where there are no traffic lights, road markings, or signs to indicate which vehicle has the right of way [5]. By leveraging ISAC environments and V2I communication, the proposed approach enhances

vehicle localization and trajectory estimation, improving intersection management and reducing collision risks.

In this paper, we present an approach to vehicle tracking at uncontrolled intersections, encompassing the design and implementation of innovative tracking algorithms and scenario-based simulation. Drawing upon insights from previous research, we propose methodology for vehicle localization, and trajectory estimation, tailored to the unique characteristics of uncontrolled intersection environments. From results, we demonstrate the effectiveness and scalability of the proposed approach, highlighting its potential to significantly enhance intersection management and improve urban mobility.

## II. Method

Using the driving scenario runner in MATLAB, we set up the simulation environment. There are  $m$  number of vehicles. From [4], the likelihood of collisions rises significantly when both vehicles are at same distances from the intersection center and have not started to take any action. The ISAC system uses the optimal waveform from [6]. With  $m$  number of vehicles and  $k$  number of communication users, we focus on the sensing part of the ISAC base station (BS). The typical scenario of the ISAC system is shown in Figure 1. The workflow is presented as follows (see Figure 2 for easy understanding).

A.) Sensing: The optimized waveform in the ISAC combines the radar waveform and complex signals from modulated communication symbols.

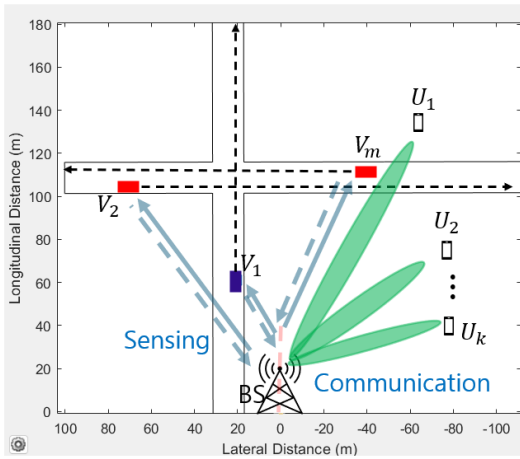


Figure 1. ISAC system with radar beam capturing vehicles at uncontrolled intersection.

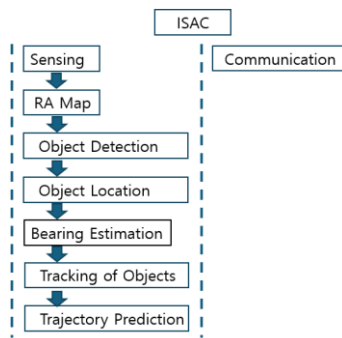


Figure 2. Steps for tracking vehicles and trajectory prediction.

B.) RA Map: Creating a Range-Azimuth (RA) map involves processing 3D radar data cube to present a detailed representation of the surroundings, essential for subsequent analysis and decision-making.

C.) Object Detection: From the RA map, clusters of points above a certain power threshold are determined and used to distinguish between different entities such as vehicles, pedestrians, obstacles, or noise.

D.) Object Location: The precise position of detected vehicles relative to the BS is crucial for accurate tracking and navigation, often achieved through methods such as sensor triangulation or geometric calculations.

E.) Bearing Estimation: The direction from which detected vehicles are approaching or moving relative to one another provides crucial spatial awareness for the navigation of vehicles. The relative bearing angles from other vehicles to each vehicle are estimated, taking advantage of the fixed location of the intersection and BS.

F.) Tracking of Objects: The vehicles' positions and speed are continuously monitored and updated. This enables the dynamic assessment and

prediction of their trajectories, facilitating proactive decision-making and response strategies.

G.) Trajectory Prediction: By analyzing historical data and current object dynamics, this stage forecasts the future paths and behaviors of tracked objects, aiding in risk assessment, collision avoidance, or strategic planning in dynamic environments.

### III. Result

For the demonstration, we considered a scenario of two vehicles, V1 and V2, moving to an uncontrolled intersection (see Figure 1). BS is located at spot (0,0). The carrier frequency of the ISAC is 6 GHz, and peak power is 500kW. The number of configured antenna elements is 16. The pulse duration is  $3.5e-08$  s, and the pulse repetition frequency is 15 kHz. The transmitted waveform from the BS containing the radar beam and modulated communication signal is shown in Figure 3.

The RA map of the received data cube is presented in Figure 4. The false detections from 150 m above are results of the trade-off in the waveform design. The range profile for the scenario indicates detected vehicles at the range of 67 and 121 m, shown in Figure 5. The angles of the detected vehicles with reference to the BS are computed using multiple signal classification (MUSIC) [7]. The locations of the vehicles in the Cartesian coordinate are derived from the range and azimuth. Subsequently, the bearing angles are determined from the vehicles' locations.

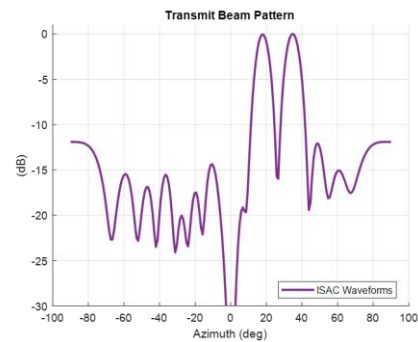


Figure 3. Transmit waveform [6].

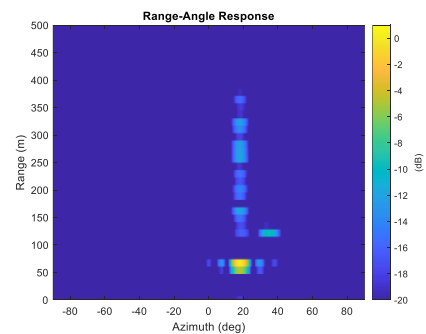


Figure 4. RA map from received signal.

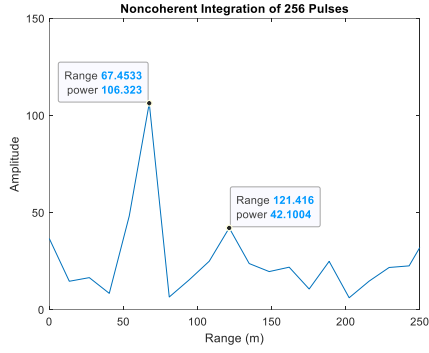


Figure 5. Range profile from received signal.

The bearing angle information provides the direction of vehicles approaching intersection with reference to others. Since the BS and the intersection are fixed, when there is a missing detection (false negative), the last known bearing indication can be used in the tracking and prediction algorithm. In Figure 6, the tracking result is illustrated. The method that combines the bearing estimation and particle filter is close to the actual trajectories of the two vehicles 1 and 2. Thus, the ISAC-based approach improved the tracking of the vehicles. The average tracking error of methods is reported in Table 1.

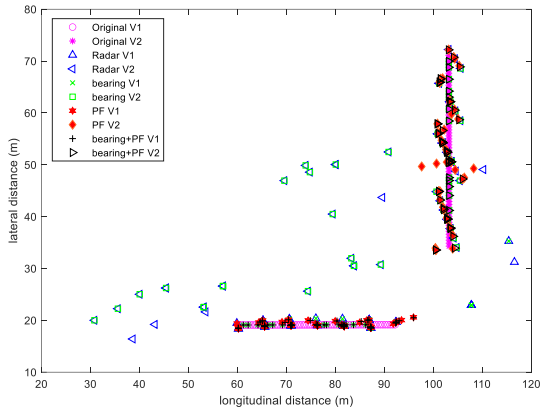


Figure 6. Range profile from received signal.

Table 1. Average Tracking Error

Average Error [m]	Vehicle 1	Vehicle 2
Radar Meas.	2.45	12.18
Bearing Est.	1.83	8.88
Particle Filter [8]	0.79	1.11
Bearing Est. + Particle Filter	<b>0.65</b>	<b>0.78</b>

#### IV. Conclusion

This paper shows the effectiveness of ISAC for dynamic vehicle tracking at uncontrolled intersection. By leveraging ISAC and advancing tracking algorithms, we significantly improved intersection management

and traffic coordination. Simulation validated the robustness and scalability of the proposed approach for such intersection.

Additionally, this study opens new avenues for intelligent transportation systems. Though focused on uncontrolled intersection, the methodology is applicable to various intersection configurations and scenarios. Future research could extend the ISAC-based approach to multi-modal transportation networks and integrate real-time traffic data analytics for adaptive control strategies.

#### ACKNOWLEDGMENT

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#### References

- [1] Zhao Z., Luliang T., Xue Y., Huazu Z., Guangyue L., and Qingquan L. "Identifying critical urban intersections from a fine-grained spatio-temporal perspective." *Travel Behaviour and Society* 34 (2024): 100649.
- [2] Mohammad S. S., and Brendan T. M. "Looking at intersections: a survey of intersection monitoring, behavior and safety analysis of recent studies." *IEEE Transactions on Intelligent Transportation Systems* 18, no. 1 (2016): 4-24.
- [3] Dresner, K., & Stone, P. (2006, July). Traffic intersections of the future. In *AAAI* (Vol. 6, pp. 1593-1596).
- [4] Huang Y., Yun W., Xuedong Y., Xiaomeng L., Ke D., and Qingwan X. "Using a V2V-and V2I-based collision warning system to improve vehicle interaction at unsignalized intersections." *Journal of safety research* 83 (2022): 282-293.
- [5] Butakov V. A., and Petros I. "Personalized driver assistance for signalized intersections using V2I communication." *IEEE Transactions on Intelligent Transportation Systems* 17, no. 7 (2016): 1910-1919.
- [6] Liu F., Longfei Z., Christos M., Ang L., Wu L., and Athina P. "Toward dual-functional radar-communication systems: Optimal waveform design." *IEEE Transactions on Signal Processing* 66, no. 16 (2018): 4264-4279.
- [7] Schmidt R., "Multiple emitter location and signal parameter estimation." *IEEE transactions on antennas and propagation* 34, no. 3 (1986): 276-280.
- [8] Li T., Miodrag B., and Petar M. D. "Resampling methods for particle filtering: classification, implementation, and strategies." *IEEE Signal processing magazine* 32, no. 3 (2015): 70-86.