Software-Defined Radar Testbed for Multi-Target Tracking

Abhishek Adhikari*, Sameer Parihar*, Sujoy Das*, Marko Jacovic*, Anthony Trezza†, Vasil Pano*, and Kapil R. Dandekar*

*Electrical and Computer Engineering, Drexel University, 3141 Chestnut Street, Philadelphia, PA, 19104, USA
{aa4338, sp3323, sd989, mj355, vp93, krd26}@drexel.edu
†Advanced Technologies Lab, Lockheed Martin Corporation, Cherry Hill, NJ, 08002, USA
anthony.t.trezza@lmco.com

***Abstract*—Modern-day radar is used extensively in applications such as autonomous driving, robotics, air traffic control, and maritime operations. The commonality between the aforementioned examples is the underlying tracking filter used to process ambiguous detections and track multiple targets. In this paper, we present a Software-Defined Radio-based radar testbed that leverages controllable and repeatable large-scale wireless channel emulation to evaluate diverse radar applications experimentally without the complexity and expense of field testing. Through over-the-air (OTA) and emulated evaluation, we demonstrate the capabilities of this testbed to perform multiple-target tracking (MTT) via Joint Probabilistic Data Association (JPDA) filtering. This testbed features the use of flexible sub-6 GHz or mmWave operation, electromagnetic ray tracing for site-specific emulation, and software reconfigurable radar waveforms and processing. Although the testbed is designed generalizable, for this paper we demonstrate its capabilities using an advanced driver-assistance system radar application.**

***Index Terms*—software-defined radio, radar, multi-target tracking**

I. Introduction

Radar plays an important role in the automotive industry, particularly to detect vehicles and pedestrians through difficult weather conditions. This capability has become especially useful due to the sensor fusion integration that takes place in intelligent vehicles by using radar, camera, and LiDAR [1]. Automotive radar provides short-range (0.2-30 m) detections for blind-spot monitoring and collision avoidance as well as long-range (30-80 m) detections for adaptive cruise control [2].

By modifying the signal bandwidth, operating center frequency, and waveform, automotive radars can be built and purchased in several different configurations to optimize for the particular use case. One of the most widely adopted radar test systems includes the suite of Texas Instruments mmWave radar sensors, offering 15 different industrial and automotive configurations [3]. These options simplify the process for a user to purchase a board, run experiments, collect data, and evaluate additional pipelines (such as computer vision or machine learning) for their specific type of application. However, these systems generally use fixed radio frequency (RF) waveforms, are limited to a small range of center frequencies, and may be costly to evaluate in the field with repeatable and reproducible testing environments [4]. Software-Defined Radio (SDR) provides a flexible general-purpose hardware platform and open-source software infrastructure to develop and evaluate new radar techniques. Integrating SDR-based radar systems with large-scale wireless channel emulation enables customizable and repeatable evaluation of scenarios that would be impractical or expensive to evaluate in the field. For a radar application, these scenarios may include urban intersections, rural roads, underground tunnels, bridges, etc.

Commercial radar sensors are commonly coupled with tracking systems. The role of a tracking system is to jointly estimate the number of targets in the scene and their trajectories, given noisy measurements from one or more sensors. Tracking systems play a crucial role in many radar applications including air traffic control, surveillance, defense, and automotive radar. Common multiple-target tracking (MTT) approaches include: *i.)* Joint Probabilistic Data Association (JPDA), *ii.)* Multiple Hypothesis Tracking (MHT), and *iii.)* filters based on Random Finite Sets [5].

The key contribution of this paper is to demonstrate how the Drexel Grid SDR testbed [6] can be used to evaluate both over-the-air (OTA) and emulated experiments using MTT filters for radar. SDR testbeds have been widely popular in traditional wireless communications research (e.g.,[7]), but have thus far seen limited application in the area of end-to-end radar system experimentation for MTT applications. We show how our SDR testbed can offer the ability to develop new, innovative tracking filters using both OTA and emulated radar tracking data. This capability allows for full customization of the radar waveform, emulated operating environment, and tracking filter.

II. Related Work

Current SDR implementations of radar systems are limited in multi-target tracking experimentation. For example, [8, 9, 10] have considered SDR-based radar with a multiple input, multiple output (MIMO) configuration and testbed architecture. However, the tracking component of the radar

This research is supported by the National Science Foundation under Grant CNS-1730140 and CNS-1828236. Any opinion, findings, and conclusion or recommendations expressed in this materials are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

is limited to single-target tracking Kalman filters. A similar configuration of SDR radar is proposed in [11], but it does not consider radar target tracking. While multi-target detections are collected in [12], the focus of it is on passive coherent location instead of active radar. While [13] uses an active radar with JPDA, this implementation uses a fixed-hardware radar (XeThru X4M03) that does not provide the level of hardware generalization that is contributed in this paper through the use of our SDR testbed.

Options have emerged for radar target simulators (e.g. [14, 15]), including hardware-in-the-loop implementations. These simulators allow users to specify multiple targets (vehicles, pedestrians, etc.) and use the simulator's built-in RF front end to send wireless signals representing the RF characteristics of the simulated targets. Implementations of this technology are shown in [16, 17]. While this work has shown results for radar in advanced driver-assistance systems, there are strict limitations on the amount of RF customization possible. By using SDR instead of the RF components used in the above-mentioned simulators, users have access to customize all three pillars of the full automotive radar process: radar waveform properties, tracking filter development, as well as customizable and reproducible site-specific environment modeling and channel emulation.

III. Background

A. Software-Defined Radio as Radar

Software-Defined Radios (SDRs) are radio frequency devices in which many of the physical layer functions are defined and controlled by software. Traditional radios require mixers, filters, oscillators, and other components to be implemented using application-specific hardware. In the scope of radar systems, these components are used for defining modulation and center frequency of the system. Modulation type and center frequencies are changed based on the application of the radar [18]. When designing a testbed architecture for rapid prototyping, it is highly beneficial to have the ability to rapidly change the radio parameters to best fit the use case.

GNU Radio is the software backbone of the system that collects data from many SDRs and processes the acquired signals [19]. It provides an easy-to-use interface with high levels of customization and the ability to integrate external software libraries with ease. The gr-radar library provides the capability to perform radar operations on SDR. Simulations for various waveforms and signal generator modulation are performed through gr-radar [20]. These simulations provide range and velocity data sets which may then be parsed and analyzed by various tracking filters.

The gr-radar library consists of multiple options for signal generated waveforms that can provide range and velocity estimation. Dual Frequency Continuous Waveform (DFCW) has been tested through the simulation and hardware experimentation.

B. Multi-Target Tracking

Multi-target tracking algorithms ingest noisy, cluttered and unlabeled measurements from one or more sensors to estimate the number of targets in the scene and their trajectories. We use the Joint Probabilistic Data Association (JPDA) algorithm to demonstrate the benefits of our SDR testbed. The JPDA algorithm is a multi-target extension of the Probabilistic Data Association (PDA) filter that assumes a known number of targets are being observed by noisy measurements with clutter. Target statistics are typically modeled as Gaussian and propagated using the Kalman filter recursion. Unlike many multi-target tracking algorithms that must solve the computationally burdensome data association problem to associate each measurement to an established track or clutter at each time step, the JPDA computes the joint probabilities of all feasible associations and updates the posterior by marginalizing over the joint probabilities per target [5]. Because it avoids the data association problem, it is often favorable for many real-time applications such as radar applications.

C. Channel Emulation

Wireless channel emulation provides environmental realism that enables the testing of dynamic environments, which would otherwise be difficult to demonstrate due to concerns about signal interference and potential for damage [21]. Such a system is able to prototype and evaluate a diverse range of wireless systems using: *i.)* field measurements to evaluate real time transceiver and channel-specific effects and *ii.)* network emulation to evaluate systems at a large scale with controllable and repeatable propagation channels.

IV. Testbed Architecture

A. Over-The-Air Radar

An X310 SDR from Ettus Research configured with a UBX 160 daughterboard was used along with two ETS-Lindgren 3117 Horn antennas. The highest center frequency available on the UBX 160 daughterboard of 5.9 GHz was chosen in order to limit the amount of interference caused by the electronic equipment located in the lab area. An Octoclock Distribution Module was integrated with the system to provide a common reference and synchronization for the radio transceivers, enabling scalability for future work.

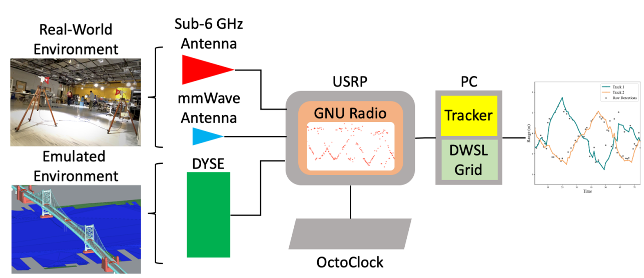

Fig. 1: Overview of Testbed Architecture

(a) Sub-6 GHz SDR Radar for MTT with Two Copper Plates

(b) 28 GHz mmWave SDR Radar Using a Spacek Transceiver

Fig. 2: Various SDR Radar Configurations

B. Spacek mmWave Transceiver

The X310 SDR daughterboards offer an operational frequency range of $10\,\mathrm{MHz}$ to $6\,\mathrm{GHz}$ [22]. To introduce greater flexibility to our SDR testbed, a TRKa-10 Spacek mmWave transceiver is used to translate the sub-$6\,\mathrm{GHz}$ frequency emitted and received from the SDR to a $28\,\mathrm{GHz}$ mmWave frequency, which is within the common operational frequency range for automotive radar sensors. The Spacek transceiver utilizes two separate channels for transmitting and receiving a signal. Both channels share a common phase-locked local oscillator (LO) that allows the up and down conversion of the transmitted and received signal [23]. In the up-conversion process, an intermediate frequency (IF) of $5.4\,\mathrm{GHz}$ is emitted from the X310 SDR and mixes with the signal generated from the LO [23]. This mixed signal is then fed into a bandpass filter to generate the transmitted $28\,\mathrm{GHz}$ RF output. Once a signal is received, the down-converting mixer is then able to convert the mmWave signal into the $5.4\,\mathrm{GHz}$ RF input for the SDR.

C. Ray Tracing and Channel Emulation

Electromagnetic ray tracing provides a wireless channel model of signals sent through site-specific user-defined environments. We used Wireless InSite [24], developed by Remcom, in this project. It allows users to create various 3D structures with specified material, antenna type, view propagation paths, and most importantly generates sets of channel impulse responses (CIR) between transceiver points. The CIR is then ported into an emulation system so that hardware may be used in the loop.

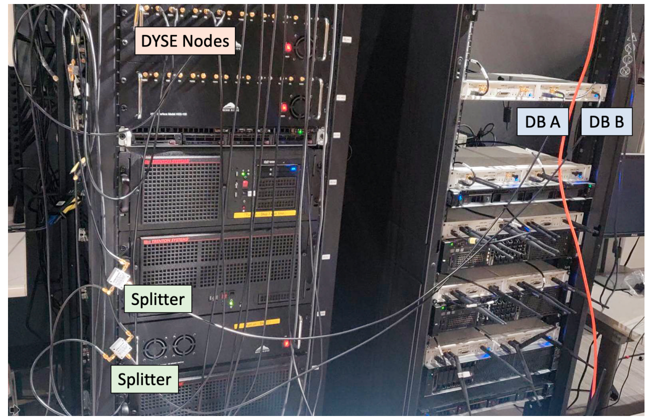

Fig. 3: DYSE Configuration

The Echo Ridge DYnamic Spectrum Environment Emulator (DYSE) is a 24-port network channel emulator that provides the capability for our SDR testbed to read the CIR data generated from Wireless InSite and test the channel on SDR. This provides the ability to swap between a variety of complex radar use-cases and test these scenarios rapidly.

In order to capture radar detections, the SDR would transmit a signal to the DYSE for processing, and the output from the DYSE would represent the received signal within the emulated environment. The gr-radar library in GNU Radio was used to calculate range and velocity values, which were saved for post-processing using an MTT filter.

V. Experiments Enabled by the Testbed

A. SDR Multi-Target Tracking

The DFCW modulation method was used to collect radar detection data. While more modern modulation methods such as the Frequency Modulated Continuous Waveform (FMCW) are more commonly used in practice, DFCW offers simplicity in its integration with additional radar system components. Preliminary results using DFCW indicate greater potential when using more advanced waveforms in future research.

The OTA SDR MTT experiment was conducted within the Drexel Wireless Systems Lab (DWSL) area. While obstructions were cleared during tests, several pieces of electronic equipment remained in the vicinity of the radar that could be causes of concern for interference. In order to improve the Radar Cross Section (RCS) of the moving targets, two copper plates were held by two individuals moving in the area.

The individuals with copper plates moved toward and away from the radar antennas, while starting at opposite ends of the experiment trajectory. These individuals were separated approximately 1.5 m apart from one another throughout the duration of the experiment. Various parameters from the MTT experimental setup can be seen in Table I.

TABLE I: MTT Radar - Experimental Parameters

Parameter	**Value**
Antenna Type	Horn
Center Frequency	5.9 GHz
Bandwidth	150 MHz
Waveform Type	Dual Frequency CW
Resolvable Range	1 to 10 m
Target Object Material	Copper

B. mmWave SDR Multi-Target Tracking

An experiment similar to Section V-A was performed to showcase the mmWave MTT capability. The RF front-end was replaced with the Spacek mmWave transceiver described in Section IV-B, and the copper plates were no longer needed due to the smaller beamwidth of the 28 GHz horn antennas used.

C. DYSE Multi-Target Tracking

Similar to the SDR MTT experiment, Wireless InSite was used to model two objects moving in opposite directions toward and away from a radar. This was done in an open room within the Wireless InSite simulation, with the goal of obtaining detections that resembled the in-lab tests.

A more complex example was then tested where a vehicular radar was placed in the center of a 3-D modeled Ben Franklin Bridge located in Philadelphia, PA. This radar would capture the trajectory of one object moving away from it and the other object moving towards.

Once these detections were collected, they were run through post processing and a JPDA filter to showcase the capability of this emulation system to prototype and test new MTT filters.

VI. Results

A. Over-The-Air MTT Radar

The JPDA filter successfully performed MTT on the two moving pedestrians in a lab environment at sub-6 GHz and mmWave, shown in Figure 4 and Figure 5, respectively. JPDA performed especially well during intersections, where each trajectory correctly retained its track assignment as opposed to diverging or switching into the wrong track. The data also accurately resembled the real-world distances measured in the lab area. Each pedestrian walked between 0 and 7 meters from the radar location, which can be observed in the results as well. Finally, detections produced by the mmWave radar contained less clutter and higher resolution. This is expected, as the smaller beamwidth of the mmWave horn antenna allowed the transmitted signal to reflect from less of the metallic equipment in the lab. The small wavelength of the signal itself allowed for smaller phase shifts in the received signal to be accounted for in the calculated range value of the radar detection.

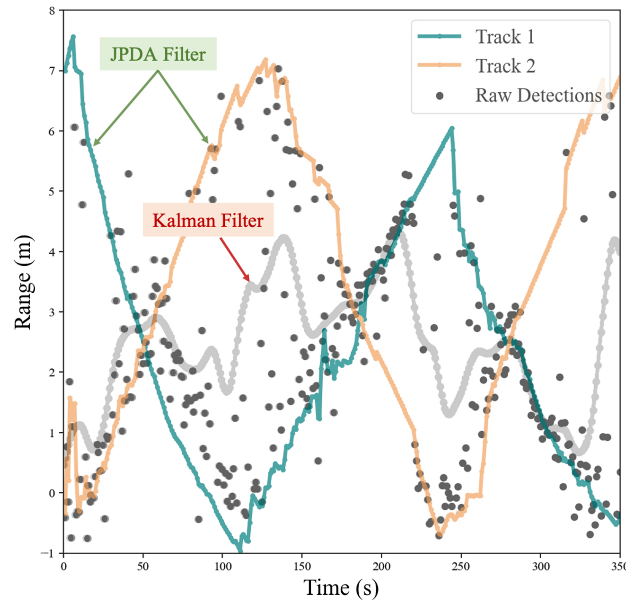

Fig. 4: JPDA Filter for MTT with Sub-6 GHz SDR Radar

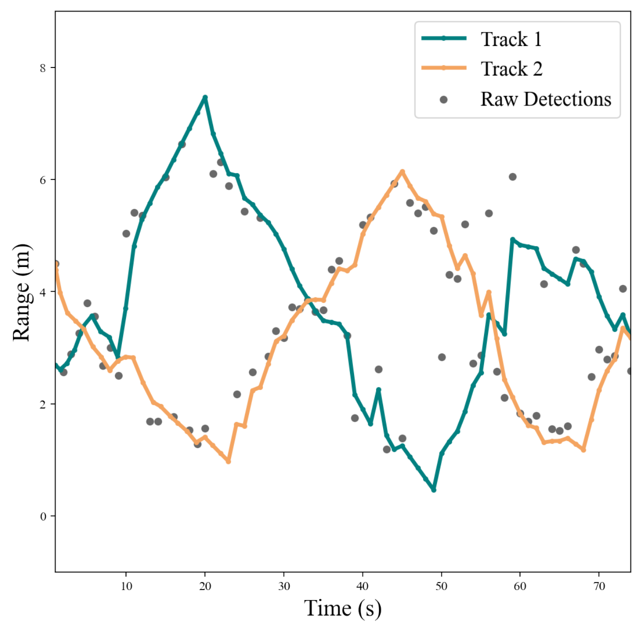

Fig. 5: JPDA Filter for MTT with mmWave SDR Radar

B. Channel Emulated Radar

In order to create channel emulated radar data, a baseline was needed to understand how the solution should look visually. Without knowing in advance as to what channel emulated radar detections would look like, we turned to the OTA experiments for ideas. As shown in OTA testing for MTT from Figure 4, an identifiable feature is the intersection of two trajectories. Successful JPDA filtering is able to track both trajectories, without its created tracks diverging upon the intersection. We carried this concept to channel emulation,

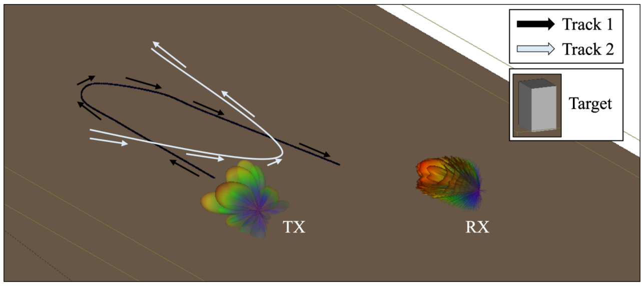

Fig. 6: Baseline Channel Emulation Scenario

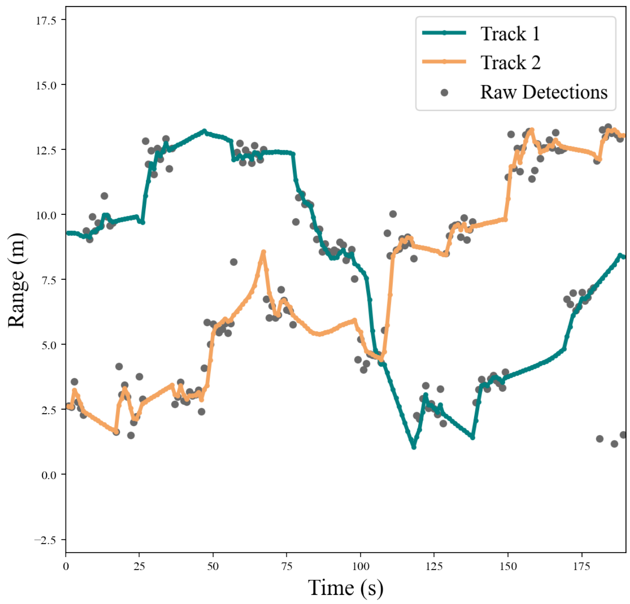

Fig. 7: MTT on Baseline Channel Emulation

where we show how a user-defined environment can represent the movement of two objects similar to the pedestrians in the lab. This can be seen in Figure 6. The resulting detections represented the intersection of two trajectories when viewed in a Range vs. Time plot. These detections were successfully tracked through a JPDA filter, shown in Figure 7. It can be observed that the tracks are very smooth, which is the result of this being an ideal radar environment with limited interference from external features.

The next step was to test a complex example that would be infeasible to test in the lab. The experiment began as a scenario file shown in Figure 8. When exposed to one moving target, the radar's time-varying channel was reversed, copied, and combined into one signal, which represents two vehicles moving in opposite directions on a bridge. This pattern was repeated for several iterations in a cyclical manner. This experiment does not currently consider the accuracy of the range values collected or the precise radar cross-section of a vehicle. Rather, the purpose of this experiment is to simply expand upon the track intersection concept shown OTA in Figure 4 and through emulation in Figure 7 by performing MTT in a real-world scenario completely defined through channel emulation. The

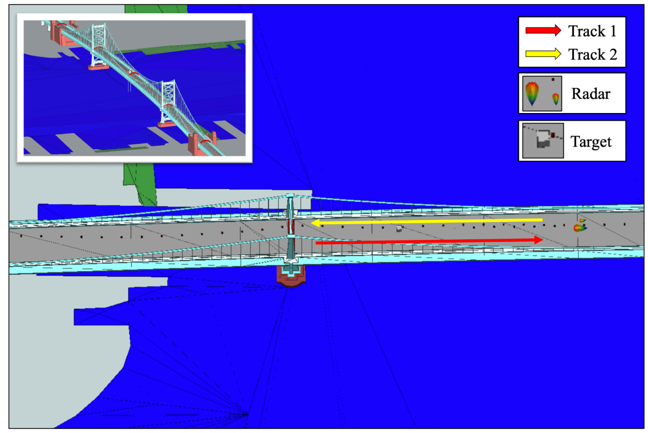

Fig. 8: MTT on Ben Franklin Bridge Through Emulation

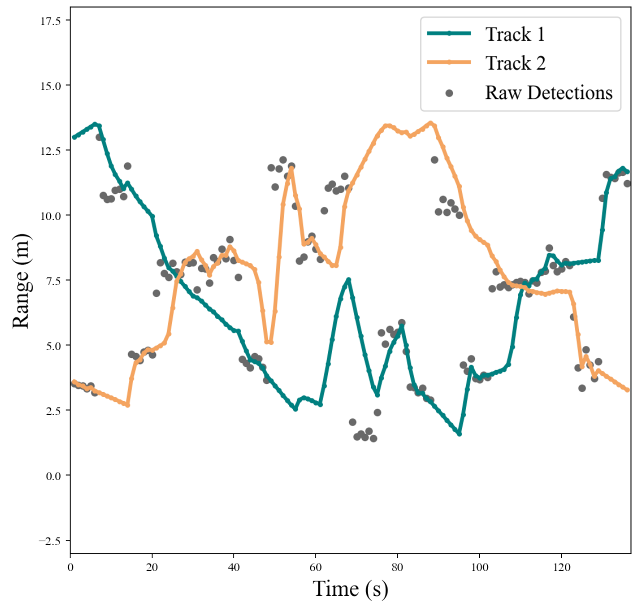

Fig. 9: Processing Detections Through JPDAF

raw detections were processed via the JPDA filter, shown in Figure 9. As expected, the tracker's output is not as smooth as the baseline test shown in Figure 7. Interference from several components of the user-defined bridge makes the collected radar measurements more difficult for the JPDA filter to track. This is good, as channel emulation is meant to make the MTT process more challenging compared to a simpler in-lab test. By customizing the emulation environment via our SDR testbed, researchers have the capability to rapidly prototype and add robustness to the tracking filters they develop. When used for MTT, the JPDA filter's capability can still identify the intersections of the resulting Range vs. Time plot and retain the track identities without divergence. These results demonstrate how our SDR testbed, validated in indoor measurements, can be applied to evaluate MTT in scenarios that would be difficult to test in the field.

VII. Conclusions

In this paper, we demonstrated how our SDR testbed [6] can evaluate both over-the-air (OTA) and emulated experiments using MTT filters for radar. By using SDR instead of fixed-hardware RF components used in existing simulators, users have access to customizing all three pillars of the full automotive radar process: radar waveform properties, tracking filter development, as well as customizable and reproducible site-specific environment modeling and channel emulation. Future work will leverage large-scale wireless channel emulation to evaluate additional automotive radar environments using various waveforms at higher center frequencies as well as provide real-time functionality for the tracking filter placed under test.

Acknowledgment

We thank Oday Bshara for his support with the mmWave transceiver, Brandon Katz for his radar system insights, and Hahn Kim for his feedback during this paper's review process.

References

[1] P. Y. Shinzato, D. F. Wolf, and C. Stiller, "Road terrain detection: Avoiding common obstacle detection assumptions using sensor fusion," in *2014 IEEE Intelligent Vehicles Symposium Proceedings*, pp. 687–692, 2014.

[2] V. K. Kukkala, J. Tunnell, S. Pasricha, and T. Bradley, "Advanced driver-assistance systems: A path toward autonomous vehicles," *IEEE Consumer Electronics Magazine*, vol. 7, no. 5, pp. 18–25, 2018.

[3] "Texas Instruments Millimeter Wave (mmWave) radar sensors." https://www.ti.com/sensors/mmwave-radar/overview.

[4] M. S. L., "Repeatability, reproducibility, and replicability: Tackling the 3R challenge in biointerface science and engineering," *Biointerphases*, vol. 14, no. 2, 2019.

[5] B.-n. Vo, M. Mallick, Y. Bar-shalom, S. Coraluppi, R. Osborne III, R. Mahler, and B.-t. Vo, *Multitarget Tracking*, pp. 1–15. American Cancer Society, 2015.

[6] K. R. Dandekar, S. Begashaw, M. Jacovic, A. Lackpour, I. Rasheed, X. R. Rey, C. Sahin, S. Shaher, and G. Mainland, "Grid software defined radio network testbed for hybrid measurement and emulation," in *2019 16th Annual IEEE International Conference on Sensing, Communication, and Networking (SECON)*, pp. 1–9, 2019.

[7] R. Doost-Mohammady, O. Bejarano, and A. Sabharwal, "Good times for wireless research," in *Proceedings of the 14th International Workshop on Wireless Network Testbeds, Experimental Evaluation & Characterization*, WiNTECH'20, (New York, NY, USA), p. 33–39, Association for Computing Machinery, 2020.

[8] K. L. Bell, J. T. Johnson, G. E. Smith, C. J. Baker, and M. Rangaswamy, "Cognitive radar for target tracking using a software defined radar system," in *2015 IEEE Radar Conference (RadarCon)*, pp. 1394–1399, 2015.

[9] S. Baskar and E. Ertin, "A software defined radar platform for waveform adaptive MIMO radar research," in *2015 IEEE Radar Conference (RadarCon)*, pp. 1590–1594, 2015.

[10] J. M. Christiansen and G. E. Smith, "Development and calibration of a low-cost radar testbed based on the universal software radio peripheral," *IEEE Aerospace and Electronic Systems Magazine*, vol. 34, no. 12, pp. 50–60, 2019.

[11] S. Costanzo, F. Spadafora, A. Borgia, H. O. Moreno, A. Costanzo, and G. D. Massa, "High resolution software defined radar system for target detection," *Journal of Electrical and Computer Engineering*, vol. 2013, p. 1–7, 2013.

[12] F. Berizzi, M. Martorella, D. Petri, M. Conti, and A. Capria, "USRP technology for multiband passive radar," in *2010 IEEE Radar Conference*, pp. 225–229, 2010.

[13] H. Qian, X. Yang, X. Zhang, Y. Ding, and L. Zhang, "PLA-JPDA for indoor multi-person tracking using IR-UWB radars," in *2020 IEEE Radar Conference (RadarConf20)*, pp. 1–6, 2020.

[14] "dSPACE Automotive Radar Test Systems (DARTS)." https://www.dspace.com/en/inc/home/products/systems/darts.cfm.

[15] Keysight, "E8718A radar target simulator, 76-81 GHz, with remote front end," Jan 2021.

[16] S. B. J. Gowdu, M. E. Asghar, R. Stephan, M. A. Hein, J. Nagel, and F. Baumgärtner, "System architecture for installed-performance testing of automotive radars over-the-air," in *2018 IEEE MTT-S International Conference on Microwaves for Intelligent Mobility (ICMIM)*, pp. 1–4, 2018.

[17] S. B. Jayapal Gowdu, M. Asghar, J. Nagel, M. Rozmann, R. Stephan, and M. A. Hein, "Comparison of real and simulated automotive radar targets measured with a reference radar," in *2018 International Conference on Electromagnetics in Advanced Applications (ICEAA)*, pp. 468–471, 2018.

[18] B.-C. Wang, *Radar Modulation and Target Detections Technique*. Wiley-Interscience.

[19] R. G. Machado and A. M. Wyglinski, "Software-defined radio: Bridging the analog–digital divide," *Proceedings of the IEEE*, vol. 103, no. 3, pp. 409–423, 2015.

[20] S. Wunsch, "GNU Radio Radar Toolbox." https://grradar.wordpress.com/.

[21] J. Kennedy, J. Carlson, and V. Chakravarthy, "Performance evaluation of spectrum sharing technologies," in *2014 IEEE International Symposium on Dynamic Spectrum Access Networks (DYSPAN)*, pp. 27–33, 2014.

[22] Ettus, "X300/X310." https://kb.ettus.com/X300/X310, 2021. Accessed: 2021-04-26.

[23] "Spacek Labs, Inc.." https://www.spaceklabs.com/categories/transceivers.

[24] REMCOM, "Wireless InSite: 3D Wireless Prediction Software." https://www.remcom.com/wireless-insite-em-propagation-software/.