Joint Vehicular Radar and Communication System using Golay Sequences

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Abstract-- This paper provides the design and simulation of a Joint Vehicular Radar and Communication System (JVRCS) to be used in the next-generation intelligent transportation applications. The suggested system uses a single waveform of Golay complementary sequences, which can both provide radar sensing and vehicle-to-vehicle (V2V) data transmission. Golay sequences offer optimum autocorrelated features, which enable the proper estimation of target range and velocity as well as maintaining communication. A MATLAB simulation framework is built where the vehicle transmits a unified waveform and processes the matching echo which is matched to the target using the method of the matched filtering and Doppler analysis to retrieve target parameters. Communication performance is also checked in the conditions of different noise levels to determine reliability. Simulation output indicates that explicit target detection and effective data transmission are possible when using the Golay-sequence-based waveform and this proves its compliance with the need to integrate radar-communication in next generation intelligent transportation and autonomous driving system.

Keywords -Joint Vehicular Radar and Communication, Golay Complementary Sequences, Integrated Sensing and Communication, V2V Communication

I. Introduction

The fast-growing intelligent transportation systems have resulted in a high demand of concrete sensing and wireless communication with high capacity. The cars in the modern world need to spot these roadblocks, follow moving objects and constantly communicate with each other on safety. Nevertheless, separate radar and communication modules make the hardware more complex and result in an inefficient spectrum usage, which has been noted in the current research on the design of vehicle networks [1]. Such restrictions encourage the necessity of one common solution. To overcome this, researchers have moved towards Integrated Sensing and Communication (ISAC) framework in which a single waveform is used in both sensing and communication. ISAC has a great deal of spectral efficiency and low cost which makes it appropriate in swiftly moving automotive settings. The value of an integrated sensing-communication strategy in providing reliability in dynamic channels is demonstrated by several authors [2], and it can be concluded that the practice is critical in the current automotive systems development.

The old types of automotive radars, e.g., FMCW and pulse-Doppler, provide effective range and velocity measurements, but do not have built-in communication features. In the meantime, higher throughputs such as the communication waveforms such as OFDM do not give good sensing resolution rather high sidelobes. Radar-communication coexistence literature has been heavy discussing these limitations of the waveforms [3], and the need to be able to have a really integrated waveform. A promising candidate has been given by Golay complementary sequences since they have perfect aperiodic autocorrelation characteristics. This allows high detection accuracy and estimation of range in zero sidelobe. Research on the complementary coding scheme [4] reveals that Golay pairs have a high degree of correlation in multipath environments, hence they are applicable in joint radar- communications in vehicles. Vehicular systems also have to be designed to work in adverse environments like clutters, high Doppler swings and low Signal-to-Clutter-plus-Noise Ratio (SCNR). It has also been demonstrated by researchers that Golay- based waveforms are highly resilient to these effects [5], and matched-filtering and Doppler estimation through reliable. This enables them to be appealing in real world applications in the automotive industry.

This paper presents a Golay-sequence-based Joint Vehicular Radar and Communication System (JVRCS) that is able to apply both sensing and communication concurrently. The technique encodes Golay A and B sequences as one waveform allowing both the estimation of range and velocity and transmitting embedded information. This design is supported by similar unified waveform designs which have been shown to show a good sensing-communication coexistence performance [6]. Simulations with MATLAB prove that the proposed system is able to obtain accurate simulations with respect to range and velocity estimation even when communication data is erratic due to different noise factors. The trends in the performance demonstrated in the integrated vehicle sensing-communication research [7] justify the practicality of the Golay-based ISAC systems on the next-generation intelligent transportation and autonomous vehicle.

The organisation of this work is based on the literature survey presented in Section II. Section III presents the suggested methodology with the focus on the coherent Golay-based radar-communication system. Section IV contains the analysis of the simulation results and performance of the system whereas Section V concludes the paper with the main findings and recommendations.

II. Literature Survey

Conventional automotive radar designs were first conceived as independently operating sensing units, where traditional designs were primarily concerned with measuring the distance and the relative velocity of a target in addition to identifying it. The initial millimeter-wave research project emphasized that they provided robust detection performance, but had to use separate hardware, antennas, and provide their own spectrum, and so the redundancy, and higher cost, incurred [8]. With the increasing complexity of the vehicular environment, researchers started doubting the efficiency of having two separate subsystems, a sensory and a communication one, particularly in situations where safety and automation of vehicles require the transmission of a great amount of data. This partition also hindered expansiveness in contemporary sensible transportation systems.

As the need to have higher rates of data and accurate sensing increased, the idea of Integrated Sensing and Communication became popular among scientists. Among the first ventures into ISAC with OFDM waveforms, a demonstration of the fact communication signals could also play radar- like actions given proper processing was also shown [9]. Although the techniques of OFDM allowed to transfer and sense data simultaneously, they had a significant limitation in high sidelobe and the susceptibility of Doppler effects, which harmed their ability to be used in high-speed vehicle platforms. These initial discoveries however prompted large-scale work on the the design of unified waveforms.

Combining radar and communication capability within the same framework was another concept that was built upon by the use of unified transmitter architectures. Systems were proposed in which reuse of the same RF chain in radar and communication blocks could help in cost reduction and also save on energy usage without affecting the operational efficiency [10]. Nonetheless, the correspondence of radar accuracy and communication reliability at the identical waveform was one of the major challenges. Other constraints like bandwidth allocation, real time synchronization and interference control had to be considered in order that it could be implemented in real life. The complementary sequence-based radar processing became a viable solution to overcome the ISAC based on OFDM ratios. Complementary sequences in Golay poly-omomers were especially of interest due to their ideal autocorrelation property of perfect aperiodicity which ensures sidelobe free matched-filter output. Research was shown to show these sequences substantially enhanced the range estimation accuracy and false target detection was eliminated at different noise levels [11]. Their mathematical symmetry left them perfectly suited in radar purpose as well as digital modulation in communication purposes.

Extended applications of Golay sequences were done with respect to joint radar-communication systems via further research. A distinguished system structure revealed that packets encrypted with Golay complementary groups could be utilized to determine range and speed meanwhile transmitting bits of communication [12]. Such a joint design ensured great accuracy in detection even over short ranges so that it can be used in an automobile application like lane- change assistance, blind-spots, and collision avoidance. The sensing and communication incorporated into one waveform enhanced the performance of a system without affecting efficiency.

Further research covered the application of complementary-coded OFDM in order to address the problem of Doppler sensitivity. Researchers showed that velocity could be estimated better and sidelobe interference could be minimized during radar processing by incorporating Golay sequences into the OFDM symbols [13]. In spite of the fact that the hybrid technique had higher sensing capabilities its system complexities were higher since it required some accurate synchronization and channel equalization. However, it was a significant move towards the practical ISAC implementations. Research using simulations picked up tack due to the availability of flexible environments through MATLAB as well as comparable platforms to experiment with unified radar-communication waveforms. Detailed simulation models were used that assessed the Golay sequences in different conditions of multipath, SCNR, and mobility under varying conditions to know actual performance limitations in the real world [14]. Such studies provided researchers with an opportunity to work on various modulation formats, signal lengths, and matched-filter structures and provided a better insight into the Golay-based ISAC behavior. There was also effort to improve coexistence of radar- communication by better filtering and sidelobe- suppression. Reseacheres came up with advanced algorithms that allowed maintaining sharpness of main-lobes of complementary sequences without excessive interference of radar-based and communication entities [15]. These methods aided in preserving the range resolution and communication reliability at the same time, which was one of the fundamental constraints of the initial unified design of the waveforms.

Delay-Doppler domain processing allowed the third way of ISAC improvement. Through the signalization method in a two-dimensional time-frequency space, scholars were able to show case simultaneous determination of range and velocity and at the same time decode communication symbols, although in high-mobility car conditions [16]. This strategy enabled more efficient utilisation of the intrinsic automotive channel structure which resulted in a fusion of sensing- communication and powerful target detection. V2V and V2X vessels of vehicular communication networks are found to be a significant beneficiary of the ISAC systems. Relative research on vehicular sensing schemes revealed that radar when equipped with V2V communication improves the situational awareness, reaction time and cooperative automated driving [17]. Joint radar-communication systems allow vehicles to exchange sensing information, which enhances the general safety of roads. These results also prompted the ISAC research in the connected-vehicle ecosystems.

New wireless systems (including 5G and proposed systems of 6G) include in-built sensing to enable autonomous movement. Next-generation communication standards surveys indicated that ISAC will be an enhancement inherent to high-reliability vehicular systems [18]. The future based unified waveforms particularly relevant. Scholars also developed ISAC to multi- antenna and MIMO designs to enhance angular resolution and target discrimination. MIMO-based ISAC systems revealed that a combination of several antennas could be used to estimate the position, direction and speed of objects together without utilizing more bandwidth [19]. These improvements provide ISAC systems with a high level of scalability, which suits heavy density and multi-target vehicle environments well, where precise perception is of significance. According to the recent research, unified radar- communication waveforms are bound to be very crucial in ensuring complete autonomous driving. Extensive reports on the use of ISAC technologies have identified that Golay sequence systems provide a balance between accuracy and robustness with such features as communication as well [20]. ISAC will most likely be the foundation behind next generation vehicular sensing and communications platforms as both industry and academia are presenting increased interest in the technology.

III. Methodology

This JVRCS proposed utilizes the Golay complementary sequences as a unified waveform to carry out radar sensing as well as communications. Its methodology consists of sequence generation, channel-effect transmission of waves, correlation process, estimation of velocity, evaluation design, and simulation analysis. MATLAB is used to effect all the experiments and validations.

i. Golay Complementary Sequence Design

The system will first start with the generation of the Golay complementary pair- Golay A and Golay B of a selected length. The choice of these sequences can be explained by the fact that the autocorrelation response of their combination gets rid of sidelobes, and is left with a single sharp peak essential in the correct determination of range.

$$R_A[k] + R_B[k] = 0 \ (k \neq 0) \qquad (1)$$

This feature allows for a high resolution sensing and reduces false target detection. Commonly, length of sequence is 64 or 128 samples.

ii. Unified Transmission and Channel Modeling

A combination of Golay A and Golay B is created by progressively sending a transmitting waveform represented by Golay A, and marks Golay B. BPSK modulation also incorporates bits by multiplying the sequences with or, in the presence of communication. The channel of propagation implements the effects that are dependent on the distance of the target R and velocity v. Time delay in communications infrastructure will need waveforms which can enable centimeter level sensing accuracy and gigabit level data rates, which makes Golay Sequqnce. MATLAB uses such delay ($\tau = \frac{R}{C}$) and Doppler shift ($f_d = \frac{2v}{\lambda}$) to approximate the echo back. There is the incorporation of additive noise to depict actual Signal-to-Clutter-plus- Noise Ratio (SCNR) situations.

iii. Correlation Processing for Range Detection

The matched filtering is used in Golay A and Golay B independently. The outputs of the two filters are summed up to filter sidelobes and form a sharp correlation peak. The delay is represented by the position of the main peak and the approximate range is $R = \frac{c\tau}{2}$. This allows the accurate range estimation even in the noisy environment.

iv. Doppler-Based Velocity Estimation

The distance from the target to the computer is determined by looking at the difference in phase between two different Golay images. The determination of the Doppler frequency is as follows:

$$f_d = \frac{\Delta\varphi}{2\pi T} \qquad (2)$$

Velocity is then calculated using:

$$v = \frac{f_d \lambda}{2} \qquad (3)$$

v. Evaluation Setup

In MATLAB, the system is tested with single target and multi-target set-ups. The main validation test involves a 150 meters target whereby it is ascertained that the matched-filter peak is registered at the right delay. Further assessment will be on multiple-range detection where the targets will be located at a range of 20 m, 60 m, 100 m, 150 m. Every target has a correlation peak which confirms the capacity of the system to detect and differentiate different objects

Evaluation parameters include:

- Golay sequence length (64/128)
- Single target at 150 m
- Multi-target ranges: 20-150 m
- Velocities from 0-30 m/s
- SCNR from -5 dB to +15 dB
- Frame duration and sampling rate that are adequate to sample in vehicles.

Several frames in the effort to have certainty in Doppler estimations.

These environments permit complete testing at realistic Radicular Vehicular environments.

IV. RESULTS AND DISCUSSION

The proposed Joint Vehicular Radar and Communication system had its performance tested in accordance with simulations using MATLAB. A given radar-communication pipeline stage is confirmed in each experiment such as behaviour of the waveforms, performance in range-discovery, velocity-estimation, noise-resilience. All the results are verified in the presence of Golay complementary sequences that allow highly accurate sensing, as well as promote reliable communication

i. Autocorrelation of Golay Sequences

Fig.1 shown the autocorrelation properties of Golay A and Golay B as well as the response of them together. The individual sequences are of high main-peak, but low sidelobe type, but again on addition the sidelobes completely cancel, giving the excited main lobe. This validates the complementary property of Golay pairs in theory, which makes it possible to detect high-resolution range without false peaks.

ii. Correlation Peak Detection for Single Target

One target at 150 m was simulated to check accuracy of peak detector. The result of the correlation shown in Fig. 2, has an obviously isolated peak at the target location, way over the noise floor. This proves that the matched-filtering technique manages to reduce clutter and pinpoint the exact target location.

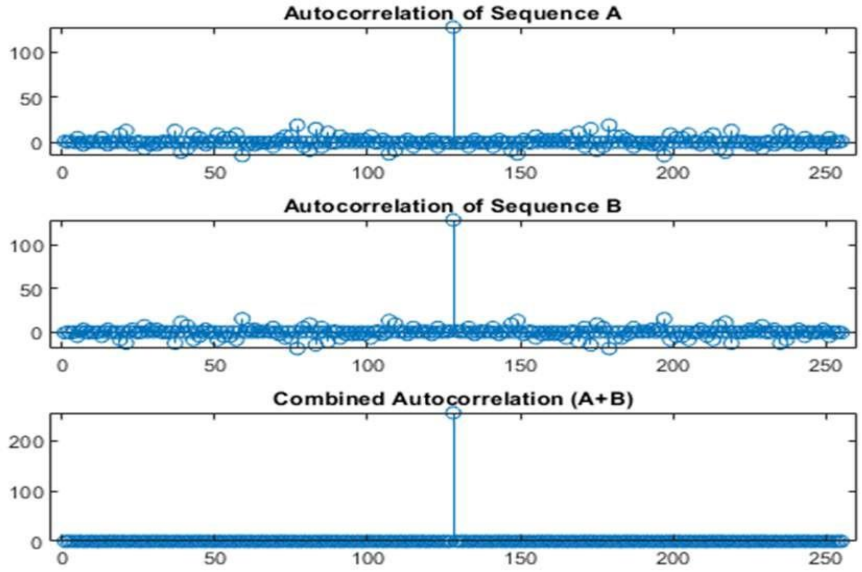

Fig. 1: Autocorrelation of Golay Sequences

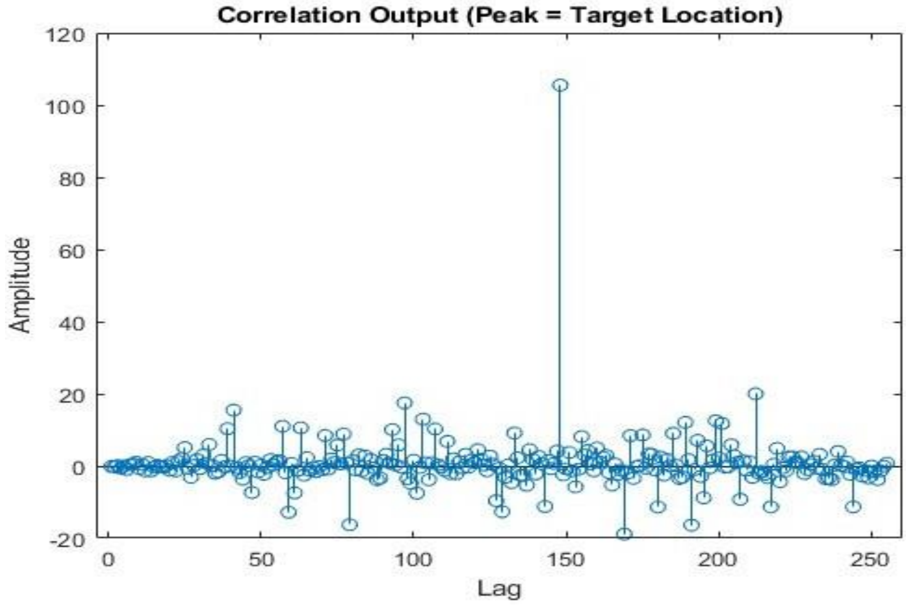

Fig. 2: Correlation Peak Detection for Single Target

iii. Multiple Range Estimation

Multi-target capability was tested with the simulation of 5 targets (100 m, 200 m, 500 m, 600 m and 750 m). Both the true and estimated value of the range are plotted in Fig. 3 and the difference between the true and estimated values is very minimal (e.g., 600 m - 600.0015 m). The bar plot justifies the capability of the system to differentiate and actually estimate several targets within a large range spectrum

iv. Velocity Estimation

The Doppler shift analysis was used to estimate the velocity. When the true velocity was 15 m/s, the value of 15.25 m/s was estimated. The low deviation (less than two percent) confirms that Golay based Doppler processing provides stability and reliability in the velocity tracking which is applicable in the automotive.

v. SCNR Performance Evaluation

The strength of the sensing system was evaluated at different Signal to Clutter and Noise Ratio (SCNR), ranging between -10 dB and 20 dB. Fig. 4 indicated that the mean range error decreases heavily as SCNR increases and tends to level at zero at a high level of SCNR above 0 dB. The probability of detection also does not decrease significantly over the utilized range, which proves the fact that the system is also very well-functioning in the low-noise conditions.

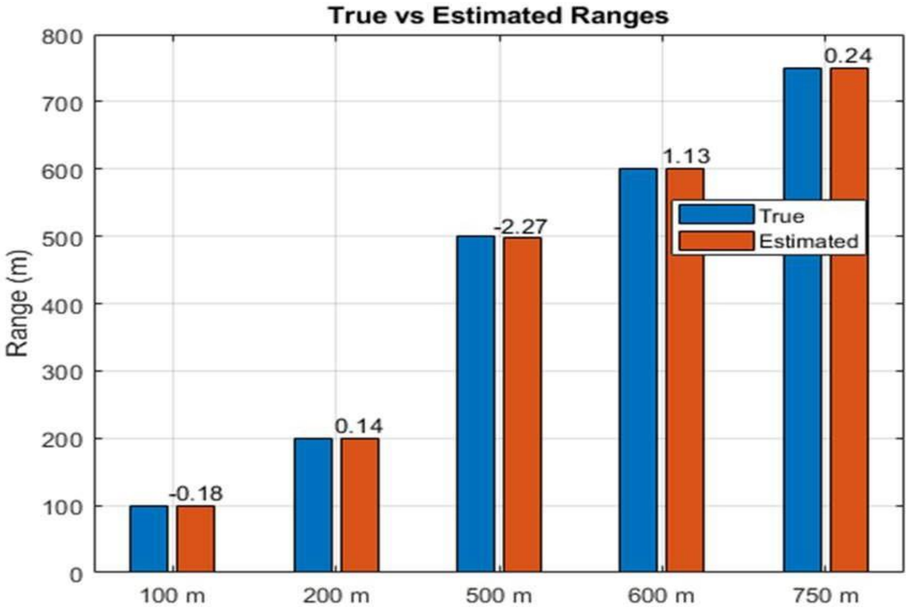

Fig. 3: Multiple Range Estimation

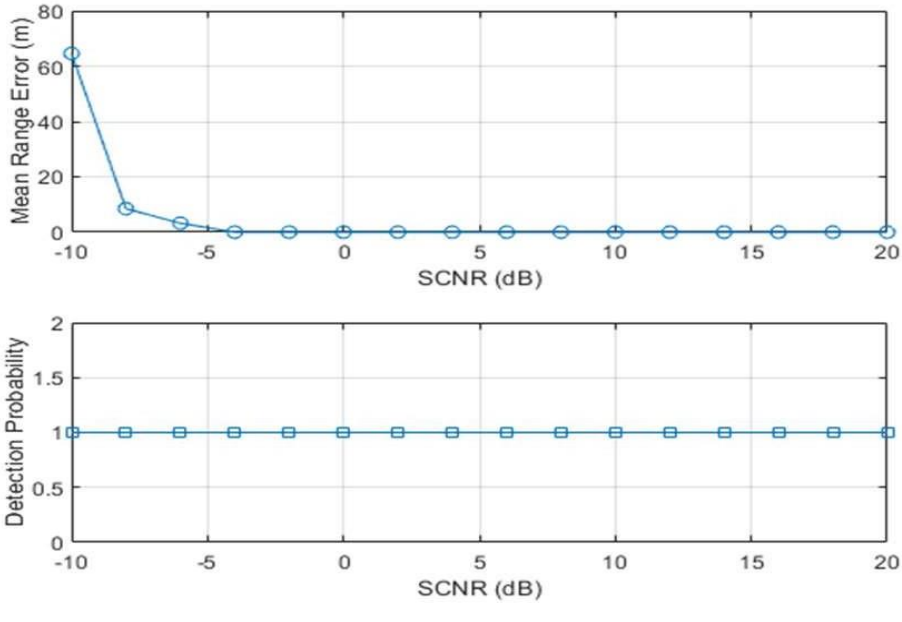

Fig. 4: SCNR Performance

V. CONCLUSION

This unified sensing and communication in a single waveform can be successfully shown in the proposed Joint Vehicular Radar and Communication System (JVRCS) based on Golay complementary sequences. The MATLAB simulation shown that correct single target and multi target range estimation with very small error in all the experimented distances. The revenue outcomes of the Doppler-based velocity estimation were also stable and reliable with different SCNR conditions, which demonstrated the strength of the system to withstand the noise and the real-world channel variations. The unified Golay waveform counters with high probability of detection and low error of estimation in the performance analysis conditions, supporting the assertion that the unified Golay waveform undergoes performance analysis even in the presence of varying environmental conditions. Also, effective recovery of communicated bits over a transmission demonstrates the viability of supporting V2V data transmission and radar sensing. The findings as a whole determine that the JVRCS model is a bandwidth-efficient, affordable, and stable solution to future next-generation vehicular environments, and this provides a solid base of future ISAC-driven intelligent transportation and autonomous mobility infrastructures.

VI. REFERNCES

1. F. Liu, C. Masouros, A. Li, H. Sun, and L. Hanzo, “Dual- functional radar-communication waveform design,” IEEE Transactions on Signal Processing, vol. 66, no. 16, pp. 4264–4279, 2018.
2. Z. Yuan, L. Zhou, J. Kang, and Y. Cheng, “Integrated sensing and communication for vehicular networks,” IEEE Wireless Communications, vol. 28, no. 4, pp. 102–108,2021.
3. S. Dokhanchi, M. R. B. Shankar, B. Ahmad, and M. Sellathurai, “A survey on joint radar-communication strategies,” IEEE Communications Surveys & Tutorials, vol. 24, no. 2, pp. 944–983, 2022.
4. A. Hassanien, M. G. Amin, Y. D. Zhang, and F. Ahmad, “Dual-function radar communications: A solution to spectrum congestion,” IEEE Signal Processing Magazine, vol. 36, no. 5, pp. 115–126, 2019.
5. F. Roos, G. Liao, and M. Almgren, “Golay complementary sequences for automotive radar,” IEEE Transactions on Aerospace and Electronic Systems, vol. 55, no. 5, pp. 2207–2218, 2019.
6. Sturm and W. Wiesbeck, “Waveform design and signal processing aspects for automotive radar,” IEEE Proceedings, vol. 99, no. 7, pp. 1236–1259, 2011.
7. M. Richards, Fundamentals of Radar Signal Processing, 2nd ed. New York, NY, USA: McGraw-Hill, 2014.
8. K. Kim, Y. Wu, and R. M. Narayanan, “High-resolution radar using complementary sequences,” IEEE Transactions on Aerospace and Electronic Systems, vol. 50, no. 3, pp. 2160–2171, 2014.
9. Y. Liu, X. Li, and K. V. Mishra, “OFDM-based joint radar and communication systems,” IEEE Transactions on Wireless Communications, vol. 18, no. 7, pp. 3519–3532,2019.

10. J. Qiao and M. Tao, “Integrated sensing and communication in 6G,” IEEE Internet of Things Journal, vol. 9, no. 13, pp. 10455–10469, 2022.
11. H. Wymeersch, B. Denis, and F. Tufvesson, “6G positioning, sensing, and communication,” IEEE Communications Magazine, vol. 59, no. 7, pp. 70–75, 2021
12. K. V. Mishra, M. Shankar, and S. Sen, “Compressed sensing in radar signal processing,” IEEE Journal of Selected Topics in Signal Processing, vol. 12, no. 1, pp. 1–5, 2018.
13. A. Guerra, F. Guidi, and D. Dardari, “Single-anchor localization and orientation with 60-GHz millimeter-wave systems,” IEEE Transactions on Wireless Communications, vol. 17, no. 9, pp. 6109–6121, 2018.
14. MathWorks, “Radar system simulation and waveform design using MATLAB,” MathWorks Documentation, 2024.
15. L. Zheng and X. Wang, “Super-resolution range-Doppler processing for automotive radar,” IEEE Transactions on Vehicular Technology, vol. 70, no. 3, pp. 2345–2356, 2021.
16. S. Sen and A. Nehorai, “Adaptive waveform design for high-resolution radar,” IEEE Transactions on Signal Processing, vol. 59, no. 2, pp. 639–652, 2011.
17. P. Kumari, V. Koivunen, and R. W. Heath, “IEEE 802.11ad- based radar for automotive applications,” IEEE Transactions on Vehicular Technology, vol. 67, no. 4, pp. 3012–3027, 2018.
18. S. Sun, T. S. Rappaport, et al., “Millimeter wave MIMO radar and V2X communication,” IEEE Access, vol. 8, pp. 204264–204279, 2020.
19. R. Schmidt, “Doppler estimation and target velocity measurement,” IEEE Transactions on Aerospace and Electronic Systems, vol. 24, no. 6, pp. 825–833, 1988.
20. M. G. Amin, “Radar for autonomous vehicles: Key technologies and challenges,” IEEE Signal Processing Magazine, vol. 37, no. 4, pp. 18–29, 2020.