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SURVEY

A Survey on Waveform Design for Radar-Communication Convergence

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ABSTRACT To provide service to an abundant number of communication users and to avoid the spectrum scarcity problem, many researchers are fascinated to work towards the convergence of radar sensing and communication systems. In addition, future intelligent systems like autonomous vehicles, Vehicle-to-everything (V2X), Unmanned Aerial Vehicles (UAV), and all smart systems are going to implement both radar and communication systems on the same platform, which motivates the researchers to focus on the development of Joint Radar-Communication Systems (JRCS). Cooperative Radar-Communication System (CRCS) and Dual Functional Radar Communication (DFRC) systems provide an opportunity for communication users to utilize radar resources without disturbing radar operation. Waveform design is essential in the development of new models and designs related to joint radar-sensing and communication systems. A cooperative radar communication system uses separate waveforms for radar and communication systems. The DFRC system uses the same waveform for radar and communication operations. So to model both joint radar communication systems one should have a clear idea regarding waveform design and its approaches. Therefore, this review paper focused on different waveform design approaches for modeling CRCS and DFRC systems. In addition, the prime objective of this review paper is to give a detailed view of the existing cooperative and dual-function waveform design approaches and provide a kick-start for new learners to work on this area.

INDEX TERMS Convergence, communication-centric waveform design, cooperative radar-communication system (CRCS), dual-functional radar-communication (DFRC) system, learning-based waveform design, radar-centric waveform design, spectrum sharing.

I. INTRODUCTION

Sensing and communication are the two significant functionalities of radio technology, which are self-designed and rely on various functions and bands of frequencies. Here, sensing is responsible for target detection and tracking, whereas communication is considered for transferring information among users. It is a well-known fact that most of the Radio Frequency (RF) spectrum has been allocated to various application-oriented services. In addition to that, with the

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advent of wireless applications and their abundant usage, there is a profound need for a higher data rate (higher bandwidth) in the area of wireless communication. Hence there is an RF spectrum congestion problem due to the limited radio spectrum.

To overcome the problem of RF spectrum scarcity, mobile network providers are exploring the opportunities to reuse RF spectrum, which is traditionally allocated to other applications. Among those, the radar frequency band is the most unused and broadest RF band well suited for wireless applications [1]. This shared spectrum access not only solves the spectrum congestion problem but also enhances the spectrum utilization efficiency. Firstly, the necessity of RF spectrum sharing between radar sensors and wireless communication systems was discussed in [2]. Further, the RF convergence of the radar sensor and communication systems was presented in [3]. According to [4], the RF spectrum-sharing approaches are classified into spectral coexistence and spectral cooperation. Mutual interference between communication and radar systems is the major problem in the coexisted radar and communication systems [5]. To overcome this problem, the RF spectral cooperation scheme was proposed in [6]. Later, a spectral co-design scheme i.e., a Dual Function Radar-Communication (DFRC) System was developed to overcome the RF spectrum scarcity problem [7].

On the other hand, the integration of mobile communication signals (3G, 4G, 5G) into radar systems represents a significant advancement in radar-communication convergence. This innovative approach holds great promise for spectrum sharing, enabling efficient utilization of the limited electromagnetic spectrum. One of the key advantages of this technology is its intuitive nature. By adopting the existing mobile communication infrastructure, radar systems can utilize the signals already present in the environment [8]. This not only reduces the need for additional hardware but also facilitates seamless integration with existing communication networks. Furthermore, using mobile communication signals for radar offers improved spectral efficiency. With the proliferation of mobile devices and the increasing demand for wireless communication, spectrum scarcity has become a significant challenge. By sharing spectrum with radar systems, mobile communication networks can operate more efficiently, leading to better service quality for users. Additionally, this technology enables radar systems to benefit from advances in mobile communication technology. The transition from 3G to 4G and now to 5G has brought about significant improvements in terms of data rates, latency, and reliability. Further, adopting 5G signals for the radars gives good range and velocity resolution which helps in tracking closely spaced and slow-moving targets [9].

Overall, employing mobile cellular signals as external radiation sources for radar is a very promising technology with great potential for spectrum sharing. Its intuitive nature, increased spectrum efficiency, and capacity to utilize developments in mobile communication technology make it an important development path for radar-communication convergence.

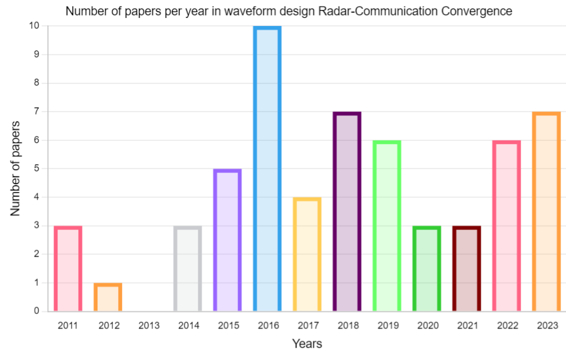

FIGURE 1. Statistics on the number of papers published in the domain of waveform design for Radar-Communication Convergence.

The joint communication and radar sensing integrate communication and radar functionalities, sharing hardware and signal processing for improved spectrum utilization efficiency, size reduction, and improved performance. Advanced signal processing techniques are crucial for efficient integration, covering transmission signal design and receiver processing in communication-centric, radar-centric, and joint design systems [10]. Selecting the probing waveform holds significance as it directly impacts slant range resolution, Doppler tolerance, clutter, and electronic countermeasures [11].

Therefore, this survey paper focuses on the role of waveform design for RF convergence of radar and communication systems, which lay a foundation for the development of various joint radar-communication system configurations. In this context, optimum waveform design emerges as a critical factor in achieving efficient coexistence between radar and communication systems [19]. In addition, a computationally efficient algorithm is employed to generate complex digital transmit and receive ultra-wideband radar and communication waveforms, achieving excellent suppression of arbitrary frequency bands and minimizing range sidelobes [20]. This survey comprehensively explores the spectrum management strategies and waveform design techniques that allow these two disparate systems to operate harmoniously. The paper critically reviews existing research and outlines the key considerations for designing waveforms that reduce interference, enhance radar and communication system performance, and promote the optimal utilization of limited frequency resources. Around the globe, there is steady research going on the waveform design for radar-communication convergence. In addition, a bar chart is depicted in Figure 1, to give an idea about the number of papers that have been published in the past 13 years on the proposed survey.

This comprehensive review delves into the intricacies of waveform design and its impact on radar-communication coexistence in diverse application domains, such as maritime, automotive, and aerospace. By summarizing the various approaches and strategies employed in waveform design, the paper equips researchers, engineers, and policymakers

TABLE 1. Recent survey papers on joint radar-communication system.

Ref. No	Main objective of the survey paper	Year
[12]	A review is conducted on various approaches involved in the coexistence of radar sensing and communication systems.	2019
[13]	Provides a waveform design perspective of mm-wave joint radar-communication systems.	2019
[7]	This survey provides various signaling schemes involved in the development of dual functional radar-communication systems.	2019
[14]	A review on state-of-the-art of joint radar communication systems.	2020
[4]	Overview of the research progress in the area of joint radar-communication systems, with special emphasis on application scenarios and technical approaches.	2020
[10]	A comprehensive survey of the state-of-the-art on joint radar and communication systems from the signal processing perspective.	2021
[15]	A survey on systems and technologies developed based on the communication and radar convergence.	2022
[16]	A review on waveform design approaches for integrated radar sensing and communication.	2022
[17]	This survey explores both present and upcoming Internet of Things (IoT) applications of joint sensing and communication systems.	2022
[18]	A comprehensive review of the multi-dimensional waveform concepts, along with generalized models are proposed for joint communication and radar systems.	2023
This survey	A review of waveform design for the convergence of radar and communication systems in the RF environment.	2023

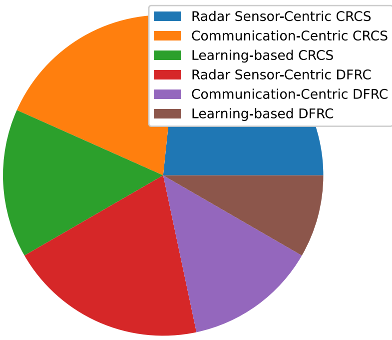

FIGURE 2. Pie-chart representation number of papers published with various techniques in the domain of waveform design for Radar-Communication Convergence.

with a comprehensive understanding of the challenges and opportunities in this ever-evolving field. The pie chart shown in Figure 2 conveys the number of papers that have been published related to various waveform design approaches involved in the development of joint radar-communication systems. In addition, it sheds light on emerging trends and innovative solutions, fostering collaboration and innovation to ensure the seamless coexistence of radar and communication systems in an increasingly crowded and interconnected wireless world.

In this survey paper, a comprehensive review has been conducted on the various waveform design approaches involved in the convergence of sensing and communication systems. In a nutshell, the following key aspects are addressed in this paper:

- Various radar-sensor centric waveform design approaches for the radar-communication convergence.
- Different communication-centric waveform design approaches for the radar-communication convergence.
- Learning-based waveform design approaches for the radar-communication convergence.

Further, Recently published survey papers are listed in Table 1, to create awareness about the trends, challenges, and opportunities in the research area of waveform design for joint radar-communication systems. As per our knowledge, the survey on constraint-based waveform design approaches, and learning-based waveform design approaches for both cooperative and DFRC systems are hardly noticed in any of the previous review papers listed in Table 1. Therefore, this survey paper focuses on various constraint and learning-based waveform design approaches for the convergence of radar and communication systems. The major contributions of this survey paper are summarized as follows:

- A deep knowledge of constraint-based optimal radar and communication waveform design approaches is provided. In addition, an awareness is created of the objective functions of the various optimization frameworks.
- For every optimization framework, the system performance metrics are identified and they are listed in the table.
- To improve the convergence of optimization problems, several learning-based strategies have been incorporated in this review paper.

To illustrate further, this study gives a comprehensive idea about how the Joint Radar-Communication System (JRCS) evolved to create a huge impact on communication and sensor society. Subsequently, a deep insight into the various optimum waveform design approaches for the development of the joint radar-communication system is incorporated. In addition, several learning-based waveform design approaches for the JRCS are presented in this survey, which was hardly reported in any of the previous survey papers.

A. INNOVATION AND REALITY

The creative aspect of this study is to involve cognitive radio principles to make the radar waveform or communication waveform adaptive to environmental conditions. This adaptive waveform design not only improves the spectrum utilization efficiency but also enhances the overall joint radar-communication system performance. Innovative modulation techniques can be deployed to design a unique waveform that is suitable for both radar and communication applications. This phenomenon can be implemented in electronic warfare functionalities to provide enhanced operational flexibility and resource utilization. Leveraging learning-based optimum waveform design is an emerging area of research. Learning-based approaches can analyze complex system dynamics

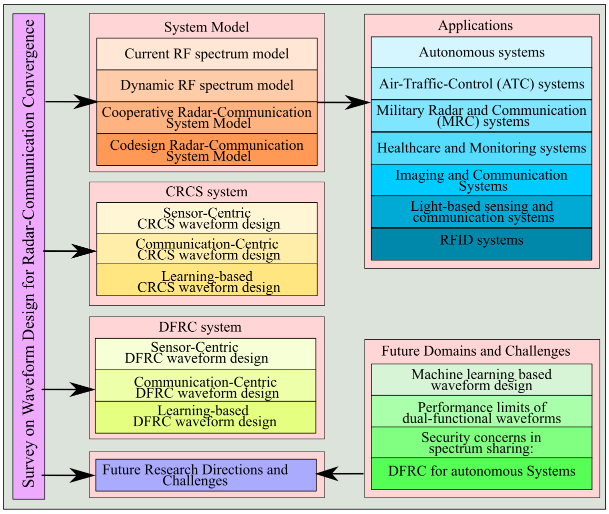

FIGURE 3. The organization of the survey paper.

and user requirements to autonomously generate waveforms that maximize performance metrics such as detection probability, communication throughput, and interference mitigation. These innovations in waveform design for radar-communication convergence contribute to the development of more efficient, adaptive, and resilient integrated systems capable of meeting the evolving demands of modern defense, surveillance, and communication applications.

In the context of radar-communication convergence, the reality of waveform design includes the practical applications, problems, and improvements that researchers and engineers face when building integrated systems. It is difficult to balance competing goals when designing waveforms that maximize radar and communication performance at the same time. To obtain desired system capabilities, engineers have to balance elements including power consumption, signal-to-noise ratio, radar range resolution, and communication data rate. Waveform design involves overcoming implementation obstacles and hardware constraints. While designing waveforms for practical applications, engineers have to take into account the capabilities and limitations of transceiver hardware, signal processing methods, and digital signal processing platforms. The reality of waveform design includes rigorous testing, validation, and verification processes to assess system performance, compliance with specifications, and adherence to operational requirements. Engineers conduct extensive simulations, field trials, and empirical testing to evaluate waveform designs and refine system implementations. Real-world radar-communication convergence systems must meet stringent cost, size, weight, and power constraints to be practical for deployment in diverse operational environments. Waveform design efforts must prioritize efficiency, scalability, and affordability to address these constraints while delivering desired performance.

The complete structure of the survey paper is clearly shown in Figure 3. The remainder of the review paper is organized as follows. Section II discusses the various

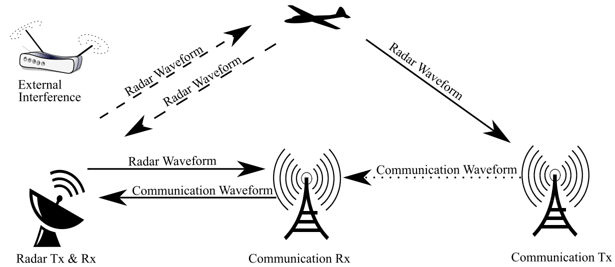

FIGURE 4. Current RF spectrum environment.

applications of coexisted radar and communication systems. Waveform design approaches for a CRCS are demonstrated in Section III. In addition, Section IV presents the waveform design approaches for a DFRC system. Section V illustrates the opportunities and future research directions of CRCS and DFRC systems. Eventually, the review paper is concluded in Section VI.

II. JOINT RADAR AND COMMUNICATION SYSTEMS AND APPLICATIONS

A. COOPERATIVE RADAR-COMMUNICATION SYSTEM MODEL

A general RF spectral congestion scenario is demonstrated in Figure 4, where both radar and communication systems are carrying out their operations in the presence of external interference. Further, both communication and radar systems are operating in the same frequency band or adjacent frequency bands. However, there is mutual interference between both radar and communication systems, when they operate in the same spectral band.

In the future, upcoming RF systems will be badly in need of spectral resources. Hence one possible solution is the convergence of RF wireless systems. According to [5], an upcoming RF spectral environment is depicted in Figure 5, where all the users are adaptive to the spectral environment. Further, both radar and communication systems are cooperative with each other. As the users are dynamic in the above scenario, they are capable enough to avoid mutual interference. Furthermore, radar and communications users can change their frequency band and work to attain the required radar estimation rate [6] and communication data rate.

To avoid this spectrum congestion problem, researchers are looking to investigate shared spectrum access [1]. Radar bands are the finest nominee to be shared with different communication systems due to a broad chunk of the spectrum being accessible at radar frequencies [1]. Moreover, the sensing mechanism is going to play a pivotal role in upcoming wireless technologies like 6G, Intelligent Transport Systems (ITS) [21], smart homes [22], and different location-oriented applications [23]. These aforementioned applications rely on efficient sensing and communication capabilities. Due to this motive, researchers are intended to focus on Radar-Communication Spectrum Sharing (RCSS) [4].

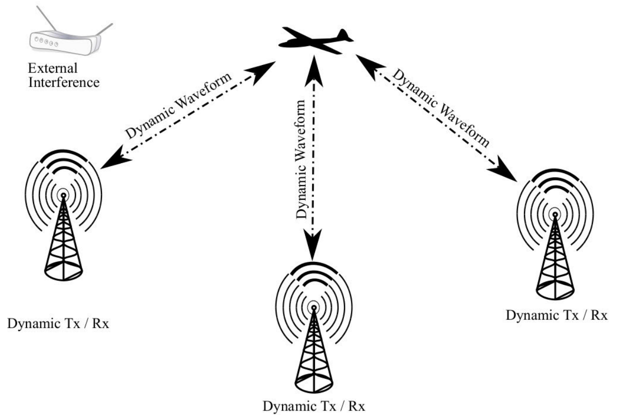

FIGURE 5. **Upcoming dynamic RF spectrum environment.**

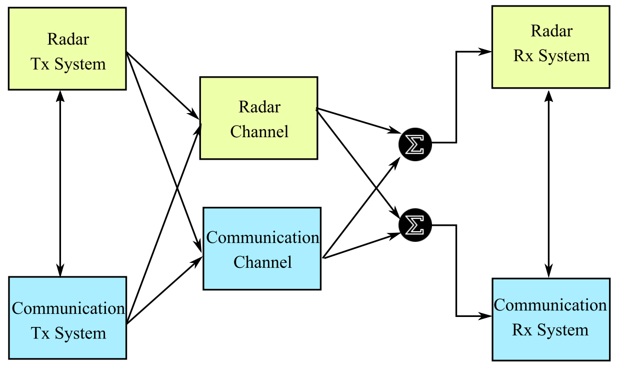

FIGURE 6. **Basic cooperative radar-communication system model.**

Radar and Communication systems both are independent systems and they have been developed separately. However, there are some similarities in both systems, especially in the receiver section [24]. In the past few years, we have seen the proliferation of vibrant academic and industrial interest toward the convergence of sensing and communication functions. In addition to that, government organizations like the Defense Advanced Research Projects Agency (DARPA) [25] started funding to ensure a better quality of military radar and military communications. As a consequence, a wide range of work has been carried out based on different design strategies, a variety of scenarios, and cooperation between the radar and communication systems. According to the literature survey, RCSS approaches have been categorized into co-existence, cooperation, and co-design.

In the coexistence category, both radar and communication transmitters are active, and both access the radar spectrum [12]. Further, both radar and communications transmitters treat one another as interferers. However, the major setback is to combat mutual interference to accomplish a reasonable performance for both radar and communication systems [26]. Initially, researchers preferred opportunistic spectrum sharing to achieve spectral coexistence [27]. In this approach, communication users are permitted to transmit when the band of frequencies is not engaged by radar. However, it is possible only when both systems are not operating at the same time. To overcome this, a null-space projection (NSP) scheme was proposed in [28], where a radar beam pattern is required to aim waves onto the null space of the interference channel connecting the radar transmitter and communication transmitter. Because of NSP, the mutual interference between two sub-systems can be minimized. In [29] and [30] the NSP scheme was considered to combat mutual interference between MIMO radar and communication systems. Nevertheless, it results in radar system performance loss. However, it is always difficult to maintain optimal beamform for the estimation of target detection and target tracking. Later a novel approach is introduced in [31] for relaxing the null steering precoder to enforce allowable interference on the information system. The general cooperative scenario block diagram is depicted in Figure 6. In the cooperation category, Channel State Information (CSI) is exchanged between radar and communication systems and assists each other to avoid mutual interference [26]. Further, a fusion center was considered in [32] to exchange the information between both the sub-systems to enhance the performance of the cooperative joint radar-communication system.

According to [32], pilot signals can be utilized to estimate the channels and share CSI with the subsystem. Apart from that, many methods have been proposed in [33] and [34] to sense the environment without transmitting a pilot signal or without coordination between subsystems. To share the spectral resources efficiently and accomplish RF convergence, a meticulous understanding of the principal performance limits of cooperative spectrum sharing is desired [3]. The general codesign scenario is depicted in Figure 7. In this scenario, both radar and communication systems are jointly designed and improve their performance due to their mutual assistance. Further, both systems are designed on a single hardware platform to optimize their performance. In the codesign category, only one active transmitter/receiver is involved in performing both sensing and communication operations [12]. Due to this reason codesign category systems are named Dual Functional Radar Communication (DFRC) systems. In DFRC systems coexistence is functional. Moreover, the DFRC system utilizes a joint waveform for both sensing and communication operations in the same bandwidth [4]. DFRC system has the advantages of less power consumption, compact size, low cost, improved performance, and more security due to enhanced information sharing [13]. The major objective of the DFRC system is to exploit resources of radar infrastructure for communication operations. DFRC systems play a pivotal role in the cognitive transportation system that needs to exchange information in a dynamic environment [35]. DFRC strategies are going to play a phenomenal role in the design of autonomous vehicles [21]. The Radio Frequency (RF) spectrum sharing between communication and radar systems has been inspired by the necessity for the coexistence of radar and communication systems. This section demonstrates the various applications related to the convergence of sensing and communication functions.

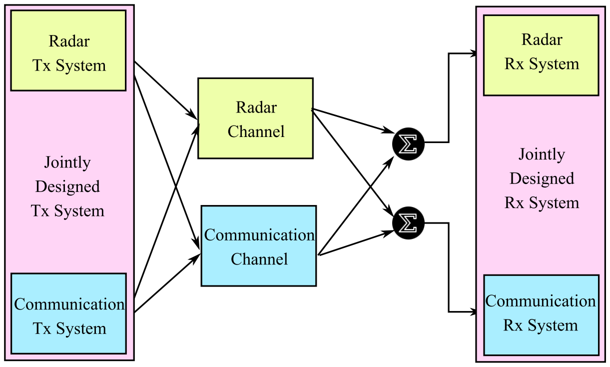

FIGURE 7. Basic codesign radar-communication system model.

B. APPLICATIONS OF COOPERATIVE RADAR-COMMUNICATION SYSTEM

1) AUTONOMOUS SYSTEMS

The mm-wave band (30GHz-300GHz) is more suitable for autonomous applications, where both sensing and communication operations are involved. Primarily mm-band is traditionally allocated to automotive radars for vehicle collision prevention and it is also used by high-level image resolution radars [36]. However, this band is also feasible for wireless communication users to perform short-range communication [37] and Long Term Evolution (LTE) [36] technology. Further, this band is proposed for Vehicle-to-Vehicle (V2V) communication for the development of autonomous cars [38]. The research community already started focusing on the possible impacts due to in-band interference [39]. As both sensing and communication applications are interconnected, researchers are strongly motivated to develop joint radar-communication systems for autonomous systems [35]. In addition to it, the mitigation algorithms for in-band interference are also highly likely to work for the joint radar-communication systems [40], [41].

2) AIR-TRAFFIC-CONTROL (ATC) SYSTEMS

In these systems, radar sensing and communication play a pivotal role in air traffic management [5]. Especially in commercial flights, where radar is utilized for object detection and tracking, and communication system is used for pilot and ATC system coordination. Initially, L-band (1GHz-2GHz) and S-band (2GHz-4GHz) are utilized for ATC radar systems. Recently, these bands have also been allotted to LTE and 5G new radio wireless technologies [42]. These 5G and 6G bands are claimed to be a strong candidate to serve as an illuminator of opportunity in passive bi-static configuration [43], [44]. In addition, the challenges associated with tracking of radar targets in in-band wireless communication interference for RadComm spectrum sharing are also presented in [45]. Thus there is a coexistence between radar and communication systems.

3) MILITARY RADAR AND COMMUNICATION (MRC) SYSTEMS

In general, the S-band (2GHz-4GHz) and C-band (4GHz-8GHz) are used for military applications like Low-Probability-Intercept (LPI) radar [46], Unmanned Aerial Vehicles (UAV) utilized for various covert operations such as track and rescue [47], reconnaissance [48], and Electronic Countermeasures (ECM), [49]. However, all the applications require both sensing and communication functionalities. Moreover, Shared Spectrum Access for Radar and Communications (SSPARC) was keen to allocate a part of the C-band for wireless communication users [50]. With the rapid growth in the usage of wireless applications, concerns are increasing for military radar band sharing [1]. The feasible coexisting military radar and communication applications are namely, LPI communication, passive radar, UAV communication and sensing, and dual-function RF systems.

4) HEALTHCARE AND MONITORING SYSTEMS

These systems utilize the Industrial Scientific and Medical (ISM) band and Wireless Medical Telemetry Service (WMTS) frequency band (1.35GHz-1.45GHz) for healthcare and monitoring purposes. To monitor the healthiness of a patient, bio-sensors are biologically embedded into the human body. bio-sensors measure the data from the human body and it is transmitted to an external signal-processing device for further action [4]. Despite of ISM band, nowadays, the 77GHz frequency is also able to perform health care operations like monitoring the blood pressure and heart beat [51]. Further, cloud-based approaches were developed to convey the bio-sensing data to external devices [52]. Thus there is a possibility to combine both sensing and communication functions. An experimental study was conducted in [53], where a tactile bio-sensor element communicates via skin layers to the external device for further signal processing. However, still, there is a lot of scope for research in this area.

5) IMAGING AND COMMUNICATION SYSTEMS

The upper millimeter(mm) wave frequency band (52.6GHz-114.25GHz) [54] has been allotted for fine-resolution image sensing and also supports large throughput-based wireless communications [5]. synthetic aperture radar (SAR) based imaging emerged as one of the prominent solutions in mmwave frequency for on-road automotive vehicle driving and parking [55]. For example, Google has introduced a project Soli, which performs accurate human gesture detection by utilizing 60GHz millimeter wave radar [56], [57]. The full potential of using the MIMO configuration in the SAR imaging demonstrated the enhanced imaging capabilities [58]. Further, this mm-wave radar can be interfaced with 5G smartphones and tablets for further device-device communication [59]. Thus Google has given the motivation to look for a smart radio that can perform both sensing and communication operations on a unique hardware platform.

6) LIGHT-BASED SENSING AND COMMUNICATION SYSTEMS

With the proliferated development of wireless technologies, the RF spectrum is scarce. This has made researchers think about light-based systems to avoid spectrum congestion issues [60]. A new technology Li-Fi (Light Fidelity) was developed in [61], which is analogous to Wi-Fi systems. The Li-fi technology was developed to fulfill user requirements like high throughput and fast data transmission [62]. Optics is also a very fast-growing technology used for remote sensing applications [63]. Subsequently, lidar is used for surveillance of wetlands [64] and optics-based remote sensing is used for sea level monitoring [65]. Here also there is a feasibility for the coexistence of Lidar and Li-Fi systems.

7) RFID SYSTEMS

A Radio Frequency Identification (RFID) system contains a reader, an antenna array of a reader, and tags. Firstly, the reader sends a sensing signal toward the tag, then the tag modulates the signal and reverts it to the reader. Then the reflected signal consists of a special signature created according to the change in the tags antenna load [66]. Communication is the principal operation of the RFID technology, as the tag reflects some valid information concerning health and identity [67]. RFID technology has also been deployed for radar target detection [68] and target localization [66]. Thus RFID system is a kind of cooperative radar-communication system as the RFID sensing is accomplished by setting up a cooperative communication link between the tag and reader.

According to the literature review presented in Section I and various applications of coexisted radar-communication systems, it is inevitable to have shared radar spectrum access with the communication system. Further, the study conducted on the coexisted radar-communication system elucidates that Co-operative Radar-Communication System (CRCS) and Dual-Functional Radar-Communication (DFRC) Systems are more suitable for simultaneous sensing and communication operations. In the Cooperation category, both subsystems use separate waveforms for Radar and Communication signal transmission [69]. Whereas the DFRC system uses a joint waveform for both sensing and communication applications, which improves spectrum utilization efficiency [7]. As we have noticed the importance of waveform design in Cooperative Radar-Communication and DFRC systems, in this review paper we are going to give a detailed survey on preliminary approaches to the design of optimum waveforms, which are appropriate for concurrent sensing and communication operations. In addition, the survey is conducted by considering the latest research articles related to the waveform design for radar-communication convergence.

III. WAVEFORM DESIGN APPROACHES FOR A CRCS

The transmitter waveform design plays a pivotal role in the development of the Cooperative Radar-Communication System (CRCS). Hence, an illustrated review of various waveform design approaches is conducted to finalize the most suitable waveform for a CRCS.

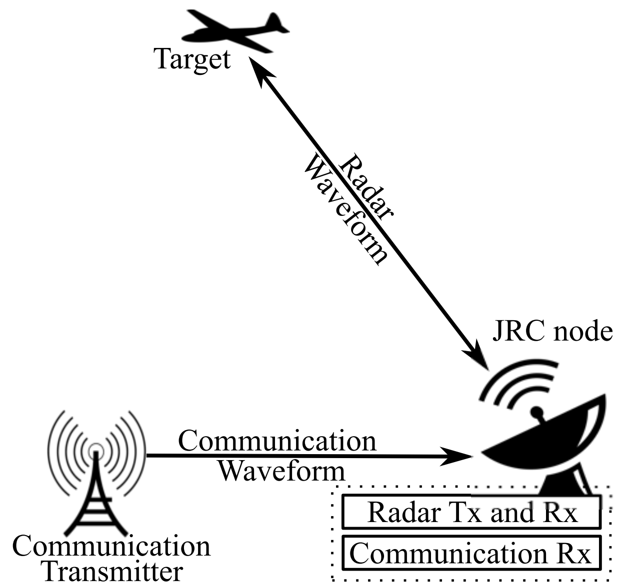

FIGURE 8. Basic cooperative radar-communication system model [26].

A. SYSTEM MODEL

Firstly to create awareness about a CRCS environment an instructional model is depicted in Figure 8. However, this model can be extended in the development of a CRCS model for various complicated scenarios. Here the Joint Radar-Communication (JRC) receiver acts as a radar transmitter/receiver and communication receiver. Here JRC receiver can perform target detection and decoding of communication signals at the same time. Moreover, only one radar target has been considered and its area of cross-section is well approximated. Here, both communication and radar are single input single output (SISO) systems. Both subsystems are allowed to access the same time-space-spectrum. In the CRCS model, a known transmitted radar waveform is used for Channel sensing purposes and it is conveyed to the communication transmitter. Thus there is cooperation between radar and communication systems. The Successive Interference Cancellation (SIC) receiver model was the major breakthrough in cooperative radar-communication systems to avoid mutual interference [6].

In a cooperative radar-communication system, a SIC receiver model has been deployed to make communication performance solely depend on the radar spectrum. In this model, it is assumed that the radar target time delay is known to the experimenter based on preliminary observations in the presence of process noise. With the target information, the target echo is predicted and it is subtracted from the JRC received signal. As we know, there is always some deviation between the predicted and actual location of the target. This deviation is mentioned as residual contribution $n_{resi}(t)$ to the JRC received signal. By decreasing the rate of communication, the SIC receiver can extract communication messages from the radar-suppressed JRC signal. The JRC receiver utilizes the extracted communication message to reconstruct and suppress the communication waveform from

TABLE 2. Summary of radar sensor-centric waveform design approaches in a CRCS.

Ref. No	Objective function	Constraints	System performance	Year
[28]	Minimizing the CRLB	NSP	Target direction estimation	2012
[70]	Matching of desired radar beam pattern	Constant envelope, NSP	Transmitted beam pattern and Mean Square Error (MSE)	2014
[19]	Maximizing the SINR	EC, MAIEC, SC	Radar target detection and tracking	2014
[71]	Minimizing the interference due to MIMO radar users at the cellular basestation	NSP	Radar transmit beam pattern	2015
[72]	Maximizing the SINR	MAIEC, RWEC, SC	Energy Spectral Density (ESD) of radar waveform	2015
[73]	Maximizing SIR	IPC at the communication receiver	Power Spectral Density (PSD) of radar and communication signals	2016
[74]	Maximizing SINR	EC, MAIEC, SC	SINR and ESD of radar waveform	2016
[30]	Minimum difference between the precoded and original radar signal.	Interference power constraint	MSE of radar waveform and BER of communication waveform	2016
[75]	Maximizing information rate	Polynomial spectral mask	Radar estimation rate and communication rate.	2016
[76]	Maximizing SINR	EC, MAIEC, SC	ESD and auto-correlation characteristics	2017
[77]	Maximizing SINR	CMC, ECC, CRC	SINR of both radar and communication systems	2018
[69]	Minimizing CRLB	RTPC, MAIEC, SPRC	Target estimation error variance	2018
[26]	Minimizing CRLB	TPEVC, SLC	Radar estimation rate and communication rate	2019
[78]	Minimizing CRLB	TPEVC, PRC	Radar estimation rate and communication rate	2023

the received signal. Now the radar signal is rescued from communication signal interference. This type of interference mitigation is named SIC. For a JRC system, the received signal z(t) is given as

$$z(t) = b_{com}\sqrt{P_{com}}\, r(t) + n(t) + \sqrt{P_{rad}}\, a_{rad}\, x(t-\tau) \quad (1)$$

Here 'b_{com}' represents the communication channel gain, P_{com} indicates the transmitted communication power, '$r(t)$' represents the received communication signal, '$n(t)$' represents the receiver thermal noise, 'P_{rad}' denotes the radar transmitted power, 'a_{rad}' represents the radar channel gain, and '$x(t-\tau)$' denotes the echo of the radar target.
The received signal at the communication receiver, after predicted radar echo suppression is obtained as,

$$\tilde{z}(t) = b_{com}\sqrt{P_{com}}\, r(t) + n(t) + \sqrt{P_{rad}}\, a_{rad}[x(t-\tau) - x(t-\tau_{pre})] \quad (2)$$

Here '$x(t-\tau_{pre})$' indicates predicted radar echo and 'τ_{pre}' indicates predicted target delay.

B. WAVEFORM DESIGN APPROACHES

In the Cooperative Radar-Communication System (CRCS), the radar and communication systems use separate waveforms for their tasks [5]. According to [69] and [26] whenever different waveforms are utilized for both sensing and communication purposes, distinct constraint-based optimization methods have been proposed. These methods have been categorized into the Sensor-centric method and communication-centric method.

1) SENSOR-CENTRIC METHOD

In this approach, radar waveform is optimized to improve the performance of a CRCS. Firstly, an adaptive radar waveform was projected onto the null space between the radar and communication systems to avoid mutual interference in a CRCS [28]. Subsequently, a Null Space Projected (NSP) constrained optimal Multiple-Input-Multiple-Output (MIMO) radar waveform was designed in [70] to avoid mutual interference in a CRCS. Later, a spectrally constrained optimal radar waveform was designed in [19] to reduce the interference to neighboring communication users in a CRCS. Further, the radar waveform was optimized based on maximizing the SINR subject to the Energy Constraint (EC), Maximum Allowable Interference Energy Constraint (MAIEC), and Similarity Constraint (SC). Whereas in [71], a radar waveform was designed using an antenna array by considering the NSP and imposing the constraint on interference power received at the MIMO cellular base stations to further mitigate the mutual interference in a CRCS. Further, an optimal radar waveform was designed based on maximizing the Signal-to-Interference-Noise-Ratio subject to MAIEC, Radar Waveform Energy Constraint (RWEC), and SC to further enhance the performance of a CRCS [72]. Furthermore, an Interference Protection Criteria (IPC) at the communication receiver was defined in [73] to improve military radar performance in a CRCS without any interference to communication users. Later, a radar waveform is optimized based on EC, MAIEC, and SC to specifically improve the performance of a radar system in a CRCS [74]. On the other side, a Small Singular Value Space Projection Method (SSVSPM) was proposed in [30], where a radar precoder was designed to avoid interference with neighboring communication users in a CRCS.

In [75], a Linear Frequency Modulated (LFM) radar waveform is developed based on a polynomial spectral mask to jointly maximize both the radar estimation rate and communication data rate in a cooperative scenario. In [76],

TABLE 3. Summary of communication-centric waveform design approaches in a CRCS.

Ref.No	Waveform design approach	System performance	Year
[35]	OFDM multi-carrier	Radar image detection and its range profile	2011
[79]	OFDM+PSUN	Bit Error Rate (BER) of a communication system	2015
[80]	LSA and LCMV beam forming	Radar target detection performance	2016
[81]	NSGA-II multi-objective evolutionary algorithm	Total probability of target detection errors and accomplishing a link between BS and UE	2016
[82]	Advanced Minimum Coupling Loss (A-MCL)	SINR for radar system and average downlink data rate for communication system	2016
[83]	Adaptive Integrated OFDM	Data information rate for a communication system and mutual information for radar system	2017
[84]	LPI based OFDM	LPI-performance in terms of total radiated power and data information rate for communication system	2018
[85]	OFDM+frequency spread Gaussian pulse signal	Averaged Root CRB (RCRB) for radar system and mutual information for communication system	2019
[86]	OFDM-based passive radar signal	Target velocity estimation for radar and BER for communication system	2020
[86]	Code division OFDM	BER for a communication system and RMSE for radar range and velocity estimation	2021
[87]	3GPP 38.211 OFDM Signal	Zero Doppler cut self-ambiguity and cross-ambiguity functions are used to analyze radar sensor performance	2022
[88]	Continuous Phase Modulation (CPM) codes	SAR image analysis using radar and mismatched filters.	2023

a Radar Environmental Map (REM) was utilized to restrict the radar waveform spectrum such that the radar band is allowed for cooperative transmission. In [77], an optimum MIMO radar waveform was designed based on maximizing the Signal-to-Interference-Noise-Ratio (SINR) at the radar receiver subjected to Constant Modulus Constraint (CMC), Similarity Constraint (SC), Energy Constraint on the Communication waveform (ECC), and Communication Rate Constraint (CRC), in a CRCS. Whereas in [69], the radar waveform was optimized to estimate the parameters of a radar target in the CRCS environment. Further, the optimization was carried out by considering CRLB as an objective function subject to the Radar Transmitted Power Constraint (RTPC), MAIEC, and Sub-carrier Power Ratio Constraint (SPRC). Later, a unique estimation error variance approach was proposed in [26], to optimize the Non-Linear Frequency Modulated (NLFM) radar waveform spectrum for improving the performance of both radar and communication systems in a CRCS. In this approach, Cramer-Rao-Lower-Bound is considered as the objective function and it is minimized subject to the Threshold Point Error Variance Constraint (TPEVC) and Spectral Leakage Constraint (SLC). In all the previous contributions, the formulated optimization problem is non-convex, which obtains only a locally optimum solution. Recently, in our previous work [78], a Spatial Branch and Bound (SBnB) Framework was considered to achieve a globally optimized solution for an NLFM radar waveform. Further, a Threshold Point Error Variance Constraint (TPEVC) and Power Ratio Constraint (PRC) to minimize the CRLB in a CRCS scenario. Furthermore, this approach has achieved improved performance in both subsystems under the CRCS environment. A quick summary of all the radar sensor-centric approaches is listed in Table 2.

2) COMMUNICATION-CENTRIC METHOD

In this approach, the communication waveform is optimized or adapted to improve the performance of a Cooperative Radar-Communication System (CRCS). Primarily, an adaptive Orthogonal Frequency Division Multiplexing (OFDM) based multi-carrier waveform was used in [35], to perform both sensing and information transmission concurrently. Further, the robustness of the OFDM waveform with reference to spectrum allocation ensures effective radar target detection [79]. Whereas in [89], a Precoded SUbcarrier Nulling (PSUN) scheme was proposed for the OFDM-based wireless communication system to cooperate with the pulsed radar in the cooperative scenario. PSUN is a novel scheme to strongly mitigate the mutual interference between pulsed radar and wireless communication systems. In [80], a novel Licensed Shared Access (LSA) was introduced to share the radar band with the communication system. Further, with the help of a Linearly Constrained Minimum Variance (LCMV) beamforming solution, the target detection performance was analyzed along with the downlink communication data transmission. In continuation to the previous work, a multi-objective optimization method was employed to ensure desired performance in the CRCS environment [81]. Later, a spatial-temporal technique along with adaptive power control in the communication base station was proposed in [82] for spectrum sharing in a CRCS scenario. An optimal OFDM waveform was designed by considering mutual information as the objective function subject to the total power constraint to improve the performance of a CRCS [83]. In [84], a Low Probability Intercept (LPI) based optimal OFDM waveform design scheme was developed for simultaneous LPI operation in radar and data operation in a communication system. Here, the transmitted power of each OFDM subcarrier is minimized subject to mutual information and information rate. In [85], a cooperative MIMO radar and MIMO communication system were examined. Further, both radar and communication systems improved their performance gain by mutual cooperation. A passive radar system was considered to estimate the target trajectory by using the OFDM waveform design presented in [86]. Whereas in [87], a machine-type new code-division(CD)-OFDM scheme was developed to achieve reliable radar target detection and communication data rate in a cooperative scenario. Here a Successive Interference Cancellation (SIC) receiver model is deployed to mitigate the mutual interference between both subsystems. Recently, Continuous Phase-Modulated (CPM) codes have been used to transmit communication information and create high-resolution synthetic aperture radar images in the CRCS environment [88]. The summary of all the communication-centric waveform design approaches for a CRCS is listed in Table 3.

3) LEARNING-BASED APPROACHES

The Radio Frequency (RF) spectrum state is quickly varying both spatially and temporally due to the coexistence of radar and communication systems. Learning-based waveform design approaches with the information from cooperative systems are one of the possible solutions to improve spectrum utilization efficiency and the performance of a CRCS [96]. Moreover, these learning-based approaches also improve the convergence time of a transmitted waveform [93]. By this learning activity, sophisticated knowledge-aided system development is possible [99]. Hence, in this section, we briefly explain the various learning methods involved in designing an optimal waveform to improve the performance of a Cooperative Radar-Communication System (CRCS).

The first major application related to cooperative radar and communication was cooperative adaptive cruise control [90]. Interestingly, the speed-controlling mechanism relies on machine learning algorithms. After a while, a new Reinforcement Learning (RL) method was developed based on the Markov Decision Process (MDP) to solve the optimization problem to mitigate the interference in a radar-communication coexisted scenario [91]. In addition to previous work, a Deep Reinforcement Learning(DRL) method was proposed in [94], to improve the radar target detection performance in a non-cooperative RADar-COMMunication (RADCOMM) coexisted scenario. Here the radar sensor learns to adapt the center frequency and bandwidth of the Linear Frequency Modulated (LFM) waveform. A constrained base online learning method was developed to design an optimal LFM waveform to achieve optimal target detection performance in a coexisted RADCOMM environment [95]. Whereas in [92], the effectiveness of the RL approach in simplifying cooperative radar-communication scenarios was investigated. Further, the performance of the CRCS system was analyzed in terms of radar-estimation-rate, and communication data rate. In [96], a Model-Based Online Learning (MBOL) method was proposed to provide an organized way to prepare effective learning algorithms for resource allocation in a Joint Radar-Communication System (JRCS). Further, a new Online Convex Optimization (OCO) framework was developed to optimize the transmitted waveforms by deploying convex optimization with the MBOL method [100] in a coexisted RADCOMM environment.

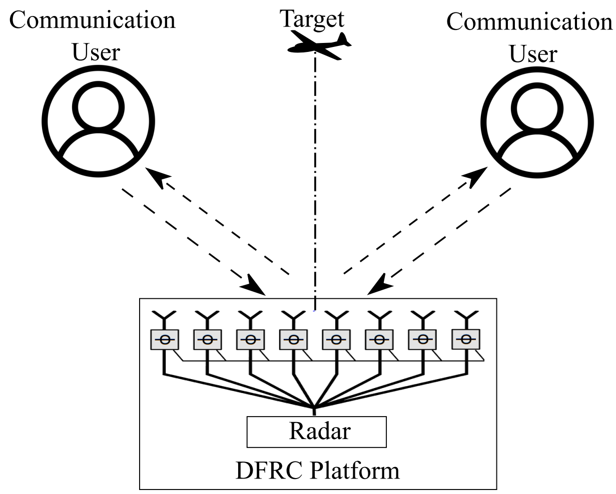

FIGURE 9. Basic DFRC system model.

Here the MBOL method was developed based on [101] and [102]. In [97], a multi-agent extension-based Proximal Policy Optimization (PPO) algorithm was proposed to improve the learning from raw observations and schedule radar and communication operations in a JRCS. Recently, a combination of Distributed Kalman Filter (DKF) and Deep Reinforcement Learning (DRL) techniques improves the performance of the anti-eavesdropping capacity of a communication system and combat jamming interference in an autonomous vehicle [98]. The summary of all the learning-based waveform design approaches for a CRCS system is presented in Table 4. In addition, the critical evaluation of the CRCS waveform design approaches is summarized in Table 5

IV. WAVEFORM DESIGN APPROACHES FOR A DFRC SYSTEM

The major challenge in a Dual-Function Radar-Communication (DFRC) System is to design a waveform that performs both radar and communication system operations. However, to create a sense of the DFRC working, a brief discussion is presented in the subsequent section.

A. SYSTEM MODEL

A DFRC system is set up with a common platform, which performs the primary radar function and communication function concurrently. We consider a DFRC scenario as shown in Figure 9, where the DFRC platform transmits a radar probing waveform towards the target and communication symbols to one or more communication users. The crux of downlink transmission is to enclose communication information into radar pulses. Here we assume that the radar Pulse Repetition Interval (PRI) is equal to the symbol duration of the communication signal. To demonstrate, the baseband signal is exploited in the form of SIMO and MIMO radar configurations.

1) SIMO RADAR

In this configuration, radar is equipped with a uniform linear array(ULA) having 'M' antennas transmitted with a power of

TABLE 4. Summary of learning-based waveform design approaches for a CRCS.

Ref.No	Waveform design approach	System performance	Year
[90]	Reinforcement learning	Adaptive cruise control	2011
[91]	Markov decision process+reinforcement learning	Optimized radar resolution and SINR	2018
[92]	Reinforcement learning	Radar estimation rate and communication data rate are analyzed	2018
[93]	LSTM recurrent neural networks	Reduces the convergence time for the optimization framework and desired radar and communication characteristics are achieved	2019
[94]	Deep reinforcement learning based LFM	Improved radar target detection performance along with satisfactory communication data rate	2020
[95]	Constrained Online learning framework	Favorable target detection performance in the presence of distortion	2021
[96]	Model-Based Online Learning (MBOL) framework	Efficient resource sharing between radar and communication systems	2022
[97]	Deep multi-agent reinforcement learning	Addressed the problem of time sharing between radar and communication systems	2022
[98]	Deep reinforcement learning	Enhances anti-eavesdropping communication capacity and RMSE for radar system	2023

TABLE 5. Critical summary of waveform design approaches for a CRCS.

Type of waveform design approach	Advantages	Disadvantages	Application conditions
Radar sensor-centric	Efficient utilization of radar spectrum	Trade-off in radar and communication system performance	Dynamic resource allocation, seamless integration of radar sensing and communication functionalities
Communication-centric	Achieving higher communication performance	Sub-optimal radar sensing performance	High communication data rate, Limited radar requirements
Learning-based	Adaptability and flexibility of the waveform	Complexity associated with training machine learning models and the requirement for large amounts of data	System requirements, computational resources, compliance related to communication protocols and spectrum utilization

'P_t'. Then for a SIMO radar, the transmitted signal vector of order M X 1 having pulse duration τ can be defined as,

$$\mathbb{S}_{\text{SIMO}}(t;\tau) = \sqrt{P_t} W_1{}^* \Phi_1(t) \tag{3}$$

here 't' represents the fast time, 'W_1' represents normalized u beam forming weight vector and $\Phi_1(t)$ represents orthonormal radar waveform. In this configuration beam forming weight vector 'W_1' and $\Phi_1(t)$ satisfies the typical radar transmitted beam pattern and Doppler range resolution.

2) MIMO RADAR

Consider a set of 'M' orthogonal waveforms, projected independently and satisfying the condition $\int_{T_\Phi} \Phi_m(t)\Phi^*_{m'}(t)dt = \delta(m-m')$. The MIMO radar transmitted signal vector with pulse duration 'τ can be expressed as,

$$S_{\text{MIMO}}(t;\tau) = \sqrt{\frac{P}{M}} \sum_{m=1}^{M} W^*_m \Phi_m(t) = \sqrt{\frac{P}{M}} W\Phi(t), \tag{4}$$

here W_m represents the M X 1 transmitted beam forming weighted vector connected with m^{th} orthogonal waveforms, $\Phi(t) \triangleq [\Phi_1(t), \ldots, \Phi_M(t)]^T$ represents set of 'M' orthogonal radar waveforms. Then M X M transmit beamforming weighted matrix is $W \triangleq \left[w^*_1, \ldots, w^*_M\right]$ is considered to be normalized i.e tr$\{W^H W\} = M$. For MIMO radar, the transmitted beamforming matrix '**W**' and a vector of orthogonal waveforms $\Phi(t)$ needs to be optimized. The radar parameters remain the same within the coherent processing interval (CPI). So, in both SIMO and MIMO configurations, communication information is transmitted either in the form of a modulating radar waveform or beam pattern.

B. WAVEFORM DESIGN

Based on the research that has been conducted on waveform design for a DFRCS, the waveform design methods are classified into sensor-centric and communication-centric methods.

1) SENSOR-CENTRIC

In this approach, the primary job is to perform radar sensing operations and perform communication data transmission by embedding communication symbols into radar pulses [103]. The first DFRC scheme was introduced by [104] where communication bits are transmitted as radar pulses based on pulse interval modulation. After a while, an Ultra Wide Band (UWB) dual functional radar and communication system was designed using a common antenna aperture [105]. Further, an LFM waveform was used for encoding data, where binary bits 0 and 1 are represented by up and down chirp waveforms. Later, an intra-pulse radar-embedded communication scheme was presented in [106] and [107] which performs Low-Probability-Intercept (LPI) based communications. However, the major setback in previous methods is, that the communication symbol rate is equivalent to the chirp rate only, which is very much less than the normal communication system symbol rate. subsequently, an optimal intra-pulse modulated radar waveform was designed based on the Signal-to-Interference-Noise-Ratio (SINR) as the objective function subject to similarity constraint and energy constraint for dual function purposes [108]. Here also communication information is embedded into radar pulses. Subsequently, efficient communication data embedding methods were developed for DFRC configurations with multi-sensor (Tx/Rx) configurations [109], [110]. Further, a new scheme was developed for a DFRC system to embed the communication information into radar pulses by utilizing the side-lobe control and waveform diversity [103]. Furthermore, a detailed survey on various signaling schemes for communication information embedded radar pulses was demonstrated in [111]. Later, a new algorithm was developed to design waveforms for a MIMO array to concurrently carry out radar and communication operations in a DFRC system [112]. However, these aforementioned approaches are confined to a very low communication data rate for safeguarding the radar operation [113].

Whereas in [114], a MIMO radar transmit beam pattern was utilized to simultaneously perform both target detection and communication data transmission in a DFRC configuration. After a while, a review of data embedding by considering various beam pattern modulation schemes namely Amplitude Modulation (AM), Phase Modulation (PM), and Index Modulation (IM) was presented in [7]. In another communication, an optimal radar beam pattern was designed for a DFRC system to perform radar target detection and communication data transmission [115]. An outage-based dual-functional radar beamforming design was proposed in [116], to accomplish high communication data rates and tracking of passive targets. A quick summary of all the radar sensor-centric waveform design approaches for a DFRC system is presented in Table 6.

2) COMMUNICATION-CENTRIC

This approach mainly relies on beamforming of the transmitted signal using multi-antenna base stations to perform radar operations is fascinating and most widely preferred [113]. Hybrid beamforming design is widely preferred for wireless communication systems to reduce power consumption, especially in a DFRC system [117]. Further, a hybrid precoding design scheme was developed for a given RF codebook in [118]. Furthermore, a hybrid beamforming design was utilized for an OFDM-based single-user MIMO system [119]. The aforementioned research articles were utilized to develop an optimum hybrid waveform design approach in [121] for the OFDM-DFRC system to improve the estimation accuracy of radar and sustain similar communication performance even in the presence of multipath fading. An Orthogonal Frequency Division Multiplexing (OFDM) waveform based on Golay block coding was designed for both sensing and communication purposes [120]. In [122], a joint beamforming design was proposed for an OFDM-based DFRC system to improve the radar target detection performance in the presence of clutter. An optimal robust beamforming design was proposed for a DFRC system to improve both sub-systems' performance by constraining the radar-radiated energy in the region of interest [123]. Recently, a Constant Modulus (CM) radar waveform was designed for a DFRC system to improve the target acquisition performance in the presence of clutter [124]. The summary of all the communication-centric waveform design approaches for a DFRC system is presented in Table 7.

3) LEARNING-BASED WAVEFORM DESIGN APPROACHES

The Machine Learning (ML) waveform design approaches play a significant role in making the DFRC system more adaptable to the spectral environment. Further, deep learning methods are preferred to perform various tasks such as target classification, optimal waveform selection, and finding optimal RF resources [125] in the DFRC environment. Thus, in this section, we briefly demonstrate various research works that have been carried out related to machine learning and deep learning approaches toward the development of an efficient DFRC system.

A Deep Reinforcement Learning (DRL) algorithm was developed to allow the Autonomous Vehicle (AV) to sense and quickly get information regarding the optimal policy of the RF environment [126]. The advantage of deep learning in the communication system is to avoid interference from radar systems was investigated in a DFRC scenario [127]. Here the LFM and FMCW radar waveforms are considered to be the interference sources to the communication system. Whereas in [128], the Double Deep Q-learning system (DDQS) and Q-learning algorithms were considered to optimize the time allocation for radar sensors and communication systems in the DFRC environment. In [129], a Reinforcement Learning (RL) based optimum waveform was designed using beam pattern modulation to improve the target detection performance corresponding to weak targets in the presence of strong clutter in the DFRC environment. Here, the downlink communication data transmission was carried out along with the target detection. A quick summary of learning-based waveform design approaches is presented in Table 8. In addition, the critical evaluation of DFRC waveform design approaches is summarized in Table 9.

V. FUTURE RESEARCH DIRECTIONS

In this paper, we have reviewed various waveform design approaches for the development of a Cooperative Radar-Communication System (CRCS) and Dual Functional Radar-Communication System (DFRCS). Based on the critical literature survey, we have noticed a few areas where researchers need to throw a lot of light to further enhance the performance of coexisted radar-communication systems.

A. MACHINE LEARNING-BASED WAVEFORM DESIGN

Most of the constraint-based multi-objective optimization problems suffer from computational complexity or high convergence time [78]. To improve the convergence time, there are some recurrent neural network-based waveform design approaches have been proposed in [93] and [128]. However, there is a lot of scope to develop advanced machine learning algorithms to reduce the computational complexity in a CRCS. In addition, there is a lot of room for improvement, especially in the area of receiver signal classification. More

TABLE 6. Summary of radar sensor-centric waveform design approaches for a DFRC system.

Ref.No	Waveform design approach	System performance	Year
[105]	LFM with up-chirp and down-chirp	Radar range resolution and BER for communication system	2007
[106]	Intra pulse modulation	LPI performance for radar and symbol error rate for the communication system	2010
[107]	Intra pulse modulation	probability of intercept for radar and BER for the communication system	2011
[108]	Intra-pulse modulation is subject to constraints	LPI for radar and symbol error rate for the communication system	2015
[109]	Sidelobe control + waveform diversity	BER for the communication system and power distribution for radar	2015
[103]	Sidelobe control with beamforming + waveform diversity	Probability of target resolution for radar and BER for the communication system	2016
[111]	radar-embedded communication signals	The signal-to-noise ratio for radar and BER for the communication system	2016
[112]	Far-field radiated emission design	PAPR for radar and BER for the communication system	2017
[114]	MIMO+transmit beamforming	Symbol error rate for the communication system and angular ambiguity mitigation for radar	2018
[115]	Beam pattern design subject to minimizing multi-user interference	Probability of detection for radar and achievable sum rate for communication system	2018
[7]	Beam pattern modulation	Overall gain analysis for radar and BER for the communication system	2019
[116]	Outage-based beamforming design	Passive target detection performance in radar and the achievable data rate for the communication system	2023

TABLE 7. Summary of communication-centric waveform design approaches for a DFRC system.

Ref.No	Waveform design approach	System performance	Year
[117]	Hybrid precoder design	Average achievable rate of a MIMO communication system	2014
[118]	Frequency selective hybrid precoder design	Spectral efficiency of a mmWave system	2016
[119]	Hybrid beamforming OFDM	Average spectral efficiency and average weighted sum rate of an mmWave system	2017
[120]	OFDM-based Golay block coding	Wideband ambiguity function and range profile are analyzed for radar Bit Error Rate (BER) is analyzed for the communication system	2019
[121]	Hybrid beamforming OFDM	Spatial spectrum matching error for radar and average spectral efficiency for the communication system	2021
[122]	Beamforming along with OFDM	maximizing radar SINR and satisfying communication SINR	2022
[123]	Robust beamforming design	RMSE estimation for radar and achievable SINR for the communication system	2023
[124]	Constant modulus waveform design	Target detection probability for radar and symbol error rate for the communication system	2023

TABLE 8. Summary of learning-based waveform design approaches for a DFRC system.

Ref. No	Waveform design approach	System performance	Year
[125]	Deep learning-based hybrid beamformer design	Accuracy and spectral efficiency of a mm massive MIMO system is analyzed	2019
[126]	Deep reinforcement learning algorithm	Maximize the communication throughput and minimize the missed detection probability in autonomous vehicles	2020
[127]	Deep learning in communication systems and LFM and FMCW radar waveforms are considered	Radar target detection performance and Communication system symbol error rate performance are analyzed	2022
[128]	Double Deep Q-learning Network (DDQN)	Optimize the time allocation for both radar and communication systems	2022
[129]	Reinforcement learning + beam pattern modulation	Improved down-link communication system performance and enhanced the radar target detection performance for the weak targets	2023

specifically, it is always a tedious task for the joint receiver to separate the target echo and wireless communication signal from the users in the existence of noise, interference, and clutter. To overcome this problem, it is feasible to apply some learning approaches like Independent Component Analysis (ICA) in a joint radar-communication system. One such scenario can be found in [130], where, they had considered compressive sensing methods for performing symbol reception and target parameter estimation at the joint receiver. Hence, it is recommended to work on advanced machine learning approaches for signal classification and modernize the receiver design for a joint radar-communication system.

Figure 10 illustrates the significance of learning approaches in the joint radar-communication system. The points to be noticed are listed below:

- A rapid waveform can be designed to eradicate the computational complexity present in the optimal waveform design process.
- Here, the AI algorithm stack quickly finds the optimized solution for any radar waveform objective function with respect to waveform constraints.
- The machine learning algorithms also play a pivotal role in signal classification at the receiver, when the received signals are embedded with noise,

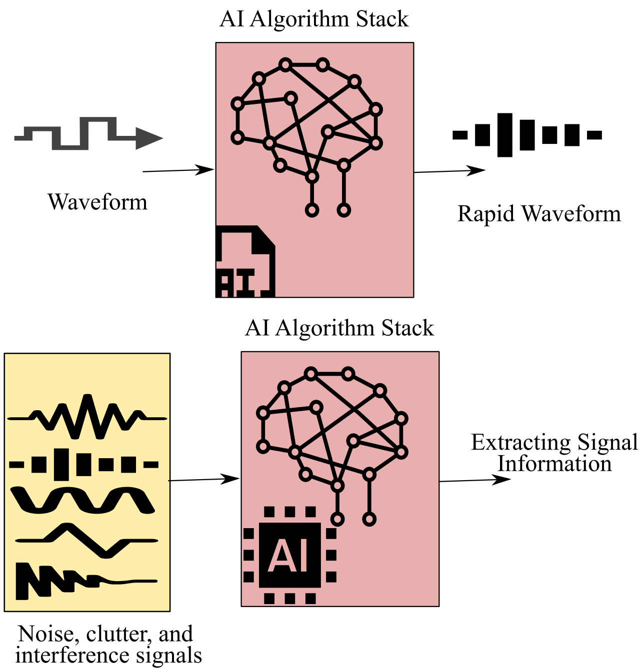

FIGURE 10. Scenario depicting the role of machine learning algorithms in designing the rapid waveform and performing the signal classification at the receiver.

interference, and clutter in a joint radar-communication system.

The implementation of machine-learning algorithms to design a waveform for a joint radar-communication system relies on the following factors:

- Availability of sufficient and relevant training data is pivotal for developing machine learning models for waveform design.
- Effective feature engineering is crucial for extracting vital information from radar and communication signals. Features may include signal characteristics, channel properties, target attributes, and environmental conditions [13].
- Selecting the right machine-learning algorithm is very critical. Various techniques such as supervised learning, unsupervised learning, reinforcement learning, and deep learning may be applicable depending on the specific objectives and characteristics of the joint radar-communication system [125].
- Training and validation of the data. In addition, the machine learning-based waveform design algorithm should be adaptable to operating conditions, channel characteristics, and system requirements.
- Performance evaluation of the machine learning-based waveform design algorithm should consider various metrics relevant to both radar and communication functionalities. These metrics may include detection and estimation accuracy, communication reliability, spectral efficiency, and overall system throughput [130].

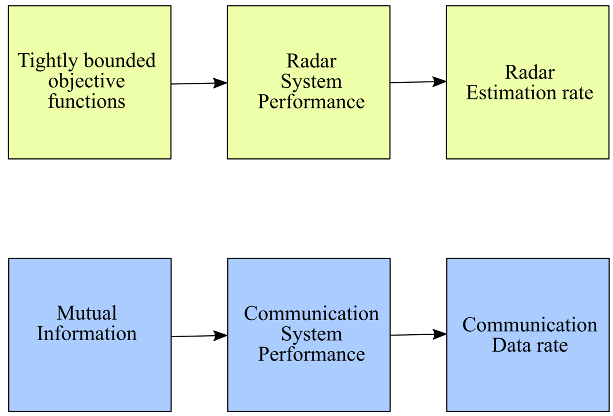

FIGURE 11. A simple block diagram to represent the bounds on the radar and communication system performance.

B. PERFORMANCE LIMITS OF DUAL-FUNCTIONAL WAVEFORMS

To understand about efficient sharing of RF spectral resources and the RF convergence of radar and communication systems, it is necessary to have an idea regarding the performance limits of a cooperative spectrum sharing [3]. These performance bounds are also helpful in target estimation performance in a CRCS spectrum sharing environment [131]. However, the performance limits of both radar and communication systems rely on performance inner-bounds and dual-functional (sensing and communication) waveforms [132]. It is known that the communication system channel capacity is well estimated in terms of mutual information between channel input and channel output. However, from the information theory perspective, radar sensing performance limits are not clearly defined like communication systems [133], [134]. Hence, a thorough investigation needs to be carried out on the performance limits of a dual-functional waveform (especially radar sensor-centric). Further, the study can be extended to derive tightly bounded objective function, sensor performance metric, connectivity between communication system data rate and radar estimation rate, and bandwidth considerations in hybrid beamforming waveform design. From Figure 11, the following aspects can be noticed for further development of a joint radar-communication system.

- The performance of a radar system completely relies on the tightly bounded objective functions subjected to suitable constraints.
- The communication system performance depends on the channel capacity and it is accurately estimated in terms of mutual information.
- To improve the radar and communication system performance, an optimum channel bandwidth should be considered to eradicate the problems of noise, interference, and clutter.
- Waveform design plays a crucial role in establishing the interconnection between the radar and communication systems for mutual transfer of information.

TABLE 9. Critical summary of waveform design approaches for a DFRC system.

Type of waveform design approach	Advantages	Disadvantages	Application conditions
Radar sensor-centric	Enhanced radar performance	Potential trade-off in communication system performance	Limited communication requirements, major priority is given to radar sensitivity and its accuracy
Communication-centric	Achieving higher communication performance	Sub-optimal radar sensing performance	Achieving high speed and reliable communication performance, radar is used only for environmental monitoring
Learning-based	Adaptability and flexibility in designing the waveform	Complexity associated with training machine learning models and the requirement for large amounts of data	Real-time adaptation, Integration capability

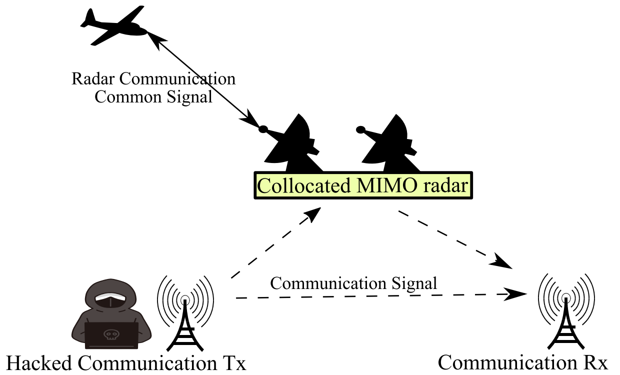

FIGURE 12. Example depicting the security concerns in a spectrum-sharing radar-communication scenario.

C. SECURITY CONCERNS IN SPECTRUM SHARING

The radar and communication spectrum-sharing approaches have raised privacy issues. In the process of radar spectrum sharing, military radar might disclose some vital security information to neighboring communication users. To avoid this, it is recommended to consider adaptive beampattern modulation schemes to provide physical layer security in a joint radar-communication system. However, some valuable information regarding security issues of joint radar-communication systems can be found in [135] and [136]. Figure 12, represents the security concerns of a joint radar-communication system. Here there is a transfer of information between radar and communication systems. However, the neighboring communication user can hack the secured information related to the radar system. According to [137], there is always a possibility that an adversary may launch an interference attack by using the precoder. Generally, the precoder contains some secured information about the radar, and communication users can hack it. However, by constraining the transmitted power of the adversaries this problem can be resolved. A thorough investigation is recommended to combat security concerns raised in a joint radar-communication system.

To maintain the transmission secrecy an artificial noise can be employed at the transmitter, provided the signal-to-noise ratio is guaranteed at the legitimate user [138]. Whereas, the machine learning models used in the joint radar-communication system should be designed with security and privacy considerations in mind. This includes protecting sensitive data, preventing adversarial attacks, and ensuring robustness against malicious exploitation [138]. In this way, one can develop a joint radar-communication system without any security issues.

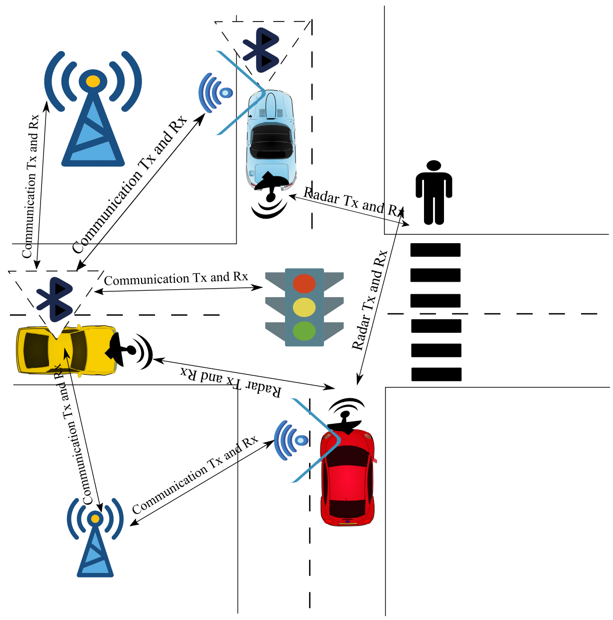

FIGURE 13. Example depicting the radar communication convergence in the on-road automotive vehicular scene.

D. DFRC FOR AUTONOMOUS SYSTEMS

The working of an autonomous system mainly depends on automotive radar and wireless communication systems. Converging these two systems and modeled as a DFRC system provides many advantages like chip power, size, throughput, security, and enhanced sensing capability [139]. Due to these advantages, the DFRC system is a good choice for autonomous systems. In Figure 13, we can see that all the vehicles are equipped with DFRC, which can simultaneously detect the other vehicles, humans, traffic lights, and poles within the vicinity. Meanwhile, traditional architectures use Bluetooth, wifi, and other communication modules to facilitate communication with traffic signals, other transmitters, and other vehicles. By deploying the DFRC, the existing communications modules are replaced.

- **Power, throughput, and size:** With the DFRC technology, it is easy to replace multiple modules (sensing and communication). Hence, the size of the overall module is less compared to multiple modules. Moreover, once the sensing is performed, the information is transmitted from the sensing module to the communication module, providing a delay. With this DFRC technology, there is no delay, and hence, the system's throughput increases. Further, due to compact size and more throughput, the overall dynamic Power of the system decreases.

- **Enhanced Sensing Capabilities**: In a scenario of occlusion, the ego may not be able to sense the scene behind the other vehicles or obstacles. In this case, the other vehicle can sense and transmit the same information to the ego. In addition to it, the multipath signals can also enrich the sensing capabilities.
- **Challenges**: The DFRC system models may not be suitable for all the driver assistance system functions [139]. Self-driving vehicles depend on various sensors, especially radar sensors, which exhibit unique robustness to heavy rain, snow, and poor light conditions. Due to the number of radars used in self-driving cars, radar interference is a serious issue. However, some novel approaches have been proposed to overcome radar interference [140]. In addition, various sensors like cameras and lidars are also used in autonomous vehicles. Combining these technologies and connecting them to a communication system is a challenging task.

Finally, a thorough investigation is required to practically introduce these DFRC strategies in autonomous vehicular environments and assess their performance in real-road environments. Hence, there is much scope for the researchers to concentrate more on various DFRC scenarios and their practical implementation possibilities for developing autonomous systems.

The DFRC reality to AV is possible, and can incrementally reach the matured stage owing to the existing prototypes

- It is already demonstrated that jointly implementing radar and communications decreases the number of antennas [141], and results in bottleneck requirements of overall system size, weight, and power consumption.
- The joint designs mitigate the mutual interference among neighboring cars, facilitate coordination and improve pedestrian detection [111].
- The embedding of digital messages in the radar probing signals supports low data rates [142], making it more suitable to serve as an additional channel to the standard communications functionalities of autonomous vehicles. This incorporation magnitudes the performance of the AV in both radar and communication aspects.

VI. CONCLUSION

In this review paper, we provided a complete survey about the research progress in the area of Cooperative Radar Communication (CRC) and Dual Function Radar Communication (DFRC) systems. Initially, application scenarios of the joint radar communication systems are explained. Subsequently, the system models of both cooperative and dual-functional radar-communication systems are discussed. These system models illustrated the importance of waveform design for transferring information between radar and communication systems. Subsequently, radar sensor-centric, communication-centric, and machine-learning-based waveform design approaches are discussed for both the Cooperative and dual-functional radar-communication systems. Further, the waveform constraints are notified for every radar waveform design approach and given a clear view of how one should perform the constraint-based waveform optimization. Furthermore, it is understood that over-constraining the waveform resulted in performance loss in the radar and communication systems. The performance metrics are identified and analyzed for every waveform design approach in the CRC and DFRC systems. Later, brand new learning-based waveform design approaches are discussed and analyzed for the joint radar-communication systems. At the end of each section, a quick summary is presented for easy understanding to the upcoming researchers. Eventually, this review article provides information regarding the concerns present in the existing waveform design approaches. Further, this article provides various challenges and research directions to the upcoming researchers in the area of waveform design. The research in this area is very trendy and rapidly growing due to the spectrum congestion problems faced by abundant communication users. In the future, we could see immense opportunities for academicians and industrialists to design the much needy joint radar-communication systems.

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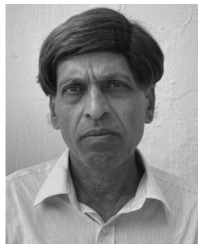

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