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Review

Joint Radar, Communication, and Integration of Beamforming Technology

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Abstract: In this paper, we dive into the exciting world of wireless communication, focusing on how millimeter-wave technology and Multiple-Input Multiple-Output phased array antennas are shaping the future of 5G and the upcoming 6G technologies. We cover the latest advancements in millimeter-wave and beamforming technologies, emphasizing their role in enhancing network security and efficiency in automotive vehicles through dual radar communication. Our discussion spans the benefits, applications, challenges, and solutions of these technologies individually from millimeter-wave to beamforming technologies and joint radar communications, alongside a look at their theoretical and practical implementations. We emphasize the integration of beamforming technology in joint radar communications for future automotive vehicles and its impact on automotive systems, smart cities, and the Internet of Things (IoT). Looking ahead, we discuss the potential of these technologies to transform future technology landscapes while also addressing the security implications of merging communication and radar capabilities. This paper aims to provide a clear view of the advancements and prospects of millimeter-wave, beamforming, and dual radar communication technologies.

Keywords: physical security; communications; beamforming; radar; MIMO

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1. Introduction

The advancement of future cellular and automotive communication relies significantly on improving millimeter-wave and Multiple-Input Multiple-Output (MIMO) systems, highlighting the need for high gain, data rate, and precision in beam direction for secure vehicle communication. Precoding techniques in multi-antenna systems, both linear methods, like Zero-Forcing (ZF) and Maximum Ratio Transmission (MRT), and nonlinear methods, such as Dirty-Paper Coding, play a vital role in enhancing wireless communication by improving signal quality without the need for channel state information. Linear methods are simpler, whereas nonlinear methods offer greater capacity [1]. Antenna arrays, including Antenna in Package, are crucial for modern wireless systems, reducing multipath fading and interference and supporting high data rates through beamforming and precoding techniques. These methods, which adjust signal amplitudes and phases, ensure that signals converge on the intended targets, utilizing interference to enhance signal clarity and reach [2–4]. Millimeter-wave technology's broad application, from medical imaging to smart automotive radars, demonstrates its versatility. It is instrumental in object detection, radar imaging, and dynamic target simulation in vehicles [2–4], and contributes to pedestrian collision avoidance by forecasting pedestrian paths and driver reactions [5]. Furthermore, research into millimeter-wave technology's polarization [6], its application in glucose sensing [7], and its role in preprocessing for AI-based imaging [8], alongside its potential in breast cancer detection [9], underscores its expansive utility across various fields.

The use of millimeter-wave technology is challenged by high attenuation, but beamforming emerges as an effective countermeasure, enhancing performance across various applications. Research highlights beamforming's versatility at millimeter-wave frequencies, particularly in the joint communication and sensing (JCAS) paradigm, where it addresses the complexities of full-duplex operations and the use of multiple beams for dual purposes in mobile communication networks [10]. Studies by Capone et al. [11] and Ning et al. [12] further underscore the significance of millimeter-wave and beamforming approaches in improving cell detection for obstacle avoidance in 5G networks and in advancing ultra-massive MIMO in terahertz communications, respectively. These technologies, including their application in Unmanned Aerial Vehicle (UAV) communications, present a symbiotic relationship that offers both potential and challenges [13]. Further investigations into beamforming techniques explore interference mitigation, precoding strategies [14–16], and the broader implications for wireless communication systems. Notably, comprehensive reviews by Chittimoju et al. [17] and Kutty et al. [18] on millimeter-wave technologies and beamforming advancements provide in-depth insights into their applications, challenges, and evolution. Rao et al. [14] contribute a detailed analysis of beamforming components, including hybrid and broadband couplers, emphasizing the diversity of the methods and designs critical to the field. Furthermore, [14,15] explore diverse beamforming methods. They delve into analog, digital, and hybrid techniques and switched and adaptive forms of beamforming, presenting a broad spectrum of approaches in this field.

Our research aims to merge radar and communication systems in automotive vehicles, leveraging millimeter-wave and beamforming technologies. This endeavor is underpinned by the pioneering work of Lazaro et al. [19], who explore car-to-car communication through modulated backscatter and frequency-modulated continuous-wave radar. Rybin et al. [20] highlight the development of a prototype communication system founded on symmetry and chaos theories, utilizing a microcontroller for operation. Further, Hieu et al. [21] demonstrate the significance of integrating radar and communication systems in autonomous vehicles through a transferable deep reinforcement learning framework, enhancing driving decision-making and safety. Butt and colleagues [22] investigate data collection via RADAR, LiDAR, and cameras, focusing on signal processing of multi-modal sensory inputs. Bilik et al. [23] and Luong et al. [24] discussed radar system advancements and resource management in JRC systems, respectively, emphasizing their importance in automotive technology. Hieu et al. [25] showcase smart dual-function radar communication systems for autonomous vehicles, stressing the necessity for simultaneous detection and communication. Our study will provide a detailed examination of millimeter-wave and beamforming technology, including the critical role of joint radar communication (JRC) and its components. This work emphasizes the integration of JRC in automotive vehicles, specifically in Section 4, highlighting its crucial role in enhancing physical security and supporting advanced driver assistance systems. It examines key technologies such as antenna design, phase shifters, variable gain amplifiers (VGAs), mixers, power combiners/dividers, power amplifiers, and buffer amplifiers essential for effective beamforming. The discussion extends to the innovative potential of these technologies, particularly focusing on the synergy between radar and communication systems and their growing importance. The narrative is supported by various designs from reputable sources, emphasizing the criticality of narrow beam technology in ensuring superior physical security through advanced beamforming systems in vehicles. The paper is structured to cover the background of millimeter-wave technology, beamforming techniques, our idea of duality radar and communication in automotive security, and prospects, culminating in a conclusive overview.

2. Background of Millimeter Wave, Applications, Problems, and Solutions

In the last decade, MIMO communication evolved from theory to practice in telecommunication, marking a significant advancement [26,27]. Millimeter-wave technology, with its 30–300 GHz frequency and 250 GHz bandwidth [28], is gaining traction for its potential in 5G/6G networks. O'Reilly et al. [29] highlight its suitability for video delivery, while Matiae, Dusan et al. [30] and Barneto et al. [31] explore its application in Orthogonal Frequency Division Multiplex (OFDM) modulation and JCAS optimization, respectively.

This underlines millimeter wave's broad applicability across sectors, including wireless communication and healthcare.

2.1. Millimeter-Wave Applications

Millimeter-wave technology plays a pivotal role across diverse applications including wireless communications, radar, imaging, and the IoT, among others. It is instrumental in advancing 5G/6G networks, as highlighted by Chakraborty et al. [32], who underscore its significance in wireless communication evolution. Brandão et al. [33] focus on millimeter-wave antennas designed for MIMO applications, emphasizing their contribution to enhancing wireless connectivity. Similarly, Ghaddar et al. [34] investigate how millimeter-wave technology performs in unique environments like subterranean mines, offering insights into its propagation characteristics when paired with directional antennas. Beyond its numerous benefits, there are challenges to consider in terms of using millimeter-wave technology. Notably, Serov et al. [35] present groundbreaking findings on using millimeter wave for measuring water-related continuums, marking significant advancements in scientific research. Despite its vast applications, the limitations of millimeter-wave technology warrant careful consideration.

2.2. Problems and Solutions

Millimeter-wave frequencies offer significant bandwidth but face challenges like higher path loss, sensitivity to weather, and complex beamforming, making urban deployment difficult [28]. Atmospheric conditions, including rain and foliage, significantly impact signal quality, with principles grounded in Friis's equation [28,36]. Directive beamforming at higher frequencies, such as 80 GHz, can achieve greater gains, improving signal strength compared to lower frequencies [28,37]. However, applications like autonomous vehicles encounter obstacles due to high path loss and atmospheric attenuation, necessitating advanced detection and communication strategies [38–40]. Human blockage and atmospheric absorption, particularly by oxygen, also affect signal performance, highlighting the need for effective deployment and technology integration [28,41–43]. Despite these challenges, millimeter-wave radar communication, with integrated beamforming, shows potential for vehicular networks and other applications. Advancements in beamforming and antenna design are crucial for enhancing MIMO technologies, including hybrid beamforming and massive MIMO systems. Adaptive modulation, relay nodes, and mesh networks play pivotal roles in optimizing frequency and channel selection. Additionally, weather monitoring and prediction are integral for network reliability, supported by hybrid network architectures and sophisticated signal processing techniques. Furthermore, regulatory support remains essential for the deployment and innovation of these technologies.

2.3. Millimeter Wave Importance in Automotive Vehicles

Wane et al. [44] introduce a groundbreaking integration of cognitive millimeter-wave MIMO phased array systems with optical sensing, opening new avenues for environmental perception and interaction. Giordani et al. [38] delve into millimeter-wave communication's challenges and prospects within vehicular networks, showcasing its potential for high data rates, enhanced capacity, and improved coverage, alongside its resilience to interference and capabilities in sensing and imaging.

Table 1 lists various papers that discuss JRC within the millimeter-wave spectrum. All target a common objective of using JRC at this frequency. However, none of the cited articles incorporate the beamforming concept.

Table 1. Millimeter wave and JRC.

S.NO	Research	Differences
[45]	Toward millimeter-wave joint radar communications: A signal processing perspective.	No Beamforming
[46]	Photonic Millimeter-Wave Joint Radar Communication System Using Spectrum Spreading Phase-Coding	No Beamforming
[47]	Adaptive Virtual Waveform Design for Millimeter-Wave Joint Communication Radar	No Beamforming
[48]	JCR70: A Low Complexity Millimeter-Wave Proof-of Concept Platform for a Fully-Digital SIMO Joint Communication Radar	No Beamforming
[49]	Future Millimeter-Wave Indoor Systems: A Blueprint for Joint Communication and Sensing	No Beamforming
[50]	Joint Communication and Localization in Millimeter-Wave Networks	No Beamforming
[51]	On Unified Vehicular Communications and Radar Sensing in Millimeter-Wave and Low Terahertz Bands	No Beamforming
[52]	Millimeter-Wave Vehicular Communication to Support Massive Automotive Sensing	No Beamforming
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3. Beamforming

Beamforming in millimeter-wave communication systems can be achieved through analog or digital means. Analog beamforming uses equipment like amplifiers, power adders, advanced antennas, and phase shifters to direct beams at specific targets, enhancing security by preventing unauthorized access and eavesdropping. This method relies on multiple antennas to produce pencil beams, offering superior security by reducing interception risks, as evidenced in several studies [15,53,54].The use of multiple antennas, particularly in MIMO systems, not only bolsters energy efficiency but also minimizes interference, thereby improving network performance [15,55–57]. Millimeter-wave technology is lauded for its high efficiency, data rates, and security, with significant contributions to energy efficiency being pivotal for future wireless networks [58–63]. Despite its advantages, millimeter wave faces propagation challenges, which are mitigated by employing smaller antennas that leverage high carrier frequencies to ensure effective signal transmission [15]. This approach enhances millimeter-wave systems' capacity and supports advanced applications, including 5G/6G. Furthermore, beamforming technologies like linear and nonlinear precoding adaptively enhance mobile system connectivity [15,64,65]. Precoding techniques, crucial for multi-antenna systems, are thoroughly explored alongside decoding in [65], underscoring their importance in modern wireless communication. Leveraging multi-antenna technology enhances wireless communication by improving privacy, spectrum efficiency, and signal strength, as detailed by researchers [66–70]. Pencil beam benefits, including targeted communication and reduced interference, underscore its importance [66–70]. Dahrouj et al. [71] further explore the efficiency gains through coordinated base station optimization in multi-antenna setups.

3.1. Linear and Nonlinear Precoding

Precoder matrix F and the role of its singular value decomposition (SVD) in stream separation and power allocation are detailed in [72], with [65] further analyzing precoding algorithms for wireless communications. Fatema et al. [73] survey linear precoding in single-cell and multicell contexts, comparing classical techniques. Equipped with full CSI, transmitters leverage NLP methods like DPC to optimally pre-subtract interference, enhancing system efficiency [74,75]. THP [75] emerges as a computationally simpler yet effective alternative to DPC, outperforming linear methods like BD in overlapping UE subspaces [75,76]. Albreem et al.'s study [65] offers a comprehensive view on NLP in massive MIMO systems, marking a significant contribution to wireless communication research.

The p matrix in Figure 1 helps to send signals correctly, the B matrix helps to improve, the K matrix helps to receive signals, and the C matrix adds extra improvement. Together, they decide how signals are sent and received, providing flexible options for better communication in different situations. In the scenario where B = 0, the generalized precoding method seamlessly transitions to the linear precoding approach as indicated in [65]. It is through the Modulo arithmetic that we finetune the average power, also elaborated upon in [65].

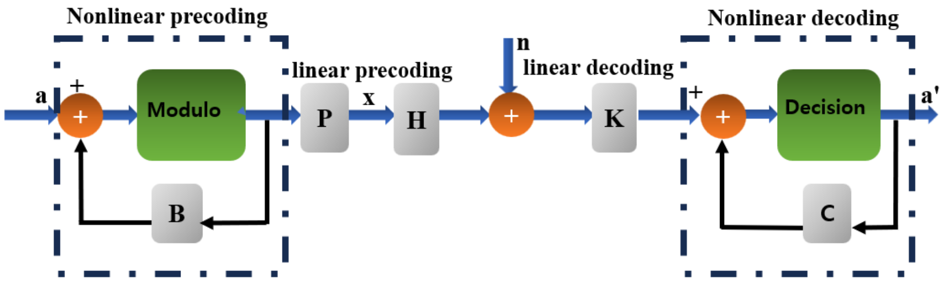

Figure 1. A modified generalized block diagram of communication systems with precoding and decoding techniques [65].

3.2. Technologies

3.2.1. Phase Shifter

Park et al. [77] explore the development of a 60 GHz low-power active phase shifter using 65 nm CMOS technology, highlighting its efficiency in beam steering and phased array applications. Their work demonstrates the advantages of impedance-invariant vector modulation in enhancing stability and isolation, employing novel vector modulator structures for precise phase adjustment. The simplified components and structures, including the vector-sum phase shifter and variable gain amplifier, are detailed with emphasis on their improved performance [77]. This streamlined approach offers significant insights into optimizing phased array and beamforming technologies.

The gain of the CS and Impedance Invariant variable gain amplifier (IIVGA) is provided in Equations (1) and (2).

$$A_{v,\mathrm{Cs}} = -\frac{\overbrace{\left(g_m - sC_{\mathrm{gd}}\right)}^{\text{complex } G_m}}{sC_{\mathrm{gd}} + sC_{\mathrm{ds}} + g_{\mathrm{ds}} + \frac{1}{sL_L}} \tag{1}$$

$$A_{v,II} = \frac{-\left(g_{m,N1} - g_{m,N2} + sC_{\mathrm{gd},N2} - sC_{\mathrm{gd},N1}\right)}{sC_{\mathrm{gd},N1} + sC_{\mathrm{gd},N2} + Y_{\mathrm{ds},N1} + Y_{\mathrm{ds},N2} + \frac{1}{sL_L}} \frac{-(N_1 - N_2)g_{m0}}{D} \tag{2}$$

where D is

$$D = (N_1 + N_2)\left(sC_{\mathrm{gd,ON}} + sC_{\mathrm{gd,OFF}} + sC_{\mathrm{ds,ON}} + sC_{\mathrm{ds,OFF}} + g_{\mathrm{ds,ON}} + g_{\mathrm{ds,OFF}}\right) + \frac{1}{sL_L} \tag{3}$$

The phase variation and admittance of CS and IIVGA are expressed below.

$$\Delta\varphi \approx \tan^{-1}\left(-\frac{\omega C_{\mathrm{gd}}}{\Delta g_m}\right) \tag{4}$$

$$\Delta Y_{\mathrm{in}} \approx s\left(\Delta C_{\mathrm{gs}}\right) + \Delta A_{v,\mathrm{CS}} sC_{\mathrm{gd}} \tag{5}$$

$$Y_{\mathrm{in,II}} \approx (N_1 + N_2)\left(sC_{\mathrm{gs,ON}} + sC_{\mathrm{gs,OFF}} + sC_{\mathrm{gd,ON}} + sC_{\mathrm{gd,OFF}}\right) + \frac{1}{sL_{\mathrm{I}}}. \tag{6}$$

In the 51–66.3 GHz range, a vector sum phase shifter (VSPS) exhibited a −3.8 dB average gain with minimal RMS gain and phase errors, consuming only 5 mW, underscoring its efficacy in automotive beamforming applications [71]. Kim et al. [78] focus on VSPS for 5G, noting performance within 30.9–41.7 GHz and a 45 mW power consumption, providing insights into millimeter-wave applications. Additionally, Singh et al. [79] enhance the Reflection-Type Phase Shifter (RTPS) for better electronic tunability at 10 GHz, demonstrating improvements over traditional models. Jing-Lin et al. [80] explore a 4-bit switched LC phase shifter, detailing its design and operational efficiency with specific characteristics like 400 mW power consumption in transmission and achieving 25 dB gain in reception [80]. These studies collectively advance our understanding of phase shifters' roles in next-generation communication technologies, highlighting significant developments in beam steering, electronic scanning, and millimeter-wave applications.

3.2.2. Variable Gain Amplifier

Park et al. [81], along with contributions from [78–80,82] and Siao et al. [83], focus on VGAs and their integration with phase shifters for enhanced signal quality and control in beamforming and phased array systems. Their studies highlight the design, implementation, and performance of VGAs using different topologies, such as Cascode and Current Steering Cascode (CSCC), with detailed comparative analysis. These VGAs, characterized by their power efficiency, gain control, and minimal phase variation, are crucial for applications requiring precise amplitude and phase manipulation. Notably, [82,83] showcase VGA's effectiveness in reducing power consumption and achieving significant gain control and phase stability. A schematic of the two-stage phase-compensated VGA is shown in [84] in which VGA1 is used for phase shifter and VGA2 for beam tapering. The power consumption is 16.8 mW, the peak gain is 9.3, and the gain controls ΔGain is 7 dB while using the CSCC topology in 65 nm technology [84]. Additionally, Lin et al. [85] address the impact of resistance–capacitance (RC) parasitics on millimeter-wave systems, offering solutions through the comparison of conventional and dual-gate (DG) MOSFET topologies, demonstrating DG MOSFET's superior performance in mitigating RC parasitics [85]. This collective research provides invaluable insights into optimizing signal amplification and conditioning for advanced communication systems. Ratnam et al. [86] pioneered the Joint Phase Time Array (JPTA) for 6G, a novel hybrid beamforming technique enhancing wireless technology and signaling future research directions. Table 2 illustrates the crucial role of beamforming significance. While the referenced papers delve into detailed explanations.

Table 2. Beamforming technology.

Ref.	Research	Differences
[87]	Dual-Iterative Hybrid Beam-forming Design for Millimeter- Wave Massive Multi-User MIMO Systems With Sub-Connected Structure	No JRC
[88]	Beam-forming Design in MIMO Symbiotic Radio Backscatter Systems	No JRC
[89]	A Systematic Review on Beam-forming Aided Channel Estimation Techniques for MIMO System	No JRC
[90]	RIS-Aided Wireless Communications: Prototyping, Adaptive Beam-forming, and Indoor/Outdoor Field Trials	No JRC
[91]	Experimental Analysis of Cooling Fan Noise by Wavelet-Based Beam-forming and Proper Orthogonal Decomposition	No JRC
[92]	Beam-forming Optimization for IRS-Aided Communications With Transceiver Hardware Impairments	No JRC
[93]	Channel Model for Location-Aware Beam-forming in 5G Ultra-Dense mm-wave Radio Access Network	No JRC
[94]	Beam-forming Optimization for Intelligent Reflecting Surface-Aided, simultaneous wireless information and power transfer (SWIPT) IoT Networks Relying on Discrete Phase Shifts	No JRC
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3.3. Components in Beamforming Circuit

Table 3 illustrates the crucial role of various components in beamforming circuits and their significance. While the referenced papers delve into detailed explanations, our emphasis is to provide insight as we prepare to employ beamforming technology in JRC, highlighting its importance for our specific application. Our beam-former device leverages essential components like antennas, power amplifier (PA), low-noise amplifier (LNA), VGA, PS, signal processing, and filters, as detailed in [64–75,81,82], with the novel integration of JRC technology.

Table 3. Components in beamforming circuit.

Components	Descriptions	Ref.
Antenna Array	Elhefnawy: Analog beamforming phased array antenna. Behera: Meta surface-loaded circularly polarized monopole antenna for RF energy harvesting at 5 GHz, and Oh highlights the vertically beamforming array antenna. Ullah et al. details a compact dual-beam, dual-band antenna for future 5G millimeter-wave mobile phones.	[95–98]
Phase Shifters	Phase shifters are crucial in beamforming systems, allowing precise adjustment of signal phases for effective beam steering.	[77–79]
Attenuators and VGAs	Attenuators allow control over signal power at each antenna element for precise adjustments, enhancing beamforming accuracy, as highlighted.	[81–83]
Hybrid Couplers/Dividers	Key components manipulate signals' phase relationships, facilitating signal distribution across antennas and effective beam steering; study explores quadrature hybrid designs based on a Branch Line Coupler for a 180-degree power splitter effect Tutkur.	[99–101]
Power Amplifiers	A two-stage millimeter-wave PA with a three-stacked structure, utilizing a 65-nm RF CMOS process, achieving stable performance, high gain, and an output power of 24.7 dBm at 22.0 GHz: Jeong.	[102]
Low-Noise Amplifiers	A high-performance wireless system component that utilizes a 65 nm CMOS process to implement a variable-gain low-noise amplifier with a constant phase feature, offering impressive characteristics including a gain of 20.8 dB at 31 GHz, a low noise figure of 3.71 dB, and stability over a gain control range of 10.6 dB from 30 to 34.5 GHz, highlighting its reliability and adaptability in real-world applications Lee.	[103,104]
Filters	Wang: Beamforming filters are enhanced through adaptive reduced-rank constrained constant modulus algorithms, optimizing joint iterative filters for improved performance in focusing on important information and blocking unwanted signals Wang.	[105,106]
Analog Signal Processing Circuitry	Analog signal processing involves utilizing various circuit components like operational amplifiers, mixers, analog multipliers, and voltage-controlled oscillators to manipulate phases. Further details are available in the references.	[107,108]
Radar	A calibration method for automotive millimeter-wave radars, demonstrating the 77 GHz radar's enhanced measurement accuracy for vehicle perception through experiments, is discussed in detail, which is crucial for JRC, and millimeter-wave radar enhances automotive safety by enabling early obstacle detection with rapid low-latency hardware processing (FPGA prototype).	[109,110]

3.4. Narrow-Band and Wide-Band Beamforming

Narrow-band beamforming enhances wireless communication through simple signal combination and adaptability to temporal changes, as explored by [111,112] in smart antennas and real-time models, respectively. Spatial filtering is essential for 5G's speed, utilizing millimeter waves and evolving into fixed and adaptive wide-band beamforming designs. [113] explore its basics, [114] focus on its use in terahertz frequency for massive MIMO, and [115] study its application in 3D single-wall imaging.

Table 4 illustrates the crucial role of various techniques of beamforming and their significance. The table explains some important beamforming techniques. Which plays a very important role in understanding the beamforming technology in different criteria.

Table 4. Beamforming techniques.

S.NO	Beamforming Techniques	Descriptions	Ref.
1	Analog Beamforming	Analog beamforming enhances communication system performance by directing signals using components like VGAs and phase shifters, proving advantageous for cost-sensitive applications over digital methods. Innovations include a switch-based architecture for MIMO systems by Zhang et al., Beam Index Modulation by Ding et al., and statistical radiation pattern analysis by Lee et al, which are discussed in detail. Further advancements in 5G by Mujammami et al., energy-efficient beamforming by Wang et al., and RF fan filters using CMOS time delay approximations by Mujammami demonstrate significant contributions to wireless communication technology.	[15,80,116–121]
2	Digital Beamforming	Digital beamforming is pivotal for advancing wireless communications and spaceborne SAR systems, as explored by Steyskal et al., Huber et al., and Barb et al., offering insights into eigenbased and grid of beams techniques for 5G enhancement. Despite its benefits in adaptability and signal handling, the high implementation cost and challenges in its application in 5G networks are being highlighted.	[122–124]
3	Hybrid Beamforming	Hybrid beamforming, blending analog and digital techniques, optimizes 5G/6G networks by enhancing connection speeds and reducing latency, as investigated by Ahmed et al. and Dilli et al. This method utilizes massive MIMO for improved signal quality, leveraging affordable phase shifters for cost-effective analog beamforming [14,15], and then employing digital signal processing (DSP) for precise beam control and interference management. The approach significantly reduces hardware costs and power consumption while boosting energy efficiency and supporting massive MIMO deployments, a critical advancement detailed by [125] and further explored in [126]. Hybrid beamforming stands out for its dual advantages of performance efficiency and economic viability in 5G/6G technology. For the hybrid beamforming technique, spectral efficiency can be obtained by the below equation [126]. $$R_{\text{hybrid}} = \max_{c \in C} \left(\frac{1}{N} \sum_{m=0}^{N-1} \log_2 \left(1 + \frac{\lvert c^H H_m w_{m,opt} \rvert^2}{\sigma^2} \right) \right) \quad (7)$$	[14,15,125–129]
4	Advance Hybrid Beamforming	Shim et al. elucidated a hybrid beamforming technique, showing its enhanced performance and efficiency in simulations over traditional methods. Detailed schematics and user sum rate equations in the paper highlight the system's advanced capabilities and optimizations for beamforming technology. For the PCS hybrid beamforming system, the sum rate for the kth and all users is calculated by the below equations discussed in [130] $$R_k = \log_2 \left(1 + \frac{\lvert \boldsymbol{H}_k \boldsymbol{V}_{RF} \boldsymbol{V}_{D_k} \rvert^2}{\sigma^2 + \sum_{l \neq k} \lvert \boldsymbol{H}_k \boldsymbol{V}_{RF} \boldsymbol{V}_{D_l} \rvert^2} \right) \quad (8)$$ $$R = \sum_{l=1}^{k} \log_2 \left(1 + \frac{\lvert \boldsymbol{H}_l \boldsymbol{V}_{RF} \boldsymbol{V}_{D_l} \rvert^2}{\sigma^2} \right) \quad (9)$$	[130]
5	Adaptive Beamforming	Adaptive beamforming, crucial for optimizing antenna array signals, employs dynamic weight adjustment to enhance signal quality and suppress interference, fundamental in 5G systems. Chen et al. investigate its application in spatial multiplexing and network enhancement, utilizing strategies like the Tchebyscheff distribution and algorithms such as least mean square (LMS) and constrained stability least mean square (CSLMS) to improve directional signal focus.	[14,15,131,132]
6	Switch Beamforming	Switched beamforming uses fixed beams for simpler antenna management, detailed in [14]. Zhang et al. advance wireless communication with photonic true-time delay beamforming, highlighting precise signal control. Ali et al. and Guan et al. explore diverse beamforming strategies and innovative Wi-Fi-based antenna switching for enhanced multi-person monitoring, respectively, emphasizing smart antennas' efficiency through direction of arrival (DOA) and adaptive algorithms.	[14,15,133,134]

Table 5 outlines beamforming technology's applications, showcasing its impact on telecommunications, automotive, JRC, mobile, healthcare, physical security, and various applications by enhancing signal precision and system efficiency.

Table 5. Applications of beamforming technology.

S.NO	Technique	Descriptions	Ref.
1	Beam Refinement	Beamforming algorithms adjust beam direction based on user device feedback, enhancing adaptation to changing conditions, user movements, and interference levels.	[135]
2	Interference Mitigation	In crowded signal-dense areas, beamforming techniques are crucial for improving communication quality and overcoming interference challenges to enhance network performance.	[15,136–138]
3	Beam Management	5G networks use dynamic beam management and beamforming techniques to maintain connectivity and signal quality for fast-moving users and changing channel conditions.	[139]
1	Beamforming in JRC	Beamforming algorithms adjust beam direction based on user device feedback, enhancing adaptation to changing conditions, user movements, and interference levels.	
2	Automotive Communications	Beamforming technology enhances automotive communication by improving V2V and V2I communication, ensuring reliable in-car services, optimizing antenna array design, mitigating interference, and enabling precise vehicle localization for autonomous driving.	[140]
3	Automotive Radar	A real-time signal processing algorithm is developed for the Texas Instruments AWR1642 chipset, presenting it as a W-band MIMO-FMCW imaging radar for automotive applications with a range resolution of 4.1 cm and an angular resolution of 14.2°, aligning with theoretical and simulation predictions in MATLAB.	[141]
1	Beamforming in 5G and 6G	Beamforming plays a significant role in 5G and 6G wireless systems, analyzing circuits and antennas, addressing technological challenges, and providing a comprehensive understanding of the field.	[142]
2	Enhanced Mobile Broadband (eMBB)	Beamforming in 5G improves signal strength, enhancing communication quality and enabling faster data transfer for better coverage and mobile broadband services.	[143]
3	Massive MIMO	5G employs massive MIMO with beamforming, using numerous antennas to serve multiple users simultaneously and enhance coverage and data rates.	[144]
1	Beamforming in Wi-Fi	Beam-forming enhances wireless connections in challenging areas, like house corners. The author emphasizes the implementation of a multi-person breathing sensing system using Wi-Fi signals.	[134]
2	Beamforming in LDACS	L-band Digital Aeronautical Communications System (LDACS), a digital data link for air–ground communication, faces disruption risks like jamming, but its robustness can be improved with beamforming and adaptive coding for superior data rates.	[145]
3	Beamforming in Radio Astronomy	Beamforming with thousands of antennas in the world's largest radio telescope, LOFAR, advances astronomical research by addressing radiofrequency interference through Intelligent Reflecting Surfaces (IRSs) with modified reflection coefficients, enhancing the quality of space observations.	[146]
1	Beamforming in Healthcare	Beam-forming improves ultrasound images for precise monitoring in dynamic environments, while the author focuses on a based multi-person breathing sensing system.	[134]
2	Acoustic beamforming	Beamforming enhances clear communication by focusing on desired acoustic signals and minimizing noise, crucial for optimizing modern wireless systems like Wi-Fi and 5G.	[147]
3	Beamforming in Seismic data Processing	NLBF, developed by Andrey Bakulin et al., enhances weak signals in onshore 3D seismic data, improving clarity by reducing interference from scattered noise.	[148]
4	Physical Security	Advanced security systems use beamforming with phased and 4D antennas for improved target tracking and threat detection, leveraging sensor fusion and deep learning.	[149]

3.5. Beamforming Problems and Solutions

Ref. [128] Terahertz (THz) communications, pivotal for 6G, leverage ultra-massive MIMO and innovative hybrid beam-forming to navigate its unique challenges, promising unparalleled bandwidth and efficiency. This exploration unveils novel architectures and future directions for optimizing THz systems. THz communications face key challenges: spatial constraints, signal blockage, complex antenna arrays, and beam squint losses. Modern wireless systems face challenges in interference, adaptive beamforming, computational complexity, massive MIMO complexities, and AI application intricacies for optimal performance [150]. The paper discusses the problem of nearing capacity limits in sub-10 GHz frequency bands due to the growing demand for wireless communication services [151]. As a solution, it suggests exploring E-band frequencies to increase capacity despite facing challenges like propagation issues. The study proposes E-band systems for both fixed and mobile applications, detailing potential designs to overcome these challenges for next-generation networks. To harness E-band frequencies for future wireless communications, the paper proposes solutions like developing specific propagation models, optimizing E-band Mobile Broadband (EMB) systems with advanced structures, and employing beamforming and MIMO technologies to enhance signal strength and capacity in both fixed and mobile networks. It addresses challenges in JRC systems including spectrum congestion, dual-function system design, optimization of weighting coefficients, non-convex optimization problems, interference management, and maintaining radar performance with communication constraints [152]. It addresses mutual interference in integrated sensing and communication (ISAC) systems by proposing a double-RIS setup to enhance signal quality and suppress interference, using a penalty dual decomposition algorithm and a low-complexity approach for different radar power scenarios, improving both communication and radar detection performance [153]. It addresses the challenge of optimizing a JRC system for simultaneous target detection and user service, proposing a solution that jointly designs the radar and communication beamforming to enhance performance and reduce complexity through an iterative algorithm, demonstrating effectiveness with simulations [154].

4. Dual Radar Communication and Network Security

In the realm of vehicular communication systems, the integration of radar and communication functionalities emerges as a pivotal advancement. Indeed, ref. [19] explores the dual utility in car-to-car interactions through modulated backscatter and FMCW radar applications. Rybin et al. [20] and Hieu et al. [21–25] further underscore the benefits of incorporating microcontrollers and deep reinforcement learning to enhance these systems, respectively, for better performance and vehicle autonomy. Butt et al. [22] and Bilik et al. [23] highlight the importance of sophisticated data acquisition and signal processing in automotive radar systems. Luong et al. [24] delve into resource management within JRC systems, evaluating performance and practical applications. Hieu et al. [25] highlight intelligent real-time dual-functional radar communication systems designed for autonomous vehicles (AVs); these innovative systems integrate both radar and communication functions, promoting efficient real-time operations crucial for the safe and effective functioning of AVs. Oh et al. [155] and Tian et al. [156] discuss innovations in antenna design and radar performance analysis, offering insights into the future of autonomous vehicle communications. Collectively, these studies illustrate the dynamic evolution of vehicle communication technologies, emphasizing the need for high-resolution detection and efficient real-time operations in advancing automotive safety and functionality. Shi et al. [157] discuss how to choose frequencies and power levels for better radar and communication in one system. The secret behind network security is the pencil beam.

4.1. Radar

FMCW radar enhances automotive safety by detecting objects and velocity, using techniques like frequency hopping to reduce interference. It is effectively used in car-to-car communication through a harmonized backscatter method, as shown in [19]. The fundamental equations of JRC focusing radar are Radar Range Equation, Target Velocity Estimation, Radar Range Equation for Received Power, Range Resolution, Range Resolution with Pulse Compression, Velocity Resolution, Ambiguity Function, and Frequency-Modulated Continuous-Wave (FMCW) Radar Signal [24]:

$$R = \frac{c\Delta T}{2} \tag{10}$$

This equation calculates the distance R between a radar system and a target object using the round-trip travel time ΔT of the radar signal. c represents the speed of light, and the factor of 2 accounts for the signal's outbound and return journey. This principle is fundamental to most radar systems for measuring object distances.

$$v = \frac{\sqrt{R_1^2 + R_2^2 - 2R_1R_2\cos\alpha}}{|t_1 - t_2|} \tag{11}$$

This equation estimates the velocity v of a target object by using the distances R_1 and R_2 from the radar to the target at two different times, t_1 and t_2. α is the angle between the radar's line of sight and the direction of the target's motion. This equation provides a way to calculate the speed of moving objects.

$$P_r = \frac{P_tG_tG_r\lambda^2\sigma F^4}{(4\pi)^3R^4} \tag{12}$$

This radar range equation calculates the received power P_r at the radar system, which is reflected from a target object. P_t is the transmitted power, G_t and G_r are the transmit and receive antenna gains, λ is the wavelength of the transmitted signal, σ is the radar cross-section of the target, F is the pattern propagation factor, and R is the distance to the target. This equation helps in understanding how different factors affect the received signal strength, which in turn influences radar system performance.

$$\Delta R = \frac{cT}{2} \tag{13}$$

This equation calculates the radar's range resolution ΔR, which is the minimum distance between two objects at which they can still be distinguished as separate targets.

$$\Delta R = \frac{c}{2B_p} \tag{14}$$

This variation in the range resolution equation considers the bandwidth B_p of the pulse for systems using pulse compression techniques. A wider bandwidth results in a finer range resolution.

$$\Delta V = \frac{c}{2f_cT_c} \tag{15}$$

The velocity resolution ΔV is determined for a given time duration T_c of the chirp (a type of radar signal modulation). f_c is the carrier frequency. This equation indicates how well a radar system can distinguish between two objects moving at slightly different velocities.

$$X(\beta, f_D) = \int_{-\infty}^{\infty} s(t)s^*(t-\beta)e^{i2\pi f_D t}dt \tag{16}$$

The ambiguity function $\chi(\beta, f_D)$ measures the distortion in received signals caused by the Doppler effect as a function of time delay β and Doppler frequency f_D. $s(t)$ is the transmitted signal, and $s^*(t)$ is its complex conjugate. This function is crucial for understanding how signal properties change with motion and propagation delays.

$$s_m(t) = e^{j2\pi f_c t + j\pi\gamma t^2}, \forall t \in \left[mT_{PRI}, mT_{PRI} + T_p\right] \tag{17}$$

This represents a signal for an FMCW radar, where f_c is the carrier frequency, γ is the frequency modulation rate, T_{PRI} is the pulse repetition interval, and T_p is the pulse duration. FMCW radars are widely used in various applications due to their ability to determine both the range and velocity of targets.

Figure 2 explains the importance of the FMCW radar which will have many advantages when use in the beamforming technology like calculating the exact location of the target, velocity and having good resolution which will have good performance in cloudy weather to use in automotive vehicles (AV).

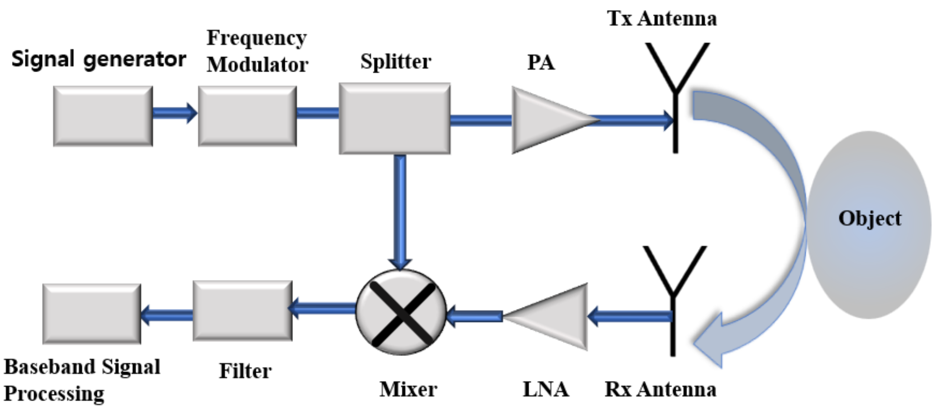

Figure 2. A modified FMCW diagram.

4.2. Communications and Beamforming

Rybin et al. [20] highlight the use of chaos-based systems for secure automotive communications, employing adaptive beamforming and signal analysis to enhance vehicle safety. Their work details a microcontroller-based chaotic communication setup, crucial for V2V and V2I interactions. Li et al. [158] introduce Oppermann sequences for vehicular radar and communication integration, enhancing efficiency. Rajkumar et al. [159] detail advancements in radar altimeters for aerial weaponry, focusing on precision and adaptability. Dhouioui et al. [160] describe a novel obstacle classification system that combines radar and camera data with machine learning for accuracy. Beamforming enhances communication systems by directing antenna signals, improving safety and driving experience in automotive applications. The key features include tracking vehicles, detecting obstacles, identifying pedestrians, aiding parking, enhancing visibility, enabling vehicles to everything (V2X), and ensuring security in a radar system. The general beam-former concept is discussed in [155], in which the author discussed a dual polarization 3D beamforming Antenna in Package (AIP) used in smart automotive vehicles. In the integration of radar and communication systems, three main approaches stand out: frequency division, time division, and code division. Frequency division employs separate frequencies and antennas for radar and communication, ensuring independence but at the cost of increased resources and spectrum usage. Time division alternates between radar and communication functionalities using a switch, offering simplicity and ease of implementation but limiting simultaneous operation and facing challenges in dynamic demand scenarios. Each approach presents a unique blend of advantages, such as simplicity and ease of integration, against disadvantages, like resource intensiveness and operational limitations, pointing to the importance of choosing the correct strategy based on specific system requirements and application contexts; the author explores cutting-edge techniques in JRC, focusing on spread spectrum, OFDM, and the novel Orthogonal Time Frequency Space OTFS waveform. It highlights their use in enhancing target detection and communication efficiency, addressing specific challenges like velocity estimation and signal distortion. Innovations aim to improve accuracy and reduce drawbacks, such as high side lobes and power issues, with OTFS showing promise for high-rate and stable communication in dynamic environments [24].

4.3. JRC and Beamforming Integration

Two main strategies for integrating communication functions within radar systems in JRC systems focus on optimizing cost and spectrum usage. The radar waveform-based solution modifies the radar's signal to carry digitally modulated data, exemplified by embedding information into FMCW radar pulses through phase modulation or frequency modulation techniques. On the other hand, the communication waveform-based solution incorporates radar functionalities into conventional communication waveforms like OFDM, where data symbols replace or modify the signal's complex weights. This method enables dual functionality but can introduce challenges such as increased sidelobes, which necessitate specific mitigation strategies like subcarrier separation or symbol-based processing algorithms [24].

Our vehicle radar system uses special techniques to improve safety features in cars (a simple diagram is shown in Figure 3, helping them to communicate and avoid accidents. We focus on controlling the radar beams to avoid signal interference, making our method unique. The radar's design allows it to switch quickly between detecting objects and sending communication signals, important for advanced driver-assistance systems. This approach is specially designed for use in cars with combined radar and communication technology. JRC systems combine radar and communication on a single platform, navigating resource-sharing challenges like spectrum congestion. Approaches to address these include using communication or radar signals, time division, and spatial beamforming to ensure efficient operation. These strategies highlight the balance between performance and integration in the evolving landscape of JRC systems [24]. Communication signal-based approaches use OFDM signals for dual radar and data transmission with challenges like signal randomness and high peak-to-average power ratio (PAPR), and radar signal-based approaches use conventional radar signals for communication but potentially compromise radar performance, necessitating advanced waveform designs [24].

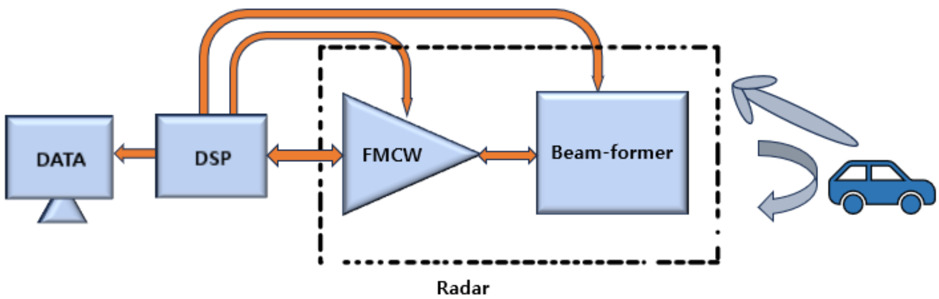

Figure 3. Radar structure with beam former.

A joint radar and communication system combines radar sensing and communication in one efficient package as shown in Figure 4, ideal for space-constrained applications like cars and planes. It starts with generating a radar waveform and then processes this signal digitally to ensure that it meets radar requirements. A special screen handles the communication aspect, coordinating data sharing. The system's core includes components for signal preparation, transmission, and reception, such as converters for digital to analog and vice versa, amplifiers for adjusting signal strength, and phase shifters for signal direction. These elements work together to accurately transmit and receive radar signals, supported by low-noise amplifiers and switches to maintain signal quality. The setup is crucial for advanced automotive technologies, aiding in safety and navigation features like collision avoidance and adaptive cruise control, demonstrating a significant advancement in integrating radar and communication technology. Our unique research improves this process by using beamforming, which focuses signals like a flashlight beam. This enhances security, making it hard for others to eavesdrop, and improves communication quality by reducing interference. In radar, beamforming allows us to precisely locate objects, boosting reliability and efficiency. So, in short, our work makes radar communication more secure and efficient. The research delves into spatial beamforming and spectrum-sharing strategies within radar and communication systems, highlighting the importance of minimizing interference through advanced techniques such as projecting radar signals into the communication receiver's null space based on the channel state information (CSI) matrix. The CSI matrix, crucial for identifying the null space where radar signals can be safely projected without affecting communication channels, is estimated using a sophisticated channel-selection algorithm. This algorithm leverages singular value decomposition (SVD) to minimize the interference between military radar systems and LTE base stations sharing specific frequency bands, as discussed in detail in the reference. Moreover, the antenna allocation methods for enhancing spectral efficiency and channel capacity in dual-function radar communication (DFRC) systems emphasize the tradeoffs and decisionmaking processes involved in designing effective spectrum-sharing mechanisms. These approaches aim to balance the optimal performance of both radar and communication functions, highlighting the nuanced considerations, such as the complexity and cost implications of different spectrum-sharing strategies, necessary to achieve coexistence with minimal performance degradation [24]. The evaluation of the diagram as shown in Figure 4 is a complex system crucial for both radar and communication, featuring components like DACs, ADCs, and amplifiers, all vital for transmitting and receiving signals. It uses beamforming, employing multiple antennas and phase shifters to direct beams accurately, essential for hitting radar targets and achieving clear communication with minimal interference. Performance is gauged through various measures: beam steering precision affects radar and communication quality; the resolution and sampling rates of DACs and ADCs influence signal integrity; component linearity is key to reducing distortion; the system's ability to handle varying signal strengths indicates its dynamic range; and managing interference and sharing resources without performance loss and adapting to environmental changes are crucial for its dual function. Additionally, power consumption, thermal management, and the system's ability to fit into different platforms and scales are important for its efficiency, reliability, and application versatility. Power can be reduced with better performance, as discussed in the Sections 3.2 and 3.3 of the beamforming section, while using components with high performance, like PA, PS, LNA, VGA, and smart antenna. CSI plays a vital role in beamforming technology, especially within JRC systems. CSI provides detailed insights into the communication link, such as signal path and obstacles, enabling the optimization of beamforming. This signal processing technique, pivotal in antenna arrays, allows for directed signal transmission to enhance signal quality and strength at the receiver. In JRC systems, beamforming and CSI work together to improve both radar and communication functions. These systems leverage shared resources, like hardware and signal processing algorithms, to efficiently achieve high-performance radar sensing and wireless communications. Understanding CSI's contribution to beamforming within JRC systems is key to advancing in fields like wireless communication and radar technology, offering a blend of improved efficiency and performance.

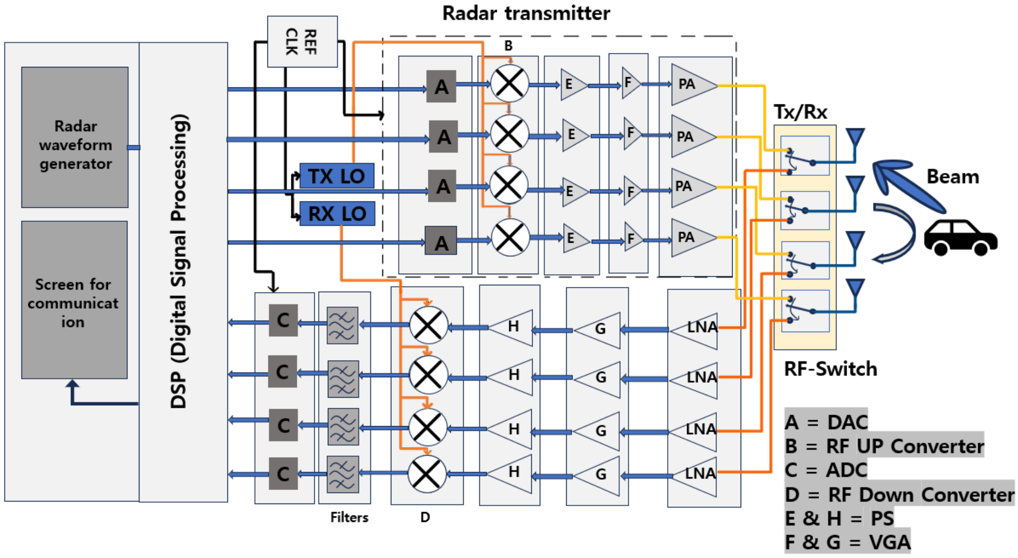

Figure 4. Joint radar communication system with beamforming.

Table 6 outlines various papers on JRC using different technologies. Many articles in this table discuss diverse methods for achieving JRC, while our unique approach involves using beamforming technology in JRC.

Table 6. Joint radar communications.

Ref.	Research	Differences
[161]	Joint radar and communication: A survey coexistence, cooperation, codesign, and collaboration	No Beamforming
[162]	Joint Radar and Communication Design: Applications, State-of-the-Art, and the Road Ahead	No Beamforming
[163]	Joint Radar Communication Systems: Modulation Schemes and System Design	No Beamforming
[24]	Radio Resource Management in Joint Radar and Communication: A Comprehensive Survey	No Beamforming
[164]	Joint Radar Communication Strategies for Autonomous Vehicles: Combining Two Key Automotive Technologies	No Beamforming
[165]	Research challenges, trends and applications for future joint radar communications systems.	No Beamforming
[45]	Toward Millimeter-Wave Joint Radar Communications: A Signal Processing Perspective	No Beamforming
[166]	A mm-Wave Automotive Joint Radar-Communications System	No Beamforming
Our Work	Review of Joint Radar, Communication, and Integration of Beamforming Technology	Beamforming

5. Problems and Solutions

The deployment of JRC systems in 5G and upcoming 6G networks encounters hurdles, notably in millimeter-wave bands, due to severe path loss and atmospheric attenuation, which are exacerbated by obstacles and weather conditions, leading to signal degradation [37]. Additionally, the unique propagation characteristics of millimeter waves, such as higher attenuation through rain and foliage and challenges in indoor signal penetration, pose significant challenges for JRC systems [28,37]. These issues necessitate advanced algorithms and strategies for maintaining connectivity and ensuring the safety and reliability of automotive applications that rely on seamless JRC integration. Several approaches are used to overcome 5G and 6G challenges and enhance JRC. Beamforming and MIMO techniques tackle signal loss, improving network quality. Smaller cell sizes and smart frequency use boost coverage. Combining the millimeter-wave approach with sub-6 GHz frequencies in hybrid networks offers faster, more reliable connections. Advanced antennas and signal processing enhance performance. Regulatory changes and making devices compatible are important for adoption. For JRC, reducing interference through techniques like time division multiplexing ensures that radar and communication systems in vehicles can work together smoothly, leading to safer roads. These strategies help to solve major issues in wireless communication and automotive technologies. The JRC design, enabling radar and communication system coexistence, faces challenges like interference, which compromises performance, and complex transmitter design, especially in dense deployments like autonomous vehicles. The proposed solutions include advanced resource management and design strategies to address these issues. For beamforming in JRC, the primary problem is interference between radar and communication systems sharing the same spectrum. The solution is spatial beamforming, specifically projecting radar signals into the null space of the radar system's channel to communication receivers, thereby minimizing interference [24]. In JRC systems, beamforming faces challenges such as interference management between radar and communication signals, spectrum sharing in crowded frequency bands, hardware limitations that restrict beamforming capabilities, and increased signal processing complexity. Solutions to these challenges include employing adaptive beamforming techniques to dynamically optimize performance, leveraging cognitive radio approaches for efficient spectrum utilization, implementing advanced signal processing algorithms to manage complex signal environments, and investing in hardware innovations like metamaterials to enhance beamforming effectiveness. These approaches aim to address the unique set of problems in integrating radar and communications systems, paving the way for more efficient and capable joint operations. In simpler terms, to improve beamforming in JRC systems, a new method focuses on using the sparse (or not densely packed) nature of millimeter-wave signals. This method compresses the signal information and then recovers it efficiently using a specific type of algorithm based on graphs. This approach helps in creating more focused beams with less effort and shows better results than older methods, making it a smarter way to handle beamforming in JRC systems [167].

6. Future Importance

When integrated with JRC for 6G networks, beamforming stands at the forefront of revolutionizing wireless communication. This technique enhances signal quality and reduces interference, crucial for the next generation of IoT applications, autonomous driving, and smart cities, by focusing signals directly toward receivers. Specifically, it propels advancements in V2X communications, offering a safer and more efficient transportation future. The innovation extends to improving network capacity and coverage, especially in densely populated areas and higher frequency bands. The works of Huang et al. [3], Pirzada et al. [168], and Zhang et al. [5] provide foundational insights into this domain. Huang et al. [3] showcase a system for targeting and beam focusing using image recognition, Pirzada et al. [168] introduce an efficient indoor wireless power system, and Zhang et al. [5] explore the potential of large antenna arrays in 6G for near-field communications. These studies highlight the significant potential beamforming holds for enhancing communication and power transfer efficiency, marking a critical step toward realizing the full promise of 6G technologies. Integrating beamforming in JRC enhances 6G by providing precise, efficient connectivity and radar sensing, paving the way for advanced autonomous systems and improved network capabilities. The key potential beamforming and MIMO in the upcoming 6G network will play a significant role as Zhang et al. [169] introduce a compact 8×8 MIMO antenna design for 5G terminals, featuring two sets of quad-element antennas with T-shaped monopoles and edge-coupled fed dipoles, achieving effective decoupling and over 50% radiation efficiency in the 3.4–3.6 GHz band.

7. Conclusions

As we conclude, we have journeyed through the advanced landscapes of millimeter-wave technology, MIMO phased array antennas, and their pivotal contributions to shaping the future of 5G and 6G technologies. This exploration has taken us deep into the mechanics of beamforming, the innovation behind dual radar communication systems, and their transformative effects on automotive vehicles and secure communication networks.

Highlighting the seamless integration of these technologies in radar and communication systems, we have delved into their applications, challenges, and the security considerations they bring to the forefront. Simplifying complex concepts, this review has spotlighted the significance of millimeter-wave and beamforming technologies, emphasizing their roles in enhancing automotive communication and ensuring network security. As we look forward, the potential of these technologies to revolutionize JRC systems in vehicles and to fortify the physical security of networks is undeniable. This narrative not only captures the current state of these technological advancements but also paints a vision of their future impact. In wrapping up, this paper serves as a bridge connecting the present with a future where these sophisticated technologies redefine wireless communication. It is a call to recognize their crucial role in the ongoing evolution of communication systems, urging us to envision a future where connectivity and security are significantly enhanced by these groundbreaking developments.

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