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Review

Review of Joint Radar, Communication, and Integration of Beam-Forming 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 beam-forming 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 beam-forming technology and joint radar communications, alongside a look at their theoretical and practical implementations. We emphasize the integration of beam-forming 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 tech 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, beam-forming, and dual radar communication technologies.

Keywords: physical security; communications; beam-forming; radar; MIMO

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1. Introduction

Future cellular and automotive communication advancements rely significantly on improving millimeter-wave and Multiple-Input Multiple-Output (MIMO) systems, highlighting the need for high gain, high data rate, and precision in beam direction for secure vehicle communication. Precoding techniques in multi-antenna systems, both linear 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 more straightforward, 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 beam-forming and precoding techniques. These methods, which adjust signal amplitudes and phases, ensure signals converge on intended targets, utilizing interference to enhance signal clarity and reach [2][3][4]. Millimeter-wave technology's broad applications, from medical imaging to innovative automotive radars, demonstrate its versatility. It's instrumental in object detection, radar imaging, and dynamic target simulation in vehicles [2][3][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 beam-forming emerges as an effective countermeasure, enhancing performance across various applications. Research highlights beam-forming'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 beam-forming in improving cell detection for obstacle avoidance in 5G networks and in advancing ultra-massive MIMO in tera-hertz 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 beam-forming techniques explore interference mitigation, precoding strategies [14][15][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 beam-forming advancements provide in-depth insights into their applications, challenges, and evolution. Rao et al. [14] contribute a detailed analysis of beam-forming components, including hybrid and broadband couplers, emphasizing the diversity of methods and designs critical to the field. The authors [14] and [15] explore diverse beam-forming methods. They delve into analog, digital, and hybrid techniques and switched and adaptive forms of beam-forming, 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 beam-forming technologies. This endeavor is underpinned by the pioneering work of [Lazaro] et al. [19], who explored car-to-car communication through modulated back-scatter and frequency-modulated continuous wave radar. [Rybin] et al. [20] highlighted the development of a prototype communication system founded on symmetry and chaos theories, utilizing a microcontroller for operation. Further, [Hieu] et al. [21] demonstrated 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] investigated 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] showcased innovative, 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 beam-forming technology, including the critical role of Joint Radar Communications (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 the key technologies such as antenna design, phase shifters, Variable Gain Amplifiers (VGAs), Mixers, power combiners/dividers, power amplifiers, and buffer amplifiers essential for effective beam-forming. The discussion extends to the innovative potential of these technologies, mainly 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 beam-forming systems in vehicles. The paper is structured to cover the background of millimeter-wave technology, beam-forming techniques, our idea of the 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 telecom, 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 wireless communication and healthcare sectors.

2.1. Millimeter-Wave Applications

Millimeter-wave technology is pivotal across diverse applications, including wireless communications, radar, imaging, and IoT. It is instrumental in advancing 5G/6G networks, as highlighted by [Chakraborty] et al. [34], who underscore its significance in wireless communication evolution. [Brandão] et al. [32] focus on millimeter-wave antennas designed for MIMO applications, emphasizing their contribution to enhancing wireless connectivity. Similarly, [Ghaddar] et al. [33] 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 with millimeter-wave usage. 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 beam-forming, making urban deployment difficult [28]. Atmospheric conditions, including rain and foliage, significantly impact signal quality, with principles grounded in Friis's equation [28,36,67]. Directive beam-forming at higher frequencies, such as 80 GHz, can achieve more significant 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, with integrated beam-forming, millimeter-wave radar communication shows potential for vehicular networks and other applications. Advancements in beam-forming and antenna design are crucial for enhancing MIMO technologies, including hybrid beam-forming and Massive MIMO systems. Adaptive modulation, relay nodes, and mesh networks are pivotal in optimizing frequency and channel selection. Weather monitoring and prediction are also integral for network reliability, supported by hybrid network architectures and sophisticated signal processing techniques. Furthermore, regulatory support remains essential for deploying and innovating these technologies.

2.3. Millimeter-Wave Importance in Automotive Vehicles

[Wane] et al. [52] 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 outlines numerous studies focusing on JRC within the millimeter-wave spectrum, all of which share the goal of leveraging JRC at this high frequency. Despite their collective aim, it is notable that the beam-forming critical technique for directional signal transmission and reception has not been utilized in any of the discussed works.

Table 1. Millimeter-wave and JRC.

S.NO	Research	Differences
[44]	Toward Millimeter-Wave Joint Radar Communications: A Signal Processing Perspective	No Beam-forming
[45]	Photonic Millimeter-Wave Joint Radar Communication System Using Spectrum Spreading Phase-Coding	No Beam-forming
[46]	Adaptive Virtual Waveform Design for Millimeter-Wave Joint Communication Radar	No Beam-forming
[47]	JCR70: A Low Complexity Millimeter-Wave Proof-of Concept Platform for a Fully-Digital SIMO Joint Communication Radar	No Beam-forming
[48]	Future Millimeter-Wave Indoor Systems: A Blueprint for Joint Communication and Sensing	No Beam-forming
[49]	Joint Communication and Localization in Millimeter-Wave Networks	No Beam-forming
[50]	On Unified Vehicular Communications and Radar Sensing in Millimeter-Wave and Low Terahertz Bands	No Beam-forming
[51]	Millimeter-Wave Vehicular Communication to Support Massive Automotive Sensing	No Beam-forming
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3. Beam-Forming

Beam-forming in millimeter-wave communication systems can be achieved through analog or digital means. Analog beam-forming 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 by studies [15,53,54]. Using multiple antennas, particularly in MIMO systems, not only bolsters energy efficiency but also minimizes interference, thereby improving network performance [15,56,57]. 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, 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, beam-forming technologies like linear and nonlinear precoding adaptive 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 [71–75]. Pencil beam benefits, including targeted communication and reduced interference, underscore its importance [71–75]. Dahrouj et al. [76] further explore the efficiency gains through coordinated base station optimization in multi-antenna setups.

3.1. Linear and Non-Linear Precoding

Precoder matrix F and its singular value decomposition (SVD's) role in stream separation and power allocation are detailed in [66], with [65] further analyzing precoding algorithms for wireless communications. [Fatema] et al. [67] 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 [68,69]. THP [69] emerges as a computationally simpler yet effective alternative to DPC, outperforming linear methods like BD in overlapping UE subspaces [69,70]. [Albreem] et al.'s study [65] offers a comprehensive view of NLP in massive MIMO systems, marking a significant contribution to wireless communication research.

The p matrix in Figure 1. helps send signals right, the B matrix helps improve, the K matrix helps receive signals, and the C matrix adds extra improvement. Together, they decide how signals are sent and received, giving 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]. Through the Modulo arithmetic, we fine-tune the average power, also elaborated upon in [65].

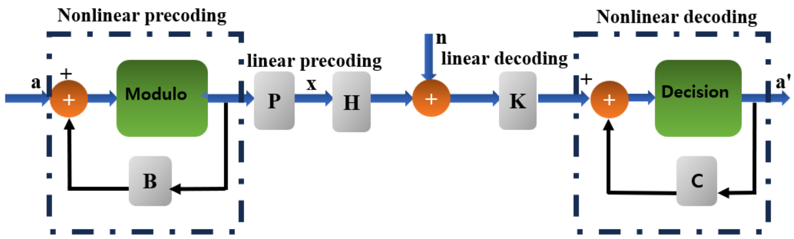

Figure 1. A modified generalized block diagram of communication systems with precoding and decoding techniques. [65].

3.2. Technologies

3.2.1. Phase Shifter

Park et al. [77] explored 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 beam-forming technologies.

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

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

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

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 5mW, underscoring its efficacy in automotive beam-forming applications [76]. Kim et al. [78] focused on VSPS for 5G, noting performance within 30.9-41.7 GHz and a 45mW power consumption, providing insights into millimeter-wave applications. Additionally, Singh et al. [79] enhanced the Reflection-Type Phase Shifter (RTPS) for better electronic tunability at 10 GHz, demonstrating improvements over traditional models. Jing-Lin et al. [80]

explored 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. [82], along with contributions from [78–81] and Siao et al. [83], focus on VGAs and their integration with phase shifters for enhanced signal quality and control in beam-forming 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, the [81] and [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 Δ Gain is 7dB while using the CSCC topology in 65nm 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 the 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 beam-forming technique enhancing wireless technology and signaling future research directions. [Oh] et al. [184] introduce a low-power, variable gain amplifier (VGA) with a 53 dB gain range, designed for efficient mobile use, consuming only 2.16 mW and offering precise gain control in a compact CMOS process. We have already designed the VGA with a gain variation of 22dB, sufficient for our beam-former with a total gain of 31 dB.

Table 2. Beam-forming Technology.

Ref	Research	Differences
[123]	Dual-Iterative Hybrid Beam-forming Design for Millimeter- Wave Massive Multi-User MIMO Systems With Sub-Connected Structure	No JRC
[124]	Beam-forming Design in MIMO Symbiotic Radio Backscatter Systems	No JRC
[125]	A Systematic Review on Beam-forming Aided Channel Estimation Techniques for MIMO System	No JRC
[126]	RIS-Aided Wireless Communications: Prototyping, Adaptive Beam-forming, and Indoor/Outdoor Field Trials	No JRC
[127]	Experimental Analysis of Cooling Fan Noise by Wavelet-Based Beam-forming and Proper Orthogonal Decomposition	No JRC
[128]	Beam-forming Optimization for IRS-Aided Communications With Transceiver Hardware Impairments	No JRC
[129]	Channel Model for Location-Aware Beam-forming in 5G Ultra-Dense mm-wave Radio Access Network	No JRC
[120]	Beam-forming Optimization for Intelligent Reflecting Surface-Aided, simultaneous wireless information and power transfer (SWIPT) IoT Networks Relying on Discrete Phase Shifts	No JRC
Our Work	Review of Joint Radar, Communications and Integration of Beam-forming Technology	JRC

3.3. Components in Beam-Forming Circuit

Table 3 illustrates the crucial role of various components in beam-forming circuits and their significance. While referenced papers delve into detailed explanations, we emphasize providing insight as we prepare to employ beam-forming 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 [64–76,81,82], with the novel integration of JRC technology.

Table 3. Components in Beam-forming Circuit.

Components	Descriptions	Ref.
Antenna Array	Elhefnawy: Analog beam-forming phased array antenna. Bikash: Meta surface-loaded circularly polarized monopole antenna for RF energy harvesting at 5 GHz and Oh: Presents an innovative end-fire array antenna that enables vertical beamforming. It significantly improves gain from 4.55 dBi to 7.79 dBi and reduces vertical beam width, marking a notable advancement in automotive antenna design. Oh: also presents an antenna capable of switching between loop and dipole modes to support multiple frequency bands or dual polarization, simplifying design and enhancing wireless communication flexibility. Ullah: detail a compact dual-beam, dual-band antenna for future 5G millimeter-wave mobile phones.	[87,88,163,164,178]
Phase Shifters	Phase shifters are crucial in beam-forming 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 beam-forming accuracy, as highlighted.	[81–83]
Hybrid Couplers/Dividers	Key components manipulate signals’ phase relationships, facilitating signal distribution across antennas and effective beam steering; a study explores quadrature hybrid designs based on a Branch Line Coupler for a 180-degree power splitter effect: Tutkur.	[89–91]
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. Oh: introduce optimized envelope tracking transmitters for wireless systems, achieving efficiencies up to 47.8% in base stations and 28% in mobile applications, highlighting significant performance improvements by emphasizing PA.	[92,93,179]
Low Noise Amplifiers	A 65 nm CMOS variable-gain low noise amplifier delivers a 20.8 dB gain and a 3.71 dB noise figure at 31 GHz, demonstrating stability and adaptability from 30 to 34.5 GHz.	[94,95]
Filters	Wang: Beam-forming 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.	[96,97]
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.	[98,99]
Radar	The study presents a calibration technique for 77 GHz automotive radars, improving vehicle detection accuracy crucial for safety, using fast FPGA processing.	[166,167]

3.4. Narrow-Band and Wide-Band Beam-Forming

Narrow-band beam-forming, crucial for wireless communication enhancement, is explored by Shakir et al. [121] and Zhang et al. [122] through smart antennas and adaptability. Essential for 5G, spatial filtering uses millimeter waves, evolving into wideband designs, as Liu et al. [130] explain the basics, Gao et al. [131] examine its use in terahertz frequency for massive MIMO, and Ahmad et al. [132] investigate 3D imaging applications.

Table 4 depicts different beam-forming techniques; we have discussed some standard methods here.

Table 4. Beam-forming Techniques.

S.NO	Beam-forming Techniques	Descriptions	Ref
1	Analog Beam-forming	Analog beam-forming 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 beam-forming by Wang et al., and RF fan filters using CMOS time delay approximations by Mujammami demonstrate significant contributions to wireless communication technology.	[15,80,100–105]
2	Digital Beam-forming	Digital beam-forming 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.	[106–109]
3	Hybrid Beam-forming	Hybrid beam-forming, 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 beam-forming [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 [113] and further explored in [114]. Hybrid beam-forming stands out for its dual advantages of performance efficiency and economic viability in 5G/6G technology. For the hybrid beam-forming technique, spectral efficiency can be obtained by the below equation [14]. $$R_{\text{hybrid}} = \max_{c\in C}\left(\frac{1}{N}\sum_{m=0}^{N-1}\log_2\left(1+\frac{\lvert c^H H_m w_{m,opt}\rvert 2}{\sigma^2}\right)\right) \quad (7)$$	[14,15,110–114]
4	Advance Hybrid Beam-forming	Shim et al. elucidated a hybrid beam-forming 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 beam-forming technology. For the PCS hybrid beam-forming system, the sum rate for the kth and all user is calculated by the below equations discussed in [115]. $$R_k = \log_2\left(1+\frac{\lvert \boldsymbol{H}_k\boldsymbol{V}_{RF}\boldsymbol{V}_{D_k}\rvert^2}{\sigma^2+\sum_{l\neq k}\lvert \boldsymbol{H}_k\boldsymbol{V}_{RF}\boldsymbol{V}_{D_l}\rvert^2}\right) \quad (8)$$ $$R = \sum_{l=1}^{k}\log_2\left(1+\frac{\lvert \boldsymbol{H}_l\boldsymbol{V}_{RF}\boldsymbol{V}_{D_l}\rvert^2}{\sigma^2}\right) \quad (9)$$	[115]
5	Adaptive Beam-forming	Adaptive beam-forming, 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.	[14,15,116,117]
6	Switch Beam-forming	Switched beam-forming uses fixed beams for simpler antenna management, detailed in [14]. Zhang et al. advance wireless communication with photonic true-time delay beam-forming, highlighting precise signal control. Ali et al. and Guan et al. explore diverse beam-forming 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.	[14,15,118,119]

Table 5 outlines beam-forming 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 Beam-forming Technology

S.NO	Technique	Descriptions	Ref
1	Beam Refinement	Beam-forming algorithms adjust beam direction based on user device feedback, enhancing adaptation to changing conditions, user movements, and interference levels.	[133]
2	Interference Mitigation	In crowded signal-dense areas, beam-forming techniques are crucial for improving communication quality and overcoming interference challenges to enhance network performance.	[15,134–136]
3	Beam Management	5G networks use dynamic beam management and beam-forming techniques to maintain connectivity and signal quality for fast-moving users and changing channel conditions.	[137]
1	Beam-forming in JRC	Beam-forming algorithms adjust beam direction based on user device feedback, enhancing adaptation to changing conditions, user movements, and interference levels.	
2	Auto-motive Communications	Beam-forming 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.	[138]
3	Auto-motive 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 4.1cm and an angular resolution of 14.2°, aligning with theoretical and simulation predictions in MATLAB.	[139]
1	Beam-forming in 5G and 6G	Beam-forming play a significant role in 5G and 6G wireless systems, analyzing circuits and antennas, addressing technological challenges, and providing a comprehensive understanding of the field.	[140]
2	Enhanced Mobile Broadband (eMBB)	Beam-forming in 5G improves signal strength, enhancing communication quality and enabling faster data transfer for better coverage and mobile broadband services.	[141]
3	Massive MIMO	5G employs massive MIMO with beam-forming, using numerous antennas to serve multiple users simultaneously and enhance coverage and data rates.	[142]
1	Beam-forming in Wi-Fi	Beam-forming enhances wireless connections in challenging areas, like house corners. The author emphasizes implementing a multi-person breathing sensing system using Wi-Fi signals.	[119]
2	Beam-forming in LDACS	L-band Digital Aeronautical Communications System (LDACS), a digital data link for air-ground communication, faces disruption risks like jamming. Still, its robustness can be improved with beam-forming and adaptive coding for superior data rates.	[143]
3	Beam-forming in Radio Astronomy	Beam-forming 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.	[144]
1	Beam-forming in Healthcare	Beam-forming improves ultrasound images for precise monitoring in dynamic environments, while [Guan] focuses on a Wi-Fi-based multi-person breathing sensing system.	[119]
2	Acoustic beam-forming	Beam-forming enhances clear communication by focusing on desired acoustic signals and minimizing noise, which is crucial for optimizing modern wireless systems like Wi-Fi and 5G.	[145]
3	Beam-forming 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.	[146]
4	Physical Security	Advanced security systems use beam-forming with phased and 4-D antennas for improved target tracking and threat detection, leveraging sensor fusion and deep learning.	[147]

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3.5. Beam-Forming Problems and Solutions

[170] Millimeter-wave 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 millimeter-wave systems. Millimeter-wave communications face key challenges: spatial constraints, signal blockage, complex antenna arrays, and beam squint losses. [168] Modern wireless systems face challenges in interference, adaptive beam-forming, computational complexity, Massive MIMO complexities, and AI application intricacies for optimal performance. [169] The paper discusses the problem of nearing capacity limits in sub-10 GHz frequency bands due to the growing demand for wireless communication services. 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 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 beam-forming and MIMO technologies to enhance signal strength and capacity in both fixed and mobile networks. [171] 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. [172] 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. [173] 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 beam-forming to enhance performance and reduce complexity through an iterative algorithm, demonstrating effectiveness with simulations.

4. Dual Radar Communication

Integrating radar and communication functionalities emerges as a pivotal advancement in the realm of vehicular communication systems. [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. [148,163], and [Tian] et al. [149] discuss innovations in antenna design, radar performance analysis, and 3D beam-forming, offering insights into the future of autonomous vehicle communications. This collection of studies illustrates 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. [150] discuss choosing 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's effectively used in car-to-car communication through a harmonized backscatter method, as shown [19]. The fundamental equations of JRC focusing radar are

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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 below [174].

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

This equation calculates the distance R between a radar system and a target object using the radar signal's round-trip travel time ΔT. 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.

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

This radar range equation calculates the received power P_r at the radar system, 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 understand how different factors affect the received signal strength, influencing 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 of the range resolution equation considers the pulse's bandwidth B_p for systems using pulse compression techniques; a more expansive bandwidth results in a finer range resolution.

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

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 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 because they can determine targets' range and velocity.

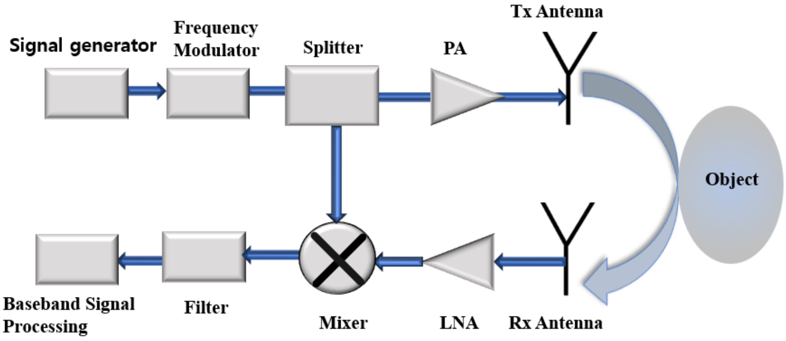

Figure 2. A modified FMCW diagram.

4.2. Communications and Beam-Forming

Rybin et al. [20] highlight using chaos-based systems for secure automotive communications, employing adaptive beam-forming 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. [151] introduce Oppermann sequences for vehicular radar and communication integration, enhancing efficiency. Rajkumar et al. [152] detail advancements in radar altimeters for aerial weaponry, focusing on precision and adaptability. Dhouioui et al. [153] describe a novel obstacle classification system that combines radar and camera data with machine learning for accuracy. Oh et al. [176] showcases a dual-channel RF transceiver module for the IEEE 802.11p standard, enhancing vehicular communication by allowing simultaneous data transmission and reception. With successful tests showing compliance with zero packet errors, the module significantly improves real-time, reliable communication in intelligent transportation systems. Beam-forming enhances communication systems by directing antenna signals, improving safety and driving experience in automotive applications. 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 [148] in which the author discussed a dual polarization 3-D beam-forming antenna in package (AIP) used in intelligent automotive vehicles. Oh et al. [177] discussed the Wireless Transceiver System Using Beam Tracking; the patent outlines a system that enhances VR/AR experiences by dynamically adjusting to head movements, reducing the need for multiple sensors, cutting costs, and minimizing latency and discomfort. It focuses on real-time, high-quality image delivery for improved user immersion and comfort. The author in [185] presents a 60GHz transceiver for wirelessly linking mobile devices to vehicle displays, achieving up to 10 Gbps data rates with minimal power use 66 mW. It is designed for mirror link applications and offers efficient high-definition content transmission. It is ideal for enhancing in-vehicle entertainment and information systems, which will help us establish communication between V2X.

Three main approaches in integrating radar and communication systems are 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 right 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 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 promising for high-rate, stable communication in dynamic environments [174].

4.3. JRC and Beam-Forming Integration

Two main strategies for integrating communication functions within radar systems in JRC systems, focusing 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 [174].

Our vehicle radar system uses special techniques to improve safety features in cars. The simple diagram is shown in Figure 3, which helps them communicate and avoid accidents. We focus on controlling the radar beams to prevent signal interference, making our method unique. The radar's design allows it to switch quickly between detecting objects and sending communication signals, necessary for advanced driver-assistance systems. This approach is 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 beam-forming to ensure efficient operation. These strategies highlight the balance between performance and integration in the evolving landscape of JRC systems [174]. Communications signal-based approaches, using 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, using conventional radar signals for communication but potentially compromising radar performance, necessitating advanced waveform designs [174]. Beam-forming technology is vast and can be used in various fields: Wireless Communications, Radar Systems, Sonar Systems, Medical Imaging, Audio Systems, Automotive, Astronomy, Space Exploration, and Wireless Power Transfer. We integrated it with the JRC to make communication fast and reliable. Beam-forming technology in ultrasound systems, as noted in [186], enables focused, non-invasive clot treatment by breaking down blood clots with precision, offering a significant advancement in medical therapies.

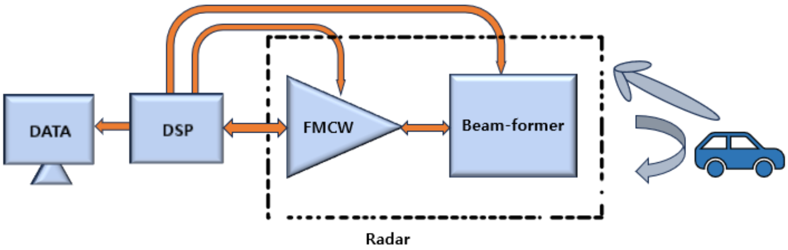

Figure 3. Radar structure with beam-former.

A joint radar and communication system combines radar sensing and communication in one efficient package, as shown in Figure 4, which is ideal for space-constrained applications like cars and planes. It starts with generating a radar waveform and then processes this signal digitally to ensure it meets radar requirements. A unique screen handles the communication aspect, coordinating data sharing. The system's core includes signal preparation, transmission, and reception components, 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 tech. Our unique research improves this process using beam-forming, 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, beam-forming lets us precisely locate objects, boosting reliability and efficiency. So, in short, our work makes radar communication more secure and efficient. The research delves into spatial beam-forming 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 the reference. Moreover, the antenna allocation methods for enhancing spectral efficiency and channel capacity in Dual-Function Radar-Communication (DFRC) systems emphasize the trade-offs and decision-making processes in designing effective spectrum-sharing mechanisms. These approaches aim to balance the optimal performance of 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 [174]. The evaluation of the diagram, as shown in Figure 4. is a complex system crucial for radar and communication, featuring components like DACs, ADCs, and amplifiers, all vital for transmitting and receiving signals. It uses beam-forming, employing multiple antennas and phase shifters to direct beams accurately, which is 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 critical to reducing distortion; the system's ability to handle varying signal strengths indicates its dynamic range; managing interference, sharing resources without performance loss, and adapting to environmental changes are crucial for its dual function. Power consumption, thermal management, and the system's ability to fit into different platforms and scales are essential for its efficiency, reliability, and versatility. The power can be reduced with better performance, as discussed in the subsection of the beam-forming section, while using components with high performance like PA, PS, LNA, VGA, and intelligent antenna. CSI plays a vital role in beam-forming technology, especially within JRC systems. CSI provides detailed insights into the communication link, such as signal path and obstacles, enabling beam-forming optimization. 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, beam-forming and CSI work together to improve 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 beam-forming within JRC systems is critical to advancing in fields like wireless communication and radar technology, offering a blend of improved efficiency and performance. The beam-forming system is based on the transceiver, receiver, and transmitter, while we have combined both in a single chip in which the scattering parameters S11, S22, and S21 parameters play essential roles in efficiency. [Oh] et al. [182] introduce a low-power, single-chip CMOS receiver and LTCC SoP for 60GHz mobile applications, achieving significant performance with a deficient power consumption of 21.9mW. Integrated with a 2x2 patch array antenna showing an 8.9dBi gain, the design highlights advancements in achieving compact, efficient, and cost-effective solutions for high data rate wireless communications at 60GHz.

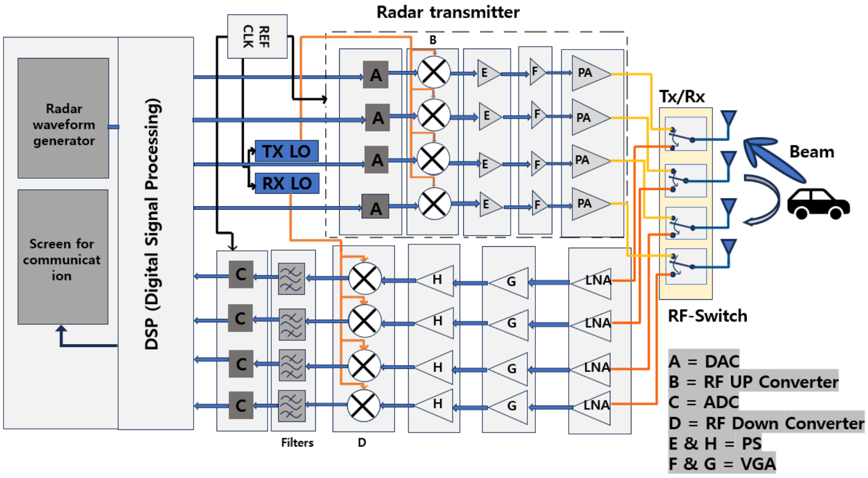

Figure 4. Joint radar communication system with beam-forming.

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 beam-forming technology.

Table 6. Joint Radar Communications.

REF	Research	Differences
[155]	Joint radar and communication: A survey coexistence, cooperation, codesign, and collaboration	No-Beam-forming
[156]	Joint Radar and Communication Design: Applications, State-of-the-Art, and the Road Ahead	No-Beam-forming
[157]	Joint Radar Communication Systems: Modulation Schemes and System Design	No-Beam-forming
[24]	Radio Resource Management in Joint Radar and Communication: A Comprehensive Survey	No-Beam-forming
[158]	Joint Radar Communication Strategies for Autonomous Vehicles: Combining Two Key Automotive Technologies	No-Beam-forming
[159]	Toward Millimeter-Wave Joint Radar Communications: A Signal Processing Perspective	No-Beam-forming
[160]	Toward Millimeter-Wave Joint Radar Communications: A Signal Processing Perspective	No-Beam-forming
[161]	A mm-Wave Automotive Joint Radar-Communications System	No-Beam-forming
Our Work	Review of Joint Radar, Communication and Integration of Beam-forming Technology	Beam-forming

In high frequency, the transmission line and parasitic components are essential to consider,[180] introduces a compact, efficient first microstrip 60GHz Rotman lens and delay line using low-temperature co-fired ceramic (LTCC) technology, enhancing beam-forming by enabling precise signal direction with reduced size and loss. A loss component must be considered in the high frequency, especially 60 GHz, and the authors Oh et al. [181] present a new grounded coplanar waveguide (GCPW) to waveguide (WG) transition in LTCC for 60GHz applications, achieving a low insertion loss of 0.775dB and wide bandwidth. Integrated into a 60GHz SiP receiver module, it successfully enabled a 648Mbps wireless data link over 3 meters, demonstrating significant improvements in loss, bandwidth, and integration simplicity for high data-rate 60GHz communications. As the RF up converter and RF down converter are also part of the beam-former in the design, we need to consider their performance. The author [Oh] et al. [183] present a new, efficient mixer for 60GHz wireless technology. They use a modern manufacturing process to enhance signal conversion while consuming less power. The millimeter-wave is compact and ideal for short-range, high-speed data transfer applications like wirelessly streaming video. Significant data transfer between vehicles via virtual reality videos and the system is fundamental regarding the communication setup. The author in [187] introduces a faster method for sending high-quality VR content over wireless networks using advanced error-correcting techniques. It can fix many errors in the data and send up to 4K video at speeds of 12.8 Gbps, all with a very low delay of just 1 ms, making VR experiences smoother and more immersive.

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, exacerbated by obstacles and weather conditions, leading to signal degradation [154]. Additionally, the unique propagation characteristics of millimeter-wave, such as higher attenuation through rain and foliage and challenges in indoor signal penetration, pose significant challenges for JRC systems [28,154]. 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. Beam-forming and MIMO techniques tackle signal loss, improving network quality. Smaller cell sizes and intelligent frequency use boost coverage. Combining millimeter-wave 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 essential for adoption. For JRC, reducing interference through techniques like time division multiplexing ensures that radar and vehicle communication systems can work together smoothly, leading to safer roads. These strategies help solve significant issues in wireless communication and automotive technologies. The JRC design, enabling radar and communication system coexistence, faces challenges like interference, compromises performance, and complex transmitter design, especially in dense deployments like autonomous vehicles. Proposed solutions include advanced resource management and design strategies to address these issues. For beam-forming in JRC, the primary problem is interference between radar and communication systems sharing the same spectrum. The solution is spatial beam-forming, specifically projecting radar signals into the null space of the radar system's channel to communication receivers, thereby minimizing interference [174]. In JRC systems, beam-forming faces challenges such as interference management between radar and communication signals, spectrum sharing in crowded frequency bands, hardware limitations that restrict beam-forming capabilities, and increased signal processing complexity. Solutions to these challenges include employing adaptive beam-forming techniques to optimize performance dynamically, 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 beam-forming effectiveness. These approaches aim to address the unique problems in integrating radar and communications systems, paving the way for more efficient and capable joint operations. To improve beam-forming in JRC systems, a new method focuses on using millimeter-wave signals' sparse (or not densely packed) nature. Using a specific graph-based algorithm, this method compresses the signal information and recovers it efficiently. With less effort, this approach helps create more focused beams and shows better results than older methods, making it a more innovative way to handle beam-forming in JRC systems [175].

6. Futuristic Importance

When integrated with JRC for 6G networks, Beam-forming stands at the forefront of revolutionizing wireless communication. This technique enhances the signal quality and reduces interference, which is 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, 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.[162], 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. [162] 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 beam-forming holds for enhancing communication and power transfer efficiency, marking a critical step toward realizing the full promise of 6G technologies. Integrating beam-forming in JRC enhances 6G by providing precise, efficient connectivity and radar sensing, paving the way for advanced autonomous systems and improved network capabilities. The critical potential beam-forming and MIMO in the upcoming 6G network will play a significant role as [Zhang] et al. [165] introduce a compact 8x8 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. Conclusion

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 deeply explored beam-forming mechanics, 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've 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 beam-forming 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 captures the current state of these technological advancements and paints a vision of their future impact. In conclusion, this paper bridges the present with a future where these sophisticated technologies redefine wireless communication. It calls on us to recognize their crucial role in the ongoing evolution of communication systems. It urges us to envision a future where these groundbreaking developments significantly enhance connectivity and security.

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