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Classification of Frequency Bands in the Joint Millimeter-Wave Sensing and Communication System (JSCS): A Comprehensive Analysis

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Abstract:

The Joint Millimeter-Wave Sensing and Communication System (JSCS) is a rapidly emerging technology that integrates sensing and communication functionalities in the millimeter-wave frequency bands. This paper presents a comprehensive analysis of the classification of frequency bands within the JSCS. The proposed classification scheme aims to facilitate efficient resource allocation and interference management in JSCS systems.

To achieve this, we first review the characteristics and potential applications of millimeter-wave frequency bands. Subsequently, we analyze the challenges and opportunities associated with the joint utilization of these bands for both sensing and communication purposes. The proposed classification scheme takes into account factors such as channel characteristics, propagation characteristics, spectrum availability, and system requirements.

We then present a detailed examination of various frequency bands, considering their suitability for different sensing and communication tasks. The classification encompasses a range of factors, including bandwidth, signal quality, interference levels, and regulatory considerations. Moreover, we discuss the impact of hardware limitations and system design constraints on the selection of frequency bands.

Furthermore, we evaluate the performance of different frequency bands in terms of their sensing capabilities and communication efficiency. We investigate the trade-offs between the two functionalities and identify optimal frequency bands for specific use cases within JSCS systems. Additionally, we explore potential techniques for mitigating interference and enhancing overall system performance.

Finally, we discuss practical implementation considerations and provide insights into the future prospects of JSCS technology. Our comprehensive analysis serves as a valuable resource for researchers, engineers, and system designers working on JSCS, facilitating informed decision-making in frequency band selection and system design.

Keywords: Joint Millimeter-Wave Sensing and Communication System (JSCS), frequency band classification, resource allocation, interference management, sensing, communication.

1. Introduction

The frequency bands used to classify mm-wave joint sensing and communication systems. Mm-wave joint sensing and communication systems operate in the frequency band between 30 GHz and 300 GHz, which corresponds to wavelengths ranging from 1 millimeter to 10 millimeters. Within this broad frequency range, it is possible to distinguish several sub-bands based on the specific characteristics and applications of the signals in each band. Here are a few examples of frequency sub-bands commonly used in mm-wave joint sensing and communication systems [[130-152](#)]:

1. E-band (60-90 GHz): The E-band is a relatively high-frequency band that is often used for short-range, high-capacity communication links. It is well-suited for applications that require large amounts of data to be transmitted over a limited area, such as in the construction of smart cities or in the operation of autonomous vehicles [[130-152](#)].
2. V-band (40-75 GHz): The V-band is a mid-frequency band that is often used for applications that require a combination of high data rates and long range. It is well-suited for applications such as wireless backhaul, which involves transmitting data over long distances between wireless base stations [[130-152](#)].
3. W-band (75-110 GHz): The W-band is a high-frequency band that is often used for applications that require extremely high data rates over short distances. It is well-suited for applications such as high-definition video transmission and high-resolution imaging.
4. K-band (18-27 GHz): The K-band is a mid-frequency band that is often used for radar applications. It is well-suited for applications that require the detection of objects or surfaces at relatively long ranges, such as in military surveillance or in automotive collision avoidance systems [[130-152](#)].
5. ISM-band (24 GHz): The 24-GHz ISM band is an unlicensed band that anyone can use without a license, as it has been designated to be used by unlicensed devices. Communication, sensing, and imaging applications make it a popular choice and our purpose in this thesis is focused on developing novel joint millimeter-wave sensing and communication system in the 24-GHz ISM band for detection, tracking, and vehicle-to-vehicle (V2V) communication [[130-152](#)].

2. Efficiency of JCR systems [[153](#)]

To calculate the performance of a joint millimeter-wave (mm-wave) sensing and communication system at a specific frequency, you will need to consider several factors, including the bandwidth, modulation scheme, antenna configuration, [channel condition](#), and power budget. The bandwidth of the system will determine the amount of data that can be transmitted within a given time period. A larger bandwidth will allow for higher data rates. The modulation scheme used will determine the number of bits that can be transmitted per symbol. Higher-order modulation

schemes such as 64QAM and 256QAM can support higher data rates but are more sensitive to noise and interference. The antenna configuration, including the number and type of antennas used, will affect the gain of the system and the beam pattern of the transmitted signal. This can impact the range and coverage of the system. The channel conditions, including the presence of noise and interference, will affect the signal-to-noise ratio (SNR) and the error rate of the system. The power budget of the system will determine the maximum range and coverage that can be achieved.

To calculate the performance of the system, we need to consider how these factors interact and use suitable modeling and simulation tools to predict the performance of the system at the desired frequency mentioned above. The specific method for calculation will depend on the specific requirements and goals of the system, as well as the available resources and constraints.

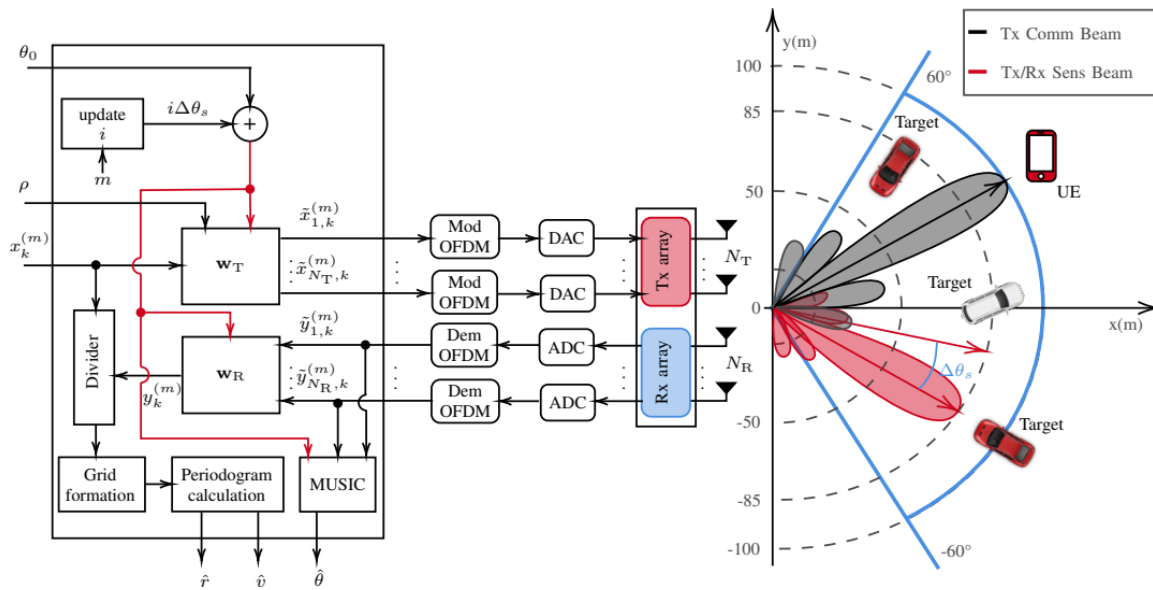


Figure 1. Sensor block diagram for a compact 5G NR-based sensor with multi-beam capability for joint communication and sensing [153].

3. Implications of Beamforming Architecture for mm-wave Localization and Sensing

Beamforming is a signal processing technique that uses antenna arrays to direct the transmitted or received signal towards a specific direction in space. This technique has been widely used in various wireless communication systems to improve the signal quality and coverage. In recent years, millimeter-wave (mm-wave) communication has emerged as a promising solution for high-speed wireless communication due to its large bandwidth availability. Moreover, mm-wave can also be used for localization and sensing applications. In this article, we will discuss the implications of beamforming architectures for mm-wave joint communication system for localization and sensing, Figure 10 [153]. It is a frequent misperception that the free space propagation loss increases with frequency. According to [6], [7], shorter wavelengths propagate further due to narrower directive beams for a given aperture area of the antennas employed. With a patch antenna operating at 3 GHz and an antenna array operating at 30 GHz of the same physical size, this is further confirmed in [8]. No of the operating frequency, we see the same amounts of propagation loss. As a result, mm-wave frequencies make it possible to utilise antenna arrays that generate highly directed beams that result in high array gains. As seen in Figure 11, the coverage area grows as array size rises in proportion to beam penetration distance [9].

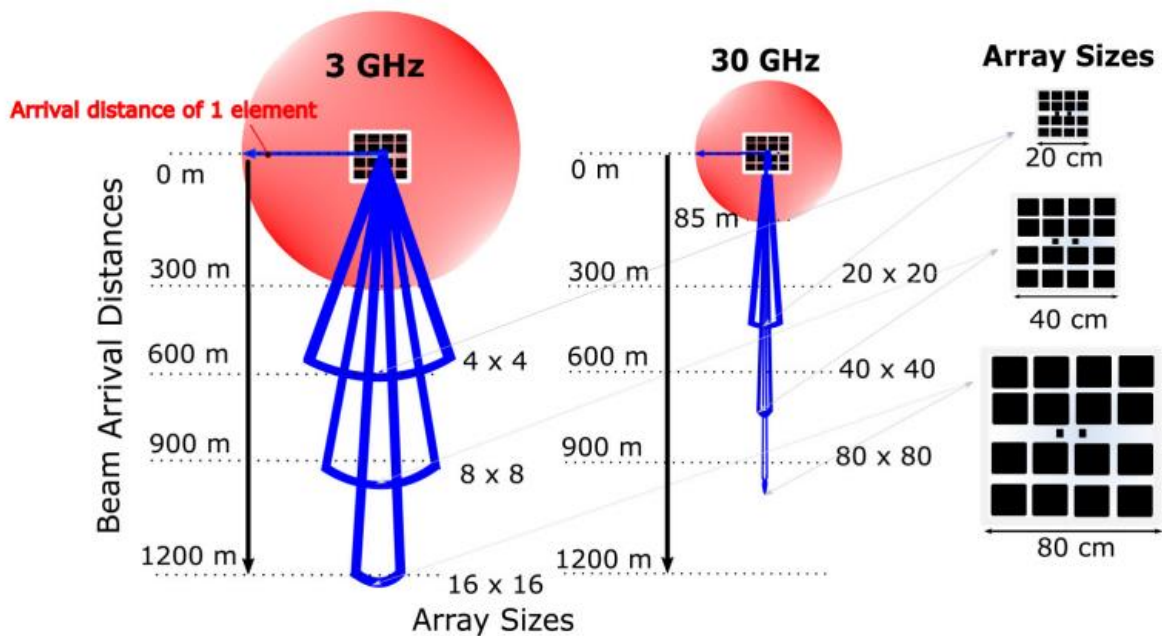


Figure 2. Beamwidth effects in relation to operating frequency and array size [9].

3.1. Types of Beamforming:

There are two types of beamforming techniques: analog beamforming and digital beamforming. Analog beamforming is a simple and low-cost solution that uses a single radio frequency (RF) chain and a phase shifter network to steer the beam towards a specific direction. However, analog beamforming has limited beamforming resolution and can only steer the beam in a fixed direction. Digital beamforming, on the other hand, uses multiple RF chains and digital signal processing to steer the beam towards a specific direction. Digital beamforming provides higher beamforming resolution and can adaptively steer the beam towards a moving target [9-56], [153].

3.2. Overview of mm-wave Joint Communication System:

mm-wave joint communication system is a communication system that uses mm-wave frequency bands for both communication and sensing applications. The system consists of multiple nodes, where each node is equipped with an antenna array and a radio transceiver [9-56], [153]. The nodes communicate with each other using mm-wave frequency bands and also use the same frequency bands for sensing applications. The sensing application involves detecting the presence or absence of objects in the environment and estimating their positions [9-56], [153]. Implications of Beamforming Architectures for mm-wave Joint Communication System: Beamforming is a critical component of the mm-wave joint communication system for localization and sensing [9-56], [153]. The following are the implications of beamforming architectures for mm-wave joint communication system [9-56], [153].

A. Spatial Resolution:

Spatial resolution is the ability of the system to distinguish between two closely spaced targets. Beamforming architectures can significantly affect the spatial resolution of the system [9-56], and [153]. Digital beamforming provides higher spatial resolution compared to analog beamforming. This is because digital beamforming can steer the beam towards a specific direction with high precision and can also adaptively steer the beam towards a moving target [9-56], and [153]. Therefore, digital beamforming is preferred for localization and sensing applications that require high spatial resolution [9-56], and [153].

B. Beamforming Gain:

Beamforming gain is the ability of the system to increase the signal-to-noise ratio (SNR) by focusing the transmitted or received signal towards a specific direction. Beamforming gain is proportional to the number of antenna elements in the array and the beamforming

resolution. Therefore, increasing the number of antenna elements and using digital beamforming can significantly increase the beamforming gain of the system [9-56], and [153]. This is particularly important for mm-wave communication systems, as they suffer from high path loss due to the short wavelength of the mm-wave frequency bands [9-56], and [153].

C. Interference Mitigation:

Interference is a major challenge in mm-wave communication systems, as the signals are highly directional and sensitive to interference from other sources. Beamforming architectures can be used to mitigate interference by steering the beam towards the desired direction and nulling the interference sources [10], [135-153]. Digital beamforming provides better interference mitigation compared to analog beamforming, as it can adaptively null the interference sources and also steer the beam towards the moving interference source [10], [135-153].

D. Energy Efficiency:

Energy efficiency is a critical aspect of any wireless communication system, as it affects the battery life and overall system cost. Beamforming architectures can significantly affect the energy efficiency of the system [10], [135-153]. Analog beamforming is more energy-efficient compared to digital beamforming, as it requires fewer RF chains and less digital signal processing [10], [135-153]. However, digital beamforming can provide higher energy efficiency compared to analog beamforming, as it can adaptively steer the beam towards [10], [135-153].

For applications like autonomous driving, [10]'s Millimeter-wave (mm-wave) joint communication radar (JCR) will enable high data rate communication and high-resolution radar scanning [10]. Nevertheless, due to the used directed communication beam, previous

JCR systems based on mm-wave communications hardware suffer from a constrained angular field of view and low estimate accuracy for radars [10], and [135-153]. For the mm-wave automobile JCR with a phased-array architecture, we present an adaptive and quick combined waveform-beamforming design in this study [10]. This design allows for a trade-off between communication and radar performances. Our JCR design leverages circulant shifts of the transmit beamformer to obtain radar channel measurements and two-dimensional compressed sensing (CS) in the space-time domain to quickly estimate the mm-wave automobile radar channel in the Doppler-angle domain with a broad field-of-view [10], and [135-153]. In [10], they optimize these circulant shifts to reduce the coherence of the CS matrix while taking into account the limitations of our problem's space-time sampling [10]. They use a normalized mean square error (MSE) measure for radar estimating and a distortion MSE metre for data transfer, which is comparable to the distortion metric in the rate-distortion theory, to assess the performance trade-offs of the JCR [3-10]. We also create a weighted average optimization problem based on MSE for the adaptive JCR coupled waveform-beamforming design [3-10]. Numerical findings show that, with a moderate worsening in the communication distortion MSE, our proposed JCR architecture permits the estimate of short- and medium-range radar channels in the Doppler-angle domain with a low normalized MSE [10]. Figure 12 depicts an example of a car's mm-wave JCR system that can simultaneously conduct SRR/MRR radar sensing with a wide field of view and V2V communication with a narrow field of view [10].

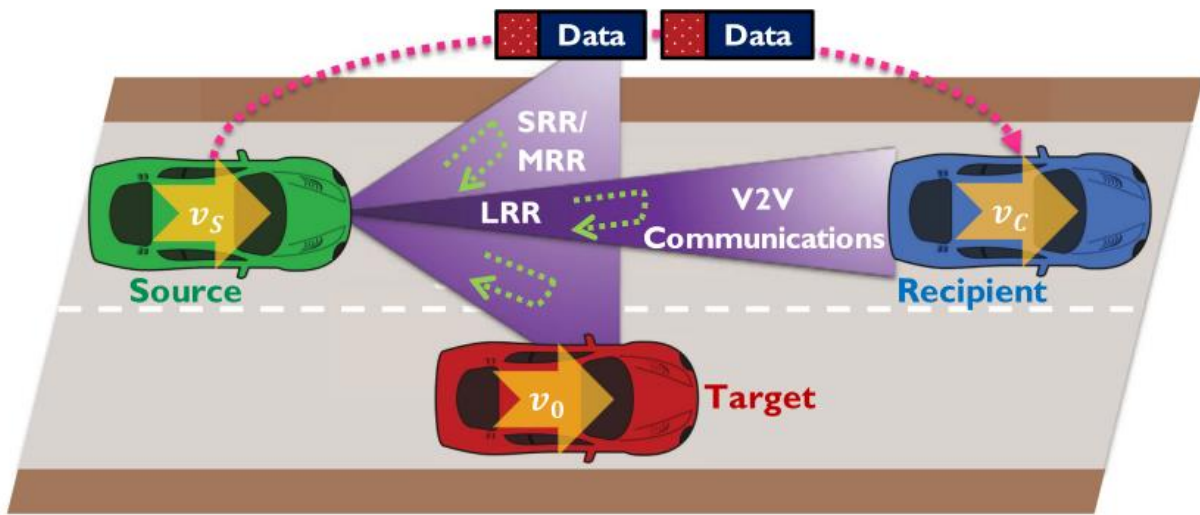


Figure 3. Illustration of an automobile mm-wave JCR system capable of performing SRR/MRR radar sensing with a large field of view and V2V communication with a small field of view concurrently. [10].

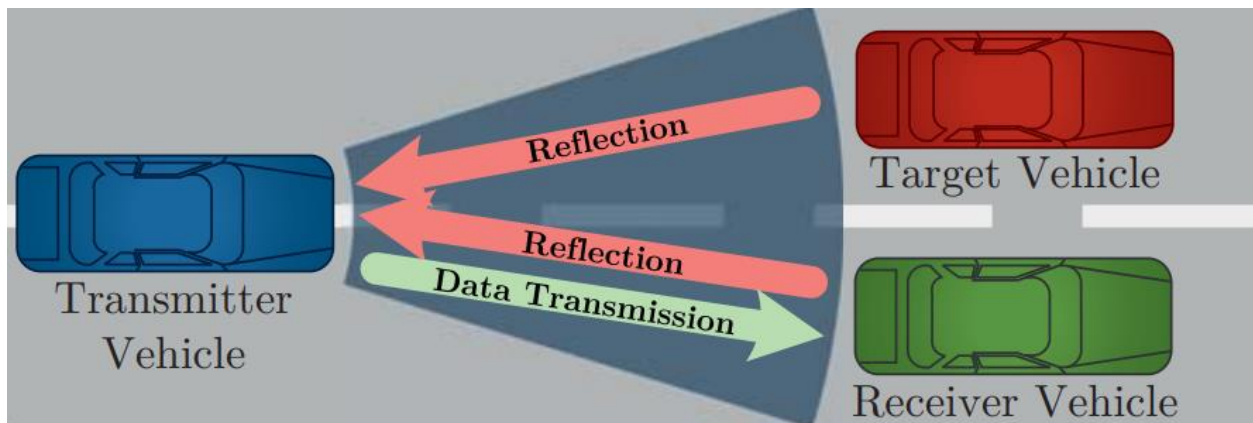


Figure 4. It generates the range-Doppler map of the illuminated area with reflections and transmits it to the receiver vehicle while transmitting data from the radar [157].

3.3. JCRS in the 24-GHz ISM band [150-157].

Millimeter-wave (mm-wave) communication refers to the use of electromagnetic waves with wavelengths in the millimeter range, typically 30 GHz to 300 GHz, for wireless communication. This frequency range is known as the millimeter-wave band or the extremely high frequency (EHF) band [3-87]. In the International Scientific Mobile (ISM) band, which is a set of radio frequency bands set aside internationally for the use of industrial, scientific, and medical (ISM) devices, the

24 GHz band (24.0-24.25 GHz) is allocated for use in the United States [150-282]. In mm-wave communication systems, the transmission range is typically limited due to the high absorption and scattering of mm-wave signals by objects in the environment. However, mm-wave communication has several potential advantages over traditional communication systems that operate at lower frequencies, such as increased bandwidth and the ability to support high data rates [150-154]. One potential application of mm-wave communication in the 24 GHz ISM band is in the development of sensors for various industrial and scientific applications [150-154]. These sensors can use mm-wave technology to detect a wide range of physical properties, including distance, velocity, and temperature. For example, mm-wave radar sensors can be used to measure the distance to an object by transmitting a burst of mm-wave energy and measuring the time it takes for the signal to be reflected back to the sensor [10-14]. Another potential application of mm-wave communication in the 24 GHz ISM band is in the development of wireless communication systems. These systems can use mm-wave technology to transmit data over short distances at high data rates [50-54]. For example, mm-wave communication systems can be used to transmit data between devices in a local area network (LAN) or to connect devices to the internet in a wireless wide area network (WAN) [150-154]. The transmission range of a mm-wave communication system in the 24 GHz ISM band depends on a variety of factors, including the transmit power, the antenna gain, and the characteristics of the environment. In general, the transmission range of a mm-wave communication system in the 24 GHz ISM band is limited to a few hundred meters, although this can vary depending on the specific application [150-154]. Overall, mm-wave communication systems in the 24 GHz ISM band have the potential to enable a wide range of sensing and communication applications, including the development of sensors for industrial and scientific applications and the development of wireless communication systems for local and wide area networks [150-154].

As compared to a communication user, traditional radars occupy a wider bandwidth. In order to achieve satisfactory range resolution, radar requires a larger bandwidth [162]. In recent years, mm-wave communications have mitigated the difference between communication and radar domains [162]. The short wavelengths and high frequencies of mm-waves enable a large number of antennas

to be accommodated in a small area, which makes beamforming possible [159-162]. The emergence of a variety of new radar applications on the consumer market is another major development that makes the joint system design possible [162]. In order to implement several safety and traffic management functions, vehicles should be equipped with both communication and radar modules. V2V communication has emerged as an important domain, and it is desirable to equip vehicles with both modules for implementing V2V communication. Furthermore, radars have been used in health applications and assisted living facilities. Radar and communication capabilities are also desirable in such applications [159-162].

According to the literature [159-162], spectrum sharing methods can be classified as cohabitation, cooperation, or codesign. Figure 14 illustrates the main concepts governing these methods [162]. There are instances in the literature when coexistence, cohabitation, and cooperation are used interchangeably [162]. Nevertheless, there are three categories that can be identified based on the working principle [159-162].

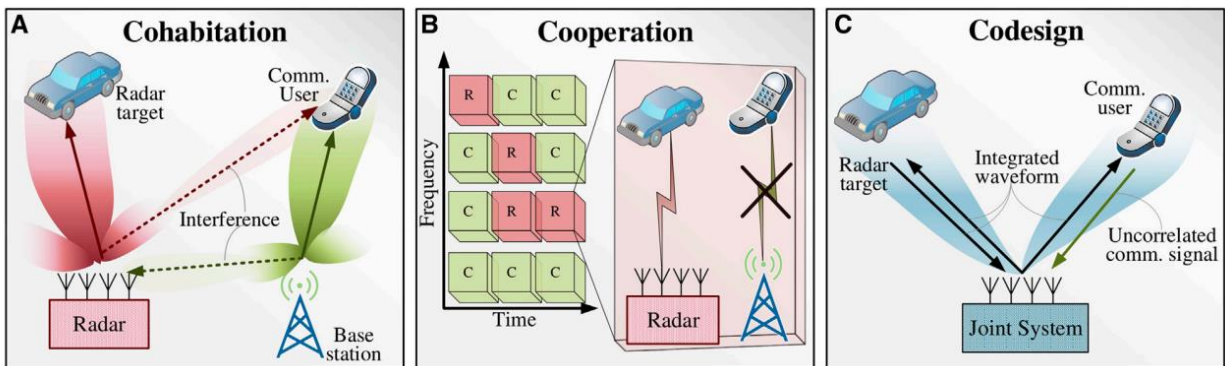


Figure 5. Cohabitation, cooperation, and codesign are all methods for sharing spectrum [162].

There are several types of mm-wave communication systems that can operate in the 24 GHz ISM band, including [150-154]:

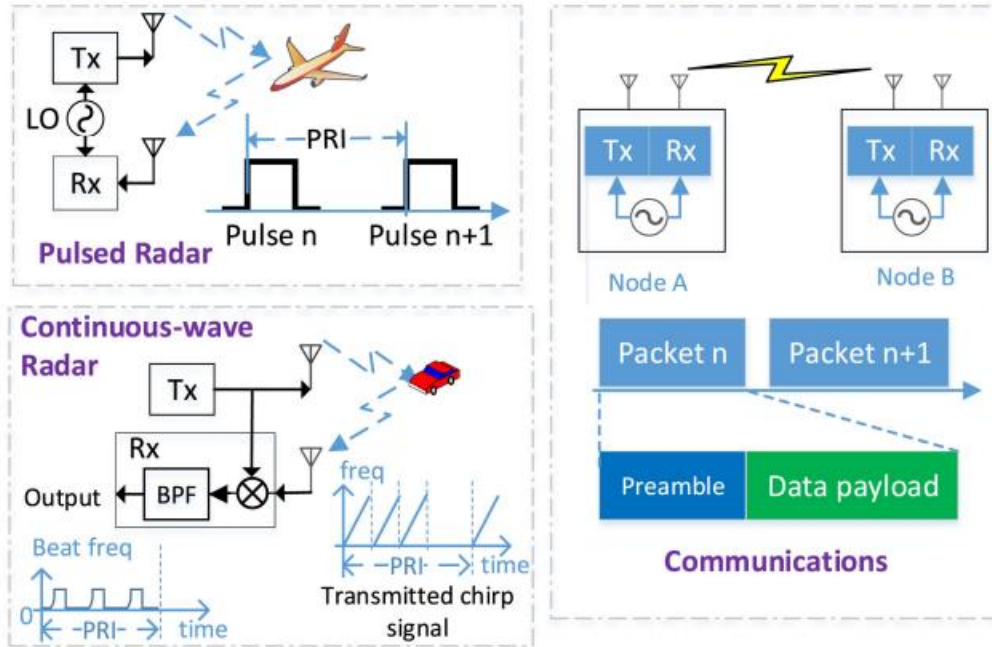


Figure 6. An illustration illustrating pulsed radars, continuous-wave radars, and communication systems. PRI: pulse repetition interval; Tx: transmitter; Rx: receiver; BPF: bandpass filter [171].

3.3.1. Pulse radar [158]:

This type of mm-wave communication system transmits a burst of mm-wave energy and measures the time it takes for the signal to be reflected back to the sensor [158-171]. Pulse radar is a type of radar system that transmits short pulses of radio frequency (RF) energy and measures the time delay between the transmission of the pulse and the reception of the reflected signal to determine the range and velocity of objects [158]. Pulse radar systems are commonly used in a variety of applications, including air and sea navigation, air traffic control, and weather forecasting. In the industrial, scientific, and medical (ISM) radio frequency band, pulse radar systems operate at frequencies between 902 MHz and 928 MHz, which are reserved for unlicensed use [158]. The ISM band is a range of frequencies that have been set aside internationally for the use of industrial, scientific, and medical devices that emit radio frequency energy, including pulse radar systems. The use of the ISM band is governed by regulations that vary from country to country [158]. Pulse radar systems have several advantages over other types of radar systems, such as frequency

modulated continuous wave (FMCW) radar. For example, pulse radar systems can provide high resolution range measurements and can operate over a wide range of distances. They are also relatively simple and inexpensive to design and build [158]. However, pulse radar systems are susceptible to interference from other RF sources and can be affected by atmospheric conditions, such as rain and snow [158].

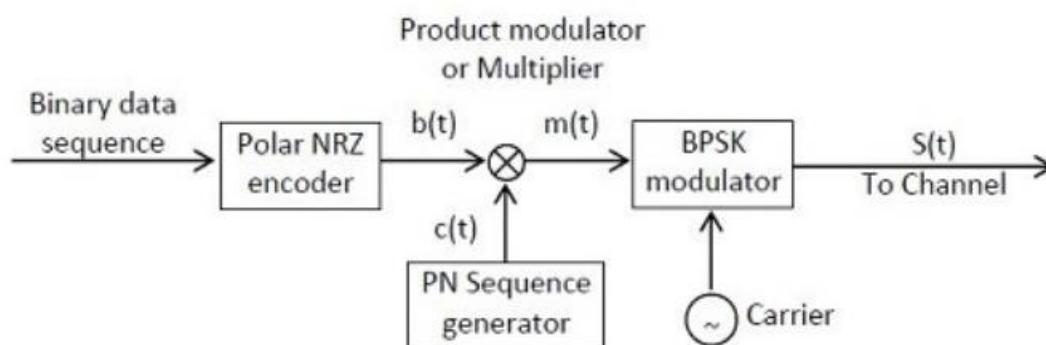


Figure 7. Direct Sequence Spread Spectrum Block Diagram [163].

3.3.2. Direct sequence spread spectrum (DSSS) [163]:

This type of mm-wave communication system spreads the transmitted signal over a wide frequency band using a spreading code. There is shown in Figure 16 a block diagram for Direct Sequence Spread Spectrum, which explains how this method works. The receiver uses the same spreading code to decode the transmitted signal [163]. In detail Direct sequence spread spectrum (DSSS) radar is a type of radar system that uses direct sequence spread spectrum technology to transmit a radio frequency (RF) signal [163]. In a DSSS radar system, the transmitted signal is spread over a wide frequency band using a spreading code, which is a predetermined sequence of binary digits (bits) [163]. The transmitted signal is then received and demodulated using the same spreading code to recover the original signal [163]. DSSS radar

systems are commonly used in a variety of applications, including air and sea navigation, air traffic control, and weather forecasting. In the industrial, scientific, and medical (ISM) radio frequency band, DSSS radar systems operate at frequencies between 902 MHz and 928 MHz, which are reserved for unlicensed use. The ISM band is a range of frequencies that have been set aside internationally for the use of industrial, scientific, and medical devices that emit radio frequency energy, including DSSS radar systems. The use of the ISM band is governed by regulations that vary from country to country [163]. DSSS radar systems have several advantages over other types of radar systems. For example, they can provide high immunity to interference from other RF sources and can operate over a wide range of distances. They are also relatively simple and inexpensive to design and build. However, DSSS radar systems are susceptible to interference from other systems that use the same spreading code, and can be affected by atmospheric conditions, such as rain and snow [163].

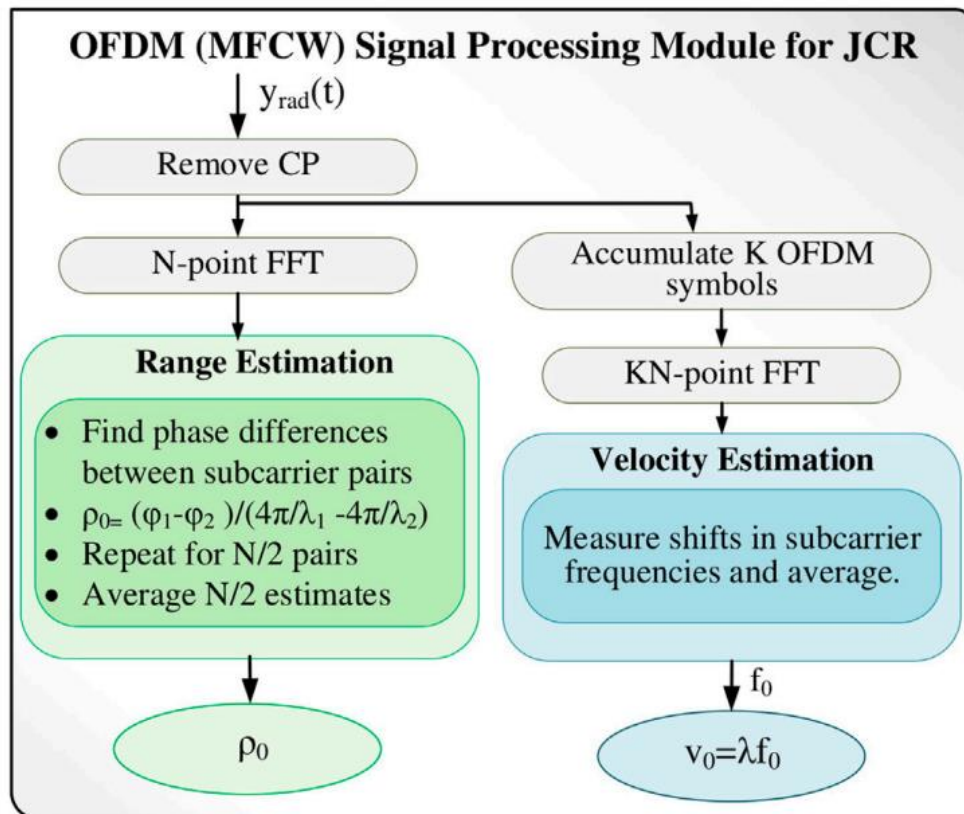


Figure 8. OFDM Signal processing Module [162]

3.3.3. Orthogonal frequency division multiplexing (OFDM)

[\[162-170\]](#):

This type of mm-wave communication system divides the transmitted signal into multiple orthogonal subcarriers and transmits the subcarriers simultaneously [\[162\]](#). The receiver demodulates the subcarriers to recover the transmitted data. In detail as shown in Figure 16, Orthogonal frequency division multiplexing (OFDM) is a type of digital modulation scheme that is used in many different communication systems, including radar systems [\[162\]](#). In an OFDM radar system (See Figures. 17-19), a wideband signal is transmitted by dividing it into a number of narrowband subcarriers that are modulated using a variety of techniques, such as phase shift keying (PSK) or quadrature amplitude modulation (QAM) [\[162\]](#). The subcarriers are then combined to form the transmitted OFDM signal [\[162\]](#). The range and velocity of objects can be determined by measuring the time delay and Doppler shift of the returned signal [\[162\]](#). In the industrial, scientific, and medical (ISM) radio frequency band, OFDM radar systems operate at frequencies between 902 MHz and 928 MHz, which are reserved for unlicensed use [\[162\]](#). The ISM band is a range of frequencies that have been set aside internationally for the use of industrial, scientific, and medical devices that emit radio frequency energy, including OFDM radar systems. The use of the ISM band is governed by regulations that vary from country to country [\[162-170\]](#).

OFDM radar systems have several advantages over other types of radar systems. They are relatively simple and inexpensive to design and build. However, OFDM radar systems are susceptible to interference from other systems that use the same subcarriers, and can be affected by atmospheric conditions, such as rain and snow [\[64\]](#), [\[162-170\]](#). As an example, in [\[64\]](#), they propose a millimeter-wave joint radar-communications (JRC) system comprising a bi-static automotive radar and vehicle-to-vehicle communications [\[162-170\]](#). We study the applicability of known phase modulated-continuous-wave (PMCW) and orthogonal-frequency division-multiple-access (OFDM) waveforms for bi-static JRC. Please refer to Figure.19 provides more details about the block diagram [\[162-170\]](#). In both cases, they design multiplexing strategies to ensure the parameter identifiably, derive JRC statistical bounds and numerically demonstrate superior

performance of proposed low-complexity JRC super-resolution algorithms over conventional two-dimensional fast Fourier transform/Multiple Signal Classification [162-170].

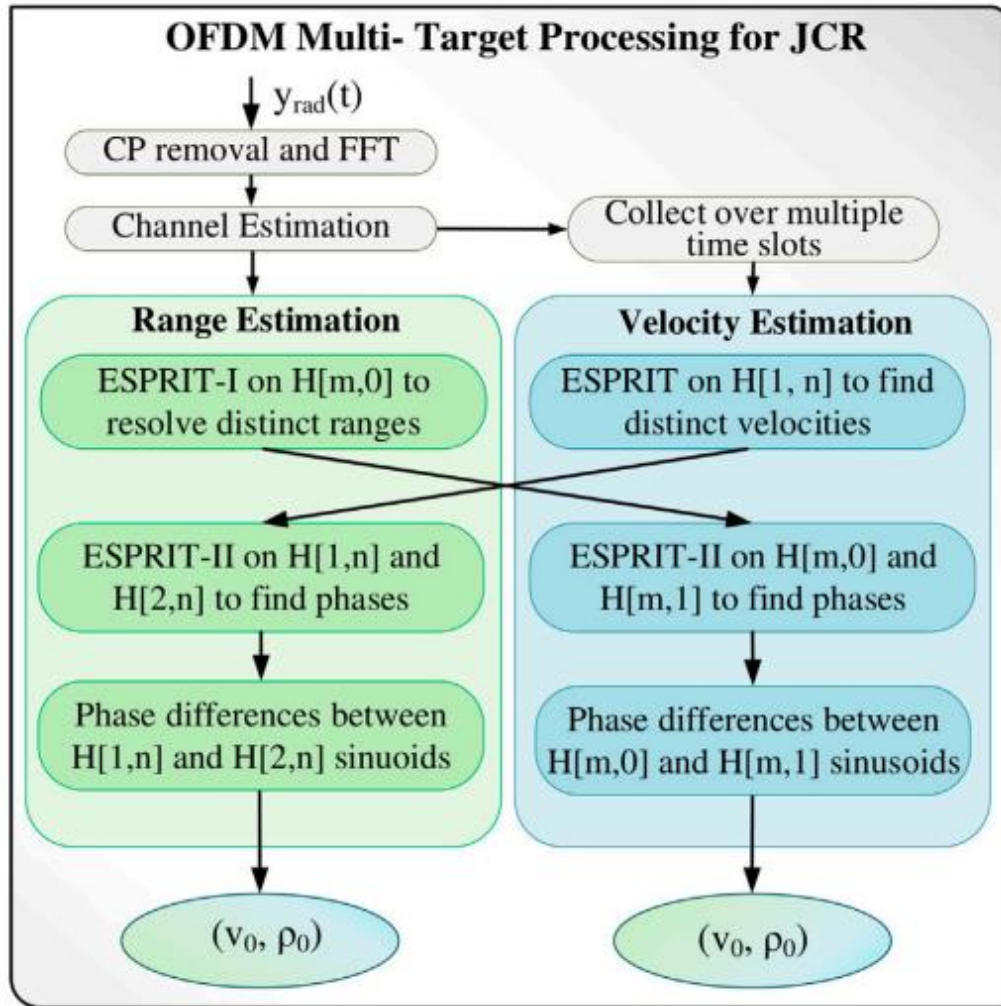


Figure 9. block diagram for OFDM based Multi-target delay and Doppler processing for joint communication radar systems [162].

Using Orthogonal Frequency Division Multiplexing (OFDM) modulation, multi-target delay and Doppler processing are used in joint communication and radar systems [162]. By using this technique, the system is able to simultaneously transmit data and perform radar operations, such as detecting and tracking targets [162]. To separate targets in the time-frequency domain, multi-target delay and Doppler processing exploit the frequency diversity of OFDM signals [162]. For different targets, OFDM symbols are designed with different delay and Doppler shifts [162]. If a

suitable processing algorithm is used to process the data, such as JRC (Joint Radar-Communication), then the system will be able to separate the echoes from different targets in order to recover the information that was transmitted [162]. Receiving OFDM signals is processed using a two-stage algorithm by JRC. An independent component analysis (ICA) technique is used to separate radar echoes from the communication signal in the first stage [162-170]. An improved Constant False Alarm Rate (CFAR) algorithm is used in the second stage to detect and track targets from radar echoes [162-170]. Figure 17 shows a block diagram for OFDM-based multi-target delay and Doppler processing for joint communication radar systems [162-170].

Multi-target delay and Doppler processing have the advantage of allowing the system to operate both communication and radar operations at the same frequency, which makes them particularly useful in applications such as unmanned aerial vehicles (UAVs) and autonomous vehicles [162-170]. Since this technique requires additional processing, it also has some limitations, such as increased complexity and reduced data rate [162-170].

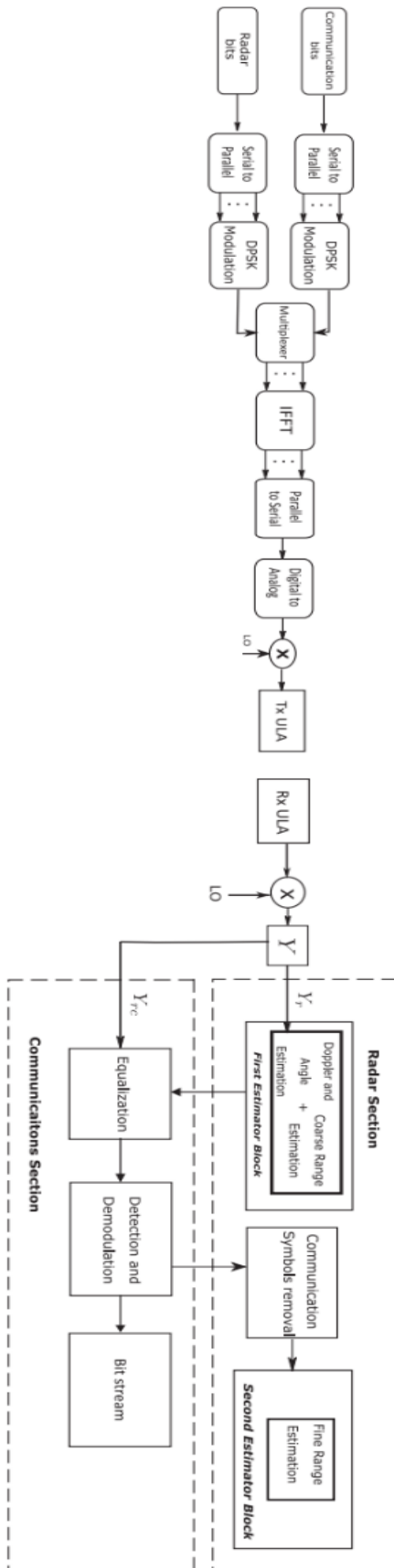


Figure 10. Block diagram of bi-static OFDMA-JRC transceiver.

3.3.4. Continuous Wave (CW) [171]:

Continuous-wave (CW) is a type of radio waveform in which a sinusoidal wave is transmitted with a constant frequency and amplitude [64], [171], [148-170]. CW signals are typically used for communication purposes, and they can be transmitted using a variety of methods, including through the air using an antenna or through a wire using a coaxial cable [168-171]. In detail, Continuous wave (CW) radar is a type of radar system that transmits a continuous wave (CW) signal and measures the time delay between the transmission of the signal and the reception of the reflected signal to determine the range and velocity of objects [64], and [148-170]. In a CW radar system, the transmitted signal is a continuous sine wave that is modulated with a small frequency shift or phase shift to distinguish the transmitted signal from the returned signal [64], [171]. The range and velocity of the object are determined by measuring the time delay [64], and Doppler shift of the returned signal [171]. In the industrial, scientific, and medical (ISM) radio frequency band, CW radar systems operate at frequencies between 902 MHz and 928 MHz, which are reserved for unlicensed use [64-145], [138-170]. The ISM band is a range of frequencies that have been set aside internationally for the use of industrial, scientific, and medical devices that emit radio frequency energy, including CW radar systems [64], [171], [148-170]. The use of the ISM band is governed by regulations that vary from country to country. CW radar systems have several advantages over other types of radar systems. For example, they can provide high resolution range and velocity measurements and can operate over a wide range of distances. They are also relatively simple and inexpensive to design and build. However, CW radar systems are susceptible to interference from other RF sources and can be affected by atmospheric conditions, such as rain and snow [64], [171], [148-170].

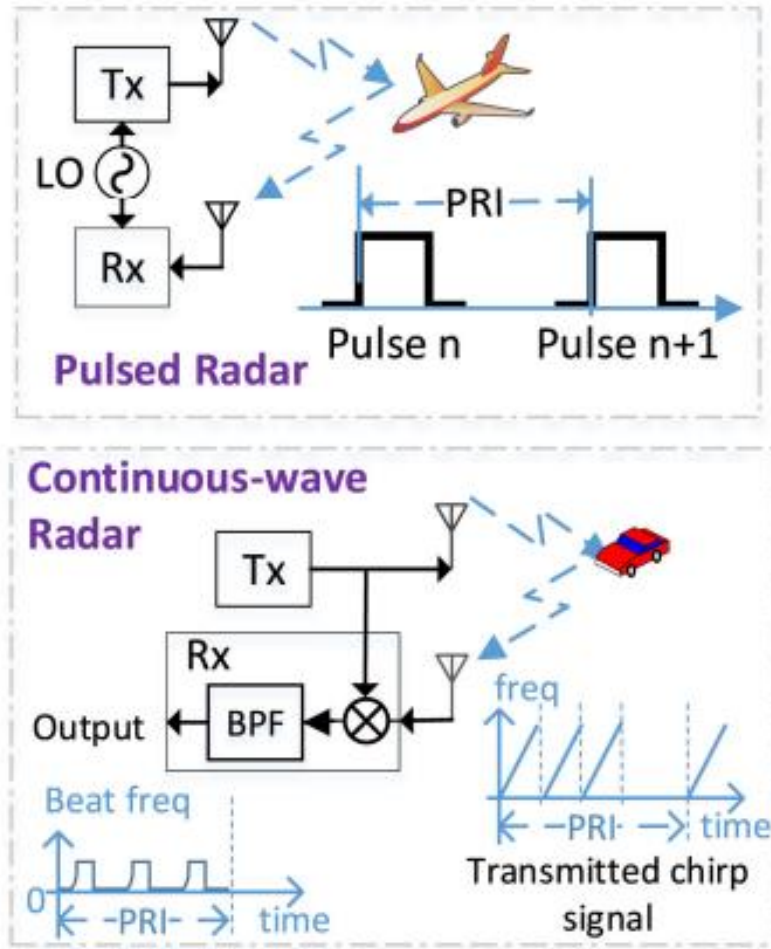


Figure 11. An illustration illustrating difference between pulsed radars, continuous-wave radars, and communication systems. PRI: pulse repetition interval; Tx: transmitter; Rx: receiver; BPF: bandpass filter [171].

For example, as already mentioned, a bi-static phase modulated continuous wave (PMCW), JRC transceiver is proposed in [64], [171], [148-170]. Figure 15 and 20 shows the block diagram of this transceiver. As it is shown, at the transmit end, the analog radar transmit signal sequence is upconverted to the carrier using a local oscillator (LO) and then modulated by the communications bit sequence in slow-time before emitted by the transmit antenna array. At the receiver, the RF signal at the antenna front-end is down converted and to yield the signal Y [171]. This signal is then processed to estimate unknown target parameters and communications symbols. They introduced two bi-static JRC paradigms that use a single waveform to convey communications data as well as radar target returns [171]. The first waveform carries forward the advantages of

stand-alone PMCW in automotive radars to a bi-static JRC [64], [171], [148-170]. The second waveform tunes the conventional OFDMA to bi-static JRC case. In both cases, we suggested radar and communications multiplexing strategies to ensure the parameter identifiability with limited set of measurements [64], [171], [148-170]. Their work expanded the existing JRC analyses by deriving some of the useful statistical bounds on estimation errors [171].

Here is a summary of the advantages and disadvantages of continuous wave (CW), pulse, orthogonal frequency division multiplexing (OFDM), direct sequence spread spectrum (DSSS), and frequency modulated continuous wave (FMCW) radar systems in the industrial, scientific, and medical (ISM) radio frequency band [64], [171], [148-170]:

Radars System	Advantages	Disadvantages
Continuous wave (CW) [171]	High resolution range and velocity measurements [171]	Susceptible to interference from other RF sources
	Wide operating range	Affected by atmospheric conditions, such as rain and snow
	Simple and inexpensive to design and build [158]	
Pulse [158]	High resolution range measurements [158]	Susceptible to interference from other RF sources [158]
	Wide operating range	Affected by atmospheric conditions, such as rain and snow
	Simple and inexpensive to design and build	
Orthogonal frequency division multiplexing (OFDM) [162-170]:	High immunity to interference from other RF sources	Susceptible to interference from other systems that use the same subcarriers

	Wide operating range	Affected by atmospheric conditions, such as rain and snow
	Simple and inexpensive to design and build	
Direct sequence spread spectrum (DSSS) [163]	High immunity to interference from other RF sources	Susceptible to interference from other systems that use the same spreading code
	Wide operating range	Affected by atmospheric conditions, such as rain and snow
	Simple and inexpensive to design and build	
Frequency modulated continuous wave (FMCW) [172,173]	Wide operating range	Lower resolution compared to pulse and CW radar systems
	Simple and inexpensive to design and build [172,173]	Susceptible to interference from other RF sources
		Affected by atmospheric conditions, such as rain and snow

The complexity of the hardware for continuous wave (CW) [171], pulse [158], orthogonal frequency division multiplexing (OFDM) [162-170], direct sequence spread spectrum (DSSS) [163], and frequency modulated continuous wave (FMCW) [172,173] radar systems can vary significantly depending on the specific design and application. Here is a rough comparison of the hardware complexity of these radar systems [140,173]:

Radar System	Hardware Complexity
Continuous wave (CW) [171]	Low to moderate

Pulse [158]	Low to moderate
Orthogonal frequency division multiplexing (OFDM) [162-170]	Moderate to high
Direct sequence spread spectrum (DSSS) [163]	Low to moderate
Frequency modulated continuous wave (FMCW) [172, 173]	Low to moderate

This comparison is based on the general principles of these radar systems and does not take into account specific design details or implementation factors [147-173]. In general, CW and pulse radar systems tend to have relatively low hardware complexity, while OFDM and DSSS radar systems may have higher hardware complexity due to the need to generate and process multiple carriers or spread the transmitted signal over a wide frequency band [149,173]. FMCW radar systems may have hardware complexity similar to that of CW and pulse radar systems, depending on the specific design [146-173].

3.3.5. Frequency modulated continuous wave (FMCW) radar [172,174]:

This type of mm-wave communication system uses frequency modulation to transmit a continuous wave signal [140-173]. The frequency of the transmitted signal is varied over time, and the reflected signal is used to measure the distance to an object [140-173]. Frequency modulated continuous wave (FMCW) is a type of radio waveform that is similar to CW but includes the additional feature of frequency modulation [171-174]. In FMCW signals, the frequency of the carrier wave is continuously varied according to a predetermined pattern, typically a linear or exponential chirp. FMCW signals are commonly used in radar systems, where they are transmitted and received to determine the range, velocity, and other characteristics of objects in the environment [140-173]. In the industrial, scientific, and medical (ISM) radio frequency band, FMCW radar systems operate at frequencies between 902 MHz and 928 MHz, which are reserved for unlicensed use [140-173]. The ISM band is a range of frequencies that have been set aside internationally for the use

of industrial, scientific, and medical devices that emit radio frequency energy, including FMCW radar systems [140-173]. The use of the ISM band is governed by regulations that vary from country to country [140-173].

For metal detection through walls in indoor environments, [174] presents a low-cost FMCW radar system [174]. The Internet of Things and super-connected societies cannot be realized without indoor remote-sensing applications, such as through-wall detection and positioning [170-174]. Among the components of the proposed system are a two-stage radio-frequency power amplifier, a voltage-controlled oscillator, circuits for frequency modulation and system synchronization, a mixer, a 3-dB power divider, a low-noise amplifier, and two cylindrical horn antennas (Tx/Rx antennas) [174]. Operational at frequencies between 5.83 and 5.94 GHz, the antenna has gain values between 6.8 and 7.8 [174]. An Arduino UNO is used to sample the backscattered Tx signal at 4.5 kHz. A customized FMCW radar algorithm is then used to analyze the sampled signal on the MATLAB platform. Based on commercial off-the-shelf components, the proposed system can detect targets within a radius of 56.3 m in an indoor environment [174]. A 4 cm-thick ply board was successfully detected with less than 10 cm accuracy by the system in this Low-cost FMCW radar system based on Arduino and ADC [174] as shown in Figure.21.

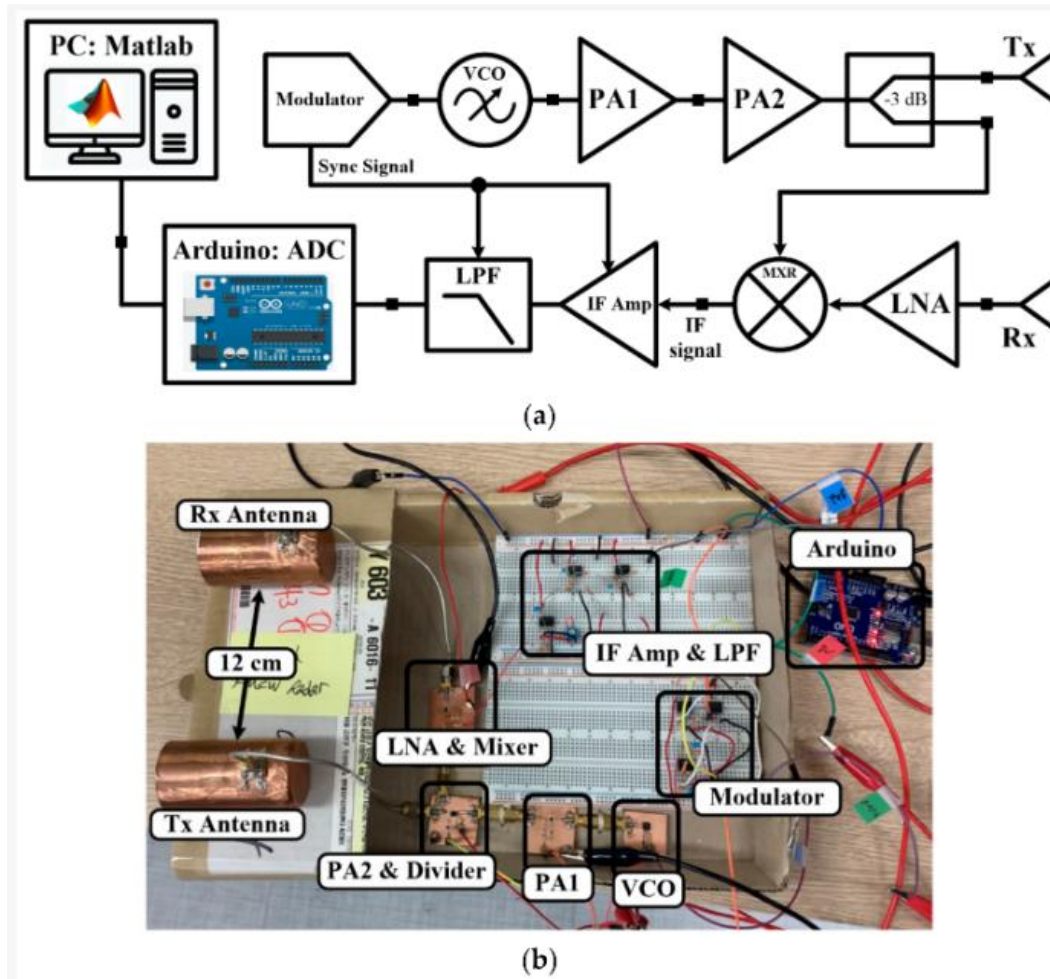


Figure 12. Low-cost FMCW radar system based on Arduino and ADC: (a) schematic diagram and (b) radar prototype [174].

3.4. Types of Beams in JCR Systems [123-173]:

Joint radar and communication systems have gained significant attention in recent years due to the increasing demand for high-performance, efficient, and reliable systems that can be used for a wide range of applications [140-173]. Different types of beams can be used in these systems to improve performance and achieve specific goals. Some of the most commonly used types of beams in joint radar and communication systems include linear, circular, elliptical, Orbital angular momentum (OAM) carrying vortex and spiral beams [140-173].

- Linear beams are the most basic type of beam used in joint radar and communication systems [\[32\]](#). They are characterized by a linear phase structure, which results in a symmetrical radiation pattern. Linear beams are typically used for simple radar and communication applications, such as range finding and basic data transmission. Linear beams are also relatively easy to generate and detect, which makes them a cost-effective solution for many applications [\[140-173\]](#).
- Circular beams are another common type of beam used in joint radar and communication systems. They are characterized by a circular phase structure, which results in a circularly symmetrical radiation pattern. Circular beams are typically used for applications that require a wide field of view, such as surveillance and target tracking. Circular beams are also relatively easy to generate and detect, which makes them a cost-effective solution for many applications [\[140-173\]](#).
- Elliptical beams are another type of beam used in joint radar and communication systems. They are characterized by an elliptical phase structure, which results in an elliptical radiation pattern. Elliptical beams are typically used for applications that require a high level of directivity, such as target tracking and imaging. Elliptical beams are also relatively easy to generate and detect, which makes them a cost-effective solution for many applications [\[140-173\]](#).
- Spiral beams are another type of beam used in joint radar and communication systems. They are characterized by a spiral phase structure, which results in a spiral radiation pattern. Spiral beams are typically used for applications that require a high level of directivity and a wide field of view, such as target tracking and imaging. Spiral beams are also relatively easy to generate and detect, which makes them a cost-effective solution for many applications [\[140-173\]](#).
- Orbital angular momentum (OAM) carrying vortex beams is another type of beam that has been proposed for use in joint radar and communication systems. OAM is a property of electromagnetic waves that describes the rotation of the wavefront around its axis of propagation [\[1-73\]](#). Vortex beams are a type of OAM-carrying wave that have a phase singularity at their center, resulting in a helical wavefront that rotates around the beam axis. Vortex beams have been proposed as a potential solution for joint radar and

communication systems operating in the ISM band at 24 GHz. The use of vortex beams in joint radar and communication systems offers several advantages over other types of beams such as the ability to carry multiple channels of information, achieve high angular resolution, improve range resolution, and resist atmospheric turbulence [1-73].

However, it's important to note that each type of beams has its own advantages and disadvantages, and the choice of beam type depends on the specific requirements of the system and the application [132-174]. Linear beams are easy to generate and detect but have low directivity, circular beams have a wide field of view but low directivity [132-74], elliptical beams have a high level of directivity but narrow field of view [32-174], spiral beams have a high level of directivity and a wide field of view but more complex to generate and detect [1-134]. Also, Vortex beams have a high level of directivity and the ability to carry multiple channels of information but more complex to generate and detect [132-174].

For uses like autonomous driving, millimeter-wave (mm-wave) joint communication radar (JCR) jointly accomplishes a high data rate communication and a high-resolution radar sensing [132-174]. Nevertheless, due to the used directed beam, previous JCR systems that are based on cutting-edge mm-wave communications gear suffer from a constrained angular field-of-view (FoV) and a poor detection rate for radars [132-174]. [32] present an adaptable and quick combined waveform-beamforming system for mm-wave JCR with a phased-array architecture to overcome this problem [32]. In [32], we describe a JCR beamformer design technique that enables a trade-off between communication data throughput and radar successful recovery rate in the angular domain [132-174]. We demonstrate how circulant shifts of the JCR beamformer developed for compressed radar sensing may be used to produce different radar data [32-99], and [132-174]. The angle-of-arrival/departure estimate of short-range radar targets is made possible by our JCR design, according to numerical results, with a high success rate and a wide field of view at the cost of a minor communication rate loss [32]. A comparison between the TX beampattern produced by our JCR design with RS-JCR and the ideal communication is presented in Figure 22 [32]. With a per-antenna power restriction, our JCR outperforms RS-JCR in terms of main lobe gain. To estimate radar AoA/AoD with a wide FoV at the cost of a slight decrease in transmission data rate, we suggested in [32] a TX-RX JCR beamformer design for the mm-wave JCR system with a phased-

array architecture. To estimate radar AoA/AoD with a wide FoV at the cost of a slight decrease in transmission data rate, we suggested in [32] a TX-RX JCR beamformer design for the mm-wave JCR system with a phased-array architecture [32]. Our method for estimating AoA and AoD for SRR targets takes use of mm-wave channel sparsity and is simple thanks to the partial DFT CS [32]. For mm-wave JCR [132-174], our suggested TX precoder and RX combiner architecture outperforms the random switching-based one, notably for a lot of antennas [32]. The findings in this study may be used to the design of low-power, compact, spectrum-efficient, and high-performance mm-wave devices that will support the sensing and communication requirements of the upcoming automotive generation [132-174]. Future work will involve both experimental validation and an expansion of our work for simultaneous range, velocity, and direction estimate [32]. The chance of a successful recovery varies with the quantity of measurements and antennas for both the proposed JCR and the expanded RS-JCR for AoA/AoD estimate, as shown in Figure 23 [32]. By adding phase randomization to the RX combiner vector in addition to the RS at the TX suggested in [32], the extended RS-JCR is made possible [132-174].

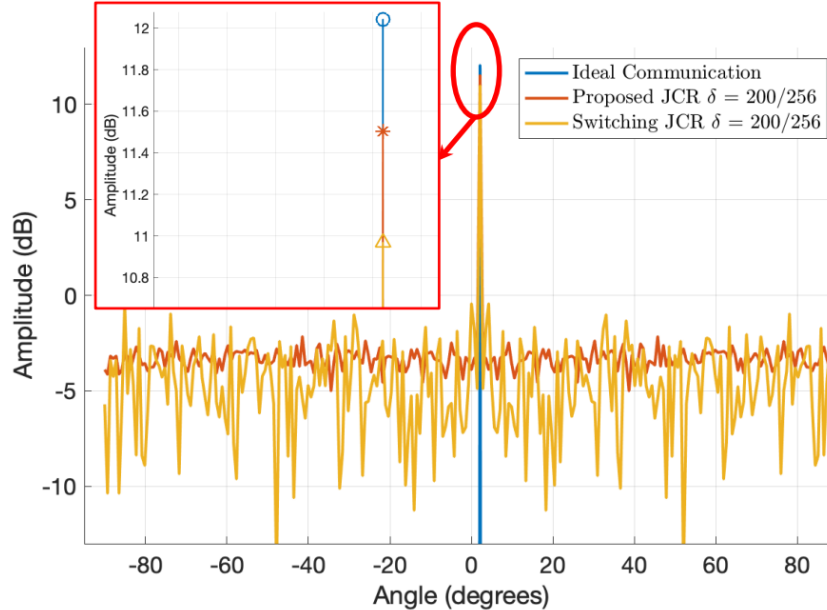


Figure 13. Comparison of the ideal communication and the TX beam pattern produced by our JCR design using RS-JCR [32].

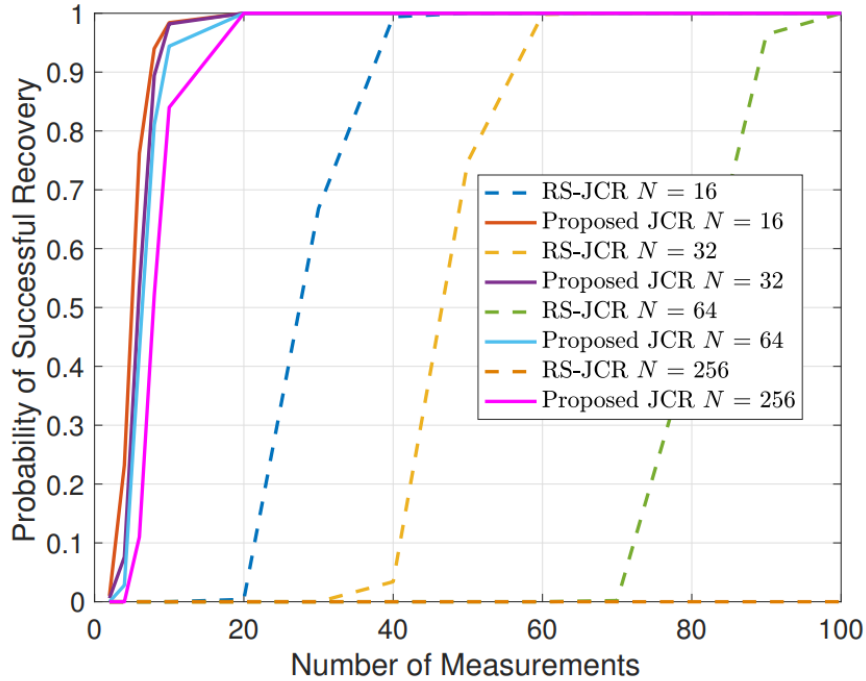


Figure 14. Comparison of our proposed JCR with the RS-JCR for different antennas and measurement counts at $d = 12$ m and $\rho = 200/256$. Performance-wise, our JCR outperforms the RS-JCR [32].

3.4.1. Advantages to use orbital angular momentum (OAM) carrying vortex beams at 24GHz ISM band [175-180]:

Orbital angular momentum (OAM) carrying vortex beams have been proposed as a potential solution for joint radar and communication systems operating in the ISM band at 24 GHz [175-180]. OAM is a property of electromagnetic waves that describes the rotation of the wavefront around its axis of propagation [175]. Vortex beams are a type of OAM-carrying wave that have a phase singularity at their center [175-180], resulting in a helical wavefront that rotates around the beam axis [175-180]. The use of vortex beams in joint radar and communication systems offers several advantages over other types of beams [180]. One major advantage of using vortex beams in joint radar and communication systems is their ability to carry multiple channels of information [180]. Vortex beams can be used to simultaneously transmit multiple communication channels or multiple radar channels [175-180], which can improve the system's overall capacity and efficiency

[180]. Additionally, because vortex beams have a unique phase structure, they can be distinguished from other types of beams, allowing for improved signal separation and interference reduction [177-178]. Another advantage of using vortex beams in joint radar and communication systems is their ability to achieve high angular resolution [180]. The helical phase structure of vortex beams allows them to be focused in a very small spot, which can provide high angular resolution for radar applications [178-180]. This can be particularly useful for imaging and tracking small or fast-moving targets [180].

Vortex beams also have the ability to improve range resolution in radar systems [175-180]. The range resolution of a radar system is determined by the width of the transmitted pulse [179-180], and the use of vortex beams can reduce the width of the transmitted pulse, which can improve range resolution [179-180]. Additionally, the unique phase structure of vortex beams can also be used to improve target discrimination, which is the ability of a radar system to distinguish between multiple targets in close proximity to one another [178-180]. Another OAM benefit is its ability to resist atmospheric turbulence, which can cause the beam to spread and degrade the system's performance [178-180]. The helical wavefront of vortex beams can resist the effects of atmospheric turbulence more than other types of beams, which can improve the system's overall robustness and reliability [175-180].

However, the use of vortex beams in joint radar and communication systems also has some limitations [175-180]. One limitation is that vortex beams are more complex to generate and detect than other types of beams [179-180]. This can increase the cost and complexity of the system, which may not be practical in some applications. Additionally, the use of vortex beams can also increase the system's power consumption, which may not be desirable in some applications [175-180]. The use of vortex beams in joint radar and communication systems operating in the ISM band at 24 GHz offers several advantages over other types of beams [175-180]. The ability to carry multiple channels of information, achieve high angular resolution, improve range resolution [175], and resist atmospheric turbulence are key advantages that make the use of vortex beams in joint radar and communication systems very promising [175]. However, the complexity and power consumption associated with vortex beams need to be considered in the system design [175-180]. Further research is needed to fully explore the potential of vortex beams in joint radar and

communication systems and to develop more efficient and cost-effective ways of generating and detecting them [175-180].

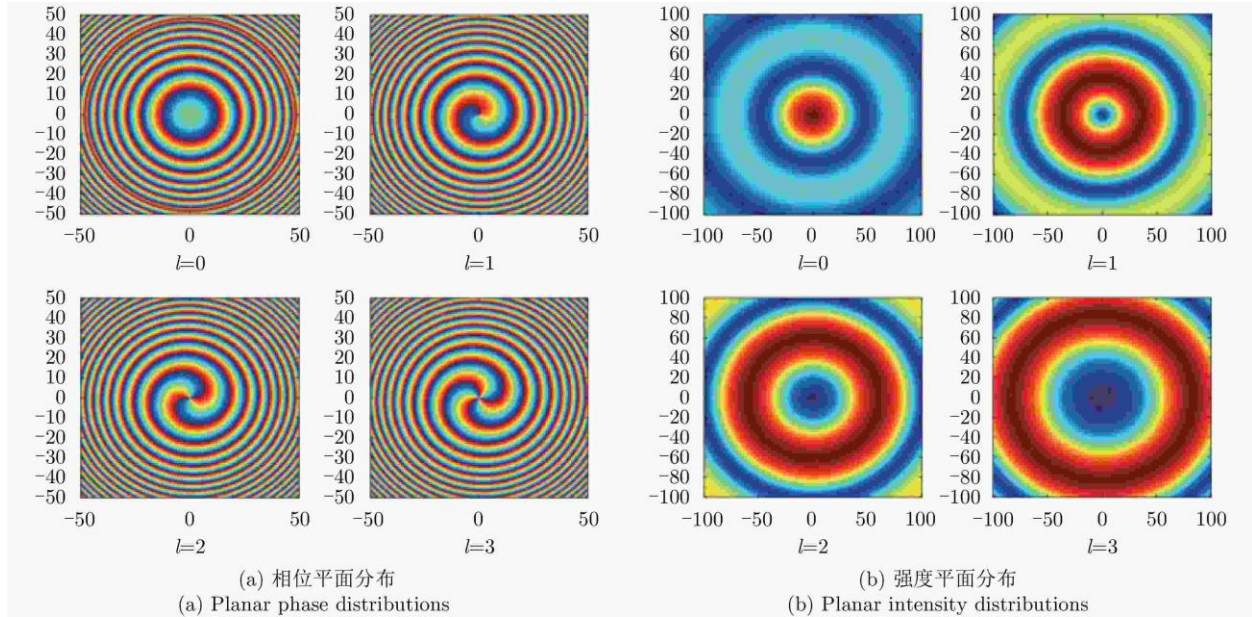


Figure 15. Vortex beam for Radar Imaging [175]

3.5. JCRS Design Concepts for Intelligent transportation system (ITS)

Radar and wireless communication are two of the most widespread and important applications of radio frequency (RF) technologies [1-34]. Radar systems use RF signals to detect and track objects, measure their range, velocity, and other characteristics [11-34]. They are used in a wide range of applications, including air and sea navigation, weather forecasting, military defense, and automotive collision avoidance [11-38]. Wireless communication systems use RF signals to transmit and receive data, voice, and other information wirelessly [123-134]. They are used in a variety of applications, including mobile phone networks, satellite communication, wireless local area networks (WLANs), and radio and television broadcasting [1-34]. Both radar and wireless communication systems operate by transmitting and receiving RF signals, and they rely on similar technologies such as antennas, RF amplifiers, and RF filters [1-134]. However, they have different

requirements and design considerations, and they are optimized for different performance metrics and application-specific requirements [1-34].

Joint sensing and communication are a strategy in which a single device or system performs both sensing and communication functions simultaneously [111-134]. This can lead to more efficient use of resources such as energy, spectrum, and hardware, as well as improved system performance in terms of data rate, accuracy, and reliability [11-134]. Joint sensing and communication systems have the potential to enable a range of applications in areas such as Internet of Things (IoT), cyber-physical systems, Intelligent transportation system (ITS) and wireless sensor networks [11-134]. One of the main components of ITS is the use of real-time data and communication systems to manage traffic flow, reduce congestion, and improve the efficiency of transportation systems [11-134]. For example, traffic management systems use cameras and sensors to gather real-time data on traffic conditions, which is then used to adjust traffic signals and manage traffic flow [11-134]. Public transportation systems use real-time data to improve the scheduling and routing of buses and trains, and to provide real-time information to passengers [11-134]. Another important aspect of ITS is the use of advanced technologies such as connected and autonomous vehicles (CAVs) to improve the safety and efficiency of transportation [111-134]. CAVs are equipped with a range of sensors and communication systems that allow them to interact with other vehicles and infrastructure, such as traffic signals and road signs [117-134]. This allows CAVs to make more informed decisions and react more quickly to changing traffic conditions. In addition to improving safety and efficiency, ITS also has the potential to reduce emissions and improve sustainability [77-134]. For example, ITS can be used to optimize the routing and scheduling of vehicles, reducing the number of unnecessary trips and the associated emissions. Some examples of joint sensing and communication systems include cognitive radios, MIMO radar systems, and compressive sensing systems [77-134]. Joint sensing and communication systems can offer a number of benefits in terms of both usage and complexity [77-134]. In terms of usage, joint sensing and communication systems can improve the efficiency of resource utilization [77-134]. For example, by combining sensing and communication functions into a single system, it is possible to reduce the number of hardware components and antennas required, which can lead to smaller, lighter, and more cost-effective devices [77-134]. Joint sensing and communication systems can also enable more flexible and

dynamic resource allocation, allowing for more efficient use of spectrum and other resources. In terms of complexity, joint sensing and communication systems can simplify the design and implementation of systems by reducing the number of components and interfaces required [23-134]. This can lead to more robust and reliable systems [79], as well as easier maintenance and upgrades. Joint sensing and communication systems can also provide a more seamless and integrated user experience, as the system can seamlessly switch between sensing and communication modes as needed [77-134]. Overall [1-134], the use of joint sensing and communication systems can lead to improved system performance, lower costs, and increased flexibility and scalability [77-134]. Both the system usage and system complexity should be significantly improved [2]. It is comprehensible in three different ways [77-134]. First off, the communication subsystem adequately shares radar properties including high power, low side-lobe, strong directivity, and anti-interference [34]. These benefits can strengthen information security, enhance communication quality, and broaden the reach of communication.

First, the high power of radar can be used to improve the range and reliability of communication [77-134]. By using high-power radar signals for communication, it is possible to transmit data over longer distances and through challenging environments such as dense urban areas or forests. This can be particularly useful for applications that require long-range or low-latency communication, such as remote control or emergency response [77-134]. Second, the low side-lobe levels of radar can be used to reduce interference and improve the quality of communication [77-144]. By using radar signals with low side-lobe levels, it is possible to minimize interference from other sources and improve the signal-to-noise ratio of the communication channel [77-134]. This can lead to more reliable and robust communication. Third, the strong directivity of radar can be used to improve the security of communication [79-134]. By using radar signals that are highly directional, it is possible to transmit data over narrow beams that are difficult to intercept or jam [77-134]. This can enhance the confidentiality and integrity of the communication. Finally, the anti-interference capabilities of radar can be used to improve the reliability and robustness of communication in challenging environments [77-154]. By using radar signals that are resistant to interference, it is possible to maintain stable and high-quality communication even in the presence of other sources of noise or interference [79-144].

This can be particularly useful for applications that require reliable communication in noisy or cluttered environments [77-134]. Second, the steady transmission has generally given radar many important benefits including minimal latency, high rate, easy installation, and quick response. There are several ways in which the steady transmission of radar signals can provide important benefits in terms of minimal latency, high rate, easy installation, and quick response [79-134]. First, the steady transmission of radar signals can minimize latency, or the delay between the transmission of a signal and its receipt at the receiver [77-134]. This is because radar systems typically transmit a continuous stream of signals, rather than waiting for a response before transmitting again [77-134]. This can be particularly useful for applications that require real-time or low-latency communication, such as control systems or emergency response. Second, the steady transmission of radar signals can enable a high data rate [45-79], or the amount of data that can be transmitted over a given time period [77-134]. This is because radar systems can transmit a large number of signals per second, allowing for the efficient transmission of large amounts of data [77-154]. This can be useful for applications that require high-bandwidth or high-throughput communication, such as video or data transfer [78-134]. Third, the steady transmission of radar signals can make it easier to install and set up a radar system [85-134]. This is because radar systems typically do not require a separate channel for transmitting and receiving signals, as they can use the same channel for both functions [79-134]. This can simplify the installation process and reduce the number of components and interfaces required. Finally, the steady transmission of radar signals can enable quick response times, as the system can continuously transmit and receive signals, allowing it to detect and respond to changes in the environment in real-time [77-134]. This can be particularly useful for applications that require fast reaction times, such as surveillance or tracking [79-134].

Thirdly, the process of manual handling can be streamlined by increasing the automation level of dual-function devices [77-134]. The applications of the intelligent transportation system (ITS) serve as one illustration of the benefits of this joint system. The use of joint sensing and communication systems can help to streamline the process of manual handling by increasing the automation level of dual-function devices [77-154]. One example of this is the application of joint sensing and communication systems in intelligent transportation systems (ITS) [134]. Intelligent

transportation systems are designed to improve the efficiency, safety, and sustainability of transportation systems by using advanced technologies such as sensors, communication networks, and data analytics [78]. Joint sensing and communication systems can play a critical role in enabling the automation and intelligent control of transportation systems by providing real-time data and communication capabilities [77-134].

For example, joint sensing and communication systems can be used to monitor and control traffic flow, detect and prevent accidents, optimize routing and scheduling, and support connected and autonomous vehicles [77-134]. By automating these tasks, joint sensing and communication systems can help to reduce the need for manual intervention and improve the efficiency and effectiveness of transportation systems [89-134]. Overall, the use of joint sensing and communication systems can help to streamline the process of manual handling and enable the automation of a wide range of applications in areas such as transportation, manufacturing, and logistics. Instead of relying on human judgment, the integrated approaches with joint radar and communication systems would enable next-generation vehicles to simultaneously reap the rewards of autonomously sensing the driving environment and cooperatively exchanging information with other vehicles about road conditions, speed, and any other vital information [154]. The integration of radar and communication capabilities in joint sensing and communication systems can enable next-generation vehicles to simultaneously sense the driving environment and exchange information with other vehicles, enabling a range of autonomous and cooperative functions [23-134].

The 24 GHz ISM (Industrial, Scientific, and Medical) band is a frequency range between 24.0 GHz and 24.25 GHz that is allocated for the use of unlicensed devices for industrial, scientific, and medical applications [77-134]. This band is widely used for a variety of applications, including radar, communication, and sensing, due to its low atmospheric attenuation and relatively high available bandwidth [79-134]. Joint radar and communication systems operating in the 24 GHz ISM band can use radar and communication technologies to simultaneously perform both sensing and communication functions [120-134]. These systems can be designed to operate in either a radar mode or a communication mode, or to dynamically switch between the two modes based on the requirements of the application [100-134].

In terms of characteristics, joint radar and communication systems operating in the 24 GHz ISM band can vary depending on the specific design and implementation of the system [77-134]. Some potential characteristics of these systems might include [77-134]:

- Operating range: The distance over which the system is able to transmit and receive signals effectively. This may depend on factors such as the transmit power, antenna gain, and atmospheric conditions [77-134].
- Data rate: The amount of data that the system is able to transmit and receive per unit of time. This may depend on factors such as the bandwidth of the system, the modulation scheme used, and the signal-to-noise ratio of the channel [77-134].
- Accuracy: The ability of the system to accurately measure and communicate data. This may depend on factors such as the resolution and sensitivity of the sensors, the processing algorithms used, and the quality of the communication channel [77-134].
- Spectral efficiency: The amount of data that the system is able to transmit and receive per unit of spectrum. This may depend on factors such as the frequency reuse scheme used, the modulation scheme employed, and the efficiency of the communication protocols [100].
- Power consumption: The amount of power that the system requires to operate. This may depend on factors such as the transmit power, the efficiency of the power amplifier, and the complexity of the processing algorithms [12-134].

As a result, we can conclude that millimeter-wave sensing and communication systems operating in the 24-GHz Industrial, Scientific, and Medical (ISM) band can be used for a variety of applications, such as vehicle-to-vehicle communication (V2V) [11-134]. The 24-GHz ISM band is a frequency band that has been designated for the use of unlicensed devices, meaning that anyone can use it without the need to obtain a license [50]. This makes it a popular choice for a wide range of applications, including communication, sensing, and imaging. One potential use of a joint millimeter-wave sensing and communication system operating in the 24-GHz ISM band is for detection and tracking [77-134]. Mm-wave technology can support the detection of objects and surfaces at relatively long ranges, making it well-suited for applications such as surveillance, collision avoidance, and asset tracking [77-134]. Another potential use of this type of system is for

V2V communication, which involves the exchange of information between vehicles. V2V communication can be used to improve safety and efficiency on the road by enabling vehicles to share information about their location, speed, and other relevant data. Mm-wave technology can support high data rates over relatively short distances, making it well-suited for V2V communication [77-154].

In general, the performance of the radar subsystem can be modeled using radar range equations, which describe the relationship between the radar's transmitted power, antenna gain, target range, and target reflectivity [33]. These equations can be used to calculate the maximum range at which the radar can detect a target of a given size and reflectivity [44]. The communication subsystem can be modeled using techniques from information theory, such as channel capacity and error rate analysis [43]. These techniques can be used to analyze the capacity of the communication channel and the probability of error in the transmitted data [77-134].

It is also important to consider the effect of the environment on the performance of both the radar and communication subsystems [34]. This can include factors such as atmospheric attenuation, which can reduce the power of the radar and communication signals as they propagate through the atmosphere [62-124], and interference from other sources [56], which can degrade the performance of the system [67]. To model the joint operation of the radar and communication subsystems, it is necessary to consider how they interact and how they can be coordinated to achieve the desired performance [44]. This can involve modeling the trade-offs between the performance of the radar and communication subsystems, as well as the design of algorithms to optimize the joint operation of the system [65].

For better radar resolution and accuracy, [181] allocates 76-81 GHz millimeter-wave (mm-wave) spectrum to automotive radar systems. JARC systems can exploit the large bandwidth in the mm-wave radar spectrum in order to support current vehicular communication in the 5.9 GHz spectrum with higher data rates. As a proof of concept, we present a complete JARC system operated in the 76-81 GHz band using SDRs and mm-wave components. Figure 23 illustrates how the proof of concept system uses pilot symbols in the OFDM waveform for radar sensing while

transmitting communication symbols in data subcarriers. To demonstrate the joint operation, we also implement video streaming capabilities.

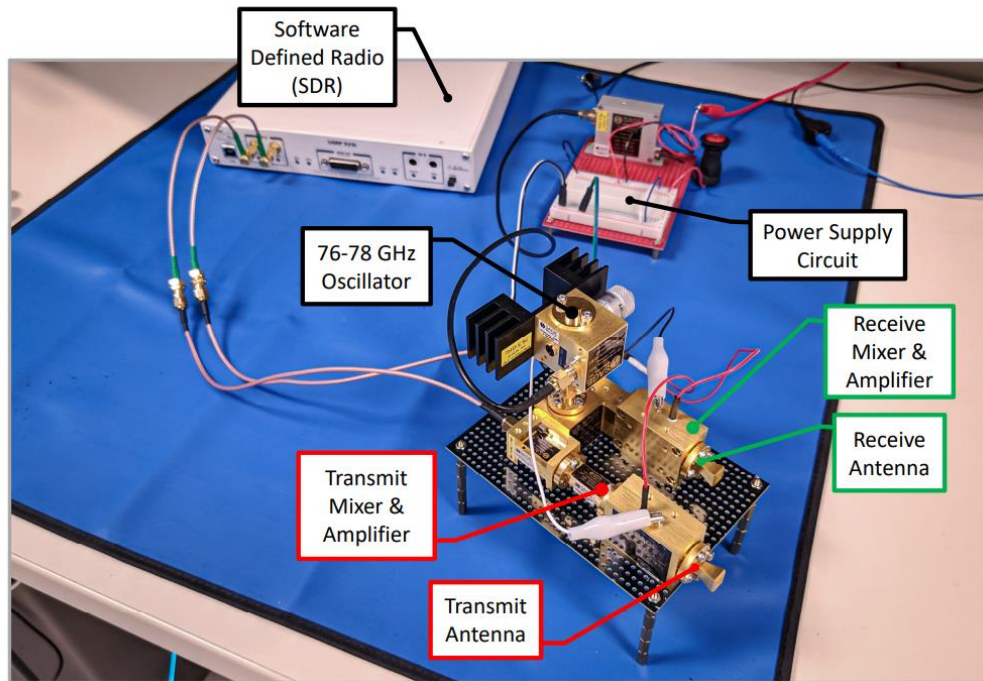


Figure 16. This is the hardware part of the joint radar transceiver reported in [181]

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