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Navigating the Challenges of Human Detection and Tracking with Joint Communication Radar Systems

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Abstract:

Human detection and tracking are vital capabilities in various applications, including surveillance, search and rescue operations, and autonomous systems. This paper addresses the challenges associated with achieving effective human detection and tracking using joint communication radar systems. By integrating radar and communication functionalities, these systems have the potential to enhance situational awareness and communication reliability in complex environments.

First, we examine the unique requirements and characteristics of human detection and tracking. We explore the challenges posed by factors such as occlusion, varying human poses and movements, cluttered environments, and the need for real-time and accurate tracking.

Next, we delve into the concept of joint communication radar systems and their advantages in overcoming these challenges. These systems exploit the shared resources and synergies between radar sensing and communication capabilities to improve human detection and tracking performance.

We discuss various techniques and algorithms employed in joint communication radar systems for human detection and tracking. These include adaptive radar waveforms, advanced signal processing techniques, data fusion methods, and machine learning algorithms. We evaluate their

effectiveness in enhancing detection accuracy, reducing false alarms, and providing robust tracking capabilities.

Furthermore, we address the integration of communication functionalities in joint systems, allowing for improved situational awareness and efficient data sharing. We discuss the benefits of utilizing radar data for communication purposes and the challenges of coexistence with radar operations in shared frequency bands.

Additionally, we explore the practical considerations and limitations associated with the deployment of joint communication radar systems. We discuss factors such as hardware constraints, system complexity, power consumption, and regulatory aspects.

Finally, we highlight ongoing research and future directions in this field, including the development of intelligent algorithms, advanced sensing technologies, and optimization techniques. We emphasize the need for interdisciplinary collaborations between radar engineers, communication experts, and computer scientists to further advance the capabilities of joint communication radar systems for human detection and tracking.

Keywords: Human detection, human tracking, joint communication radar systems, radar sensing, communication reliability, signal processing, data fusion, machine learning, situational awareness.

1. Introduction

There are several challenges that can arise when attempting to detect and track human targets in joint systems that involve communication. Some of these challenges include [\[3-5\]](#), [\[11-14\]](#), [\[20-28\]](#), [\[31\]](#), and [\[34-39\]](#):

1. **Interference:** Radio frequency interference from other sources, such as other radar systems or electronic devices, can make it difficult to accurately detect and track human targets [\[3-5\]](#).
2. **Range:** The range at which a radar system can detect and track human targets is limited by the power of the transmitter and the sensitivity of the receiver. As the range increases,

the accuracy of the system may decrease due to factors such as signal attenuation and interference [11-14], [20-28], [31].

3. Clutter: The presence of other objects in the environment, such as buildings or vegetation, can cause clutter that makes it difficult to accurately detect and track human targets [11-14], [20-28], [31].
4. Occlusion: When a human target is partially or fully blocked by other objects, it can be difficult to detect and track [11-14], [20-28], [31]. Occlusion is a phenomenon in which an object is partially or fully blocked by other objects, making it difficult to detect or track [11-14]. This can occur in computer vision, where algorithms are used to analyze and interpret visual data, such as images or videos [11-17]. Occlusion can also occur in other fields, such as robotics, where sensors may be blocked by obstacles or other objects [11-14], making it difficult to accurately detect and track the target. Occlusion occurs when a human target is partially or fully obscured by other objects, such as buildings, vehicles, or other people [20-28]. This can make it difficult for computer vision algorithms to detect and track the human target accurately [11-14]. Occlusion can be caused by a number of factors, including changes in the environment [11-14], the movement of other objects [20-28], [31], and the camera's field of view [31]. The degree of occlusion can also vary, with some objects only partially obscuring the target [20-28], while others may completely hide it from view [20-28], [31]. To overcome the challenges posed by occlusion, researchers have developed several techniques, such as [20-28], [31]: multi-view-based methods: These methods use multiple cameras to capture the same scene from different angles, which can help to overcome occlusion by providing a more complete view of the scene [20-38]. 3D Reconstruction: This method uses depth information to reconstruct a 3D model of the scene, which can help to overcome occlusion by providing a more complete view of the scene [25-28], [39].

5. Non-cooperative targets [\[20-28\]](#), [\[31\]](#): If a human target is not equipped with a radar reflector or is not actively cooperating with the tracking system [\[31\]](#), it can be difficult to accurately detect and track their movement [\[39\]](#).
6. Synchronization [\[20-28\]](#), [\[31\]](#): The timing and phase of signal transmissions and receptions between communication and radar systems are crucial for the proper operation of joint millimeter-wave (mm-wave) communication and radar systems [\[20-128\]](#), [\[131\]](#). Synchronization refers to the process of aligning the timing and phase of the signal transmissions and receptions between the communication and radar systems [\[20-128\]](#), [\[131\]](#).

2. Synchronization:

In joint millimeter-wave (mm-wave) communication systems and radars, synchronization refers to the process of aligning the timing and phase of the signal transmissions and receptions between the communication and radar systems [\[3-5\]](#), [\[11-14\]](#), [\[20-28\]](#), [\[31\]](#), and [\[34-39\]](#). This is necessary to ensure that the communication and radar signals do not interfere with each other, and that the radar can accurately detect targets while the communication system is transmitting and receiving data [\[31\]](#), and [\[34-39\]](#):

There are several types of synchronization that can be used in mm-wave communication and radar systems, including [\[3-5\]](#), [\[11-14\]](#):

1. Time synchronization: This involves aligning the timing of the communication and radar signals so that they do not overlap and cause interference [\[3-5\]](#), [\[11-14\]](#), [\[20-28\]](#), [\[31\]](#), and [\[34-39\]](#). This can be achieved through the use of a common clock or timing reference [\[3-5\]](#), [\[11-14\]](#), [\[20-28\]](#).
2. Frequency synchronization: This involves aligning the carrier frequencies of the communication and radar signals to ensure that they do not interfere with each other [\[3-5\]](#), [\[11-14\]](#). This can be achieved through the use of frequency synthesizers or other frequency control techniques [\[20-28\]](#), [\[31\]](#), and [\[34-39\]](#).

3. Phase synchronization: This involves aligning the phase of the communication and radar signals to ensure that they are in-phase, which can help to improve the accuracy of the radar detections [31], and [34-39].
4. Polarization synchronization: This involves aligning the polarization of the communication and radar signals, which can help to reduce the interference between them [3-5], [11-14], [20-28], [31], and [34-39].

Synchronization is a critical aspect of joint mm-wave communication and radar systems, as it ensures that the systems can operate effectively together without causing interference [3-5], [11-14], and [20-28]. It is important to note that synchronization requirements for the communication and radar system might be different [13-53], [110-114], so the synchronization techniques should be chosen accordingly. The timing and phase of signal transmissions and receptions between communication and radar systems are crucial for the proper operation of joint millimeter-wave (mm-wave) communication and radar systems [121-181]. Accurate synchronization of the timing and phase of the signals ensures that the communication and radar systems can operate effectively without causing interference to each other [3-5], [11-14], [20-38], [131], and [34-139]. It also ensures that the radar can accurately detect targets while the communication system is transmitting and receiving data. Time synchronization is the process of aligning the timing of the communication and radar signals so that they do not overlap and cause interference [3-5], [11-14], [20-28]. This is particularly important in mm-wave communication systems [3-5], [11-14], [20-28], as the signals are transmitted at very high frequencies and are therefore highly susceptible to interference [31], and [34-39]. By ensuring that the communication and radar signals are transmitted at different times, it is possible to reduce or eliminate the potential for interference [3-5], [11-14], and [20-28].

Frequency synchronization is the process of aligning the carrier frequencies of the communication and radar signals to ensure that they do not interfere with each other [3-5], [11-14], [20-28], [31], and [34-181]. In mm-wave communication and radar systems, the carrier frequencies are typically in the range of 30 GHz to 300 GHz. These high frequencies are highly susceptible to interference, and it is essential to ensure that the communication and radar signals are transmitted at different frequencies to avoid interference [3-5].

Phase synchronization is the process of aligning the phase of the communication and radar signals to ensure that they are in-phase [150]. This can help to improve the accuracy of the radar detections, as the radar system is able to more accurately detect and track targets when the signals are in-phase [3-5], [11-14], [20-28], [31], and [34-39]. Additionally, phase synchronization helps to reduce the interference between communication and radar signals, by ensuring that the signals are not out-of-phase and thus creating destructive interference [181], [152].

Polarization synchronization is the process of aligning the polarization of the communication and radar signals [56]. This helps to reduce the interference between the signals, by ensuring that the signals are not orthogonally polarized, thus creating destructive interference [3-5].

Synchronization between the communication and radar systems is crucial for the proper operation of joint mm-wave communication and radar systems [3-5], [11-14], [20-28], [31], and [34-39]. It is important to note that synchronization requirements for the communication and radar system might be different [11-14], [20-28], so the synchronization techniques should be chosen accordingly. One of the most important aspects of synchronization is the use of a common clock or timing reference [11-114], [20-128]. This allows the communication and radar systems to operate using the same timebase, which ensures that the timing and phase of the signals are aligned [114]. This is particularly important in mm-wave communication and radar systems, as the signals are transmitted at very high frequencies and are therefore highly susceptible to interference [123]. In order to achieve accurate synchronization [85], it is also important to have a robust and reliable communication link between the communication and radar systems [98]. This can be achieved through the use of wired or wireless communication links, such as Ethernet or Wi-Fi [112]. The communication link should have low latency and high reliability [113], to ensure that the timing and phase information can be accurately transmitted between the systems [67]. Another important aspect of synchronization is the use of advanced signal processing techniques [118]. This can include the use of digital signal processing (DSP) algorithms to improve the accuracy of the synchronization [87], as well as the use of machine learning algorithms to adapt the synchronization to changing conditions in the environment [93].

2.1. Synchronization challenges in JCR's:

There are several ways to achieve synchronization in joint millimeter-wave (mm-wave) communication and radar systems [11-14], [20-28]. The most common method is the use of a common clock or timing reference, which allows the communication and radar systems to operate using the same time base [11-114], [20-128]. This ensures that the timing and phase of the signals are aligned, which reduces the potential for interference between the systems [114], [25].

Another method is the use of frequency synchronization [11], [14], which involves aligning the carrier frequencies of the communication and radar signals to ensure that they do not interfere with each other [11-14], [20-28]. This can be achieved through the use of frequency synthesizers or other frequency control techniques [11-14], [20-28].

Phase synchronization is another method, which involves aligning the phase of the communication and radar signals to ensure that they are in-phase [18], [20-28]. This can help to improve the accuracy of the radar detections, as well as reduce the interference between the communication and radar signals [11-14], [20-28].

Polarization synchronization is also a method, which involves aligning the polarization of the communication and radar signals [11-14], [20-128]. This helps to reduce the interference between the signals, by ensuring that the signals are not orthogonally polarized, thus creating destructive interference [45].

Additionally, advanced signal processing techniques can be used to improve the synchronization [11-14], [20-28]. This can include the use of digital signal processing (DSP) algorithms to improve the accuracy of the synchronization [11-14], [20-28], as well as the use of machine learning algorithms to adapt the synchronization to changing conditions in the environment [11-14], [20-28].

In the case of not having synchronization, the systems can use different techniques to achieve the best performance, for example [11-14], [20-28]:

- One possible approach is to use different bands for the communication and radar systems. This can help to reduce the potential for interference, as the signals will not be transmitted at the same frequency [81], [120-118].

- Another approach is to use adaptive modulation and coding techniques for the communication system, which can help to reduce the potential for interference by adjusting the transmission parameters based on the current level of interference [81], [120-118].
- For the radar system, beamforming techniques can be applied to narrow the transmission and reception beams to avoid interference from the communication system [81], [120-118].

It is important to note that achieving synchronization is not always possible or necessary, depending on the specific application and the requirements of the communication and radar systems. In some cases, it may be possible to use the systems without synchronization, but this may come at the cost of reduced performance or increased interference [81], [120-118].

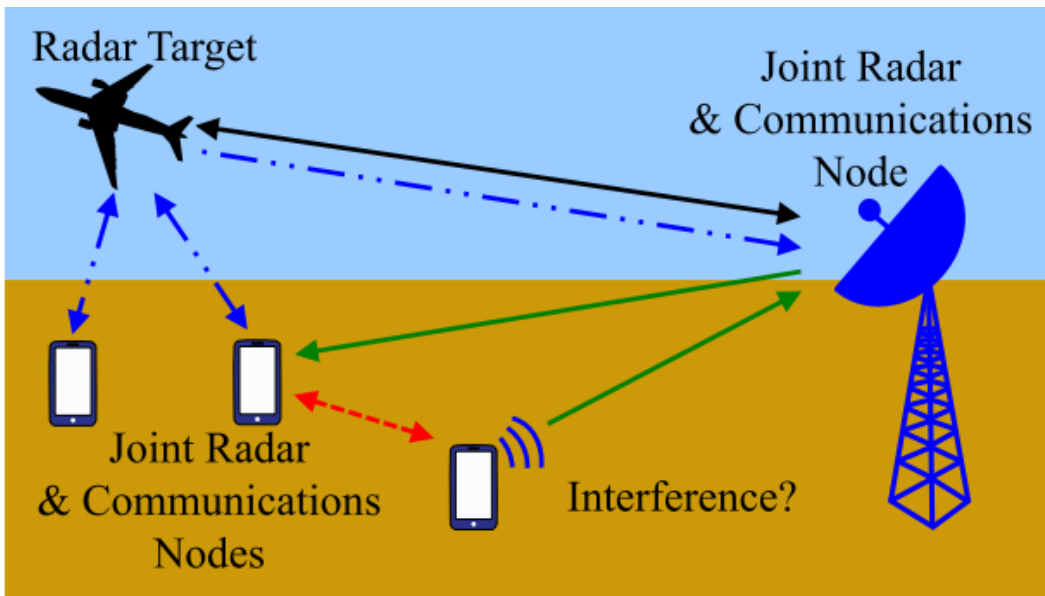


Figure 1. Convergence of RF signals is difficult, as illustrated by this example. Co-designing future systems will not just mitigate interference but also ensure that they consider each other as they operate [182].

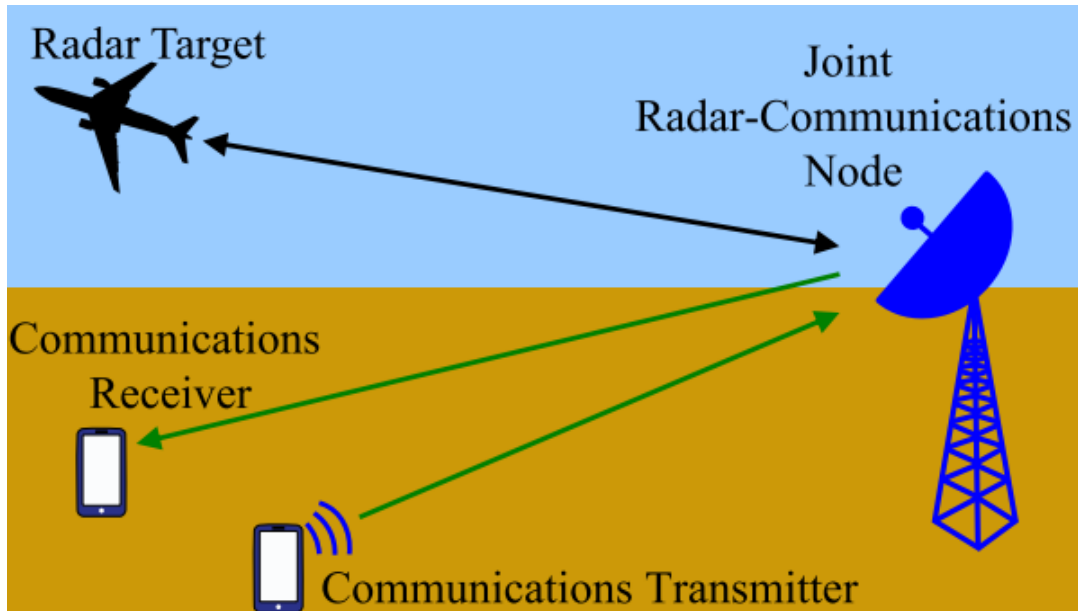


Figure 2. This is a simplified version of the complicated RF convergence scenario shown previously for the joint radar-communications system. Nevertheless, it provides a basis for discussing future work, and enables tractable, intuitive solutions to be developed [182].

2.2. Hardware Synchronization Options for a 24GHz JCR's:

Synchronization is a critical aspect of any communication or radar system [81], [120-118], as it ensures that all components of the system are operating in harmony and able to effectively exchange information [51]. In a joint communication and radar system operating at 24GHz, synchronization must be carefully managed to ensure optimal performance [81], [120-118], [182]. One key synchronization option for such a system is the use of a common timing reference, such as a GPS or other global navigation satellite system (GNSS) [181], [120-118] as shown in Figures 26, and 27 [182]. This allows all components of the system to be synchronized to a precise and accurate time, ensuring that signals and data are transmitted and received at the correct times [81], [120-118]. This can be particularly important in a radar system, where precise timing is essential for accurate target detection and tracking [120-118]. Another synchronization option is the use of a common frequency reference, such as a crystal oscillator [81], [120-118]. This allows

all components of the system to be operating at the same precise frequency [182], ensuring that signals and data are transmitted and received at the correct frequencies [120-118]. This can be particularly important in a communication system [181-182], where precise frequency control is essential for maintaining a clear and interference-free signal [182]. In addition to these options [182], [120-118], a joint communication and radar system operating at 24GHz may also make use of advanced synchronization techniques such as time-hopping, frequency-hopping, and spread-spectrum techniques [11-114], [20-128]. These techniques can be used to further enhance the system's performance and reduce the likelihood of interference from other systems operating in the same frequency band [114], [110-128].

One of the main challenges in synchronizing a joint communication and radar system operating at 24GHz is the need to coordinate the different requirements and constraints of the communication and radar components [11-114], [120-182]. Communication systems typically place a greater emphasis on data rate and bandwidth [110-114], [128], while radar systems typically place a greater emphasis on range and resolution [182]. Careful system design and coordination is required to ensure that the system can effectively balance these competing requirements [11-114], [20-128].

Hardware synchronization options can include the use of [114], [110-128]:

1. PLL (Phase-Locked Loop) or frequency synthesizer: This can be used to synchronize the local oscillator frequencies of the radar and communication components, ensuring that they are operating at the same precise frequency [114], [110-128].
2. GPS or GNSS receiver: This can be used to synchronize the system's timing reference to a precise and accurate time, ensuring that signals and data are transmitted and received at the correct times [114], [110-128].
3. Time and frequency distribution system: This can be used to distribute precise timing and frequency reference signals to all components of the system, ensuring that they are all operating in synchronization [110-128].

4. Synchronization and control module: This can be used to manage and coordinate the synchronization of the various components of the system, such as the radar, communication and data processing components [\[114\]](#), [\[128\]](#).
5. Synchronization and control software: This can be used to configure and manage the synchronization of the various components of the system, such as the radar, communication and data processing components [\[110-128\]](#).
6. Synchronization over the wireless link: In case of wireless communication between different components, specific techniques such as time-hopping, frequency-hopping, and spread-spectrum techniques can be used to achieve synchronization over the wireless link [\[114\]](#), [\[110-128\]](#).

2.3. Sensing Approaches at 24 GHz JCRS's

Various sensor concepts can be used for human target detection using 24 GHz FMCW (Frequency Modulated Continuous Wave) joint radar and communication systems. One approach is to use a radar system that is specifically designed for detecting human targets [\[1-114\]](#), [\[110-128\]](#). These types of radar systems can use advanced algorithms to analyze the radar return signals and identify characteristic features that are indicative of a human target [\[114\]](#), [\[58-100\]](#). For example, the radar system may be able to detect the presence of human-like limbs or the movement patterns of a walking person [\[119\]](#). Another approach is to use a radar system that is capable of detecting a wide range of objects and then apply machine learning algorithms to classify the detected objects as human or non-human [\[182\]](#). This type of system would require a training dataset of radar returns from human and non-human targets [\[114\]](#), [\[11-18\]](#), which the machine learning algorithm could use to learn the characteristics that differentiate human targets from other types of objects. In addition to radar, other types of sensors can also be used for human target detection. For example, thermal cameras can detect the heat signature of a human body, and video cameras can

capture images or video of a person. These sensors can be used alone or in combination with radar to improve the accuracy and reliability of human target detection.

It is also possible to use a joint radar and communication system for human target detection. In this case, the communication system could be used to transmit a signal that is specifically designed to be reflected off of a human body, and the radar system could be used to detect the reflected signal [3-5], [11-14], [20-28]. This approach could allow the system to detect the presence of a human target even in situations where the target is not visible to other types of sensors [3-5], [11-14], [20-28], [31], and [34-39].

Using a camera with an image processing and feature detection algorithm is one approach to detecting human targets. Video cameras can capture images or video of a person and image processing algorithms can be used to analyze the visual data and identify characteristic features that are indicative of a human target [3-5], [31], and [34-39]. There are many different image processing and feature detection algorithms that can be used for this purpose [3-5], [11-14], [20-28], [31], and [34-39], including edge detection, pattern recognition, and object classification algorithms [1]. These algorithms can be used to detect features such as human-like limbs, facial features, and clothing patterns, which can help to distinguish human targets from other types of objects [3-5], [11-14], [20-28].

Using a camera for human target detection has the advantage of being able to provide a visual image of the target, which can be useful for identifying and tracking specific individuals [3-5], [11-14], [20-28], [31], and [34-39]. However, the performance of a camera-based system can be affected by factors such as lighting conditions, occlusion, and the distance to the target. In addition to using a camera, other types of sensors can also be used for human target detection [3-5], [11-14], [20-28], [31], and [34-39]. Tracking classified targets can be accomplished using advanced algorithms like temporal differencing and template matching. Temporal difference and template matching are two different approaches that can be used for target tracking in joint radar and communication systems [23]. Temporal difference is a method of reinforcement learning that involves estimating the value of a state by considering the difference between the current and previous states [1-8]. This can be useful for tracking targets that are moving over time [6-9], as it allows the system to update its estimates of the target's position based on its previous movements.

Template matching, on the other hand, involves comparing a pre-defined "template" of a target with observations in order to identify and track the target [6-9]. This approach can be useful when the appearance of the target is known in advance and remains relatively constant over time. Both of these approaches have advantages and disadvantages that need to be considered when implementing them in a joint radar and communication system [11-19]. Temporal difference may be more robust in the face of changing target appearance or environments, but it can be computationally intensive [23-39]. Template matching can be more efficient, but it may not be as effective when the appearance of the target changes significantly [10-49].

The use of alternative sensor concepts such as acoustic waves [6, 7, 8, 9] and mm-waves [10] ensures a greater level of privacy [3-5], [11-14], [20-28], [31], and [34-39]. There are several sensor concepts that use different types of waves or energy to detect and track targets, which can offer certain advantages over traditional radar systems. Acoustic waves, or sound waves, can be used in underwater or air-based sonar systems to detect and track objects by measuring the time it takes for a sound wave to travel to and from the target [3-5], and [34-39]. Acoustic sensors are relatively inexpensive and can operate in challenging environments, such as underwater or in fog, but they have limited range and can be disrupted by noise or clutter [3-5], [11-14], [31], and [34-39].

Radar-based systems use electromagnetic waves, typically in the radio frequency or microwave range, to detect and track targets. Radar systems have several advantages compared to other sensing concepts [3-5], [11-14], [20-28], [31], and [100-156]:

1. Long range: Radar systems can detect and track targets at long ranges, depending on the frequency and power of the radar signal and the size and reflectivity of the target.
2. All-weather capability: Radar systems can operate in a variety of weather conditions, including rain, fog, and snow, as long as the radar signal is not absorbed or scattered too significantly.
3. Versatility: Radar systems can be used to detect and track a wide range of targets, including aircraft, vehicles, ships, and missiles, and can also measure the range, velocity, and angle of the target.

4. High resolution: Modern radar systems can provide high resolution images and measurements of targets, allowing for accurate tracking and identification.
5. Passive operation: Radar systems can operate in a passive mode, where they only receive and analyze reflected signals, rather than emitting their own signals. This can make radar systems less detectable and more covert.

Overall, radar-based systems are widely used for a variety of applications due to their long range, all-weather capability, versatility, and high resolution [3-5], [11-14], [20-28], [31], and [100-156]. However, they also have some limitations, such as sensitivity to atmospheric conditions, interference from other sources, and the possibility of being jammed or spoofed [3-5], [11-14], [20-28], [31], and [100-156]. Radio frequency and microwave radar systems, which operate at lower and higher frequencies, respectively, can have ranges of several hundred kilometers, depending on the power of the radar signal and the size and reflectivity of the target [3-5], [31], and [100-156]. Mm-wave radar systems, which operate at much higher frequencies, have a shorter range of several hundred meters [31], and [100-156]. Infrared sensors, which detect heat emitted by objects, have a similar range of several hundred meters [3-5], [11-14], [20-28], [31], and [100-156].

It is important to note that the range of a sensing system depends on a variety of factors, including the frequency and power of the signal [54], the size and reflectivity of the target, and the environment in which the system is operating [123], [154]. Radar systems have several advantages over other sensing concepts, such as ultrasonic systems and cameras, which require line-of-sight to detect and track targets. Radar systems use pulsed, broadband electromagnetic waves that can penetrate walls, allowing them to detect and track targets that are hidden or occluded from view. In contrast to infrared or lidar sensors, which use non-visible light to detect and track targets, radar systems use electromagnetic waves that can operate in a wider range of environments and conditions [120-181]. Radar systems can work in harsh environments, such as rain, dust, or fog, and are less affected by these conditions than infrared or lidar sensors.

However, it is important to note that radar systems also have their own limitations and challenges. They can be disrupted by certain materials or weather conditions, and they can be sensitive to interference from other sources. In addition, radar systems can be detected and jammed or spoofed

by adversarial parties [3-5], [11-14], [20-28], [31], and [100-156]. By evaluating interferometric signals, radar systems can also detect micro motions in the micrometer range, such as vital signs. In the case of detecting micro motions such as vital signs, the radar system would need to be able to detect very small changes in distance between the radar system and the object. This can be done using interferometry, which involves combining two or more waves in order to extract information about their relative phase difference. By carefully analyzing the interference pattern produced by the combination of the transmitted and reflected radio frequency signals, it is possible to detect very small changes in distance. This can be used to detect micro motions such as the beating of a heart or the movement of chest muscles as a person breathes [3-5], [11-14], [20-28], [31], and [100-156].

2.4. Challenges in multitarget detection with FMCW radar

It is possible to track humans at short ranges of up to 5 meters using 24-GHz FMCW radars based on Six-Port interferometry [14-28]. Six-port interferometry is a technique that uses six ports to measure the reflection and transmission characteristics of a device or system [33-76]. It is often used in microwave and millimeter-wave applications, such as in radar systems [3-5], [11-14], [20-28], [31], and [100-156]. Vital-Doppler standard deviation is a measure of the variability in the Doppler shift of a radar signal due to movement or changes in the characteristics of the target being tracked [45-87]. It is often used to monitor the vital signs of living organisms, such as heart rate and respiration rate [67]. In summary, a 24-GHz FMCW radar based on Six-Port interferometry and utilizing vital-Doppler standard deviation could be used for short-range human tracking up to 5 meters by measuring the Doppler shift of the radar signal caused by the movement of the human body [3-5], [11-14], [20-28], [31], and [100-156].

One of the main advantages of FMCW radar is its ability to simultaneously measure the range, velocity, and angle of multiple targets [3-5], [11-14], [20-28], [31], and [100-156]. This is achieved

by comparing the transmitted waveform with the reflected waveform received by the radar antenna [3-5] and [100-156].

In a multitarget detection scenario, FMCW radar can detect multiple targets by separating the returns from each target using a process known as pulse compression. Pulse compression is achieved by modulating the transmitted waveform with a known code, such as a pseudo-random noise (PRN) code [100-156]. The reflected waveform from each target is then correlated with the transmitted waveform, and the resulting correlation function provides information about the range and velocity of each target [31], and [100-156].

One of the main challenges in multitarget detection with FMCW radar is the presence of clutter and interference [3-5], [11-14], [20-28], [31], and [100-156]. Clutter is any unwanted return that is not from a target of interest, and it can include reflections from terrain, buildings, trees, and other stationary or moving objects [3-5]. Interference is any unwanted signal that is present in the radar's operating frequency band, and it can include signals from other radar systems, wireless communication systems, and atmospheric effects [100-156]. To mitigate the effects of clutter and interference, FMCW radar systems often employ various techniques such as adaptive beamforming, frequency agility, and pulse-to-pulse processing [100-156]. Adaptive beamforming involves forming and steering the radar beam in a direction that maximizes the signal-to-noise ratio (SNR) of the return from the target of interest [1-62]. Frequency agility involves rapidly changing the operating frequency of the radar to avoid interference from other sources [1-34]. Pulse-to-pulse processing involves comparing the returns from successive pulses to identify and track targets of interest [3-5], [11-14], [20-28].

Another challenge in multitarget detection with FMCW radar is the resolution of closely spaced targets [3-5], [11-14], [20-28], [31], and [100-156]. The range resolution of an FMCW radar is inversely proportional to the bandwidth of the transmitted waveform [140-173]. Therefore, increasing the bandwidth of the transmitted waveform can improve the range resolution of the radar, but at the expense of increased noise and reduced range accuracy [140-173]. To resolve closely spaced targets [140-173], FMCW radar systems often employ multiple transmitting and receiving antennas to form a synthetic aperture, which can provide improved range and angle resolution [140-173].

In summary [1-182], FMCW radar is well suited for multitarget detection due to its ability to simultaneously measure the range, velocity, and angle of multiple targets [140-173]. However, the presence of clutter and interference can degrade the performance of the radar, and the resolution of closely spaced targets can be challenging [145-179]. Various techniques such as adaptive beamforming, frequency agility, and pulse-to-pulse processing can be employed to mitigate these challenges and improve the performance of the radar in multitarget detection scenarios [140-182].

2.5. Maximize the signal-to-noise ratio (SNR) in FMCW JCSR's:

There are several techniques that can be used to maximize the signal-to-noise ratio (SNR) in joint Frequency-Modulated Continuous Wave (FMCW) radar communication systems:

1. Adaptive beamforming: This involves forming and steering the radar beam in a direction that maximizes the SNR of the return from the target of interest. By focusing the energy of the radar beam in the direction of the target, the SNR of the return signal can be increased.
2. Frequency agility: This involves rapidly changing the operating frequency of the radar to avoid interference from other sources. By operating at a frequency where the interference is low, the SNR of the return signal can be increased.
3. Pulse-to-pulse processing: This involves comparing the returns from successive pulses to identify and track targets of interest. By using information from multiple pulses, the SNR of the return signal can be increased through signal averaging.
4. Antenna design: The design of the radar antenna can also affect the SNR of the return signal. By using an antenna with a high gain and a narrow beamwidth, the SNR of the return signal can be increased.
5. Modulation schemes: The use of a suitable modulation scheme can also affect the SNR of the return signal. For example, using a linear frequency modulated (LFM) waveform can improve the SNR compared to a sawtooth waveform due to its lower sidelobes.

6. Receiver design: The design of the radar receiver can also affect the SNR of the return signal. By using a receiver with a high dynamic range and good noise immunity, the SNR of the return signal can be increased.
7. Noise reduction techniques: Techniques such as filtering and adaptive noise cancelling can be used to reduce the noise in the received signal, thereby increasing the SNR.

By implementing these techniques, it is possible to maximize the SNR in joint FMCW radar communication systems, which can improve the performance of the radar and enhance its capabilities for multitarget detection and communication.

2.6. Losing tracks and assigning ghost targets:

In joint Frequency-Modulated Continuous Wave (FMCW) radar communication systems, it is possible for the radar to lose track of a target, or to assign a "ghost" target that does not actually exist. Losing track of a target can occur when the radar's tracking algorithm is unable to maintain a sufficient signal-to-noise ratio (SNR) for the return signal from the target. This can happen when the target moves out of the radar's field of view, when the target becomes occluded by other objects, or when the target's reflectivity changes significantly. To prevent the radar from losing track of a target, it is important to design the tracking algorithm to be robust and to have a low failure rate. This can be achieved by using techniques such as Kalman filtering, which combines information from multiple pulses to estimate the state of the target.

Ghost targets, also known as false alarms or clutter, are targets that are detected by the radar but do not actually exist. Ghost targets can be caused by reflections from stationary objects, such as buildings or terrain, or by interference from other sources, such as other radar systems or wireless communication systems.

To reduce the occurrence of ghost targets, it is important to design the radar system to have a high probability of detection and a low probability of false alarm. This can be achieved by using techniques such as pulse-to-pulse processing, which compares the returns from successive pulses

to identify and track targets of interest, and by using adaptive beamforming, which forms and steers the radar beam in a direction that maximizes the SNR of the return signal.

In joint Frequency-Modulated Continuous Wave (FMCW) radar communication systems, losing track of a target or assigning ghost targets can be caused by hardware-related issues, such as hardware failures or malfunctions, as well as by software-related issues, such as algorithmic failures or interference from other sources.

Hardware-related issues that can cause the radar to lose track of a target or assign ghost targets include:

1. Antenna failure: If the radar antenna is damaged or malfunctions, it may not be able to transmit or receive signals properly, which can lead to lost tracks or ghost targets.
2. Transmitter failure: If the radar transmitter fails or malfunctions, it may not be able to transmit a sufficient signal to the target, which can lead to lost tracks.
3. Receiver failure: If the radar receiver fails or malfunctions, it may not be able to properly process the return signal from the target, which can lead to lost tracks or ghost targets.
4. Data processing failure: If the data processing hardware fails or malfunctions, it may not be able to properly extract the target information from the received signal, which can lead to lost tracks or ghost targets.

Tuning forks can be used to test the effectiveness of the provided radar as a human detector and vehicle tracker. A calibrated tuning fork can be used to test the effectiveness of a radar system as a human detector and vehicle tracker by simulating the reflections that would be produced by a human or a vehicle. The tuning fork can be struck and held in front of the radar antenna to produce a reflection that is similar to that of a human or a vehicle. To use the calibrated tuning fork as a human detector, the fork should be struck and held in front of the radar antenna at a distance and orientation that is representative of a human standing in front of the radar. The reflection produced by the fork will be similar to that of a human, with the size and shape of the reflection being determined by the size and shape of the fork. To use the calibrated tuning fork as a vehicle tracker, the fork should be struck and mounted on a vehicle in a position that is representative of a radar reflector on a vehicle. The reflection produced by the fork will be similar to that of a vehicle, with the size and shape of the reflection being determined by the size and

shape of the fork and the position of the fork on the vehicle. By comparing the reflections produced by the calibrated tuning fork with the reflections produced by actual humans and vehicles, it is possible to assess the effectiveness of the radar system as a human detector and vehicle tracker. This can be done by measuring the radar's range, velocity, and angle accuracy, as well as its ability to distinguish between multiple targets.

There are several factors that can affect the effectiveness of the radar system as a human detector and vehicle tracker, including the radar's operating frequency, the size and shape of the fork, the distance and orientation of the fork relative to the radar, and the presence of clutter and interference. To maximize the effectiveness of the radar as a human detector and vehicle tracker, it is important to carefully calibrate the tuning fork to match the size and shape of a human or a vehicle, and to select an operating frequency that is appropriate for the intended application. It is also important to design and configure the radar system to have a high probability of detection and a low probability of false alarm, and to employ techniques such as adaptive beamforming and pulse-to-pulse processing to mitigate the effects of clutter and interference.

2.6.1. Human tracking of Joint communication system and radar in the 24-GHz ISM band

Human tracking is the process of continuously monitoring the position and movement of individuals in a given environment. In the context of a joint communication and radar system operating at 24GHz in the ISM band, human tracking can be a challenging task due to the high operating frequency and the potential for interference from other systems [49]. One key aspect of human tracking in a joint communication and radar system operating at 24GHz is the use of advanced radar signal processing techniques. These can include techniques such as pulse compression, matched filtering, and constant false-alarm rate (CFAR) detection. Pulse compression techniques can be used to increase the range resolution of the radar, allowing it to detect and track individuals at longer distances. Matched filtering can be used to improve the

signal-to-noise ratio, allowing the radar to detect weaker signals and track individuals in cluttered environments. CFAR detection can be used to reject false targets and reduce the likelihood of false alarms [50]. Another aspect of human tracking in a joint communication and radar system operating at 24GHz is the use of advanced beamforming techniques. Beamforming can be used to steer the radar's main beam in different directions, allowing it to detect and track individuals in different locations. It can also be used to form multiple beams, allowing the radar to simultaneously track multiple individuals in different directions.

In addition to these techniques, a joint communication and radar system operating at 24GHz may also make use of advanced data processing techniques such as multi-target tracking, human classification, and data fusion. Multi-target tracking can be used to track multiple individuals over time, while human classification can be used to classify different types of individuals based on their radar signature. Data fusion can be used to combine information from multiple sources to improve target detection and tracking. One of the main challenges in human tracking in a joint communication and radar system operating at 24GHz is the need to coordinate the different requirements and constraints of the communication and radar components. Communication systems typically place a greater emphasis on data rate and bandwidth, while radar systems typically place a greater emphasis on range and resolution. Careful system design and coordination is required to ensure that the system can effectively balance these competing requirements. Another significant challenge for human tracking in the 24GHz ISM band is the potential for interference from other systems operating in the same band. The ISM band is a shared frequency band, where multiple devices and systems operate, which can cause significant interference. This challenge can be mitigated by using advanced interference suppression techniques such as adaptive filtering, beamforming, and spread-spectrum techniques.

In addition to these technical challenges, there are also ethical and legal considerations to take into account when using a joint communication and radar system for human tracking. These include issues such as privacy, surveillance, and data protection. It is important to ensure that the system is designed and operated in compliance with relevant laws and regulations, and that appropriate measures are in place to protect the privacy and rights of individuals.

In conclusion, human tracking is a complex task that requires the use of advanced radar signal processing techniques, beamforming, data processing techniques and interference suppression techniques. A joint communication and radar system operating at 24GHz in the ISM band can provide an effective solution for human tracking, but careful system design and coordination is required to ensure that the system can effectively balance the different requirements and constraints of the communication and radar components and mitigate the interference from other systems operating in the same band. Additionally, it is important to consider the ethical and legal implications of using a joint communication and radar system for human tracking and take appropriate measures to protect the privacy and rights of individuals.

2.6.2. Challenges of human tracking in ISM band:

One key challenge for human tracking in a joint communication and radar system operating at 24GHz is the potential for interference from other systems operating in the same band. The ISM band is a shared frequency band, where multiple devices and systems operate, which can cause significant interference. This can make it difficult for the system to accurately detect and track individuals in the presence of other signals.

Another challenge for human tracking in a joint communication and radar system operating at 24GHz is the high operating frequency. At 24GHz, the radar system is operating at a high frequency, which can make it more difficult to detect and track individuals, particularly in cluttered environments. High frequency radar systems are also more susceptible to atmospheric absorption and scattering, which can further degrade the system's performance.

A third challenge for human tracking in a joint communication and radar system operating at 24GHz is the need to coordinate the different requirements and constraints of the communication and radar components. Communication systems typically place a greater emphasis on data rate and bandwidth, while radar systems typically place a greater emphasis on range and resolution. Careful system design and coordination is required to ensure that the system can effectively balance these competing requirements.

A fourth challenge for human tracking in a joint communication and radar system operating at 24GHz is the need for advanced signal processing techniques. These can include techniques such as pulse compression, matched filtering, and constant false-alarm rate (CFAR) detection. These techniques can be computationally intensive, which can increase the system's power consumption and reduce its overall performance.

A fifth challenge for human tracking in a joint communication and radar system operating at 24GHz is the potential for privacy and surveillance concerns. The use of radar and communication systems for human tracking can raise ethical and legal concerns related to privacy and surveillance. It is important to ensure that the system is designed and operated in compliance with relevant laws and regulations, and that appropriate measures are in place to protect the privacy and rights of individuals.

2.6.3. Effects of high data rate on human tracking in the 24-GHz ISM band of a joint communication system and radar

A joint communication and radar system operating at 24GHz in the ISM band can provide a high data rate for human tracking. However, this high data rate can also have a number of effects on the system's performance, particularly when it comes to human tracking.

One effect of high data rate on human tracking in a joint communication and radar system operating at 24GHz is increased system complexity. A high data rate requires more advanced signal processing techniques and a larger amount of data storage and transmission capacity. This can increase the complexity of the system and make it more difficult to implement and maintain.

Another effect of high data rate on human tracking in a joint communication and radar system operating at 24GHz is increased power consumption. A high data rate requires more processing power, which can increase the system's power consumption and reduce its overall performance. This is particularly important for systems that are powered by batteries or solar cells.

A third effect of high data rate on human tracking in a joint communication and radar system operating at 24GHz is increased susceptibility to interference. A high data rate requires a larger

bandwidth, which can increase the system's susceptibility to interference from other systems operating in the same band. This can make it more difficult for the system to accurately detect and track individuals in the presence of other signals.

A fourth effect of high data rate on human tracking in a joint communication and radar system operating at 24GHz is increased susceptibility to multipath propagation. The high data rate may cause the signal to be spread over a larger bandwidth and thus increase the probability of multipath propagation, which can cause errors in the tracking process.

A fifth effect of high data rate on human tracking in a joint communication and radar system operating at 24GHz is increased complexity in data processing. The high data rate can make it difficult for the system to process the data in real-time, which can result in delays in the tracking process.

In conclusion, a high data rate can have a number of effects on human tracking in a joint communication and radar system operating at 24GHz in the ISM band. It can increase system complexity, power consumption, susceptibility to interference and multipath propagation, and complexity in data processing. Careful system design and optimization is required to balance the need for high data rate with the need for accurate human tracking. It is important to ensure that the system is designed to minimize these effects while still providing the desired performance.

2.6.4. Effects of Doppler effect on human tracking JCSR in the 24-GHz ISM band

The Doppler effect is a phenomenon that occurs when a wave source, such as a radar or a sound, is moving relative to an observer or a receiver. It causes a change in the frequency or wavelength of the wave as it propagates through space. When the source of a wave is moving towards an observer, the frequency of the wave will appear to increase, and the wavelength will appear to shorten. This is known as a blue shift. Conversely, when the source is moving away from the observer, the frequency will appear to decrease, and the wavelength will appear to lengthen, which

is known as a red shift. This effect can be observed in both sound waves and electromagnetic waves, such as radar or light.

The Doppler effect can be mathematically described using the following equation:

$$f_{\text{observed}} = f_{\text{source}} * (c / (c + v_{\text{source}}))$$

Where f_{observed} is the observed frequency, f_{source} is the frequency of the wave source, c is the speed of light, and v_{source} is the velocity of the source relative to the observer.

For example, in the case of a radar system, a radar transmitter sends out a signal at a certain frequency. If a target is moving towards the radar, the signal will be reflected back to the radar receiver at a higher frequency due to the Doppler effect. By measuring the difference in frequency between the transmitted signal and the reflected signal, the radar can calculate the velocity of the target. In case of sound waves, when a source of sound such as a siren on a moving car, the sound waves will be compressed as the car approaches an observer and expanded as the car moves away from the observer, causing an increase or decrease in the frequency respectively. The Doppler effect can also be observed in light waves. For example, when a star is moving away from the Earth, its light will be shifted towards the red end of the spectrum, and when it is moving towards the Earth, its light will be shifted towards the blue end of the spectrum. This effect is known as the "redshift" and "blueshift" respectively.

It's important to note that the Doppler effect is dependent on the relative motion between the source and the observer. If both the source and the observer are moving at the same velocity in the same direction, there will be no observed change in frequency. Also, the effect is more pronounced when the relative velocity between the source and observer is high. The Doppler effect can have a significant impact on the performance of a joint communication and radar system operating at the 24-GHz ISM band when used for human tracking. One major impact is on the accuracy of the system's velocity measurements. The Doppler effect causes a shift in the frequency of the radar signal reflected off a moving target, and this shift can be used to calculate the target's velocity. However, the Doppler shift caused by a person's motion can be relatively small compared to the radar's operating frequency, making it challenging to accurately measure the person's velocity. Another impact is on the system's ability to distinguish between multiple targets. When

multiple targets are in close proximity, the Doppler shift caused by each target's motion can overlap, making it difficult to separate the returns from each target and track them individually.

The Doppler effect can also affect the system's range resolution. The Doppler shift caused by a target's motion can cause the radar return from that target to spread out over a range of frequencies. This can make it challenging to accurately determine the range to the target, especially when the target is moving at a high velocity.

Finally, the Doppler effect can also make it more difficult to track a target over time. As a target moves, the Doppler shift caused by its motion will change, and the radar will need to continuously update its measurements to account for this change. This can make it more challenging to maintain a stable track on the target.

In conclusion, the Doppler effect can have a significant impact on the performance of a joint communication and radar system operating at the 24-GHz ISM band when used for human tracking. It can affect the accuracy of velocity measurements, the ability to distinguish between multiple targets, range resolution and make it more difficult to track a target over time.

2.6.5. Connections of Doppler effect, high data rate, and synchronization in JCRS

There is a connection between the Doppler effect, high data rate, and synchronization in joint communication systems and radars. The Doppler effect can have a significant impact on the performance of a joint communication and radar system operating at high data rate. As the relative velocity between the transmitter and receiver increases, the Doppler shift also increases, making it more challenging to accurately measure the velocity of the target. This can lead to errors in the data transmitted and received, which can reduce the system's overall performance and data rate. Furthermore, the Doppler effect can also affect the system's ability to maintain synchronization. Synchronization is crucial for maintaining accurate communication and radar measurements. When multiple targets are present, the Doppler shift caused by each target's

motion can overlap, making it difficult to separate the returns from each target and maintain accurate synchronization.

To overcome the effect of the Doppler shift, advanced techniques such as frequency modulation, pulse compression and adaptive filtering are used to improve the system's performance. These techniques can reduce the impact of the Doppler shift on the system's measurements, increase the data rate, and maintain synchronization even in the presence of high relative velocities. Additionally, the use of phased array antennas in joint communication systems and radars can also help mitigate the effects of Doppler shift. These antennas use multiple elements that can be electronically controlled to steer the beam in a specific direction, allowing the system to track multiple targets simultaneously. This can help to improve the system's overall performance and data rate. Doppler effect can have a significant impact on the performance of joint communication systems and radars operating at high data rate. It can affect the accuracy of velocity measurements, the ability to maintain synchronization, and can lead to errors in the data transmitted and received. However, advanced techniques and the use of phased array antennas can mitigate these effects and improve the system's overall performance and data rate. The Doppler effect can have a significant impact on the performance of joint communication systems and radars operating at high data rate. It can affect the accuracy of velocity measurements, the ability to maintain synchronization, and can lead to errors in the data transmitted and received. However, advanced techniques and the use of phased array antennas can mitigate these effects and improve the system's overall performance and data rate.

Increasing the data rate in joint communication systems and radars can exacerbate the problems caused by the Doppler effect. The Doppler effect can cause a shift in the frequency of the signal, which can lead to errors in the data transmitted and received. At high data rates, these errors can become more frequent and have a greater impact on the system's overall performance.

One of the crucial challenges with increasing the data rate is maintaining synchronization between the transmitter and receiver. When the data rate is high, the system must be able to accurately process and transmit large amounts of information in a short period of time. The Doppler effect can make it difficult to maintain synchronization, as the shift in frequency caused by the motion of the target can cause errors in the timing of the transmitted and received signals. Another

challenge is the ability to accurately measure the velocity of the target. The Doppler effect can cause a shift in the frequency of the radar signal reflected off a moving target, and this shift can be used to calculate the target's velocity. However, at high data rates, the Doppler shift caused by the target's motion can become more pronounced, making it more challenging to accurately measure the target's velocity. Additionally, at high data rates, the system's ability to distinguish between multiple targets can be affected. When multiple targets are in close proximity, the Doppler shift caused by each target's motion can overlap, making it difficult to separate the returns from each target and track them individually. This can lead to errors in the system's measurements and reduce the overall performance.

To mitigate these problems, advanced techniques such as adaptive filtering, pulse compression, and frequency modulation can be used to improve the system's performance at high data rates. These techniques can reduce the impact of the Doppler shift on the system's measurements, increase the data rate, and maintain synchronization even in the presence of high relative velocities. Additionally, the use of phased array antennas in joint communication systems and radars can also help mitigate the effects of Doppler shift. These antennas use multiple elements that can be electronically controlled to steer the beam in a specific direction, allowing the system to track multiple targets simultaneously. Increasing the data rate in joint communication systems and radars can exacerbate the problems caused by the Doppler effect. The Doppler effect can cause a shift in the frequency of the signal, which can lead to errors in the data transmitted and received. Maintaining synchronization and accurately measuring the velocity of the target can be challenging at high data rates. However, advanced techniques and the use of phased array antennas can mitigate these effects and improve the system's overall performance at high data rates.

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