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Research on Anti-Jamming for Vehicle Millimeter Wave Radar Based on Frequency Hopping Technology

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Abstract: To address the interference issues among vehicle millimeter wave radars, this chapter proposes an anti-jamming technique that involves frequency hopping of the signal at the transmitter side. By varying the frequency of the radar transmission signal and based on different frequency hopping sequences, it is possible to distinguish between the transmission signal and interference signals, thereby achieving the purpose of interference suppression. This study validates the anti-jamming performance of the proposed solution under different interference conditions through theoretical analysis and simulation. The simulation results indicate that the scheme can effectively suppress interference in scenarios with both single and multiple targets, enhancing the system's stability and reliability.

1. Introduction

With the increasing interest in autonomous driving, radar is becoming the preferred technology for safety and driving assistance applications such as blind spot detection, collision avoidance, and emergency braking[1][2]. Due to its strong anti-interference ability, high ranging accuracy, strong penetration ability in complex environments, and all-weather performance, millimeter-wave radar can provide more reliable environmental perception[3]. In addition, millimeter wave radar is small in size, light in weight and high in spatial resolution. Therefore, millimeter wave radar has certain advantages in intelligent driving and is widely used. But as more and more vehicles are equipped with millimeter wave radars, the radar devices are likely to cause mutual interference in adjacent lanes[4][5]. When there is mutual interference between radars, it will cause the detection radar to misjudge the target, such as false alarm or missing detection, so that the vehicle takes wrong braking action, posing a huge threat to social public safety[6], so the mutual interference between the vehicle radar is a key problem to be solved[7]. At present, many scholars have studied the mutual interference between vehicle-mounted radars. Frequency hopping technology is widely used in the field of military communication because of its good anti-interference performance [8]. In [9] applies game theory to frequency-hopping communication and deduces the necessary and sufficient conditions of Nash equilibrium under linear constraints. In [10] proposes an integrated intelligent anti-jamming method for frequency-hopping systems based on modern signal processing, which includes interference recognition and interference suppression algorithms, and can improve the robustness of frequency-hopping systems to various interferences without increasing bandwidth and hopping rate.Because frequency hopping technology can avoid spectrum aliasing to a certain extent and improve anti-jamming performance, this paper presents an anti-jamming system of vehicle millimeter wave radar based on frequency hopping technology. In the vehicle millimeter wave radar system, enhancing the detection accuracy and anti-jamming capability for targets is crucial. To cope with complex traffic environments and various interferences, this system employs frequency hopping technology and a mean-based target detection algorithm. Frequency hopping technology, by rapidly switching between different frequencies, effectively reduces the impact of interference, thereby improving the stability and anti-jamming capability of the radar signal. The mean-based algorithm adaptively adjusts the detection threshold according to the changes in background noise and target signals, effectively controlling false alarms, thus precisely identifying targets in complex backgrounds.

2. Frequency Hopping Principle

Frequency hopping spread spectrum communication is a communication method that uses code sequences for multi-frequency shift keying. Its carrier frequency changes according to a certain pattern with a certain level of pseudo-randomness, thereby possessing strong anti-jamming capabilities. It is widely used in fields such as secure communication and drone communication. By rapidly switching between different frequencies, the signal is dispersed across the frequency domain, making it difficult for interference signals to continuously disrupt the radar system, thus enhancing the system's anti-jamming capability. At the receiver side, the signal is de-hopped according to the same sequence to achieve data transmission. For vehicle millimeter wave radars, since the working frequency band may be interfered with by other radars, communication devices, and other noise sources, employing frequency hopping technology to send signals through constant changes between frequencies can leverage the spectrum spreading characteristic. This makes the millimeter wave radar system less susceptible to narrowband interference. Not only can it improve the anti-jamming capability of the radar system, but it can also reduce the competition for spectrum resources and increase spectrum efficiency.

3. System Structure

The system structure of this scheme is shown in Figure 1. Initially, the waveform generator produces the required waveform, followed by data modulation, where the data to be transmitted is combined with the basic waveform to carry the relevant content information. After the data modulation is complete, the modulated signal undergoes frequency hopping modulation. The generation of the hopping signal relies on a pseudo-random sequence produced by a pseudo-code generator. Then, a frequency synthesizer generates the corresponding frequency signals based on this sequence, achieving frequency switching of the hopping signal. This enhances the security and anti-jamming capability of the vehicle millimeter wave radar system. Since vehicle millimeter wave radars receive signals from other radars, causing interference and affecting the radar's detection performance, the receiver uses the same hopping sequence as the transmitter to perform de-hopping on the received signals. This effectively separates the target echo signals from the received signals. Afterwards, beamforming processes the extracted signals. This technique, by weighting and phase adjusting the received signals, strengthens the signal from the desired direction, thereby improving the accuracy of target detection. Additionally, the system performs pulse compression on the signals after beamforming to improve the radar system's range resolution, enabling more precise distinction of targets at different distances in the time domain. This achieves high-resolution detection and localization of targets. Finally, target detection is carried out using a target detection algorithm.

The SO-CFAR algorithm used in the target detection process is a classic method optimized for false alarm control and enhanced detection performance in complex environments. It adaptively adjusts the detection threshold to accommodate changes in noise and varying target intensities, making it more sensitive to changes in target signals. This capability makes the SO-CFAR algorithm particularly suitable for vehicle millimeter wave radar scenarios, effectively improving the accuracy of target detection.

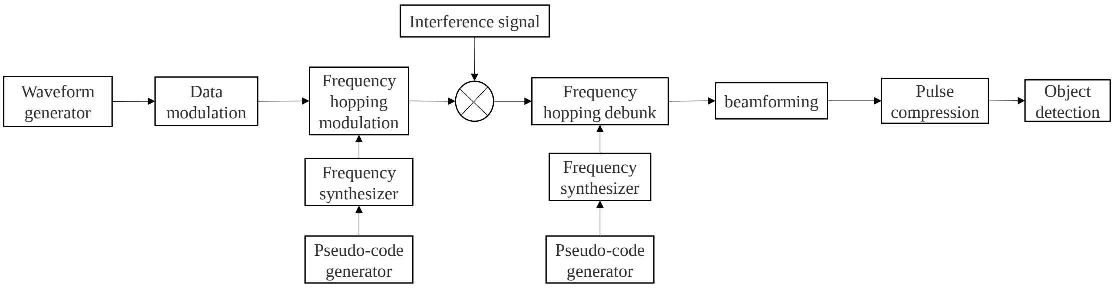

Figure 1: Structure of frequency-hopping anti-jamming system of vehicle millimeter wave radar.

The frequency hopping system selects different frequencies according to different code elements to transmit, and the receiving end generates the same frequency hopping sequence as the sending end to unhop the received signal. Provided with N frequency hopping points, the frequency hopping signal generated by FH module can be expressed as

$$x(t)=\sum_{n=1}^{N} \exp\left\{ j\times 2\pi[(f_n t+\frac{1}{2}kt^2)]\right\} \tag{1}$$

Where f_n indicates that the frequency synthesizer produces a series of FM output frequencies, n=1,2,... ,N.

When there is no interference, the radar echo signal can be expressed as

$$x(t)=\sum_{n=1}^{N} \exp\left\{ j\times 2\pi[(f_n(t-t_d)+\frac{1}{2}k(t-t_d)^2)]\right\} \tag{2}$$

Where, t_d represents the delay of the target echo signal.

When the echo signal received by the radar system contains interference signals, the signal can be expressed as

$$x_{rec}(t)=x_n(t)+x_{\text{int}}(t) \tag{3}$$

Where, $x_n(t)$ represents the target echo signal, $x_{int}(t)$ represents the interference signal. The frequency-hopping signal of formula (1) is put into the output model of receiving interference echo of formula (3), and the echo signal with interference is obtained as

$$\begin{aligned} x_{rec}(t)=&\sum_{n=1}^{N}\exp\left\{ j\times 2\pi[f_n(t-t_d)+\frac{1}{2}k(t-t_d)^2]\right\} \\ &+\exp\left\{ j\times 2\pi[f^I t_d^I+\frac{1}{2}k^I(t-t_d^I)^2\right\} \end{aligned} \tag{4}$$

Where, f^I represents the carrier frequency of the jamming radar, k^I represents the slope of the jamming source, and $t_d{}^I$ is the delay between the transmitted signal and the jamming signal.

4. Simulation experiment and result analysis

In this section, a simulation experiment is designed to simulate the vehicle driving on the road, and the performance of the radar frequency hopping technology is analyzed based on this background.

Table 1 shows the parameter design of the FH vehicle-mounted mmwave radar system, and the simulation experiment sets different number of targets and different number of interference sources, aiming to comprehensively evaluate the performance of the radar under these changing conditions. The simulation results of traditional frequency-less technology and frequency-hopping interference suppression technology are analyzed.

Table 1: Simulation parameters.

argument	Local radar
Initial carrier frequency	77GHz
Frequency modulation bandwidth	150 MHz
Frequency hopping number	200 /period
Hop frequency interval	753kHz

4.1. No Interference

When the target vehicle is located 100 meters from the radar, and it is not affected by signals from other radars, the energy of its reflected echo signal exceeds the SO-CFAR detection threshold. The target vehicle can be accurately detected, as shown in Figure 2.

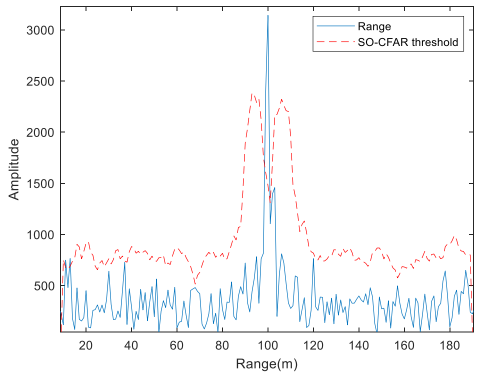

Figure 2: Range spectrum without interference.

4.2. Single Target Interference

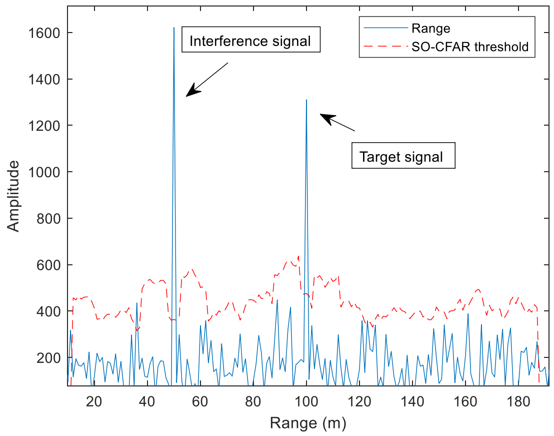

Figure 3: A range spectrum at the time of interference.

When there is one target and one source of interference, with the target located 100 meters from the detection radar at a speed of 20m/s, and the interfering radar 50 meters from the detection radar, without employing a frequency hopping scheme for interference suppression, the related ranging results are as shown in Figure 3. It can be observed from the figure that there are two peak values in the range spectrum, located at 50 meters and 100 meters, respectively. As mentioned earlier, due to the influence of the interference signal, the detection radar can detect not only the target signal but also the transmission signals from other radars. The corresponding range-Doppler plot is shown in Figure 4, which also displays a target signal and an interference signal.

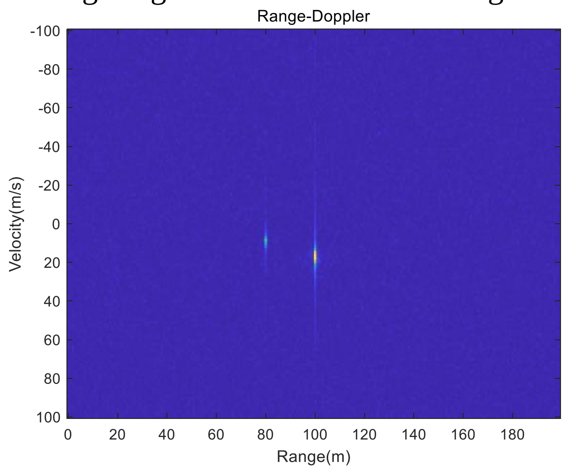

Figure 4: The distance at which one interferes - Doppler chart.

For this experiment, using the frequency hopping method proposed in this paper to suppress the interference signal, the results are as shown in Figure5. It can be observed that there is only one peak in the range spectrum located at 100 meters, and the signal amplitude exceeds the SO-CFAR detection threshold, allowing for accurate ranging of the target while successfully suppressing the interfering target. Figure 6 shows the range-Doppler plot after interference suppression, from which it can be seen that the detected target distance and speed information are consistent with the preset data. In other words, by applying this scheme for interference suppression, accurate ranging and speed measurement of the target signal can be achieved. This simulation experiment demonstrates that, in the case of single target interference, the method proposed in this paper can effectively suppress mutual interference between vehicle radars.

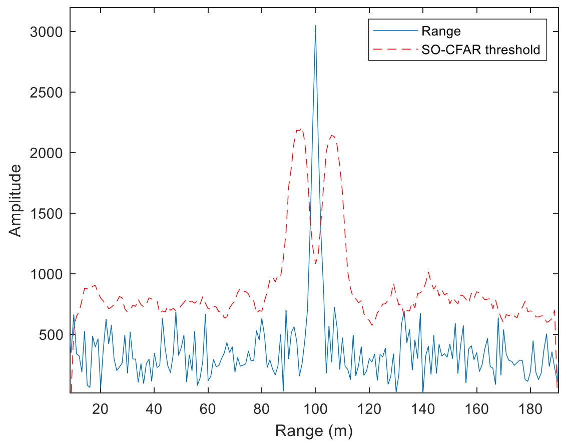

Figure 5: Range spectrum after interference suppression.

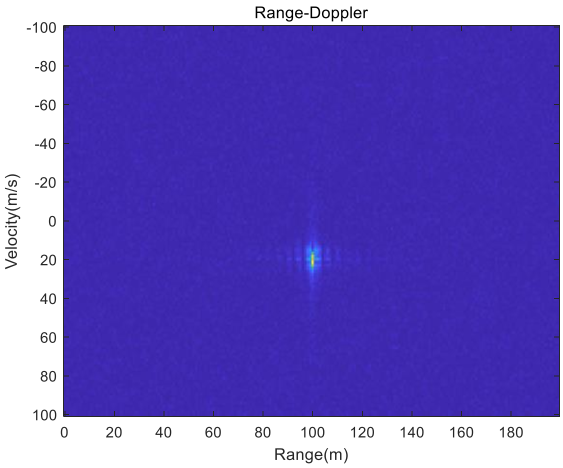

Figure 6: Range-Doppler plot after interference suppression.

4.3. Multiple Target Interference

When there are two targets and two sources of interference, the results of the vehicle millimeter wave radar's range and speed measurements are as shown in Figure 7 and Figure 8. The targets are located 100 meters and 120 meters away from the detection radar, respectively, with speeds of 10m/s and 20m/s. As can be seen in the figure, without interference suppression, the range spectrum as shown in Figure7 contains four peak values, located at 50 meters, 100 meters, 120 meters, and 150 meters. The peaks at 100 meters and 120 meters represent the distance information of the target signals, while the signals detected at 50 meters and 150 meters come from other radars. The corresponding range-Doppler plot is shown in Figure 8, where the detection results of distance and speed information match the preset positions and speeds. Moreover, it can be observed that with an increase in the number of interferences, the baseline noise also increases, leading to potential false detections or missed detections by the radar, severely affecting the normal operation of vehicles.

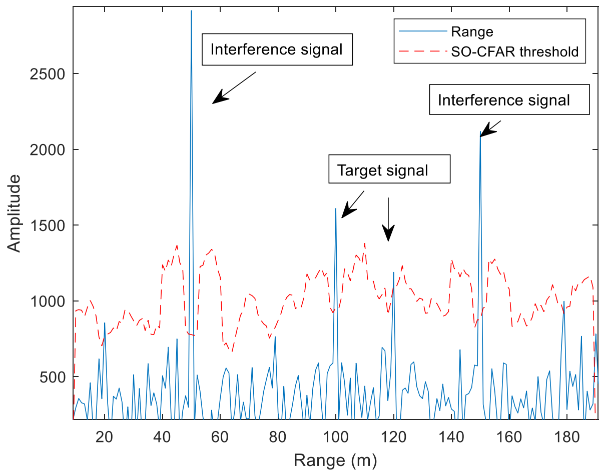

Figure 7: The distance diagram of the two interferences.

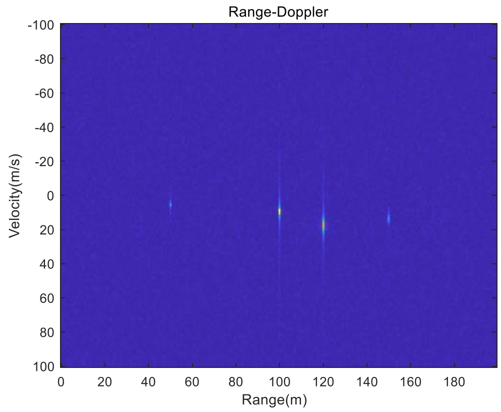

Figure 8: The distance between the two interferences - Doppler chart.

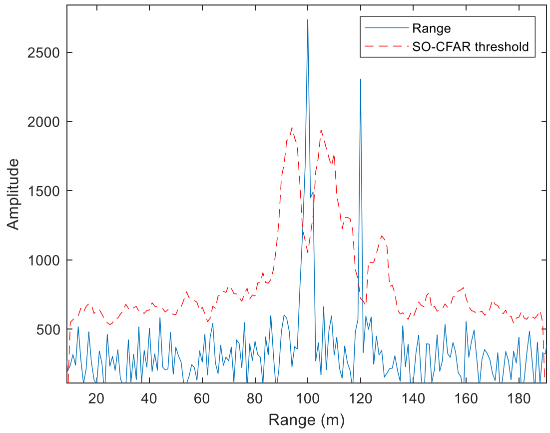

Figure 9: Range spectrum after interference suppression.

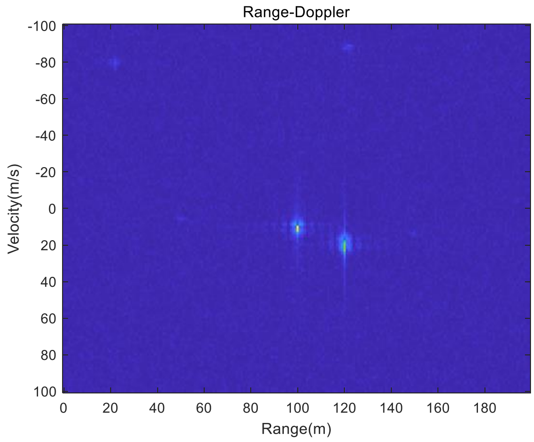

Figure 10: Range-Doppler plot after interference suppression.

To reduce the impact of interference signals on radar detection performance, the frequency hopping technique proposed in this chapter was used for interference suppression. The ranging chart, as shown in Figure 9, only contains distance information for the target signals located at 100m and 120m, with the target echo energy exceeding the SO-CFAR detection threshold. In other words, after frequency hopping, the interference signals were effectively suppressed, and the detection radar could accurately detect the positions of the targets. By performing a Fourier transform on the range spectrum, the range-Doppler plot is obtained as shown in Figure 10, where the information of two targets can be observed. This means that the frequency hopping interference suppression scheme not only has a significant effect on suppressing single target interference but also demonstrates good interference suppression performance in scenarios with multiple target interference

5. Result Analysis

The simulation results show that the presence of interference signals can affect the radar's detection results when no interference suppression is carried out. However, when the vehicle millimeter wave radar employs the frequency hopping suppression method proposed in this chapter, it can accurately measure range and speed in scenarios with single target interference and multiple target interferences, as indicated by the relevant output peak information. Although the level of baseline noise increases with the number of interferences, this does not affect the accuracy of the method's ranging and speed measurement results under interference. The experimental results demonstrate that the anti-interference method proposed in this chapter exhibits good suppression effects under different numbers of interferences.

6. Conclusions

This paper proposes a coded frequency hopping interference suppression scheme. It first introduces the basic principles of frequency hopping technology, followed by the introduction of the mean-based CFAR algorithm, due to the potential of CA-CFAR to produce misses and a higher false alarm rate. An improved algorithm, SO-CFAR, is then introduced to address the issues of high false alarm rates and target shadowing, showing good performance in multi-target environments. The scheme encodes signals at the transmitter to achieve continuous frequency hopping, effectively avoiding the frequency overlap between interference signals and target signals, thereby enhancing the anti-interference capability of the vehicle millimeter wave radar system. Through simulation analysis, the scheme's anti-interference performance under different interference conditions for vehicle millimeter wave radar is examined. Interference suppression in single target scenarios and multi-target scenarios was conducted, and the simulation experiments validated that the method proposed in this paper can suppress interference signals while ensuring accurate detection of target signals, both in single and multiple target interferences. This indicates that frequency hopping vehicle millimeter wave radar possesses excellent anti-interference performance.

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