A Time Jitter DDMA MIMO Automotive Radar Waveform

Jianhu Liu[1], Hongfei Lian[2](✉), Qiao Chen[1], and Sijia Chen[1]

[1] Beijing Rxbit Electronic Technology Co., Ltd., Beijing, China
{liujianhu,chenqiao,chensijia}@racodf.com
[2] National Key Laboratory of Science and Technology on Automatic Target Recognition, Changsha, China
lianhongfei97@163.com

Abstract. Aiming at the problems of low utilization of time and space and Doppler ambiguity of high-velocity targets in the traditional multiple input multiple output (MIMO) waveform of automotive radar, a time jitter Doppler frequency division multiplexing automotive radar waveform is proposed. This waveform jitters the pulse repetition interval stagger in the time domain, uses the phase difference between odd and even sequences to realize velocity ambiguity resolution, and realizes waveform orthogonality in the frequency domain through unequal spacing Doppler frequency modulation between multiple antennas, which improves the time-space transmission efficiency. In addition, an echo separation method based on non coherent accumulation is proposed, which can effectively solve the problem of target matching under Doppler frequency division multiplexing waveform. The effectiveness of the proposed waveform and signal processing method is verified by simulation experiments, and the waveform has strong application value in automotive radar engineering practice.

Keywords: Automotive radar · Multiple input multiple output · Time jitter · Doppler frequency division multiplexing · Incoherent accumulation

1 Introduction

Automotive Millimeter wave radar has wide coverage, high reliability, all-weather and all-weather target detection capabilities, and with the development of technology, the cost will be lower and lower [1–5]. This makes the Automotive Millimeter Wave Radar become one of the irreplaceable core sensors in the advanced driving assistance system. Automotive radar can realize high-resolution range and velocity estimation by transmitting linear frequency modulation continuous wave (FMCW) in millimeter wave band, and the cost is greatly reduced compared with laser radar [6–10]. Due to the limitation of physical space, the on-board millimeter wave radar is small in size, and due to the complex driving environment of vehicles, it is necessary to reconstruct the environmental information with high accuracy [11, 12]. Therefore, most of the on-board millimeter wave radars adopt multiple input multiple output (MIMO) system. MIMO automotive

Q. Liang et al. (Eds.): CSPS 2022, LNEE 874, pp. 26–32, 2023.
https://doi.org/10.1007/978-981-99-2362-5_4

radar uses linear frequency modulation continuous wave combined with other mechanisms to achieve waveform orthogonality. The commonly used orthogonal waveforms include time division multiplexing, frequency division multiplexing, code division multiplexing and Doppler frequency division multiplexing. The time division multiplexing MIMO system is the most commonly used in automotive radar. Only one antenna transmits in a pulse time period. Its transmission mechanism is simple and easy to implement in engineering, so it is widely used in automotive radar. However, in the time-division MIMO waveform, due to the time-division transmission of each antenna, not only the utilization rate of time and space is low, but also the pulse repetition rate is reduced, which aggravates the problem of Doppler ambiguity. In the frequency division multiplexing orthogonal waveform, the carrier frequencies of multiple transmitting antennas are different, but due to hardware limitations, there is only one VCO in the existing linear frequency modulation continuous wave automotive radar chip, which can not realize frequency division multiplexing, so it is not feasible in engineering. In the code division multiplexing waveform, multiple transmitting antennas transmit mutually orthogonal code sequences, and the receiving end can realize the separation of transmitted signal echoes after matched filtering. However, in this waveform, the code sequences cannot achieve ideal complete orthogonality, so there will be interference redundancy between the code sequences, resulting in the rise of bottom noise, which seriously affects the detection and estimation of targets, especially weak and small targets. The Doppler frequency division multiplexing waveform modulates the linear phase between the pulses of multiple transmitting antennas to achieve separation in the Doppler dimension. However, this waveform reduces the Doppler tolerance and is prone to Doppler ambiguity, which will seriously affect the detection performance of automotive radar.

In view of the above problems, this paper proposes a new waveform of time jitter Doppler frequency modulation based on the multi transmit and multi receive automotive radar system. The waveform performs pulse repetition interval stagger jitter in time domain to achieve sequence diversity, uses jitter phase difference between odd and even sequences to complete velocity ambiguity resolution, and achieves Doppler frequency orthogonality through inter pulse phase modulation in frequency domain to adapt to multi-channel angle measurement processing. This waveform can effectively solve the problem of vehicle radar velocity ambiguity, and can also take into account the multi-channel angle measurement.

2 Time Jitter DDMA MIMO Waveform

2.1 Waveform Description

This paper proposes a time jitter DDMA MIMO waveform based on the traditional linear frequency modulation sequence. The time-frequency relationship of the transmitted signal is shown in Fig. 1. The waveform realizes sequence interleaving diversity by pulse repetition interval stagger jitter in the time domain, and realizes Doppler frequency orthogonality by inter pulse phase modulation of multiple transmit antennas in the frequency domain.

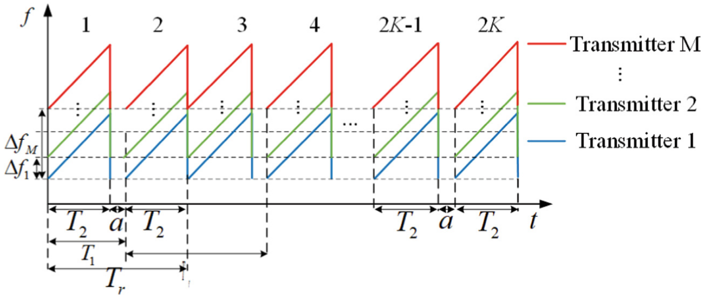

Fig. 1. Time frequency diagram of time jitter DDMA MIMO waveform

In the time domain, the waveform can be decomposed into odd and even pulse sequences of length K, wherein the pulse time interval in the odd pulse sequence is T_1, and the pulse time interval in the even pulse sequence is T_2, and $T_1 = T_2 + a$. The frequency modulation duration of all pulses in this waveform is T_2 and the frequency modulation bandwidth is consistent. In the frequency domain, the three transmitting antennas realize unequal interval Doppler frequency division multiplexing through inter pulse phase modulation. Among them, the transmitting antenna 1 is not modulated, the Doppler frequency difference between the transmitting antenna 2 and the transmitting antenna 1 is Δf_1, the Doppler frequency difference between the transmitting antenna 3 and the transmitting antenna 1 is Δf_2, …, The Doppler frequency difference between the transmitting antenna m and the transmitting antenna 1 is Δf_{M-1}. In order to reliably overcome the maximum velocity limit without the assumption of a single target, the waveform performs Doppler frequency modulation between multiple transmit antennas based on a vacant subband. Take the antenna array with three transmitters and four receivers as an example. If one empty subband is set, the modulation phase relationship of multiple transmitting antennas is shown in Fig. 2 and Fig. 3.

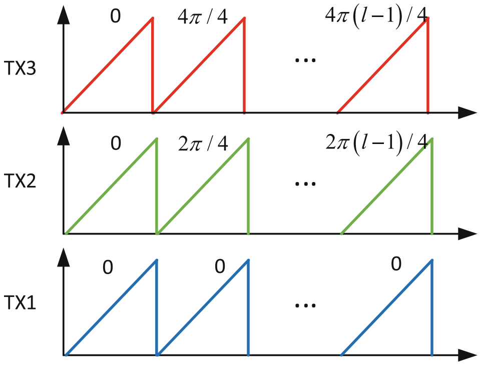

Fig. 2. Schematic diagram of modulation phase of time jitter DDMA waveform

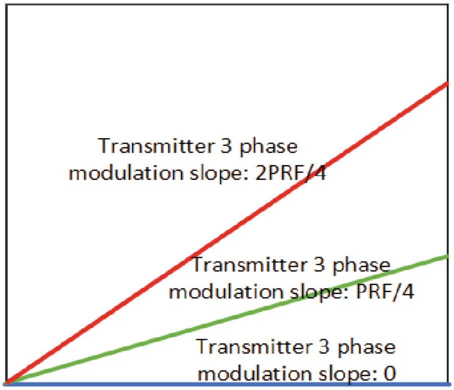

Fig. 3. Schematic diagram of modulation phase slope of time jitter DDMA waveform

In the above modulation method, the Doppler frequency division multiplexing between multiple antennas is realized by inter pulse phase modulation. The modulation phase of the m $(1 \leqslant m \leqslant M)$ th pulse of the k $(1 \leqslant k \leqslant K)$ th transmitting antenna in the odd and even sequences can be expressed as

$$\varphi_{mk} = \exp[j2\pi \frac{f_{\mathrm{r}}}{M+1}(m-1)(k-1)T_{\mathrm{r}}] \tag{1}$$

2.2 Time Jitter DDMA MIMO Waveform Signal Processing

Since the pulse repetition intervals of the two sub pulses in this waveform are different, the odd and even frequency modulation sequences need to be processed separately. The equivalent repetition period of the two pulse sequences is T_{r}. From the signal modulation scheme, after performing two-dimensional FFT on odd sequence and even sequence, there are multiple focal points in the two-dimensional spectrum of the parity sequence. Therefore, first of all, it is necessary to match the target to obtain the ambiguous Doppler frequency of the target. Here, a target matching method based on non coherent accumulation is proposed.

Suppose that the number of transmitting antennas is M, the number of receiving antennas is N, and the number of Doppler frequency modulated subbands is $P(M < P)$. The steps of the method are as follows.

Step 1: Non coherent accumulation of data of all receiving channels.

Step 2: Divide the matrix obtained in step 1 into P equally spaced subbands according to the Doppler dimension.

Step 3: According to the modulation method of the transmitting antenna, m consecutive sub bands in the P frequency bands are selected in sequence, and then non coherent accumulation is performed again to form M accumulation bands.

Step 4: Select the target with the largest peak value of the corresponding position in the M accumulation frequency bands as the target position to complete the target matching process.

After the target matching is completed by the above method, the range and ambiguous Doppler index of the target can be obtained, and the range and ambiguous Doppler frequency of the target can be obtained.

Next, the phase difference ambiguity resolution is performed. Referring to the idea in [13], first extract the phase sum of the peak points in the two sequences ξ_1 and ξ_2, and consider the phase winding, then define

$$\varphi_\mathrm{d} = \xi_2 - \xi_1 - 2\pi f_{D,amb}(T_2 + a) \tag{2}$$

Next, define

$$\delta_\mathrm{d} = \frac{\varphi_\mathrm{d}}{2\pi} - \left[\frac{\varphi_\mathrm{d}}{2\pi}\right] \tag{3}$$

It can be deduced that the relationship δ_d with Doppler ambiguous number q is

$$q = \begin{cases} \delta_\mathrm{d}\dfrac{2T_\mathrm{r}}{a}, & -\dfrac{1}{4} < \delta_\mathrm{d} < \dfrac{1}{4} \\ \left(\delta_\mathrm{d} + \dfrac{1}{2}\right)\dfrac{2T_\mathrm{r}}{a}, & \dfrac{1}{4} < \delta_\mathrm{d} < \dfrac{1}{2} \\ \left(\delta_\mathrm{d} - \dfrac{1}{2}\right)\dfrac{2T_\mathrm{r}}{a}, & -\dfrac{1}{2} < \delta_\mathrm{d} < \dfrac{1}{4} \end{cases} \tag{4}$$

The Doppler ambiguity number of the target can be obtained from (4), and the target Doppler frequency is

$$f_\mathrm{D} = f_\mathrm{D,amb} + q \cdot f_\mathrm{D,max}, q \in \mathbb{Z} \tag{5}$$

So far, the target velocity ambiguity resolution is completed. Finally, a virtual transceiver array is formed by Doppler frequency division multiplexing to complete multi-channel angle measurement.

3 Simulation

This section takes the 3-transmit and 4-receiver radar as an example. The waveform parameters of the simulation test are shown in Table 1.

Set four targets with different distances, velocitys and angles. The target parameters and estimation results are shown in the Fig. 4 and Table 2.

It can be seen from the results in Table 2 that the waveform proposed in this paper can accurately estimate the target parameters, which verifies the effectiveness of the waveform.

Table 1. Typical parameter examples of automotive radar system

Parameter	Value
f_0/GHz	77
band /MHz	150
Number of transmitter	3
Number of receiver	4
PRT/μs	50
Number of pulses	192
T_1/μs	60
T_2/μs	40

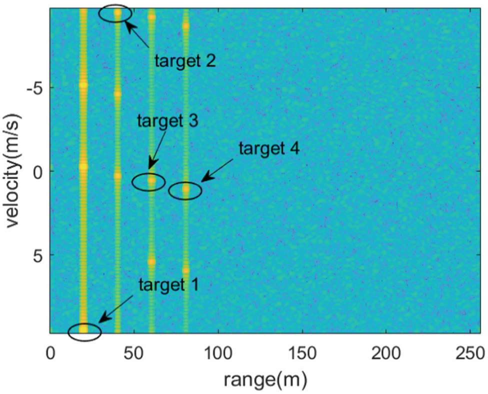

Fig. 4. Multi target spectrum results

Table 2. Simulation target parameter estimation results

	Target 1	Target 2	Target 3	Target 4
Target distance/m	20	40	60	80
Target velovity/(m/s)	−10	10	20	40
Target angle/(°)	10	20	30	40
Estimated distance/m	19.96	40.3	60.2	80.62
Estimated ambiguous velovity /(m/s)	9.47	−9.47	0.3	1.10
Estimated q	−1	1	1	2
Estimated velovity /(m/s)	−10.01	10.01	20.01	40.06
Estimated angle/(°)	10.08°	20.02°	30.05°	20.02°

4 Conclusion

In order to solve the problems of low utilization of time and space and Doppler ambiguity of high-velocity targets, a new waveform of time jitter Doppler frequency division multiplexing is proposed in this paper. The waveform performs sequence diversity in the time domain, velocity ambiguity resolution by using the phase difference caused by pulse repetition interval jitter, and Doppler frequency division multiplexing by inter pulse phase modulation of multiple transmit antennas in the frequency domain. The multi-target simulation test results show that the waveform has excellent non ambiguous velocity measurement and multi-channel angle measurement capabilities while taking into account the transmission efficiency. It has strong application value for the engineering practice of automotive radar.

References

1. Stockle, C., Herrmann, S., Dirndorfer, T., Utschick, W.: Automated vehicular safety systems: robust function and sensor design. IEEE Signal Process. Mag. **37**(4), 24–33 (2020)
2. Sun, S., Zhang, Y.D.: 4D automotive radar sensing for autonomous vehicles: a sparsity-oriented approach. IEEE J. Select. Top. Sign. Process. **15**(4), 879–891 (2021)
3. Sun, S., Petropulu, A.P., Poor, H.V.: MIMO radar for advanced driver-assistance systems and autonomous driving: advantages and challenges. IEEE Sign. Process. Mag. **37**(4), 98–117 (2020)
4. Bilik, I., Longman, O., Villeval, S., Tabrikian, J.: The rise of radar for autonomous vehicles: signal processing solutions and future research directions. IEEE Signal Process. Mag. **36**(5), 20–31 (2019)
5. Sun, S., Zhang, Y.D.: Four-dimensional high-resolution automotive radar imaging exploiting joint sparse-frequency and sparse-array design. In: ICASSP 2021 - 2021 IEEE International Conference on Acoustics, Speech and Signal Processing (ICASSP), pp. 8413–8417 (2021)
6. Metz, C., et al.: Fully integrated automotive radar sensor with versatile resolution. IEEE Trans. Microw. Theory Tech. **49**(12), 2560–2566 (2001)
7. Steinhauer, M., Ruoss, H.-O., Irion, H., Menzel, W.: Millimeter-wave-radar sensor based on a transceiver array for automotive applications. IEEE Trans. Microw. Theory Tech. **56**(2), 261–269 (2008)
8. Lin, Y.-C., Lee, T.-S., Pan, Y.-H., Lin, K.-H.: Low-Complexity high-resolution parameter estimation for automotive MIMO radars. IEEE Access **8**, 16127–16138 (2020)
9. Wollitzer, M., et al.: Multifunctional radar sensor for automotive application. IEEE Trans. Microw. Theory Tech. **46**(5), 701–708 (1998)
10. Uysal, F.: Phase-coded FMCW automotive radar: system design and interference mitigation. IEEE Trans. Veh. Technol. **69**(1), 270–281 (2020)
11. Ding, X., et al.: Theory and practice: a two-channel automotive radar for three-dimensional object detection. Eur. Radar Conf. **2015**, 265–268 (2015)
12. Xu, Z., et al.: Simultaneous monitoring of multiple people's vital sign leveraging a single phased-MIMO radar. IEEE J. Electromagn. RF Microw. Med. Biol. **6**(3), 311–320 (2022)
13. Wang, Y.K.: Research on signal processing method for chirp squeeze automotive radar. In: Nanjing University of Science & Technology, p. 149 (2018)