Integrated Radar and Communication System Based on Stepped Frequency Continuous Waveform

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***Abstract*—In this paper, a new system of integrated radar and communication which bases on stepped frequency continuous waveform is put forward. Specifically, firstly, the binary communication data are modulated into stepped frequency continuous waveform through BPSK modulation, which can make the communication data hide in the radar waveform. Secondly, we provide a signal separate method which can divide the radar signal and communication signal in the baseband mixed signal. So this integrated system can transmit binary data precisely with little influence on the radar sensing performance. Finally, we evaluate the radar sensing performance and wireless communication performance via simulation results. The results show that the proposed integrated system has a lower SER meanwhile guaranteeing the radar sensing performance.**

精确地，严谨的

BER: Bit Error Ratio 误比特率

SER: Symbol Error Ratio 误符号率

I. Introduction

Radar sensing system and wireless communication system are two important systems which are equipped on one electronic platform [1]. During the past few years, a great effort has been made in the field of fusion system of wireless communication and radar sensing. In order to maximize the integration of radar system and communication system, an integrated waveform is designed to fulfill the radar function and communication function [2], [3]. Compared with the previous separated radar and communication system [4], this integrated system has a larger advantage. It can reduce the volume of the platform and the interference between each other by sharing the transmitter part, the receiver part and the signal processing part.

The integrated radar and communication system based on direct-sequence spread spectrum (DSSS) technology was studied in [5], [6], which allows for secure communication and high-resolution ranging at the expense of utilizing excessive spectrum resources. However, the peak-to-sidelobe ratio is limited by the imperfect auto-correlation characteristics of the pseudo-random codes. In addition, the spread spectrum technique requires a huge amount of computations for Doppler processing.

The integrated radar and communication system based on Chirp signal was studied in [7], [8] at the same time. They used a series of Chirp signals that have different center frequency but the same frequency modulated rate as the communication signal. One chirp signal represents one communication data. Thus the rate for communication is very low.

调频斜率

Recently, the integrated radar and communication system based on the orthogonal frequency-division multiplexing (OFDM) technology was discussed in [9], [10]. However, the high implementation cost of the OFDM system impedes its wide applications due to the complex signal processing and high peak-to-average power ratio of the OFDM signals.

The stepped frequency continuous waveform [11] usually has a high frequency and easy to implement. By transmitting a series of single frequency continuous signal step by step, it can compound a stepped frequency continuous signal with ultra-wide bandwidth. This paper mainly discusses an integrated system based on the stepped frequency continuous waveform. The focus is on how to generate and demodulate the integrated signal in the integrated radar and communication system. Because of the low frequency of the selected communication signal, this system can complete the transmission of binary data with little negative influence on the radar sensing performance. Meanwhile, this design of the joint integrated waveform can hide the communication data in the radar waveform and improve the utilization of the equipment greatly.

The rest of this paper is organized as follows. Firstly, we will bring a brief introduction to the method of integrated radar and communication system. Secondly, the model of the integrated radar and communication system which bases on stepped frequency continuous waveform will be constructed and the method of signal processing technique will be discussed. Finally, by analyzing the simulation results, the performance of the integrated radar and communication system will be verified. The conclusion shows the validity of the proposed method.

II. Integrated Radar and Communication System

A. Design of the joint waveform

The traditional stepped frequency continuous waveform $s(t)$ can be expressed as

步频持续波束

$$
\begin{aligned}
s(t) &= \sum_{k=0}^{K} real\big(exp(j2\pi f(t)t)\big), \\
f(t) &= f_L + k\Delta f \times rect\Big(\frac{t - kT_0 - \frac{T_0}{2}}{T_0}\Big)
\end{aligned}
\tag{1}
$$

f(t) 表示频率.

若为LFM信号, 则 $f(t) = f_0 + \frac{\mu}{2} t$

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where f_L represents the starting frequency of the stepped frequency continuous waveform, Δf and T_0 are the frequency interval and time duration of every frequency point respectively, K is the total number of the frequency point.

In the near-field situation, as the starting frequency of the stepped frequency continuous waveform reaches over 1GHz, thus we can choose a phase-modulated signal that is out of the bandwidth of the stepped frequency signal as the communication carrier signal. Binary communication data is modulated into stepped frequency continuous waveform through BPSK modulation. This mixing method is easy to implement because the communication data is usually very short, and it has little influence on the radar sensing performance.

In order to obtain a stable beat signal when mixing the received response signal with the referenced stepped frequency signal, a simple-frequency signal without BPSK modulation should be used to modulate the beginning and the end of every frequency point of the stepped frequency continuous waveform. This can be achieved by enlarging the binary communication data. The way to generate the transmitting joint signal will be discussed in the following parts.

Assuming that the binary communication data is $A(t)$, enlarge the binary communication data as follows:

$$B(t) = \begin{cases} A(t) & \frac{T_0}{4} + kT_0 < t < \frac{3T_0}{4} + kT_0 \\ 1 & others \end{cases} \tag{2}$$

Modulate the enlarged communication data $B(t)$ through BPSK modulation. This has the same effect as using a BPSK signal with "1" to modulate the beginning and the end of every frequency point. After modulation, the communication signal $s_c(t)$ can be expressed as

$$s_c(t) = real\big(B(t)exp(j(2\pi f_0 t + \varphi_0))\big) \tag{3}$$

where f_0 is the carrier frequency, φ_0 is the carrier phase. It is a low frequency signal compared with the stepped frequency signal.

Then mix the communication signal $s_c(t)$ with the stepped frequency signal $s(t)$ by multiplying. The integrated signal produced can be expressed as

$$\begin{aligned} s_t(t) &= s(t)s_c(t) \\ &= real\big(B(t)exp(j(2\pi f_0 t + \varphi_0))\big)\sum_{k=0}^{K} exp(j2\pi f(t)t)\big) \end{aligned} \tag{4}$$

仅调制信号包络

In the mixed integrated signal, the stepped frequency signal is the carrier signal. As the communication signal has low frequency and only modulates the signal envelope, so it will has little impact on the stepped frequency radar signal.

B. System Design

UWB 超宽带

The integrated radar and communication system mainly bases on the high frequency and ultra-wide bandwidth of the stepped frequency continuous waveform. The system chart is as shown in Fig. 1. The data processing steps are as follows:

The mixed integrated signal is as shown in (4). It will be emitted after amplification. Assume that the radar has one transmitting antenna and one receiving antenna, then the received response signal can be expressed as:

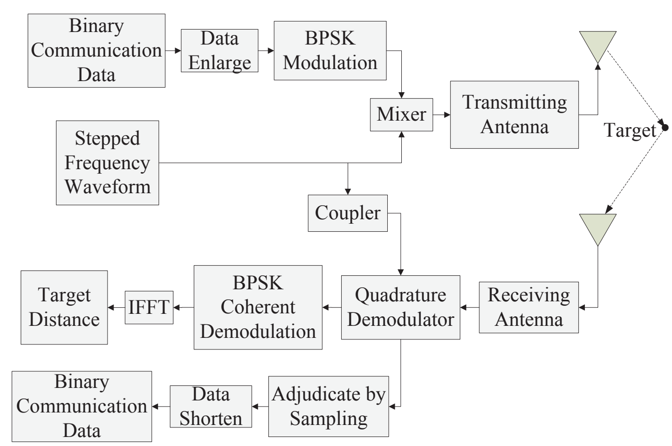

Fig. 1. Integrated radar and communication system chart

回波：

$$\begin{aligned} s_r(t) &= s_t(t-\tau) \\ &= s(t-\tau)s_c(t-\tau) \\ &= real\big(B(t-\tau)exp(j(2\pi f_0(t-\tau) + \varphi_0))\big) \\ &\quad \sum_{k=0}^{K} exp(j2\pi f(t-\tau)(t-\tau))\big) \end{aligned} \tag{5}$$

where τ is the two way round-trip time delay of the target. In the near-field situation, the time delay usually satisfies $\tau << T_0$.

近距离

求积分

The received response signal and the referenced stepped frequency signal $s(t)$ are mixed through quadrature demodulation. Then make the signal pass through a low-pass filter to remove the high frequency component. After processing, the mixed signal can be expressed as

低通滤波

$$\begin{aligned} mix(t) = real\big(B(t-\tau)exp(j(2\pi f_0(t-\tau) + \varphi_0)\big) \\ \sum_{k=0}^{K} exp(-j2\pi f(t-\tau)\tau)\big) \end{aligned} \tag{6}$$

It can be concluded from the formula(6)that the $mix(t)$ is the mixed signal of the communication signal $s_c(t-\tau)$ and the traditional stepped frequency beat signal $u(t)$. The maximum frequency of the mixed signal is $f_0 + max\{f_b, f_d\}$. f_b is the maximum frequency of the communication baseband signal. And f_d is the maximum frequency of the beat signal. Since the beat signal usually has a low frequency, normally $f_d << f_b$, it only displays in the signal envelope obtained after demodulation. In the communication terminal, the communication baseband signal is obtained through BPSK coherent demodulation. Then judge the baseband signal by sampling, the binary communication data will be obtained. In the radar terminal, mix the mixed signal by using a BPSK signal with the carrier frequency f_0. Then by making the signal pass through a low-pass filter with a cut-off frequency of $f_c = \frac{1}{2T_0}$, the receiving radar baseband signal can be reconstructed. The range of the target is estimated by applying the Inverse Fast Fourier Transform (IFFT) to the reconstructed radar baseband signal.

UWB：带宽几个G，无需载波

C. System Performance Analysis

From the above system chart and processing steps, it can be seen that the influence on the detection performance of radar mainly focuses on the other received signal. To get rid of the unwanted integrated signal, an unique identification number should be added to each radar. As the identification number is encoded in the communication signal, thus whether or not to keep this time delay information can be judged while demodulating the communication signal. When it can be confirmed that the received response signal is the wanted signal, then reconstruct the radar baseband signal and fulfill the target ranging through IFFT.

求积分解调

In the mixed signal obtained after quadrature demodulation, only a little part of energy is used to reflect the characteristics of the beat signal. This will 不可避免地 inevitably affect the radar signal to noise ratio (SNR). The SNR can be improved through reducing the width of BPSK modulation signal at each frequency point.Thus to improve the radar detection performance, the communication signal should be as short as possible.

通信信号越短，则每bit时宽越大，每bit的能量就越大，则SNR越大

III. System Simulation Results

In this system, the starting frequency of the stepped frequency waveform is $f_L = 1.6GHz$, the frequency interval of each frequency point is $\Delta f = 2MHz$, the time duration of every frequency point is $T_0 = 100\mu s$,and the total number of the frequency point is $K = 300$. The BPSK signal has a carrier frequency of $f_0 = 1MHz$ and a symbol rate of $500kbps$. There is one target with the range of 6 meters. The simulation channel is an additive white gaussian noise channel (AWGN) and the simulation time is a stepped frequency signal cycle.

Since the mixing method of communication signal and stepped frequency continuous waveform is easy to implement, we only discuss the mixed signal obtained after quadrature demodulation. As the transmission data and processing method of the 300 frequency points are the same, we use one frequency point to view the whole signal form after processing.Fig. 2 shows one frequency point time domain waveform of the mixed signal obtained after quadrature demodulation. We can see that the beat signal only displays in the mixed signal envelope.

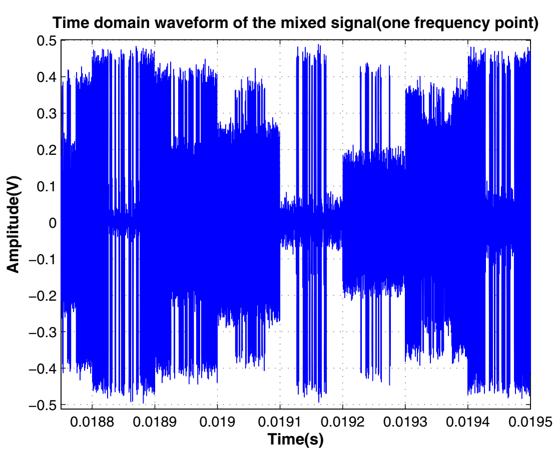

Fig. 2. Time domain waveform of the mixed signal(one frequency point)

差拍信号

Fig. 3 shows the spectrum of the mixed signal. From the figure we can see that the stepped frequency beat signal is located at 1MHz of the spectrum, the communication signal that is modulated by the beat signal is located at -1MHz of the spectrum. We can separate the communication signal and radar signal through different filters.

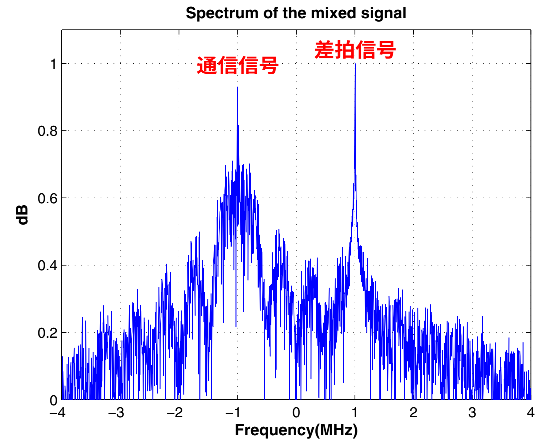

Fig. 3. Spectrum of the mixed signal

In the communication terminal, Fig. 4 shows one frequency point time domain waveform of the communication signal, which is obtained after BPSK demodulation. We can see that the binary communication data only modulate the beginning and the end of every step of the communication signal.

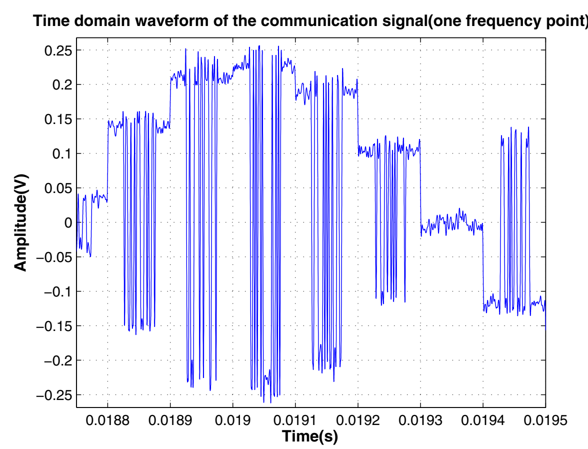

Fig. 4. Time domain waveform of the communication baseband signal(one frequency point)

Fig. 5 shows the spectrum of the communication signal.

Fig. 6 shows the bit error rate of binary communication data in this system. Compared with the single BPSK communication signal, they nearly has the same bit error rate under the condition of $SNR \geq 8$. So the method in this system has good communication performance.

汉明窗

In the radar terminal, we add an hamming window to the baseband signal to restrain the side-lobe. Fig. 7 shows the spectrum of the reconstructed radar baseband signal.

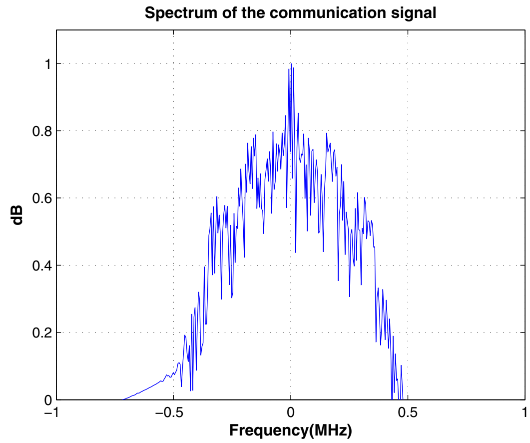

Fig. 5. The spectrum of the communication baseband signal

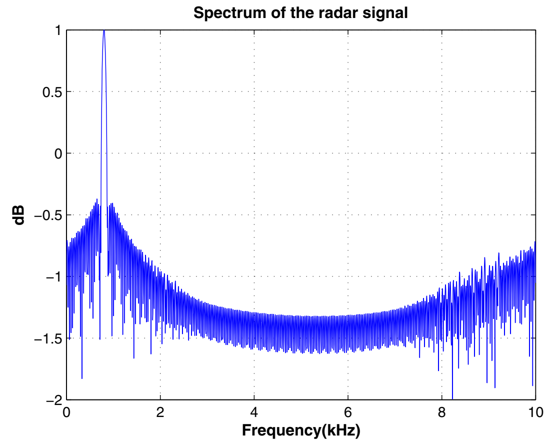

Fig. 7. The spectrum of the radar baseband signal

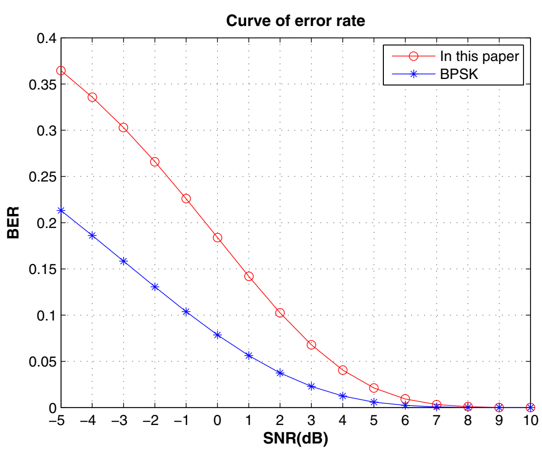

Fig. 6. The BER of binary communication data

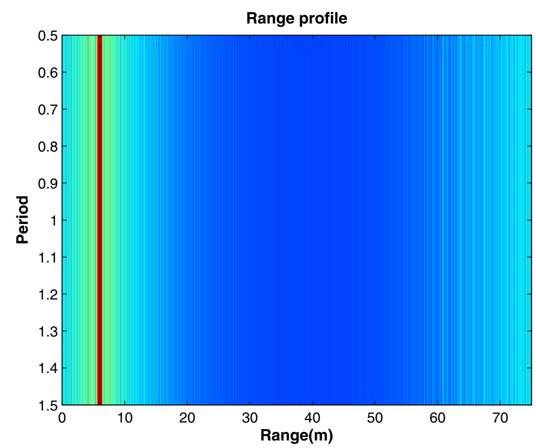

Fig. 8. Range profile(one target)

误比特率

Fig. 8 shows the target location by making an IFFT to the reconstructed radar baseband signal. From the range profile, the target can be seen clearly.

分析了、…

IV. Conclusions

三句话: ① In this paper, the integrated radar and communication system based on stepped frequency continuous waveform have been deeply analyzed. 仿真结果表明 ② Simulation results indicate that this system can fulfill binary communication data transmission precisely while making little interference to the radar sensing performance. ③ It is an important trend of the development of the electronic integrated systems in the future. 发展趋势

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