Waveform Design for High Speed Radar-Communication Integration

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Abstract: The integration of radar and communication is a good way to achieving 微型化 miniaturization of the equipment, easing the tension of spectrum resource and reducing the interference between the radar and communication equipment. Recent research mainly concentrates on realizing the function of transmission and detection in one integrated equipment and improving the performance of radar with the random communication symbols, while improving the spectrum efficiency in communication is lack of study, which is also very important with the rapid growth of the need for multimedia transmission in either vehicular networking or battlefield. In this paper, based on multicarrier chirp signal (OFD-LFM), a spectrum effective integrated waveform with multiple symbols on each pulse is proposed and demodulation algorithm is work out. Simulation results show that optimal demodulation can be achieved simply by addition, subtraction and matching filtering, and the ambiguity function won't be influenced by the random communication symbols.

Keywords: radar-communication integration; waveform design; spectrum efficiency

I. INTRODUCTION

Radar and communication has been developed independently for several decades, and has their own routine of waveform design, signal processing, and so on. But in fact, their devices have many similarities, such as antenna, amplifier, A/D and D/A converter, baseband digital signal processing chip. So there is solid foundation of integration in case of the equipment. The contradiction between the spectrum shortage and the growing need for multimedia transmission is getting more and more serious. These problem can be eased by integrating the radar and communication equipment, so the study of integration of radar and communication with high spectrum efficiency is meaningful and urgent.

In the year of 1996, the Office of Naval Research first proposed the concept of radar-communication integration, which is the AMRFC program [1]. Wu [2] proposed a time division integration scheme, in which one radar pulse is followed by one communication signal pulse. The scheme in fact is that communication are realized using radar's equipment. However, the scheme results in the growth of the pulse width, which as a result reduces the range resolution of the radar.

This paper concentrates on integrated waveform design, which means one single waveform can achieve transmission and detection at the same time.

Sturm [3] and Garmatyuk [4] applies the OFDM signal in communication directly to detection and tracking in radar. However, the OFDM signal carried communication symbols has a high peak-to-average ratio, which can be easily affected by the nonlinear effect of the amplifier on radar. In addition, the correlation of the OFDM signal is also worse than that of the classic radar waveforms.

Chirp signal is widely used in radar [5], and there are a number of studies of integration waveform design based on chirp. Roberton [6] proposed that an integrated waveform can be composed by the addition of up-chirp and down chirp, and one communication symbol can be multiplied to one of the chirp signal on each pulse. Liu [7] proposed that there can be more than one communication symbols on each pulse.

MIMO radar has been rapidly developed in recent years [8]. Each sub-array sends orthogonal pulses, which can be used as spread spectrum sequence of communication, precisely. For example, Deng [9] uses the phase-coded sequence, Gaspare [10] imported multi-carrier orthogonal frequency division of chirp signal (OFD-LFM), Li [11] uses multi-carrier chirp signals with alternating positive and negative FM rate as communication and radar, separately. However, based on the above schemes, each sub-array can only transmit one communication symbol in one pulse, resulting in low spectrum efficiency in communication.

一篇论文要有自己的关注点

This paper concentrate on promoting spectrum efficiency and simplifying demodulation algorithm. Based on the OFD-LFM scheme in [11], multiple symbols are carried on each communication subcarrier like [7], and the maximum number of communication symbols carried by each subcarrier without interference is studied. A simple algorithm composed of addition, subtraction, and matching filtering is proposed and simulation result is given to illustrate that optimal demodulation is achieved. As for the radar subcarriers, the ambiguity function is compared with the single chirp signal, and the results show that the communication symbols make no influence on radar performance.

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II. System Model

A. Chirp signal

Chirp signal is widely used in radar. It has obvious advantages in terms of detection and tracking because of large bandwidth-delay product, insensitive to Doppler, and so on [5].

Chirp signal can be expressed as,

$$S_{LFM}(\mathrm{t}) = \mathrm{rect}\left(\frac{\mathrm{t}}{\tau}\right) e^{j2\pi\left(f_c+\frac{\mu}{2}t\right)t} \tag{1}$$

where τ is the pulse width, $\mathrm{rect}\left(\frac{t}{\tau}\right) = \begin{cases}1 & 0<t<\tau \\ 0 & else\end{cases}$, $\mu = \frac{B}{\tau}$, B is the bandwidth of the chirp signal. If $\mu > 0$, the signal is an 'up-chirp', whereas is a 'down-chirp'. Integration waveform based on single chirp can be, Let T_p represents pulse interval time (PIT), the integration waveform $S(t)$ with Q pulse in total is,

$$S(t) = \sum_{q=0}^{Q-1} \mathrm{rect}\left(\frac{t-qT_p}{\tau}\right) S_q^s(t) \tag{2}$$

where $\mathrm{rect}(x) = \begin{cases}1 & 0<x<1 \\ 0 & else\end{cases}$. $S_q^s(t)$ is the integration signal on the q-th pulse,

$$S_q^s(t) = \mathrm{rect}\left(\frac{t}{\tau}\right)\left(x_q(t)e^{j2\pi\left(f_c+\frac{\mu}{2}t\right)t} + e^{j2\pi\left(f_c-\frac{\mu}{2}t\right)t}\right) \tag{3}$$

where $x_q(t)$ is the communication signal transmitted on the q-th pulse.

B. OFD-LFM scheme

The integration waveform based on OFD-LFM in [11], like OFDM, uses chirp pulses as subcarriers. They have same bandwidth, pulse width, and the spacing of the adjacent subcarrier. As long as there is appropriate spacing, chirp subcarriers can also be quasi-orthogonal. The even and odd subcarrier with positive and negative FM rate are used for communication and radar, respectively. As a result, the random communication symbols will have little influence on the detection and tracking performance of radar.

The integration signal on the q-th pulse will be,

$$S_q(t) = \sum_{n=0}^{\frac{N_f}{2}-1}\left[x_{n,q}S_{LFM,2n}(t-qT_p) + S_{LFM,2n+1}(t-qT_p)\right] \tag{4}$$

where $S_{LFM,n}$ is a chirp signal with bandwidth B_0, pulse width τ, and FM rate μ.

$$S_{LFM,n}(t) = e^{j2\pi\left(f_0+n\cdot\Delta f+(-1)^n\frac{\mu}{2}t\right)t} \tag{5}$$

To keep quasi-orthogonality between the subcarriers,

$$\Delta f = \frac{D}{\tau}, D \in N^* \tag{6}$$

Fig.1 gives a sign of how the spectrum occupied by each subcarrier. The left and right diagonals represents even and odd carriers (the serial number of the carriers starts from 0), respectively. The graph takes $N_f = 4$ for example. So the total bandwidth B and the spacing between the adjacent subcarriers Δf will be,

$$B = B_0 N_f \tag{7}$$

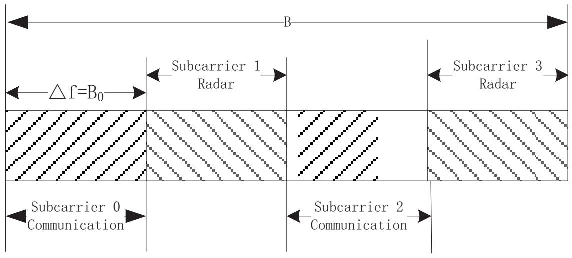

Figure 1. A sign of subcarrier occupation in frequency domain.

$$\Delta f = B_0 \tag{8}$$

Combine (6) and (8), bandwidth delay product(BDP) of each subcarrier is,

$$B_0\tau = D \tag{9}$$

C. The proposed M-symbol integration waveform

For the integration waveform described above, one communication subcarrier can only transmit one communication symbol in one pulse. However, the bandwidth-delay produce D in radar usually can be several tens to thousands, which results in low spectral efficiency. Based on this structure, M-symbol integration waveform is proposed.

For each communication subcarrier on each pulse, the number of communication symbols is M, and each symbol last for $\frac{\tau}{M}$. So the communication signal carried by subcarrier k on the q-th pulse is,

$$x_{n,q}^M(t) = \sum_{m=0}^{M-1} x_{n,q}^M[m]\,rect\left(\frac{t-qT_p-\frac{m}{M}\tau}{\frac{\tau}{M}}\right) \tag{10}$$

So the integration signal on the q-th pulse is,

$$S_q^M(t) = \sum_{n=0}^{\frac{N_f}{2}-1}\left[x_{n,q}^M(t)S_{LFM,2n}(t-qT_p) + S_{LFM,2n+1}(t-qT_p)\right] \tag{11}$$

The other parameters are the same with that in Ⅱ-B.

III. Demodulation Algorithm For Integration Waveform

解调算法

Suppose the signal go through the AWGN channel and arrived at the receiver. As we know, if it is a fading channel in fact, equalization can equal the received signal to that of a signal through AWGN channel. So the follow analysis is based on AWGN channel.

For the OFD-LFM integration waveform in 2.2, the receiver receives a pulse and then uses the matching filter to estimate $x_{k,q}$,

$$\hat{x}_{k,q} = \frac{1}{\tau}\int_{qT_p}^{qT_p+\tau}\left(S_q(t)+n(t)\right)S_{LFM,k}^*(t-qT_p)dt \tag{12}$$

where $n(t)$ is the white Gaussian noise. Solve (12),

$$\hat{x}_{k,q} = x_{k,q} + \sum_{n=0}^{\frac{N_f}{2}-1} P_{2n+1} + n' \tag{13}$$

$$P_{2n+1} = \frac{1}{\tau}\int_0^{\tau} S_{LFM,2n+1}(t)S_{LFM,k}^*(t)dt$$

$$= \int_0^1 e^{j2\pi D(2n+1-k-t)t} dt \quad (14)$$

Numerical calculation shows that $N_f * |P_{2n+1}| \ll 1$, so it can be ignored when estimating $x_k(q)$. As a result, $\hat{x}_{k,q}$ in (12) is an optimal estimation of $x_k(q)$.

For the integration waveform proposed, because the number of communication symbol is extended to M, the length of the matching filter will be reduced to $\frac{\tau}{M}$. If matching filtering is applied to the received signal directly,

$$\hat{x}_{k,q}^M[m] = \frac{M}{\tau}\int_{qT_p+\frac{m}{M}\tau}^{qT_p+\frac{(m+1)}{M}\tau} \left(S_q^M(t)+n(t)\right)S_{LFM,k}^*(t-qT_p)dt \quad (15)$$

where $n(t)$ is the white Gaussian noise. Solve (15),

$$\hat{x}_{k,q}^M[m] = x_{k,q}^M[m] + \sum_{\substack{n=0\\ n\neq k/2}}^{\frac{N_f}{2}-1} P_{2n}^M[m] + \sum_{n=0}^{\frac{N_f}{2}-1} P_{2n+1}^M[m] + n' \quad (16)$$

$P_{2n}^M[m]$ represents the interference brought by the even subcarrier (also the communication subcarrier),

$$P_{2n}^M[m] = \frac{M}{j2\pi D}\left[\frac{x_{n,q}^M[m]}{2n-k} e^{j2\pi(2n-k)m\frac{D}{M}}\left(e^{j2\pi(2n-k)\frac{D}{M}}-1\right)\right] \quad (17)$$

For $P_{2n}^M[m]$, when $M=\frac{D}{z}\ (z\in N^+)$, $P_{2n}=0$ will always hold, which means the interference brought by the even subcarrier will be fully eliminated.

While $P_{2n+1}^M[m]$ represents the interference brought by the odd subcarrier (also the radar subcarrier),

$$P_{2n+1}^M[m] = \frac{M}{\tau}\int_{\frac{m}{M}\tau}^{\frac{m+1}{M}\tau} S_{LFM,2n+1}(t)S_{LFM,k}^*(t)dt$$
$$= Me^{\frac{j\pi D(2n+1-k)}{2}}\int_{\frac{m}{M}}^{\frac{m+1}{M}} e^{-j2\pi D\left(t-\frac{2n+1-k}{2}\right)^2} dt \quad (18)$$

When M is very large, $P_{2n+1}^M[m]$ can be approximated to,

$$\tilde{P}_{2n+1}^M[m] = e^{\frac{j\pi D(2n+1-k)}{2} - j2\pi D\left(\frac{m}{M}-\frac{2n+1-k}{2}\right)^2} \quad (19)$$

It can be found that $\left|\tilde{P}_{2n+1}^M[m]\right| = 1$, which is comparable with $\left|x_{k,q}^M[m]\right|$, so the interference brought by the radar subcarrier can't be ignored. To solve the problem, this paper proposed that after receiving the integration signal, firstly, the radar subcarrier should be diminished in time domain,

$$y(t) = S_q^M(t) + n(t) - \sum_{n=0}^{\frac{N_f}{2}-1}\left[S_{LFM,2n+1}\left(t-qT_p\right)\right] \quad (20)$$

Then matching filtering is applied to $y(t)$,

$$\hat{x}_{k,q}^M[m] = \frac{M}{\tau}\int_{qT_p+\frac{m}{M}\tau}^{qT_p+\frac{(m+1)}{M}\tau} y(t)S_{LFM,k}^*(t-qT_p)dt \quad (21)$$

Solve (21),

$$\hat{x}_{k,q}^M[m] = x_{k,q}^M[m] + P_{2n} + n' \quad (22)$$

As long as $M=\frac{D}{z}\ (z\in N^+)$, $P_{2n}=0$ will always hold, which means optimal demodulation is achieved.

IV. SIMULATION RESULTS

A. communication performance 通信性能

There is an almost M-times-promotion of spectral efficiency compared with the OFD-LFM signal with one communication symbol in one pulse at each subcarrier, and maximal M can be equal with D, the bandwidth delay product of each subcarrier. Compare the BER performance of the integration signal with a single chirp signal whose parameters are the same with one subcarrier in the integration waveform and is modulated the same communication symbols. Simulation results in AWGN channel and frequency-selective fading channel (also known as multipath channel) is showed in Fig.2. The parameters in simulation are listed in Table 1.

Both in AWGN channel and fading channel, the BER performance are almost the same between the integration signal and the single chirp signal, which means the proposed integration signal can be well used as communication waveform, and the demodulation algorithm can almost completely eliminate the interference brought by the adjacent channel and achieve the optimal decoding performance.

Compare BER performance in multipath channel with that in AWGN channel, there is a loss of 1.5~2dB, mainly because of the SNR loss in channel equalization.

B. Ambiguity performance

Ambiguity function (AF) obtained by the correlation between the sent and received signals is a good measure of the radar's detection and tracking ability. Usually, the AF with a sent signal $S(t)$ should be represent as,

$$A(t;F_D) = \left|\int_{-\infty}^{\infty} S(x)e^{j2\pi F_D x}S^*(x-t)dx\right| \quad (23)$$

The AF of the integration signal is calculated for each radar-subcarrier, 每个子载波

$$A_i(t;F_D) = \left|\int_{-\infty}^{\infty} S_q^M(x)e^{j2\pi F_D x}S_{LFM,2n}^*(x-t)dx\right| \quad (24)$$

By letting $F_D=0$ and $t=0$, the distance and velocity AF can be obtained respectively. Fig.3 and Fig.4 compares the distance and velocity AF between the integration signal and the single

TABLE I. SIMULATION PARAMETERS

Parameter	Value
Constellation map	QPSK(with Gray code)
Number of subcarrier	$N_f = 8$
Bandwidth of each subcarrier	$B_0 = 0.1MHz$
Bandwidth-delay product	D=256
Number of communication symbol of each subcarrier in one pulse	M=256
Overlap ratio between adjacent subcarriers	$\alpha = 0,0.3$
Strength of multipath	h0=[0,-8,-15]dB
Time delay of multipath	$T_d = [0,3,7] * \frac{\tau}{D}$
The energy per bit to noise power spectral density ratio	$\frac{E_b}{N_0} = [0:1:15]$

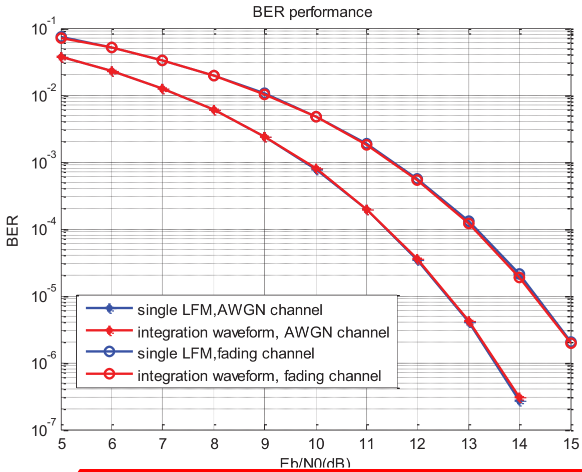

Figure 2. BER performance of the integration waveform and the single LFM signal in AWGN and multipath channel

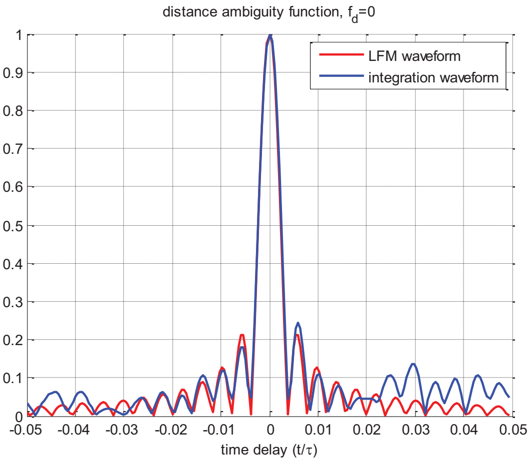

Figure 3. Distance AF of the integration signal and the single chirp signal.

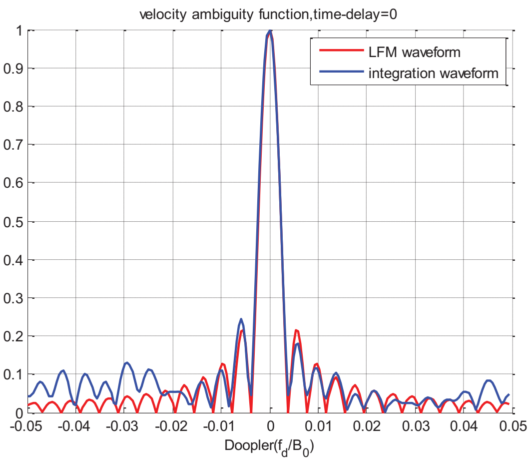

Figure 4. Velocity AF of the integration signal and the single chirp signal.

chirp signal, whose parameters are the same with that in IV-A. Fig.3 and Fig.4 show that the main lobes of the two are almost totally coincide, the first sidelobe of the integration AF fluctuates slightly, and the other clutters elevated slightly. In a word, the integration signal with communication symbols does not diminish the AF performance for each radar-subcarrier. Furthermore, multiple radar-subcarriers can be combined to improve radar performance.

V. Conclusion

This paper proposed a high speed radar-communication integration waveform. The waveform is based on OFD-LFM, and the chirp subcarriers with alternating positive and negative μ are used as communication and radar, respectively. The number of communication symbols carried by each communication subcarrier is extended to M, thus the spectrum efficiency is almost M-fold higher than the one symbol OFD-LFM integration waveform, as long as M is divided by the bandwidth-delay product D. A simple demodulation algorithm composed of addition, subtraction and matching filtering is suggested. The ambiguity function of the integration waveform is studied, demonstrating that the random communication symbols carried by the communication-subcarrier has little influence on the AF of the radar-subcarrier.

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