A Power-Efficient Radar Waveform Compatible with Communication

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本文主要是讲述一种新的调制方案。

***Abstract*—Multifunctional radar is a trend in the future. Employing radar system for high data rate, long range, anti-intercepted communication by using its wide bandwidth, high power and directing property has been a research hotspot nowadays. Thus radar-communication compatible waveform design is a key technique. In this paper, a constant envelope minimum-shift keying orthogonal frequency division multiplexing (CE-MSK-OFDM) modulation scheme is proposed. The modulation scheme can simultaneously mitigate the inherent drawbacks of MSK-OFDM and constant envelope OFDM (CE-OFDM). To make the CE-MSK-OFDM signal have the compatible characters, a suitable system parameterization for operation at 10GHz that fulfills the requirements for both radar and data communications is derived. Then the feasibility of the system parameters and the performance of radar and communications are verified with Matlab simulations. The simulation results reveal that the CE-MSK-OFDM signal can implement the integration of the radar and communications well.**

I. Introduction

THE idea of combining radar and data communications on a common platform has been proposed for a long time [1]. Based on the advantages of high spectral efficiency and strong resistance to muti-path selective fading, orthogonal frequency division multiplexing (OFDM) has been introduced to implement the integration of radar and data communications [2]–[3].

However, high peak-to-average power ratio (PAPR) seriously restricts the practical application of OFDM. Many techniques have been proposed to mitigate the PAPR in OFDM system [4]–[5]. 减轻，缓和 But all of these methods are applied to address PAPR problem at the cost of reducing spectral efficiency, increasing complexity, or degrading the performance of OFDM system.

To further address the PAPR problem, constant envelope OFDM (CE-OFDM) is proposed recently based on phase modulation or frequency modulation technique [6]–[7]. Simultaneously, in order to achieve the integration of radar and communications, some scholars begin to study the CE-OFDM radar by analyzing the feasibility and performance of the CE-OFDM radar signal [8]–[9].

Though CE-OFDM can mitigate PAPR in theory, the higher-order terms of phase modulated signal are inevitable and each data is spread over multiple subcarriers in CE-OFDM system [10], which will induce a large intercarrier interference (ICI). To decrease ICI, minimum-shift keying (MSK) is applied in OFDM system for its fast roll-off side-lobe spectrum [11]–[12]. Unfortunately, MSK-OFDM has an inherent shortage that its PAPR is still very large. Thus, in this paper the CE-MSK-OFDM modulation scheme is proposed to mitigate the inherent shortages of MSK-OFDM and CE-OFDM. 内在的，固有的

The rest of this paper is organized as follows. Section II describes the principle of CE-OFDM and CE-MSK-OFDM. 原理 In Section III, system parameterization of the CE-MSK-OFDM signal that fulfills the requirements for both radar and data communications are designed and a group of system parameters are presented. In Section IV, the feasibility of the system parameters and the performance of radar and communications are verified with Matlab simulations.

理论分析

II. Theoretical Analysis of CE-MSK-OFDM

A. Principle of CE-OFDM

The complex envelope of the OFDM baseband signal can be expressed as

$$m(t)=\sum_{m=0}^{M-1}\sum_{n=0}^{N_s-1} I_{n,m}\psi_n(t-mT) \tag{1}$$

T: symbol period

with N_s being the number of subcarriers, M being the number of symbols modulated on each subcarrier, $I_{n,m}$ representing the m-th symbol modulated on the n-th subcarrier, T being the OFDM symbol period, and $\psi_n(t)$ denoting the n-th orthogonal subcarrier

$$\psi_n(t)=\exp(j2\pi f_n t)rect(t/T),\ n=0,1,\cdots,N_s-1. \tag{2}$$

These subcarriers are orthogonal when

$$\text{正交条件}\ \Delta f=1/T \tag{3}$$

where Δf represents the subcarrier spacing. With this choice we obtain the individual subcarrier frequency

$$f_n=f_0+n\Delta f,\ n=0,1,\cdots,N_s-1 \tag{4}$$

with f_0 being an arbitrary frequency.

Then transform this baseband signal through a phase modulator

$$s(t)=A\exp[j\mu\cdot m(t)] \tag{5}$$

where $\mu=2\pi h$ represents the modulation index and A is the amplitude of this phase modulated signal.

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To obtain a constant envelope signal as defined in (5), the input of the phase modulator should be a real signal. In [13], a method by reconstructing the OFDM input data symbols is introduced. According to this method, the reconstructed data symbols vector is

$$I_m=\left\{0,I_{0,m},\cdots,I_{n,m},\cdots,I_{N_0-1,m},0,I^*_{N_0-1,m},\cdots,I^*_{n,m},\cdots,I^*_{0,m}\right\} \quad (6)$$

where N_0 is the number of effective data symbols contained in one OFDM symbol. Then the number of subcarriers is $N_s=2N_0+2$. The zeros added to the data symbols vector are to maintain the conjugate symmetry. 共轭对称性

Though CE-OFDM scheme can decrease PAPR effectively, it bears a larger ICI compared with conventional OFDM modulation scheme as its data symbol energy is spread in frequency domain, which can be explained by the Taylor series expansion of $s(t)$ in terms of $m(t)$

$$\begin{aligned} s(t)&=A\exp\left[j\mu\cdot m(t)\right]\\ &=A\left\{1+j\mu\cdot m(t)-\frac{\mu^2\cdot m(t)^2}{2!}+\cdots+\frac{\left[j\mu\cdot m(t)\right]^n}{n!}+\cdots\right\}. \end{aligned} \quad (7)$$

It can be seen from (7) that when the modulation index μ is big enough, the symbol modulated on a subcarrier will induce many high frequencies laying on other subcarriers, which will lead to a large ICI and reduce the performance of communications system. If we make the modulation index to be a smaller value, the higher-order terms are negligible and only the first two terms contribute:

$$s(t)=A\exp\left[j\mu\cdot m(t)\right]\approx A\left[1+j\mu\cdot m(t)\right]. \quad (8)$$

Under this condition, the CE-OFDM signal is equivalent to the conventional OFDM signal though a relatively large DC term is added. However, we can hardly detect the quadrature component of the CE-OFDM signal with large noise or interference because it is approaching to 0. Thus, the intercarrier interference of the CE-OFDM signal becomes a new problem to be solved. In the following, we will introduce the MSK technology to solve this problem for its fast roll-off side-lobe power spectrum.

B. *Principle of CE-MSK-OFDM*

MSK is a continuous phase frequency modulation scheme which can engender a constant envelope. The baseband MSK signal can be expressed as

$$s_{MSK}(t)=\exp\left[j\left(\theta_k+a_k\cdot\frac{\pi t}{2T}\right)\right],\ kT\le t\le(k+1)T \quad (9)$$

where a_k is the k-th data symbol ($a_k=\pm1$), T is the MSK symbol period, and θ_k represents the phase of the k-th symbol. To ensure that the phase is consecutive at the time of symbol change, θ_k should be
连续的

$$\begin{aligned}\theta_n&=\theta_{n-1}+\left(a_{n-1}-a_n\right)\cdot\frac{n\pi}{2}\\ &=\begin{cases}\theta_{n-1}, & a_n=a_{n-1}\\ \theta_{n-1}\pm n\pi, & a_n\ne a_{n-1}\end{cases}.\end{aligned} \quad (10)$$

Assuming that the MSK symbol period is as same as QPSK, their normalized power spectrums are shown in Fig. 1. Compared with QPSK, the power spectrum of the MSK signal is more compact and decays much faster, the main-lobe width is relatively more narrow which will make the adjacent channel interference smaller. Thus, the MSK-OFDM modulation scheme will exploit a better performance in decreasing ICI.

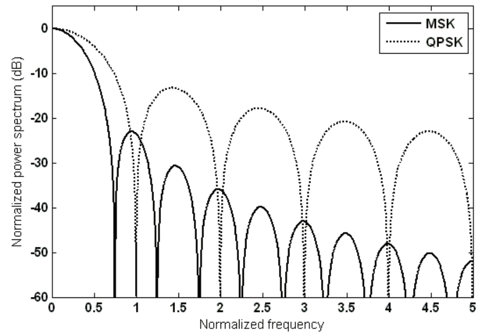

Fig. 1. Normalized power spectrum of MSK and QPSK

Based on (1) and (9), the MSK-OFDM baseband signal can be expressed as

$$s_{MSK\_OFDM}(t)=\sum_{n=0}^{N_s-1}\exp\left[j\left(\theta_{n,k}+a_{n,k}\cdot\frac{\pi t}{2T}\right)\right]\cdot\exp\left(j2\pi f_n t\right) \quad (11)$$

where T represents the MSK-OFDM symbol period, $0\le t\le T$.

Then transfer the baseband MSK-OFDM signal through a phase modulator, we will get the CE-MSK-OFDM baseband signal

$$s_{CE\_MSK\_OFDM}(t)=A\exp\left[j\mu\cdot s_{MSK\_OFDM}(t)\right]. \quad (12)$$

We can see that the envelope of the CE-MSK-OFDM signal is a constant A, which contributes to 0 dB PAPR and makes it to be more power-efficient than MSK-OFDM signal.

III. System Parameterization

System parameterization is crucial in the design of integrated radar and communications signal, which must fit the requirements from both radar and communications perspective. Nowadays, the frequency bands of radar and communications have been greatly coincident. A suitable frequency band for both radar and communications is 10GHz. Therefore, the following system parameterization will be regarded for 10GHz. Nevertheless, the described parameterization procedure can be adapted to any suitable band providing sufficient radar reflectivity and tolerable attenuation for the communications application.

A. *Common Restrictions*

Given the physical characteristics of transmission channel, system parameterization in the integrated radar and communications system has some common restrictions that mainly concern the Doppler shift as well as the propagation delay here.

1) Subcarrier spacing: During the transmission of the integration signal, there will exist a Doppler shift for the relative movement between the system platform and the target. In comparison to communications propagation in the case of radar propagation twice the Doppler shift occurs, which results in

$$f_{d\_radar} = 2 f_{d\_comm} = 2 v_{rel} / c_0 \qquad (13)$$

with v_{rel} being the relative velocity between the platform and scatterer , f_{d_radar} and f_{d_comm} are the Doppler shift of radar and communications for the same relative velocity.

To maintain the orthogonality between the subcarriers and avoid the ICI, the subcarrier spacing Δf should be much larger than the Doppler shift produced by the maximum relative velocity. The limit $\Delta f > 5 f_{d\_radar,\max}$ will ensure the orthogonality of the subcarriers and even be applicable for the relative velocities higher than $v_{rel\_\max}$.

2) Cyclic prefix: In the multi-path fading channel, there exists transmission delay for both the radar and communications application, which results in the generation of inter-symbol interference (ISI). To avoid ISI between the subsequent OFDM symbols, and maintain the orthogonality between each subcarrier, each OFDM symbol must be extended at the transmitter with a prefix containing a partly cyclic repetition of itself with duration of T_p called cyclic prefix (CP). One way to add the CP is shown in Fig. 2.

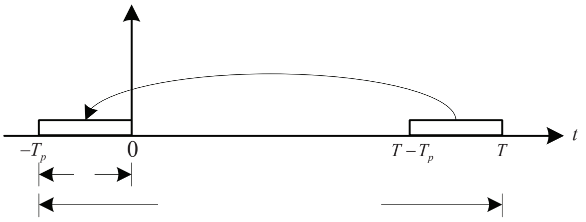

Fig. 2. The way to add the cyclic prefix

Therefore, to avoid the ISI, the CP duration should meet $T_p > \tau_{\max}$, where $\tau_{\max}$ represents the total maximum signal travel time between platform and scatterer instead of only the time difference as for pure communications links.

B. Restrictions from the Radar Perspective 共同的限制

Apart from the common restrictions from radar and communications, there exist some individual restrictions from the radar perspective. 雷达自身限制

1) Symbol period: In radar systems, to obtain a larger transmission power and high signal to noise ratio (SNR) at the input of the radar processor, the energy of the signal to be processed must be maximized. In practical applications, where the transmit power is limited, it means the integration time of the processor must be chosen as long as possible. Therefore, the CE-MSK-OFDM symbol period T must be chosen as long as possible without violating the limitation of the subcarrier spacing

$$\Delta f = 1/T > 5 f_{d\_radar,\max} \; . \qquad (14)$$

2) Range resolution: Range resolution is an important parameter in radar performance which reflects the ability distinguishing the targets in the distance dimension. Essentially, the range resolution Δr is dependent on the bandwidth of the radar signal. That is
本质上来讲，距离分辨率取决于信号的带宽大小。

距离分辨力：
$$\boxed{\Delta r = \frac{c_0}{2B}} \qquad (15)$$
root mean square .rms

with B representing the signal bandwidth.The rms bandwidth of the CE-MSK-OFDM signal can be expressed as

$$B_{rms} = \max\left(2\pi h, 1\right)\left(N_s / T\right). \qquad (16)$$
Ns:载波数
T:符号周期

Therefore, the choice of radar range resolution directly determines the number of subcarriers and the CE-MSK-OFDM symbol period. Meanwhile, in order to facilitate the realization of modulation and demodulation of the OFDM signal using IFFT and FFT, the number of subcarriers is usually chosen to be an integer multiple of 2.

Based on the constraints regarded so far, a group of suitable system parameters for a CE-MSK-OFDM system for joint radar and communications operations have been designed which are shown in Table I.

TABLE I SYSTEM PARAMETERS

Symbol	Parameter	Value
f_c	Carrier frequency	10 *GHz*
N_s	Number of subcarriers	512
M	Number of symbol period	32
T	Symbol period	20 μs
T_p	CP duration	6.67 μs
h	Modulation index	[0,1]

IV. SIMULATION RESULTS

To verify the feasibility and the performance of the designed system parameters, simulations are carried out from radar and communications perspective by Matlab.

A. Ambiguity Function

According to the designed parameters shown in Table I, the ambiguity function of the CE-MSK-OFDM signal is calculated and simulated, which are plotted in Fig. 3 and Fig. 4.

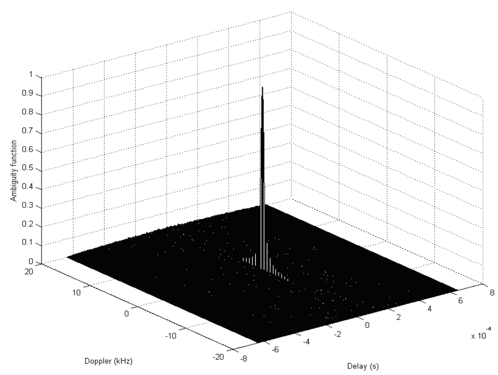

Fig. 3. Ambiguity function of the CE-MSK-OFDM signal

From Fig. 3 and Fig. 4, we can see that the ambiguity function of the CE-MSK-OFDM signal is close to thumbtack shape, which suggests that it has a satisfying radar performance.

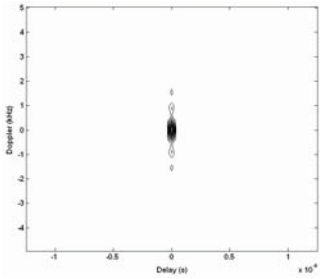

Fig. 4. Contour of ambiguity function

B. Radar Range Profile

In order to verify the feasibility and the dynamic range, the system parameters is tested with one single point scatterer with radar cross section $\sigma = 30\ dBm^2$ and relative velocity $v_{rel} = 0 m/s$ at a distance of $R_{rel} = 1000\ m$. The radar range profile of the CE-MSK-OFDM signal calculated from the received signal is plotted in Fig. 5.

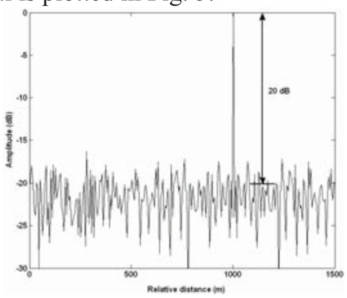

Fig. 5. Radar range profile of the CE-MSK-OFDM signal

Fig. 5 indicates that the scatterer is sharply depicted at a distance of $1000\ m$ and the MSR can achieve $20\ dB$. The only sidelobe occurring are those resulting from the Fourier transform. By applying windowing functions in the DFT processing, much higher sidelobe attenuation can be achieved.

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C. Bit Error Rate

To verify the communication performance , the BER (Bit Error Rate) performance of the CE-MSK-OFDM signal and CE-QPSK-OFDM signal is simulated in AWGN channel, which is plotted in Fig. 6.

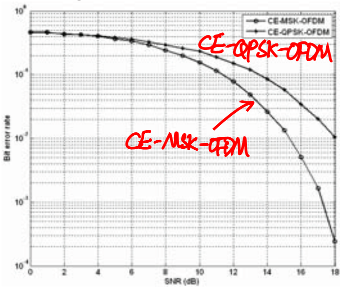

Fig. 6. Bit error rate performance

Compared with CE-QPSK-OFDM signal, the CE-MSK-OFDM signal has a better BER performance, which proves that the CE-MSK-OFDM signal has greatly eliminated the intercarrier interference.

V. CONCLUSION

In this paper, a radar-communication compatible waveform is designed based on CE-MSK-OFDM modulation scheme, which can be used to realize the integrated radar and communication system. In the next step, we will try to design the system architecture based on CE-MSK-OFDM and implement it in hardware.

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