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Waveform design for integrated radar and communication system with orthogonal frequency modulation

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The exponentially increasing demand for spectrum from commercial communication applications has created additional stress on defense applications. The waveform design method to realize the integration of radar and communications for spectrum sharing has thus gained focus. In this study, we develop a frequency modulation (FM) scheme for the integrated radar and communication system with orthogonal FM function. The FM of our proposed waveform is a weighted sum of multiple sub-FM functions. This technique, which is based on sub-FM terms comprising the signal that is mathematically orthogonal in the inner product domain, is developed by rationally designing the sub-FM term. The information-bearing communication sequences are carried out by the coefficients of different sub-FM terms. These sub-FM terms are designed to be real for high-power efficiency, to be mathematically orthogonal with one another for the demodulation procedure, and to have a large degrees of freedom for bulk data transfer. The performance of the designed waveform, including time-bandwidth product, auto-ambiguity function, cross-ambiguity function, and demodulation procedure, is analyzed. Simulation results, which are presented to verify the performance of the designed waveform, show that the designed waveform has the capacity to realize radar and communication integration in one joint platform.

1. Introduction

The demand from the radio spectrum is exponentially increasing due to the rapid development of commercial communication applications [1,2]. Given the fixed and limited spectrum resource, this demand imposes additional stress on radar applications. Consequently, radars have since operated in a contested and congested environment. To meet this demand, operators of radar and communication systems have been encouraged to share radio spectrum [3,4].

The conventional solution is to separate the radar and communication systems spatially, spectrally, or temporally. These approaches are primarily aimed at addressing interferences that separately operating systems can cause to one another. Subsequently, the main issue is how to mitigate the interference. In this study, we do not require this separation, and we instead investigate the fundamental radar and communication co-existence with the same signal to enable the two subsystems to work collaboratively on a single device [5–7]. Thus, the interference of each system can be mitigated, and the performance of the entire system can be promoted.

As two classical electronic systems, a radar system and a communication system may seem similar. However, each waveform possesses its own characteristic and is used for different missions. For a successful communication signal, a main task is to maximize the entropy embedded into the transmitted waveform [8]. For a radar system, the waveform requires a coherent and restrictive form to obtain a pulse compression gain to maximize detection performance [9]. Thus, an integrated waveform that simultaneously performs radar and communication functions should have both characteristics.

The current research on the waveform design for an integrated radar and communication system can be divided into three classes, namely, waveform diversity, phase modulation to a base radar waveform, and communication signals that serve as short-range radar emissions. Given that waveform diversity can exploit the degrees of freedom (DOFs) of time, frequency, code, and polarization, the same diversity approach can be applied in the waveform design of an integrated radar and communication system, particularly by setting a group of waveforms in which each represents the information-bearing communication sequence according to the mapping relationship [10]. In [11,12], the information-bearing sequences are modulated by waveform diversity and sidelobe level control. However, the modulated symbol number of this approach is limited to the elements of the multiple input multiple output

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(MIMO) system. In [13], a waveform for an integrated radar and communication system is proposed by exploiting the code freedom to deal with interferences. However, the echo must be separated at the receiver, which will lower the energy used for radar detection and constrict radar detection range. Given the limited DOFs of the diversity approach and the efficiency of the communication demodulation procedure, this type of method is unsuitable for an integrated radar and communication system in high data transfer environments.

In [14,15], the phase modulation method for a linear frequency modulation (LFM) signal was used to achieve radar and communication integration. In [14], an approach of embedding the information-bearing communication sequence into the LFM pulse with the minimum shift keying (MSK) scheme was proposed. The phase shift keying (PSK) scheme with adjustable parameters was used in [15]. To accommodate a large unambiguous detection range and the timely separation of transmission and reception, a radar always operates in pulse mode. In the pulse Doppler mode, the duty cycle is always low, which leads to a narrow pulse width. When the number of modulated symbols in a pulse width increases, a spectrum leakage occurs [14], which decreases the pulse compression gain and degrades bit error rate (BER) performance. In [16], an approach of embedding communication symbols into a radar waveform was proposed, in which the information-bearing sequences are carried into the continuous phase modulation term, and then this phase is attached to a poly-phase-coded frequency modulated radar waveform. When the number of the modulated symbols increases, the performance of the ambiguity function declines. This kind of phase modulation method is difficult for realizing bulk data transfer due to the modulation type and characteristic of the system.

With constructive properties, the orthogonal frequency division multiplexing (OFDM) communication signal has found wide use in radar applications [17,18]. For a high data transfer rate, OFDM communication signals have been served as short-range radar emissions for automotive applications [19–22]. The OFDM signal is the sum of many subcarrier components via the inverse fast Fourier transform (IFFT) operation and thus has a peak to average power ratio (PAPR) problem [23]. High PAPR is one of the most detrimental characteristics of the OFDM system because it degrades the efficiency of the power amplifier in the transmitter. For most radar applications, the waveform of an integrated radar and communication system requires high-power efficiency for long-distance sensing. The waveform should possess a constant envelope to maximize transmitted energy efficiency [24].

Therefore, an appropriate waveform for integrated radar and communication system should include the following properties: large time-bandwidth product, easy to modulate multiple bits in one pulse, high-power efficiency with spectral containment, and the desired ambiguity function shape. By exploiting the frequency diversity structure, the OFDM system can realize bulk data transfer where information-bearing sequences are carried by different subcarriers. The energy efficient frequency modulation (FM) waveform has been widely employed in radar applications for a large time-bandwidth product to solve the contradiction between range resolution and detection range. This scenario raises an interesting question. Can a design method be realized for synthesizing an energy efficient FM waveform through a set of design parameters (e.g., the OFDM signal is the sum of many subcarrier components via the IFFT operation)? According to series expansion, a function can be decomposed into a linear combination of complete function system. The decomposition procedure mainly contains two parts, the base function and the coefficient. On this basis, we develop a FM scheme that is synthesized by a weighted sum of multiple sub-FM terms. These sub-FM terms are mathematically orthogonal with one another in the inner-product domain, and the coefficients of

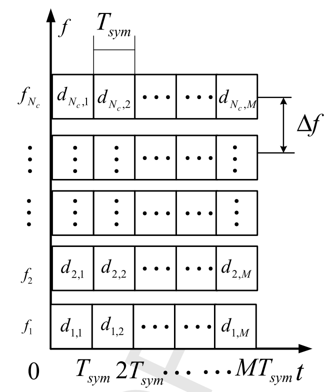

Fig. 1. Time–frequency scheme of OFDM.

the different sub-FM terms act as the information-bearing communication sequences that must be transferred. The performance of the designed waveform, including time-bandwidth product, auto-ambiguity function, cross-ambiguity function, and demodulation procedure, is analyzed. Given that these operations are applied at phase term, the designed waveform has constant envelope with high-power efficiency. The designed integrated waveform also has a large time-bandwidth product with a large pulse compression gain. The auto-ambiguity function has a thumbtack-like shape, and the cross-ambiguity function has a low level. The data transfer rate is decided by the DOF of the sub-FM term and the pulse repetition frequency (PRF) of the system.

2. Waveform design for the integrated radar and communication system with orthogonal FM

2.1. Frequency diversity in OFDM system

As shown in Fig. 1, the OFDM transmission scheme is a type of multichannel system that exploits the orthogonality among the subcarriers. The message bits are first mapped into a sequence of PSK or quadrature amplitude modulation (QAM) symbols at the OFDM transmitter. The number of carriers is denoted by N_c, and they are subsequently converted into N_c parallel streams. Each N_c symbol is subjected to serial-to-parallel (S/P) conversion by different subcarriers. Finally, the subcarrier components are added via the IFFT operation.

Fig. 1 indicates that the communication symbols are modulated by the subcarriers. The multicarrier scheme of OFDM renders bulk data transfer easy. However, its high PAPR degrades the efficiency of the power amplifier at the transmitter. Inspired by the frequency diversity scheme in the OFDM system, we develop a FM scheme. The proposed FM is synthesized by multiple sub-FM terms, which are mathematically orthogonal in the inner product domain. The information-bearing communication sequences are carried by the coefficients of the different sub-FM terms. This orthogonality is applied at the communication receiver for demodulation. Compared with the frequency diversity structure in the OFDM system, our proposed waveform is a type of diversity in FM.

2.2. Proposed orthogonal FM scheme for the integrated radar and communication system

The energy efficiency and large time-bandwidth product of FM waveforms have been the primary reasons why they are so widely employed in radar applications. For a given FM signal, the transmitted waveform can be written as

$$s(t) = a(t)e^{j\phi(t)} = a(t)e^{j\varphi(t)}e^{j2\pi f_c t} \tag{1}$$

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