A Radar-Communication Integrated Signal of OFDM Based on Four-Phase Code

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Abstract. Traditional radar signal has only detection function. With the advent of technologies such as Internet of Vehicles and driverless cars, radar-communication integrated signal has got more attention, which can realize communication and radar detection using the same signal. However, the uncertainty of communication information such as transmitting the same information continuously can influence radar detection performance. In this paper, a radar-communication integrated signal of OFDM based on four-phase code is proposed. This signal combines radar-communication integrated signal of OFDM with orthogonal four-phase-coded sequences optimized by genetic algorithm in MIMO radar, these four-phase-coded sequences form a set and the radar-communication integrated signal of OFDM can carry communication information by different permutations of these sequences without damaging radar detection performance. The simulation results show that the four-phase-coded sequences have good autocorrelation and cross-correlation properties, and the radar-communication integrated signal of OFDM using these sequences has good detection performance, which can meet the practical requirements.

Keywords: Radar-communication integration · OFDM · Four-phase code

1 Introduction

Radar-communication integrated signal can improve spectrum utilization ratio and reduce interference between devices, so it is significant to research radar-communication integrated signal. In the design of radar-communication integrated signal, OFDM which is widely used in communication system has many advantages [1], for instance, it is easy to synchronize and equalized and it has high spectral efficiency. As a radar signal, OFDM has good detection performance [2–4].

As for polyphase code, it is widely used in MIMO radar. To avoid interference between different signal channels, polyphase code is optimized to be more orthogonal [5, 6]. However, the polyphase code used in MIMO radar does not carry communication information generally.

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In this paper, we design a radar-communication signal of OFDM based on four-phase code. By constructing four-phase-coded sequence set optimized by genetic algorithm, the radar-communication integrated signal can carry communication information and the detection performance can not be affected. The remainder of this paper is organized as follows. Section 2 introduces radar-communication integrated signal model and genetic algorithm, and analyzes the ambiguity function. Section 3 introduces four-phase-coded sequence set optimized by genetic algorithm, explains how to combine the sequence set with radar-communication integrated signal. Section 4 gives the simulation results and Sect. 5 gets conclusion.

2 Signal Model and Genetic Algorithm

2.1 Signal Model

Traditional OFDM radar emits only one OFDM signal in a pulse, if we use traditional OFDM radar for communication, it will be processed in multiple pulses and be not convenient to synchronize. In this paper, a kind of radar-communication integrated signal is used. In this signal, there are multiple subpulses in a pulse and each subpulse is an OFDM signal. In this way, communication can be realized in one pulse, and the receiver is easier to synchronize.

Suppose that each pulse consists of N OFDM symbols, each OFDM symbol has M subcarriers, the baseband signal can be expressed in the following form:

$$s(t) = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} a(m,n) \exp\{j2\pi m\Delta f(t - nT)\} rect\left[\frac{t - nT}{T}\right] \tag{1}$$

In the formula, T is an OFDM symbol period, $\Delta f = 1/T$ is the frequency interval of the carrier, $a(m,n)$ is the communication information modulated on the mth subcarrier of the nth OFDM symbol, *rect* is a step function for symbol duration. Figure 1 shows the time-frequency domain representation of this radar-communication signal.

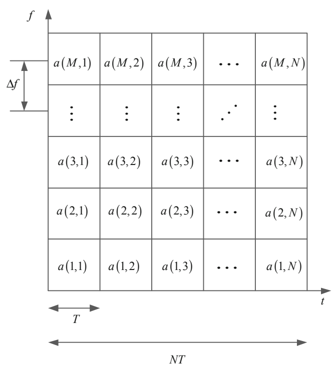

Fig. 1. Time-frequency domain representation of radar-communication integrated signal

2.2 Analysis of Ambiguity Function

The ambiguity function of Radar, which is related to the transmitted waveform, is an effective tool for radar signal analysis and waveform design. It can reflect the distance and speed resolution, ambiguity and measurement accuracy. To get high resolution of distance and Doppler, an ideal ambiguity function should be a shape of pushpin. In other words, it has a single central peak and the rest of the energy is evenly distributed across the distance and Doppler plan.

The definition of the ambiguity function is:

$$\chi(\tau, f_d) = \int_{-\infty}^{+\infty} s(t)s^*(t-\tau)\exp\{j2\pi f_d t\}dt \tag{2}$$

Where $s(t)$ is the signal function, * is conjugation of the signal, τ is the time delay of the echo received by radar after the signal reaches the target and f_d is the Doppler frequency offset generated by the target motion.

Bring Eq. (1) to Eq. (2). Without loss of generality, we simplify the equation in the condition of $-NT < \tau < 0$. Let $\lfloor t/T \rfloor = k$, $\tau' = \tau + (1 + |k|)T$, $\tau'' = \tau + |k|T$, so $\tau' = \tau'' + T$, $-T < \tau'' \le 0$, $0 < \tau' \le T$. We can get the following [7]:

$$\begin{aligned}\chi(\tau, f_d) = & \sum_{n=1}^{N-1-|k|} \exp\{j2\pi(n-1)f_d T\}\chi^{+}_{n-1,n+|k|}(\tau', f_d) \\ & + \sum_{n=0}^{N-1-|k|} \exp\{j2\pi n f_d T\}\chi^{-}_{n,n+|k|}(\tau'', f_d)\end{aligned} \tag{3}$$

Where $\chi^{-}_{n,q}(\tau, f_d)$ and $\chi^{+}_{n,q}(\tau, f_d)$ represent the ambiguity function of the nth OFDM symbol and qth OFDM symbol, $^-$ represents $-T \le \tau \le 0$ and $^+$ represents $0 < \tau < T$. Without loss of generality, let $f_d = 0$, we get:

$$\chi(\tau, 0) = \sum_{n=1}^{N-1-|k|} \chi^{+}_{n-1,n+|k|}(\tau', 0) + \sum_{n=0}^{N-1-|k|} \chi^{-}_{n,n+|k|}(\tau'', 0) \tag{4}$$

When $(T + \tau'')\Delta f/2$ can be ignored, we get:

$$\begin{aligned}\chi^{-}_{n,n+|k|}(\tau'', 0) = & (T+\tau'') \sum_{i=-N+1}^{0} \sum_{p=-i}^{M-1} a(p+i, n)a^*(p, n+|k|) \\ & \exp\{j2\pi p\Delta f \tau''\}\exp\left\{j2\pi i\Delta f \frac{T+\tau''}{2}\right\} \\ & + (T+\tau'')\sum_{i=1}^{N-1}\sum_{p=0}^{M-i-1} a(p+i, n)a^*(p, n+|k|) \\ & \exp\{j2\pi p\Delta f \tau''\}\exp\left\{j2\pi i\Delta f \frac{T+\tau''}{2}\right\}\end{aligned} \tag{5}$$

$$\chi^{+}_{n-1,n+|k|}(\tau',0) = (T-\tau')\sum_{i=-N+1}^{0}\sum_{p=-i}^{M-1} a(p+i,n-1)a^{*}(p,n+|k|) \exp\{j2\pi p\Delta f\tau'\}\exp\left\{j2\pi i\Delta f\frac{T+\tau'}{2}\right\} + (T-\tau')\sum_{i=1}^{N-1}\sum_{p=0}^{M-i-1} a(p+i,n-1)a^{*}(p,n+|k|) \exp\{j2\pi p\Delta f\tau''\}\exp\left\{j2\pi i\Delta f\frac{T+\tau'}{2}\right\} \quad (6)$$

In order to get high resolution of distance and Doppler, the value of Eq. (4) sidelobe should be small. As we can see in Eq. (5) and Eq. (6), adjusting $a(m,n)$ can change the value of Eq. (4). For convenience of expression, we let $\mathbf{a}(n) = [a(1,n),\ldots,a(M,n)]^{T}$. The specific requirements are that the value of aperiodic cross-correlation function of $\mathbf{a}(n_1)$ and $\mathbf{a}(n_2)$ should be small, and the value of sidelobe of the aperiodic autocorrelation function of $\mathbf{a}(n)$ should be small, where n_1 and n_2 represent different OFDM symbol. In other words, the communication information modulated on different OFDM symbol should have good autocorrelation and cross-correlation properties for good ambiguity function.

2.3 Genetic Algorithm

Genetic algorithm (GA) is an analogy of biological evolution, it can solve optimization problem by robust and adaptive searching. The main step of GA is encoding the results to population and optimizing the results by selection, crossover and mutation. The specific steps of GA are listed as follows:

Step 1: Code the actual problem, and generate the initial population randomly. The initial population represents initial solutions.
Step 2: Define the fitness function. Each individual in population has a value of fitness function. Initialize the probability of crossover and mutation.
Step 3: Select a part of the population to do crossover and mutation, then get new population.
Step 4: Calculate the fitness function value of the new population, if the new population meets the requirements, output the results, or else, jump to step 3.

3 Design of Radar-Communication Signal Based on Four-Phase Code

Through the above analysis, we know the communication information modulated on different OFDM symbols should have good autocorrelation and cross-correlation properties for good shape of ambiguity function. For traditional radar, the information modulated on OFDM is fixed. For radar-communication integrated signal, however, the communication information is uncertain, which can damage the radar detection performance. A typical example is transmitting the same information continuously.

In order to ensure the performance of radar detection, we construct polyphase code sequence set. Four-phase-coded sequence is selected in this paper, the reason is that random four-phase-coded sequences have good autocorrelation and cross-correlation properties, then using genetic algorithm to optimize them, the sequences can have better autocorrelation and cross-correlation properties. Suppose the sequence set has L sequences, the length of each one is M, the sequence set can be expressed as:

$$S(L,M) = \begin{bmatrix} \phi_1(1) & \phi_1(2) & \dots & \phi_1(M) \\ \phi_2(1) & \phi_2(2) & \dots & \phi_2(M) \\ \vdots & \vdots & \ddots & \vdots \\ \phi_L(1) & \phi_L(2) & \dots & \phi_L(M) \end{bmatrix} \tag{7}$$

Where $\phi_l(m) \in \{0, \pi/2, \pi, 3\pi/2\}$, $1 \le l \le L$. $[\phi_l(1) \;\; \phi_l(2) \; \dots \; \phi_l(M)]^T$ is the information carried on radar-communication integrated signal, that is to say, it should replace $\mathbf{a}(n)$. The autocorrelation and cross-correlation of four-phase-coded sequences can be expressed as:

$$A(\phi_l, k) = \begin{cases} \frac{1}{M}\sum\limits_{m=1}^{M-k} \exp\{j[\phi_l(m) - \phi_l(m+k)]\} & 0 \le k < M \\ \frac{1}{M}\sum\limits_{m=-k+1}^{M} \exp\{j[\phi_l(m) - \phi_l(m+k)]\} & -M < k < 0 \end{cases} \tag{8}$$

$$C(\phi_p, \phi_q, k) = \begin{cases} \frac{1}{M}\sum\limits_{m=1}^{M-k} \exp\{j[\phi_q(m) - \phi_p(m+k)]\} & 0 \le k < M \\ \frac{1}{M}\sum\limits_{m=-k+1}^{M} \exp\{j[\phi_q(m) - \phi_p(m+k)]\} & -M < k < 0 \end{cases} \tag{9}$$

GA is used to optimize $A(\phi_l, k)$ and $C(\phi_p, \phi_q, k)$. When we use genetic algorithm, we should define cost function. In order to make different sequences have great autocorrelation and cross-correlation properties, we define cost function as:

$$E = \sum_{l=1}^{L}\sum_{k=1}^{M-1} |A(\phi_l, k)|^2 + \sum_{p=1}^{L-1}\sum_{q=p+1}^{L}\sum_{k=-(M-1)}^{M-1} |C(\phi_p, \phi_q, k)|^2 \tag{10}$$

In order to use GA [8], we should expand out the sequence set. In particular, each individual of GA can be expressed as $\phi_1(1) \; \dots \; \phi_1(M) \dots \phi_L(1) \; \dots \; \phi_L(M)$, then we should initialize crossover probability and mutation probability. Let $F = 1/E$ be the adaptability function, then go into the loop. After GA processing, more orthogonal sequence set can be got.

The processed sequence set does not carry information itself, but we can map information to the sequences. Different permutations of sequences can map different information. In this way, the same information can be mapped to different sequences and the performance of radar detection is guaranteed.

It is worth noting that the permutation of L sequences will be used to transmit information, which can reduce communication rate compared with transmitting information directly using the same signal model. For convenience of expression, we let $\boldsymbol{\psi} = [\phi(1), \cdots, \phi(M)]^T$. For example, When $L = 3$, the information bit 00 can be mapped to $[\boldsymbol{\psi}_1\ \boldsymbol{\psi}_2\ \boldsymbol{\psi}_3]$, and 01 can be mapped to $[\boldsymbol{\psi}_1\ \boldsymbol{\psi}_3\ \boldsymbol{\psi}_2]$. Assume that the communication rate in this way is r_1 and the communication rate by transmitting information directly is r_2, the ratio of r_1 and r_2 is:

$$\frac{r_1}{r_2} = \frac{\log_2(L \times (L-1) \times \cdots \times (L-M+1))}{2MN} \tag{11}$$

The actual communication rate r_1 can be expended by expending the size of the sequence set $S(L, N)$, the number of subcarrier in an OFDM symbol and the number of OFDM in a pulse. Reducing the period of OFDM symbol is also a choice.

4 Simulation Results

In the simulation, we set an OFDM symbol period to 0.1 μs, one OFDM symbol has 40 subcarrier and one pulse has 40 OFDM symbol. The size of the four-phase-coded sequence set is 80×40. Two sequences are randomly selected in the set and Fig. 2 shows their aperiodic cross-correlation and aperiodic autocorrelation.

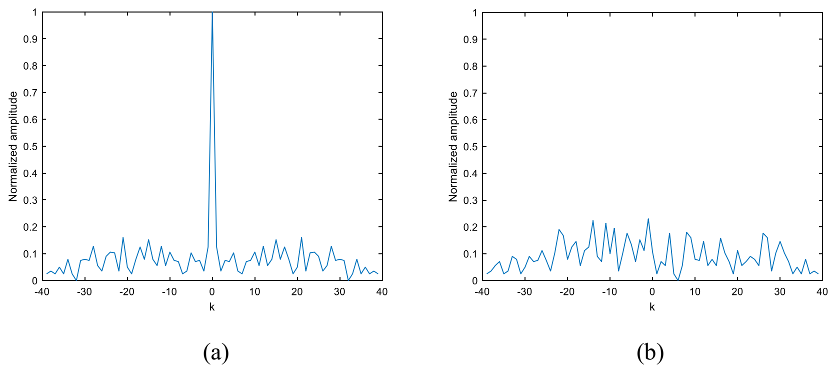

Fig. 2. (a) Aperiodic autocorrelation (b) Aperiodic cross-correlation

As can be seen from Fig. 2, the four-phase-coded sequences have good autocorrelation and cross-correlation properties. By the previous analysis, we know these sequences meet the requirement of radar-communication integrated signal. Then we select 40 sequences from the sequences set randomly, Fig. 3 and Fig. 4 show the ambiguity function.

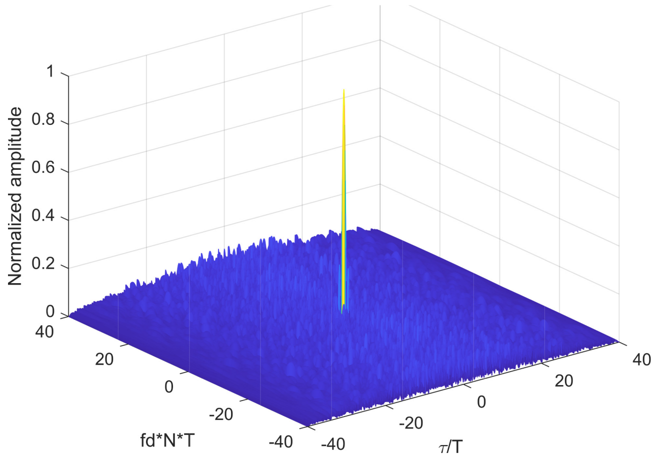

Fig. 3. Ambiguity function of radar-communication integrated signal

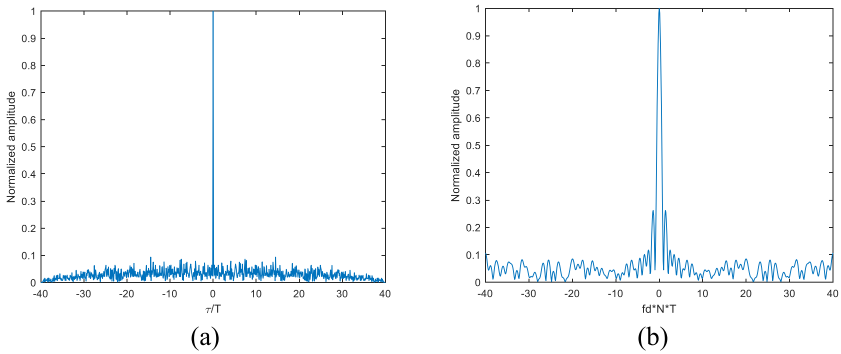

Fig. 4. (a) Section of distance of the ambiguity function (b) Section of speed of the ambiguity function

As can be seen from Fig. 3 and Fig. 4, the ambiguity function has a single central peak and the rest of the energy is evenly distributed across the distance and Doppler plan. It shows that the radar-communication integrated signal of OFDM using four-phase-coded sequences has good detection performance.

In this simulation, we choose 40 subcarriers in an OFDM symbol and 40 OFDM symbols in a pulse. In actual practice, the size of radar-communication integrated signal can be changed, such as 16 and 64 subcarriers in an OFDM symbol, which is convenient to FFT. And according to the hardware performance, different OFDM periods can be selected to meet practical requirements.

5 Conclusion

In this paper, a radar-communication integrated signal of OFDM based on four-phase code is proposed. The simulation results show that the four-phase-coded sequences optimized by GA have good autocorrelation and cross-correlation properties, and the radar-communication integrated signal using these sequences has good radar detection capability. Although compared with direct transmitting information the rate of communication is lower, it ensures radar performance. And the rate of communication can be increased by changing the parameters. The radar-communication integrated signal designed in this paper can be applied to driverless operation system, which requires good radar detection performance and stable communication rates.

References

1. Manosueb, A., Kosseyaporn, J., Wardkein, P.: An adaptive demodulation for OFDM signal. In: 2016 International Symposium on Intelligent Signal Processing and Communication Systems (ISPACS), pp. 1–6 (2016)
2. Levanon, N.: Multifrequency complementary phase-coded radar signal. Proc. Radar Sonar Navig. **147**(6), 276–284 (2000)
3. Tigrek, R.F., Heij, W.J.A.D., Genderen, P.V.: Multi-carrier radar waveform schemes for range and doppler processing. In: 2009 IEEE Radar Conference, pp. 1–5 (2009)
4. Sturm, C., Wiesbeck, W.: Waveform design and signal processing aspects for fusion of wireless communications and radar sensing. Proc. IEEE **99**(7), 1236–1259 (2011)
5. Deng, H.: Polyphase code design for orthogonal netted radar systems. IEEE Trans. Signal Process. **52**(11), 3126–3135 (2004)
6. Khan, H.A., Edwards, D.J.: Doppler problems in orthogonal MIMO radars. In: 2006 IEEE Conference on Radar, pp. 24–27 (2006)
7. Liu, Y.J., Liao, G.S., Yang, Z.W.: Ambiguity function analysis of integrated radar and communication waveform based on OFDM (in Chinese). Syst. Eng. Electron. **38**(9), 2008–2018 (2016)
8. Liu, B., He, Z., Zeng J., Liu B.: Polyphase orthogonal code design for MIMO radar systems. In: 2006 CIE International Conference on Radar, pp. 1–4 (2006)