Pulse Compression Analysis for OFDM-Based Radar-Radio Systems

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Abstract. Orthogonal frequency division multiplexing (OFDM) radar has been studied in the last years for its suitability to combine simultaneous radar-radio (RadCom) operations. There exists the problem of low data rate and high range sidelobes in an OFDM-based RadCom System using the classic pulse compression processing. To solve the problem, a signal model in which monopulse is composed of multi-OFDM symbols is presented. The analysis of pulse compression processing through ambiguity function is presented, where the effects of Doppler and random phase codes on pulse compression are discussed in detail. Theoretical analysis and simulation results show that the presented method can obviously alleviate the effects of the random phase codes on range performance of OFDM signals, while keeps high data rate.

Keywords: OFDM · Radar-radio · Pulse compression
Ambiguity function

1 Introduction

The joint operation of radar-radio (RadCom) systems using one common waveform, have recently been studied to integrate wireless communications and sensing within a single transceiver platform [1]. The study on RadCom systems is mainly to improve the spectrum efficiency and cost effectiveness. A typical application area is the intelligent transportation networks which require the ability of inter-vehicle communication as well as reliable environment sensing.

Orthogonal frequency division multiplexing (OFDM) is a widely adopted modulation format for communications. Due to the wide bandwidth of the adopted waveform, it can be used for high range resolution radar [2,3], and dual use of communication and radar functions in a single platform [4,5]. Due to their advantages on high spectral efficiency, thumbtack-liked ambiguity function, good Doppler tolerance [6], flexible waveform structure and easy implementations [7], OFDM signals are attractive to both academic and industrial researchers.

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When considering the range processing approaches in OFDM-based RadCom systems, a modulation symbol-based processing technique that estimates the range of a target at short range was presented in [1]. It completely removed the influence of the communication data, and the achieved range resolution was generally in the order of 1 m. A classical correlation-based processing was presented in a Ultra Wideband OFDM system [4], where one subcarrier carried 1 bit data, resulting in a low data rate and high range sidelobes. A subspace projection method based on the compensated communication information was appeared in [8], in which the transmitted radar pulses were consisted of multi-OFDM symbols to improve the data rate, that leaded to high computational complexity. A non-linear least squares approach using weighted OFDM modulation was presented in [9], which also had a low data rate. A novel OFDM radar signal processing scheme which retrieved range information was derived in [10], in which the priori knowledge of the target position was required. A subspace-based algorithm based on rotation invariance to obtain range profile of a target was developed in [11], which suffered from a high computational burden. In conventional pulsed radar systems, each pulse only transmit one single OFDM symbol, which generally leads to the problems including range ambiguity and low transmission data rate.

In views of the above, an OFDM waveform with random phase modulation that transmits monopulse consisting of multi-OFDM symbols is presented to improve data rate, and the analysis of the pulse compression is presented to improve range resolution. The paper is organized as follows. The signal model of OFDM signals is given in Sect. 2. The analysis of pulse compression using ambiguity function is presented in Sect. 3. The simulation results are given in Sect. 4. Conclusion of the paper is given in Sect. 5.

2 Signal Model

2.1 Transmitted Signal

We consider a monostatic radar transmitting monopulse which is composed of multi-OFDM symbols, each symbol consists of transmitted data modulated onto a set of orthogonal subcarriers. Then the complex envelope of OFDM radar can be represented as [12]

$$x(t) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} d_{m,n} e^{j2\pi f_n t} \mathrm{rect}\left(\frac{t - mT_s}{T_s}\right) \tag{1}$$

where N is the number of subcarriers, M is the number of symbols, T_s is the OFDM symbol duration, $d_{m,n} = e^{j\varphi_{m,n}}$ denotes the communication data on the nth subcarrier of the mth symbol, which is transmitted using m-ary phase shift keying (m-PSK) modulation schemes, and rect $\left(\frac{t}{T_s}\right)$ is a rectangular window of duration T_s.

Interference between individual subcarriers is avoided based on the following condition given by

$$f_n = n\Delta f = \frac{n}{T_s} \quad n = 0, \ldots, N-1 \tag{2}$$

2.2 Pulse Compression Processing

Pulse compression is performed to achieve range (delay) estimation using a matched filter whose impulse response is equal to $H(t) = x^*(-t)$, where $*$ denotes the complex conjugate. The matched filter output can be expressed as

$$MF = \int_{-\infty}^{\infty} x(t)x^*(t-\tau)dt \tag{3}$$

Where τ is the relative time delay.

The Doppler shift caused by the movement of the target is also taken into consideration. The received signal can be expressed as a delayed version of the transmitted signal multiplied by a complex exponential that represents the Doppler shift. Hence, the equivalence of the pulse compression processing output to the ambiguity function expression is used to assess the radar performance of OFDM signals [13], which can be expressed as

$$\chi(\tau, \upsilon) = \int_{-\infty}^{\infty} x(t)x^*(t-\tau)e^{j2\pi\upsilon t}dt \tag{4}$$

where υ is the relative Doppler shift.

3 Analysis of Pulse Compression Processing

In this section, we discuss performances of the pulse compression processing based on the ambiguity function. We mainly focus on the effect of Doppler and random phase codes on pulse compression.

3.1 Mathematical Expression of Ambiguity Function

Firstly, we give the mathematical expression of the ambiguity function for the OFDM signal. Substituting (1) into (4), we obtain

$$\begin{aligned} \chi(\tau, \upsilon) = & \sum_{m=0}^{M-1}\sum_{n=0}^{N-1}\sum_{p=0}^{M-1}\sum_{q=0}^{N-1} d_{m,n}d_{p,q}^{*}e^{j2\pi q\Delta f\tau} \\ & \times \int_{0}^{MT_s} e^{j2\pi((n-q)\Delta f+\upsilon)t}\text{rect}\left(\frac{t-mT_s}{T_s}\right)\text{rect}\left(\frac{t-pT_s-\tau}{T_s}\right)dt \end{aligned} \tag{5}$$

Assuming $\lfloor \frac{\tau}{T_s} \rfloor = i$, where i is an integer. Setting $\tau' = \tau - iT_s$ and $\tau'' = \tau - (i+1)T_s$. Substituting τ' and τ'' into (5), we can get

$$\chi(\tau, \upsilon) = \sum_{p=0}^{M-1-i} \chi_1(\tau', \upsilon) + \sum_{p=1}^{M-1-i} \chi_2(\tau'', \upsilon) \tag{6}$$

where

$$\begin{aligned} \chi_1(\tau', \upsilon) = (T_s - \tau') &\sum_{p=0}^{M-1-i} \sum_{n=0}^{N-1} \sum_{q=0}^{N-1} d_{p+i,n} d^*_{p,q} \\ &\times e^{j2\pi \frac{(n+q)\Delta f \tau'}{2}} e^{j2\pi \frac{n-q}{2}} e^{j2\pi\upsilon \frac{(2(p+i)+1)T_s + \tau'}{2}} \\ &\times \text{sinc}\Big\{((n-q)\Delta f + \upsilon)(T_s - \tau')\Big\} \end{aligned} \tag{7}$$

$$\begin{aligned} \chi_2(\tau'', \upsilon) = (T_s + \tau'') &\sum_{p=1}^{M-1-i} \sum_{n=0}^{N-1} \sum_{q=0}^{N-1} d_{p+i,n} d^*_{p-1,} \\ &\times e^{j2\pi \frac{(n+q)\Delta f \tau''}{2}} e^{j2\pi \frac{n+q}{2}} e^{j2\pi\upsilon \frac{(2(p+i)+1)T_s + \tau''}{2}} \\ &\times \text{sinc}\Big\{((n-q)\Delta f + \upsilon)(T_s + \tau'')\Big\} \end{aligned} \tag{8}$$

and $\text{sinc}(x) = \sin(\pi x)/(\pi x)$.

3.2 Pulse Compression Loss

The pulse compression loss due to Doppler has been analyzed for one single OFDM symbol case in [6], where the compression loss indicates the loss at the output of the matched filter as compared to the zero Doppler case. To limit the compression loss lower than 1dB, it has shown that the Doppler shift should not exceed $\Delta f/4$. Herein, we are interested in the compression loss for the case of monopulse containing M OFDM symbols. Hence, we can give an expression for the compression loss (L_{pc}) due to Doppler as

$$L_{pc}[\text{dB}] = 20 \lg |\chi(0, 0)| - 20 \lg |\chi(0, \upsilon)| \tag{9}$$

Let $\eta = \frac{\upsilon}{\Delta f}$ be the normalized Doppler shift obtained through dividing the Doppler shift by the subcarrier separation. In order to reduce the effect of the random phase codes in (9), we run 100 Monte carlo simulations, and the mean value of L_{pc}[dB] at different η is shown in Fig. 1.

As show in Fig. 1, it can be seen that compression loss increases as η rises. The marker shows that the 1dB compression loss occurs at $\upsilon \approx \frac{\Delta f}{4M}$. This observation complies with the result given in [6] for one single OFDM symbol case. Indeed, an equivalent monpulse containing multi-OFDM symbols would be obtained when the subcarrier spacing is dropped to $\frac{\Delta f}{M}$.

From the above analysis, if we want to set a maximum allowable compression loss of 1dB, the maximum target velocity can be given as $V_{\max} = \frac{cB}{8NMf_c}$, where B is the system bandwidth and f_c is carrier frequency.

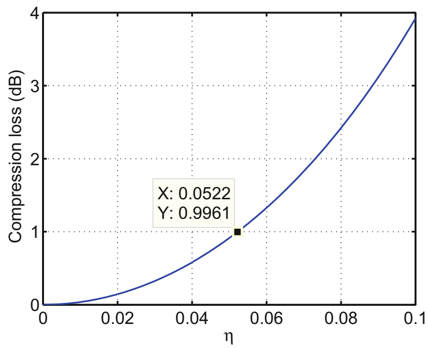


Fig. 1. Compression loss as a function of the normalized Doppler shift for $N = 16$ subcarriers, $M = 5$ OFDM symbols, the symbol duration $T_s = 0.1\,\mu$s

3.3 Effect of Random Phase Codes on Range Performance

The pulse compression precessing to achieve the range profile of a target, results in high sidelobes for transmitting random phase codes. Therefore, the effect of random phase codes on the range ambiguity function is analyzed as follows.

Substituting $\upsilon = 0$ in (6), we can obtain the range ambiguity function of the OFDM signal

$$\chi(\tau, 0) = \sum_{p=0}^{M-1-i} \chi_1(\tau', 0) + \sum_{p=1}^{M-1-i} \chi_2(\tau'', 0) \tag{10}$$

where

$$\begin{aligned}\chi_1(\tau', 0) =& (T_s - \tau') \sum_{p=0}^{M-1-i} \sum_{n=0}^{N-1} \sum_{q=0}^{N-1} d_{p+i,n} d^*_{p,q} \\ & \times e^{j2\pi \frac{(n-q)\Delta f(\tau' + T_s)}{2}} e^{j2\pi q \Delta f \tau'} \beta_1\end{aligned} \tag{11}$$

$$\begin{aligned}\chi_2(\tau'', 0) =& (T_s + \tau'') \sum_{p=1}^{M-1-i} \sum_{n=0}^{M-1} \sum_{q=0}^{N-1} d_{p+i,n} d^*_{p-1,q} \\ & \times e^{j2\pi \frac{(n-q)\Delta f(\tau'' + T_s)}{2}} e^{j2\pi q \Delta f \tau''} \beta_2\end{aligned} \tag{12}$$

and

$$\beta_1 = \text{sinc}\left\{(n-q)\Delta f(T_s - \tau')\right\} \tag{13}$$

$$\beta_2 = \text{sinc}\left\{(n-q)\Delta f(T_s + \tau'')\right\} \tag{14}$$

From (11) and (12), we get that β_1 and β_2 have great effects on performance of range ambiguity function.

Firstly, in (13), we get the term $0 < \Delta f(T_s - \tau') < 1$, giving an integer N_1, the values of β_1 are located in the mainlobe of sinc function when $|n - q| < N_1$. Hence, (11) can be approximated as

$$\chi_1(\tau',0) \approx (T_s-\tau') \times \left\{ \sum_{k=-N_1+1}^{0} \sum_{q=-k}^{N-1} d_{p+i,q+k} d_{p,q}^* e^{j2\pi \frac{k\Delta f(\tau'+T_s)}{2}} e^{j2\pi q \Delta f \tau'} + \sum_{k=1}^{N_1-1} \sum_{q=0}^{N-1-k} d_{p+i,q+k} d_{p,q}^* e^{j2\pi \frac{k\Delta f(\tau'+T_s)}{2}} e^{j2\pi q \Delta f \tau'} \right\} \tag{15}$$

The expression in (15) shows that, in order to improve the range resolution, phase codes on the pth and $(p+i)$th OFDM symbols has a better aperiodic cross-correlation function (CCF) for $|k| < N_1$.

Secondly, in (14), we get the term $0 < \Delta f(T_s + \tau'') = \Delta f \tau' < 1$. Then, the values of β_2 are located in the mainlobe of sinc function when $|n-q| < N_2$, where N_2 is an integer. Hence, (12) can be approximated as

$$\chi_2(\tau'',0) \approx (T_s+\tau'') \times \left\{ \sum_{k=-N_2+1}^{0} \sum_{q=-k}^{N-1} d_{p+i,q+k} d_{p-1,q}^* e^{j2\pi \frac{k\Delta f(\tau''+T_s)}{2}} e^{j2\pi q \Delta f \tau''} + \sum_{k=1}^{N_2-1} \sum_{q=0}^{N-1-k} d_{p+i,q+k} d_{p-1,q}^* e^{j2\pi \frac{k\Delta f(\tau''+T_s)}{2}} e^{j2\pi q \Delta f \tau''} \right\} \tag{16}$$

The expression in (16) shows that the phase codes on the pth and $(p+i+1)$th OFDM symbols has a better aperiodic CCF for $|k| < N_2$ to improve range resolution. Besides, the more N_1, the less N_2. For $i = 0$, we get that phase codes of each OFDM symbol has the aperiodic auto-correlation function (ACF) to improve range resolution.

Finally, we consider a special case of $\tau = iT_s$, (10) can be changed as

$$\chi(iT_s,0) = T_s \sum_{p=0}^{M-1-i} \sum_{n=0}^{N-1} \sum_{q=0}^{N-1} d_{p+i,n} d_{p,q}^* (-1)^{n-q} \mathrm{sinc}(n-q) \tag{17}$$

From (17), $\chi(iT_s,0) = 0$ when $n \neq q$. Hence, (17) can be rewritten as

$$\chi(iT_s,0) = T_s \sum_{p=0}^{M-1-i} \sum_{n=0}^{N-1} d_{p+i,n} d_{p,n}^* \tag{18}$$

which only depends on the phase codes. If we take the expected value of $\chi(iT_s,0)$ only have the minimum value for $0 < i < M-1$, then the phase codes of different OFDM symbols should be orthogonal.

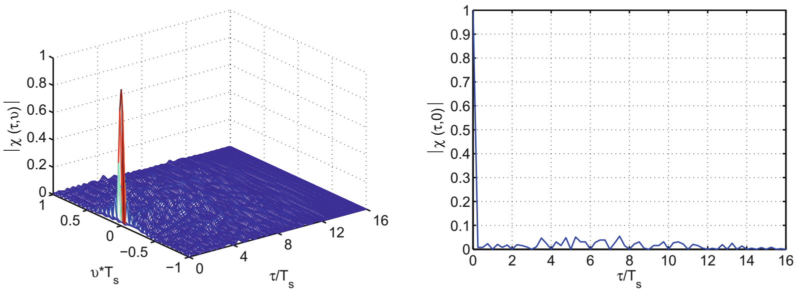
From the above analysis, we can get that in order to reduce the effect of transmitted data on the radar performance, the phase codes must possess excellent aperiodic ACF and CCF.

4 Simulations Results

4.1 Ambiguity Function Analysis

From the above analysis, we can select the phase codes with excellent aperiodic ACF and CCF to improve radar performance. Hence, we introduce two phase coding to investigate the performance of ambiguity function of the OFDM signal in this simulation. The first phase codes is constructed based on Walsh matrix using genetic algorithm (GA) for optimization presented in [14], the second is based on the consecutive ordered cyclic shift of m-sequence.

The signal parameters are designed as follows: the carrier frequency $f_c = 5.9\,\text{GHz}$, number of subcarriers $N = 32$, number of symbols $M = 16$, symbol duration $T_s = 0.1\,\mu\text{s}$. We construct a Walsh matrix of size $N \times N$ and m-sequence of length N, and the transmitted data of length M is randomly generated. We limit the volume computations of ambiguity function over a region $\Re = \{0 \leq \tau \leq MT_s, |\upsilon| \leq 1/T_s\}$. The ambiguity diagram of the OFDM signals based on the two phase codes are shown in Figs. 2 and 3, respectively.



(a) (b)

Fig. 2. Ambiguity diagram of OFDM signal using phase codes based on Walsh matrix using GA for optimization (a) ambiguity function (b) range ambiguity function

As shown in Figs. 2 and 3, the ambiguity function of Fig. 2(a) presents a thumbtack-type in both delay and Doppler domains, while of the Fig. 3(a) has a high sidelobes in all domains. In Fig. 2(b), the sidelobes reduction of range ambiguity function has been improved evidently. Besides, $\chi(\tau, 0) = 0$ when the delay is integral multiple of symbol duration. We run 100 Monte carlo simulations, and the mean value of peak sidelobe (PSL) in Fig. 2(b) and Fig. 3(b) are $-26.47\,\text{dB}$ and $-12.84\,\text{dB}$, respectively.

From the above, we can get that the OFDM signal using the first phase codes provides a better radar performance. This is because, the phase codes has a better aperiodic ACF and CCF, and keeps strict orthogonality, which has been shown in [14]. While, m-sequence has a better aperiodic ACF, but a worse CCF, because the periodic characteristic of m-sequence results in a peak at a certain shift.

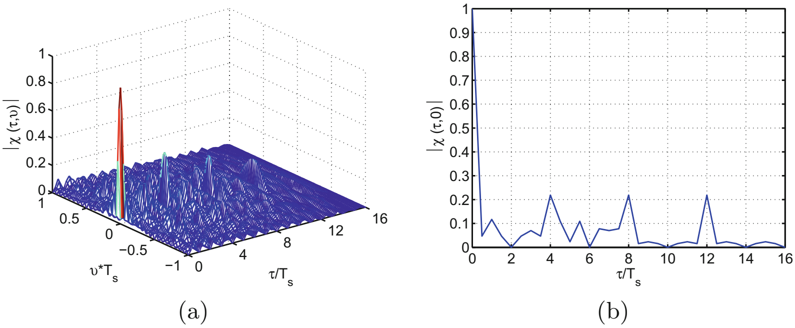


Fig. 3. Ambiguity diagram of OFDM signal using phase codes based on the consecutive ordered cyclic shift of m-sequence (a) ambiguity function (b) range ambiguity function

4.2 Range Profile

We demonstrate the performance of the pulse compression processing using OFDM signals based on the the above two phase codes. The signal parameters setting is the same as before, adding in additive white Gaussian noise (AWGN) and signal-to-noise (SNR) is 10 dB. We consider a point target with $R = 100\,\text{m}$ and $V = 10\,\text{m/s}$, and the normalized range profile is show in Fig. 4.

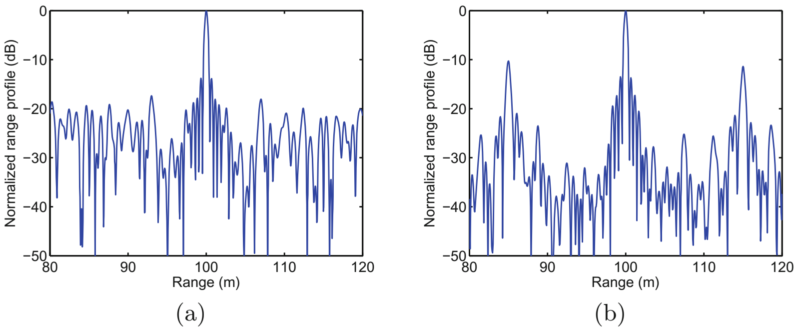


Fig. 4. Normalized range profile of a point target with $R = 100\,\text{m}$ and $V = 10\,\text{m/s}$ for OFDM signal using the two phases codes (a) Walsh matrix using GA for optimization (b) the consecutive ordered cyclic shift of m-sequence

It can be seen that in Fig. 4, the OFDM signal using the first phase codes has better sidelobes characteristics in range profile, this observation complies with the result of ambiguity function analysis. The simulation results show that the phase codes which possess a better auto and cross correlation properties can improve the range resolution.

5 Conclusion

In this paper, the analysis of pulse compression processing in an OFDM-based radar-radio system is presented. The monopulse signal is composed of mult-OFDM symbols with random phase modulation, results in a high data rate. The analysis of the algorithm based on ambiguity function is presented. From theoretical analysis and simulation results, we can get that: (i) an expression of pulse compression loss due to Doppler is given, which is a function of the Doppler frequency and symbol number. In order to limit the compression loss, setting a limit to the allowed target velocity is needed. (ii) The phase codes which possess excellent aperiodic auto and cross correlation properties can improve range resolution. If the priori knowledge of the transmitted data is known, we can use pre-coding method that makes phase codes has a better correlation properties to both improve the range performance and data rate.

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