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Automatic target recognition using waveform diversity in radar sensor networks

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Abstract

In this paper, we perform a number of theoretical studies on constant frequency (CF) pulse waveform design and diversity in radar sensor networks (RSN): (1) the conditions for waveform co-existence, (2) interferences among waveforms in RSN, (3) waveform diversity combining in RSN. As an application example, we apply the waveform design and diversity to automatic target recognition (ATR) in RSN and propose maximum-likehood (ML)-ATR algorithms for non-fluctuating target as well as fluctuating target. Simulation results show that our waveform diversity-based ML-ATR algorithm performs much better than single-waveform ML-ATR algorithm for non-fluctuating targets or fluctuating targets. Conclusions are drawn based on our analysis and simulations.

Keywords: Radar sensor networks; Waveform diversity; Automatic target recognition; Maximum-likelihood; Interferences; Ambiguity function

1. Introduction

The network of radar sensors should operate with multiple goals managed by an intelligent platform network that can manage the dynamics of each radar to meet the common goals of the platform, rather than each radar to operate as an independent system. Therefore, it is significant to perform signal design and processing and networking cooperatively within and between radar sensors. In this letter, we will study waveform design and diversity for radar sensor networks.

In the existing works on waveform design and selection, Bell (1993) used information theory to design radar waveform for the measurement of extended radar targets exhibiting resonance phenomena. In (Baum, 1991) singularity expansion method was used to design some discriminant waveforms such as K-pulse, E-pulse, and S-pulse. Sowelam and Tewfik (2000) developed a signal selection strategy for radar target classification, and a sequential classification procedure was proposed to minimize the average number of necessary signal transmissions. All the above studies and design methods were focused on the waveform design or selection for a single active radar or sensor. In (Skolnik, 2001) cross-correlation properties of two radars are briefly mentioned and the binary coded pulses using simulated annealing (Deng, 1996) are highlighted. However, the cross-correlation of two binary sequences such as binary coded pulses (e.g. Barker sequence) are much easier to study than that of two analog radar waveforms. In this paper, we will focus on the waveform diversity and design for radar sensor networks using constant frequency (CF) pulse waveform.

The rest of this paper is organized as follows. In Section 2, we study the co-existence of radar waveforms. In Section 3, we analyze the interferences among radar waveforms. In Section 4 we propose a RAKE structure for waveform

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diversity combining and propose maximum-likelihood (ML) algorithms for automatic target recognition (ATR). In Section 5, we provide simulation results on ML-ATR. In Section 6, we conclude this paper and provide some future works.

2. Co-existence of radar waveforms

For radar sensor networks, the waveforms from different radars will interfere with each other. We choose constant frequency (CF) pulse waveform for radar i as

$$x_i(t) = \sqrt{\frac{E}{T}}\exp[\mathrm{j}2\pi(\beta+\delta_i)t], \quad -T/2 \leqslant t \leqslant T/2 \tag{1}$$

which means there is a frequency shift δ_i for radar i. To minimize the interference from one waveform to the other, optimal values for δ_i should be determined to have the waveforms orthogonal to each other, i.e., let the cross-correlation between $x_i(t)$ and $x_n(t)$ be 0

$$\begin{aligned}\int_{-T/2}^{T/2} x_i(t)x_n^*(t)\mathrm{d}t &= \frac{E}{T}\int_{-T/2}^{T/2}\exp[\mathrm{j}2\pi(\beta+\delta_i)t] \\ &\quad\times\exp[-\mathrm{j}2\pi(\beta+\delta_n)t]\mathrm{d}t \\ &= E\mathrm{sinc}[\pi(\delta_i-\delta_n)T]\end{aligned} \tag{2}$$

If we choose

$$\delta_i = \frac{i}{T} \tag{3}$$

where i is a dummy index, then (2) can have two cases

$$\int_{-T/2}^{T/2} x_i(t)x_n^*(t)\mathrm{d}t = \begin{cases} E & i=n \\ 0 & i\neq n\end{cases} \tag{4}$$

So choosing $\delta_i = \frac{i}{T}$ in (1) can have orthogonal waveforms, i.e., the waveforms can co-exist if the carrier spacing is $1/T$ between two radar waveforms. However, orthogonality among the reflected waveforms (echoes) may not hold because of time delay and doppler shift ambiguity during transmission and reflection, so we need to study the interferences of waveforms in RSN.

3. Interferences of waveforms in radar sensor networks

3.1. RSN with two radar sensors

We are interested in analyzing the interference from one radar to another if there exist time delay and doppler shift. For a simple case where there are two radar sensors (i and n), the ambiguity function of radar i (considering interference from radar n) is

$$\begin{aligned}A_i(t_i,t_n,F_{D_i},F_{D_n}) &= \bigg|\int_{-\infty}^{\infty}[x_i(t)\exp(\mathrm{j}2\pi F_{D_i}t). \\ &\quad + x_n(t-t_n)\exp(\mathrm{j}2\pi F_{D_n}t)]x_i^*(t-t_i)\mathrm{d}t\bigg|\end{aligned} \tag{5}$$

$$\begin{aligned}&\leqslant \bigg|\int_{-T/2+\max(t_i,t_n)}^{T/2+\min(t_i,t_n)} x_n(t-t_n) \exp(\mathrm{j}2\pi F_{D_n}t)x_i^*(t-t_i)\mathrm{d}t\bigg| \\ &\quad + \bigg|\int_{-T/2+t_i}^{T/2} x_i(t) \exp(\mathrm{j}2\pi F_{D_i}t)x_i^*(t-t_i)\mathrm{d}t\bigg| \\ &= \bigg|\int_{-T/2+\max(t_i,t_n)}^{T/2+\min(t_i,t_n)} x_n(t-t_n) \exp(\mathrm{j}2\pi F_{D_n}t)x_i^*(t-t_i)\mathrm{d}t\bigg| \\ &\quad + \left|\frac{E\sin[\pi F_{D_i}(T-|t_i|)]}{T\pi F_{D_i}}\right|\end{aligned} \tag{6}$$

To make analysis easier, we assume $t_i = t_n = \tau$, then (6) can be simplified as

$$\begin{aligned}A_i(\tau,F_{D_i},F_{D_n}) &\approx |E\mathrm{sinc}[\pi(n-i+F_{D_n}T)]| \\ &\quad + \left|\frac{E\sin[\pi F_{D_i}(T-|\tau|)]}{T\pi F_{D_i}}\right|\end{aligned} \tag{7}$$

3.2. RSN with M radar sensors

It can be extended to an RSN with M radars. Assuming time delay τ for each radar is the same, then the ambiguity function of radar 1 (considering interferences from all the other $M-1$ radars with CF pulse waveforms) can be expressed as

$$\begin{aligned}A_1(\tau,F_{D_1},\ldots,F_{D_M}) &\approx \sum_{i=2}^{M}|E\mathrm{sinc}[\pi(i-1+F_{D_i}T)]| \\ &\quad + \left|\frac{E\sin[\pi F_{D_1}(T-|\tau|)]}{T\pi F_{D_1}}\right|\end{aligned} \tag{8}$$

4. Waveform diversity and combining with application to ATR

In RSN, The radar sensors are networked together in an ad hoc fashion. Scalability concern suggest a hierarchical organization of radar sensor networks with the lowest level in the hierarchy being a cluster. In RSN, each radar can provide their waveform parameters such as δ_i to their clusterhead radar, and the clusterhead radar can combine the waveforms from its cluster members. In RSN with M radars, the received signal for clusterhead (assume it is radar 1) is

$$r_1(u,t) = \sum_{i=1}^{M}\alpha(u)x_i(t-t_i)\exp(\mathrm{j}2\pi F_{D_i}t) + n(u,t) \tag{9}$$

where $\alpha(u)$ stands for complex radar cross section (RCS) and its magnitude can be modeled using non-zero con-