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Architecture, Parameters Estimation and Coherent Performance Analysis of a Distributed Network Radar System

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Abstract

In this study, a general signal-processing architecture and signal model based on orthogonal frequency division linear frequency modulation (OFD-LFM) signal and feedback mechanism are proposed for distributed network radar system (DNRS). Furthermore, the influence of coherence accuracy, such as the accuracy of parameters estimation, the accuracy of spatial synchronization and the baseband frequency distance of OFD-LFM signal, on radar performance is simulated using this signal model. The relationship between these accuracy factors and the detection signal-to-noise ratio (SNR) is discussed based on the simulation.

1 Introduction

Modern radar technologies allow detection of complex targets with low visibility over large distances, without sacrificing the stealth capability of the station. Such objectives are nearly impossible to achieve with one single transceiver by merely increasing its radiation aperture or transmitting power. To this end, early efforts mainly focuses on applying bi-static or multi-static radar systems [1]. Absent of coherence technologies, these systems took advantage of additional information implicated in the spatial scattering characteristics of electromagnetic fields, thus, combined with statistical processing and parameter estimation methods, increasing the visibility of weak targets and eliminating possible blind areas [2].

Based on the multi-static theory, latest network radar systems, i.e. distributed network radar systems (DNRS) or distributed coherent radar systems (DCRS) introduce time-frequency synchronization and coherence in the signal processing. By effectively adding a multi-input-multi-output (MIMO) detection stage and calibrating the time and phase in a fully coherent manner in the following stages, the radiation aperture and the transmitting power of each radar node is fully utilized. Theoretically, when operating in a fully coherent mode, the DNRS or DCRS can achieve a N^3 times signal-to-noise ratio (SNR) enhancement compared to a single radar node with equivalent power, in which N is the number of radar nodes. Meanwhile, by spatially organizing the radar node and applying a single-input-multi-output (SIMO) detection mode, the detectability of the radar system can be significantly reduced. During recently years, validation systems of coherent network radars are built, mostly consisting two nodes or three nodes. Their detection models are analyzed, and their performance is simulated and measured [3–5].

Due to high requirement of time, frequency, and spatial synchronization capability of the network radar system, the SNR enhancement of the radar is usually compromised or even deteriorated due to the practical system inaccuracy. Accordingly, in network radar systems, one crucial question is how the accuracy of synchronization and parameter estimation affects the detection performance of the radar system. This paper tries to answer this question by first establish a complete signal model in a two node DCRS. The return signal is fully parameterized with respect to the time, phase, and frequency synchronization accuracy. Then, with analytical simulations, the relationships between the SNR enhancement and the synchronization accuracy as well as the parameter estimation accuracy are characterized, and the result analyzed.

The rest of this paper is organised as follows. Section 2 gives a typical architecture of DNRS. Section 3 simulates the performance of the radar system under different parameter estimation accuracies and coherent accuracies. The paper is concluded with Section 4.

2 General Architecture of DNRS

There are two architectures for DNRS, that is, the master-slave architecture and the cooperative architecture. In the master-slave architecture, all radars transmit signals while only a master radar receives the echoes. However, in the cooperative architecture, all radars transmit signals and receive signals, and their data are transferred to a processing center for the coherent parameters (CPs) estimation. The cooperative architecture provides an improvement in processing gain for the coherence parameter estimates relative to the master-slave arrangement. In this section, we only discuss the cooperative architecture whose workflow is illustrated in Figure 1.

Firstly, the DNRS works in multi-input multi-output (MIMO) mode, CPs are estimated and a improvement on SNR

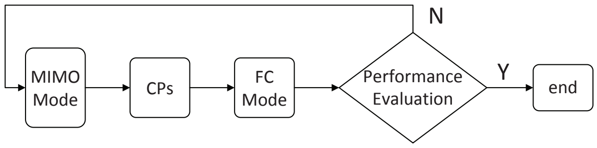

Figure 1. Workflow of DNRS

gain could be obtained. Then, the DNRS turns to fully coherent (FC) mode, CPs are estimated again and used to realise coherent on transmit and receive and a better improvement on SNR gain is obtained. Eventually, if the coherent performance is not good, the DNRS will turn to MIMO mode to re-estimate CPs.

3 Simulation and Analysis

In this section, the workflow and coherent performance of DNRS are simulated with MATLAB. Then, the influence of coherence accuracy, such as the accuracy of parameters estimation, the accuracy of spatial synchronization and the baseband frequency distance of OFD-LFM signal, on radar performance is discussed and simulated as well. In the following simulations, assumed that DNRS has 2 unit radars with 2 transmitters and 2 receivers, pulse repetition period is $10\,\mu$s, chirp signal is selected as the baseband signal, time width $T = 1\,\mu$s and bandwidth $B = 10$ MHz, the carrier frequency $f_0 = 2.4$ GHz, peak power of transmitter $P_t = 0.1$ W, radar cross section of the target $\sigma = 0.3\,\mathrm{m}^2$. In order to improve the receiving SNR of radar echo, multi-pulses coherent integration is adopted. Echoes, through a matched filter, are integrated coherently by Fourier transformation in the slow time dimension, the maximum values of each distance direction are the echoes after coherent integration, the number of integration period $N = 50$. The SNR at the receiver of DNRS $SNR_i = -20$ dB. The channel noise is the additive white Gaussian noise (AWGN).

3.1 Coherent Performance Simulation of DNRS

By coherent processing, N^2 and N^3 SNR gain could be obtained (N is the number of unit radars) in MIMO mode and FC mode. In this simulation, assumed that the baseband frequency distance between two radars $|f_2 - f_1| = 5$ MHz, main lobe gain of transmitter and receiver $G = G_t = G_r = 20$ dB.

Figure 2 and Figure 3 show that 6 dB and 9 dB SNR gain are obtained in MIMO mode and FC mode over a single radar. This simulation results verify that the signal-level fusion algorithm in DNRS is right.

3.2 Influence of Parameters Estimation Accuracy on Coherent Performance

Precise estimations of CPs are the premise and the core to realise signal-level fully coherent synthesis in DNRS. How-

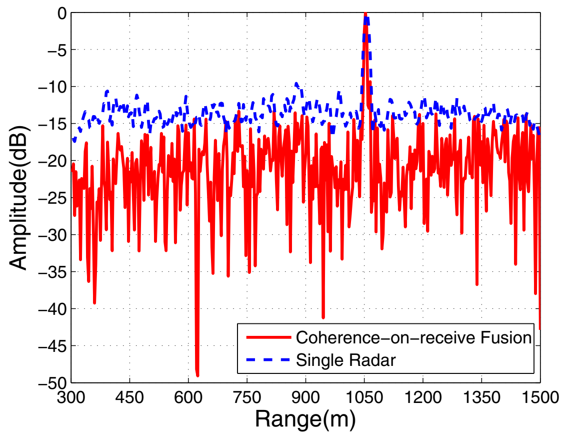

Figure 2. Output signals after coherent synthesis in MIMO mode

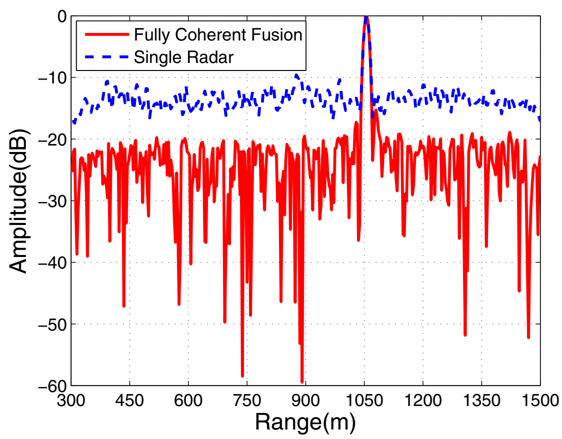

Figure 3. Output signals after coherent synthesis in FC mode

ever, if there are errors in parameters estimation, coherent synthesis performance will be affected.

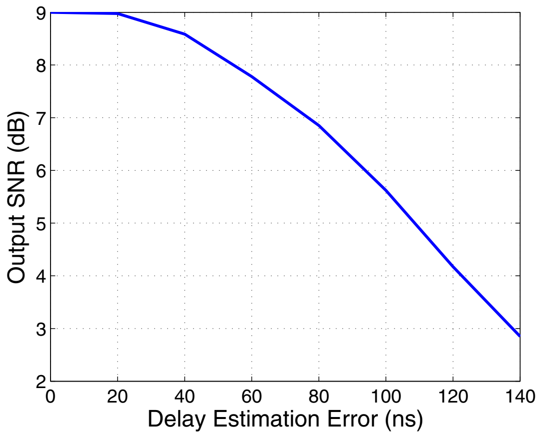

Figure 4. Influence of delay estimation errors on radar performance

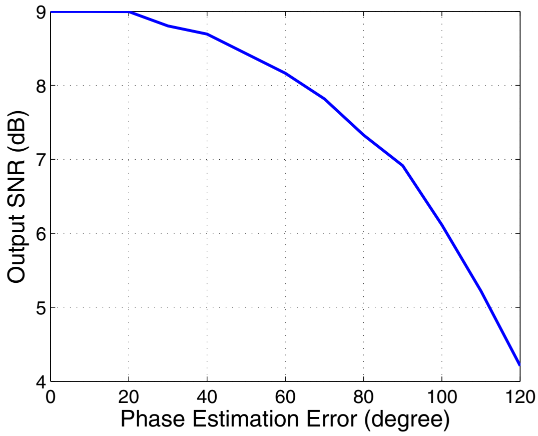

Figure 5. Influence of phase estimation errors on radar performance

In this simulation, the influence of parameters estimation accuracy on coherent synthesis performance is investigated. Assumed that there is no error in phase estimation when influence of delay estimation error on the coherent synthesis performance (improved output SNR) is simulated. In a similar way, there is no error in delay estimation when influence of phase estimation error on the coherent synthesis performance is simulated. The main lobe gain of transmitter and receiver $G = G_t = G_r = 20\,\text{dB}$, distance between the target and radar A, $R_A = 1050\,\text{m}$, distance between the target and radar B, $R_B = 950\,\text{m}$. Each value point is obtained by 100 times independent simulation. Figure 4 shows that with the increase of delay estimation error, the coherent synthesis performance of DNRS (improved output SNR) gradually decreases. In order to achieve good synthesis performance, the time delay estimation error should be controlled in $(0,40)\,\text{ns}$. Figure 5 shows that with the increase of phase estimation error, the coherent synthesis performance of DNRS also decreases gradually. In order to achieve good synthesis performance, the phase estimation error should be controlled in $(0,60)$ degree.

3.3 Influence of Baseband Frequency Distance on Parameters Estimation Accuracy

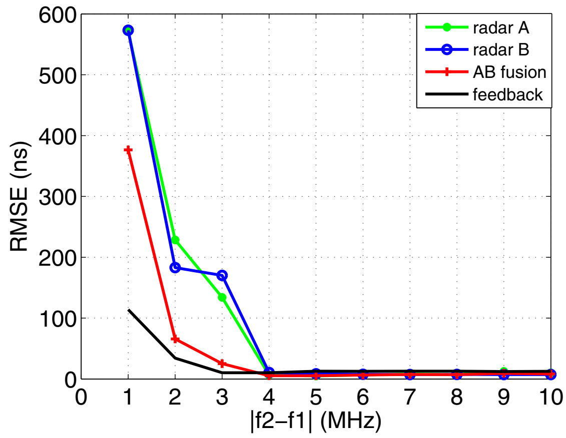

Figure 6. Influence of baseband frequency distance on delay estimation accuracy

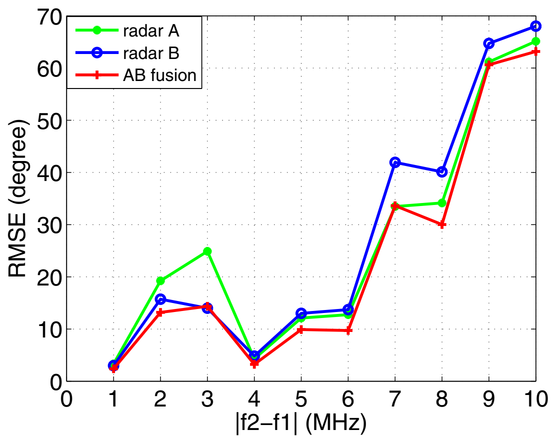

Figure 7. Influence of baseband frequency distance on phase estimation accuracy

In this simulation, the influence of baseband frequency distance on parameters estimation is investigated. Assumed that main lobe gain of transmitter and receiver $G = G_t = G_r = 20\,\text{dB}$, $f_s = 1/T = 1\,\text{MHz}$. The baseband frequency of radar A, $f_1 = 0\,\text{MHz}$, and the baseband frequency of radar B, $f_2 = \lambda f_s, \lambda = 1 \sim 10$, thus, the frequency distance $|f_2 - f_1| = \lambda f_s$, distance between the target and radar A, $R_A = 1050\,\text{m}$, distance between the target and radar B, $R_B = 900\,\text{m}$. RMSE represents root mean square error of parameters estimation. Each value point is obtained by 100 times independent simulation. Figure 6 shows that with the increase of the baseband frequency distance, RMSE of delay estimation decreases gradually and finally tends to be stable. When the baseband frequency distance from 1 MHz to 4 MHz, RMSE is large. So the appropriate baseband frequency distance should be from 4 MHz to 10 MHz. Noted that when the baseband frequency distance is small, feedback mechanism can significantly reduce RMSE of parameters estimation. Figure 7 shows that with the increase of the baseband frequency distance, RMSE of phase estimation increases generally. Combined Figure 5 and Figure 7, in order to achieve good synthesis performance, the appropriate baseband frequency distance should be from 1 MHz to 8 MHz. From the above analysis of delay and phase estimation, the appropriate baseband frequency distance should be from 4 MHz to 8 MHz.

3.4 Influence of Spatial Synchronization Accuracy on Coherent Performance

When the spatial synchronization between transmitter and receiver is realized, that means the main lobe of the receiving and transmitting antenna is aligned with the target, and the target reflection signal can be well received. However, when the spatial synchronization error occurs, which means the main lobe of the receiving antenna is not aligned with target, the receiving SNR enhancement will be affected.

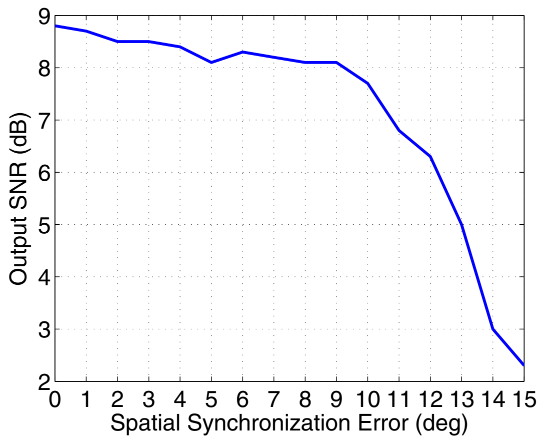

Figure 8. Analysis of coherent synthesis performance based on spatial synchronization error

In this simulation, the influence of spatial synchronization accuracy on coherent synthesis performance is investigated. Assumed that maximum of main lobe gain of transmitter and receiver $G = G_t = G_r = 20\,\text{dB}$. The distance between the target and radar A, $R_A = 1050\,\text{m}$, distance between the target and radar B, $R_B = 950\,\text{m}$. The antenna aperture $d = 3\,\text{m}$, thus, the 3 dB beam width (half power angle) is 21 degrees. Each value point is obtained by 100 times independent simulation. Assumed that the delay difference and phase difference have been compensated accurately. Figure 8 shows that with the increase of spatial synchronization error, the coherent synthesis performance of DNRS (improved output SNR) gradually decreases. In order to achieve good synthesis performance, the spatial synchronization error should be controlled in $(0, 9^\circ)$.

4 Conclusion

In this paper, a novel signal-processing architecture and signal model based on orthogonal frequency division linear frequency modulation (OFD-LFM) signal and feedback mechanism are proposed for DNRS. The signal-level fusion algorithm of DNRS is verified with simulations and a great SNR enhancement is achieved in MIMO mode and FC mode respectively. Furthermore, some technological challenges of DNRS, such as the accuracy of parameters estimation, the accuracy of spatial synchronization and the baseband frequency distance of OFD-LFM signal on radar performance has been investigated. The research work in this paper will be very helpful to the realisation and application of the new radar technology of DNRS.

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