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Optimization for distributed Radar Sensor Network (RSN) and MIMO-RSN in flat fading channels

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ABSTRACT

Investigation in distributed Radar Sensor Network (RSN) and MIMO-RSN are more like two parallel paths other than one research field in current literature. In this paper, we address the comparison between optimal fusion scheme of distributed-RSN and optimal power control of MIMO-RSN for target detection. We first establish the wireless statistic channel model for these two types of RSNs under flat fading channel condition. Using Jake's model, Rayleigh flat fading channel is obtained. Then we provide optimization for the fusion scheme and the power control. Both amplitude and phase of the received signals are applied to the optimal/suboptimal fusion schemes for the distributed-RSN. Water-filling, the optimal power control scheme is utilized in the MIMO-RSN, where two suboptimal schemes (equal power and channel inversion) are also investigated to provide a comparison. The detection performance is analyzed and compared in terms of probability of detection (P_d) and probability of false alarm (P_{fa}). The simulation results show that the water-filling in MIMO-RSN achieves the best performance, whereas the optimal fusion scheme for distributed-RSN obtains worse performance than the equal power control in MIMO-RSN, and the channel inversion in MIMO-RSN gets the worst performance, which has almost the same performance as the suboptimal fusion scheme in distributed-RSN.

1. Introduction

Radar Sensor Network (RSN) can be utilized to investigate a large area and observe targets from different directions. Distributed RSN employs distributed radar sensors that are monostatic. Each sensor contains only one transmitting and receiving element and it works independently [1].

Investigations show the advantage of distributed RSN over a single radar for target detection performances. Liang [2] studies on constant frequency (CF) pulse waveform design and diversity in RSN and apply to automatic target recognition (ATR). He also proposes maximum-likelihood (ML)-ATR algorithms for nonfluctuating target as well as fluctuating target. Liang [3] proposes an orthogonal waveform model for the system, which eliminates interference when no Doppler shift is introduced. She also studies orthogonal waveforms and spatial diversity under the condition of the Doppler shift in both coherent and noncoherent distributed RSNs [1]. Xu [4] investigates the use of information theory to design waveforms for the measurement of extended radar targets in distributed RSN. Ly [5] works on a diversity scheme based on waveform design and space–time adaptive processing to improve the detection performance of Radar Sensor Networks in the presence of certain types of interference.

Concept of MIMO radar is motivated by the development in communication theory: MIMO systems can

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achieve high capacity with space division multiple access benefits applied.

Studies illustrate that MIMO systems have the potential to dramatically improve the performance of detection over single antenna systems. Fishler [6] carries out MIMO radar system design and performance analysis in terms of the Cramer–Rao bound of the mean-square estimating on the target direction. Li and Stoica [7] show that waveform diversity enables the MIMO radar superiority in several fundamental aspects. Xu [8] considers MIMO radar waveform optimization for multiple targets in the presence of spatially colored interference and noise. Robey [9] introduces MIMO radar processing techniques that utilize multiple space–time coded waveforms with multiple receive phase centers to obtain enhanced radar performance. Unlike beamforming, which presumes high correlation between signals either transmitted or received by an array, the MIMO concept exploits the independence between signals at the array elements.

Although current literature has seen superior potentials of both distributed-RSN and MIMO-RSN, fusion scheme of distributed-RSN is seldom investigated. Only some works of data fusion have been explored [10]. Power control in MIMO system has been explored under different conditions [11–16]. However, their principle objective is the increase in network capacity or energy efficiency, ignorant of the improvement in target detection performance.

To the best of our knowledge, this is the first time that the fusion scheme and power control optimization of the two RSNs are compared under flat fading condition in terms of target detection performance. In this work, the optimal (maximal ratio combining, MRC)/suboptimal (equal gain combining, EGC) fusion scheme of distributed-RSN, optimal (water-filling)/suboptimal (equal power and channel inversion) power control of MIMO-RSN are all analyzed under a flat fading channel condition. MRC products a set of weight values to signals to maximize the output. EGC applies signal phase to avoid counteractive effect of opposite phase. Water-filling cut out some bad state channel to save energy. Equal allocation uses no information of channel state. Channel inversion, allocating power to get the same signal to noise ratio (SNR) in each channel, is applied as a comparison.

The remainder of this paper is organized as follows. Section 2 proposes channel models of distributed-RSN and MIMO-RSN. Section 3 describes the combining method for target detection. Section 4 provides simulation with analysis, and Section 5 summarizes our investigation.

2. Channel models of distributed-RSN and MIMO-RSN

We model the wireless propagation of RSN under small scale multipath fading since RSN sensors are powered by battery with small range of detection. The received signal at baseband is

$$r(t) = \left[\sum_{n=1}^{N} \alpha_n(t) e^{-j2\pi f_c \tau_n(t)}\right] x(t-\tau) \tag{1}$$

where $\alpha_n(t)$ and $\tau_n(t)$ are the gain and delay of the *nth* scatterer, respectively. Thus the complex gain of the channel is

$$\begin{aligned}\rho(t) &= \sum_{n=1}^{N} \alpha_n(t) e^{-j2\pi f_c \tau_n(t)} \\ &= \sum_{n=1}^{N} \alpha_n(t)\cos\theta_n(t) - j\cdot\sum_{n=1}^{N}\alpha_n(t)\sin\theta_n(t) \\ &= A(t) - j\cdot B(t).\end{aligned} \tag{2}$$

Rayleigh fading is investigated here as it is the most commonly used model. Due to the non-line-of-sight (NLOS) propagation, $E[A(t)] = E[B(t)] = 0$. Based on the Central Limit Theorem, $A(t)$ and $B(t)$ are Gaussian random variables with identical and independent distribution when N is large enough. The joint pdf of $A(t)$ and $B(t)$ is

$$f_{AB}(a,b) = \frac{1}{2\pi\sigma_z^2}\exp\left[-\frac{a^2+b^2}{2\sigma_z^2}\right] \tag{3}$$

which leads to the Rayleigh distribution amplitude $\alpha = \sqrt{A^2(t)+B^2(t)}$ with parameter σ_z,

$$f_\alpha(x) = \frac{x}{\sigma_z^2}\exp\left[-\frac{x^2}{2\sigma_z^2}\right], \quad x \ge 0. \tag{4}$$

Many techniques have been used to model the Rayleigh fading channel. Jakes model, which is chosen in this work, is a simplified and widely used method to simulate the frequency nonselective Rayleigh fading channel based on the idea of sum of sinusoids (SOS), assuming that N equal strength rays arrive at a moving receiver with uniformly distributed arrival angles. Eq. (2) is reformulated into:

$$\begin{aligned}\rho(t) &= \rho_I(t) + j\cdot\rho_Q(t) \\ &= \sqrt{2}\left\{\left[2\sum_{N}^{n=1}\cos\beta_n\cos 2\pi f_n t + \sqrt{2}\cos\alpha\cos 2\pi f_m t\right]\right. \\ &\quad \left. + j\left[2\sum_{N}^{n=1}\sin\beta_n\cos 2\pi f_n t + \sqrt{2}\sin\alpha\cos 2\pi f_m t\right]\right\}\end{aligned} \tag{5}$$

where

$$f_n = f_m\cos(2\pi n/N), \quad n = 1, 2, \ldots, M,$$

$$M = \frac{1}{2}\left(\frac{N}{2}-1\right). \tag{6}$$

The random phase $\beta_n = \phi_n = -2\pi(f_c+f_m)\tau_n$, and $\alpha = \beta_N$.

The model of distributed-RSN is showed in Fig. 1, where ρ_{1i} and ρ_{2i} are the complex channel gain of the signal transmitted and received by sensor i respectively. Thus,

$$A_{ri} = G_l\cdot\alpha\cdot\rho_{1i}\cdot\rho_{2i}\cdot A_{ti} \tag{7}$$

where A_{ti} and A_{ri} are the transmitted and received signals of sensor i, G_l is the product of transmit and receive antenna gain, and α is the radar cross-section parameter. The average received power of sensor i is

$$E[A_{ri}^2] = E\{[\rho_{1i}\cdot\rho_{2i}]^2\}\cdot A_{ti}^2 = 4\eta^4 A_{ti}^2 \tag{8}$$

assuming that ρ_{1i} and ρ_{2i} are independent and has the same Rayleigh parameter η.