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Multitarget detection in heterogeneous radar sensor network with energy constraint

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ABSTRACT

Heterogeneous radar sensor networks (HRSNs) are gaining popularity due to the superior detection performance compared to conventional homogeneous radar sensor networks. In this paper, under the assumption that radar sensors perform differently in target detection and energy management, we propose optimized energy allocation scheme based on different fusion approaches for both single moving target and multiple moving targets. For one target detection situation, two decision fusion algorithms, the optimized energy allocation – likelihood ratio (OEA-LR) and the optimized energy allocation – approximate likelihood ratio (OEA-ALR) are proposed to improve the system detection performance given system energy constraint. In multi-target detecting environment, two decision fusion algorithms, namely likelihood ratio with ML function (LR-ML) and approximate likelihood ratio with ML function (ALR-ML) are also investigated and the optimized energy allocation scheme, the algorithm of likelihood function with the minimum Bayes risk (LF-BR) are also proposed. Performances are compared and analyzed in terms of probability of detection, probability of false alarm, detection probability of multiple hypothesis, number of local RSs, etc. via simulations. The proposed approaches not only optimize the energy allocation in HRSNs, but also offer an appropriate tradeoff between resource consumption and target detection performance.

1. Introduction

Traditional radar sensor networks (RSNs) apply homogeneous radar sensors with the same capabilities in target detection, energy supply, memory storage, communication and reliability, etc. However, RSNs are made up of time-varying channels due to the mobility of targets, performance bottleneck in a homogeneous RSN has been demonstrated via theoretical analysis, simulation experiments and testbed measurements [1]. Heterogeneous radar sensor networks (HRSNs) consisting of multi-sensors with different modalities (e.g., video/audio, acoustic/seismic, optical/wireless, stationary/mobile, and chemical/electrical) are gaining popularity in recent sensor developments including battlefield surveillance, environment, structure monitoring and others [2–6]. These literatures showed that HRSNs can significantly improve network performance compared to conventional RSNs.

HRSNs possess dissimilar energy resources: some sensors may directly connect to electrical energy systems without energy constraints, whereas other wireless sensors are powered by limited batteries with different capacities. Therefore, equal stress on energy efficiency and sensing mobility is not the case for HRSN. Careful resource management, i.e., how to balance the energy dissipation of powerful and energy-constrained sensors while considering different degrees of target detection in HRSN is still an open research issue.

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Decision fusion in distributed detection has been developed extensively in the past decades. Without considering the fading channel, the optimum decision fusion rules have been proposed assuming that the local sensors are independent [7,8]. Data fusion rules based on statistical correlation of the observations have also been investigated [9,10]. The above results are mainly obtained with the assumption of lossless communication, which is not realistic for HRSNs, where the transmitted information has to experience both channel fading and noise. Motivated by this, the optimal decision fusion rule over fading channel and noise has been developed and the optimum fusion rules for both low and high SNRs have also been investigated [11–13]. In RSN, in order to improve the multi-targets detection performance, different types of radar waveforms have been considered [14,15] and different graphical deployment strategies of RSs have been analyzed [16]. In most wireless sensor network (WSN) applications, resource constraints, especially the energy constraint often limit the transmission range for each sensor node. Radio transmission is the major power consumers among all the functions for a sensor node. Therefore, many methods, such as optimizing power allocation and sensor selections have been investigated to solve the problem of detection with constrained system resources [17–20]. Nevertheless, all the above decision fusion rules have been developed in homogeneous sensor networks.

In this paper, we explore decision fusion rules with optimized power allocation schemes in HRSNs, which consist of heterogeneous radar sensors (RSs) with different target detection performances. We consider a set of RSs deployed in a large area to detect the presence of moving targets. These RSs are stationary and able to transmit signals adaptively with a proper energy cost.

Based on the heterogeneity of HRSNs, for one target detection situation, two decision fusion algorithms, namely the optimized energy allocation – likelihood ratio (OEA-LR) and the optimized energy allocation – approximate likelihood ratio (OEA-ALR) are proposed and compared to improve the system detection performance given system energy constraint. In multi-target detecting environment, we assume that the local RSs can not only detect whether the target is present or not, but also recognize which target is detected. Therefore, the binary coding method is applied to assign a binary bit to each target, making the multiple target detection problem a multiple hypotheses test, i.e., 2^M hypotheses for M targets. We not only propose three decision fusion algorithms, namely likelihood ratio with ML function (LR-ML), approximate likelihood ratio with ML function (ALR-ML) and the algorithm of likelihood ratio with the minimum Bayes risk (LF-BR) for multi-target detection, but also raise the optimized energy allocation scheme in multi-target detecting environment.

The remainder of this paper is organized as follows. Section 2 formulates the decision fusion rules for single target detection over fading channels and additive Gaussian white noise (AWGN) in HRSNs, obtains the optimized energy allocation scheme and analyzes the target detection performance. Section 3 propose the decision rules for multi-target detection in HRSNs and formulates the problem of energy allocation optimization. Simulation results and performance analysis are provided in Section 4. Section 5 concludes this paper.

2. Fusion rules of single target detecting

2.1. Fusion rules

In this work, we apply a parallel fusion model that a number of heterogeneous RSs sending data based on H_0 (target-absent) or H_1 (target-present) to the fusion center over fading channels and AWGN shown in Fig. 13. We assume that the kth local RS transmits $u_k \in \{+v_k, -v_k\}$ to the fusion center with the probability of false alarm P_{fk} and the probability of detection P_{dk}, respectively, i.e., $P\{u_k = +v_k/H_0\} = P_{fk}$ and $P\{u_k = +v_k/H_1\} = P_{dk}$, $k = 1, \dots, K$. The observation of the kth RS at the fusion center is

$$y_k = u_k \times h_k + n_k \tag{1}$$

where h_k is the kth channel's fading envelope with $h_k > 0$, and n_k is zero mean Gaussian noise with variance σ^2.

Using the fusion model above and assume local RSs are independent, we can get the expression of the optimal likelihood ratio (LR) fusion statistic $\Lambda(\mathbf{y})$, depending on the prior information of fading channel h_k, noise variance σ^2 and local RS's performances P_{fk}, P_{dk}.

$$\Lambda(\mathbf{y}) = \frac{f(\mathbf{y}/H_1)}{f(\mathbf{y}/H_0)} = \prod_{k=1}^{K} \frac{P_{dk} e^{-(y_k - v_k h_k)^2/2\sigma^2} + (1-P_{dk}) e^{-(y_k + v_k h_k)^2/2\sigma^2}}{P_{fk} e^{-(y_k - v_k h_k)^2/2\sigma^2} + (1-P_{fk}) e^{-(y_k + v_k h_k)^2/2\sigma^2}} \tag{2}$$

where $\mathbf{y} = [y_1, \dots, y_K]$ is a vector containing the observations of all the local RSs at the fusion center. The approximate expression of the logarithm of LR at low SNR can be expressed as

$$X = \sum_{k=1}^{K} (P_{dk} - P_{fk}) y_k h_k v_k \tag{3}$$

2.2. Energy allocation via optimization

There are four parts of energy consumption for the local RSs, namely sending signal to the target, receiving radar echoes from the target, sending message to the fusion center, and calculation. Compared with the other three parts, calculation consumption is the least and can be ignored here. For simplicity and clarification, we only optimize the allocation energy of sending message to the fusion center. Our task is to decide how much energy should be sent to the fusion center for each local RS. X shown in (3) follows Gaussian distribution with mean μ_x and variance σ_x^2. If each channel experiences independent Rayleigh fading with unit power ($E[h_k^2] = 1$), then we have

$$\mu_{x/H_i} = \mathbf{a}_i^T \mathbf{t}, \quad \sigma_{x/H_i}^2 = \mathbf{t}^T \mathbf{B}_i \mathbf{t} + \mathbf{c}^T \mathbf{t} \sigma^2, \quad i = 0, 1 \tag{4}$$

Where,

$$\mathbf{t} = [t_1, \dots, t_K]^T, \quad \mathbf{c} = [c_1, \dots, c_K]^T$$
$$\mathbf{a}_i = [a_{i1}, \dots, a_{iK}]^T, \quad \mathbf{b}_i = [b_{i1}, \dots, b_{iK}]^T, \quad i = 0, 1 \tag{5}$$

$\mathbf{B}_i$ is a diagonal matrix whose diagonal elements are vector $\mathbf{b}_i$ and the elements of vector $\mathbf{t}$, $\mathbf{c}$, $\mathbf{a}_i$, $\mathbf{b}_i$ are defined in Table 1. Denote the system level detection probability and