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Distributed detection of a non-cooperative target via generalized locally-optimum approaches

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ABSTRACT

In this paper we tackle distributed detection of a non-cooperative target with a Wireless Sensor Network (WSN). When the target is present, sensors observe an unknown random signal with amplitude attenuation depending on the distance between the sensor and the target (unknown) positions, embedded in white Gaussian noise. The Fusion Center (FC) receives sensors decisions through error-prone Binary Symmetric Channels (BSCs) and is in charge of performing a (potentially) more-accurate global decision. The resulting problem is a one-sided testing with nuisance parameters present only under the target-present hypothesis. We first focus on fusion rules based on Generalized Likelihood Ratio Test (GLRT), Bayesian and hybrid approaches. Then, aimed at reducing the computational complexity, we develop fusion rules based on generalizations of the well-known Locally-Optimum Detection (LOD) framework. Finally, all the proposed rules are compared in terms of performance and complexity.

1. Introduction

1.1. Motivation and related works

Wireless sensor networks (WSNs) have attracted significant attention due to their potential in providing improved capabilities in performing detection and estimation [1,2], reconnaissance and surveillance, with a wide range of applications, comprising battlefield surveillance, security, traffic, and environmental monitoring [3]. Distributed detection is among the fundamental tasks that a WSN needs to accomplish which has been investigated in the recent years [4].

Due to bandwidth and energy constraints, it is often assumed that each sensor quantizes its own observation with a single bit before transmission to the FC. This may be the result of a dumb quantization [5,6] or represent the estimated decision regarding the detection event [7–10]. In the latter case, the decisions of individual sensors are collected by the FC and combined according to a specifically-designed fusion rule aiming at improved detection performance. In [11], the optimum strategy to fuse the local decisions at the FC has been obtained under the conditional independence assumption. The optimal fusion rule in both Neyman–Pearson and Bayesian senses, which is derived from the likelihood ratio test [12], is commonly referred to as *Chair-Varshney* (CV) rule. It amounts to a threshold detector on the weighted sum of binary sensor detections, with each weight depending on sensor detection and false alarm probabilities.

Unfortunately, the local detection probability is seldom known or difficult to estimate when the detection event relates to revealing a target described by a spatial signature. In fact, in the latter case the detection probability depends on the (unknown) constitutive parameters of the target to be detected, such as the average power and the target location (see Fig. 1.1). Without the knowledge of the local detection probabilities, the optimal fusion rule becomes impractical and an attractive alternative is the so-called*Counting Rule* (CR) test, i.e. the FC counts the number of local detections in the WSN and compares it with a threshold [13]. A performance analysis of the CR has been provided in [14] for a WSN with randomly deployed sensors. Unfortunately, CR suffers from performance degradation when trying to detect spatial events. Indeed, though CR is a very reasonable approach arising from different rationales [4,7,8], it does not make any attempt to use information about the contiguity of sensors that declare (potential) target presence. Therefore, based on these considerations, several studies have focused on design of fusion rules filling the performance gap between the CV rule and the CR.

In [15] a two-step decision-fusion algorithm is proposed, in which sensors first correct their decisions on the basis of neighboring sensors, and then make a collective decision as a net-

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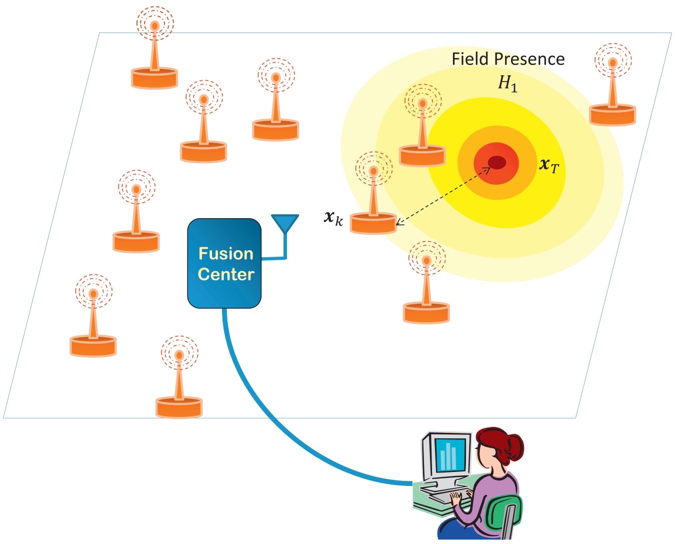

Fig. 1.1. Distributed detection of a non-cooperative target with spatial signature: system model.

work. It is shown that in many situations relevant to random sensor field detection, the local vote correction achieves significantly higher target detection probability than decision fusion based on the CR. Also, for the proposed approach, an explicit formula for FC threshold choice (viz. false-alarm rate determination) was provided, based on normal approximation of the statistic under the target-absent hypothesis. A simple and more accurate alternative for threshold choice based on the beta-binomial approximation is proposed in [16]. In [17] the Generalized Likelihood Ratio Test (GLRT) for the distributed detection of a target with a deterministic Amplitude Attenuation Function (AAF) and known emitted power is developed, and its superiority is shown in comparison to the CR. It is worth noticing that a similar model assuming a deterministic AAF was employed to analyze the (approximate) theoretical performance of CR in [14]. Differently, a stochastic AAF (subsuming the Rayleigh fading model) is assumed in [18] and [19], the latter being able to account for possible amplitude fluctuations. In the same works, also a scan statistic and Bayesian-originated approaches were obtained and compared with existing alternatives. In both works, the average emitted power of the target is however assumed *known*.

However, in many cases it is of practical importance to assume that also the (average) target emitted power is not available at the FC, which well fits the case of an *uncooperative* target, i.e. there is no preliminary agreement between target and sensors in order to exchange the information related to the (average) emitted power or make it possible to be estimated. Examples of practical interest for an uncooperative target are the primary user in a cognitive-radio system or an oil-spill source measured by an underwater sensor network. To the best of authors' knowledge, a few works have dealt with the latter case. In [20], a GLRT was derived for the case of unknown target position and emitted power and compared to the CR, the CV rule and a GLRT based on the awareness of target emitted power. It has been shown that the loss incurred by the proposed GLRT is marginal when compared to the "power-clairvoyant" GLRT. Differently, in [21] an asymptotic locally-optimum detector was obtained for a WSN with (random) sensors positions following a Poisson point process. Remarkably, the aforementioned study accounted for unknown emitted power. Unfortunately, the deterministic AAF there employed implicitly assumed that FC has available the target position, thus limiting its applicability, though some numerical analysis to investigate mismatched AAF performance was provided.

1.2. Summary of contributions

In this paper, we focus on decentralized detection of a non-cooperative target with a spatially-dependent emission (signature). We consider the practical setup in which the received signal at each individual sensor is embedded in white Gaussian noise[1] and affected by Rayleigh fading, with an AAF depending on the sensor-target distance (viz. stochastic AAF). The Rayleigh fading assumption is employed here to account for fluctuations of the transmitted signal due to multipath propagation. For energy- and bandwidth-efficiency purposes, each sensor performs a local decision on the absence/presence of the target and forwards it to a FC, which is in charge of providing a more accurate global decision. With reference to this setup, the main contributions of the present work can be summarized as follows:

- We first review the scenario where the emitted power is available (thus the sole target position is unknown) at the FC, in order to understand the basics of the problem under investigation and list various alternatives employed in the open literature, such as GLRT [17] and Bayesian approaches. Then we switch to the more realistic case of unknown target location and power, which is typical in surveillance tasks. In this context we provide a systematic analysis of several detectors based on: (*i*) GLRT [20], (*ii*) Bayesian approach and (*iii*) hybrid combinations of the two (for sake of completeness).
- In order to reduce the computational complexity required by these approaches, we also develop two *novel* sub-optimal fusion rules based on the locally-optimum detection framework [22]. The first relies on Bayesian assumption for the sole target position, whereas the latter obviates the problem by resorting to Davies rationale [23]. The design and the analysis of such practical rules and their comparison to the aforementioned alternatives represents the main contribution of this work. We underline that, since a uniformly most powerful test does not exist for our problem (because of the unknown parameters), nothing can be said in advance on their relative performance. All the aforementioned detectors are also compared in terms of computational complexity;
- The scenario at hand is then extended to the demanding case of imperfect reporting channels (typical for battery-powered sensors implementing low-energy communications), modeled as Binary Symmetric Channels (BSCs). The proposed fusion rules are then extended to take into account the (additional) reporting uncertainty, under the assumption of *known* Bit-Error Probabilities (BEPs).
- Finally, simulation results are provided to compare all the considered rules in some practical scenarios and to underline the relevant trends.

1.3. Paper organization and manuscript notation

The remainder of the paper is organized as follows: in Section 2 we describe the system model, with reference to local sensing and FC modeling. In Section 3.1 we recall and discuss the problem of distributed detection under the assumption of a known average target emitted power. Differently, Section 3.2 is devoted to the development of fusion rules which deal with the additional uncertainty of unknown power. Then, in Section 3.3 we extend the

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[1] The Gaussian assumption for measurement noise is only made here for the sake of simplicity; generalization of the present framework to non-Gaussian noise is possible and will be object of future studies.