Information Fusion 45 (2019) 190–201

Contents lists available at ScienceDirect

Information Fusion

journal homepage: www.elsevier.com/locate/inffus

Distributed decision fusion under nonideal communication channels with adaptive topology

Junhai Luo[*,a,b], Jing Ni[a], Zuoting Liu[a]

[a] School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China
[b] Department of Electrical Engineering and Computer Science, University of Tennessee Knoxville, Knoxville, TN, 37919, USA

A R T I C L E I N F O

Keywords:
Distributed detection
Decision fusion
Nonideal channels
Topology architecture
Neyman–Pearson criterion

A B S T R A C T

Multi-sensor decision fusion has attracted some attention in information fusion field, meanwhile, the distributed target detection has been a well-studied topic in the multi-sensor detection theory. This paper investigates the increase in detection reliability that an adaptive network (with adaptive topologies and nonideal channels and decision fusion rules) can provide, compared with a fixed topology network. We consider a network, consisting of K-local uncertainty sensors and a Fusion Center (FC) tasked with detecting the presence or absence of a target in the Region of Interest (ROI). Sensors transmit binary modulated local decisions over nonideal channels modeled as Gaussian noise or fading channels. Assuming that the signal intensity emitted by a target follows the isotropic attenuation power model, we consider three classes of network topology architectures: (1) serial topology; (2) tree topology, and (3) parallel topology. Under the Neyman–Pearson (NP) criterion, we derive the optimal threshold fusion rule with adaptive topology to minimize the error probability. Extensive simulations are conducted to validate the correctness and effectiveness of the proposed algorithms.

1. Introduction

As we all know, multi-sensor data fusion is mainly divided into two types, namely centralized data fusion and distributed data fusion. In a centralized data fusion system, the flow of information proceeds from the sensing nodes to the central control node, usually through multiple hops. The control node collects all the data while carrying out the computations, and makes a decision. Conversely, in a distributed data fusion system, there is typically an iterated exchange of data among the nodes. It determines an increase of the time necessary to reach a decision. Because distributed data fusion system has the advantages of greater performance and reliability than centralized data fusion system, we usually adopt the detection system in distributed multi-sensors. Distributed decision fusion has been studied for serval decades and numerous research results have been proposed. Employing distributed detection [1,2], each local sensor makes a decision based on its own observation and transmits it to the Fusion Center (FC) which makes the global decision according to the results of the local sensors. Although centralized detection achieves the highest performance, it is at the cost of large bandwidth and more communication energy to obtain real-time results. Hence, distributed detection is a preferable research direction [4–6].

Three basic fusion topology architectures are well known: namely parallel topology [7–12] serial topology [13–15] and tree topology [13–16]. The authors in [3,10] summarized three types of topology architectures. Unlike parallel topology where all sensors make decisions independently, sensors in a serial structure cooperatively determine whether the target is present or not in the Region of Interest (ROI). The tree topology was introduced briefly [2], where each sensor with no children (named “leaf node”) sends a message to its immediate father, then any sensor upon receiving a message from all of its immediate children (named “branch node”) computes its own message, as a function of the received messages and its own observation, finally, the FC (the root of the tree) makes the final decision according to its own observation and the received messages. Tree topology architectures have been the focus on many types of studies for data fusion. However, there are still some inevitable problems. The parallel topology sends all data to the FC and aggravates the burden of the FC, while the serial topology increases transmission time and if there is a breaking point in the serial structure, decisions of sensors before this breaking point cannot contribute to the FC, which will lead to information loss. Tree topology increases the computational sources. Moreover, there are many difficulties facing data fusion in all kinds of environments. For example, in sensor networks, the communication range, the power of a sensor and the computational source are always limited.

Considering the nonideal communication channels, Eritmen and

* Corresponding author at : School of Electronic Engineering, University of Electronic Science and Technology of China, Chengdu, 611731, China.
E-mail addresses: junhai_luo@uestc.edu.cn (J. Luo), 814646634@qq.com, 18280288169@163.com (Z. Liu).

https://doi.org/10.1016/j.inffus.2018.02.001
Received 15 September 2017; Received in revised form 31 January 2018; Accepted 10 February 2018
Available online 13 February 2018

Keskinoz [23] investigated the distributed decision fusion in the hierarchical WSN, which consists of local sensors, local fusion centers (CLHs) and the FC. In the hierarchical system model, every local sensor transmits the decision to its own CLH and every CLH sends the transitional decision based on their own cluster members to the FC where the final decision is made. This paper took the fading and noise between the adjacent hierarchies into consideration and focused on binary hypotheses (e.g., corresponding to the absence and presence of a target respectively). Combining the model established above with the NP formulation, Eritmen and Keskinoz [23] derived Likelihood Ratio Test (LRT) -based fusion rules named LRT-CSI and LRT-CS, utilizing the complete fading Channel State Information (CSI) and exact phase information together with Channel envelope Statistics (CS) respectively. Finally, Eritmen and Keskinoz [23] analyzed the computation complexity and numerical results.

In [26], the authors developed the channel aware decision fusion rule involving multi-hop transmissions in canonical parallel structure. Assuming a simple memoryless relay scheme and a flat fading channel, the LRT decision fusion rule is derived for the two cases: with complete channel knowledge and with the knowledge of channel fading statistics. For two cases, by relaxing the requirement of the amount of prior information that is not or hard to be available in a real implementation, the authors further reduced the LRT-based fusion rules to some simple suboptimum form at low and high channel SNR, respectively.

In this paper, we consider a network/system with M sensors/local detectors and the FC. The task of this network is to detect the presence of absence of a target in ROI at a specific location. We state a serial topology decision fusion rule under nonideal channels called as Serial Reconstruction Rule (SRR). We focus on the fusion algorithm based on tree topology combined with the orderly full binary tree and discuss the optimal threshold fusion rule problem. Different from the conventional tree topology, the sensors in tree topology are well ordered and the fusion center achieves the highest Signal Amplitude (SA). A fusion decision rule which takes the channel noise into consideration based on this topology is presented. Meanwhile, the fusion rule of the parallel structure under the noisy channel is stated. By introducing the probability of error, we prove that with equal prior probability there is a concave function of the likelihood ratio threshold used in the sensor decision rule. In the case of minimizing the probability of error, the optimal threshold can be obtained.

The main contributions of this paper are as follows:

- We consider three classes of network topologies: sequential topology, tree topology and parallel topology and derive the decision rules to minimize the error probability at the FC when the communication channels are modeled as Gaussian noise with zero- mean and variance σ^2.
- Under NP criterion, the optimal local thresholds are proposed for the LRT of the local decision fusion rules between the sensors and the FC. These optimal rules, although different for network topologies are all LRTs over nonideal communication channels.
- Compared with the detection performance of different topologies and the optimization of target detection, this paper is an effort to bridge this gap and overcome the rather unexplored venue. Simulation results show that the detection performance is improved and superior to other fusion algorithms
- Compared with the hierarchical structure in [23], the detection performance of tree topology achieves improvement due to combining the local observation of CLHs and the FC.
- Compared with the optimal LRT-based fusion rules using parallel topology in [26], we propose how to determine the optimal threshold value which results in the better performance of this work.

The remainder of this paper is organized as follows. Section 2 briefly reviews some existing distributed decision fusion algorithms. Section 3 addresses the multi-sensor fusion problem description. Section 4 presents distributed fusion algorithms for three types of topologies under nonideal channels. Section 5 proposes the optimal threshold fusion rules. We present numerical results in Section 6 and conclude in Section 7.

2. Related work

Data fusion has been proposed as an effective signal processing technique to improve the system-wide performance of distributed systems, especially distributed data fusion. In distributed detection system, binary detection has some advantages over other detection approaches in terms of the required bandwidth, reliability, and complexity. In binary detection, the central processor processes only binary decisions (0 or 1) received from the distributed sensors. There are two major criteria for optimum binary distributed detection: Bayesian criterion and NP criterion. Note that the communication channels between sensors and the FC or inter-sensor channels in numerous classical literature are considered to be ideal (error-free).

In [3], the authors solved the problem of the optimal threshold under the Bayesian criterion. It was shown that when local decisions are independent, the optimal fusion rule is to minimize the probability of error which is a quasiconvex function of the likelihood ratio threshold if the prior probabilities of the two hypotheses are known. In [8,9], the authors analyzed the problem of distributed Bayesian hypothesis testing with data fusion and presented different generalized formulations. A novel two-tier calibration approach was proposed for fusion, and the problem of system-level calibration for target detection was formulated based on the two-tier approach. The problem of serial-distributed detection over a noisy channel was the subject of an in-depth analysis.

A more detailed analysis was made on parallel topology and serial topology by Yin et al. [8], Kailkhura et al. [9], Huang and Bode [10], Bentley [11], Viswanathan and Aalo [12] and the comparison was drawn. In [12], the paper described an algorithm for decentralized estimation in 2-tree networks that correctly accounts for common information in communication, allowing consistent and scalable operation. It showed the correct operation of the algorithm on 2-tree networks, mixed 1 and 2-tree networks, and operation with missing nodes and links. In [9], considering the problem of optimal Byzantine attacks or data falsification attacks on distributed detection mechanism in tree-based topologies, the authors presented an algorithm to solve their problems in polynomial time. In [14], the authors provided a general framework to show how an efficient design of a wireless sensor network requires a joint combination of in-network processing and communication. In particular, they showed that inferring the structure of the graph describing the statistical dependencies among the observed data can provide important information on how to build the sensor network topology and how to design the flow of information through the network. In [16], the authors proposed a centralized hard fusion scheme accepting discrete sensor decisions without requiring a priori probability of target presence.

In [17,18], each sensor made a local decision by conducting the LRT and sent the local decision to the FC to perform global log-LRT, then the FC made a final decision. In [19], a Uniformly Most Powerful (UMP) detector based on the LRT was developed, and an elegant test rule for target presence or absence was also derived. Typically, the performance of local sensors was hard to calculate. Therefore in [20], a suboptimal fusion rule requiring less prior information was proposed, which we called Counting Rule (CR). CR employed the total number of decisions transmitted from local sensors for hypothesis testing at the FC. In [21], CR was extended to the case where the total number of sensors was uncertain. Authors in [22–25] took into account of the imperfect communication channels between the sensors and the FC, such as noisy channels and fading channels. In [22], noisy communication links were considered and a Bayesian framework for distributed detection was presented, where noisy links were modeled as Binary Symmetric Channels (BSC). In [23], distributed detection fusion was investigated