On-Line Sensor Fault Detection Based on Majority Voting in Wireless Sensor Networks

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Abstract

Wireless sensor networks (WSN) are composed of a large number of sensor nodes and usually used to monitor a region of interest. The sensor nodes are very prone to damage due to low-cost design and random deployment. Additionally, faulty nodes may degrade the performance of the distributed hypothesis testing. This work addresses fault isolation in WSN where the fusion center attempts to identify faulty nodes through temporal sequences of received local decisions. Owing to the computing capability constraint in WSN, the primary goal of this investigation is to design a low-complexity sensor fault detection scheme, which can detect most sensor faults by using the majority voting technique. The simulation results show the proposed approach is effective in terms of identifying faulty members in a network.

1 Introduction

The problem of distributed decision fusion in wireless sensor networks (WSN) has received much attention because of many important applications [1], [4], [6], [8]. Sensor nodes in WSN are deployed in the region of interest for collecting data. All sensor nodes transmit their decisions to a fusion center after determining individual decisions. The fusion center then makes a final decision based on these preliminary local decisions.

WSN usually consist of a large number of sensor nodes, which are deployed in inaccessible and harsh environments. Furthermore, the sensor nodes are prone to damage as a result of low-cost design and random deployment. Additionally, placing sensor nodes in inaccessible areas makes them irreplaceable. Therefore, the design of distributed detection in WSN needs to be fault tolerant. The types of sensor faults in WSN may range from simple stuck-at faults to random sensor faults, which render prior failure probability models unsuitable for the design of distributed detection in WSN. For this reason, the primary goal of this study is to design an effective fault detection scheme, which can tolerate most sensor faults by employing the fusion technique.

The fusion center may make a wrong decision when the combined effect of the number of faulty nodes and sensor fault types is great. In order o provide fault-tolerance capability in distributed detection, the detection system can remove the unreliable local decisions transmitted from faulty sensor nodes during the process of final decision making. This work considers the fault detection based on a collaboratively sequential detection scheme. The problem formulation in this study is that fusion center needs to identify faulty nodes at every time step. In the decision fusion process, the data of faulty nodes will be discarded for making more dependable final decisions. The considered scenario can be applied in many applications such as forest fire monitoring and surveillance system, etc. The deployed sensor network in these applications may need to report its decision at every time step; for this reason, an appropriate strategy can be immediately selected when an unexpected event occurs.

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Some related investigations have addressed several variants of fault detection problems. Fault detection problems by central testing can be found in [2], [3]. The distributed fault detection problem for general nonlinear, non-Gaussian stochastic systems with multiple sensor nodes has been addressed [5]. The work in [7] applies the non-parametric statistics-based technique for identifying the faulty sensor nodes in a sensor network.

This work also considers the problem of sensor fault detection as follows. The fusion center can identify a faulty node by judging whether its behavior is very different from the others since each node sends its local decision to the fusion center at every time step. Therefore, a sensor fault detection scheme with a record table, which records the history of all local decisions during the fusion process, is proposed. Because of the computing capability constraint in WSN, the proposed scheme just applies the majority voting technique to differentiate between normal nodes and faulty nodes.

The remainder of this investigation is organized as follows. Section 2 formally presents the system model and the problem formulation. The details of the proposed sensor fault detection scheme are described in Section 3. Section 4 shows the performance evaluation of the proposed approach by simulation. Finally, conclusions are drawn in Section 5.

2 System model

This section provides the system model and the considered sensor fault types.

2.1 Network operation

A two-layer detection system is considered in this work, as illustrated in Fig. 1. The parallel fusion system, which consists of N identical sensor nodes and a fusion center, is used to determine whether an unknown binary hypothesis is H_0 or H_1. The prior probabilities of H_0 and H_1 are assumed to be known. Each member of N sensor nodes is denoted by s_i, where i = 1, …, N. Let x_i^t denote the observation of the i^{th} sensor node and u_i^t denote the binary decision of the i^{th} node, where i = 1, …, N and t represents the time index. This study assumes that the observations across sensor nodes are independent and identically distributed condition on phenomenon.

Assume that an identical local decision rule is employed at each sensor node and each node independently makes a binary decision based only

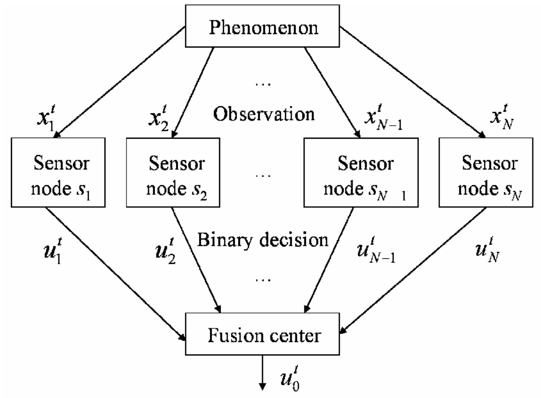

Figure 1. System model of a parallel fusion network.

on its observation. The local decision u_i^t of sensor node s_i is obtained through the local decision rule γ as

$$u_i^t = \gamma(x_i^t). \tag{1}$$

Each sensor node reports its local decision to the fusion center at each time step. A decision ‘0’ is sent if the sensor node makes a decision in favor of H_0; otherwise, a decision ‘1’ is transmitted.

Consider the fusion center is processing its information at time step t. All preliminary decisions up to time step t from all nodes are available at the fusion center. The fusion center begins to identify faulty members by utilizing the proposed sensor fault detection scheme. In the fusion process, the fusion center removes the data of faulty nodes for making a more believable final decision.

2.2 Sensor fault types

A sensor network is very likely to contain faulty nodes, because sensor nodes are usually low-cost and deployed randomly. Additionally, the sensor faults may include hardware or software damage resulting in all misbehavior; hence, the types of sensor faults are diverse.

Three kinds of sensor faults are considered in this work. In one fault type, a faulty sensor node is frozen to transmit a fixed local decision ‘0’ to the fusion center regardless of the real observation. This type of sensor fault is named stuck-at-zero fault. Similarly, a fault type is called stuck-at-one fault when a faulty node always transmits a fixed decision ‘1’. Another type of sensor fault is that a faulty sensor node reports randomly its decision regardless of the present hypothesis and called random fault. The fusion center in this study does not know the sensor fault types in advance. The proposed scheme identifies faulty members just according to the behavior of each node.

3 Sensor fault detection scheme

The identical local decision rule employed at each node is derived in this section. The record table, which records the history of all local decisions during the fusion process, is formally introduced. The record table actually plays a key role for fault detection in this study. The details of the proposed sensor fault detection scheme are described finally.

3.1 Local decision rule

The detection of known signals in Gaussian noise is considered in this study. The event observed by node s_i is $x_i^t = m + z_i^t$, where m is the transmitted signal and z_i^t is a Gaussian random variable with zero mean and unit variance. The density functions of the observation in H_0 and H_1 are respectively expressed as

$$P(x_i^t \mid H_0) = \frac{1}{\sqrt{2\pi}} e^{\frac{-(x_i^t)^2}{2}}, \tag{2}$$

$$P(x_i^t \mid H_1) = \frac{1}{\sqrt{2\pi}} e^{\frac{-(x_i^t - m)^2}{2}}. \tag{3}$$

The local decision rule is continuously derived. First of all, compute the log-likelihood ratio test with threshold λ and then get the equation as

$$\ln \frac{P(x_i^t \mid H_1)}{P(x_i^t \mid H_0)} \underset{u_i^t = 0}{\overset{u_i^t = 1}{\gtrless}} \ln \lambda. \tag{4}$$

After some mathematical manipulations with (2), (3), and (4), the following equation can be obtained

$$x_i^t \underset{u_i^t = 0}{\overset{u_i^t = 1}{\gtrless}} \frac{1}{m}(\ln \lambda + \frac{1}{2}m^2). \tag{5}$$

Equation (5) is the local decision rule employed at each sensor node for deciding the local decision. However, faulty nodes willfully report decisions regardless of the local decision rule.

3.2 Record table

This investigation considers that sensor nodes sequentially transmit local decisions to the fusion center. A sensor node can be reasonably assumed to be faulty when its behavior is very different from the majority of nodes. Recording the history of local decisions transmitted from all nodes is a method to represent the behavior of sensor nodes, since the fusion center receives each node's decision at every time step. Therefore, a record table is designed to record the behavior of each node at each time step. Let R_i^t denote the rate of decision '1', which has been transmitted to the fusion center by the i^{th} node at time step t as

$$R_i^t = \frac{1}{t}\sum_{j=1}^{t} u_i^j. \tag{6}$$

Each R_i^t shows the present condition of local decisions transmitted by s_i and is independent of all other nodes. For example, if a sensor node has ever sent three decisions '1' to the fusion center at the first five time steps, its rate of decision '1' is recorded as 3/5. For instance, a node has never transmitted decision '1' to the fusion center at the first seven time steps and then its rate of decision '1' is recorded as 0/7. The value of R_i^t is just between 0 and 1 obviously.

3.3 Proposed scheme

The fusion center can identify faulty nodes through comparing each node's behavior. The rates of decision '1' of normal sensor nodes are similar since they have the same density function. A sensor node has the highest probability to be faulty when its rate is very different from the other nodes. For making a distinction between normal nodes and faulty nodes, the proposed scheme divides the entire rate value into q equal regions. Let p_i denote the range of each rate region as

$$\text{range of } p_i = [\frac{i-1}{q}, \frac{i}{q}),$$

where i = 1, …, q. Exceptionally, the 1.0 rate value is included in the last rate region.

The R_i^t of each node can be corresponded to a rate region. At each time step, the number of nodes in each rate region is initialized to 0 first. After updating the record table, the R_i^t of each node is placed to the corresponding rate region. A rate region owning the maximum number of nodes can be easily found. The fusion center then identifies faulty nodes by using the majority voting technique. However, all normal nodes do not always exactly locate in the same rate region. Several normal nodes possibly locate in the neighbor regions. For this reason, the proposed scheme marks every three continuous rate regions to form a group except the first and the last groups. Let g_i denote the range of each rate group as

$$g_1 = p_1 + p_2,$$

$$g_i = p_{i-1} + p_i + p_{i+1},$$

$$g_q = p_{q-1} + p_q,$$

where i = 2, …, q−1. Rate groups are presently used to replace rate regions for lowering the probability of erroneous judgment. Similarly, the fusion center scans all rate groups for discovering a group which possesses the maximum count of nodes at each time step. A node is determined to be faulty by the fusion center if its rate does not locate in the group having the maximum number of sensor nodes.

The counts of nodes in different groups are sometimes equal. If two groups, g_a and g_b, have the same number of nodes, the fusion center will select g_a when rate region p_a has a larger count of nodes; if p_a and p_b also own the identical number of nodes, the detection system will randomly select one rate group.

4 Simulation results

The error rate of fault detection in this study is described first in this section. The performance of the proposed sensor fault detection scheme is then evaluated. The types of sensor faults and the actual number of faulty nodes are unknown in advance in these simulations.

4.1 Error rate of fault detection

This investigation decides the error rate of fault detection through comparing the results detected by the proposed scheme with the real conditions. For instance, the proposed approach identifies two faulty sensor nodes at time step t, but all nodes are actually normal. The error rate at this time step is indicated as $2/N$. For example, there are three faulty nodes in fact, but the proposed scheme only detects two of them. The error rate in this condition is then indicated as $1/N$. Restated, the error rate of fault detection in this work is the rate of difference between the detected result and the reality.

4.2 Simulation setup

This study lets the conditional densities at the sensor nodes be Gaussian with unit variance. Under H_0 and H_1, the mean at all nodes is assumed to be zero and m respectively. Accordingly, the signal-to-noise ratio (SNR) can be defined as $20 \log_{10} m$. The number of deployed nodes N is set to 10 in all simulated conditions, and the likelihood ratio threshold λ is set to 1. Let N_F denote the real number of faulty sensor nodes in the network. In the following simulations, the number of rate partitions q is set to 10.

Each simulated scenario is iterated 1,000,000 times to obtain the simulated performance. The true hypothesis and the fault type of individual faulty node are randomly decided at the beginning of every iteration step. The results with the time step on the horizontal axis and the error rate of fault detection on the vertical axis are illustrated in Fig. 2 to Fig. 6.

4.3 Results and analysis

The result at 0 dB SNR in a fault-free situation is shown in Fig. 2. The error rate rises in the first three time steps. The reason is no rate group can be formed in these three time steps because every possible value of rate is distinct from each other. Therefore, the fusion center identifies faulty nodes through comparing the number of nodes in each rate region. From time step four, several rate groups are formed and they lower the probability of erroneous judgment. Additionally, each R_i^t in this case is gradually similar to other normal sensor nodes. Nevertheless, sensor nodes in WSN are very likely to be faulty because of random deployment, low-cost design, and harsh environments. Therefore, the fault-free situation is not the primary issue in this study.

A network with two stuck-at-zero faults at 0 dB SNR is continuously simulated. Fig. 3 shows the result of fault detection. The rates of nodes are unstable in the first several time steps. Therefore, the corresponding rate regions of normal nodes are mutable. The error rate will gradually lower when time increases. The stuck-at-zero faults can be easily identified regardless of the true hypothesis H_1 or H_0. The reason is that the sensor faults deviate from the normal nodes significantly.

The performance of the proposed approach is demonstrated when two of the deployed sensor nodes are random faults. SNR is still set to 0 dB. In fact, the behavior of this fault type is not significantly different from that of a normal node. However, the faulty nodes can still be detected by applying the majority voting technique. The error rate of fault detection in this condition gradually declines, as illustrated in Fig.4.

An actual network probably contains various fault types at the same time. For convenience, a sensor network, which simultaneously contains three sensor fault types including stuck-at-zero fault, stuck-at-one fault, and random fault, is investigated. The fault type of individual faulty node is randomly decided at the beginning of every iteration step. The error rates of fault detection in the situations with two and three faulty nodes are respectively shown in Fig. 5 and Fig. 6. The results show most faulty nodes can be identified apparently. For this reason, the proposed scheme has the capability to assist the fusion center in making more dependable decisions by isolating most senor faults.

5 Conclusions

This study investigated the problem of detecting faulty sensor nodes by applying the majority voting technique at every time step. The simulation results show that the proposed scheme with a record table, which only records the rate of decision '1' of each node during the monitor process, is effective in terms of fault detection. Most importantly, the proposed sensor fault detection scheme does not need complex operations. For this reason, the precious energy resource in WSN could be saved. The number of faulty nodes in this investigation is fixed during the whole monitor process. This work will be continuously improved for dealing with the increasable number of faulty nodes in a network as the further work.

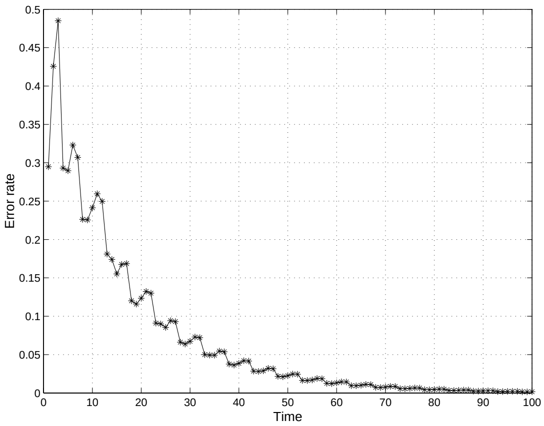

Figure 2. Error rate in a fault-free situation at 0 dB SNR.

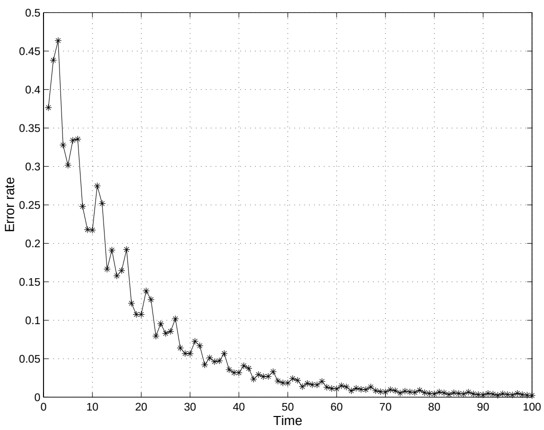

Figure 3. Error rate in a network with two stuck-at-zero faults at 0 dB SNR.

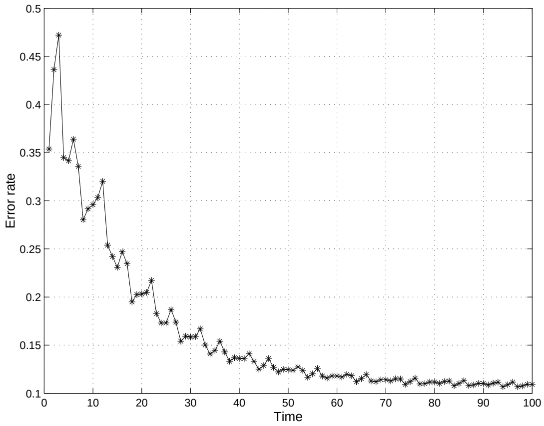

Figure 4. Error rate in a network with two random faults at 0 dB SNR.

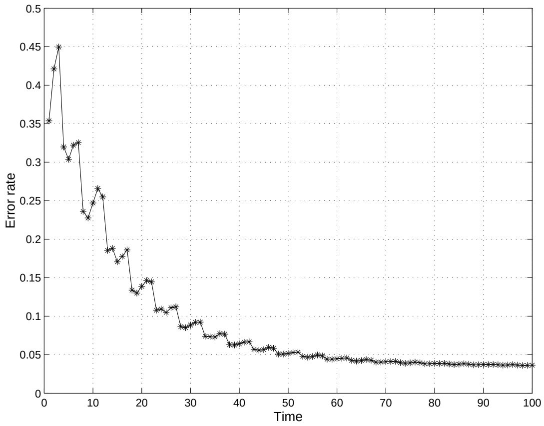

Figure 5. Error rate in a network with two mixed faults at 0 dB SNR.

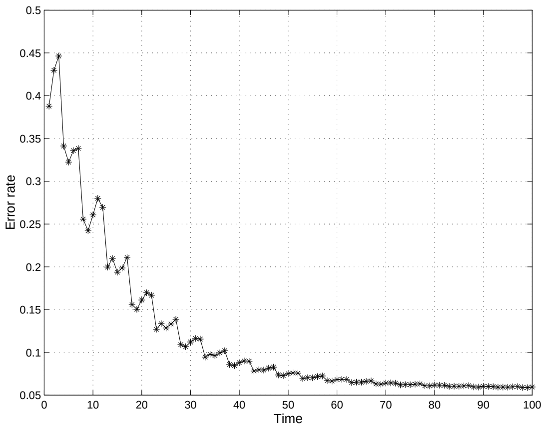

Figure 6. Error rate in a network with three mixed faults at 0 dB SNR.

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