Postprint: Node Diagnosability under the PMC Model for Network Faults

Authors: Liu Feng, Liang Jiarong, Guo Yang, Xie Min, Mo Haimiao

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Abstract

Fault diagnosis is of great importance in ensuring system stability. Traditional fault diagnosis research mostly overlooks local characteristics of the system. Under the PMC model, to address this issue, the concept of node diagnosability is introduced, and through research on node diagnosability methods, sufficient conditions for node diagnosability degree and a new t-diagnosable algorithm STFDA are obtained. Finally, n-dimensional hypercube networks and n-dimensional star networks are analyzed from the perspective of node diagnosability, the correctness of the obtained sufficient conditions is verified, and the algorithm is applied to these two types of networks for fault diagnosis. The implementation of the sufficient conditions and the STFDA algorithm utilizes a new structure ST. The time complexity of the STFDA algorithm is O(Nδ), where δ is the maximum degree of nodes in the network. Compared with other algorithms, the time complexity of the algorithm is significantly reduced.

Full Text

Preamble

Research on Node Diagnosability of Network Faults Under the PMC Model

Liu Feng[1,2], *Liang Jiarong*[1,2], *Guo Yang*[1,2], *Xie Min*[1], *Mo Haimiao*[1,2]

[1]School of Computer and Electronic Information, Guangxi University, Nanning 530004, China
[2]Guangxi Key Laboratory of Multimedia Communications and Network Technology, Nanning 530004, China

Abstract: Fault diagnosis is crucial for ensuring system stability. Most traditional fault diagnosis research has overlooked local structural characteristics.

To address this issue under the PMC model, this paper introduces the concept of node diagnosability. Through the study of node diagnosability methods, we obtain sufficient conditions for node diagnosability and propose a novel t-diagnosable algorithm called STFDA. Finally, we analyze n-dimensional hypercube networks and n-dimensional star networks from the perspective of node diagnosability, verifying the correctness of the derived sufficient conditions and applying the algorithm to diagnose faults in these two networks. The implementation of both the sufficient conditions and the STFDA algorithm utilizes a new structure called ST. The time complexity of the STFDA algorithm is O(Nδ), where δ represents the maximum degree of nodes in the network. Compared with other algorithms, this represents a significant reduction in time complexity.

Keywords: system-level fault diagnosis; PMC model; node diagnosability; ST structure; t-diagnosable algorithm

0 Introduction

With the continuous development of computer technology, the scale of processors in multiprocessor systems has reached thousands. Due to the increased scale and highly frequent data exchange among processors, faults in processing units are inevitable. To ensure system reliability, the system must have the capability for self-fault diagnosis to quickly, effectively, and accurately identify faulty processors. In network fault diagnosis, there are two main strategies: (a) circuit-level diagnosis, which requires external assistance and makes the diagnosis process overly complex and impractical; and (b) system-level diagnosis, which utilizes the processing capabilities of processors within the system to enable mutual testing and completes fault diagnosis through analysis of these test results.

In research on system-level diagnosis, Preparata et al. proposed the PMC model [1]. Under this model, a multiprocessor system is abstracted as an undirected connection graph G(V,E), where V represents the set of processors and E represents the connections between processors. If (v_i, v_j)   E, then v_i sends a test signal to v_j, and v_j sends feedback to v_i. By detecting the feedback signal, the state of v_j is determined. In the PMC model, if a system can diagnose all faulty processors when the number of faulty nodes does not exceed t, the system is called t-diagnosable. Since then, extensive research has been conducted on fault diagnosis under the PMC model. For example, Hakimi and Amin [2] provided characterization conditions for t-diagnosable systems; Guo et al. [3] studied conditional fault diagnosis under PMC; Liang and Chen [4] investigated the t-diagnosability of augmented hypercube networks; Dahbura and Masson [5] discussed t-fault diagnosis algorithms; and Ye and Liang [6] presented a five-round adaptive diagnosis algorithm for Hamiltonian networks, among others.

Notably, these research achievements primarily consider the global perspective, paying little attention to local structural features. However, ignoring local features sometimes causes us to lose important information, leading to unsatisfactory diagnosis results. For instance, suppose system S_1 is t_1-diagnosable and system S_2 is t_2-diagnosable. When S_1 and S_2 are connected through minimal links to form a composite system S_3, the overall diagnosability of S_3 is likely only min(t_1, t_2). That is, only when the number of faulty processors does not exceed min(t_1, t_2) can all faulty processors be diagnosed. In reality, however, t_1 + t_2 faulty processors can be accurately diagnosed because S_1 is t_1-diagnosable and S_2 is t_2-diagnosable. This performance degradation occurs because local features are ignored, reducing overall performance.

Additionally, industrial applications have demands for local diagnosis. According to these requirements, we only need to ensure that all faulty processors in a designated subsystem can be accurately diagnosed, without concern for the state of processors in other parts of the system. This demand for local diagnosis is common in large-scale and very-large-scale integrated systems.

This paper focuses on using node diagnosability [7] to study the node diagnosability degree and network fault diagnosis algorithms for local system components. Node diagnosability is similar to system diagnosability but can be viewed as system diagnosability on a local structure. Unlike system diagnosability, node diagnosability focuses more on whether a single node is faulty, emphasizing the detection of that node' s state. Using node diagnosability methods, we obtain sufficient conditions for determining node diagnosability under the PMC model. To satisfy these conditions, we further propose the ST structure. With the help of the ST structure, we design a t-diagnosable algorithm for network systems with time complexity O(Nδ), where δ is the maximum degree of nodes in the network. Many regular network topologies can model multiprocessor systems, among which hypercube networks [8] and star networks [9] are two classic examples. These networks have high concurrency and loose coupling characteristics, and research on them is abundant [10-13]. To verify the correctness of our conclusions, we finally analyze these two classic networks and apply our algorithm to them.

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1 Preliminary Knowledge

In the PMC model, processor faults are assumed to be permanent (not intermittent). A fault set represents the collection of all faulty processors. In a multiprocessor system G(V,E), processor v_i tests v_j, and the test result is denoted by a_{ij} (a_{ij}   {0,1}). If v_i tests v_j as faulty, then a_{ij} = 1; if v_i tests v_j as correct, then a_{ij} = 0; if v_i itself is faulty, the test result is random. Assign the value of a_{ij} to the directed edge <v_i, v_j> to obtain a directed weighted graph (V,C). The collection of all a_{ij} is called the syndrome s of the system. The system fault diagnosis problem is: using s and G(V,E) to find the fault set of the system. Figure 1 [Figure 1: see original paper] shows a 4-cube with fault set {P_0,P_2,P_3,P_5} under PMC.

For syndrome s, if there exists a node set F such that for all (x,y) C: if x F and y F, then a_{xy} = 0; if x F and y F, then a_{xy} = 1. Then F is said to be compatible with s, and F is an Allowable Fault Set (AFS) of s. Figure 2(a) [Figure 2: see original paper] provides a relevant example. Due to the randomness of fault diagnosis results, s may have multiple AFSs. When s has exactly one AFS, the system is t-diagnosable, and this AFS is the desired fault set.

Two different sets F_1 and F_2 are said to be distinguishable if and only if: there exists (x,y) C such that x F_1 F_2 and y F_1 F_2 (where denotes symmetric difference). It can be seen that if any two AFSs of system G(V,C) are distinguishable, then the system is t-diagnosable. Figure 2(b) [Figure 2: see original paper] shows an example where F_1 and F_2 are distinguishable.

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2 Node Diagnosability

As mentioned in the introduction, fault diagnosis research from a global perspective may overlook some local features of the system. This chapter uses node diagnosability to study local system components. Unlike system diagnosability, node diagnosability focuses on the diagnosability of a single node: if node x is faulty, regardless of whether other nodes can be detected, x must be detectable as faulty. Based on this, we obtain the definition of node diagnosability.

Definition 1. For system G(V,C), when x is faulty, if every AFS of G(V,C) contains node x, then node x is node diagnosable [7].

It can be seen that if faulty node x is node diagnosable, then x must be in the intersection of all AFSs. From this, we obtain the following inference.

Inference 1. For system G(V,C), if node x is node diagnosability, then for any two different subsets F_1 and F_2 of V, if x F_1 F_2, then F_1 and F_2 are distinguishable.

Node diagnosability can be viewed as system diagnosability on a local structure, and there is similarity between them. Corresponding to system diagnosability, the maximum t that satisfies the node diagnosability condition is called the node diagnosability degree of that node.

Theorem 1. Under the PMC model, system G(V,E) is t-diagnosable if and only if the node diagnosability degree of all nodes in the system is greater than or equal to t.

Proof.
Necessity. By contradiction, assume the system is not t-diagnosable. Then there must exist two different AFSs, F_1 and F_2, that are indistinguishable. Let x be

any node in F_1 F_2. Then this node is not node diagnosable, contradicting the premise.

Sufficiency. By contradiction, assume there exists a node x that is not node diagnosable. Then there exist F_1 and F_2 that are indistinguishable, contradicting the assumption that the system is t-diagnosable.

From Theorem 1, we can determine the t-diagnosability of a system by judging the node diagnosability degree of nodes in the system. This is very beneficial for studying the t-diagnosability of some highly symmetric networks because most nodes in these networks are equivalent, and we only need to diagnose the node diagnosability degree of a few or even one node.

Theorem 2. For system G(V,E), for any integer p ($0 \leq p \leq$ t-1), let S be any subset of V with cardinality p, and let x be a node in V-S. If $|L\ (S)| \geq 2(t-p)+1$, then the node diagnosability degree of x is greater than or equal to t.

Proof. By contradiction, assume the node diagnosability degree of x is less than t. From Inference 1, there exist unequal F_1 and F_2 with $|F_1|,|F_2| \leq t$ and x F_1 F_2 such that F_1 and F_2 are indistinguishable. Let S = F_1 F_2, then $|S| = p$. Since x S, we have x V-S. Let L (S) denote the maximum connected component in G(V-S) through node x, and |L (S)| represents the number of nodes in this component. Because F_1 and F_2 are indistinguishable, there exists a node y L (S) such that y F_1 F_2 and (x,y) E. Since F_1 and F_2 are indistinguishable, for any node w L (S), w F_1 F_2. Therefore, $|L\ (S)| \leq 2(t-p)$, contradicting the condition $|L\ (S)| \geq 2(t-p)+1$. Figure 3 [Figure 3: see original paper] shows two cases of L (S).

To satisfy the condition in Theorem 2, we present a special structure called ST.

Definition 2. For G(V,E), let x V. If there exists a subgraph H(V ,E) satisfying: V = {x} {v_1 | $1 \leq i \leq t$} {v_2 | $1 \leq i \leq t$}, E = {(x,v_1) | $1 \leq i \leq t$} {(x,v_2) | $1 \leq i \leq t$} {(v_1 ,v_2) | $1 \leq i \leq t$}, and $\deg(x) \geq t$, then this structure is called ST. Figure 4 [Figure 4: see original paper] shows a schematic diagram of the ST structure.

Theorem 3. For system G(V,E), if there exists an ST structure on x V, then the node diagnosability degree of x is greater than or equal to t.

Proof. In ST, arbitrarily select t-1 nodes other than x to form set S. From the ST structure, there must exist $|L\ (S)| \geq 2(t-p)+1$. From Theorem 2, the node diagnosability degree of x is greater than or equal to t. Figure 5 [Figure 5: see original paper] shows two possible subgraph examples.

Based on Theorems 1-3, we can obtain a sufficient condition for system t-diagnosability:

Inference 2. For G(V,E), the system is t-diagnosable if and only if: (a) $|V| \geq 2t+1$; (b) $\deg(v) \geq t$ for all v V; (c) ST exists on any node in V.

Research results on t-diagnosability are abundant [14]. For example, when $n \geq$

5, the t-diagnosability of n-dimensional hypercube networks (Q) is n [15]; when $n \geq 4$, the t-diagnosability of n-dimensional star networks (S) is n-1 [15]; when $n \geq 6$, the t-diagnosability of n-dimensional augmented hypercube networks is 2n-1 [12],[16,17], etc.

From Inference 2, if ST structure exists on every node of the system, then the system diagnosability is greater than or equal to t. Therefore, the node diagnosability problem is transformed into finding ST structures on nodes, which is obviously much simpler. For most network systems, especially regular networks such as crossed cubes, twisted cubes, augmented cubes, and star networks [9], as long as their dimensions are sufficiently large, it is easy to find ST structures on their nodes. Next, we will use the ST structure to obtain a new t-diagnosable algorithm for systems and apply it to Q and S to verify its effectiveness.

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3 Algorithm

Before presenting the algorithm, we introduce some necessary definitions. In the ST structure, there are directed diagnostic edges $<v_1 ,x>$ and $<v_2 ,x>$ ($1 \leq i \leq t$). The diagnostic results are denoted by a_1 and a_2 , with possible values shown in Figure 6 [Figure 6: see original paper]. Let R(a_1 ,a_2) represent the four possible cases of diagnostic results: R(0) = (0,0), R(1) = (0,1), R(2) = (1,0), R(3) = (1,1). Let |R(i)| denote the occurrence count of R(i) in ST, with Σ_{i=0}^{3} |R(i)| = t.

Theorem 4. For G(V,C), if the number of faulty nodes does not exceed t and ST structure exists on x V, then: (a) if |R(0)| > |R(1)|, then x must be correct; (b) if |R(0)| < |R(1)|, then x must be faulty.

Proof.
(a) By contradiction. Assume x is faulty. Then: if R(0) occurs, both v_1 and v_2 must be correct; if R(1) occurs, both v_1 and v_2 must be faulty; if R(2) or R(3) occurs, at least one of v_1 and v_2 is faulty. Therefore, there are at least |R(1)| + |R(2)| + |R(3)| faulty nodes in ST. Since |R(0)| + |R(1)| + |R(2)| + |R(3)| = t and |R(0)| > |R(1)|, we have |R(1)| + |R(2)| + |R(3)| > t/2, meaning there are more than t faulty nodes, contradicting the assumption that faulty nodes do not exceed t. Therefore, x must be correct.

(b) By contradiction. Assume x is correct. Then: if R(0) occurs, both v_1 and v_2 may be correct (no faulty nodes); if R(1) occurs, both v_1 and v_2 must be faulty; if R(2) or R(3) occurs, at least one of v_1 and v_2 is faulty. Therefore, there are at least |R(1)| + |R(2)| + |R(3)| faulty nodes in ST. Since |R(0)| < |R(1)|, we have |R(1)| > t/2, meaning there are more than t faulty nodes, contradicting the assumption. Therefore, x must be faulty.

Algorithm: STFDA
Input: G(V,C) with ST structure, where |V| = N and $t \leq (|V|-1)/2$
Output: Fault set F'

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begin:
1. Label all nodes from 0 to N-1; set i = 0;
2. While i < N do:
   a. Using Theorem 4, determine the state of node i and mark it.
      If correct, mark T and go to step 3;
      If faulty, mark F and go to step 4;
3. Based on node i's test results for its neighbors, determine and mark their states.
   If result is 0, mark T; if 1, mark F. i = i+1, go to step 2;
4. Mark all nodes with diagnostic result 0 as F, i = i+1, go to step 2;
5. After traversal, extract all nodes marked F as F'.
   If |F'| > t, the system is not t-diagnosable, exit;
   If |F'| $\leq$ t, F' is the desired fault set, end.
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Note: When there is a marking conflict (attempting to mark a node as T or F when it has already been marked as F or T), the system is not t-diagnosable, exit algorithm directly.

For quick and convenient lookup, the |R(i)| values of ST structures on nodes can be recorded in a diagnostic table. Assuming table lookup time is negligible, the diagnosis time for a node is O(δ), where δ is the node' s degree. Additionally, in regular networks, δ is generally small. The time complexity of these networks' diagnosis algorithms is O(Nδ).

In 1974, Hakimi and Amin proposed the necessary and sufficient conditions for t-diagnosability under the PMC model [2]. Based on this, Dahbura and Masson proposed a t-diagnosable algorithm [5]. Different from t-diagnosability, t/k-diagnosability requires that all faulty nodes can be isolated in a node set of size not exceeding t. Compared to t-diagnosability, it allows correct nodes to be misdiagnosed as faulty but ensures all faulty nodes are diagnosed. Hakimi and Chwa proposed the necessary and sufficient conditions for t/k-diagnosability under the PMC model [18], and Yang and Masson et al. proposed a t/k-diagnosable algorithm based on this [19]. Additionally, under the MM* model different from the PMC model, Sengupta and Dahbura proposed the necessary and sufficient conditions for t-diagnosability and gave a t-diagnosable algorithm under MM*. Tang and Yang improved this algorithm to reduce its time complexity to O($\delta\Delta^{2}\cdot{}^{5}$t) [20], where Δ and δ represent the maximum and minimum node degrees, respectively. The time complexity comparison of various algorithms is shown in Table 1 .

Table 1: Comparison of Time Complexities

Algorithm	Time Complexity
PMC Traditional t-diagnosable Algorithm	O(N$t^{2}\cdot{}^{5}$)
PMC Traditional t/k-diagnosable Algorithm	O(Nt^{3})
MM* Traditional t-diagnosable Algorithm	O($\delta\Delta^{2}\cdot{}^{5}$t)
STFDA Algorithm	**O(Nδ)**

Comparing the algorithms, the STFDA algorithm has a time complexity of only O(Nδ), which is much smaller than other algorithms, thus reducing implementation cost. Additionally, STFDA is simpler, more effective, easier to understand, and faster to implement.

4 Applications

Hypercube networks and star networks, as abstractions and representatives of various practical models, have been widely applied, such as hypercube networks in MIMD systems and BCube and MDCube in data center networks based on hypercube structures [21]. Hypercube networks have superior topological properties and can embed specific networks like ring networks, linear networks, and mesh networks [8]. As an abstraction and representative of these networks, hypercube networks are studied in this paper with our algorithm applied to them. The star network situation is similar and will not be elaborated.

We first prove that both networks have ST structures on their nodes, further obtain their diagnosability, verify the correctness of the derived diagnosability by checking it, and finally use the proposed STFDA algorithm to diagnose faults in these two network systems. Of course, how to implement the algorithm in practical networks requires further consideration.

4.1 n-Dimensional Hypercube Network (Q)

Hypercubes and their variants have excellent characteristics of high concurrency and loose coupling, making them suitable for system construction [22,23]. Research on their diagnosability is important and necessary.

An n-dimensional hypercube can be generated recursively from lower-dimensional cubes by connecting corresponding nodes of two (n-1)-dimensional cubes. Therefore, all nodes in a hypercube are equivalent. Figure 1 shows a 4-cube formed by connecting two 3-cubes. An n-dimensional hypercube contains 2^n nodes, labeled with n-bit binary numbers $a_1a_2 \cdots a$, where a {0,1} and $1 \leq i \leq n$. If two nodes are adjacent, their labels differ in exactly one bit. For example, node 0000 is adjacent to 0001 and 1000. The distance between any two connected nodes equals the number of different bits (Hamming distance).

Inference 3. The system diagnosability of Q is n when $n \geq 5$.

Proof. Label the nodes in ST as follows: x' s label is $a_1a_2 \cdots a$. Exchange the 1st and (i+1)th bits of x' s label to get a new label and assign it to v_1 , then exchange the 1st and (i+2)th bits to get a label and assign it to v_2 , where $1 \leq i \leq$ n-1. Figure 7(a) [Figure 7: see original paper] shows an ST labeling example on Q when $n \geq 5$. Therefore, ST structure exists on nodes of Q , and the node diagnosability degree is n. Since all nodes in Q are equivalent, from Inference 2, the system diagnosability of Q is n, consistent with known research [15].

Apply the STFDA algorithm to Q . First, label the nodes of Q . Second, starting from the node labeled 0, determine the state of node 0 by comparing the sizes of |R(0)| and |R(1)| on its ST structure, and mark it. Third, based on node 0' s test results for its neighbors, mark their states. Move to the next node and repeat the above operations until reaching node N-1. During diagnosis, if there is a node marking conflict or the number of nodes marked F exceeds t, then the number of faulty nodes exceeds t, and the algorithm exits directly. Otherwise, extract all nodes marked F as the fault set.

4.2 n-Dimensional Star Network (S)

Let S denote the n-dimensional star network [9]. S contains n! nodes, labeled with random permutations of numbers 1,2,⋯,n, such as 1234, 1243, etc. In S , nodes A = a_1a_2⋯a ⋯a and B = a_1a_2⋯a ⋯a are adjacent if exchanging the 1st and i-th bits of A' s label yields B' s label, where $1 < i \leq n$ and $i \neq j$. That is, if exchanging the 1st and i-th bits of node A' s label yields node B' s label, then A and B are adjacent. All nodes in S have degree n-1. Figure 8 [Figure 8: see original paper] shows the structure diagram of S .

Inference 4. The system diagnosability of S is n-1 when $n \geq 4$.

Proof. Label the nodes in ST as follows: x' s label is a_1a_2⋯a ⋯a . Exchange the 1st and (i+1)th bits (mod n) to get a new label and assign it to v_1 , then exchange the 1st and (i+2)th bits (mod n) to get a label and assign it to v_2 , where $1 \leq i \leq$ n-1. Figure 7(b) [Figure 7: see original paper] shows an ST labeling example on S when $n \geq 4$. Therefore, ST structure exists on nodes of S , and the node diagnosability degree is n-1. Since all nodes in S are equivalent, from Inference 2, the system diagnosability of S is n-1, consistent with known research [24].

Apply the STFDA algorithm to S . First, label the nodes of S . Second, starting from the node labeled 0, determine the state of node 0 by comparing the sizes of |R(0)| and |R(1)| on its ST structure, and mark it. Then, based on node 0' s test results for its neighbors, mark their states. Move to the next node and repeat the above operations until reaching node N-1. During diagnosis, if there is a node marking conflict or the number of nodes marked F exceeds t, then the number of faulty nodes exceeds t, and the algorithm exits directly. Otherwise, extract all nodes marked F as the fault set.

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5 Conclusion

This paper studied network node diagnosability under the PMC model from the perspective of local diagnosis, including node diagnosability degree and fault diagnosis algorithms. The conclusions are: (a) Node diagnosability degree is related to node degree. If an ST structure related to node degree t exists on system nodes, then the node diagnosability degree is greater than or equal to t; (b) For networks with ST structure, we propose a new fault diagnosis algorithm STFDA that is simple, effective, easy to understand, with time complexity O(Nδ), where δ is the degree of network nodes. In some regular networks, the time complexity is O(log N). For networks with ST structure, the algorithm significantly reduces fault diagnosis cost. However, for networks where ST structure does not exist on nodes, algorithm implementation is difficult. How to use node diagnosability methods for fault diagnosis in these networks is a problem for future research. Finally, we applied the algorithm to classic networks Q and S , achieving fault diagnosis for these abstract networks. Further research is needed on how to apply the algorithm to specific network systems, such as tree networks and Omega networks, for practical engineering implementation.

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Note: Figure translations are in progress. See original paper for figures.