# Diagnosis in a Network of Processors: Centralized and Distributed Models and Algorithms

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## Abstract

Fault diagnosis, testing and tolerance in large scale computer and communicatin systems is a topic of great interest to the computer and communications research communities. In this paper we give a broad survey of an area called system level diagnosis initiated by Preparata, Metze and Chien. Our survey includes different models of diagnosis and related diagnosis and dignosability algorithms. In particular, we have given a detailed view of distributed diagnosis. We believe most of these works form the foundation of the research in the emerging area of fault tolerance in a mobile environment.

## 1 Introduction

Continuing advances in the semiconductor technology have made possible the development of very large computer systems comprising hundreds of thousands of processors or units. As the complexity and the computing power of these systems increase, fault tolerance and reliability become acute areas of concern. Yet it is impossible to build such systems without defects. As the size of a system grows, it is more likely to develop faults both in the manufacturing process and during the operation period. Testing of such systems becomes extremely difficult due to their large sizes. First, the complexity of test generation for such large systems is overwhelming. Second, the application of test data, and observation and analysis of test responses are extremely difficult and costly, even if test data could be generated. This problem may be further aggravated by possible geographical distribution of units. Testing of such systems with the traditional stimuli-supplying and responses-observing philosophy has become virtually impossible. Therefore, it is important for computing systems to have the capability to automatically detecting and identifying components.

In 1967, Preparata, Metze and Chien [38] proposed a model and a framework, called ***System-Level Diagnosis***, for dealing with the above problem. In the more than four decades following this pioneering work, several issues arising from the application of this framework have been investigated and resolved. Many of these results have profound theoretical and practical implications. Most of the early research efforts in system-level diagnosis focused on theoretical advances with an effort to gain an understanding of fundamental algorithmic issues in this area. Subsequent efforts focused on enhancing the applicability of system-level diagnosis based approaches to practical scenarios. Specifically, the focus has been on: 1) Probabilistic diagnosis and application to VLSI testing and 2) On-line distributed diagnosis of a network of processors.

## 2 Models of System Level Diagnosis

In System-Level Diagnosis and the PMC model proposed by Preparata, Metze and Chien [38] for diagnosis of large systems, the units are made to test each other through the interconnects instead of having a centralized tester to test the whole system. The result of such an inter-unit test may be unreliable since the testing unit may be faulty itself. Therefore, the whole set of test outcomes must be analyzed to locate the real faulty units. No postulate is to be made in the course of test outcome analysis either on the status (fault-free or faulty) of any of the units or on the correctness of any of the test outcomes produced by the testing units. In the following, we will use units and nodes, system and network interchangeably.

Figure 1 shows an example of inter-node testing, where each node is represented by a vertex and each test by an arc. An arc from vertex *u* to vertex *v* means that *u* tests *v*. Test outcomes are classified as fault-free or faulty. The set of test outcomes is called the ***syndrome*** of the system.

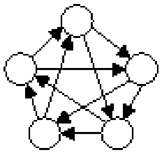
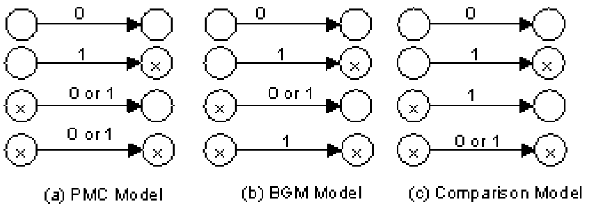


Fig. 1 A system with five units



(a) PMC Model (b) BGM Model (c) Comparison Model

Fig 2 Test outcomes under the PMC, BGM, and Comparison models

Legend: ⊗ faulty unit ○ fault-free unit

Nodes can test others or can be tested by others. It is assumed that test outcomes produced by fault-free testing nodes are always correct while those produced by faulty testing nodes can be anything (fault-free or faulty), irrespective of the status of the tested nodes. This kind of test outcome interpretation has since been known as the ***PMC model***. The PMC model is described in Figure 2(a). The labels on the arcs represent the possible test outcomes. The labels 0 and 1 correspond to the outcomes fault-free and faulty, respectively. Preparata, Metze and Chien also introduced the concept of *t*-diagnosable systems. A system is said to be ***t-diagnosable*** if all faulty nodes can be identified from any syndrome produced by the system as long as the number of faulty nodes present does not exceed *t*. The ***degree of diagnosability*** of a system is the maximum number of faulty nodes that can be diagnosed correctly.

There are three major issues associated with system-level diagnosis: the characterization problem, the diagnosability problem, and the diagnosis problem. The characterization problem is to find necessary and sufficient conditions to achieve a given degree of diagnosability in terms of test assignment, which specifies who tests whom. The diagnosability problem is to determine the degree of diagnosability for a given test assignment. Finally, the diagnosis problem is to identify the fault set from the test outcomes. Hakimi and Amin [18] presented the first full characterization of *t*-diagnosable systems. Sullivan [50] solved the diagnosability problem giving a polynomial-time algorithm to determine the largest value of *t* for which a given system is *t*-diagnosable. Dahbura and Masson [10] solved the *t*-fault diagnosis problem. They presented an $O(n^{2.5})$ diagnosis algorithm for *t*-diagnosable systems. Other works on t-fault diagnosis on the PMC model include [1] [24] [26] [37] [51] [46] [11].

In addition, several variations of the PMC model such as the BGM model (as in Figure 2(b)) have been proposed in the literature arising from different considerations of fault types, ways of testing, test invalidation, etc [4] [9] [34]. Chwa and Hakimi [9], and Maeng and Malek [34] suggested that the stimuli-supplying/response observing type testing schemes be replaced by comparison of computed results. This is known as the ***comparison model***. This model is described in Figure 2(c). The outcome, for each pair of nodes whose outputs are compared, is labeled 0(1), if the outputs agree (disagree). It is assumed that the outputs of a fault-free node and a faulty node always disagree and the outputs of faulty nodes may or may not disagree.

## 3 Diagnosis of Large Fault Sets

In multiprocessor systems, such as those implementable in VLSI and Wafer Scale Integration (WSI), the number of nodes - in this context we use nodes and processors interchangeably - in a system can be very large. Moreover, the commonly used interconnection networks such as the rectangular grids, and the hypercubes, are very symmetrical and sparse. If the testing links are the same as the communication links between the processors, the degree of t-diagnosability of such systems is very small. To address this issue, Somani, Agarwal and Avis [45] have proposed a generalized theory of diagnosis providing necessary and sufficient conditions for any fault pattern of any size to be diagnosable. Motivated by the need to be able to diagnose large fault sets in sparse systems Das et al. [14] introduced the concept of ***local diagnosis*** and proposed to place reasonable local constraints to achieve a higher overall diagnosability degree. They also showed that many regular interconnected structures such as the hypercube and the rectangular grid are locally diagnosable. They also presented a simple algorithm for diagnosis of such systems. This algorithm is also amenable for a distributed implementation. However, much work remains to be done with regard to the complete characterization of locally diagnosable systems and their diagnosis.

Sequential *t*-fault diagnosis and *t/s*-diagnosis allow for more nodes to be faulty in sparsely connected systems at the cost of prolonging diagnosis time or of misidentifying some fault-free nodes. A system is ***sequentially t-diagnosable*** if and only if, given a syndrome, at least one faulty node can be correctly identified, provided that the number of faulty nodes in the system does not exceed *t*. A system is ***t/s-diagnosable*** if and only if, given a syndrome, the set of faulty nodes can be isolated to within a set of *s* nodes, provided that the number of faulty nodes in the system does not exceed *t*. Das et al [13] and Raghavan [39] have given characterizations of t/s-diagnosable systems. Das et al [13] have also given a diagnosis algorithm for *t/s*-diagnosable systems. Raghavan and Tripathi [40] showed that sequential *t*-diagnosability is Co-NP-Complete for both PMC as well as BGM models. Kavianpour and Friedman [25] considered a very interesting special case of *t/s*-diagnosability, the ***t/t-diagnosability***. They showed that with the same degree of connection the degree of *t/t*-diagnosability might double the degree of *t*-diagnosability. An $O(n^{2.5})$ diagnosis algorithm for t/t-diagnosable systems was given by Yang, Masson and Leonetti [54]. Das et al. [15] presented an $O(n^{3.5})$ diagnosis algorithm for *t/t+1*-diagnosable systems.

Somani and Peleg [47] introduced a new measure of diagnosability, called ***t/k*-diagnosibility**. This is similar to *t/s*-diagnosability except that there is an upper bound on the number of incorrectly diagnosed nodes regardless of the number of actual faulty nodes in the system. They have analyzed the *t/k*-diagnosability of hypercubes, star graphs and two dimensional meshes and have demonstrated that for these systems, a substantial increase in the degree of diagnosability is achieved at the cost of a small number of incorrectly diagnosed nodes.

Recently, there has been considerble research on what is called the conditional diagnosability. In this model, not all neighboring processors are allowed to be faulty. References [19,21,30,32,53 ] provide a detailed view of the current literature in this area.

## 4 Adaptive System-Level Diagnosis

In adaptive system-level diagnosis schemes, tests are assigned dynamically, instead of assigning all of them at the outset and decoding the test outcomes. So, adaptive diagnosis requires fewer tests. In [36], Nakajima proposed an adaptive diagnosis scheme. Here, a completely connected system is assumed which restricts its applicability. This approach is further studied in [37]. Vaidya and Pradhan [52] proposed a new adaptive scheme called ***safe system-level***

***diagnosis***. The safe-diagnosis approach ensures that up to *t* faulty nodes can be located and up to *u* faulty nodes, where $u > t$, can be detected. In this approach, a minimal amount of fault location capability is sacrificed to attain a large degree of fault detection capability. Feng, Bhuyan and Lombardi [17] proposed an adaptive diagnosis algorithm for hypercube systems. The diagnostic cost (measured in terms of the number of test links and diagnosis time) is very low for this scheme.

## 5 Probabilistic Diagnosis

Probabilistic diagnosis is yet another approach to allow diagnosis of large fault sets. The emphasis here is to identify all faulty nodes with a very high probability. This approach was initiated by Maheswari and Hakimi [35]. Dahbura, Sabnani and King [12], considered probabilistic diagnosis with comparison testing. Scheinerman [44] gave a probabilistic diagnosis algorithm which correctly identifies every node as *n* tends to infinity, as long as each node compares with slightly more than $log\ n$ nodes. Blough [8] showed that correct diagnosis with high probability was impossible if each node was tested by only $O(log\ n)$ other nodes. Further results were presented by Blough, Sullivan, and Masson [7]. Rangarajan and Rangarajan [41] considered performing multiple tests to achieve correct diagnosis of constant degree connection structures. Slightly more than $log\ n$ tests are performed with respect to each test link. They showed that the probability of correctly identifying every node approaches one as *n* tends to infinity. They further showed that the number of test links per node and the number of tests per test link can be traded off as long as the product of these two parameters grows as $O(\log n)$ as *n* tends to infinity. Laforge et al [29] presented another approach to diagnosing constant degree systems.An extensive review of probabilistic diagnosis results may be found in Lee and Shin [31]. Applications of probabilistic approaches to VLSI testing may be found in [42], [22], and [23].

## 6 Distributed System-Level Diagnosis

Most diagnosis algorithms based on the PMC model are assumed to be executed on a single highly reliable supervisory node. A single supervisory node is a bottleneck in a system with a large number of processing nodes. Distributed diagnosis algorithms which exploit the inherent parallelism available in a multiprocessor system would be desirable. The approaches reviewed use one of two fault models: the ***Byzantine failure*** model and the ***stopping failure*** model [33]. In the case of a stopping failure, a node ceases to function without warning. Stopping failures are intended to model unpredictable node crashes. In the case of a Byzantine failure, a node may exhibit completely unconstrained behavior. Byzantine failures are intended to model any arbitrary node malfunction, including, for instance, failures of individual subcomponents.

## 6.1 On-line Distributed System-Level Diagnosis: SELF and Related Algorithms

Distributed system-level diagnosis was first considered in the early works by Kuhl, Reddy and Hosseini [27][28][20] in which each fault-free node in a distributed system reliably receives test results through its neighbors to perform diagnosis. In this work the Byzantine failure model was used. It was assumed that the total number of faulty nodes is restricted to *t* or fewer nodes, and that the test assignment graph is fixed, i.e. each node tests a fixed set of neighboring nodes. In the SELF distributed algorithm [28] fault-free nodes forward test results to neighboring nodes which are then propagated to other nodes. No assumption is made regarding faulty nodes which can propagate erroneous test results. Each node collects the test information and independently determines the status of all the nodes in the system. In the NEW_SELF distributed algorithm [20] the key idea is that a fault-free node accepts test information from one of its neighbors only if it has tested that neighbor and determined it to be fault-free. This ensures that test result reports are propagated reliably along fault-free testing chains. For correct diagnosis, the NEW_SELF algorithm requires that every fault-free node receives all the tests results of every fault-free node in the system. This condition is satisfied if every node in the system is tested by $t+1$ other nodes. These algorithms allow both link and node failures.

## 6.2 Event-driven Technique for Distributed System-Level Diagnosis

In 1990, Biancini et al [5], proposed an event-driven technique to adapt Kuhl and Reddy's approach for an Ethernet-based network of workstations. To reduce the communication overhead required by Kuhl and Reddy's approach, they used an event-driven technique wherein only when a node is first detected as faulty or when a newly repaired node rejoins the network is the new information forwarded in the system. Test results are forwarded by a node only if it differs from the information stored at the node. The test assignment graph is such that each network node tests $t+1$ of its next logical neighbors, where $t$ is the maximum number of faulty nodes that can be tolerated. This strategy significantly reduces the number of messages required to arrive at a diagnosis for systems where the test assignment given above can be applied. These works allow both link and node failures. They also permit repairs during the execution of the algorithm.

## 6.3 Adaptive Distributed System-Level Diagnosis

A further refinement of the approach of Biancini et al was to replace single-step diagnosis by an adaptive strategy wherein the test assignment, instead of being fixed, is determined by the fault situation [6]. This adaptive distributed system-level diagnosis approach also removes the bound on the number of faulty nodes in the system. This results in a sparse test assignment topology, a logical ring of fault-free nodes in a connected network. On occurrence of a fault, the information is forwarded in the network and the fault-free nodes rearrange the test assignment topology to preserve the ring structure. Duarte and Nanya [16] proposed a hierarchical adaptive distributed diagnosis algorithm for fully connected networks. This algorithm has better diagnosis latency than Bianchini and Buskens' algorithm. In [48][49] Su and Thulasiraman have proposed the design of adaptive distributed diagnosis algorithms using the multilevel paradigm. This design achieves considerable reduction in latency. They have shown how this can be integrated in a network monitoring protocol.

In [43], Rangarajan, Dahbura and Ziegler presented a distributed diagnosis algorithm for an arbitrary network in which each fault-free node ensures that exactly one fault-free neighbor - if it exists - is testing it. Nodes perform their tests periodically and if a failure event is detected then the information is propagated using validating transactions. The fault model for nodes considered in this case is the stopping failure model where a node simply ceases to operate without alerting other nodes and a bounded delay is assumed for communicating links. This work allows node failures and repairs to occur during the execution of the algorithm.

## 6.4 Gossiping and Consensus in a Distributed Environment

In [3] Bagchi and Hakimi presented a distributed algorithm for the gossiping problem in a faulty environment and demonstrated its application in distributed system level diagnosis. They assumed the Byzantine failure model and used a tree testing topology. The system is required to be *t*-diagnosable if *t* faults are to be permitted. In this work link failures are not considered. Also it is assumed that no processor can become faulty and that no processor is repaired during the execution of the algorithm. Bagchi and Hakimi pointed to "a growing overlap" between the field of fault diagnosis and the field of consensus in distributed systems. Barborak, Malek and Dahbura [2] described results of interest in these fields.

## 7 Summary

In this paper we have given a broad survey of an area called system level diagnosis initiated by Preparata, Metze and Chien. Our survey includes different models of diagnosis and related diagnosis and dignosability algorithms. In particular, we have given a detailed view of distributed diagnosis. We believe most of these works form the foundation of the research in the emerging area of fault tolerance in mobile environment.

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