

**MAXIMAL DIAGNOSIS FOR
WIRING NETWORKS**

BY

Jung-Cheun Lien and Melvin A. Breuer

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Los Angeles, CA. 90089-0781**

Maximal Diagnosis for Wiring Networks*

Jung-Cheun Lien and Melvin A. Breuer
Department of EE-Systems
University of Southern California
Los Angeles, CA 90089-0781

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Abstract

Previous work on the diagnosis of faults in a wiring network has been based on the assumption that both open and short faults do not exist on the same net. When this assumption is released, these results fail to identify all diagnosable faults. The non-diagnosability of these faults, including shorts between nets, represent a serious deficiency. In this report we analyze and explain the causes for these deficiencies. In addition, we provide new theoretical results and test algorithms, and show how these deficiencies can be overcome. A test set, which is generated based on these results, can identify all diagnosable faults in a wiring network with arbitrary open and short faults. Two adaptive diagnosis algorithms are also presented which can reduce the number of test vectors while retaining the same level of diagnostic resolution.

1 Introduction

Detecting and locating faults in wiring networks on a printed circuit board has drawn much attention since the emerging of the boundary scan architecture [1]. In this architecture each primary input/output pin of a chip is associated with a boundary scan (B-S) cell. Each chip has a boundary scan register consisting of all the B-S cells. During the test mode a scan chain is formed by cascading boundary scan registers of several chips. Through this chain a test controller can access the I/O pins of every chip. Thus a virtual

bed-of-nails capability is achieved. With this capability the wiring nets can be isolated from the chips and tested without the need to physically probe the board. In this way it is possible to test the new generation of boards which allow for limited probing due to the use of surface mounted devices and tape automated bonding technology. Note that if non-boundary scan devices are used, physical probes may still be required.

Many papers have dealt with the problem of finding test sets for detecting and locating faults in a wiring network [2, 3, 4, 5, 6, 7, 8, 9, 10]. Usually opens are modeled as stuck-at faults and are diagnosed separately from the shorts. This is based on the assumption that a net cannot be associated with both an open and short faults. Very comprehensive results are presented by Jarwala and Yau [7], where a framework for the detection and diagnosis of wiring networks is discussed. In particular, the *diagonally independent* property is identified. It is shown that a test set with this property is sufficient for the diagnosis of all shorts in one-step, where the results are analyzed after all test vectors have been applied.

However, as shown in this report, when the assumption concerning open and short faults is released, a test set having the diagonally independent property is insufficient for achieving complete diagnosis. In fact, there are certain faults that cannot be diagnosed without repair. Some of these non-diagnosable faults are listed in Section 2.3. Furthermore, it is shown that none of the previous results can identify all diagnosable faults. The causes for this deficiency are identified and characterized in Lemmas 1 and 2. A diagnostic level DR5, which refers to the case where all diagnosable faults can be identified, has been formulated. A term called maximal diagnosis is defined using two conditions. We show that these two conditions are both necessary and sufficient for achieving the diagnostic level DR5.

Both one-step and two-step diagnosis are ad-

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dressed in this report. In the former case, responses are analyzed only after all test vectors have been applied. In the latter case, responses are analyzed after a fixed part of the test vectors have been applied. Based on this analysis, additional test vectors are then generated and applied. Final analysis is then carried out.

For one-step diagnosis, a property called *set-cover independent* is identified. Based on this property a fundamental theorem on diagnosing wiring faults is presented. The theorem gives both necessary and sufficient conditions for identifying all diagnosable faults. A universal test set is then presented. This test set can achieve maximal diagnosis for an arbitrary network without assuming a specific fault model.

For the two-step diagnosis, two adaptive diagnosis algorithms are presented. Compared with one-step diagnosis, these algorithms can reduce the number of test vectors while retaining the same level of diagnostic resolution by using a two-step scheme. In the first step, a detection sequence is applied and the responses are evaluated. Based on the initial results, a second sequence is applied to achieve the required diagnosis. The test vector size is reduced since some information about the network has been employed in the generation of the second sequence.

This report is organized as follows. In Section 2 the preliminaries for the diagnosis of wiring networks are introduced. Addressed are the fault model, notation and definitions, non-diagnosable faults, diagnostic resolution, some previous results and the deficiencies of these results. In Section 3 theorems dealing with diagnosing wiring faults are presented, followed by a universal test set. In section 4 two adaptive algorithms are presented. Conclusions are presented in Section 5.

2 Preliminaries

A wiring network consists of many nets. A net contains one or more drivers and one or more receivers. The logic value of a net can be controlled via one of its drivers and observed by all of its receivers. For a multi-driver net, only one driver can be enabled at a time. The others must be disabled. In addition, while testing a wiring network, only the drivers and receivers of nets are accessible. A fault-free net can transfer the logic value from an enabled driver to its receivers correctly. A receiver of a fault-free net can only receive from its associated drivers. The objective of diagnosis of a wiring network is to find a set of test vectors which can be applied to identify as

many faults in the network as possible. No structural information about the network is assumed in this work.

2.1 Fault Model

Two types of physical faults, namely open and short, are assumed. More than one physical break are possible in an opened net. Ignoring fan-out nodes and shorts, multiple opens are modeled as a single open along a wire segment. Also more than one physical bridge are possible between two shorted nets. Multiple shorts are modeled as a single short between two wire segments.

If two or more nets are shorted, the resulting behavior can be modeled either (1) a wired-OR, (2) a wired-AND, or (3) a strong-driver, where one driver dominates the resulting behavior. In all cases, all nets involved in a short will have the same resulting logic value. The wired-OR fault model is assumed in this discussion unless mentioned otherwise.

A net shorted to a power line VCC (GND) will exhibit a stuck-at 1 (stuck-at 0) behavior. If a net contains an open, the logic value interpreted by all floating receivers of the opened net will be the same, which could be either a soft stuck-at 1 or a soft stuck-at 0. A logic value of a net shorted to a wire segment at a soft logic value cannot be forced to this soft value. The soft stuck-at 1 model is assumed for a floating net unless mentioned otherwise. In Figure 1, the logic value of the point A is soft stuck-at 1.

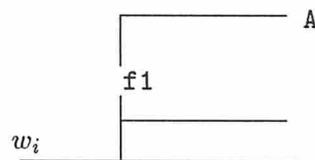


Figure 1: A soft stuck-at 1 case.

Both opens and shorts can occur on the same net. If a net contains both opens and shorts, the logic value received by the receivers is determined by the combined effect of both opens and shorts.

A short to an open net is illustrated in Figure 2, where A takes the logic value of B.

2.2 Notation and definitions

The notation and definitions used in this report follow the conventions established in [7]. For convenience, some of this information is repeated here.

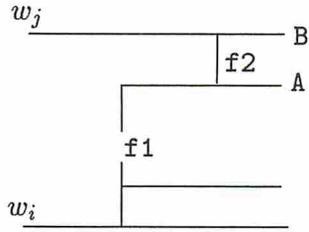


Figure 2: A short in an opened net.

- Parallel Test Vector (*PTV*): the vector applied to all nets of a wiring network in parallel.
- Sequential Test Vector (*STV*): the vector applied to a net, over a period of time, by a sequence of *PTVs*.
- Test Set (or test sequence) S : the collection of all *STVs*. Each column of S is a *PTV* and each row of S is a *STV*.
- Sequential Response Vector (*SRV*): the response of a net to a *STV*.
- Syndrome: the *SRV* of a faulty net.
- Aliasing syndromes: the resulting syndrome of a set of faulty nets is the same as a correct *SRV* of a net not in the set.
- Confounding syndromes: the identical syndromes that results from multiple independent faults.

The following definitions are also used.

- OR-Cover: A vector V_i *OR-covers* another vector V_j if for every bit position in V_j that is 1, the corresponding bit in V_i is also 1. For example, $STV_i=(1101)$ OR-covers $STV_j=(0101)$, or STV_j is OR-covered by STV_i . The OR-cover is used in the wired-OR fault model. In a similar fashion one can define an AND-cover for the wired-AND fault model. In this report, the term OR-cover is abbreviated as *cover*.
- Independent set: A test set S is an *independent set* if no STV_i can cover another $STV_j, j \neq i$.
- Set-cover: Let V_J be the result of wire-ORing a set of vectors V_{j1}, \dots, V_{jk} . A vector V_i *set-covers* the vectors V_{j1}, \dots, V_{jk} if V_i covers V_J .
- Set-covering syndrome: A *set-covering syndrome* is a syndrome that results from a set of shorted nets (W') that either covers a *SRV* or is covered by a *SRV* of some net w_i not in W' .

- Set-cover independent: Let $S=(STV_1, \dots, STV_n)$ be a test set for a set of nets $W = (w_1, \dots, w_n)$. S is *set-cover independent* if for $i = 1, \dots, n$, STV_i is not covered by or covers the union (for wired-OR, intersection for wired-AND) of any subset of vectors in $S - STV_i$. In the other words, for every SRV_i in S no set-covering syndrome can exist.

2.3 Non-diagnosable Faults

A fault f is said to be *non-diagnosable* if there does not exist a test set S and an algorithm A such that by applying S to the network and processing the responses using algorithm A , f can be identified. Note that all single faults are diagnosable. Based on the described model, there are faults that are non-diagnosable. Some of these non-diagnosable faults are listed below.

- In a set of nets that are shorted with each other, there are some opens that are non-diagnosable. For example, in Figure 3 the open fault f1 on net w_2 is non-diagnosable. Since w_1 and w_2 are electrically common, it is impossible to find a test to detect the open.

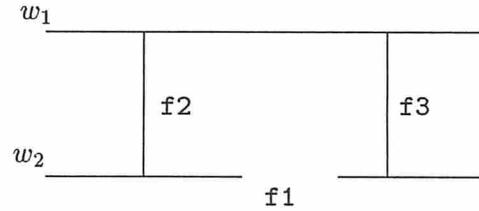


Figure 3: An open that is non-diagnosable.

- The short between a set of opened nets is non-diagnosable. For example, in Figure 4, it is impossible to identify the short f1 between w_1 and w_2 since no receivers are connected to the shorted wires.

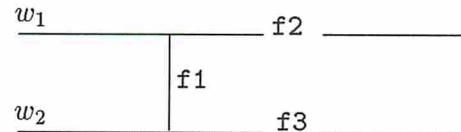


Figure 4: A short that is non-diagnosable.

- There exists three possible reasons for a faulty net that has all-1 responses to a test (1) the net is shorted with a VCC power line, (2) the net is

opened and floating (soft stuck-at 1 model), and (3) the net is shorted with other nets such that the combined result is an all-1 vector (wired-OR model). The third case can be distinguished from the others by applying an all-0 PTV. The first two cases cannot be distinguished.

2.4 Diagnostic Resolution

Various levels of diagnostic resolution are possible in testing a wiring network. Listed below are six such levels. They are listed in ascending order of their diagnostic resolution, i.e., DR1 has the lowest diagnostic resolution, and DR6 has the highest diagnostic resolution.

DR1: Determine whether the entire network is fault-free.

DR2: Identify all faulty nets.

DR3: For each and every net, determine whether it is fault-free without knowing the response of the other nets.

DR4: Identify all faulty nets. In addition, for nets without shorts, identify the existence of nets having opens. For a faulty net without open faults, identify all nets that are shorted to it.

DR5: Identify all faulty nets. In addition, identify all faults that are diagnosable.

DR6: Identify all faulty nets. In addition, identify all the opens and shorts in the network.

In DR1, one is only interested in determining the health status of the entire network. No further diagnostic information is provided. In DR2, all faulty nets are identified. No information about what type of faults associated with each net is provided. In DR3, all faulty nets are identified. In determining the health status of net, only its response is required. No information about the response of other nets are needed. This scheme is most suitable for a built-in self-test type of design. In DR4, all faulty nets are identified. The faults associated with each nets can be identified if they belong to those cases described above. In DR5, all faulty nets are identified. More faults can be identified than in the case of DR4. In DR6, all faulty nets are identified. In addition, all the faults, including opens and shorts, are identified.

For the purpose of repairing a wiring network, it is desirable that as many faults as possible be identified. Due to the fact that some faults cannot not be

identified without first repairing other faults, DR6 cannot be reached. An example would be a net with multiple opens. In this work, we focus on achieving DR5.

2.5 Previous Results

Previous results focus on diagnostic resolution ranging from DR1 to DR4. Some typical results for the testing of a network consisting of 4 nets are listed below. These results are based on the assumption that both opens and shorts cannot exist on the same net.

Counting Sequences: Kautz[2]

$$S = \begin{bmatrix} 0 & 0 & 1 \\ 0 & 1 & 0 \\ 0 & 1 & 1 \\ 1 & 0 & 0 \end{bmatrix}$$

This test set consists of a simple counting sequence, where all-0 and all-1 STVs are not used. This test can achieve the DR1 diagnostic levels. The size of the test set is $\lceil \log(n+2) \rceil$, where n is the number of nets.

Complementary Counting Sequence: Wagner[4]

$$S = \left[\begin{array}{cc|cc} 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \\ 0 & 0 & 1 & 1 \end{array} \right]$$

This test set consists of a counting sequence and its complement. All-0 and all-1 STVs can be used. The size of the test set is $2\lceil \log n \rceil$. This test set can achieve diagnostic level DR3. By eliminating the aliasing syndromes, the *self-diagnosis* property is achieved, which allows the determination of the health status of a net by examining only its *SRV*.

Maximal Independent Set: Cheng et al. [9]

$$S = \begin{bmatrix} 1 & 1 & 0 & 0 \\ 1 & 0 & 1 & 0 \\ 1 & 0 & 0 & 1 \\ 0 & 1 & 1 & 0 \end{bmatrix}$$

Constant weight codes, which means that every STV has the same number of 1s, is a class of independent test sets. These test sets can achieve diagnostic level DR3. The size of the test set is minimal for self-diagnosis when the number of 1s in a SRV is half of the number of PTVs, which is referred to as a maximal independent set [9].

Diagonally Independent Sequence: Jarwala and Yau[7]

$$S = \begin{bmatrix} x & x & x & 1 \\ x & x & 1 & 0 \\ x & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

The x represents either a 0 or a 1. This test set can achieve the diagnostic level DR4. Both aliasing and confounding syndromes can be eliminated. All pairs of nets that are shorted are identified.

2.6 Deficiencies in Previous Results

Recall that these results are based on the assumption that both opens and shorts cannot exist on the same net. However, when this assumption is released, there exists certain types of opens and shorts that cannot be identified. For example, the diagonally independent sequence

$$S = \begin{bmatrix} 0 & 1 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 \end{bmatrix}$$

cannot identify the short fault f1 in Figure 5 nor the open fault f2 in Figure 6.

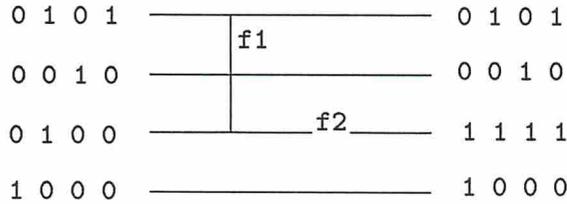


Figure 5: A short that cannot be identified by a diagonally independent sequence.

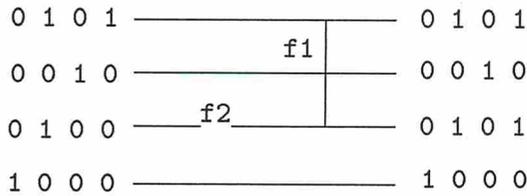


Figure 6: An open that cannot be identified by a diagonally independent sequence.

The following lemmas summarize these cases which cannot be completely handled by previous results.

Lemma 1 *A test set S cannot identify the short between two nets w_i and w_j if (a) there is an open which is closer to the receiver of net w_i than the short, and (b) STV_i is covered by STV_j .*

Proof:

SRV_i is the all-1 vector since no logic value is transferred to the receiver. $SRV_j = STV_j$ since STV_j covers STV_i . Therefore, it is impossible to know whether there is a short between w_i and w_j . \square

Figure 5 is an example of Lemma 1.

Lemma 2 *A test set S cannot identify the open in a net w_i if there exists another net w_j such that (a) there is a short between w_i and w_j which is closer to the receiver of w_i than the open, and (b) STV_j covers STV_i .*

Proof:

Since $SRV_j = SRV_i = STV_j$, one cannot be certain whether there is a "contribution" from STV_i to SRV_i . Therefore, the open cannot be identified. \square

Figure 6 is an example of Lemma 2.

Both Lemma 1 and 2 can be generalized to multiple nets. For example, in Figure 7 the short fault f1 cannot be identified by a maximal independent set. This is because STV_3 is set-covered by $SRV_1 = SRV_2 = 1110$. Therefore it is impossible to determine whether the short f1 exists or not.

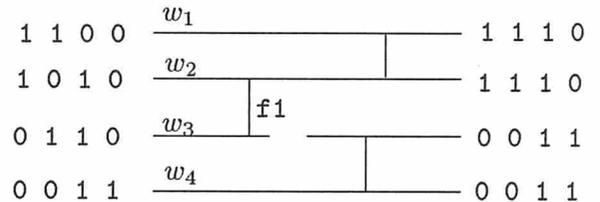


Figure 7: A short that cannot be identified by an independent test set.

In summary, none of the previous results can identify all faults described above, these includes the diagonally independent sequence [7], the maximal independent set[9], and the complementary counting sequence[4].

The existence of non-identified shorts and opens in a network represents a major deficiency in diagnosis. We next describe a test set that can diagnose these shorts and opens.

3 One-Step Diagnosis

Due to the existence of non-diagnosable faults in a wiring network, it is impossible to identify all faults without repair or access to points of the nets other than the drivers and receivers. The term **maximal diagnosis** is defined as follows.

Let $W = (w_1, w_2, \dots, w_n)$ be a set of nets to be tested, D_i be the set of drivers of net w_i , and R_i be the set of receivers of net w_i . A test set S can achieve *maximal diagnosis* for W when the following two conditions are verified.

- Condition C1: For $i = 1, \dots, n$, by analyzing the responses obtained from the application of S , the existence of the connection (D_i, R_i) can be determined.

The connection (D_i, R_i) exists if for all k , each driver $d_{ik} \in D_i$ can *transfer* its logic value to all receivers in R_i correctly. A driver in D_i is said to *transfer* its logic value to a receiver R_i if SRV_i covers STV_i . Note that only one driver can be enabled for a given net at one time. In other words, if the connection (D_i, R_i) exists, then the application of STV_i to the enabled driver of w_i will make true one of the following: (1) $SRV_i = STV_i$, or (2) SRV_i covers STV_i .

- Condition C2: For all $i, j, i \neq j$, by analyzing the responses obtained from the application of S , the existence of the connection (D_i, R_j) can be determined.

The connection (D_i, R_j) does not exist if for all k , each driver $d_{ik} \in D_i$ does not transfer its logic value to any receivers in R_j . In other words if the connection (D_i, R_j) does not exist, the application of STV_i to the enabled driver of w_i will make true one of the following: (1) $SRV_j \neq STV_i$, or (2) SRV_j does not cover STV_i .

Theorem 1 *Diagnostic level DR5 can be achieved by a test set S iff S can achieve maximal diagnosis.*

Proof:

(a) Sufficiency:

The test set S can verify both Condition C1 and C2 since S can achieve maximal diagnosis for a network W . By definition DR5 is achieved if all diagnosable faults in W can be identified. There are two type of faults in W , namely opens and shorts. We discuss them separately in the following.

(1) opens: An open on a net w_i can be diagnosed if the connection (D_i, R_i) does not exist. Since S can achieve maximal diagnosis, this connection is determined in Condition C1. Thus S can identify all diagnosable opens in W .

(2) shorts: A short between two nets w_i and w_j can be diagnosed if one of the following is true: (a) there exists a driver D_k such that both connections (D_k, R_i) and (D_k, R_j) exist; (b) there exists a receiver R_k such that both connections (D_i, R_k) and (D_j, R_k) exist. The existence of these connections can be determined by S using Condition C2. Thus S can identify all diagnosable shorts in W .

From (1) and (2), all diagnosable faults can be identified. Therefore the diagnostic level DR5 can be achieved. Thus we prove the sufficiency aspect of maximal diagnosis.

(b) Necessity:

Assume that S cannot achieve maximal diagnosis. By definition, there exist at least one connection the existence of which cannot be determined. Two cases are possible: (1) if the connection is of the form (D_i, R_i) then there can be an open fault on net w_i that cannot be identified; (2) if the connection is of the form $(D_i, R_j), i \neq j$, then there can be a short between w_i and w_j that cannot be identified. In both cases, the faults can be identified by a walking ones sequence. Thus, by definition, these faults are diagnosable. Therefore the diagnostic level DR5 cannot be achieved. Thus the maximal diagnosis property is necessary. \square

In this report the generation of test sets that can achieve maximal diagnosis are discussed. The generated test sets thus can achieved diagnostic level DR5 in which all diagnosable faults are identified. This is the best diagnostics one can achieve without accessing points on the net other than the drivers and receivers.

Lemma 3 *For the wired-OR (wired-AND) model, any test set S is set-cover independent iff S has the walking ones (zeros) sequence as its subsequence.*

Proof:

(a) Sufficiency:

This is obvious since the walking ones sequence is set-cover independent.

(b) Necessity:

Suppose that the test set S is set-cover independent. For a given STV_i , there must exist a PTV such that its i th bit is 1 and all other bits are 0. This is true for all $STV_i, i = 1, \dots, n$. By arranging S properly

(by swapping rows and columns), a walking ones sequence can be constructed. Therefore, S contains a subsequence which is a walking ones sequence. \square

We next present a theorem from which a test set can be derived for achieving maximal diagnosis.

Theorem 2 *A test set S can achieve maximal diagnosis for a network W in one-step iff S is set-cover independent.*

Proof:

(a) Sufficiency:

Suppose that S is set-cover independent. No set-covering syndrome can exist. For each and every net w_i Condition C1 can be verified by checking if SRV_i covers STV_i . If this is not true then there is at least an open fault between the driver and the receivers of the net w_i . Since no set-covering syndrome can exist, no drivers of other nets can cover the STV_i .

Condition C2 can be verified as follows. If STV_i cannot cover SRV_i , then for every bit in SRV_i that is not covered by the STV_i , there is a short between the receiver of w_i and a driver w_j whose STV_j covers that bit.

Since both Conditions C1 and C2 can be verified, maximal diagnosis is achieved and the sufficiency aspects of the theorem have been demonstrated.

(b) Necessity:

Suppose that S is not set-cover independent. There exists at least one STV_i that is covered by another STV_j . When the following two faults occur the existence of the connection (D_i, R_i) cannot be determined: (1) a short between w_i and w_j , and (2) an open on w_i that is closer to the driver than the short. This means that Condition C1 cannot be satisfied. Thus, by definition, maximal diagnosis is not achieved. \square

From Lemma 3 and Theorem 2, we can conclude that any test set that can achieve maximal diagnosis must have a walking ones (zeros) sequence as its subsequence. From Theorem 2 and 1 we can conclude that a set-cover independent test set can achieve the diagnostic level DR5.

Example 1: The short that cannot be identified by a diagonally independent sequence in Figure 5 can be identified by a set-cover independent sequence (see Figure 8).

Universal Test Set:

Assuming the wired-OR model and that a floating net is modeled as a soft stuck-at 1, a test set that can

0 0 0 1	f1	0 1 0 1
0 0 1 0		0 0 1 0
0 1 0 0	f2	1 1 1 1
1 0 0 0		1 0 0 0

Figure 8: Achieving maximal diagnosis using a set-cover independent sequence.

achieve maximal diagnosis for a network consisting of 3 nets can be constructed as follows.

$$\left[\begin{array}{c|ccc} 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 0 \end{array} \right]$$

The all-0 PTV is used to distinguish between the cases (1) all nets are shorted together (all 1s for SRVs) and (2) all nets are opened.

Similarly, if the wired-AND model is used and an open and floating net is modeled as a soft stuck-at 0, a test set for maximal diagnosis can be constructed by a walking zeros sequence followed by an all-1 PTV.

In summary, a universal test set for maximal diagnosis, without making any assumption on the nature of the faults, is as follows.

$$S_{universal} = \left[\begin{array}{c|ccc|c|ccc} 1 & 1 & 1 & 0 & 0 & 0 & 0 & 1 \\ 1 & 1 & 0 & 1 & 0 & 0 & 1 & 0 \\ 1 & 0 & 1 & 1 & 0 & 1 & 0 & 0 \end{array} \right]$$

4 Two-Step Diagnosis

Two-step diagnosis refers to the fact that diagnosis is done by applying two test sequences. The results of the first test sequence is used in generating the second test sequence. This type of diagnosis is also known as adaptive diagnosis.

Two adaptive algorithms that can achieve maximal diagnosis with a reduced number of PTVs are presented next. The test sets for both algorithms do not have the set-cover independent property since certain information about the network is employed in generating the second test sequence.

4.1 Adaptive Algorithm A1

1. Apply a maximal independent set (S_M). Collect and analyze the responses. Stop if no faults are detected.

2. Partition the nets into two groups. The partitioning is done as follows. For a net $w_i, i = 1, \dots, n$, if (a) $STV_i = SRV_i$ and (b) SRV_i is unique, include w_i into group 0, else group 1.
3. Apply a walking ones sequence S_F to all nets in group 1, and all-0 vectors to all nets in group 0.

The objective of the first sequence is to achieve the self-diagnosis property by eliminating aliasing syndromes. The maximal independent set is the minimal size test set that can achieve this objective [9]. The number of PTVs required by the first sequence is p , where p is the smallest integer satisfying $C_{\lfloor p/2 \rfloor}^p \geq n$, and $C_{\lfloor p/2 \rfloor}^p$ represents all possible combinations of choosing $\lfloor p/2 \rfloor$ items out of p items. The total number of PTVs required by this algorithm is $p + F$, where F is the number of nets in group 1.

We next show by an example that algorithm A1 can achieve maximal diagnosis. Let W be a network of 4 nets, where w_1 and w_2 are two nets in group 0 and w_3, w_4 are in group 1. If both Conditions C1 and C2 can be verified then maximal diagnosis is achieved.

Let S_{A1} be the test generated by Algorithm A1,

$$S_{A1} = (S_F, S_M) = \left[\begin{array}{cc|cccc} 0 & 0 & 1 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 & 1 & 0 \\ 0 & 1 & 1 & 0 & 0 & 1 \\ 1 & 0 & 0 & 1 & 1 & 0 \end{array} \right]$$

Table 1 shows when a connection between a driver and a receiver is checked. Note that the existence of all connections must be able to be determined in order to achieve maximal diagnosis. Checking the existence of connections of the form (D_i, R_i) is necessary to verify Condition C1; checking the connections $(D_i, R_j), i \neq j$, is necessary to verify Condition C2.

Seq.	Connections checked
S_M	$(D_1, R_1), (D_1, R_2), (D_1, R_3), (D_1, R_4)$ $(D_2, R_1), (D_2, R_2), (D_2, R_3), (D_2, R_4)$
S_F	$(D_3, R_1), (D_3, R_2), (D_3, R_3), (D_3, R_4)$ $(D_4, R_1), (D_4, R_2), (D_4, R_3), (D_4, R_4)$

Table 1: Checking connections using Algorithm A1.

The connection (D_1, R_1) does exist since (a) in the sequence (S_M) , for every i it is impossible to find a subset from $S - STV_i$, whose wired-OR result equals STV_i , (b) $STV_1 = SRV_1$ and (c) SRV_1

is unique. Similarly, the connection (D_2, R_2) exists. The connections (D_1, R_2) and (D_2, R_1) do not exist since the existence of any one of them will make $SRV_1 = SRV_2$, which contradicts the fact that $SRV_1 \neq SRV_2$.

The existence of the connection (D_1, R_3) is also verified by (S_M) for the follow reason. If this connection exists, SRV_1 must equal SRV_3 since there is no open on w_1 . However SRV_1 is unique, so we know that this connection doesn't exist. In a similar manner the other connections are checked by (S_M) .

The connections (D_3, R_i) and $(D_4, R_i), i = 1, \dots, 4$ are verified by the sequence S_F . Maximal diagnosis can be achieved in this example since the existence of all connections can be determined. The efficiency of this algorithm depends on the value of F . In the case when $F \approx n$, the number of PTVs is close to that of a walking ones sequence.

4.2 Adaptive Algorithm A2

1. Apply a maximal independent set (S_M) . Collect and analyze the responses. Stop if no faults are detected.
2. Partition nets into group 0 and 1 (as Algorithm A1).
3. Partition nets in group 1 such that all nets with the same SRV are in the same group. Number these new groups from 1 to G . Let K be the cardinality of the largest group.
4. Apply a walking ones sequence S_G to all groups in parallel except to group 0 for which the all-0 vectors are applied.
5. Apply another walking ones sequence S_K across groups. That is, all nets in the same group are modeled as a single net. Again the all-0 vectors are applied to all nets in group 0. The number of PTVs is G .

The total number of PTVs for Algorithm A2 is $p + G + K$. In general this algorithm requires fewer PTVs than Algorithm A1. This is because in Algorithm A1 the F nets in group 1 is now partitioned into G groups in Algorithm A2. It is obvious that $F \geq G + K$.

We next show that Algorithm A2 can achieve maximal diagnosis by checking Conditions C1 and C2.

Let W be a network with seven nets. After the application of S_M , three groups are formed. Let w_1 ,

w_2 be in group 0, w_3, w_4 be in group 1, and w_5, w_6, w_7 be in group 2. In this example $n = 7$, $G = 2$ and $K = 3$. According to Algorithm A2, the total test set S_{A2} consists of a maximal independent set of 5 PTVs (S_M), followed by 3 walking ones PTVs (S_G), which again are followed by another 2 walking ones PTVs (S_K).

$$S_{A2} = \left[\begin{array}{cc|ccc|cccc} 0 & 0 & 0 & 0 & 0 & 1 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 & 1 & 0 & 0 & 1 & 0 \\ 0 & 1 & 0 & 1 & 0 & 1 & 0 & 0 & 0 & 1 \\ 1 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 1 & 0 & 1 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 1 \end{array} \right]$$

Seq.	Connections checked
S_M	$(D_1, R_1), (D_1, R_2), (D_1, R_3), (D_1, R_4), (D_1, R_5), (D_1, R_6), (D_1, R_7), (D_2, R_1), (D_2, R_2), (D_2, R_3), (D_2, R_4), (D_2, R_5), (D_2, R_6), (D_2, R_7).$
S_G	$(D_3 D_5, R_1), (D_3 D_5, R_2), (D_3 D_5, R_3), (D_3 D_5, R_4), (D_3 D_5, R_5), (D_3 D_5, R_6), (D_3 D_5, R_7), (D_4 D_6, R_1), (D_4 D_6, R_2), (D_4 D_6, R_3), (D_4 D_6, R_4), (D_4 D_6, R_5), (D_4 D_6, R_6), (D_4 D_6, R_7), (D_7, R_1), (D_7, R_2), (D_7, R_3), (D_7, R_4), (D_7, R_5), (D_7, R_6), (D_7, R_7).$
S_K	$(D_3, R_1), (D_3, R_2), (D_3, R_3), (D_3, R_4), (D_3, R_5), (D_3, R_6), (D_3, R_7), (D_5, R_1), (D_5, R_2), (D_5, R_3), (D_5, R_4), (D_5, R_5), (D_5, R_6), (D_5, R_7), (D_4, R_1), (D_4, R_2), (D_4, R_3), (D_4, R_4), (D_4, R_5), (D_4, R_6), (D_4, R_7), (D_6, R_1), (D_6, R_2), (D_6, R_3), (D_6, R_4), (D_6, R_5), (D_6, R_6), (D_6, R_7).$

Table 2: Checking connections using Algorithm A2.

Table 2 shows how Conditions C1 and C2 can be verified. From the discussion in Algorithm A1, it is clear that for $i = 1, \dots, 7$ connections (D_1, R_i) and (D_2, R_i) are checked after the application of S_M .

The existence of connections $(D_7, R_i), i = 1, \dots, 7$, are checked by S_G since it contains a PTV which applies 1 to w_7 and 0 to all other nets. The existence of connections $(D_i, R_j), (D_k, R_j)$ or both is denoted by $(D_i|D_k, R_j)$. After the application of S_G , the existence of both $(D_3|D_5, R_3)$ and $(D_3|D_5, R_5)$ are checked. Suppose that one of them does not exist, then S_K can easily distinguish among

the three possible connections. Suppose that both $(D_3|D_5, R_3)$ and $(D_3|D_5, R_5)$ exist, then one of the following 9 cases is true:

1. (D_3, R_3) and (D_3, R_5) exist;
2. (D_3, R_3) and (D_5, R_5) exists;
3. $(D_3, R_3), (D_3, R_5)$ and (D_5, R_5) exist;
4. (D_5, R_3) and (D_3, R_5) exist;
5. (D_5, R_3) and (D_5, R_5) exists;
6. $(D_5, R_3), (D_3, R_5)$ and (D_5, R_5) exist;
7. $(D_3, R_3), (D_5, R_3)$, and (D_3, R_5) exist;
8. $(D_3, R_3), (D_5, R_3)$, and (D_5, R_5) exists;
9. $(D_3, R_3), (D_5, R_3), (D_3, R_5)$ and (D_5, R_5) exist.

The connections (D_3, R_3) and (D_3, R_5) cannot both exist for the following reason. Suppose that they both exist. Then one can conclude that $SRV_3 = SRV_5$, which contradicts the fact that w_3 and w_5 are in different groups. Similarly, the connections (D_5, R_3) and (D_5, R_5) cannot both exist. Therefore, the above 9 cases are reduced to two cases, namely cases 2 and 4. The sequence S_K can distinguish between these two cases.

Similarly, the existence of both $(D_4|D_6, R_4)$ and $(D_4|D_6, R_6)$ are checked by S_G . The sequence S_K then can distinguish the two cases, namely (1) the existence of connection (D_4, R_4) and (D_6, R_6) , or (2) the existence of connections (D_4, R_6) and (D_6, R_4) .

All other connections are similarly checked. Since both Conditions C1 and C2 can be verified, maximal diagnosis is achieved.

4.3 Deficiencies in Previous Adaptive Algorithms

Method 3: [9]

This algorithm first applies a counting sequence, based on the initial results, a second sequence is applied. The STV of the second sequence represents the number of 0s in the corresponding STVs of the first sequence. The purpose of the second sequence is to make sure that the overall test set S is independent. This algorithm can achieve self-diagnosis. No confounding syndromes can be identified. Also, the fault f_1 in Figure 7 cannot be detected by this algorithm.

W-Test Algorithm: [3]

This algorithm is similar to Algorithm A1 except that the first sequence is a counting sequence S_C , i.e., in the W-Test algorithm the test set consists of only S_C and S_F . We next show an example in which the W-Test Algorithm cannot achieve maximal diagnosis.

Part of a wiring network is shown in Figure 9,

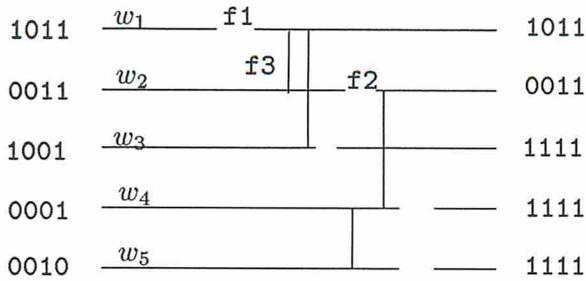


Figure 9: Deficiency in the W-Test Algorithm.

where the counting sequence S_C have been applied. For $i = 1, 2$ $STV_i = SRV_i$ and SRV_i is unique, thus both w_1 and w_2 will be put into group 0. This means that the opens f1, f2 and the short f3 will not be identified since during the application of a walking ones sequence all nets in group 0 will be kept at 0.

Therefore, to avoid putting a net into group 0 by mistake, it is necessary to apply an independent set which can achieve the *self-diagnosis* property. Both Algorithm A1 and A2 will not put w_1 and w_2 into group 0. Thus the faults associated with them can be identified by either S_F or (S_G, S_K) .

C-Test Algorithm: [7]

The C-Test Algorithm first applies a counting sequence, then based on the analysis of the syndromes, one or more PTVs are applied.

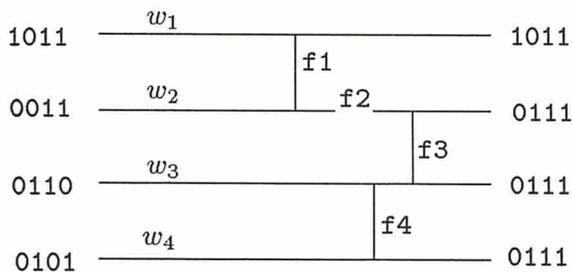


Figure 10: Deficiency in the C-Test Algorithm.

Part of a wiring network is shown in Figure 10, where a counting sequence has been applied. In the C-Test Algorithm both short faults f3 and f4 can be identified immediately. However, since no aliasing or confounding syndromes are related to $SRV_1 = 1011$, the fault f1 and f2 cannot be identified.

Using the same example, the diagnosis sequence in both Algorithm A1 and A2 will apply a walking ones sequence to w_2, w_3, w_4 since they are in the same group. Thus all faults in the network can be identified.

5 Conclusions

The results presented in this report outperform all previous results in that all diagnosable faults can be identified. We have shown that there exists diagnosable faults in a wiring network that cannot be identified by any of the previous results, which includes the complementary counting sequence [4], the independent set [9], the diagonally independent sequence [7], the W-Test Algorithm [3], the C-Test Algorithm [7] and the Method 3 in [9]. The faults that lead to the deficiencies for previous results are summarized and explained in Lemma 1 and 2.

Various levels of diagnostic resolution are defined. DR5 refers to the diagnostic level where all diagnosable faults are identified. We have also defined maximal diagnosis in terms of Conditions C1 and C2, which, as shown in Theorem 1, proved to be both necessary and sufficient for achieving diagnostic level DR5.

A property called set-cover independent is also presented. A test sequence that is set-cover independent must have a walking ones sequence as its subsequence. We have shown in Theorem 2 that a set-cover independent set is both necessary and sufficient for achieving maximal diagnosis. Based on this theorem a universal test set is presented. This test set can achieve maximal diagnosis for a wiring network without a specific fault model.

Two adaptive algorithms that can achieve maximal diagnosis have been presented. They can reduce the size of the test set by employing two-step diagnosis. Both algorithms first apply a maximal independent set to eliminate the aliasing syndromes. The responses are then analyzed and based on the initial results, the second part of the test set is generated. Without the information from the first part, it is impossible to reduce the size of the test set. Algorithm A2 requires less PTVs than Algorithm A1. However, we do not know whether Algorithm A2 generates the shortest possible test set.

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Jung-Cheun Lien and Melvin A. Breuer

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Department of Electrical Engineering - Systems
University of Southern California
Los Angeles, CA. 90089-0781
(213)740-4469

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