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The relationship between extra connectivity and *t/k*-diagnosability under the PMC model①

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Abstract

It is well-known that connectivity is closely related to diagnosability. If the relationships between them can be established, many kinds of diagnosability will be determined directly. So far, some notable relationships between connectivity and diagnosability had been revealed. This paper intends to find out the relationship between extra connectivity and t/k-diagnosability under the PMC (Preparata, Metze, and Chien) model. Then, applying this relationship, the t/k-diagnosability of bijective connection (BC) networks are determined conveniently.

Key words: extra connectivity, t/k-diagnosability, the PMC model

0 Introduction

Connectivity and diagnosability are generally considered as two important indicators that are used to evaluate the reliability of multiprocessor computer systems. They are also considered as two closely related parameters. So far, some important results had been achieved in the study of connectivity and diagnosability. But there are still some outstanding diagnosability measurement problems, especially for interconnection networks with insufficient regularity and symmetry.

Research shows that the various diagnosability of the interconnection network will increase with the improvement of the relevant connectivity, and show an obvious linear relationship. If it can be found out the relationship between diagnosability and related connectivity, it can be greatly simplified the measurement process of diagnosabilities and quickly calculate various diagnosabilites of a series of interconnection networks. Therefore, it is a very important and valuable scientific issue to study the relationship between connectivity and diagnosability.

1 Preliminaries

In general, a multiprocessor system can be modeled by $G(V,E)$, where $V(G)$ and $E(G)$ are the node set and the edge set, respectively. Let $x \in V(G)$ and $A,B \subset V(G)$, $N(x)$ is the set of all the neighbors of x, $N(A) = \bigcup_{a \in A} N(a) - A$ and $N_B(A) = N(A) \cap B$. The connectivity $k(G)$ of G is an important measure for fault tolerance of G. However, connectivity underestimates the resilience of large networks[1]. To compensate for this shortcoming, many kinds of connectivity are introduced, such as conditional connectivity[2], restricted connectivity[3], super connectivity[4], extra connectivity[5], et al. Among them, g-extra connectivity of G, written as $k_g(G)$, is the minimum size over all the g-extra cuts of G. Any subset $F \subset V(G)$ is a g-extra cut of G if $G - F$ is disconnected and each component of $G - F$ has size at least $g + 1$. Clearly, $k_0(G) = k(G)$.

In the operation of multiprocessor systems, identifying faulty processors is an important problem. In the process of identifying faulty processors, a fault diagnosis model and a diagnosis strategy are indispensible. At present, one of the widely adopted fault diagnosis model is PMC (Preparata, Metze, and Chien) model[6]. Under the PMC model, each pair of adjacent nodes can be allowed to test each other. If the tester is fault-free (faulty), its outcomes are correct (unreliable, respectively). For any edge $(u,v) \in E(G)$, $u \xrightarrow{0} v$ ($u \xrightarrow{1} v$) represents the outcome of test $u \rightarrow v$ is fault-free (faulty, respectively). In addition, $u \overset{00}{\leftrightarrow} v$ represents $u \xrightarrow{0} v$ and $v \xrightarrow{0} u$. A collection of all the test results is called a

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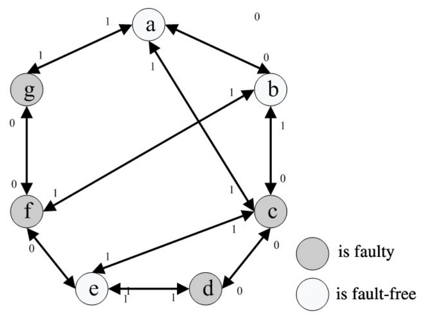
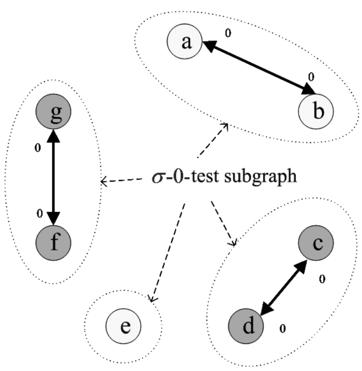
syndrome σ. Ref. [7] introduced the t/k-diagnosis strategy, which requires that when the number of fault nodes does not exceed t, all fault nodes can be isolated in a set of node and at most k nodes might be misdiagnosed. The t/k-diagnosability of G, is the maximum of t such that G is t/k-diagnosable[7]. The t/k-diagnosability of a series of regular networks under PMC model is determined[8-15]. It is well-known that the constraints of t/k-diagnosability and k-extra connectivity are basically the same. Therefore, Refs [11] and [12] believe that it is an interesting direction to analyze the relationship between extra connectivity and t/k-diagnosability. In this paper, the relationship between g-extra connectivity and t/k-diagnosability under the PMC model are revealed.

2 σ-0-test subgraph

Under the PMC model, given a graph G and a syndrome σ, each connected subgraphs or isolated points is called a σ-0 -test subgraph of G by removing all those edges whose outcomes are '1'[16]. The set of all the σ-0-test subgraph of G is denoted by $T_\sigma(G)$. Then, $V(T_\sigma(G)) = V(G)$ and $E(T_\sigma(G)) = \{(u,v) \in E(G), u \overset{00}{\leftrightarrow} v\}$ (see Fig. 1).



(a) syndrome σ



(b) $T_\sigma(G)$

Fig. 1 The illustration of σ-0-test subgraph

Given a syndrome σ, for any σ-0-test subgraph $S \in T_\sigma(G)$, all the nodes in S have the same status (fault-free or faulty). Then, under the PMC model, the following properties are shown as follows.

Property 1 Given a syndrome σ, let F be a fault set of G. Then any component C of G-F is a σ-0-test subgraph of G and each node in C is fault-free.

Property 2 Given a syndrome σ, let F be a fault set of G. Then F will be divided into one or several σ-0-test subgraphs of G.

3 The relationship between extra connectivity and t/k-diagnosability under the PMC model

Let X_n be an n-dimensional interconnection network and X_n can be divided into to copies of X_{n-1}, written as L and R. Then, the following four conditions will be used in the rest of this paper.

(1) Let $S \subset V(R)$ (or $S \subset V(L)$) with $|S| = g \geqslant 1$, $|N_R(S)| + |N_L(S)| \geqslant k_{g-1}(X_n)$ for $n \geqslant 8$ and $1 \leqslant g \leqslant n-4$.

(2) For any positive integers g, g_0 and g_1 with g, g_0, $g_1 \geqslant 1$. If $g = g_0 + g_1$, then $k_{g_0-1}(X_{n-1}) + k_{g_1-1}(X_{n-1}) \geqslant k_{g-1}(X_n)$ for $n \geqslant 8$ and $1 \leqslant g \leqslant n-4$.

(3) The function $f(g) = k_g(X_n)$ increases with increasing g for $n \geqslant 8$ and $1 \leqslant g \leqslant n-4$.

(4) $k_{g+1}(X_n) \geqslant k_g(X_n) + n - g - 4$ for $n \geqslant 8$ and $1 \leqslant g \leqslant n-5$.

Theorem 1 Let $S \subset V(X_n)$ with $|S| = g$. If X_n satisfies the conditions (1) and (2), $|N(S)| \geqslant k_{g-1}(X_n)$ for $n \geqslant 8$ and $1 \leqslant g \leqslant n-4$.

Proof The proof is by induction on g. If $g = 1$, $|S| = 1$. Then $|N(S)| \geqslant k(X_n) = k_0(X_n)$. Hence, the theorem is true for $g = 1$. Assume that $|N(S)| \geqslant k_{h-1}(X_n)$ with $|S| = h$ and $2 \leqslant h \leqslant g-1$.

Decompose X_n into two copies of X_{n-1}, denoted by L and R. Let $S_0 = S \cap V(L)$ and $S_1 = S \cap V(R)$. Let $|S_0| = g_0$ and $|S_1| = g_1$. Then $g_0 + g_1 = g$. Without loss of generality, let $|S_0| \leqslant |S_1|$.

Case 1 $|S_0| = 0$.

Since $|S_0| = 0$, $|S_1| = g$ and $|N(S)| \geqslant |N_R(S_1)| + |N_L(S_1)|$. By condition (1), $|N_R(S)| + |N_L(S)| \geqslant k_{g-1}(X_n)$. So, $|N(S)| \geqslant k_{g-1}(X_n)$.

Case 2 $|S_0| \geqslant 1$.

Since $|S_0| \geqslant 1$, $|N(S)| \geqslant |N_L(S_0)| + |N_R(S_1)|$ such that $N_L(S_0) = N(S_0) \cap V(L)$ and $N_R(S_1) = N(S_1) \cap V(R)$. By the induction hypothesis, $|N_L(S_0)| \geqslant k_{g_0-1}(X_{n-1})$ and $|N_R(S_1)| \geqslant k_{g_1-1}(X_{n-1})$. By condition (2), $|N_L(S_0)| + |N_R(S_1)| \geqslant k_{g_0-1}(X_{n-1}) + k_{g_1-1}(X_{n-1}) \geqslant k_{g-1}(X_n)$. So, $|N(S)| \geqslant k_{g-1}(X_n)$.

The theorem holds.

Theorem 2 If $X_n (n \geqslant 8)$ satisfies the conditions (1) - (3), let $S \subset V(X_n)$ and $2 \leqslant g+1 \leqslant |S| \leqslant n-4$. Then $|N(S)| \geqslant k_g(X_n)$.

Proof Let $|S| = h$. By Theorem 1, $|N(S)| \geqslant k_{h-1}(X_n)$. By condition (3), $k_{h-1}(X_n) \geqslant k_g(X_n)$. Hence, $|N(S)| \geqslant k_g(X_n)$.

Theorem 3 If $X_n (n \geqslant 8)$ satisfies the conditions (1) - (4) and $|V(X_n)| > 2k_g(X_n) + g - 1$, let $F \subset V(X_n)$ with $|F| \leqslant k_g(X_n) - 1$ and $1 \leqslant g \leqslant n/2 - 3$. If $X_n - F$ is disconnected, $X_n - F$ has a largest component $C_1 (|C_1| \geqslant g+1)$ and the union of the remaining components has at most g nodes.

Proof Let all the components of $X_n - F$ be $C_1, C_2, \cdots, C_m$ with $|C_1| \geqslant |C_2| \geqslant \cdots \geqslant |C_m|$. Suppose that $|C_1|, |C_2|, \cdots, |C_{r-1}| \geqslant g+1$ and $|C_r|, |C_{r+1}|, \cdots, |C_m| \leqslant g$ for $r \geqslant 1$.

Thus, $|F| \geqslant |N(C_r \cup C_{r+1} \cup \cdots \cup C_m)|$. Suppose that $g+1 \leqslant |C_r| + |C_{r+1}| + \cdots + |C_m| \leqslant n-4$. By Theorem 2, $|F| \geqslant |N(C_r \cup C_{r+1} \cup \cdots \cup C_m)| \geqslant k_g(X_n)$, which contradicts $|F| \leqslant k_g(X_n) - 1$. Therefore, either $|C_r| + |C_{r+1}| + \cdots + |C_m| \geqslant n-3$ or $|C_r| + |C_{r+1}| + \cdots + |C_m| \leqslant g$. Suppose that $|C_r| + |C_{r+1}| + \cdots + |C_m| \geqslant n-3$. Since $|C_r|, |C_2|, \cdots, |C_{r-1}| \leqslant g \leqslant n/2 - 3$, $(n-4) - (g+1) = n - g - 5 \geqslant (2g+6) - g - 5 > g$. Therefore, there exists a union H of some components of $C_r, C_{r+1}, \cdots, C_m$, such that $n - 4 \geqslant |H| \geqslant g+1$ (see Fig. 2). By Theorem 2, $|N(H)| \geqslant k_g(X_n)$, which contradicts $|F| \leqslant k_g(X_n) - 1$. Therefore, $|C_r| + |C_{r+1}| + \cdots + |C_m| \leqslant g$.

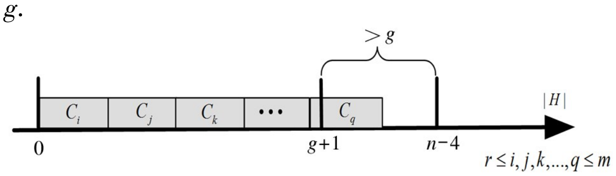


Fig. 2 The illustration of $|H|$

Since $|C_r| + |C_{r+1}| + \cdots + |C_m| \leqslant g$ and $|F| \leqslant k_g(X_n) - 1$ and $|V(X_n)| > 2k_g(X_n) + g - 1$, $|C_1| + |C_2| + \cdots + |C_{r-1}| = |V(X_n)| - |F| - (|C_r| + |C_{r+1}| + \cdots + |C_m|) > 2k_g(X_n) + g - 1 - (k_g(X_n) - 1) - g > k_g(X_n) > 0$. Therefore, there exists at least a component C_1 of $X_n - F$ such that $|C_1| \geqslant g+1$ nodes.

If $X_n - F$ has at least two components, where each component has at least $g+1$ nodes. That is $|C_1|, |C_2|, \cdots, |C_{r-1}| \geqslant g+1$ with $r \geqslant 3$. Suppose that there exists a component C_i with $n - 4 \geqslant |C_i| \geqslant g + 1 \geqslant 2$ and $1 \leqslant i \leqslant r-1$. By Theorem 2, $|N(C_i)| \geqslant k_g(X_n)$. Then $|F| \geqslant |N(C_i)| \geqslant k_g(X_n)$, which contradicts $|F| \leqslant k_g(X_n) - 1$. Therefore, $|C_1|, |C_2|, \cdots, |C_{r-1}| \geqslant n - 3 \geqslant g + 2$, which shows that $F \cup C_r \cup C_{r+1} \cup \cdots \cup C_m$ is a $(g+1)$-extra cut of X_n. Thus, $|F \cup C_r \cup C_{r+1} \cup \cdots \cup C_m| = |F| + |C_r| + |C_{r+1}| + \cdots + |C_m| \geqslant k_{g+1}(X_n)$. By condition (4), $k_{g+1}(X_n) \geqslant k_g(X_n) + n - g - 4$. Since $|C_r| + |C_{r+1}| + \cdots + |C_m| \leqslant g$ and $1 \leqslant g \leqslant n/2 - 3$,

$$
\begin{aligned}
&|F| + |C_r| + |C_{r+1}| + \cdots + |C_m| \geqslant k_{g+1}(X_n) \\
&\Rightarrow |F| \geqslant k_{g+1}(X_n) - (|C_r| + |C_{r+1}| + \cdots + |C_m|) \\
&\Rightarrow |F| \geqslant (k_g(X_n) + n - g - 4) - g \\
&\qquad = k_g(X_n) + n - 2g - 4 \\
&\qquad \geqslant k_g(X_n) + (2g + 6) - 2g - 4 \\
&\qquad \geqslant k_g(X_n) + 2,
\end{aligned}
$$

which contradicts $|F| \leqslant k_g(X_n) - 1$. So, $X_n - F$ has exactly one component which have at least $g+1$ nodes.

Theorem 4 If $X_n (n \geqslant 8)$ satisfies the conditions (1) - (4) with $|V(X_n)| > 2k_g(X_n) + g - 1$ and $1 \leqslant g \leqslant n/2 - 3$, let F be a fault set with $|F| \leqslant k_g(X_n) - 1$. Then, under any syndrome δ produced by F, the maximal σ-0-test subgraph of X_n is fault-free.

Proof If $X_n - F$ is connected, $|V(X_n) - F| = |V(X_n)| - |F| \geqslant 2k_g(X_n) + g - 1 - (k_g(X_n) - 1) = k_g(X_n) + g$. Since $|F| \leqslant k_g(X_n) - 1$, $|X_n - F| > |F|$. By Property 1, $X_n - F$ is a the maximal σ-0-test subgraph of X_n and each node of $X_n - F$ is fault-free. If $X_n - F$ is disconnected, by Theorem 3, $X_n - F$ has a largest component $C (|C| \geqslant g+1)$ and the union of the remaining components has at most g nodes. By Property 1, C is a σ-0-test subgraph. Since

$$
\begin{aligned}
|C| &\geqslant |V(X_n)| - |F| - g \\
&> 2k_g(X_n) + g - 1 - (k_g(X_n) - 1) - g \\
&= k_g(X_n),
\end{aligned}
$$

$|C| > |F|$. Therefore, by Properties 1 and 2, C is the maximal σ-0-test subgraph and each node of C is fault-free.

Theorem 5 If $X_n (n \geqslant 8)$ satisfies the conditions (1) - (4) with $|V(X_n)| > 2k_g(X_n) + g - 1$, then X_n is $k_g(X_n) - 1/g$-diagnosable for $1 \leqslant g \leqslant n/2 - 3$.

Proof Let F be a fault set of X_n with $|F| \leqslant k_g(X_n) - 1$. By Theorem 3, $X_n - F$ has a largest component $C (|C| \geqslant g+1)$ and the union of the remaining components has at most g nodes. By Theorem 4, C is the maximal σ-0-test subgraph and every node in C is fault-free. Therefore, there are $|F| + g$ nodes undiagnosed. Then, all the faulty nodes can be isolated to within a set of at most $|F| + g$ nodes.

There are at most g nodes might be misdiagnosed. Therefore, X_n is $k_g(X_n) - 1/g$-diagnosable.

4 Application to BC networks

An n-dimensional bijective connection (BC) network is denoted by B_n with $|V(B_n)| = 2^n$. B_n can be divided into two copies of B_{n-1}, written as L and R, and there exists a perfect matching between L and R (see Fig. 3). Then B_n has the following lemmas.

Lemma 1 [8] Let $S \subset V(B_n)$ with $|S| = g$ and $1 \leqslant g \leqslant n+1$. Then, $|N(S)| \geqslant \frac{1}{2}g^2 + (n - \frac{1}{2})g + 1$ for $n \geqslant 5$.

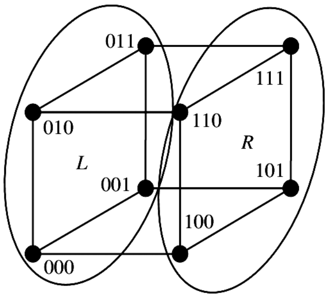


Fig. 3 The topology of B_3

Lemma 2 [17] $k_g(B_n) = n(g+1) - \frac{1}{2}g(g+3)$ for $n \geqslant 4$ and $1 \leqslant g \leqslant n-4$.

Lemma 3 For any three positive integers g, g_0 and g_1 with $g, g_0, g_1 \geqslant 1$. If $g = g_0 + g_1$, where $n \geqslant 5$ and $1 \leqslant g \leqslant n-3$, then $k_{g_0-1}(B_{n-1}) + k_{g_1-1}(B_{n-1}) \geqslant k_{g-1}(B_n)$.

Proof By Lemma 2,

$$\begin{aligned} & k_{g_0-1}(B_{n-1}) + k_{g_1-1}(B_{n-1}) \\ &= (n-1)g_0 - \frac{1}{2}(g_0-1)(g_0+2) \\ &\quad + (n-1)(g_1) - \frac{1}{2}(g_1-1)(g_1+2) \\ &= (n-1)(g_0+g_1) \\ &\quad - \frac{1}{2}(g_0^2 + g_0 - 2 + g_1^2 + g_1 - 2) \\ &= (n-1)g - \frac{1}{2}(g^2+g-4) + g_0g_1 \end{aligned}$$

and $k_{g-1}(B_n) = ng - \frac{1}{2}(g-1)(g+2)$. Then,

$$\begin{aligned} & k_{g_0-1}(B_{n-1}) + k_{g_1-1}(B_{n-1}) - k_{g-1}(B_n) \\ &= (n-1)g - \frac{1}{2}(g^2+g-4) + g_0g_1 \\ &\quad - ng + \frac{1}{2}(g-1)(g+2) \\ &= -g + g_0g_1 + 1 \\ &= -(g_0+g_1) + g_0g_1 + 1 \\ &= (g_0-1)(g_1-1) \geqslant 0. \end{aligned}$$

Therefore, $k_{g_0-1}(B_{n-1}) + k_{g_1-1}(B_{n-1}) \geqslant k_{g-1}(B_n)$.

Lemma 4 Decompose a $B_n (n \geqslant 5)$ into two B_{n-1}, written as L and R. Let $S \subset V(R)$ (or $S \subset V(L)$) with $|S| = g \geqslant 1$. Then, $|N_R(S)| + |N_L(S)| \geqslant k_{g-1}(B_n)$ for $1 \leqslant g \leqslant n-3$.

Proof By Lemma 1, $|N_R(S)| \geqslant \frac{1}{2}g^2 + (n - \frac{3}{2})g + 1$. By Lemma 2, $k_{g-1}(B_n) = ng - \frac{1}{2}(g-1)(g+2)$. Then,

$$\begin{aligned} & |N_R(S)| + |N_L(S)| - k_{g-1}(B_n) \\ &= |N_R(S)| + g - k_{g-1}(B_n) \\ &\geqslant \frac{1}{2}g^2 + (n - \frac{3}{2})g + 1 + g - ng \\ &\quad + \frac{1}{2}(g-1)(g+2) \\ &= \frac{1}{2}g^2 - \frac{3}{2}g + 1 + g + \frac{1}{2}g^2 + \frac{1}{2}g - 1 \\ &= g^2 \geqslant 0. \end{aligned}$$

Therefore, $|N_R(S)| + |N_L(S)| \geqslant k_{g-1}(B_n)$.

Lemma 5 Function $f(g) = k_g(B_n) = n(g+1) - \frac{1}{2}g(g+3)$ is monotonically increasing with increasing g when $n \geqslant 4$ and $1 \leqslant g \leqslant n-4$.

Proof The derivative of $f(g)$ is $f'(g) = n - g + \frac{3}{2}$. Since $1 \leqslant g \leqslant n-4$, $f'(g) > 0$. Therefore, $f(g)$ is monotonically increasing with increasing g.

Lemma 6 $k_{g+1}(B_n) \geqslant k_g(B_n) + n - g - 4$, for $n \geqslant 8$ and $1 \leqslant g \leqslant n-5$.

Proof Since $1 \leqslant g \leqslant n-5$, $1 \leqslant g+1 \leqslant n-4$. By Lemma 2,

$$\begin{aligned} & k_{g+1}(B_n) - k_g(B_n) - n + g + 4 \\ &= n(g+2) - \frac{1}{2}(g+1)(g+4) - n(g+1) \\ &\quad + \frac{1}{2}g(g+3) - n + g + 4 = 2 \geqslant 0. \end{aligned}$$

Lemma 7 B_n (is $k_g(B_n) - 1)/g$-diagnosable, for $n \geqslant 8$ and $1 \leqslant g \leqslant n/2 - 3$.

Proof Since $|V(B_n)| = 2^n$ and $k_g(B_n) = n(g+1) - \frac{1}{2}g(g+3)$, $|V(B_n)| > 2k_g(B_n) + g - 1$. By the definition of B_n and Lemmas 3 – 6, B_n satisfies the conditions (1) – (4). Therefore, by Theorem 5, B_n is $(k_g(B_n) - 1)/g$-diagnosable.

5 Conclusion

In the design and operation of large-scale multiprocessor systems, reliability is a key issue to be considered. It is well-known that connectivity and diagnosability are two crucial subjects for reliability and fault tolerability and they are closely related to each other. This paper establishes a relationship between extra connectivity and t/k-diagnosability under the PMC model. Then, using this relationship, it is proved that B_n is

$(k_g(B_n)-1)/g$-diagnosable.

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