Journal of Discrete Algorithms ••• (••••) •••–•••

Contents lists available at ScienceDirect

Journal of Discrete Algorithms

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Excessive index for mesh derived networks

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ARTICLE INFO

Article history:
Available online xxxx

Keywords:
Matching
Perfect matching
Excessive index
Mesh
Cylinder
Torus

ABSTRACT

A matching in a graph $G = (V, E)$ is a subset M of edges, no two of which have a vertex in common. A matching M is said to be perfect if every vertex in G is an endpoint of one of the edges in M. The excessive index of a graph G is the minimum number of perfect matchings to cover the edge set of G. In this paper we determine the excessive index for mesh, cylinder and torus networks.

1. Introduction

The interconnection network is responsible for fast and reliable communication among the processing nodes in any parallel computer [11]. Processing and distribution of data using interconnection networks have become indissoluble elements of the development of our society. Many systems consider communications among internal entities as a key factor in their performance. Examples of these systems are VLSI (very large-scale integration) circuits, image processing, simulations of diverse types of chemical reactions, telephone networks, computer networks and many others. The need for ever increasing computing power is a current problem in modern technology. Parallel computing with multiple processors is a feasible approach to tackle this problem. To implement this approach many communication schemes are necessary, including the interconnection of processors. Thus network design concepts become imperative elements in our life.

Various research and development results on how to interconnect multiprocessor components have been reported in literature. One of the most popular architectures is the mesh-connected computer, in which processors are placed in a square or rectangular grid, with each processor being connected by a communication link to its neighbors in up to four directions. Tori are meshes with wrap around connections to achieve vertex and edge symmetry. Meshes and tori are among the most frequent multiprocessor networks available today in the market [16].

A classic problem in graph theory and theoretical computer science is that of finding subgraphs of a given graph with prescribed vertex degrees. Subgraphs of prescribed vertex degrees are commonly referred to as factors [8]. A k-factor of graph G is defined as a k-regular spanning subgraph of G. A *matching* in a graph $G = (V, E)$ is a subset M of edges, no two of which have a vertex in common. A matching M is said to be *perfect* (or 1-factor) if every vertex in G is an endpoint of one of the edges in M. A perfect matching of a graph is a spanning subgraph which is regular of degree one. A *near-perfect* (or near 1-factor) matching covers all but exactly one vertex. Tutte has characterized graphs which contain

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[1] This work is supported by the Department of Science and Technology, Government of India, Project No. SR/S4/MS: 595/09.

http://dx.doi.org/10.1016/j.jda.2014.07.001

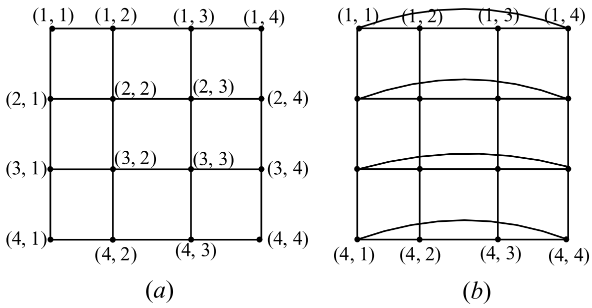

Fig. 1. (a) 4×4 mesh network connecting 16 nodes (b) 4×4 cylinder network connecting 16 nodes.

1-factors [18]. Beineke and Plummer [1] proved that every block with a 1-factor always contains at least one more, and a result due to Petersen [14] showed that every cubic graph with no bridges contains a 1-factor [17]. There are a number of famous conjectures and open problems on perfect matchings including Berge–Fulkerson conjecture, Fan Raspaud conjecture and problems on maximum or minimum number of perfect matching, induced matching partition, matching preclusion and many others including *excessive index* problem.

2. An overview of the paper

A graph G is *1-extendable* if every edge of G belongs to at least one 1-factor of G. A 1-*factor* cover of G is a set F of 1-factors of G such that $\bigcup_{F \in \mathcal{F}} F = E(G)$. A 1-factor cover of minimum cardinality is called an *excessive factorization* [3]. The *excessive index* of G, denoted $\chi'_e(G)$, is the size of an excessive factorization of G. We define $\chi'_e(G) = \infty$ if G is not 1-extendable. A graph G is 1-factorizable if its edge set $E(G)$ can be partitioned into edge-disjoint 1-factors. An *excessive near* 1-*factorization* of a graph G is a minimum set of near 1-factors whose union contains all the edges of G [5]. Excessive index has a number of applications particularly in *scheduling theory* to complete the process in minimum possible time [6]. The problem of determining whether a regular graph G is 1-factorizable is *NP*-complete [10].

Bonisoli et al. [3] observed that the problem of determining the excessive index for regular graphs is *NP*-hard. Cariolaro et al. [4] determined the excessive index of complete multipartite graphs, which proved to be a challenging task. The excessive index of a bridgeless cubic graph has been studied by Fouquet et al. [9]. Further excessive index are being calculated for regular graphs in [2,13]. Rajasingh et al. have determined excessive index for honeycomb [15], butterfly [15], hexagonal [12] and 3-D mesh network [12]. In general, it is proved that $\chi'_e(G) \geq \chi'(G)$ where $\chi'(G)$ is the edge-chromatic number (chromatic index) of G and that the difference between $\chi'_e(G)$ and $\chi'(G)$ can be arbitrarily large [3]. In this paper we determine the excessive index for mesh, cylinder and torus networks.

3. A general results on excessive index

Theorem 1. *(See [3].) Let G be a graph. Then* $\chi'_e(G) \geq \Delta$.

Theorem 2. *(See [7].) Every r-regular bipartite graph,* $r \geq 1$*, is* 1*-factorable.*

Theorem 3. *Let G be a regular bipartite graph of even order. Then* $\chi'_e(G) = \Delta$.

Theorem 4. *Let* $G(V, E)$ *be a graph of odd order with maximum degree* Δ*. If* $|E| > \Delta \times \lfloor \frac{|V(G)|}{2} \rfloor$*, then* $\chi'_e(G) \geq \Delta + 1$.

Proof. Each of the perfect matchings in G covers $\lfloor \frac{|V(G)|}{2} \rfloor$ edges. Thus $\bigcup_{1 \leq i \leq \Delta} M_i$ will cover at most $\Delta \times \lfloor \frac{|V(G)|}{2} \rfloor$ edges. □

4. Excessive index of mesh derived networks

Definition 1. Let P_n denote a path on n vertices. For $m, n \geq 2$, $P_m \times P_n$ is defined as the two dimensional mesh with m rows and n columns. It is denoted by $M_{m \times n}$. See Fig. 1(a).

Definition 2. Let C_n and P_n denote a cycle and a path on n vertices respectively. For $m, n \geq 2$, $C_m \times P_n$ is defined as the two dimensional cylinder with m rows and n columns. It is denoted by $CY_{m \times n}$. See Fig. 1(b).

Definition 3. Let C_n denote a cycle on n vertices. For $m, n \geq 2$, $C_m \times C_n$ is defined as the two dimensional torus with m rows and n columns. It is denoted by $T_{m \times n}$. See Fig. 2.

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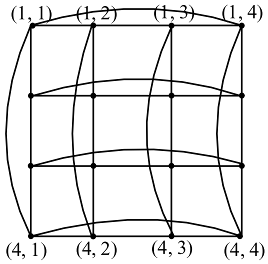

Fig. 2. 4×4 torus network connecting 16 nodes.

Remark 1. The vertex of $M_{m\times n}$, $C_{m\times n}$ and $T_{m\times n}$ in the ith row and jth column is denoted by (i, j), $1 \le i \le m$, $1 \le j \le n$. See Figs. 1 and 2.

Remark 2. In $M_{m\times n}$, $CY_{m\times n}$ and $T_{m\times n}$, maximum degree $\Delta = 4$. Then by Theorem 1, $\chi'_e(G) \ge 4$ when $G \simeq M_{m\times n}$ or $CY_{m\times n}$ or $T_{m\times n}$.

4.1. Excessive index for mesh

Theorem 5. *Let G be the mesh network $M_{m\times n}$, $m + n$ even, $m > 2$, $n > 2$. Then $\chi'_e(G) = 4$.*

Proof. Let

$$M_1 = \{((i, j), (i, j+1)),\ 1 \le i \le m,\ j \text{ odd}, 1 \le j \le n\},$$
$$M_2 = \{((i, j), (i, j+1)),\ 1 \le i \le m,\ j \text{ even}, 1 \le j \le n\},$$
$$M_3 = \{((i, j), (i+1, j)),\ i \text{ odd}, 1 \le i \le m,\ 1 \le j \le n\}$$

and

$$M_4 = \{((i, j), (i+1, j)), i \text{ even}, 1 \le i \le m, 1 \le j \le n\}.$$

See Fig. 3.

Clearly $M_1 \cup M_2$ covers all edges parallel to X-axis and $M_3 \cup M_4$ covers all edges parallel to Y-axis. If m and n are even then M_i, $i = 1, 3$ are perfect. To make M_2 and M_4 perfect, include the edges $((i, j), (i+1, j))$, $j = 1, n$, i odd, $1 \le i \le m$ in M_2 and $((i, j), (i, j+1))$, $i = 1, m$, j odd, $1 \le j \le n$ in M_4.

If m and n are odd then M_i, $1 \le i \le 4$ is not near 1-factor. To make them near-perfect, include the edges $((i, n), (i+1, n))$, i odd, $1 \le i \le m$ in M_1, $((i, 1), (i+1, 1))$, i odd, $1 \le i \le m$ in M_2, $((m, j+1), (m, j+1))$, j odd, $1 \le j \le n$ in M_3 and $((1, j), (1, j+1))$, j odd, $1 \le j \le n$ in M_4. □

Lemma 1. *Let G be the mesh network $M_{m\times n}$, $m + n$ odd, $m > 2$, $n > 2$. Then $\chi'_e(G) \ge 5$.*

Proof. Without loss of generality let m be odd and n be even. Suppose that $\chi'_e(G) < 5$ and M_1, M_2, M_3, M_4 are perfect matchings that cover the edge set of G. Consider the vertex $(1, 1)$ and the edges $((1, 1), (1, 2))$, $((1, 1), (2, 1))$ incident to it. In order that M_i's are perfect there are three cases,

(i) The edge $((1, 1), (1, 2))$ is in one M_i and $((1, 1), (2, 1))$ is in remaining three M_i's.
(ii) The edge $((1, 1), (1, 2))$ is in three M_i's and $((1, 1), (2, 1))$ is in remaining one M_i.
(iii) The edge $((1, 1), (1, 2))$ is in two M_i's and $((1, 1), (2, 1))$ is in remaining two M_i's.

Then the edges $((1, 2), (1, 3))$ and $((1, 2), (2, 2))$ cannot be in same M_i in case (i) and the edges $((2, 1), (2, 2))$ and $((2, 1), (3, 1))$ cannot be in same M_i in case (ii), since $\deg(1, 2) = \deg(2, 1) = 3$.

Now the edge $((1, 1), (1, 2))$ is in two M_i's and $((1, 1), (2, 1))$ is in the remaining two M_i's. Consider the path P: $(1, 1)(2, 1)\ldots(m, 1)$ which is of even length. Since $\deg(i, 2) = 4$, $2 \le i \le m-1$, the edge $((i, 1), (i, 2))$, $2 \le i \le m-1$ should be in exactly one M_i. Hence alternate edges in the path P are in two M_i's. Finally the edge $((m-1, 1), (m, 1))$ is in one M_i which implies that the edge $((m, 1), (m, 2))$ is in remaining three M_i's, which is not possible. □

The following theorem proves that the bound obtained in Lemma 1 is sharp.

Theorem 6. *Let G be the mesh network $M_{m\times n}$, $m + n$ odd, $m > 2$, $n > 2$. Then $\chi'_e(G) = 5$.*

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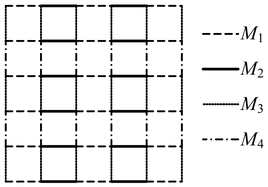

Fig. 3. The edges selected in M_i, $1 \le i \le 4$ of $M_{6\times 6}$ is shown in the figure.

Proof. Without loss of generality let m be even and n be odd.

Let

$$M_1 = \{((i,j),(i,j+1)),\ 1 \le i \le m,\ j \text{ odd}, 1 \le j \le n\},$$
$$M_2 = \{((i,j),(i,j+1)),\ 1 \le i \le m,\ j \text{ even}, 1 \le j \le n\},$$
$$M_3 = \{((i,j),(i+1,j)),\ i \text{ odd}, 1 \le i \le m,\ 1 \le j \le n\},$$
$$M_4 = \{((i,j),(i+1,j)),\ i \text{ even}, 1 \le i \le m,\ 1 \le j \le n-1\}$$

and

$$M_5 = \{((i,j),(i+1,j)),\ i \text{ even}, 1 \le i \le m,\ 2 \le j \le n\}.$$

Clearly $M_1 \cup M_2$ covers all edges parallel to X-axis and $M_3 \cup M_4 \cup M_5$ covers all edges parallel to Y-axis. Moreover M_3 is perfect. To make M_i, $i = 1,2,4,5$ perfect, include the edges $((i,n),(i+1,n))$, i odd, $1 \le i \le m$ in M_1, $((i,1),(i+1,1))$, i odd, $1 \le i \le m$ in M_2, $((i,j),(i,j+1))$, $i = 1,m$, j odd, $1 \le j \le n$ and $((i,n),(i+1,n))$, i odd, $1 \le i \le m$ in M_4 and $((i,j),(i,j+1))$, $i = 1,m$, j odd, $1 \le j \le n$ and $((i,1),(i+1,1))$, i odd, $1 \le i \le m$ in M_5. □

4.2. Excessive index for cylinder

Theorem 7. *Let G be the cylinder network $CY_{m\times n}$, n even. Then $\chi'_e(G) = 4$.*

Proof. Let

$$M_1 = \{((i,j),(i,j+1)),\ 1 \le i \le m,\ j \text{ odd}, 1 \le j \le n\},$$
$$M_2 = \{((i,j),(i,j+1)),\ 1 \le i \le m,\ j \text{ even}, 1 \le j \le n,\ j \bmod n\},$$
$$M_3 = \{((i,j),(i+1,j)),\ i \text{ odd}, 1 \le i \le m,\ 1 \le j \le n\}$$

and

$$M_4 = \{((i,j),(i+1,j)),\ i \text{ even}, 1 \le i \le m,\ 1 \le j \le n\}.$$

Clearly $M_1 \cup M_2$ covers all edges parallel to X-axis and $M_3 \cup M_4$ covers all edges parallel to Y-axis. If m is even then M_i, $i = 1,2,3$ are perfect. To make M_4 perfect, include the edges $((i,j),(i,j+1))$, $i = 1,n$, j odd, $1 \le j \le n$ in M_4.

If m is odd then M_1 and M_2 are perfect. To make M_3 and M_4 perfect, include the edges $((m,j),(m,j+1))$, j odd, $1 \le j \le n$ in M_3 and $((1,j),(1,j+1))$, j odd, $1 \le j \le n$ in M_4. □

Lemma 2. *Let G be the cylinder network $CY_{m\times n}$ where m is even and n is odd, $m > 2$, $n > 2$. Then $\chi'_e(G) \ge 5$.*

Proof. Suppose $\{M_1, M_2, M_3, M_4\}$ covers the edge set of G. Consider the cycle C_n: $(1,1)(1,2)\ldots(1,n)(1,1)$ where $\deg(1,j) = 3$, $1 \le j \le n$ in G. The edges incident with each of these vertices $(1,j)$, $1 \le j \le n$ whose other end is $(2,j) \in V(G \backslash C_n)$ should be in exactly one M_i, since $\deg(2,j) = 4$, $1 \le j \le n$. Thus in order to have a perfect matching alternate edges in C_n should be in two M_i's which is not possible, since C_n is of odd length. □

The following theorem proves that the bound obtained in Lemma 2 is sharp.

Theorem 8. *Let G be the cylinder network $CY_{m\times n}$ where m is even and n is odd, $m > 2$, $n > 2$. Then $\chi'_e(G) = 5$.*

Proof. Let

$$M_1 = \{((i,j),(i,j+1)),\ 1 \le i \le m,\ j \text{ odd}, 1 \le j \le n-1\},$$
$$M_2 = \{((i,j),(i,j+1)),\ 1 \le i \le m,\ j \text{ even}, 1 \le j \le n\},$$

$$M_3 = \{((i,j),(i+1,j)),\ i \text{ odd}, 1 \le i \le m,\ 2 \le j \le n-1\} \cup \{((i,j),(i+1,j)),\ i \text{ even}, 1 \le i \le m,\ j = 1, n\},$$
$$M_4 = \{((i,j),(i+1,j)),\ i \text{ even}, 1 \le i \le m,\ 1 \le j \le n-1\}$$

and

$$M_5 = \{((i,1),(i,n)),\ 1 \le i \le m\} \cup \{((i,j),(i,j+1)),\ 1 \le i \le m, j \text{ even}, 2 \le j \le n-3\}.$$

Clearly $M_1 \cup M_2 \cup M_5$ covers all edges parallel to X-axis and $M_3 \cup M_4$ covers all edges parallel to Y-axis. To make M_i, $1 \le i \le 5$ perfect, include the edges $((i,n),(i+1,n))$, i odd, $1 \le i \le m$ in M_1, $((i,1),(i+1,1))$, i odd, $1 \le i \le m$ in M_2, $((i,1),(i,n))$, $i = 1, m$ in M_3, $((i,j),(i,j+1))$, $i = 1, m$, j odd, $1 \le j \le n-1$ and $((i,n),(i+1,n))$, i odd, $1 \le i \le m$ in M_4 and $((i,n-1),(i+1,n-1))$, i odd, $1 \le i \le m$ in M_5. □

Theorem 9. *Let G be the cylinder network $CY_{m\times n}$ where m and n are odd. Then $\chi'_e(G) = 4$.*

Proof. Let

$$M_1 = \{((i,j),(i,j+1)),\ 1 \le i \le m,\ j \text{ odd}, 1 \le j \le n\} \cup \{((i,n),(i+1,n)),\ i \text{ odd}, 1 \le i \le m\},$$
$$M_2 = \{((i,j),(i,j+1)),\ 1 \le i \le m,\ j \text{ even}, 1 \le j \le n,\ j \bmod n\} \cup \{((i,1),(i+1,1)),\ i \text{ odd}, 1 \le i \le m\},$$
$$M_3 = \{((i,j),(i+1,j)),\ i \text{ odd}, 1 \le i \le m,\ 2 \le j \le n-1\} \cup \{((i,1),(i,n)),\ 1 \le i \le m\}$$

and

$$M_4 = \{((i,j),(i+1,j)),\ i \text{ even}, 1 \le i \le m,\ 1 \le j \le n\}.$$

Clearly $M_1 \cup M_2 \cup M_3$ covers all edges parallel to X-axis and $M_1 \cup M_2 \cup M_3 \cup M_4$ covers all edges parallel to Y-axis. Moreover M_1 and M_2 are near-perfect. To make M_3 and M_4 near-perfect, include the edges $((m,j),(m,j+1))$, j even, $1 \le j \le n-3$ in M_3 and $((1,j),(1,j+1))$, j odd, $1 \le j \le n$ in M_4. □

4.3. Excessive index for torus

The torus network $T_{m\times n}$ where m and n are even is a regular bipartite graph. Hence by Theorem 3, excessive index is 4. The following result shows that even if one of m, n is odd, the excessive index of the torus network is 4.

Theorem 10. *Let G be the torus network $T_{m\times n}$ where $m+n$ odd, $m > 2$, $n > 2$. Then $\chi'_e(G) = 4$.*

Proof. Without loss of generality let m be even and n be odd.
Let

$$M_1 = \{((i,j),(i,j+1)),\ 1 \le i \le m,\ j \text{ odd}, 1 \le j \le n\} \cup \{((i,n),(i+1,n)),\ i \text{ odd}, 1 \le i \le m\},$$
$$M_2 = \{((i,j),(i,j+1)),\ 1 \le i \le m,\ j \text{ even}, 1 \le j \le n,\ j \bmod n\} \cup \{((i,1),(i+1,1)),\ i \text{ odd}, 1 \le i \le m\},$$
$$M_3 = \{((i,j),(i+1,j)), i \text{ odd}, 1 \le i \le m,\ 2 \le j \le n-1\} \cup \{((i,1),(i,n)),\ 1 \le i \le m\}$$

and

$$M_4 = \{((i,j),(i+1,j)),\ i \text{ even}, 1 \le i \le m,\ 1 \le j \le n,\ i \bmod m\}.$$

Clearly $M_1 \cup M_2 \cup M_3$ covers all edges parallel to X-axis and $M_1 \cup M_2 \cup M_3 \cup M_4$ covers all edges parallel to Y-axis. Also each M_i, $1 \le i \le 4$ is perfect. □

Lemma 3. *Let G be the torus network $T_{m\times n}$ where m and n are odd. Then $\chi'_e(G) \ge 5$.*

Proof. By Theorem 4, since $|E| = 2 \times mn > 4 \times \lfloor \frac{|mn|}{2} \rfloor$, $\chi'_e(G) \ge \Delta + 1 = 5$. □

The following theorem proves that the bound obtained in Lemma 3 is sharp.

Theorem 11. *Let G be the torus network $T_{m\times n}$ where m and n are odd. Then $\chi'_e(G) = 5$.*

Proof. Let

$$M_1 = \{((i, j), (i, j+1)),\ 1 \le i \le m,\ j \text{ odd}, 1 \le j \le n-1\} \cup \{((i, n), (i+1, n)),\ i \text{ odd}, 1 \le i \le m\},$$
$$M_2 = \{((i, j), (i, j+1)),\ 1 \le i \le m,\ j \text{ even}, 1 \le j \le n\} \cup \{((i, 1), (i+1, 1)),\ i \text{ odd}, 1 \le i \le m\},$$
$$M_3 = \{((i, j), (i+1, j)),\ i \text{ odd}, 1 \le i \le m,\ 2 \le j \le n-1\} \cup \{((i, 1), (i, n)),\ 1 \le i \le m\},$$
$$M_4 = \{((i, j), (i+1, j)),\ i \text{ even}, 1 \le i \le m,\ 1 \le j \le n\}$$

and

$$M_5 = \{((1, j), (m, j)),\ 1 \le j \le n\}.$$

Clearly $M_1 \cup M_2 \cup M_3$ covers all edges parallel to X-axis and $M_1 \cup M_2 \cup M_3 \cup M_4 \cup M_5$ covers all edges parallel to Y-axis. Moreover M_1 and M_2 are near-perfect. To make M_i, $3 \le i \le 5$ near-perfect, include the edges $((m, j), (m, j+1))$, j even, $1 \le j \le n-3$ in M_3, $((1, j), (1, j+1))$, j odd, $1 \le j \le n-2$ in M_4 and $((i, j), (i, j+1))$, $2 \le i \le m-1$, j odd, $1 \le j \le n-2$ and $((i, n), (i+1, n))$, i even, $1 \le i \le m-3$ in M_5. □

5. Conclusion

In this paper we determine the excessive index of mesh, cylinder and torus networks. Computing the excessive index for other interconnection networks such as hypercube, Benes, circulant network, hypertree, Christmas tree are under investigation.

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