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Implementing FEFOM Load Balancing Algorithm on the Enhanced OTIS-*n*-Cube Topology

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***Abstract*— The Optical Transpose Interconnection System; OTIS for short; optoelectronic interconnection network architecture is an interesting alternative for future-generation parallel processing systems due to its promising and attractive topological properties. Recently, many enhancements were presented on OTIS topologies including the Enhanced OTIS-n-Cube interconnection networks. Therefore, performance improvement characteristics of such a potential architecture need to be investigated; one of which is load balancing technique. This paper focuses on implementing an efficient algorithm for load balancing on the potential Enhanced OTIS-n-Cube interconnection networks. This algorithm is called Factor-Optical-Factor Exchange Model; FOFEM for short.**

Keywords*—component, formatting, style, styling, insert *(key words)

I. Introduction

The OTIS architecture was first proposed by Marsden et al. [1]. OTIS has gained considerable attention. Significant efforts have been employed in studying and improving several aspects of OTIS networks. A few studies addressed more improvements on the topological properties of the OTIS interconnection network [2, 3]. In [3], an Enhanced OTIS-*n*-Cube topology was introduced; the new proposed network has many good topological features such as regular degree, semantic structure, low diameter, and ability to embed graphs and cycles.

The significance of load balancing lies in its effect on improving the speedup in processing time, which is a major objective in all parallel processing systems. Based on this fact, this research is dedicated towards studying and solving the load balancing problem on Enhanced OTIS-*n*-Cube interconnection networks, with the motivation of creating an efficient solution that will have a valuable contribution to the enhancement of the Enhanced OTIS-*n*-Cube interconnection networks' performance [4]-[8].

Therefore, all aspects of performance improvement on this promising architecture should be studied and evaluated, one of which is the load balancing problem, which is studied on Enhanced OTIS-Cube interconnection networks in this research.

The proposed method is called **Factor-Optical-Factor Exchanges Method (FOFEM)**, which is based on the Diffusion-Exchange-Diffusion scheme (DED-X) proposed in [9] for load balancing on OTIS interconnection networks. The basic idea of FOFEM was presented in [10] where it was implemented on another topology called Extended OTIS-Cube [3].

II. Background and Related Work

This section presents a background study on OTIS interconnection networks. It also presents the research work related to load balancing on deferent topological networks in general and on OTIS-Cube networks in specific since it is the core of this research.

A. Introduction to Optical Interconnection Networks

In optical networks processors are located on separate chips and interconnected through free space interconnects. The idea behind this separation is to utilize the benefits of both the optical and electronic technologies. Processors within a group are connected by a certain interconnecting topology, while the transposing group and processor indexes achieve inter-group links. The Optical Transpose Interconnection System; OTIS; is one of the most famous type of optical networks.

Processors within OTIS networks are partitioned into groups, where each group is realized on a separate chip with electronic inter-processor connects. Using *n*-cube as a factor network will yield the OTIS-*n*-Cube in denoting this network. The hypercube; or cube for short; has been used as a factor topology for its attractive properties [11]–[14].

The factor network can be any of the traditional interconnection networks, such as the Hypercube or Cube for short, which is an interesting interconnection network topology, such that ***n*** processors in a *n*-Cube are organized in $\log_2 n$ dimensions, where only two nodes are connected along each dimension. Two nodes in *n*-Cube are connected if the hamming distance between the binary representations of their processors numbers is one, in another word; if they differ only in one bit. Each of the groups in Fig. 1 is a 2-Cube.

Constructing OTIS-*n*-Cube is formed by "multiplying" a cube topology by itself. The set of vertices is equal to the Cartesian product on the set of vertices in the factor cube network. The set of edges *E* in the OTIS-*n*-Cube consists of two subsets, one is from the factor cube, called *cube*-type edges, and the other subset contains the *transpose* edges. The OTIS approach suggests implementing *cube*-type edges by electronic links since they involve intra-chip short links and implementing transpose edges by free space optics. Throughout this paper the terms "*electronic move*" and the "*OTIS move*" (or "*optical move*") will be used to refer to data transmission based on electronic and optical technologies, respectively.

Although the OTIS-*n*-Cube network has many attractive topological properties it suffers from having limited optical links between the different groups. When the source and destination nodes are in two different groups, it creates a congestion problem to most of the paths that have to pass through this particular optical link because only one optical link connects two distinguished groups. Furthermore, alternative paths are too long compared to the short path because they have to be routed via a third group which required passing via two optical links in addition to the electronic moves in each group to reach the destination.

Many more advanced researches were conducted to improve the OTIS interconnection network including improving the topological properties of OTIS [2, 3, 15, 16]. In [3] Das proposed a potential topology and presented the topological properties of this promising network; e.g. size, regularity, and short diameter. In [16], Authors presented a fault tolerant routing algorithm using unsafe vectors for a similar topology. The detailed studies on the topological and routing properties of the Enhanced OTIS Cube were presented in [2, 3] and [17].

In the Enhanced OTIS-*n*-Cube, the address of a node u = ⟨g, p⟩ from V is composed of two components. Fig. 1 shows a 16 processor Enhanced OTIS-2-Cube, solid arrows represent transpose edges while dashes arrows represent opposite edges. The notation ⟨*g*, *p*⟩ is used to refer to the group and processor addresses respectively, two nodes $\langle g_1, p_1\rangle$ and $\langle g_1, p_2\rangle$ are connected by a direct edge if one of the following cases occurs:

1-If $g_1 = g_2$ and $(p_1, p_2) \in E_0$ where E_0 is the set of edges in *n*-cube network, in this case the two nodes are connected by an electronic edge if their labels differ only by one bit position.

2-If $g_1 = p_2$ and $p_1 = g_2$, in this case the two nodes are connected by a transpose edge.

3-If $g_1 = p_1$, then the node $\langle g_1, p_1\rangle$ is connected to the node $\langle g_2, p_2\rangle$ via a transpose edge obtained by complementing all the bits of $\langle g_1, p_1\rangle$.

The attractive outcomes of the research on OTIS revealed its ability to achieve Terra bit throughput at a reasonable cost. Based on this, several research efforts have been employed towards studying OTIS and investigating its usefulness for real-life applications [4]-[6]. This paper investigates the load balance problem for the Enhanced OTIS-*n*-Cube [3] and implements FEFOM load balancing algorithm for this potential topology.

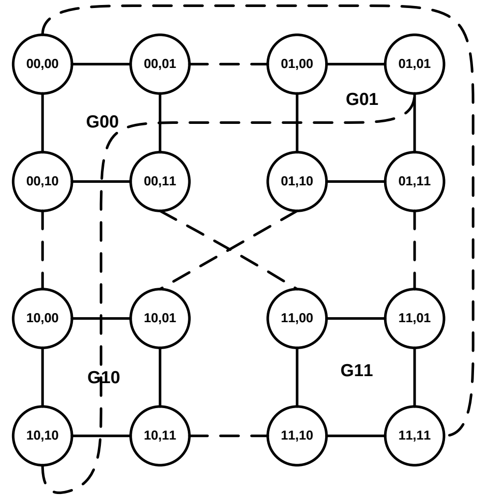

Figure1. Enhanced OTIS-2-Cube

B. *Introduction to Load Balancing*

One of the most important algorithms used in parallel processing system is load balancing. The load balancing algorithm has been studied using different approaches on various networks.

Ranka, Won, and Sahni [11] introduced the Dimension Exchange Method (DEM) on Hypercube interconnection networks. It is a simple heuristic method that is based on averaging over loads of directly connected processors, where for each dimension *d*, every two processors connected along the d^{th} dimension exchange their loads sizes, and according to the average, the processor with excess load transfers the amount of extra load to its neighbor. The advantage of DEM is that every processor can redistribute tasks to its neighbor processors without the information of global distributions of tasks. However, the worst case error in this method is $log_2 n$ on an *n*-Cube, where the error is defined as the difference between the maximum and the minimum number of tasks assigned to processors [7].

Zhao, Xiao, and Qin proposed hybrid schemes of diffusion and dimension exchange, called DED-X, for load balancing on OTIS network [9]. The core of DED-X is to divide the load balancing process into three stages by a process of Diffusion-Exchange-Diffusion, where a traditional diffusion scheme, X (such as First Order Scheme (FOS), Second Order Scheme (SOS), and Optimal (OPT)) , is applied on various stages of the load balancing process to achieve load balancing on OTIS factor networks [9]. The simulation results of the proposed schemes have shown significant promotion in efficiency and stability [9]. The same authors have generalized, in another work, several DED-X schemes for load balancing on homogeneous OTIS to produce the Generalized Diffusion-Exchange-Diffusion schemes, GDED-X, to achieve load balancing on Heterogeneous OTIS networks [18]. The usability of the proposed schemes was shown theoretically and experimentally to be better than traditional X schemes for load balancing on heterogeneous OTIS networks [18].

Error reduction was the objective of several next researches. Better results were achieved by Rim et al. [12, 13], where they adapted DEM to perform efficient dynamic load balancing on Hypercube interconnection networks through proposing a new method, the odd even method that reduces the non-uniformity to no more than $1/2 \log_2 P$. Additional advantages are achieved by introducing new techniques for hiding communication overheads involved in load balancing [13]. Jan and Hwang suggested an efficient algorithm for perfect load balancing on Hypercube multiprocessors, based on the well-known DEM [19].

III. FEFOM Load Balancing Algorithm for Enhanced OTIS-*n*-Cubes

The proposed Factor-Optical-Factor Exchange Method (FOFEM) for load balancing on Enhanced OTIS-*n*-Cube is based on the well-known Diffusion and Dimension Exchange Method (DED-X) for load balancing on OTIS Hypercube networks. The reason of using DED-X as a base for our method is due to its important parameters characterizing the performance of the proposed algorithm which include load balancing accuracy, number of iterative steps, and amount of flow on communication links [10].

In the FOFEM the dynamic load balancing problem on Enhanced OTIS-*n*-Cube can be stated as follows: Given an Enhanced OTIS-*n*-Cube of P processors, divided into 2^n groups; $P=2^n \times 2^n$. The dynamic load balancing problem is to obtain an exactly or approximately equal load distribution among the Enhanced OTIS-*n*-Cube's processors. For an Enhanced OTIS-Cube, the proposed strategy balances the processors' loads in three phases. The main concept of the proposed method is based on obtaining an equal local load distribution among all processors in each group, First, by redistributing the loads within each group locally, so that all processors in each group have an exactly or approximately the same load of all processors in that group. Then, each group balances its processors' loads across all groups by exchanging processors load through the optical links so that all group loads are equal or approximately equal. The third phase is a repetition of phase one which is to redistribute the change of load coming from other groups among local processors in each group. Fig. 2 presents the proposed FOFEM algorithm for load balancing on an Enhanced OTIS-*n*-Hypercube [3].

Algorithm: FOFEM_ENHANCED_OTIS-*n*-Cube
Input: Unbalanced Enhanced OTIS-*n*-Cube
Output: Balanced Enhanced OTIS-n-Cube with equal or approximate load on each processor

d: the dimension along which processors are connected

Factor Load Balancing
For all Groups ($G_1, G_2, \ldots, G_{2^n}$) do in parallel
{
For (d = 1; d <=n; d++) do
{
For all pairs of processors P_i, P_j such that the binary representation
of i and j differ only in the d^{th} bit position, do in parallel
Exchange P_i's, P_j's load sizes along factor interconnect;
TotalLoad = Load (P_i) + Load (P_j);
Load(P_i)=Floor(TotalLoad/2)
Load (P_j)=Ceiling(TotalLoad/2);
}
}

Optical Load Balancing
For all Groups ($G_1, G_2, \ldots, G_{2^n}$) do in parallel
For (d = 1; d <= n; d++) do in parallel
{ /* For all pairs of processors P_i, P_j such that P_i, P_j belong to
different groups and there is an optical link between them */
Exchange P_i's, P_j's loads sizes along the electrical link;
if (P_i and P_j node addresses are completely complementing each other
and node's group address=processor address)
{ TotalLoad = Load (P_i) + Load (P_j);
Load(P_i)=Ceiling(TotalLoad/2)
Load (P_j)=Floor(TotalLoad/2);
}
else exchange values between P_i and P_j
}

Main_FOFEM
{ Call (**Factor Load Balancing);**
Call (**Optical Load Balancing);**
Call (**Factor Load Balancing);**
}

Figure 2: The FOFEM Algorithm for Load Balancing on Enhanced OTIS-*n*-Cube

FOFEM performs load balancing in three phases. During phases one and three, each is preformed in steps equal to the dimension of factor network. Phase two is performed in one parallel step.

Phase 1: Exchanges within the Factor network
Within each group, every two nodes redistribute their loads equally divided along the d^{th} bit dimension. These exchanges are done in n steps where n is the dimension of factor network, as indicated in Factor Load Balancing function of the algorithm shown Fig. 2.

Phase 2: Redistribute load across groups
Each pair of nodes that share an optical link will redistribute their load to be equally divided on both nodes if their group

addresses are differ only in the first bit, otherwise the two nodes will exchange their load.

Phase 3: Exchanges within the Factor network (repetition of phase 1)

In phase 1, each group distributes its total load among its local nodes, so that each node will have an approximation of equal load size within its group. This is done by redistributing the load of every pair of nodes their local addresses differ by only one bit along the d^{th} dimension where $1 \leq d \leq n$.

In phase 2, the algorithm redistributes the load of the whole network to be equally divided among the existing groups. This is done by exchanging the network load across the groups in a way that all groups redistribute their loads among each other via the optical links connecting these groups. By the end of this phase, all groups have an approximately equal size of total load

The third phase is a repetition of phase one, so the total size of every group is redistributed equally among its local nodes. This leads to the result that every node has an approximation of equal load across the whole network.

Example: To illistrate the proposed FOFEM method, this example explore the deployment of load balancing on an Enhanced OTIS-2-Cube, shown in Fig. 3, where there are four groups, each group contains four local nodes. Every node has an address in the form of $\langle g, p \rangle$, where g is the group address and p is the processor address; node address. Each node operates on an assigned load; the number next to each node indicates current load size. Nodes are connected by electrical links within the group, whereas nodes are interconnected through optical interconnections across the groups, optical links are shown as dashed lines while electrical links are shown as solid lines.

Fig. 4 and Fig. 5 show phase 1 of the FOFEM algorithm. In Fig. 4, every pair of nodes their processor addresses differ only in the first dimension redistribute their load to be approximately equally divided; as shown in the bold arrows, while Fig. 5 shows the redistribution of loads among pair of nodes differ in the second dimension. By the end of this phase, the reader can see that nodes within each group are having almost the same load size.

Fig.s 6 shows the second phase. Any two nodes connected via an optical link, the method redistribute the two nodes' load equally if their group addresses differ only in the first bit; otherwise they exchange their load size. For example, the two nodes $\langle 10, 11 \rangle$ and $\langle 11, 10 \rangle$ were having 7 and 11 load size consequently, after this phase the load size become 9 for both nodes. while, the two nodes $\langle 00, 11 \rangle$ and $\langle 11, 00 \rangle$ were having 9 and 11 load size consequently, after this phase the load size became 11 and 9 since they exchange their load size in this case.

Fig. 7 and Fig. 8 show the illustration of third phase. Again this phase will redistribute the load size within each group local nodes via the 1st and 2nd dimensions consequently. By then end of this phase all nodes will have an approximate equal load size as shown in Fig. 8.

The proposed algorithm is efficient since it can reach a final state of load balancing in $2n+1$ communication steps. Phases one and three take n communication steps each; $2n$ for both, while phase two takes one single communication step.

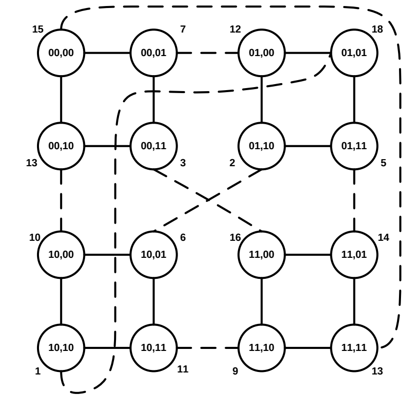

Figure 3. Enhanced OTIS-2-Cube

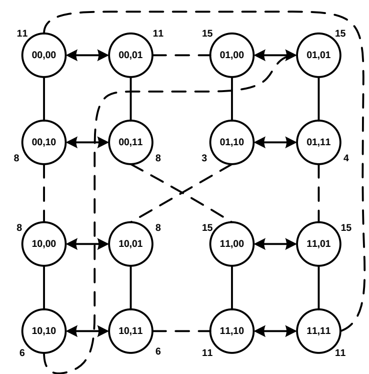

Figure 4. Enhanced OTIS-2-Cube

(Factor Load Balancing - Phase 1)

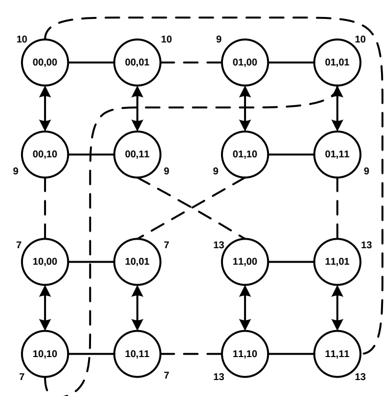

Figure 5. Enhanced OTIS-2-Cube

(Factor Load Balancing - Phase 1)

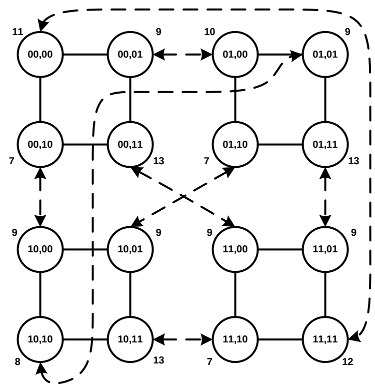

Figure 6. Enhanced OTIS-2-Cube

(Optical Load Balancing - Phase 2)

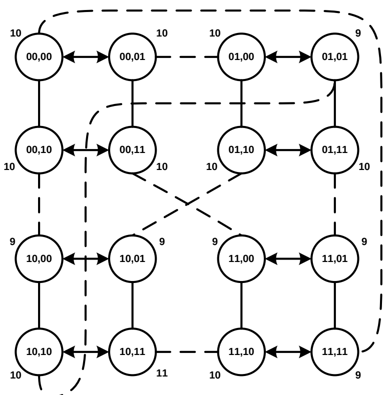

Figure 7. Enhanced OTIS-2-Cube

(Factor Load Balancing - Phase 3)

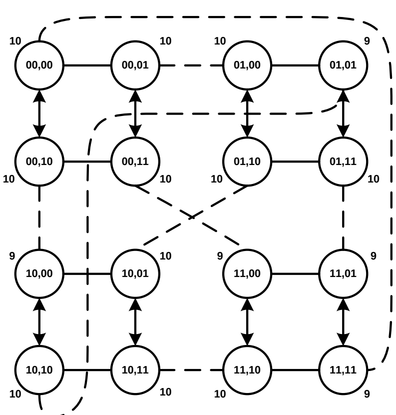

Figure 8. Enhanced OTIS-2-Cube

(Factor Load Balancing - Phase 3)

IV. Conclusion

This paper presented an efficient load balancing Algorithm for the Enhanced OTIS-*n*-cubes. The new algorithm is called Factor-Optical-Factor Exchanges Method (FOFEM) based on the well known Diffusion-Exchange-Diffusion Method (DED-X). The main concept of the proposed Algorithm is based on obtaining an approximation of equal load distribution among all nodes in the network. A theoretical study was conducted on the FEFOM algorithm for the Enhanced OTIS-*n*-Cubes.

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