Topological Properties Assessment for Hyper Hexa-Cell Interconnection Network

Basel A. Mahafzah, Mohammed Alshraideh, Luay Tahat, and Nada Almasri

***Abstract*—** The core of a parallel processing system is the interconnection network by which the system's processors are connected. Due to the great role played by the interconnection network's topology in improving the parallel processing system's performance, various topologies have been proposed in the literature. This paper presents the topological structure and properties of a hybrid interconnection network topology, referred to as the Hyper Hexa-Cell (HHC), in which the topological structure is based on Hexa-Cell and hypercube. The major topological properties of the HHC topology have been presented and investigated, including its size, diameter, minimum and maximum node degree, cost, and bisection width. A comparative study is then conducted between the HHC and other interconnection networks' topologies; including multilayer hex-cells, hex-cell, hypercube, chained-cubic tree, tree-hypercube, hyper-mesh, and mesh-of-trees, in terms of the above mentioned topological properties. The concluding results showed the excellence of the HHC over these interconnection networks.

***Keywords*—** Hexa-Cell, Interconnection Networks, Topological Properties, Topological Structure.

I. Introduction

THE need for parallel processing in computers has grown during the past decade, which has led to the introduction of new interconnection networks to support parallel processing. In general, interconnection networks are divided into two categories; namely, static and dynamic networks. In static networks, a direct link appears between a processor and other processors through point-to-point links; such as hypercube, mesh, ring, star, tree, fat-tree topologies, etc. [1], while in dynamic networks, a processor and other processors, as well as memory banks, are connected through multiple intermediate stages of interconnection networks; such as bus-based networks, multistage interconnection networks, and crossbar switching networks [1].

Additionally, interconnection networks can be categorized based on the type of communication links that connects processors; electronic and optoelectronic. Examples of electronic interconnection networks are hypercube, mesh, ring, tree, etc. [1] and examples of optoelectronic interconnection networks are Optical Chained–Cubic Tree (OCCT) and Optical Transpose Interconnection System (OTIS), where there are various structures for OTIS; such as OTIS Hyper Hexa-Cell (OHHC), OTIS-Hypercube, OTIS-Mesh, and many more [2]–[5].

In this paper, the topological structure and properties of a static electronic interconnection network called Hyper Hexa-Cell (HHC) is presented, which is suitable for large parallel computers by taking the advantageous characteristics of both Hexa-Cell and hypercube. Despite the difficulties of measuring and comparing the "goodness" of suggested network topologies [6], this paper uses the most common quantitative comparison metrics to evaluate the suggested HHC network and compare it to others. The HHC interconnection network is compared with multilayer hex-cells (MLH), hex-cell (HC), hypercube (Q), chained-cubic tree (CCT), tree-hypercube (TQ), hyper-mesh (HM), and mesh-of-trees (MOT) interconnection networks in terms of the following topological properties: size, diameter, minimum and maximum node degree, cost, and bisection width. Therefore, the main contributions of this paper are:

- It describes the design and structure of the HHC interconnection network, where HHC is based on Hexa-Cell and hypercube.
- It presents the topological properties in terms of size, diameter, minimum and maximum degree, cost, and bisection width for HHC.
- In addition, it compares HHC with MLH, HC, Q, CCT, TQ, HM, and MOT, in terms of the above mentioned topological properties.

The rest of this paper is organized as follows: Section 2 presents a background and summarizes related work to interconnection networks. Section 3 presents the topological structure and properties of HHC topology. Section 4 presents a comparison assessment, where the HHC interconnection network is compared with MLH, HC, Q, CCT, TQ, HM, and MOT interconnection networks in terms of several topological properties. Section 5 concludes the research work results and presents suggested future work.

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II. Background and Related Work

There are several well-known basic interconnection networks, such as hex-cell, hypercube, mesh, ring, tree, star and many more. Over the years, many researchers have studied these interconnection networks and several applications have been applied over these interconnection networks [1], [7]. However, some of these basic interconnection networks have major issues with their topological properties; such as high diameter and/or high cost. To enhance these topological properties, some researchers came up with hybrid interconnection networks, where these hybrid interconnection networks are based on two or more basic interconnection networks; such as MLH, CCT, TQ, HM, MOT, etc. [8]–[13].

The HC is relatively a new basic interconnection network [7], where it has a low cost in terms of number of links in comparison to hypercube topology as an advantage, but it has a high diameter in comparison to hypercube as a disadvantage for large network size.

As a basic interconnection network, the hypercube is well-known as one of the best interconnection networks in terms of some topological properties; such as low diameter and high connectivity in comparison to other basic interconnection networks; such as mesh, ring, and tree [1], [14]. A hypercube is a multidimensional mesh of processors with exactly two processors in each dimension. A zero-dimensional hypercube is a single processor. A one-dimensional hypercube is constructed by connecting two zero-dimensional hypercubes. In general, a (d+1)-dimensional hypercube is constructed by connecting the corresponding processors of two d-dimensional hypercubes [1].

The MLH is a new hybrid interconnection network [13], where its structure is based on HC. MLH is scalable and it has a better diameter than HC, but as a disadvantage, it has a high diameter in comparison to hypercube topology for large network size.

The CCT interconnection network is presented in [8], [15] where the structure is based on both tree and hypercube topologies; in which chains of hypercubes are arranged in a tree structure; thus, taking the advantages of both topologies. CCT makes a fair compromise between the two topologies by supporting their advantages and reducing their drawbacks. While tree topology has a good maximum node degree for some applications and good diameter with a basic routing algorithm, it is not considered as a practical topology because of its low bisection width and the absence of the parallel paths. On the other hand, although the hypercube has attractive properties, its major drawback for some applications is the increasing maximum node degree for massive parallel processing. Thus, CCT combines both topologies trying to take advantages of each.

TQ networks were introduced in [12] as new fixed interconnection networks. It was shown that they have many hypercube features such as self-routing and partitioning. In addition, they have advantages over hypercube in extendibility, diameter, and average distance. It was also shown that the TQs have great partitioning flexibility. In [12], researchers presented point-to-point routing algorithms for the TQ networks. Three optimal algorithms were presented. All of the presented algorithms take messages from the source node to the destination nodes using the shortest path, where the shortest path is calculated in a distributed manner by all nodes along the path from source to destination.

The topological properties of the HM interconnection network were studied in [9], [16]. The HM network combines two well-known interconnection networks; hypercube and mesh. The HM networks take the advantages of the hypercube network and overcome its large maximum node degree by combining it with the mesh network, which has a low fixed degree that does not increase when the network size increases. The study shows that the HM exhibits the appealing properties of its two constituent networks, and it reduces its major drawbacks.

The MOT, which owns two favorable properties: small diameter and large bisection, is known as the fastest network when considered in terms of speed [10], [11]. Combinatorial properties of MOT were presented in [10], [11]. More specifically, this paper shows the wide diameter, fault diameter, and Rabin number, which are three generalizations of diameter, of a two dimensional MOT.

III. Hyper Hexa-Cell Topology

The structure of HHC is based on both Hexa-Cell and hypercube structures. The Hexa-Cell has low cost in terms of the number of links as an advantage, but it has a high diameter as a disadvantage. The hypercube interconnection network has the advantages of smaller diameter, Hamiltonian, and recursive structure [1], [14].

A. Topological Structure

The topological structure of HHC is based on the topological structure of Hexa-Cell and hypercube topologies. The definition of the hypercube is presented by Definition 1. Also, the definition and the labeling of the HHC graph are presented by Definition 2. Each dimension of the HHC is a combination of one-dimensional HHC and a hypercube of dimension d. The smallest dimension of HHC is one, and it is the base for the other dimensions of HHC. Examples of HHC graphs of one, two, and three dimensions are shown in Fig. 1(a–c), respectively.

Definition 1: A d-dimensional hypercube, where $d \geq 0$, is an undirected graph consisting of 2^d node labeled from 0 to 2^{d-1} binary strings and has $d \times 2^{d-1}$ edges, such that there is an edge between two nodes if and only if the binary representations of their labels differ in precisely one bit [1], [14].

Definition 2: A Hyper Hexa-Cell (HHC) of dimension d_h, where $d_h \geq 1$, is an undirected graph. HHC is constructed by replacing 2^d nodes of a hypercube of dimension d by one-dimensional HHC graphs. Each one-dimensional HHC graph represents a group in the HHC graph, and each d_h-dimensional

HHC represents a hypercube of dimension d_h–1. Each node *v* in the HHC graph is labeled by a pair <*g-label*(*v*), *n-label*(*v*)>, where *g-label* and *n-label* are called group and node labels, respectively. For each node *v*, in each group, the *g-label* is presented by a binary string starting from 0 to d_h–1 and the *n-label* is represented in the same way as the node in a one-dimensional HHC graph. Also, as in the hypercube topology, two nodes in the HHC graph are connected by a direct link if and only if the binary representation of their group labels differs at exactly one-bit position. The binary representation of the group has d_h–1 bits [17].

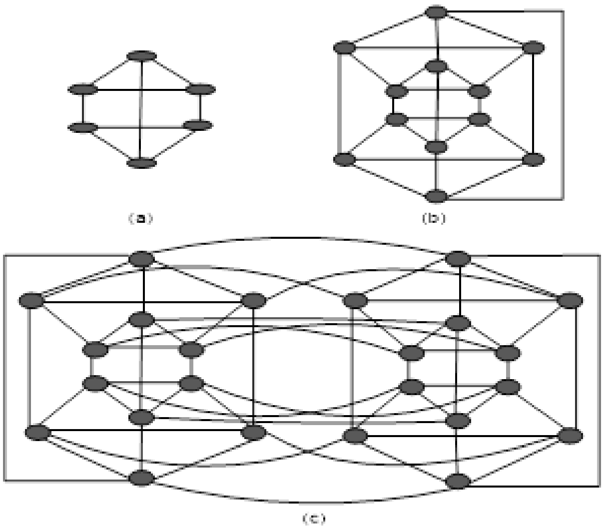

Fig. 1 HHC graphs of one, two, and three dimensions are shown in parts (a–c), respectively.

B. *Topological Properties*

The definitions of the following topological properties: size, diameter, minimum and maximum node degree, cost, and bisection width, are presented in Definitions 3–8, respectively. Also, the topological properties of HHC are presented in Theorems 1–6.

Definition 3: The size is the number of nodes in the interconnection network.

Theorem 1: The size of the HHC interconnection network is $6\times2^{d_h-1}$.

Proof. In the HHC interconnection network, the minimum number of nodes is six. This is when we have only one group, and the number of groups is equal to 2^{d_h-1} which represents the size of a hypercube [5], [17] since we replaced each node in the hypercube by one-dimensional HHC. Therefore, the size of the HHC is equal to $6\times2^{d_h-1}$ [17]. □

Definition 4: The diameter is the shortest path between the farthest two nodes in the network.

Theorem 2: The diameter of the HHC interconnection network is d_h+1.

Proof. The maximum distance in each group of HHC will always be two steps, which is between one of the top triangle's node and with one of the nodes in the bottom of the opposite triangle; for example, the distance between node <0,000> and node <0,110> in Fig. 2 is two (see dashed bold lines). Since the d_h-dimensional HHC consist of 2^{d_h-1} groups arranged as d_h–1 dimensional hypercube, and the diameter of a hypercube is d_h–1 [1]; then, the total diameter of HHC is d_h–1+2 which is d_h+1 [17]. □

Fig. 2 shows a two-dimensional HHC contains two groups, which represent a hypercube of one dimension where each node in the hypercube is a group of a one-dimensional HHC. To reach the destination node <1,110> from the source node <0,000>, we need one step to reach the node <1,000> in the destination's group, another two steps to reach the destination node <1,110> within the destination's group, which gives a total of three steps. So, the diameter of the two-dimensional HHC is three (see solid bold lines).

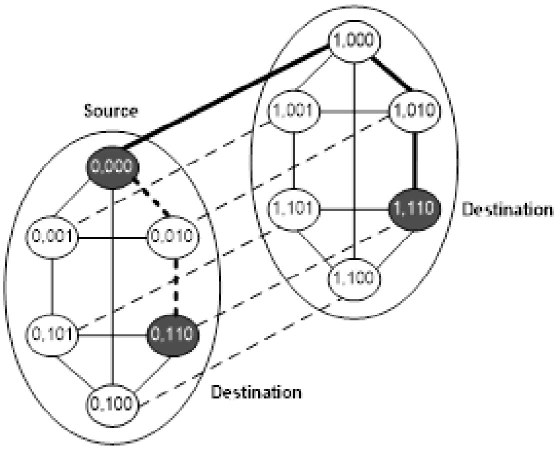

Fig. 2 The diameter of two-dimensional HHC.

Definition 5: The minimum node degree is the minimum number of links that are connected to it.

Theorem 3: The minimum node degree of the HHC interconnection network is d_h+2.

Proof. Each node in the HHC has the same degree; that is each node is connected with three nodes in the same group and with d_h–1 corresponding nodes in other groups, giving a total of d_h–1+3 = d_h+2. □

Definition 6: The maximum node degree is the maximum number of links that are connected to it.

Theorem 4: The maximum node degree of the HHC interconnection network is d_h+2.

Proof. Each node inside each group of HHC is connected to three nodes, in addition to d_h–1 links which represent the maximum node degree of a hypercube of dimension *d* [1], [5] that connects it with its corresponding nodes in other groups of the d_h-dimensional HHC, this gives a total of d_h–1+3 which is equal to d_h+2. Therefore, the maximum node degree of an HHC is equal to d_h+2 [17]. □

Fig. 3 illustrates the maximum node degree of a two-dimensional HHC, which is represented by dashed bold lines, where node <00,000> is connected to nodes <00,001>,

<00,010>, and <00,100> within same group giving a total of three, in addition to node <01,000> in another group. Therefore, the maximum node degree of a two-dimensional HHC is equal to four.

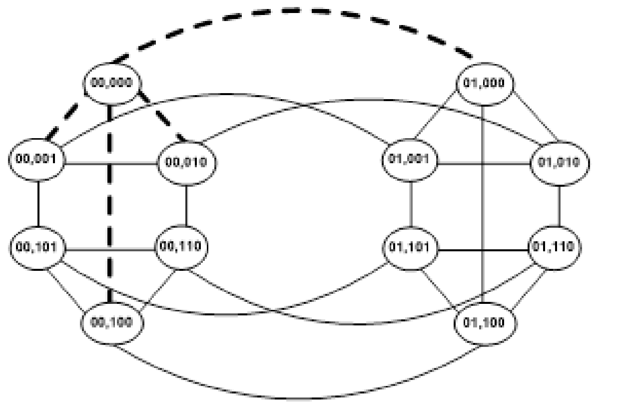

Fig. 3 The maximum node degree of a two-dimensional HHC.

Definition 7: The cost is the number of communication links in the network.

Theorem 5: The cost of the HHC interconnection network is $((6\times 2^{d_h-1}) \times (d_h+2))/2$.

Proof. Each node in each group of HHC has d_h+2 neighbor nodes connected with them via direct links. The size of HHC in each group is equal to $(6\times 2^{d_h-1})$; so, the number of links in each group is $((6\times 2^{d_h-1}) \times (d_h+2))/2$, where we divide the results by two because the links are undirected [17]. □

Definition 8: The bisection width is the minimum number of communication links that must be removed to partition the network into two equal halves.

Theorem 6: The bisection width of the HHC interconnection network is $(6\times 2^{d_h-1})/2$.

Proof. To partition the network into two equal halves we need to divide the number of nodes in an HHC by two. Since the total number of nodes in HHC is equal to $(6\times 2^{d_h-1})$, then half the number of nodes is the total number of nodes divided by two. So, the bisection width of HHC is $(6\times 2^{d_h-1})/2$. □

IV. Comparison and Assessment

It is essentially impossible to fairly compare interconnection networks, simply because there are too many parameters and topological properties [6]. The most suitable way for evaluating a new topology is to conduct a comparative study between the topological properties of both; the new topology and the other topologies that are familiar by their appealing topological properties. In this paper, it has been chosen to compare HHC with the following topologies: MLH, HC, Q, CCT, TQ, HM, and MOT in terms of the following topological properties: size, diameter, minimum and maximum node degree, cost, and bisection width. These interconnection networks are chosen according to their preference, strong properties, and the good qualities they exhibit over other topologies.

In order to evaluate the HHC interconnection network, each of the HHC's topological properties needs to be calculated for growing sizes of HHC and compare it with other interconnection networks corresponding to the mentioned topological properties.

The topological properties equations for these mentioned interconnection networks are presented in Table I, where d_h is the dimension of HHC, d is the dimension of the hypercube, k is the number of layers in MLH, t is the depth of MLH and HC, N is the number of nodes in HC, h is the height of the tree, and r is the row size of the mesh. Table II shows the various sizes of these interconnection networks. The size is categorized into three categories; small, medium, and large.

The comparison results for all mentioned interconnection networks in terms of the mentioned topological properties are shown in Tables III–VII. Table III shows the diameter for various sizes of these interconnection networks. The diameter of HHC and TQ is the best; that is both HHC and TQ have the shortest path between the farthest two nodes compared with other interconnection networks due to their good connectivity, whereas the HC has the worst diameter, which depends on its depth and number of nodes. In general, as the network size increases the diameter of all interconnection networks increases too.

Tables IV and V show the minimum and maximum node degree for all mentioned interconnection networks, respectively. The best interconnection networks in terms of minimum node degree are those that have a larger number of multiple distinct paths between any two nodes in the network. As shown in Table IV, HHC and Q have the highest values, whereas HC, TQ and MOT topologies have the worst minimum node degree. This means that HHC and Q achieve higher connectivity compared to others. Thus, as the network size increases the minimum node degree increases too, except for MLH, HC, TQ and MOT topologies since they have a constant minimum node degree. For some applications, the best interconnection networks in terms of maximum node degree are those which have static low degree, which means as the size of the network increases the maximum node degree stays as is; this means scaling up the system can be done without replacing the old nodes with new ones. In our comparison, in Table V, this is achieved by MLH, HC, and MOT interconnection networks, which have a constant maximum node degree. Whereas, for other applications, the best interconnection networks in terms of maximum node degree are those that have a high degree; regardless of their scalability. In Table V, this is achieved by the TQ interconnection network for medium and large network sizes, but for small network size, it is achieved by the CCT interconnection network. However, the HHC interconnection network has a good maximum node degree since it is higher than MLH, HC, and MOT, and lower than TQ.

Many researchers neglect the cost of the interconnection network since the goal is to gain speed. However, to construct any interconnection network for large scale computing, it is still important to build it with minimal cost, which depends on the number of communication links. Thus, the number of communication links in any interconnection network depends on many factors; such as size and minimum and maximum node degree. For instance, when there is a large number of nodes and the minimum and maximum node degree are also large, this yields a large number of communication links. In general, as the network size increases the cost of the network increases too. Table VI shows the cost of various interconnection networks for small, medium, and large sizes, respectively. The lowest cost interconnection network is MOT, whereas the highest cost interconnection network is Q. Thus, HHC network cost is less than Q, CCT, TQ and HM networks.

Table VII shows a comparative study based on the bisection width property, where a high bisection width is more desirable. From this table, it is obvious that the Q, TQ, and HM topologies have the highest bisection width, where they have the same values. Our HHC topology has a higher bisection width than MLH, HC, CCT, and MOT for medium and large network sizes, which is a factor in increasing its reliability. As, for small network size, CCT has a higher bisection width than HHC. The MOT topology has the lowest bisection width for all network sizes. In general, as the network size increases the bisection width increases too for all topologies.

Table I Topological properties of various interconnection networks.

Topology	Size	Diameter	Min Degree	Max Degree	Cost	Bisection Width
HHC	$6\times 2^{d_h-1}$	d_h+1	d_h+2	d_h+2	$((6\times 2^{d_h-1})\times(d_h+2))/2$	$(6\times 2^{d_h-1})/2$
MLH	$6k\times t^2$	$4t-1+k$	3	4	$k(9t^2-3t)+(k-1)\times 6(2t-1)$	$2t\times k$
HC	$6t^2$	$4\sqrt{(N/6)}-1$	2	3	$3N/2-3\sqrt{(N/6)}$	$2\sqrt{(N/6)}$
Q	2^d	d	d	d	$d\times 2^{d-1}$	2^{d-1}
CCT	$2^{h+d+1}-2^d$	$2h+d-1$	$d+2$	$d+5$	$2^{h+d}(d+4)-2^d(d/2+h+4)$	$2^d\,(h+1.5)$
TQ	$2^{h+1}-1$	h	2	$h+2$	$2^h(h+1)-1$	2^h
HM	$2^d\times r^2$	$d+2r-2$	$d+2$	$d+4$	$d2^{d-1}\,r^2+2^d(2r^2-2r)$	$2^{d-1}\times r^2$
MOT	$3r^2-2r$	4 floor(log r)	2	3	$4r^2-4r$	r

Table II Various interconnection networks sizes.

Size Range		Size							
		HHC	***MLH***	***HC***	***Q***	***CCT***	***TQ***	***HM***	***MOT***
Small	6 – 16	12	12	6	16	12	15	16	8
	21 – 32	24	24	24	32	28	31	32	21
Medium	48 – 65	48	48	56	64	60	63	64	65
	96 – 128	96	96	96	128	124	127	128	96
	192 – 256	192	192	216	256	248	255	256	225
Large	384 – 512	384	384	384	512	504	511	512	481
	768 – 1024	768	768	1014	1024	1008	1023	1024	936

Table III The diameter of various interconnection networks for different sizes.

Size Range		Diameter							
		HHC	***MLH***	***HC***	***Q***	***CCT***	***TQ***	***HM***	***MOT***
Small	6 – 16	3	5	3	4	3	3	4	4
	21 – 32	4	7	7	5	5	4	5	4
Medium	48 – 65	5	9	11	6	7	5	6	8
	96 – 128	6	11	15	7	9	6	9	8
	192 – 256	7	17	23	8	10	7	10	12
Large	384 – 512	8	19	31	9	12	8	11	12
	768 – 1024	9	23	51	10	13	9	12	16

Table IV The minimum node degree of various interconnection networks for different sizes.

Size Range		Minimum Node Degree							
		HHC	***MLH***	***HC***	***Q***	***CCT***	***TQ***	***HM***	***MOT***
Small	6 – 16	4	3	2	4	4	2	4	2
	21 – 32	5	3	2	5	4	2	5	2
Medium	48 – 65	6	3	2	6	4	2	6	2
	96 – 128	7	3	2	7	4	2	5	2
	192 – 256	8	3	2	8	5	2	6	2
Large	384 – 512	9	3	2	9	5	2	7	2
	768 – 1024	10	3	2	10	6	2	8	2

Table V The maximum node degree of various interconnection networks for different sizes.

Size Range		Maximum Node Degree							
		HHC	***MLH***	***HC***	***Q***	***CCT***	***TQ***	***HM***	***MOT***
Small	6 – 16	4	4	3	4	7	5	6	3
	21 – 32	5	4	3	5	7	6	7	3
Medium	48 – 65	6	4	3	6	7	7	8	3
	96 – 128	7	4	3	7	7	8	7	3
	192 – 256	8	4	3	8	8	9	8	3
Large	384 – 512	9	4	3	9	8	10	9	3
	768 – 1024	10	4	3	10	9	11	10	3

Table VI The cost of various interconnection networks for different sizes.

Size Range		Cost							
		HHC	***MLH***	***HC***	***Q***	***CCT***	***TQ***	***HM***	***MOT***
Small	6 – 16	24	18	6	32	24	31	32	8
	21 – 32	60	42	30	80	68	79	56	24
Medium	48 – 65	144	78	75	192	160	191	192	80
	96 – 128	336	174	132	448	348	447	576	120
	192 – 256	768	306	306	1024	828	1023	896	288
Large	384 – 512	1728	654	552	2304	1708	2303	2048	624
	768 – 1024	3840	1350	1482	5120	3920	5119	4608	1224

Table VII The bisection width of various interconnection networks for different sizes.

Size Range		Bisection Width							
		HHC	***MLH***	***HC***	***Q***	***CCT***	***TQ***	***HM***	***MOT***
Small	6 – 16	6	4	2	8	10	8	8	2
	21 – 32	12	8	4	16	14	16	16	3
Medium	48 – 65	24	8	6	32	18	32	32	5
	96 – 128	48	16	8	64	22	64	64	6
	192 – 256	96	16	12	128	44	128	128	9
Large	384 – 512	192	32	16	256	52	256	256	13
	768 – 1024	384	64	26	512	104	512	512	18

V. Conclusion and Future Work

Many interconnection networks have been proposed in the last few decades. An observable fact is that high performance may be accompanied by design complexity and increased cost. None of these interconnection networks, until now, is proved to outperform all of the others. As a basic static topology, the hypercube topology is considered as one of the strongest topologies, which has a good diameter and high bisection width, but because of its high cost which forms a major drawback when massive parallelism is applied, many researchers worked to find alternatives for this topology while preserving the same advantages. On the other hand, the Hexa-Cell topology has a low cost, but very high in diameter.

This paper presented the topological structure and properties of a hybrid interconnection network called Hyper Hexa-Cell (HHC), which is based on the advantageous characteristics of both Hexa-Cell and hypercube interconnection networks. Moreover, HHC topology has been evaluated in terms the following topological properties: size, diameter, minimum and maximum node degree, cost, and bisection width, and it has been compared to MLH, HC, Q, CCT, TQ, HM, and MOT interconnection networks in terms of these mentioned topological properties.

The comparative study results have shown that HHC has the best diameter and minimum node degree, good maximum node degree, reasonable cost, and good bisection width for medium and large network sizes.

HHC interconnection network is developed to support parallel algorithms for solving computation and communication-intensive problems. In [17], two broadcast communication operations, using the store-and-forward technique, have been applied to HHC interconnection networks. These broadcast operations are one-to-all and all-to-all; which allow a message to be transmitted through the shortest path from the source node to all other nodes. These broadcast communication operations over HHC perform very well in terms of maximum communication steps, communication latency, and speed. Thus, applying different parallel algorithms, such as load balancing, sorting, and searching algorithms on HHC can be considered as future work, in order to show the effectiveness of the HHC interconnection network.

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