A Spanning Bus Connected Hypercube: A New Scalable Optical Interconnection Network for Multiprocessors and Massively Parallel Systems

Ahmed Louri, *Senior Member, IEEE,* and Costas Neocleous

***Abstract*— A new scalable interconnection topology suitable for massively parallel systems called the spanning bus connected hypercube (SBCH) is proposed. The SBCH uses the hypercube topology as a basic building block and connects such building blocks using multidimensional spanning buses. In doing so, the SBCH combines positive features of both the hypercube (small diameter, high connectivity, symmetry, simple routing, and fault tolerance) and the spanning bus hypercube (SBH) (constant node degree, scalability, and ease of physical implementation), while at the same time circumventing their disadvantages. The SBCH topology permits the efficient support of many communication patterns found in different classes of computation such as bus-based, mesh-based, tree-based problems as well as hypercube-based problems. A very attractive feature of the SBCH network is its ability to support a large number of processors while maintaining a constant degree and constant diameter. Other positive features include symmetry, incremental scalability, and fault-tolerance. An optical implementation methodology is proposed for SBCH. The implementation methodology combines both the advantages of free space optics with those of wavelength division multiplexing techniques. A detailed analysis of the feasibility of the proposed network is also presented.**

***Index Terms*— Interconnection networks, massively parallel processing, optical interconnects, product networks, scalability, wavelength division multiplexing.**

I. Introduction

PROGRESS IN very large scale integrated (VLSI) technology combined with the escalating demands for more processing power and speed have recently produced a technological environment in which massively parallel processors (MPP's) with hundreds or even thousands of processing elements (PE's) are becoming commonplace (examples include Intel Paragon, Cray T3D and T3E, IBM SP-1,2, MasPar MP-1,2, Stanford Dash, etc.). The interconnection network, not the PE's or the speed of these systems, is proving to be the decisive and determining factor in terms of cost and performance [1]–[4].

To this end, several topologies have been proposed to fit different styles of computation. Examples include crossbars, multiple buses, multistage interconnection networks, and hypercubes, to name a few. Among these, the hypercube has received considerable attention due mainly to its good topological characteristics (small diameter, regularity, high connectivity, simple control and routing, symmetry and fault tolerance), and its ability to efficiently permit the embedding of numerous topologies such as rings, trees, meshes, shuffle-exchange, among others [5]. However, a drawback of the hypercube is its lack of scalability which limits its use in building large size systems out of smaller size systems. The lack of scalability of the hypercube stems from the fact that the node degree is not bounded and varies as $\log_2 N$. This property makes the hypercube cost prohibitive for large N. Most hypercube-based interconnection networks proposed in the literature [6]–[13] suffer from similar size scalability problems.

Recently, some networks have been introduced that are a product of hypercube topology with some fixed degree networks such as the mesh, the tree, and the de Bruijn [4], [11], [14] in the quest of preserving the properties of the hypercube while improving its scalability characteristics. Notable among theses is the optical multimesh hypercube (OMMH) [15], [16]. The OMMH is a network that combines the positive features of the hypercube (small diameter, regularity, high connectivity, simple control and routing, symmetry and fault tolerance) with those of a mesh (constant node degree and size scalability). The OMMH can be viewed as a two-level system: a local connection level representing a set of hypercube modules and a global connection level representing the mesh network connecting the hypercube modules. The OMMH network has been physically demonstrated using a combination of free-space and fiber optics technologies, and has shown good performance characteristics [17] for a reasonable size network. However, for very large networks (greater than one thousand PE's), the OMMH experiences a logarithmic increase in terms of diameter and requires a large amount of fiber which makes the implementation complicated and expensive.

In this paper, we propose a novel network that improves the topological characteristics as well as the implementation and performance aspects of the OMMH network. The new network topology proposed is called *spanning bus connected hypercube*

Manuscript received June 17, 1996; revised February 21, 1997. This work was supported by the NSF under Grant MIP 9310082.

The authors are with the Department of Electrical and Computer Engineering, The University of Arizona, Tucson, AZ 85721 USA.

Publisher Item Identifier S 0733-8724(97)04337-5.

(SBCH) and possesses a constant degree and a constant diameter while preserving all the properties of the hypercube. The SBCH, similar to the OMMH, employs the hypercube topology at the local connection level. The global connection level connecting the hypercube modules is a spanning bus hypercube network [18]. The spanning bus hypercube is a D-dimensional lattice of width w in each dimension. Each node is connected to D buses, one in each of the orthogonal dimensions; w nodes share a bus in each dimension. The spanning bus hypercube offers small node degree, small diameter, low cost, and scalability. It can be scaled up by expanding the size of the spanning buses [18]. However, expanding the size of the buses leads to an $O(w)$ increase in traffic density [18] which in turn leads to *bus congestion* problems [19]. The advantage of the SBCH network is that it utilizes the hypercube local interconnection level to decrease the traffic density therefore alleviating the bus congestion problems encountered in pure SBH networks. This feature allows the SBCH buses to support a larger number of processors than the SBH network, and thus allowing larger systems to be built. As such, the SBCH is an incrementally scalable with a high degree of connectivity and a low diameter. Additionally, we also propose an optical implementation of such a network. Optical interconnects offer many desirable features such a very large communication bandwidth, reduced crosstalk, immunity to electromagnetic interference, and low-power requirements [3], [4], [20]–[27].

II. Structure of Spanning Bus Connected Hypercube Network

In this section, we formally define the structure of the SBCH network and discuss its properties.

A. Topology of the SBCH Interconnection Network

The topology of the SBCH can be described as an undirected graph, $G_{\text{SBCH}} = (V, E)$ where V represents a set of nodes and E represents a set of edges. The SBCH can also be viewed as a product hybrid graph because it combines a D-dimensional spanning bus hypercube graph and a boolean hypercube graph in such a way that if $G = G1 \times G2$ where $G1$ represents the spanning bus hypercube graph and $G2$ the boolean hypercube graph then the Cartesian product of their vertices is $V1 \times V2 = [(u2, u1) | u2 \in V2$ and $u1 \in V1]$ [11].

The size of the SBCH is characterized by a three-tuple (w, n, D) where $w, n,$ and D are positive integers. The first parameter, w, defines the number of nodes attached to a bus. The second parameter n is the degree of the point-to-point n-cube (hypercube). The third parameter D identifies the number of buses spanned by a PE in the network.

For an SBCH-(w, n, D), the number of nodes $|V|$ is equal to $w^D 2^n$. A node address in the SBCH is denoted by a $(w+1)$-tuple $(a_1, a_2, \ldots, a_w, a_n)$ using a mixed radix system, where for $i = 1$ to $i = w, 0 \leq a_i \leq (w-1)$, and $0 \leq a_n \leq (2^n - 1)$.

Given the set of nodes (V), the set of edges (E) is constructed as follows. For two nodes $(a_1, a_2, \ldots, a_w, a_n)$ and $(b_1, b_2, \ldots, b_w, b_n)$ where for $i = 1$ to $i = w, 0 \leq a_i < w$, for $j = 1$ to $j = w, 0 \leq b_i < w, 0 \leq a_n < 2^n$, and $0 \leq b_n < 2^n$.

1) The two nodes span the same bus if (1) $a_n = b_n$ and (2) for $i = 1$ to $i = w$ there are only two components, a_i and b_i, that are identical while all the other components are different.
2) There is a link (called a hypercube link) between two nodes if and only if for $i = 1$ to $i = w$ (1) $a_i = b_i$, and (2) a_n and b_n differ by one bit position in their binary representation (Hamming distance of one).

In this paper, we only consider SBCH networks with $D = 2$. Therefore, in the notation the third parameter, D, will be dropped. Consequently, an SBCH$(w, n, 2)$ network will be referred to as SBCH(w, n). Fig. 1(a) shows an SBCH(2,

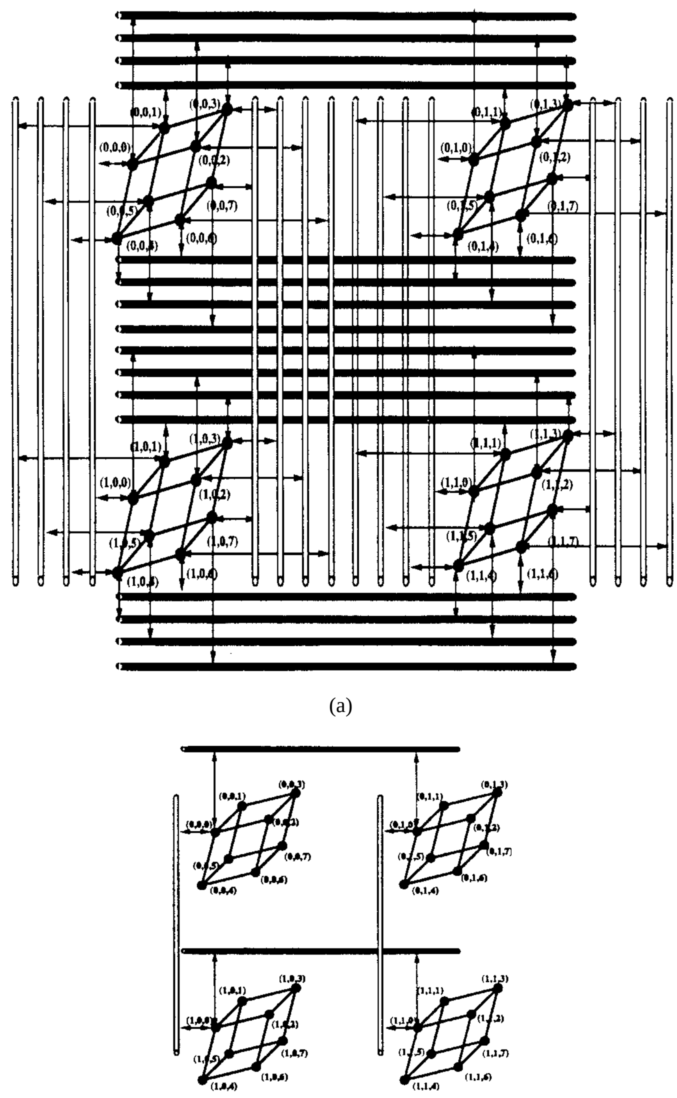


Fig. 1. (a) An example of the spanning bus connected hypercube network: a SBCH(2, 3) (32 nodes) interconnection is shown. Solid thick lines represent bus connections while bold thin lines represent point-to-point hypercube connections. (b) An example of a 2-D SBH subnetwork within a SBCH(2, 3) network. Note that the nodes that construct the 2-D SBH belong to different hypercube modules but they possess the same binary hypercube address representation within their corresponding hypercube modules. Eight such 2-D SBH's co-exist in the SBCH(2, 3) interconnection.

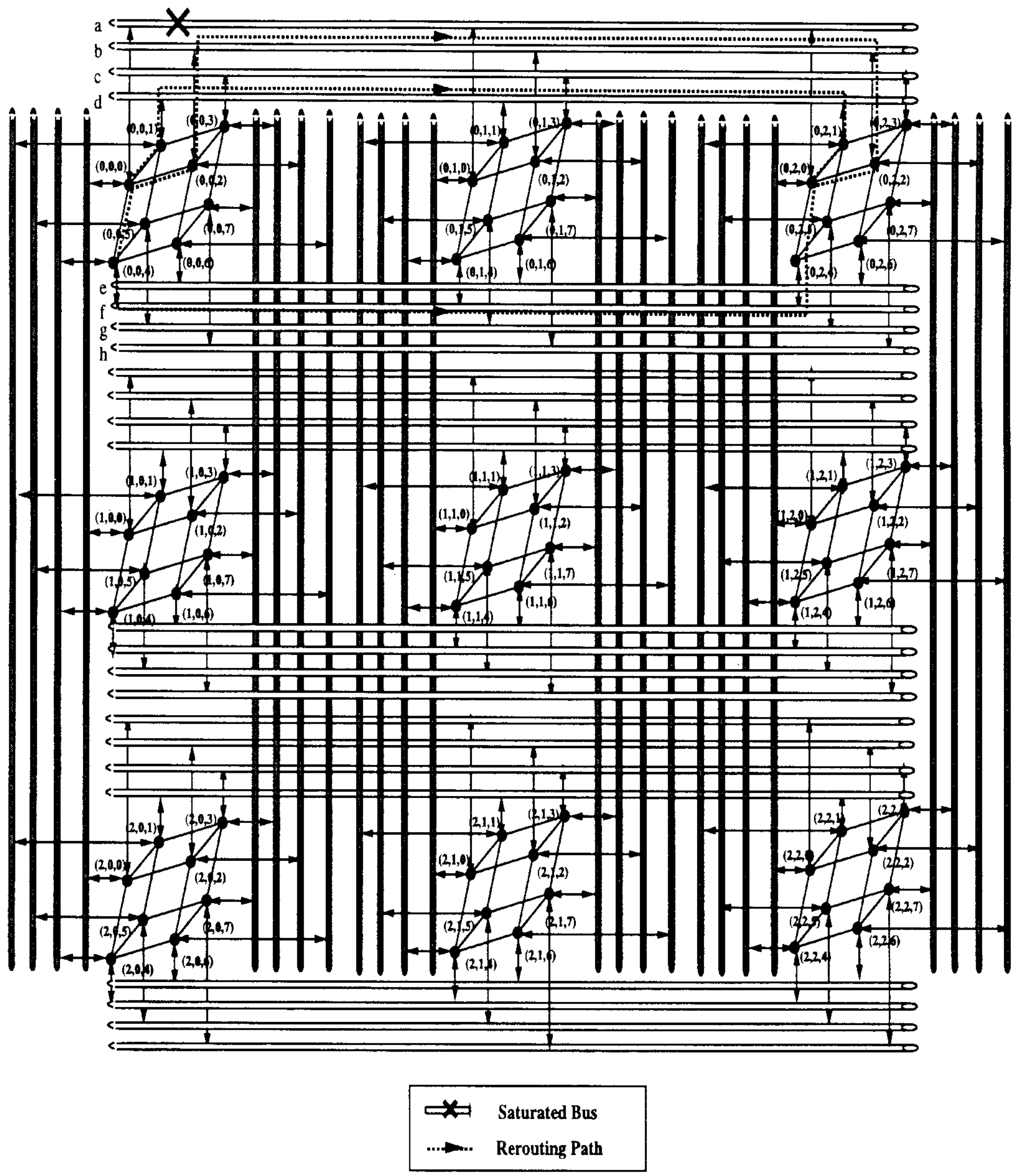


Fig. 2. A SBCH(3, 3) (72 nodes) interconnection. This SBCH network can be constructed by adding hypercube modules along a row and a column to a SBCH(2, 3) network.

3) interconnection where solid lines represent point-to-point hypercube links, and dark thick lines represent buses. Small dark circles represent nodes of the SBCH network which are, in this paper, abstractions of processing elements or memory modules or switches. Note that, because $D = 2$ each node spans two buses, one bus along each dimension. Furthermore, there are three bidirectional point-to-point links attached to a node which correspond to the hypercube links. A careful observation of Fig. 1(a), shows that the node addresses satisfy the connection rules outlined earlier. As can be seen in Fig. 1(a), the SBCH(2, 3) consists of $2^2 \times 2^3 = 32$ nodes. It can be viewed as eight concurrent two-dimensional (2-D) SBH's. Note that w horizontal buses and w vertical buses are needed to form one $w \times w$ 2-D SBH network. Fig. 1(b) shows one such 2-D SBH formed by nodes with the same hypercube addresses and belonging to different hypercube modules. Similar considerations take place for the other seven 2-D SBH's in Fig. 1(a). The SBCH(2, 3) network can also be viewed as four concurrent three-dimensional (3-D) hypercubes in which four nodes having identical hypercube addresses form a 2×2 spanning bus hypercube. The SBCH(2, 3) in Fig. 1(a) looks like a hypercube-clustered spanning bus network. In general, there are 2^n 2-D SBH's and w^2 hypercube modules (for $D = 2$). Note than when w is one the SBCH becomes a pure hypercube network while when n is zero it becomes a pure spanning bus network. This implies that both, the hypercube and the SBH can be thought of as subnetworks of the SBCH network.

The choice of two parameters w and n completely determines the size of the network, the resources and implementation requirements, and the scaling complexity. The w parameter determines the size of the buses while the n-

parameter defines the size of the hypercubes. From a scaling viewpoint, two scaling rules can be applied for an SBCH(w, n) network. The first rule which we call fixed-w rule keeps the size of the buses constant and increases the size of the network by increasing n. The second rule which we call fixed-n rule keeps the size of the hypercube constant and increases the size of the network by increasing w. Clearly, the advantage of the SBCH(w, n) network is its flexibility to scale up using either or a combination of the two scaling rules.

For instance, the size of the SBCH can grow without altering the number of links per node by expanding the size of the buses; for example, 3-D hypercubes can be added on the perimeter of the 2-D spanning bus hypercubes of Fig. 1. Fig. 2 illustrates an SBCH(3, 3) which is constructed by expanding the SBCH(2, 3) network by adding hypercube modules along an outer row and an outer column. The existing configuration of the nodes of the SBCH(2, 3) network did not change because each node still spans two buses and still has three bidirectional point-to-point links for the hypercube connections. This option allows the SBCH to be truly size scalable.

B. Message Routing in the SBCH Interconnection Network

Due to the regularity and symmetry of the SBCH architecture, a distributed routing scheme can be implemented without global information. At the source node, the message is formatted with the source address, the destination address, message length, and a few control bits such as semaphore bits. The interprocessor message traffic of a node gets redistributed into two categories, i.e., the hypercube communication and the spanning bus communication. If the source and the destination of the message are within the same hypercube subnetwork of the SBCH network, the routing procedure is exactly the same as that of the regular hypercube network. Similarly, if the source and the destination of the message are within the same spanning bus subnetwork of the SBCH network, the routing procedure is exactly the same as that of a regular bus connected network.

If neither of the above two cases is true, the source and the destination of the message share neither a hypercube nor a 2-D SBH. The routing scheme for this case is first to use the hypercube routing scheme until the message arrives at the same 2-D SBH where the destination resides, and then to use the bus routing scheme for the message to arrive at the destination. Or the 2-D SBH routing scheme can first be applied to forward the message to the same hypercube where the destination resides, and then the message can reach the destination using the hypercube routing scheme. We can also mix the hypercube and the spanning bus routing until the message is forwarded to the same hypercube or to the same spanning buses where the destination resides, and then we can forward the message to the destination using the hypercube or the spanning bus routing scheme, respectively.

C. Properties of the SBCH Interconnection Network

1) Diameter and Link Complexity: The diameter of a network is defined as the maximum distance between any two processors in the network. Thus, the diameter determines the maximum number of hops that a message may have to take. Bearing in mind that $D = 2$, the diameter of a 2-D spanning bus hypercube is two. The diameter of hypercube with N nodes is $n = \log_2 N$ therefore the diameter of SBCH(w, n) is $(n+2)$. For the SBCH(w, n) network, $N = w^2 2^n$ therefore $n = \log_2 (N/w^2)$. Consequently the diameter of the SBCH(w, n) network can be written as $\log_2 (N/w^2)+2$. Using the fixed-w scaling rule the diameter of the SBCH(w, n) network experiences a logarithmic increase $(O(\log_2 N))$ when the network size increases. However, using the fixed-n scaling rule would make the diameter constant for any network size. The constant value is $n + 2$.

Link complexity or node degree is defined as the number of physical links per node. For a regular network where all nodes have the same number of links, the node degree of the network is that of a node. The node degree of a hypercube with N nodes is $n = \log_2 N$ and that of a 2-D spanning bus hypercube is two. A node of an SBCH(w, n) network possesses links for both the hypercube connections and the bus connections. Consequently, the node degree of the SBCH network is $(n+2)$ or $\log_2 (N/w^2) + 2$. Again, when using the fixed-w scaling rule the SBCH network experiences a logarithmic increase in degree $(O(\log_2 N))$; however when the network is expanded using the fixed-n scaling rule, the degree becomes constant $(n + 2)$.

2) Bisection Width: The bisection width of a network is defined as the minimum number of links that have to be removed to partition the network into two equal halves [28]. The bisection width indicates the volume of communication allowed between any two halves of the network with an equal number of nodes. The bisection width of a n-dimensional hypercube is $2^{(n-1)} = N/2$ since that many links are connected between two $(n-1)$-dimensional hypercubes to form a n-dimensional hypercube. Since there are w^2 such n-dimensional hypercubes connecting 2^n 2-D spanning bus hypercubes the bisection width of an SBCH(w, n) is equal to $w^2 \times 2^{n-1} = N/2$.

3) Granularity of Size Scaling: Ideally, it should be possible to create larger and more powerful networks by simply adding more nodes to the existing network. For a 2D SBH the granularity of size scaling is only $2w+1$ since at a minimum one bus per dimension could be added to the network in order to increase its size. Therefore, the granularity of the size scaling in an $w \times w$ 2-D SBH of $N = w^2$ nodes is $2N^{1/2} + 1$. However, the size of a hypercube can only be increased by doubling the number of nodes; that is, the granularity of size scaling in an n-dimensional hypercube is 2^n. Earlier, we explained how the SBCH(w, n) network can be scaled up using two different scaling rules. When the fixed-w scaling rule is applied, the granularity of size scaling follows the hypercube size scaling. Therefore, the granularity of size scaling using the fixed-w-rule is $w^2 \times 2^n = N$. When the fixed-n scaling rule is used, the granularity of size scaling follows that of the SBH. Therefore, the granularity of size scaling following the fixed n-rule is $2^n(2w+1) = 2(N/w) + 2^n$. Note that the granularity of size scaling using the fixed w-rule is $O(N)$ while for the fixed-n rule is $O(N/w)$.

TABLE I
TOPOLOGICAL CHARACTERISTICS OF SEVERAL POPULAR NETWORKS

Network	*Size*	*Degree*	*Diameter*	*Links*	*cost*
BHC	$N = 2^n$	$\log_2 N$	$\log_2 N$	$\frac{N}{2}(\log_2 N)$	$\frac{N}{2}(\log_2 N)^2$
Torus	$N = w^D$	$2\log_w N$	$\frac{w}{2}\log_w N$	$N\log_w N$	$\frac{Nw}{2}(\log_w N)^2$
GHC	$N = r^n$	$(r-1)\log_r N$	$\log_r N$	$\frac{N(r-1)}{2}\log_r N$	$\frac{N(r-1)}{2}(\log_r N)^2$
NNMH	$N = r^n$	$2\log_r N$	$\frac{r}{2}\log_r N$	$2\frac{N}{2}\log_r N$	$\frac{Nr}{2}(\log_r N)^2$
SBH	$N = w^D$	$\log_w N$	$\log_w N$	$\frac{N}{w}\log_w N$	$\frac{N}{w}(\log_w N)^2$
HCN	$N = 2^{2d}$	$(\frac{1}{2})(\log_2 N) + 1$	$\log_2 N$	$((\frac{N}{4})(\log_2 N) + \frac{N}{2})$	$((\frac{N}{4})(\log_2 N) + \frac{N}{2})(\log_2 N)$
CCC	$N = d \times 2^d$	3	$\frac{(5d-2)}{2}$	$\frac{3}{2}d \times 2^d$	$\frac{3}{4}d \times 2^d(5d-2)$
HdB	$N = 2^{(n+c)}$	$\log_2 N - c + 4$	$\log_2 N$	$\frac{N}{2}(\log_2 N - c + 4)$	$\frac{N}{2}\log_2 N(\log_2 N - c + 4)$
FPT	$N = 10^n$	$3\log N$	$2\log N$	$\frac{3N}{2}\log N$	$3N(\log N)^2$
OMMH	$N = l^2 2^n$	$4 + \log_2 \frac{N}{l^2}$	$l + \log_2 \frac{N}{l^2}$	$\frac{N}{2}(4 + \log_2 \frac{N}{l^2})$	$\frac{N}{2}(4 + \log_2 \frac{N}{l^2})(l + \log_2 \frac{N}{l^2})$
SBCH	$N = w^2 2^n$	$2 + \log_2 \frac{N}{w^2}$	$2 + \log_2 \frac{N}{w^2}$	$\frac{N}{2}(\frac{4}{w} + \log_2 \frac{N}{w^2})$	$\frac{N}{2}(2 + \log_2 \frac{N}{w^2})(\frac{4}{w} + \log_2 \frac{N}{w^2})$

4) Cost: It is difficult to exactly evaluate the cost of an interconnection network for there are many factors to consider in the final construction of the network. This includes not only the topological characteristics of the network but also the the underlying implementation technology, the cost of implementing routing and control, packaging, and other physical and environmental issue. In this section we only consider the topological cost. It is clear that the topological cost of a network depends on its degree and diameter. A network with low degree usually has a large diameter, and a network with low diameter most of the times posses a large degree [11]. Consequently, a network with large degree contains a large number of links while a network with low degree contains a small number of links. Bearing the above in mind, we define the topological cost as the product of diameter and number of links in the network. Hence the cost of the SBCH(w, n) network is $(2+n)^2 w^2 2^n = (2+n)^2 N$.

5) Average Message Distance: The average message distance in a network is defined as the average number of links that a message should travel between any two nodes. Since the SBCH is a muti-hop network, the message is bound to travel a certain distance before reaching its destination. In order to obtain a realistic comparison between different networks with different link complexity, some normalization should be made. For this purpose, it is assumed that the communication bandwidth available at a node is constant. As a consequence, the available communication bandwidth per link at a node decreases as the number of links at a node increases. In this context, the normalized average message distance is used as the average message distance multiplied by the number of links at the node [14]. It seems reasonable to assume that an efficient and realistic multicomputer system will gradually show heavier traffic over short distances than over long communication paths since tasks can be partitioned into smaller subtasks which would usually be assigned to neighboring processors. For our SBCH network we assume that communication decays as the distance of the source node to the destination node increases. We assume that newly created tasks diffuse from areas of high processor utilization to areas of lower processor utilization with a bound on the maximum migration distance. Based on these assumptions, we are using the decay routing distribution [29] to characterize the mean internode distance of the SBCH topology.

The general form of the mean internode distance is given in [29]

$$\bar{l} = \sum_{l=1}^{l\max} lP(l) \tag{1}$$

where $P(l)$ represents the probability for a packet to reach its destination at distance l. Then, following the discussion in [29], the average message distance under the decay routing distribution is estimated

$$\bar{l} = \frac{d-1}{(d^{l\max} - 1)} \sum_{l=1}^{l\max} d^{l-1} \tag{2}$$

$$= \frac{(dl\max - l\max - 1)\, d^{l\max} + 1}{(d-1)(d^{l\max} - 1)} \tag{3}$$

where $l\max$ is the diameter of the network and d denotes the locality of communication. Values of d closer to one denote uniform routing distribution while values of d closer to zero mean a nearest neighbor communication pattern. To calculate the normalized mean internode distance, we simply multiply the mean internode distance shown in (3) with the number of links at a node of the network. The normalized mean internode distance of an SBCH(w, n) is the sum of the normalized mean internode distance of a 2-D SBH and a regular point-to-point hypercube. Graphs of the normalized mean internode distance for different values of d are shown in Fig. 4(a) and (b).

6) Fault Tolerance: Due to the concurrent presence of buses and hypercubes in the SBCH, rerouting of messages in the presence of a single faulty link or a single faulty node can easily be done with little modification of existing fault-free routing algorithms. In the SBCH, any single faulty link or any single faulty node can be sidestepped by only two additional hops as long as that particular node is not involved in the communication, namely, the node is neither the source nor the destination for any message. This can be shown as follows. A message in the SBCH is routed using a bus routing function if both the source and the destination of the message are in the same 2-D spanning bus hypercube subnetwork, or a hypercube routing function if they are in the same hypercube subnetwork, or a combination of these two routing functions if those of the message are neither in the same bus nor in the same hypercube subnetwork. Consider the rerouting scheme in the presence of a single faulty link when the bus routing function is being applied. When we refer to a faulty link of

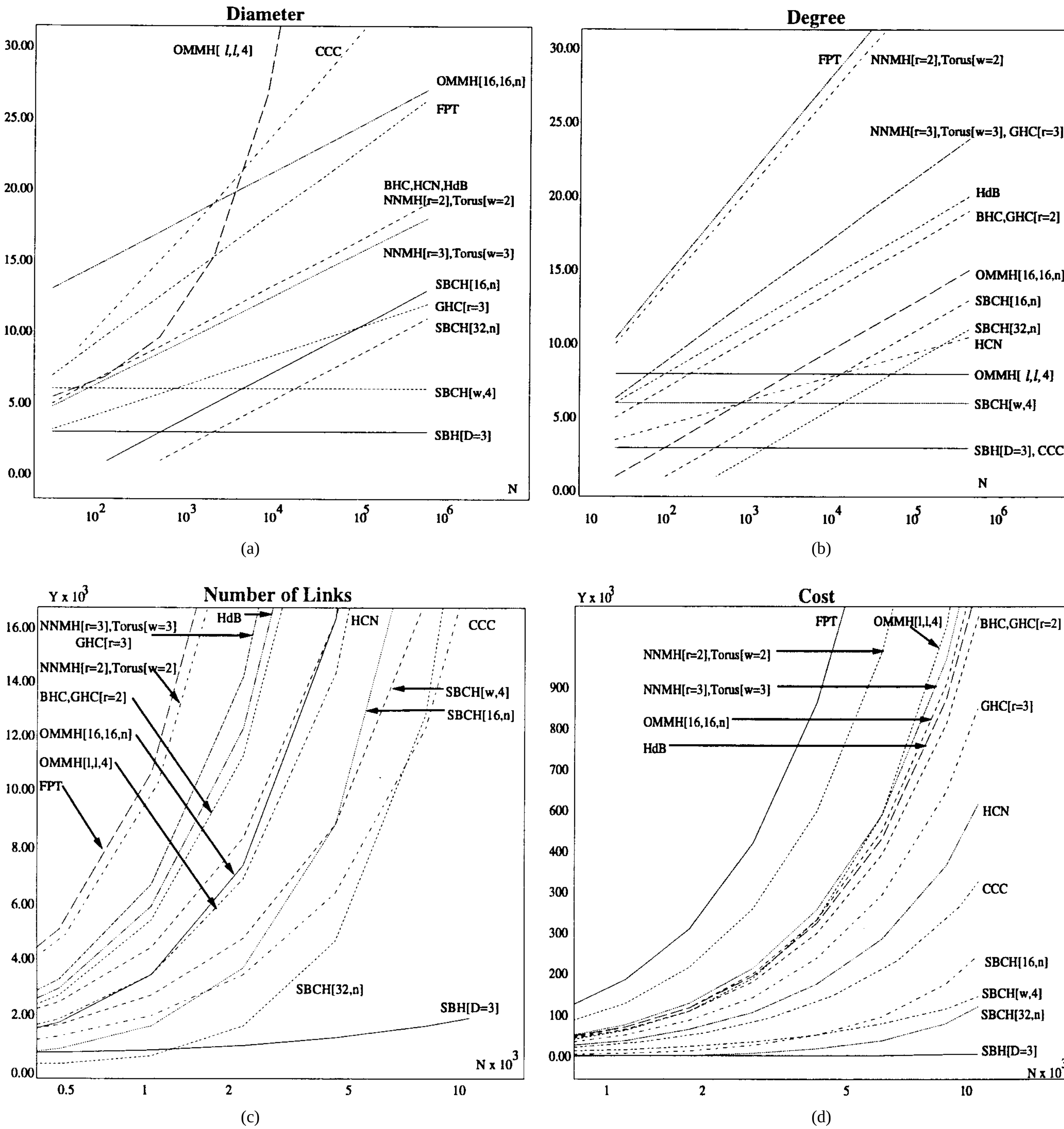
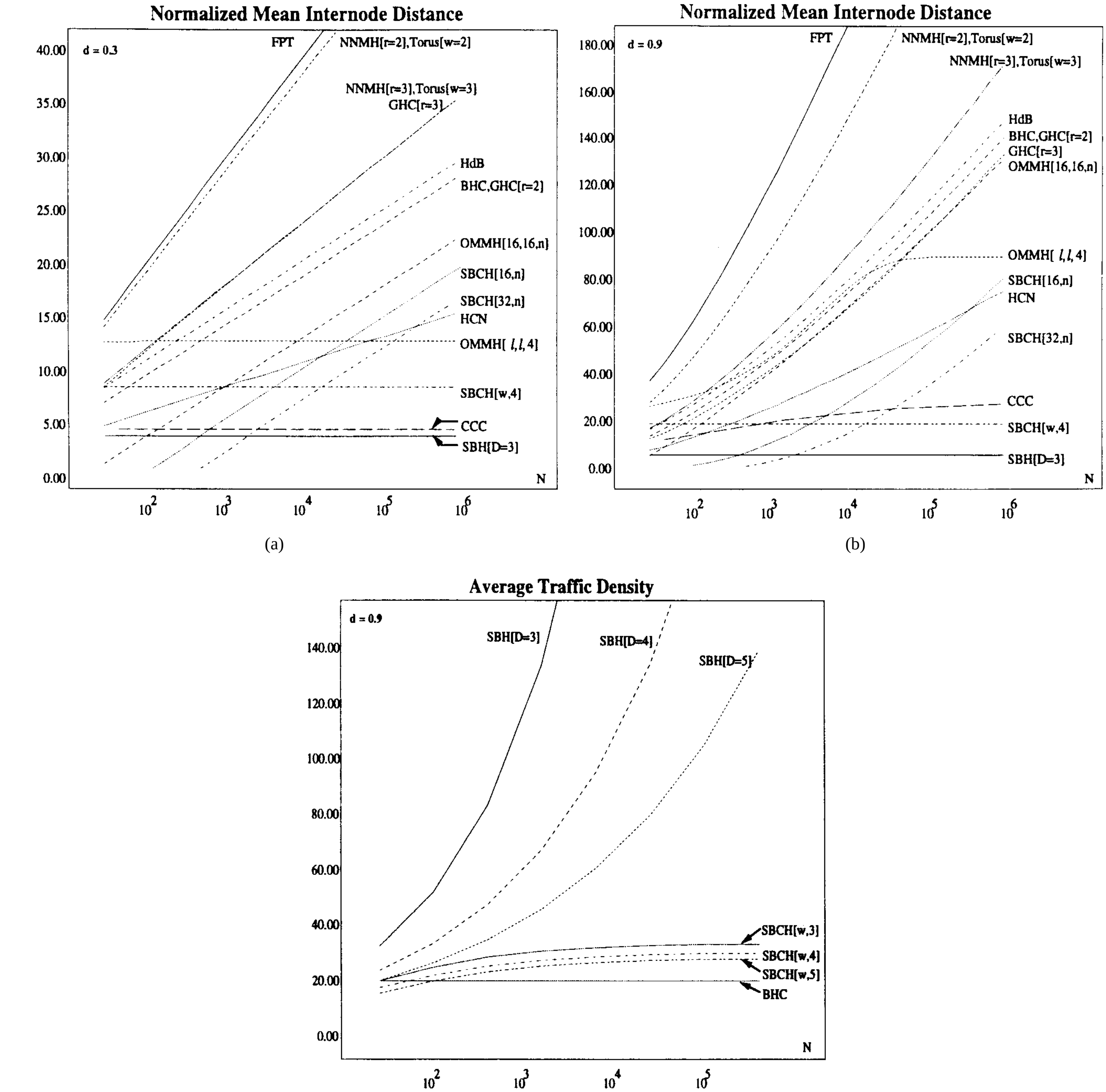


Fig. 3. Network comparisons for (a) diameter, (b) degree, (c) number of links, and (d) topological cost.

a bus network we mean that a PE can not access the bus due to a bus failure. In such a case the PE would not be able to communicate with other PE's that share the same bus subnetwork. The problem can be solved by forwarding the data to the neighboring bus subnetwork via one hop of the hypercube link (n such neighboring two-dimensional buses exist in SBCH(w,n)). By using the neighboring bus subnetwork, the message arrives at a node which is one hop away from the destination since the message has been routed in the neighboring bus subnetwork to detour the faulty bus. Similarly, a single faulty link when the hypercube routing function is being applied can be sidestepped by forwarding the message to the neighboring hypercube via a bus operation. In general for a SBCH(w,n) network n two-hop rerouting schemes are available to by-pass a faulty bus.

III. Comparisons of SBCH with Popular Networks

In this section we compare the SBCH network with existing well known topologies. These include the Boolean hypercube (BHC) [5], the generalized hypercube (GHC) [9], the nearest neighbor mesh hypercube (NNMH) [23], the torus network [29], the spanning bus hypercube (SBH) [18], the hierarchical cubic network (HCN) [6], the cube-connected-cycle (CCC) [30], the hyper-deBruijn (HdB) [31], the folded Peterson (FPT)



(c)

Fig. 4. (a) Normalized mean internode distance at $d = 0.3$. (b) Normalized mean internode distance at $d = 0.9$. (c) Average traffic density of the SBH and SBCH networks with $N = 1000$ PE's.

[32], and the optical multimesh hypercube (OMMH) [15]. The comparison parameters include diameter, degree, number of links, normalized mean internode distance, topological cost, and average traffic density. The topological characteristics of the above networks are indicated in Table I. The results of the comparison are shown in Figs. 3 and 4.

In the figures, the SBCH(32, n) notation denotes that the network is expanded following the fixed$_{w=32}$ rule; that is, the size of the buses is kept constant (32 PE's per bus) and the size of the hypercube module is changed to have the same network size for comparison purposes. Likewise, the SBCH$(16, n)$ notation means that the network is expanded following the fixed$_{w=16}$ rule. The SBCH$(w, 4)$ notation denotes that the network is expanded following the fixed$_{n=4}$ rule which means that the size of the hypercube module is kept fixed $(n = 4)$ and the size of the buses is increased. Note that when expanding the SBCH network some mathematical constraints exist. In Section II-C, the degree and diameter of the SBCH network were derived; they are both equal to $\log_2 (N/w^2) + 2$. The first term of the equation is a factor of both the number of nodes in the entire network(N) and the size of the buses(w). The constraint is that $N \geq w^2$ because otherwise the $\log_2 (N/w^2)$ factor of the degree/diameter equation will give a negative number which would be unacceptable. Additionally, this constraint must be met for the network to be complete. The notation (16, 16, n)-OMMH denotes that the size of the mesh network in the OMMH is fixed while the size of the hypercube is varied. Similarly the (l, l, 4)-OMMH notation denotes that the size of the hypercube is fixed and the mesh size is varied. Finally, the notation SBH($D = 3$) means that the dimension of the SBH network is kept constant and the size of the buses(w) is changed.

A. Diameter and Degree

Fig. 3(a) and (b) show the graph comparisons of the in terms of diameter and degree as the network size is increased. At the key mark of 10 000 nodes (desirable for MPP's), SBH($D = 3$), $\mathrm{SBCH}(32, n)$, $\mathrm{SBCH}(w, 4)$ and SBCH(16, n) exhibit very good performances in terms of diameter and degree with values 3, 5, 6, and 7, respectively. The CCC reveals very good degree(3), but it also exhibits a fairly large diameter(17). The OMMH(l, l, n) experiences the worst diameter(29) and the FPT the worst degree(27). Even though at 10 000 nodes the SBCH(32, n) reveals better characteristics than the SBCH(w, 4) the later is more desirable because it possesses constant degree and diameter, features that allow it to be scalable. The SBCH(32, n) on the other hand, experiences a logarithmic increase in degree and diameter, features that make it difficult to scale up to a larger number of processors. In general, from Fig. 3(b), most of the hybrid networks show a logarithmic increase in their degree which makes it difficult for them to scale up in size.

B. Number of Links and Cost

Fig. 3(c) and (d) show the graphs comparisons in terms of the number of links and topological cost as the networks scale up in size. The SBH($D = 3$), $\mathrm{SBCH}(32, n)$, $\mathrm{SBCH}(w, 4)$, $\mathrm{SBCH}(16, n)$ and CCC reveal the best performance characteristics in terms of number of links and topological cost while the FPT, NNMH and Torus seem to require a larger number of links leading into a higher topological cost.

C. Normalized Mean Internode Distance

Fig. 4(a) and (b) illustrate the graph comparisons in terms of normalized mean internode distance with localized distribution routing ($d = 0.3$) and with uniform distribution routing ($d = 0.9$). Again at 10 000 nodes, the SBH($D = 3$), $\mathrm{BCH}(32, n)$, $\mathrm{SBCH}(w, 4)$, $\mathrm{SBCH}(16, n)$, and CCC exhibit the best normalized mean internode distances with values close to 5 for $d = 0.3$ and 15 for $d = 0.9$. The FPT, NNMH and Torus experience the worst normalized mean internode distances with values close to 40 for $d = 0.3$ and 200 for $d = 0.9$. Fig. 4(a) and (b) indicate that, with the decay routing distribution model, the normalized mean internode distance of the SBCH having fixed size hypercubes (SBCH(w, 4)) is constant with respect to the growth of the network while that of the other networks(excluding the SBH, CCC, and OMMH with fixed size hypercubes) grow logarithmically with respect to the network size.

D. Average Traffic Density

As emphasized in Section II, the advantage of the SBCH(w, n) network over the SBH network is its ability to use the point-to-point hypercube links to alleviate the buses. A very good measure indicating that, is the average traffic density. The average traffic density is defined as the product of the average distance and the total number of nodes, divided by the total number of communication links [23]. In the Introduction, we mentioned that the average traffic density of the SBH network increases as $\vee(w)$ [18]. Using the definition stated above the average traffic density of the SBCH(w, n) network can also be calculated

$$T_{\mathrm{SBCH}} = \frac{\overline{Nl}N}{\frac{N}{2}\left(\frac{4}{w} + n\right)}. \tag{4}$$

The normalized internode distance $(\overline{Nl})$ is equal to $\bar{l} \times (n+2)$. Therefore the average traffic density is

$$T_{\mathrm{SBCH}} = \frac{2(n+2)\bar{l}}{\left(\frac{4}{w} + n\right)} \tag{5}$$

where $\bar{l}$ can be estimated from (3). Equation (5) reveals that when the fixed$_n$ rule is followed to expand the network the average traffic density of the SBCH(w, n) is essentially independed of w. This feature allows the network to utilize a much larger number of nodes along the buses. Fig. 4(c) presents graph comparisons between SBH, SBCH and BHC networks for uniform routing distribution ($d = 0.9$). The BHC has low traffic density and it is insensitive to variations in network size. The SBCH network demonstrates more traffic density than the BHC, but for larger network size it also exhibits no sensitivity to variations in network size. On the other hand, the SBH network shows an increase in traffic density, therefore for larger networks the SBH network most likely would experience severe bus congestion problems which will lead to large message delays.

The SBH network despite its better topological characteristics(diameter, degree, cost etc.) would most likely experience bus saturation problems for large number of PE's. The advantage of the SBCH network is that in addition to its very good topological characteristics it demonstrates insensitivity in traffic density when the network scales up in size. This feature allows the SBCH network to grow up in size with less chance for bus saturation problems. Nevertheless, even if bus saturation problems appear, the SBCH network does not experience the same message delays because it can utilize the point-to-point hypercube links to redirect the packets from another path. In the SBCH network the saturated bus can be sidestepped by only two additional hops as long as that particular saturated bus is not involved in the communication. Fig. 2 demonstrates a rerouting scheme assuming a bus saturation problem. Assume that in Fig. 2 node (0, 0, 0) wants to send a packet to node (0, 2, 0) via the horizontal bus a. In case of a bus saturation problem, the package will need to follow a different routing path. Three different routing paths are available and are all shown in Fig. 2

with thick dotted lines. The packet can utilize three hypercube links to access bus b, bus d, or bus f. By using one of the three buses the packet will arrive at a node which is one hop (one hypercube link) way from the destination link. Note that, in each of the three rerouting paths two additional hops were necessary to by-pass the saturated bus.

IV. Optical Implementation of the SBCH Network

Obviously an electronic implementation of the proposed SBCH network is feasible. One methodology would be to use multiprocessor board technology (e.g., multichip module technology) for the hypercube subnetwork connections and backplanes for the bus connections. To limit the number of boards required, k hypercube modules can be clustered together on a single multipocessor board. However, for a large number of PE's, and a greater bandwidth and interconnect density, conventional backplanes have major limitations [3], [4], [33]. These include signal skew, wave reflection, impedance mismatch, skin effects, interference, among many others. A possible alternative is the use of optical interconnects. Optical interconnects offer many communication advantages over electronics, including gigahertz transfer rates in an environment free from capacitive loading effects and electromagnetic interference, high interconnection density, low-power requirements, and possibly a significant reduction in design complexity through the use of multiple access techniques and the third dimension of free-space optics. The effectiveness of optical interconnects has been extensively examined [3], [4], [20]–[26], [34], [35]. In the following we propose an all optical implementation of the SBCH(w, n) network where the hypercube modules are implemented using free-space space-invariant optics [4], [15]–[17], [36] and the bus modules are implemented using wavelength division multiple access (WDMA) techniques. We refer the reader to [4], [15]–[17], and [36] for the free-space portion and concentrate on the WDM here.

A. Implementation of Spanning Bus Hypercube Using WDMA Techniques

In this section, the implementation of the spanning bus hypercube subnetwork using WDMA techniques is presented. To exploit the large communication bandwidth of optics, WDMA techniques that enable multiple multi-access channels to be realized on a single physical channel can be utilized. In a WDMA system the optical spectrum is divided into many different logical channels, each channel corresponding to a unique wavelength. These channels are carried simultaneously on a small number of physical channels, e.g., a fiber. Additionally, each network node is equipped with a small number of transmitters and receivers, some of these being dynamically tunable to different wavelengths. Optical Passive star Couplers can be utilized for the WDMA channels [37]. The purpose of an $N \times N$ star coupler is to couple light from one of its N input guides to all the N output guides uniformly. Star couplers with a 128 × 128 ports and the capability of handling more than hundred different wavelengths are feasible with currently available technology. An experimental ISDN switch architecture using eight 128 × 128 multiple star couplers to handle over ten thousand input port lines has been reported [38].

The SBCH(w, n) network consists of w^2 hypercube modules and $2^n w \times w$ 2-D spanning bus hypercubes. From the discussion above, every hypercube module is bipartitioned into two planes called $plane_l$ and $plane_r$. In the SBCH network all $plane_l$s are grouped together to form a plane called $Plane_L$ while all $plane_r$s are grouped to form another plane called $Plane_R$. The SBH buses can be implemented by interconnecting the individual plane$_l$'s of Plane$_L$ and plane$_r$'s of Plane$_R$. The hypercube modules are implemented using free space optics to provide the connectivity between plane$_l$'s and plane$_r$'s. Additionally, 2^{n-1} 2-D spanning bus hypercube subnetworks per plane (Plane$_L$ or Plane$_R$) need to be implemented. Each 2-D SBH consists of $2w$ buses, therefore a total of $2w \times 2^{n-1}$ buses per Plane are required.

A trivial implementation of the SBH subnetwork is to assign a distinct wavelength for every PE in Plane$_L$ and Plane$_R$ and then perform WDMA techniques to implement the buses. However, such a straightforward method requires a prohibitively large number of different wavelengths and fiber. For example for an SBCH(4, 3) consisting of 128 PE's, a total of 64 wavelengths would be necessary. A wavelength assignment technique [15], [24] can be employed to reduce the number of wavelengths used in the system. Let's take a running example, an SBCH(4, 3). Fig. 5 shows how wavelengths are assigned for each PE of Plane$_L$. The following wavelengths are assigned to the first row: $\lambda_1, \lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8$. Then, $\lambda_2, \lambda_3, \lambda_4, \lambda_5, \lambda_6, \lambda_7, \lambda_8, \lambda_1$ are assigned as wavelengths in the second row. In general, wavelength assignment in a row is achieved by rotating the wavelength assignment of the previous row by one column. This wavelength assignment results in no two PE's in the same row or column of Plane$_L$ having an identical wavelength. Similar considerations take place for PE's of Plane$_R$. With this wavelength assignment technique, the total number of wavelengths required to implement the SBCH(4, 3) network is reduced from 64 to 8. In general, for an SBCH(w, n) the following wavelength assignment for the first row must be performed: $\lambda_1, \lambda_2, \cdots, \lambda_{w2^{(n-1)/2}}$, and then, $\lambda_2, \ldots, \lambda_{w2^{(n-1)/2}}, \lambda_1$, are assigned to the PE's of the second row and so on. Thus an implementation of an SBCH(w, n) with the above wavelength assignment requires no more than $w \times 2^{(n-1)/2}$ wavelengths.

Referring to Fig. 5, the wavelengths assigned to the PE's of the first row are divided into two groups of four wavelengths each. The groups are as follows: $(\lambda_1, \lambda_3, \lambda_5, \lambda_7)$ and $(\lambda_2, \lambda_4, \lambda_6, \lambda_8)$. Each of these groups correspond to the implementation of a row-wise bus. Every PE in the group should be capable of tuning in to any of the wavelengths assigned to that group. For example, the node of group1 with wavelength λ_1 must be able to tune to wavelengths $\lambda_3, \lambda_5, \lambda_7$ which correspond to wavelengths that were assigned to the other PE's of that group. Rotating the wavelength assignments in the groups of the previous rows will form the new wavelength groups that correspond to every row. Similarly, each column of Fig. 5 must be divided into two groups of four wavelengths each. For example, for the second column of

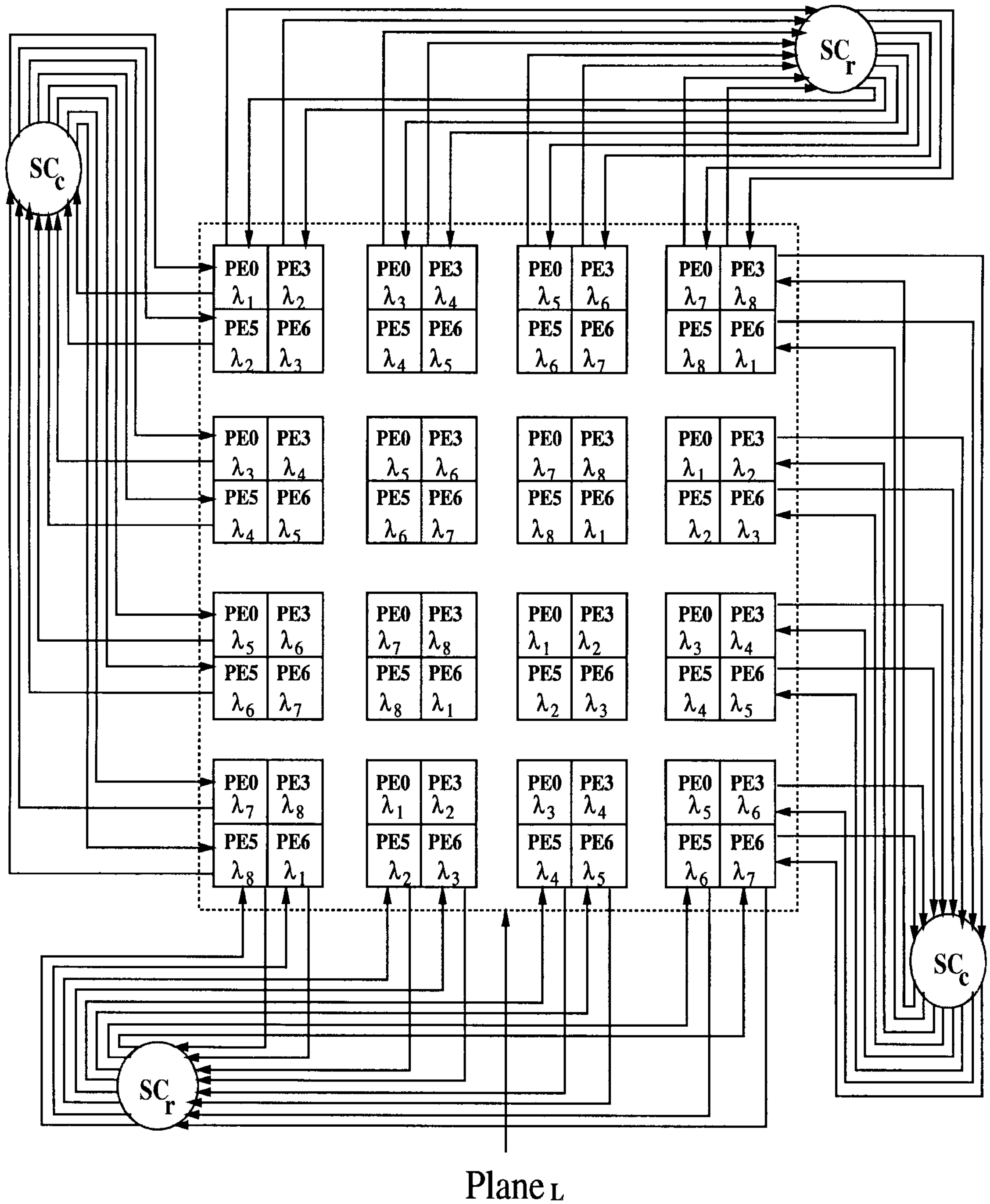


Fig. 5. An optical implementation of Plane$_L$ of a SBCH(4, 3) network using optical star-couplers. We need two tunable transmitters/receivers for every node. Similar connections exist for Plane$_R$. For clarity of the figure only a few buses are shown. Note that each SC$_r$ implements two row-wise buses while every SC$_c$ implements two column-wise buses.

Fig. 5 the following groups are formed: $(\lambda_2, \lambda_4, \lambda_6, \lambda_8)$ and $(\lambda_3, \lambda_5, \lambda_7, \lambda_1)$. Each of these wavelength groups correspond to the implementation of a column-wise bus. Again, rotation of the column-wise wavelength assignment will result in the formation of the wavelength groups for the other columns.

We now consider the overall optical implementation of an SBCH(w, n). For simplicity and without loss of generality, we consider the implementation of an example network of size SBCH(4, 3). Fig. 5 shows an example Plane$_L$ of the SBCH(4, 3) network. We assume that each PE has three light sources; one fixed source, S_h which illuminates the HOE to generate the required hypercube links and the other two relatively tunable sources S_r and S_c are coupled into optical fibers to implement the two spanning buses. It should be noted that full tunability is not required here. In fact, each laser source should be tunable for a single wavelength group only. For example, the sources of the PE's of the first row in Fig. 5 are tunable within the range $\lambda_1, \lambda_3, \lambda_5, \lambda_7$ (or $\lambda_2, \lambda_4, \lambda_6, \lambda_8$). This reduced range increases the efficiency, the yield, and the tuning speed of the light sources. Furthermore, each PE is equipped with three receivers: one receiver R_h receives light from the free-space optics implementing the hypercube and the other two receivers R_r and R_c receive light from fibers coming from star couplers. The key component that provides bus connectivity here is the tunable-transmitter fixed-receiver scheme. The wavelength assignment shown in Fig. 5 corresponds to the receiver wavelength assignment of every PE. Other PE's can communicate with a particular PE by simply tuning in to the wavelength assigned to that PE. Therefore, it is important that tunable devices with sufficient tuning range as well as tuning time be available. Rapid progress is being made in the development of tunable devices, both in the range over which they are tunable, and their tuning times [38], [39]. Current tuning ranges are in the 4–10 nm and the tuning times vary from nanoseconds to milliseconds [38].

Referring to Fig. 5, each node utilizes two star couplers, one for each spanning bus. Let each star coupler that implements the row-wise buses be SC_r and each star coupler that implements the column-wise buses be SC_c. In a given SBCH-network, a SC_r multiplexes light from S_r sources coming from nodes lying on the same row of the plane while SC_c multiplexes light from S_c sources coming from nodes lying on the same column of the plane. Note that instead of using a star coupler for every row-wise or column-wise bus, every star coupler implements $2^{(n-1)/2} = 2$ buses of $w = 4$ number of nodes. Which row-wise or column-wise buses are implemented is dictated by the wavelength assignment and wavelength grouping explained earlier. For example, the SC_r of the first row of Fig. 5 implements the buses with wavelengths $(\lambda_1, \lambda_3, \lambda_5, \lambda_7)$ and $(\lambda_2, \lambda_4, \lambda_6, \lambda_8)$, respectively.

In order to alleviate bus collisions (e.g., different messages destined to the same PE at the same time), the time domain along each subchannel can be utilized. Time division multiple access techniques can be combined with the proposed WDMA scheme. This issue is beyond the scope of this paper.

V. Power Analysis of the Optical Implementation

In this section, we present some system noise calculations to investigate the BER capabilities of the proposed optical implementation of the SBCH network. Calculation of BER of an optical system requires estimation of the signal-to-noise ratio (SNR). Estimation of total power losses, leading into receiver sensitivity calculation is required for the SNR. In what follows, the optical power loss of the implementation methodology is calculated. Then the receiver sensitivity is estimated and consequently the BER of the proposed implementation is evaluated.

A. Optical Power Loss for WDMA Implementation

The number of PE's that an optical system can support is determined by the emitting power of the transmitter, the required receiver sensitivity and the losses occurred between the transmitter and the receiver. Let L_{sf} be the source to fiber coupling loss, L_{fd} be the fiber to detector coupling loss, and L_f be the fiber attenuation loss. Let L_e be the excess loss of the optical star coupler. To estimate the star coupler splitting loss, the input power to the coupler and the fan-out is required. Let P_{in} be the power coming into the coupler from an input channel and P_{out} is the power coming out from an output channel then $L_{sp} = 10 \log (P_{\text{out}}/P_{\text{in}})$.

The total transmission loss is then:

$$L_{\text{total}} = L_e + L_{sp} + dL_f + L_{sf} + L_{fd} \tag{6}$$

P_{out} is equal to P_{in}/k where k is the fan-out of the star coupler. For the SBCH k can is $w \times 2^{(n-1)/2}$ (number of PE's on a row or column of Plane_L or Plane_R). Consequently, (6) can be rewritten as

$$L_{\text{total}} = L_e - 10 \log k + dL_f + L_{sf} + L_{fd} - 3. \tag{7}$$

To estimate the total loss of the optical system, values from commercially available components are considered. We assume laser diodes sources with characteristics +7 dBm. Also the insertion loss for a commercially available fiber coupler is taken as −1 dB while fiber to detector losses are −0.46 dB. The fiber loss is taken as 0.3 dBs/Km, but since d is in the order of cm's the total fiber loss is negligible. In addition, a −3 dB loss has being added for engineering errors. Rearranging (7) and using the above values, the number of PE's supported by the star couplers given a desirable BER can be determined. For a desired 10^{-17} BER the required receiver sensitivity of the GaAs Metal-Semiconductor FET Transimpedance [40] can be calculated as −19.2 dBm. For laser diodes of 7.0 dBm power the total loss in the optical system should be −26.2 dB yielding a star coupler fan-out of $k = 118$. This value is within the capabilities of current star coupler technology. The optical fanout of star couplers reported up to date is 128 × 128 [38]. For $k = 118$ large SBCH networks are feasible. For example, a SBCH(30, 5) network supporting about 28 800 PE's could be implemented. It should be noted, however, that when the the number of PE's attached to a bus increases, so does the star coupler attenuations. This in turn increases the detector sensitivity. However, an increase in detector sensitivity would also increase the BER. Therefore, when designing the spanning buses using passive star couplers trade-offs between desirable BER and number of PE's need to be considered.

VI. Conclusions

In this paper, we proposed a novel hybrid network which significantly improves hypercube-based topologies in general and the spanning bus hypercube (SBH) and the optical multi-mesh hypercube in particular. The key attractive features of the proposed network include the possibility of a constant diameter and a constant degree network while it is feasible to interconnect thousands of processors at a reasonable cost. Additionally, the network is incrementally scalable and fault-tolerant. These features make SBCH very suitable for massively parallel systems. The topological characteristics of the proposed network was compared with several other well known networks and it is shown that SBCH compares extremely well with the SBH, the binary hypercube, the generalized hypercube, the nearest neighbor mesh hypercube, the torus network, the hierarchical cubic network, the cube-connected cycle, the hyper-deBruijn, and the folded Peterson. A WDMA technique utilizing star couplers has been proposed for the optical implementation of the SBCH network. Analysis of the implementation reveals that a more than 20 000 PE SBCH network is currently feasible with BER less than 10^{-17}.

REFERENCES

[1] K. Hwang, *Advanced Computer Architecture: Parallelism, Scalability, Programmability*. New York: McGraw-Hill, 1993.
[2] H. J. Siegel, *Interconnection Networks for Large-scale Parallel Processing*. New York: McGraw-Hill, 1990.
[3] H. S. Stone and J. Cocke, "Computer architecture in the 1990s," *Comput.*, pp. 30–38, Sept. 1991.
[4] A. Louri and H. Sung, "3D Optical Interconnects for high-speed interchip and interboard communications," *Comput.*, vol. 27, pp. 27–37, Oct. 1994.
[5] Y. Saad and M. H. Schultz, "Topological properties of hypercubes," *IEEE Trans. Comput.*, vol. 37, pp. 867–872, July 1988.
[6] K. Ghose and K. R. Desai, "Hierarchical Cubic Networks," *IEEE Trans. Parallel Distrib. Syst.*, vol. 6, pp. 427–435, Apr. 1995.
[7] J. M. Kumar and L. M. Patnaik, "Extended hypercube: A hierarchical interconnection network of hypercubes," *IEEE Trans. Parallel Distrib. Syst.*, vol. 3, pp. 45–57, Jan. 1992.
[8] N.-F. Tzeng and S. Wei, "Enhanced hypercubes," *IEEE Trans. Comput.*, vol. 40, pp. 284–294, Mar 1991.
[9] L. N. Bhuyan and D. P. Agrawal, "Generalized hypercube and hyperbus structures constructing massively parallel computers," *IEEE Trans. Comput.*, vol. C-33, pp. 323–333, 1984.
[10] Q. M. Malluhi and M. A. Bayoumi, "The hierarchical hypercube: A new interconnection topology for massively parallel systems," *IEEE Trans. Parallel Distrib. Syst.*, vol. 5, pp. 17–30, Jan. 1994.
[11] C. Chen, D. P. Agrawal, and J. R. Burke, "dBCube: A new class of hierarchical multiprocessor interconnection networks with area efficient layout," *IEEE Trans. Parallel Distrib. Syst.*, vol. 4, pp. 1332–1344, Jan. 1993.
[12] K. Efe, "The crossed cube architecture for parallel computation," *IEEE Trans. Parallel Distrib. Syst.*, vol. 3, pp. 513–524, Sept. 1992.
[13] K. Hwang and J. Ghosh, "Hypernet: A communication efficient architecture for constructing massively parallel computers," *IEEE Trans. Comput.*, vol. C-36, pp. 1450–1466, Dec. 1987.
[14] J. R. Goodman and C. H. Sequin, "Hypertree: A multiprocessor interconnection topology," *IEEE Trans. Comput.*, vol. C-30, pp. 923–933, 1981.
[15] A. Louri and H. Sung, "A scalable optical hypercube-based interconnection network for massively parallel computing," *Appl. Opt.*, vol. 33, pp. 7588–7598, Nov. 1994.
[16] A. Louri and H. Sung, "An optical multi-mesh hypercube: A scalable optical interconnection network for massively parallel computing," *J. Lightwave Technol.*, vol. 12, pp. 704–716, Apr. 1994.
[17] A. Louri, S. Furlonge, and C. Neocleous, "Experimental demonstration of the optical multi-mesh hypercube: A scalable interconnection network for multiprocessors and multicomputers," *Appl. Opt.*, vol. 35, no. 35, pp. 6909–6920, Dec. 10, 1996.
[18] L. D. Wittie, "Communication structures for large networks of microcomputers," *IEEE Trans. Comput.*, vol. C-30, pp. 264–273, Apr. 1981.
[19] G. Lerman and L. Rudolph, *Parallel Evolution of Parallel Processors*. New York: Plenum, 1993.
[20] M. R. Feldman, C. C. Guest, T. J. Drabik, and S. C. Esner, "Comparison between electrical and free space optical interconnects for fine grain processor arrays based on connection density capabilities," *Appl. Opt.*, vol. 28, pp. 3820–3829, 1989.
[21] J. W. Goodman, F. J. Leonberger, S. Y. Kung, and R. A. Athale, "Optical interconnections for VLSI systems," *Proc. IEEE*, vol. 72, pp. 850–866, July 1984.
[22] D. M. Chiarulli, S. P. Levitan, R. G. Mehlen, M. Bidnurkar, R. Ditmore, G. Gravenstreter, Z. Guo, C. Qiao, M. F. Sakr, and J. P. Teza, "Optoelectronic buses for high-performance computing," *Proc. IEEE*, vol. 82, pp. 1701–1709, Nov. 1994.
[23] P. W. Dowd, "Wavelength division multiple access channel hypercube processor interconnection," *IEEE Trans. Comput.*, vol. 41, pp. 1223–1241, Oct. 1992.
[24] Y. Li, A. W. Lohmann, and S. B. Rao, "Free-space optical mesh-connected bus networks using wavelength-division mutiple access," *Appl. Opt.*, vol. 32, pp. 6425–6437, 1993.
[25] P. B. Berra, A. Ghafoor, M. Guizani, S. J. Marcinkowski, and P. A. Mitkas, "Optics and supercomputing," *Proc. IEEE*, vol. 77, pp. 1797–1815, Dec. 1989.
[26] D. S. Miller, "Optics for low energy communication inside digital processors: Quantum detectors, sources, and modulators as efficient impedance converters," *Opt. Lett.*, vol. 14, pp. 146–148, 1989.
[27] A. Louri and R. Gupta, "Hierarchical optical ring interconnection (HORN): Scalable interconnection network for multiprocessors and multicomputers," *Appl. Opt.*, vol. 36, no. 2, pp. 430–442, Jan. 10, 1997.
[28] V. Kumar, A. Grama, A. Gupta, and G. Karypis, *Introduction to Parallel Computing: Design and Analysis of Algorithms*. New York, NY: Benjamin/Cummings Publishing Co., 1994.
[29] D. A. Reed and R. M. Fujimoto, *Multicomputer Networks: Message-Based Parallel Processing*. Cambridge, MA: M.I.T. Press, 1987.
[30] F. P. Preparata and J. Vuillemin, "The cube-connected cycles: a versatile network parallel computation," *Commun. ACM*, vol. 24, pp. 300–309, May 1981.
[31] E. Ganesan and D. K. Pradhan, "The hyper-deBruijn networks: Scalable versatile architecture," *IEEE Trans. Parallel Distrib. Syst.*, vol. 4, pp. 962–978, Sept. 1993.
[32] S. K. Das and A. K. Banerjee, "Hyper Peterson network: Yet another hypercube topology," *J. Parallel Distrib. Comput.*, vol. 12, pp. 283–289, July 1992.
[33] P. Sweazey, "Limits of performance of backplane buses," in *Digital Bus Handbook*. New York: McGrew-Hill, 1990.
[34] A. A. Sawchuk, C. S. Raghavandra, B. K. Jenkins, and A. Varma, "Optical crossbar networks," *IEEE Comput.*, vol. 20, pp. 50–62, Jun. 1987.
[35] A. D. McAulay, *Optical Computer Architectures: the Application of Optical Concepts to Next Generation Computers*. New York: Wiley, 1991.
[36] A. Louri and H. Sung, "Efficient implementation methodology for three-dimensional space-invariant hypercube-based free-space optical interconnection networks," *Appl. Opt.*, vol. 32, pp. 7200–7209, Dec. 1993.
[37] D. M. Chiarulli, S. P. Levitan, R. G. Mehlen, G. Gravenstreter, and J. P. Teza, "Multiprocessor interconnection networks using partitioned optical passive star (POPS) topologies and distributed control," in *Proc. First Int. Workshop on Massively Parallel Processing Using Optic. Interconnections*, Cancun, Mexico, Apr. 26–27 1994, pp. 70–80.
[38] A. Cisneros and C. A. Brackett, "A large ATM switch based on memory switches and optical star couplers," *IEEE J. Select. Areas Commun.*, vol. 9, pp. 1348–1360, Oct. 1991.
[39] P. F. Moulton, "Tunable solid state lasers," *Proc. IEEE*, vol. 80, pp. 348–364, Mar. 1992.
[40] T. V. Moui, "Receiver design for high-speed optical fiber systems," *J. Lightwave Technol.*, pp. 243–267, vol. 2, 1984.

Ahmed Louri (S'86–M'88–SM'95) received the M.S. and Ph.D. degrees in computer engineering from the University of Southern California, Los Angeles, CA, in 1984 and 1988, respectively. He received the Diplome D'engenieur (engineer degree) in electrical engineering from the University of Science and Technology, Oran, Algeria, in 1982.

He is currently an Associate Professor of Electrical and Computer Engineering at the University of Arizona, Tucson, AZ, and Director of the Optical Networking and Parallel Processing Laboratory. Prior to joining the Univeristy of Arizona, he worked as a researcher with the Computer Research Institute at the University of Southern California where he conducted extensive research in parallel processing, multiprocessor system design and optical computing. His research interests include computer architecture, parallel processing, optical computing, and optical interconnects. He has published numerous journal and conference articles on the above topics.

Dr. Louri received the "Best Article of 1991 Award" from IEEE Micro. In 1988, he was the recipient of the NSF Research Initial Award. In 1994, he was the recipient of the Advanced Telecommunications Organization of Japan Fellowship, Ministry of Post and Telecommunications, Japan. In 1995, he was the recipient of the Centre Nationale de Recherche Scientifique (CNRS), Fellowship, France. In 1996, he was the recipient of the Japanese Society for the Promotion of Science Fellowship. He has served as a member of the Technical Program Committee of several conferences including OSA Topical Meeting on Optics in Computing, OSA/IEEE Conference on Massively Parallel Processors using Optical Interconnects, among others. In 1996, he was the General Chair of the Workshop on Optics in High-Performance Computing, at Euro-Par'96 Lyon France. He is a member of the ACM, the OSA, and SPIE.

Costas Neocleous, photograph and biography not available at the time of publication.