An Efficient Signal Distinction Scheme for Large-scale Free-space Optical Networks Using Genetic Algorithms

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1 Introduction

Free-space optical interconnection networks can be classified into two types, *space variant* and *space invariant*, according to the degree of space variance [1]. The degree of space variance determines the network's complexity and regularity. A totally space variant network allows a completely arbitrary interconnection between nodes, whereas a totally space invariant network has a definite, regular structure with all the nodes having the same connection patterns. In terms of physical implementations, the degree of space variance can be interpreted as the degree of sharing beam steering optics among the nodes of a given network. In other words, all nodes in a totally space-invariant network can share a single beam steering optics (considering multiple fanouts as one steering optics) to realize the given network topology, whereas, in a totally space variant network, each node requires a distinct beam steering optics. This is one of the reasons why space variant networks require complex optical implementations that often result in low interconnection density and high cost.

However, space invariant networks require mechanisms for distinguishing the origins of incoming beams (or signals) detected at the node since several signals may arrive at the same time if the node degree of the network is greater than one. We can distinguish the origins of the incoming signals if each signal has unique wavelength (wavelength division multiplexing) or each signal arrives at uniquely assigned timeslot (time division multiplexing). For an N-node network, this would require up to N different wavelengths or N timeslots. Therefore, for a large-scale interconnection network, the requirement for the prohibitively large number of wavelengths makes such solutions impractical since the number of wavelengths from the currently available light sources is very limited. Similarly, the use of large number of timeslots would result in unacceptably large communication latency. It should be noted that the incoming signal distinction problem can be easily solved in space variant networks since we can have each incoming beam hit on a difference detector within the receiving node. This can be done easily in totally space variant networks because each incoming signal has its own beam steering optics. The incoming signal distinction by the use of a unique detector for each incoming signal is based on the concept of space division multiplexing. In a totally space-invariant network with N nodes, a trivial space division multiplexing scheme always exists if each node has $N-1$ detectors. In this paper, we present a method for reducing the required number of detectors per node for incoming signal distinction in a space-invariant network.

2 Motivation

Let us consider an example network of a linear array with 4 nodes as shown in Fig. 1. Fig. 1.a shows the topology of the 4-node linear array and Fig 1.b presents a side view of a totally space invariant optical implementation. A beam steering optics is responsible for generating two fanouts, one fanout to the right neighboring node and the other to the left neighboring node. We can see from the figure that all nodes have the same connection pattern and, con-

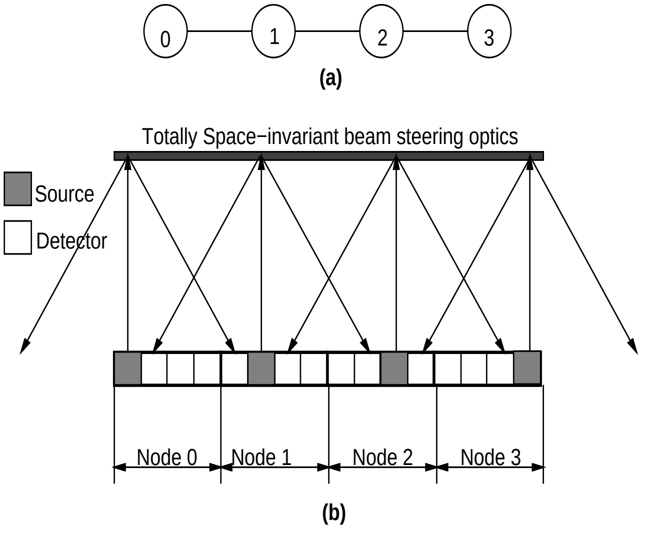


Figure 1: An example network of a 4-node linear array. (a) the topology. (b) A totally space-invariant optical implementation. Each node is connected to neighboring nodes on both side except nodes on extreme ends.

sequently, can share a single beam steering optics to provide all the required optical links. The source position of each node is different from those of the others so that the incoming signals can be distinguished by the positions of the detectors. Similar straightforward spatial encoding of source positions at the nodes is used in the design of optical hypercube networks [2, 3].

However, such straightforward encoding scheme requires too many unused detectors for large-scale networks. For an N-node network with node degree k, only k different signals may simultaneously arrive at a node since the node is connected to k nodes. Thus, in the space division multiplexing technique, only $k + 1$ (k detectors and 1 source) pixels per node are utilized and the remaining $N - k - 1$ pixels are wasted. This area waste is significant if $N >> k$. For example, the straightforward spatial encoding in a ten-dimensional hypercube network would result in $(1024 - 11 = 1013)$ unused pixels per node, which is not acceptable.

In what follows, we present a novel scheme which can greatly reduce the total number of unused pixels.

3 Proposed Signal Distinction Scheme

An efficient signal distinction scheme is to find the minimum number of detector pixels per node required for the incoming signal distinction in a given network. This problem can be re-stated if we represent a given network as a graph where a vertex and an edge represent a node and a link, respectively. Let V (E) represent the set of vertices (edges) in a graph, G.

Problem: Given a graph $G = (V, E)$, a positive integer $K \leq |V|$, which is a representation of a network, is G K-colorable? i.e., does there exist a function $f : V \rightarrow 0, 1, \cdots, K - 1$, for all i and j, such that $f(i) \neq f(i_1) \neq f(i_2) \cdots \neq f(i_j)$ where i_j represent all neighbors of node i.

The above problem is NP-complete since it can be reduced into the *Graph K-Colorability* problem which is known as NP-complete [4]. In general, NP-complete problems are very hard to solve unless the problem size is small enough. Using genetic algorithms (GAs), we solved the above modified colorability problem to get efficient signal distinction schemes for the mesh, the hypercube, and the binary de Bruijn networks [5].

GAs were developed to study the adaptive process of natural systems and to develop artificial systems that mimic the adaptive mechanism of natural systems [6]. GAs can also be applied to various optimization problems such as the traveling salesman problem. In a given problem, a set of potential solutions (called a population of individuals) to the problem is initially created at random. Each solution is evaluated to give some measure of its fitness. Then a new set of solutions (next generation of the population) is formed by selecting better (fitter) solutions. Some of the new solution set undergos transformation by means of *genetic* operators such as *mutation* and *crossover*. The mutation is an operation which alters a small part of a solution. The crossover creates new solutions by combining parts from several other solutions. The probabilities of the mutation and the crossover are control parameters which affect the convergence rate of GAs. Thus, GAs use the notion of survival of the fittest by passing good genes (potential solutions) to the next generation and combining different genes to explore new search points.

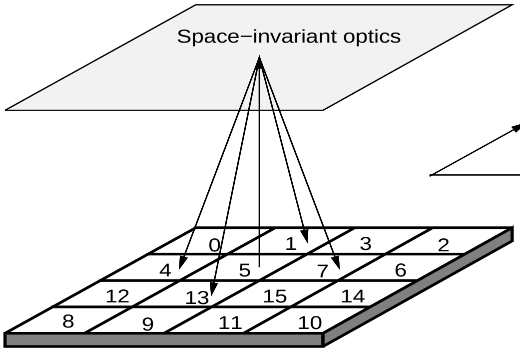
We used a new type of GAs, called the Enhanced Parallel Genetic Algorithm (EPGA) [7], since we were unable to get solutions using conventional simple GAs as the network size grows. Using the concept of the Hierarchical GA [8], the running time of the EPGA was significantly reduced. Details of the EPGA are beyond the scope of this paper and interested readers should refer to [7]. Table 1 shows the minimum number of distinct colors or number of distinct pixels required using the EPGA for the mesh with wraparound connections, the hypercube, and the binary de bruijn networks. A number in the parenthesis indicates the theoretical optimal number of pixels per node which is equivalent to the node degree (optimal number of detectors) plus 1 (one source).

Network Size	Hypercube	Mesh	de Bruijn
16 nodes	8 (5)	8 (5)	7 (5)
64 nodes	11 (7)	8 (5)	9 (5)
256 nodes	18 (9)	8 (5)	9 (5)
1,024 nodes	26 (11)	9 (5)	11 (5)

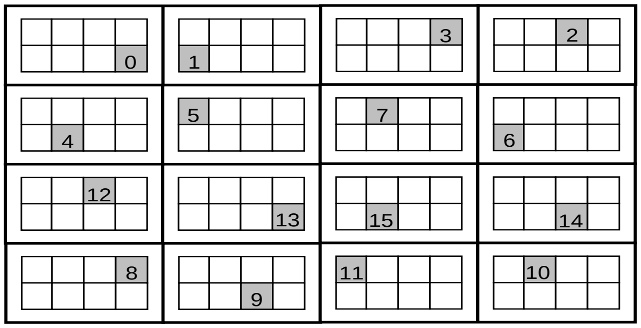
Table 1: Minimum number of pixels (a source and multiple detectors) per node required for a given size network. Note that node degree of the hypercube increases logarithmically with respect to the network size, whereas those of the mesh and the binary de Bruijn are constant. A number in the parenthesis indicates the theoretical optimal number of pixels. The mesh is assumed to have wraparound connections.

For example, for a 256-node hypercube (8-dimensional hypercube), the proposed scheme requires only 18 pixels for the space division multiplexing technique, whereas the straightforward space division multiplexing technique would require as many as 256 pixels per node.

Fig. 2 demonstrates an example of the source position encoding, found by the proposed scheme, for the four-dimensional hypercube network with 16 nodes. The beam steering optics for the totally space-invariant optical implementation of such networks is based on [2].



(a) Optical Interconnect Model



(b) Spatial encoding of source pixel positions

Figure 2: (a) A 3D model of totally space-invariant beam steering optics for implementing optical hypercube networks [2]. The beam steering optics generates 8 fanouts of which amounts of spatial shifts are $\pm 1col$, $\pm 1row$, $\pm 3col$, and $\pm 3row$, respectively. (b) Spatial encoding of source pixel positions in a 4-dimensional hypercube network with 16 nodes. Each node has 8 pixels; a source and 7 detectors. A dark pixel represents a source and the position of the source pixel is the spatial encoding of the corresponding node address as indicated by a number. White pixels represent detectors.

A dark pixel and a white pixel represent a source and a detector, respectively. Note that the node address is spatially encoded by the position of the source pixel. The corresponding address is indicated by a number in the source pixel. For a four-dimensional hypercube network, the proposed scheme requires 8 pixels per node which is a 50% saving compared to 16 pixels per node required by the straight forwarding encoding scheme.

4 Discussions

A free space space-invariant design approach is simple to design and can provide higher interconnect density compared to the space-variant approach. However, the space-invariant design utilizes given power less efficiently than the space-variant approach. In addition, the space-invariant approach often results in low resource utilization for distinguishing incoming signals; i.e., the approach may require many unused detectors when space division multiplexing technique is used for signal distinction. In this paper, we have presented an efficient scheme for distinguishing incoming signals. We first formulated the problem as a modified graph colorability problem and solved it using a new type of genetic algorithm called the Enhanced Parallel Genetic Algorithm. The proposed scheme significantly reduces the number of the unused detectors, which enables the use of space division multiplexing technique in large-scale optical networks.

The proposed signal distinction scheme can also be used in wavelength division multiplexing and/or time division multiplexing techniques by considering the spatial positions as distinct wavelengths or timeslots, respectively. With wavelength or time division multiplexing techniques, each node has a single detector unlike the multiple detectors with the space division multiplexing technique. A receiving node distinguishes the origin of the incoming signal by identifying the wavelength of the signal or the timeslot the signal occupies.

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