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Reliable Networks Based on General Passive Routing Devices

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***Abstract*— Survivable passive network architectures based on interconnecting a small number of AWGs have been described in prior work. Such networks are desirable for communication between a small number of users in environments that are susceptible to a high rate of failure and where providing power in the network core is difficult. In this paper, it is shown that these network designs can be improved if passive devices that have routing properties different from those of the standard AWG are considered. Devices with routing matrices represented by Latin squares and devices with more arbitrary routing patterns are considered here. This illustrates that developing the capability to manufacture more general passive routing devices is a worthwhile goal.**

***Index Terms*— Arrayed waveguide grating (AWG), bipartite network, Latin router, Latin square, passive optical networks (PON), self-healing networks, survivable networks**

I. INTRODUCTION

Survivable passive networks are desirable for applications where the environment is subject to a high rate of failure and where providing power is difficult. Some examples include: a network that has been rapidly deployed for disaster recovery, where the network fibers are likely not well protected; a network near a battlefield, where delivering power to the core of the network is not possible; and, a network in a military plane or other mobile platform, where it may be desirable that the network infrastructure be completely passive to minimize power drain [1]. It is assumed that the number of users requiring communication and the geographic extent of such a network is relatively small (i.e., tens of users and a network diameter of a few miles). Furthermore, it is assumed that high data rates (e.g., 10 Gbit/s) are required between the users, which is best met with a fiber-optic network as opposed to using radio or free-space optics.

Passive optical communication networks are often realized using star-based architectures where each end-user is connected to a port of a single arrayed waveguide grating (AWG) router [2]-[4]. AWGs are favored for such networks (e.g., as opposed to passive splitters) due to their wavelength-reuse properties, where W wavelengths can be used to support communication between W^2 pairs of users at once. Protection for such networks is typically accomplished by deploying multiple star networks, such that if a failure brings down one star, a diversely routed star network remains intact [5]. One drawback to this redundant-star approach is the potential difficulty in deploying the required number of diverse fiber routes.

Reference [1] proposes an alternative reliable passive network architecture based on distributed AWG routers. The networks employ AWGs arranged in survivable topologies, with specific interconnection patterns between adjacent AWGs. The users are equipped with tunable transmitters and receivers (or transmitter and receiver arrays). As described in [1], protection against multiple concurrent failures can be realized with such an architecture. Furthermore, depending on the configuration of the AWGs, different types of protection can be provided; e.g., 1:1 protection vs. 1+1 protection.

All of the designs in [1] make use of standard AWGs, where the mapping of input ports to output ports can be represented by a particular Latin square, as described in more detail in Section II. A Latin square is defined as an MxM table where each row and each column contains a permutation of the values {0, 1, …, M-1}. In this paper, we investigate designing survivable networks using alternative passive routing devices. First, we consider passive routers where the input/output mappings can be represented by Latin squares that are different from the standard-AWG Latin square. Second, we consider passive devices where the routing function is more arbitrary. Using these alternative routers, we show that desirable passive survivable designs can be produced that cannot be accomplished with a standard AWG having the same number of ports.

One of the goals of this paper is to demonstrate that the particular input/output mapping of the standard AWG is not necessarily the optimal mapping for a given application. Thus, component designers should consider techniques for constructing alternative devices, where more flexible mappings can be realized. Research is already underway in this direction. For example, references [6]-[9] propose techniques using planar lightwave circuit (PLC) technology for constructing alternative passive routing devices, for purposes of supporting non-uniform traffic demands and waveband-based routers.

Section II reviews the properties of AWGs and Latin squares. Section III summarizes the architecture proposed in [1]. Section IV discusses desirable properties related to protection. Section V considers designs based on Latin squares and Section VI discusses design techniques. Section VII considers designs based on more arbitrary routing patterns.

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II. AWGs AND LATIN SQUARES

The relevant routing properties of AWGs are covered in this section. For more detailed information regarding the underlying physical nature of AWGs, see [10].

Consider an AWG of size MxM (i.e., M input ports and M output ports). In a typical AWG implementation, if wavelength λ_i enters on input port j, it will exit on output port $(i+j)$ modulo M. Note that the operation is cyclic, such that wavelengths λ_{i+kM}, for $k \geq 0$, are routed in an identical manner. In each period of wavelengths, where a period is M consecutive wavelengths, there is exactly one wavelength that goes from each input port to each output port.

The routing properties of an MxM AWG can be represented by a Latin square of order M, where each row and each column contains a permutation of the values {0, 1, …, M-1}. The Latin squares corresponding to the input/output mapping of a 5x5 AWG and a 6x6 AWG are shown in Fig. 1(a) and Fig. 1(b), respectively. The rows represent the input ports and the columns represent the wavelengths (only one period of wavelengths, from 0 to M-1, is illustrated); the jth, kth table entry represents the output port when wavelength λ_k enters on input port j. For example, in Fig. 1(a), if wavelength 3 enters on input port 2, it will exit on output port 0. One could equivalently define an AWG routing matrix where the rows are the input ports, the columns are the output ports, and the jth, kth entry is the wavelength required to go from input j to output k. This routing matrix can also be represented by a Latin square. (This Latin square is said to be a conjugate of the representation of Fig. 1 because the roles of the columns and the table entries are swapped [11].) However, for ease of tracing the path of a wavelength through a network, the convention used in Fig. 1 is preferable.

Wavelengths

Input Ports	**0**	**1**	**2**	**3**	**4**
0	0	1	2	3	4
1	1	2	3	4	0
2	2	3	4	0	1
3	3	4	0	1	2
4	4	0	1	2	3

(a)

Wavelengths

Input Ports	**0**	**1**	**2**	**3**	**4**	**5**
0	0	1	2	3	4	5
1	1	2	3	4	5	0
2	2	3	4	5	0	1
3	3	4	5	0	1	2
4	4	5	0	1	2	3
5	5	0	1	2	3	4

(b)

Fig. 1 Latin square representing the routing functions of a: (a) standard 5x5 AWG and (b) standard 6x6 AWG. The table entries indicate the output ports.

The Latin squares shown in Fig. 1 are not unique. Clearly, swapping any two rows or any two columns produces a different Latin square. There are additional Latin squares that cannot be obtained by such simple transformations. For details on the relationship among the Latin squares of a given order, and the number of such Latin squares that exist, see [11]. Using the input/output mapping imposed by Latin squares other than the canonical AWG Latin square potentially produces more desirable networks, as described in Section V. We refer to any device where the routing function can be represented by a Latin square as a *Latin router* [12].

III. SURVIVABLE NETWORK OF AWGs

The passive networks described in [1] are based on a small number of AWGs that are arranged in survivable topologies with specific patterns of interconnection. Of the M input ports, A of them are designated as ingress ports; A of the M output ports are independently designated as egress ports. Each AWG has D directly connected neighbors (e.g., in a bi-directional ring topology, D equals two). C ports are used for interconnection with each neighbor, where the C fibers that run between neighbors can be deployed in the same conduit. These interconnecting fibers are referred to as the core fibers. All ports are used; thus, $M = A + C \cdot D$.

A subset of the end-users is assigned to each one of the AWGs. The details of how the users connect to the AWGs are covered in Section III.A. Any two users can communicate by establishing a connection between the respective AWGs of the two users. Furthermore, the connection can be protected such that it is not brought down by one, or possibly multiple, failures. (Other practical issues such as network control, support for multicast connections, and end-to-end loss are covered in [1] and are not repeated here.)

Figure 2(a) illustrates a bi-directional ring topology composed of four standard 6x6 AWGs, numbered 0 through 3. Each AWG has two ingress ports and two egress ports, and there are two interconnections between each pair of neighboring routers (i.e., A = 2 and C = 2). The port configuration can be represented by Table 1, where the notation of [1] is used in the table. I_i represents an ingress port, E_i represents an egress port; the X_i^{th} output port of one router is connected to the X_i^{th} input port of its X^{th} neighbor; the Y_i^{th} output port of one router is connected to the Y_i^{th} input port of its Y^{th} neighbor. The X and Y neighbor designations are as shown in Fig. 2(b).

TABLE 1. PORT CONFIGURATION CORRESPONDING TO FIG. 2(A)

Port Number	0	1	2	3	4	5
Input Ports	I_0	I_1	X_0	X_1	Y_0	Y_1
Output Ports	E_0	E_1	Y_0	X_0	Y_1	X_1

Consider launching wavelengths λ_0 through λ_5 on the two ingress ports of AWG 0 (due to the cyclic properties of AWGs, it is necessary to consider only the wavelengths in one period of wavelengths; all other periods produce the same results). Assuming the routing function follows the standard AWG input/output mapping shown in Fig. 1(b), then the resulting paths through the network are as follows (the numbers indicate the AWG number):

Launched on Ingress Port 0: λ_0: 0 – 0; λ_1: 0 – 0; λ_2: 0 – 3; λ_3: 0 – 1 – 0; λ_4: 0 – 3 – 2; λ_5: 0 – 1 – 2 – 3

Launched on Ingress Port 1: λ_0: 0 – 0; λ_1: 0 – 3 – 2 – 1; λ_2: 0 – 1 – 2; λ_3: 0 – 3 – 0; λ_4: 0 – 1; λ_5: 0 – 0

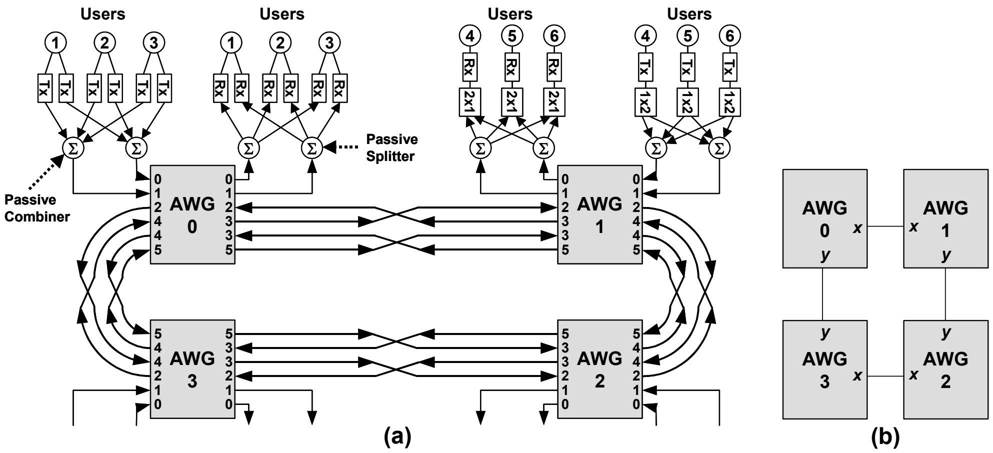


Fig. 2 (a) Bi-directional ring with four standard 6x6 AWGs. The users attached to AWGs 2 and 3 are not shown. Input and output ports on the AWGs are designated by the direction of the arrows. For example, both input port #3 and output port #3 are depicted on one side of the AWG, to simplify illustrating the interconnections between AWGs. (b) The X and Y neighbor designations.

There are two diverse paths between AWG 0 and each of the other three AWGs, such that the network is protected against a single failure to any core fiber or to any AWG (other than the source and destination AWGs). For example, paths 0-3 and 0-1-2-3 are supported between AWGs 0 and 3. Each of the AWGs is configured identically; therefore, diverse paths exist between any two AWGs. Additionally, there are paths that enter and immediately exit on the same AWG (e.g., 0-0). These paths are necessary to allow communication between two users that are attached to the same AWG.

Transmission paths that cross multiple AWGs require that the AWGs have low loss and flat, stable passbands [13], [14]. Furthermore, because of the requirement that the network be passive, the AWGs must be athermal [15]. While the references indicated here provide some measure of confidence that a small network of AWGs is feasible, experimentation is still required to demonstrate this. As noted in [1], factors such as crosstalk, dispersion, polarization, and temperature-dependence need to be investigated further. The goal of this paper is to illustrate the benefits that can be gained by using passive devices with routing patterns that are different from the standard AWG. Any such device would need to be athermal, low loss, and have good cascadability properties as well.

The minimum required AWG size (or, more generally, Latin router size) can be generalized for networks with R routers and N required diverse paths between router pairs. The M wavelengths launched on the A access ports of any router produce at most $A \bullet M$ ‘useful’ paths, where A^2 of the paths immediately terminate on the same router. The remaining ($A \bullet M - A^2$) paths must be sufficient to provide at least N diverse paths to each of the (R-1) other routers. Thus, M must be large enough to satisfy:

$$A \bullet M - A^2 \geq N(R-1)$$

or:

$$M \geq [N(R-1) + A^2] / \mathrm{A}$$

In practice, M may need to be larger than the minimum, due to a particular arrangement producing non-useful paths that pass through the same router multiple times.

A. User Architectures

Each end-user is connected to the ingress and egress ports of one of the AWGs. In Fig. 2(a), Users 1 through 3 are assigned to AWG 0, whereas Users 4 through 6 are assigned to AWG 1. (To simplify the figure, the users attached to the other two AWGs are not shown.) As described in [1], there are various means of connecting the users to their respective AWGs. For example, in the figure, the users attached to AWG 0 are each equipped with two transmitters and two receivers. One transmitter from each of the users feeds into a passive combiner, forming a local area network (LAN). This transmit LAN feeds into the first ingress port on AWG 0. Similarly, the first egress port of AWG 0 feeds into a passive splitter, forming a receive LAN. The receive LAN feeds one receiver of each of the users. The second transmitter and receiver of each user form a second transmit LAN and receive LAN, which are connected to the second ingress and egress ports of the AWG, respectively. In order to establish a desired connection, the transmitter and receiver on the corresponding ingress port and egress port of the source and destination are turned on and tuned to the proper wavelength.

The users attached to AWG 1 are equipped with a single transmitter and receiver. Each user has an active 1x2 switch to allow its transmitter to access either of the transmit LANs, and an active 2x1 switch to allow its receiver to access either of the receive LANs. It is assumed that power is available at the user locations, such that active switches are permitted at the network edge. This arrangement is lower cost than equipping each user with two transmitters and receivers. However, it supports fewer protection options; e.g., 1+1 protection cannot be supported.

In either user configuration, a particular wavelength on an ingress or egress port can be used by at most one user at a time. If additional wavelengths are needed to support the desired level of traffic, then additional wavelength periods of the AWGs must be used.

The fibers that are used to connect the users to their respective AWGs are referred to here as the access fibers.

IV. DESIRABLE NETWORK PROPERTIES

This section enumerates several properties that may be desirable when designing a survivable network. In the next section, it is shown that non-standard Latin routers can potentially support a greater number of these properties than can be supported by a corresponding standard AWG.

A. Support for 1+N Protection

With 1+N protection, there are (N+1) diverse paths established between the source and destination, such that the connection is protected against *N* concurrent failures. No switching is required in order to recover from a failure; the destination simply chooses the best of the N+1 signals it receives. In order to support 1+N protection with the architecture described here, the users must be equipped with (N+1) transmitters and receivers, and the diverse paths must originate on diverse ingress ports and terminate on diverse egress ports.

The focus here is initially on 1+1 protection, providing protection against a single failure. Note that the configuration of Fig. 2(a) does not support 1+1 protection even though it provides diverse paths between any two AWGs. For example, as enumerated in Section III, the two paths between AWGs 0 and 3 both originate on ingress port 0 of AWG 0. Given that only one transmitter of an end-user is connected to a given ingress port, this would prevent both paths from being simultaneously established.

B. Support for 1:N Protection without Switching

Users with a single transmitter/receiver can employ 1:N protection, where a protect path is established after the current path fails. As shown by the users attached to AWG 1 in Fig. 2(a), if the protect path originates on a different ingress port than the primary path does, then the 1x2 switch must be activated to move the transmitter to the other ingress port (a similar operation occurs if the primary and protect paths exit on different egress ports). If the 1x2 switch is slow to reconfigure, then the delay in the restoration process may be unacceptably long. Thus, it would be desirable to have an architecture where, for a given source and destination, both the primary and protect paths originate on the same ingress ports and terminate on the same egress ports. This eliminates the need to reconfigure a switch at the time of a failure, and only requires that the transmitter and receiver be retuned to select the protect path.

C. Support for Unprotected Connections with a Single Ingress Port and Single Egress Port

Some users may not require protected connections. It is desirable that such users be equipped with a single transmitter and receiver, and that no 1x2 or 2x1 switch be required. Thus, the user must be able to access each of the other AWGs by being connected to a single ingress port and a single egress port. Communication with users on different AWGs is accomplished by retuning the transmitter and receiver.

D. Multiple Path Sets in a Wavelength Period

Assume that the distribution of end-users and connection load is such that *P* protected connections may need to be simultaneously supported between any two AWGs. Furthermore, assume that each period of *M* wavelengths produces *Q* protected paths between each pair of *M*x*M* AWGs. (For example, the network of Fig. 2 produces one such set of paths.) Then the number of wavelength periods required to satisfy the offered load is $\lceil P/Q \rceil$, and the total number of required wavelengths is $\lceil P/Q \rceil \cdot M$. It is desirable to minimize the number of required wavelengths such that coarser (and lower cost) wavelength spacing can be used. Thus, architectures that produce multiple protected path sets per period are generally desirable (assuming the required *M* is not excessively large).

V. DESIGNS BASED ON LATIN ROUTERS

We start this section with a small example to demonstrate that non-standard Latin routers can produce results that are not attainable with a similarly sized standard AWG. The network shown in Fig. 3 is composed of three routers arranged in a unidirectional ring pattern. (The end-users are not shown in the figure.) Each router has one ingress port, one egress port, and four ports to connect to the adjacent router. Assume that the routing function is represented by the 5x5 Latin square shown in Fig. 4. This Latin square is different from the standard 5x5 AWG Latin square shown in Fig. 1(a). (One cannot use simple transformations to move between these two Latin squares. These two squares are said to belong to different *main classes*, and in fact, represent the only two main classes of 5x5 Latin squares [11].)

With the arrangement of routers shown in Fig. 3 and using the routing matrix of Fig. 4, the following paths are produced starting with router 0:

λ_0: 0 – 0; λ_1: 0 – 1– 2; λ_2: 0 – 1; λ_3: 0 – 1; λ_4: 0 – 1 – 2

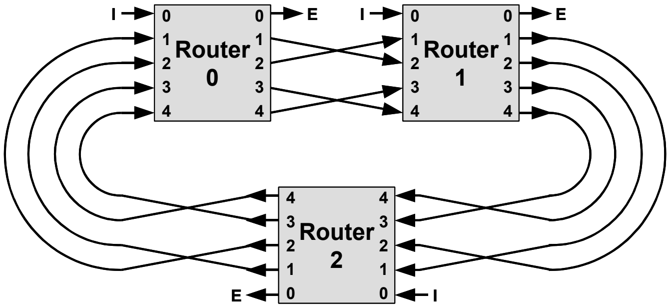


Fig. 3 Unidirectional ring with three routers. The routing function is assumed to be as shown in Fig. 4.

	Wavelengths				
Input Ports	**0**	**1**	**2**	**3**	**4**
0	0	1	2	3	4
1	1	3	0	4	2
2	2	4	3	1	0
3	3	0	4	2	1
4	4	2	1	0	3

Fig. 4 Input/output mapping of one non-standard 5x5 Latin router. The table entries indicate the output ports.

Thus, one period of wavelengths produces two identical paths to each of the other two routers, and one path that starts and ends on the same router. Again, because all routers have an identical configuration, the paths originating on the other routers have a similar pattern.

It can be shown that the above results cannot be obtained with any possible arrangement of ingress ports, egress ports, and interconnections between standard AWGs, even if each AWG is configured independently of the others. This demonstrates that different Latin routers can produce fundamentally different results.

A. Bi-directional Ring with Four Latin Routers

Reference [1] looked at several architectures for a four-AWG bi-directional ring that could provide protection against any single failure. AWGs up to size 10x10 were considered, where the AWGs were configured with two ingress ports and two egress ports. In all of the architectures considered, the four AWGs were uniformly configured. Various configurations were found that could satisfy a subset of the properties outlined in Section IV. However, none of the configurations satisfied more than three of the properties. (For an example of a design based on 8x8 AWGs that satisfies three of the properties, see [16].)

Wavelengths

Input Ports	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**
0	0	1	2	3	4	5	6	7
1	1	4	6	0	7	2	5	3
2	2	3	7	6	5	4	1	0
3	3	6	4	5	0	1	7	2
4	4	5	0	1	2	7	3	6
5	5	2	1	7	6	3	0	4
6	6	7	3	2	1	0	4	5
7	7	0	5	4	3	6	2	1

Fig. 5 Input/output mapping of one non-standard 8x8 Latin router. The table entries indicate the output ports.

TABLE 2. PORT CONFIGURATION OF THE NON-STANDARD 8X8 LATIN ROUTER

Port Number	0	1	2	3	4	5	6	7
Input Ports	I_0	I_1	X_2	X_0	Y_1	Y_2	Y_0	X_1
Output Ports	E_0	X_0	X_1	E_1	Y_0	Y_1	Y_2	X_2

TABLE 3. PATHS ORIGINATING ON ROUTER 0 PRODUCED BY RING OF FOUR NON-STANDARD 8X8 LATIN ROUTERS

Path	**Ingress/Egress**	**Path**	**Ingress/Egress**
0-1	0/0(7), 1/1(0)	0-3-2-1	0/0(5), 1/1(2)
0-1-2	0/0(2), 1/1(5)	0-3-2	0/0(4), 1/1(1)
0-3	0/0(6), 1/1(6)	0-1-2-3	0/0(1), 1/1(4)
0-0	0/0(0), 0/1(3), 1/0(3), 1/1(7)		

It is possible, however, to meet all four desired properties using a bi-directional ring of four, uniformly configured, non-standard 8x8 Latin routers. Approximately 5% of the non-standard Latin routers considered produced the desired results (each of the routers considered represented a different main class). One such non-standard Latin router representation is shown in Fig. 5. For this particular Latin router, the desired port configuration is shown in Table 2.

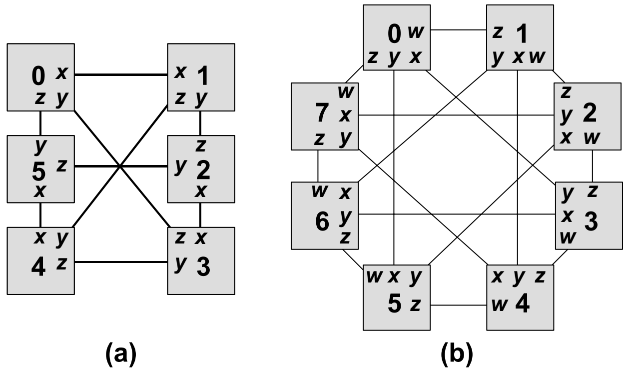
The resulting paths originating on Router 0 in one period of wavelengths are shown in Table 3. The notation *i/e(w)* indicates the ingress port, the egress port, and the wavelength that produces the particular path. Two sets of diverse paths are produced in each period. 1+1 protection can be provided; i.e., one diverse path uses ingress port 0 and egress port 0, and the other diverse path uses ingress port 1 and egress port 1. For 1:1 protection without switching, both diverse paths can be obtained using ingress port 0 and egress port 0, or using ingress port 1 and egress port 1. All unprotected users can communicate with each other if they connect, for example, to ingress port 0 and egress port 0. Thus, this design using an 8x8 non-standard Latin router is better than any of the designs produced using standard uniformly-configured AWGs, up to size 10x10.

B. 3,3 Bipartite Architecture

Another survivable topology is six nodes connected in a 3,3-bipartite arrangement, as shown in Fig. 6(a). Such a topology provides protection against any two link or node failures. In [1], a 3,3-bipartite design was provided that supports 1+2 protection. The design was realized using standard 12x12 AWGs with three ingress and egress ports. A 1+2 protected design with a 3,3-bipartite topology was not found with AWGs smaller than 12x12 (only scenarios where the AWGs were uniformly configured were considered).

However, a 1+2 design can be realized using non-standard 9x9 Latin routers arranged in a 3,3-bipartite topology. One particular Latin square that produced this design is shown in Fig. 7. The port configuration is shown in Table 4, where the designations of the *X*, *Y*, and *Z* neighbors are shown in Fig. 6(a). The resulting paths, originating at Router 0, are shown in Table 5. Three-way diversity is provided in both the access and core fibers.

Achieving a design with a smaller router is desirable because the router size affects the number of wavelengths that need to be supported on a fiber. Assume that the traffic load is such that it is necessary to support up to four concurrent connections between any two routers. With the 9x9 Latin router design, a total of 36 wavelengths are required, which can be satisfied with standard 100-GHz wavelength spacing in the C-band. With the 12x12 AWG design, 48 wavelengths are required, which requires closer wavelength spacing and is thus less desirable. Additionally, less fiber is required with the 9x9 router design because there are only two fibers interconnecting each neighboring router as opposed to three interconnecting fibers with the 12x12 AWG design.



(a) **(b)**

Fig. 6 (a) 3,3-bipartite topology. (b) 4,4-bipartite topology.

Wavelengths

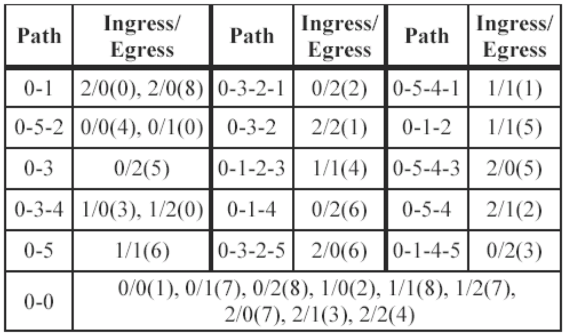
Input Ports	0	1	2	3	4	5	6	7	8
0	1	3	7	2	8	0	6	4	5
1	0	8	3	7	2	6	1	5	4
2	2	7	8	4	5	1	0	3	6
3	3	5	4	1	0	8	7	6	2
4	8	1	5	6	3	2	4	7	0
5	7	4	0	3	6	5	2	8	1
6	5	2	6	0	7	4	3	1	8
7	4	6	2	8	1	3	5	0	7
8	6	0	1	5	4	7	8	2	3

Fig. 7 Input/output mapping of one non-standard 9x9 Latin router. The table entries indicate the output ports.

TABLE 4. PORT CONFIGURATION OF THE NON-STANDARD 9X9 LATIN ROUTER

Port Number	0	1	2	3	4	5	6	7	8
Input Ports	I_0	I_1	I_2	X_0	Z_0	Y_0	Y_1	Z_1	X_1
Output Ports	Y_0	Z_0	X_0	E_0	E_1	E_2	X_1	Y_1	Z_1

TABLE 5. PATHS ORIGINATING ON ROUTER 0 PRODUCED BY A 3,3-BIPARTITE ARRANGEMENT OF NON-STANDARD 9X9 LATIN ROUTERS



Path	Ingress/ Egress	Path	Ingress/ Egress	Path	Ingress/ Egress
0-1	2/0(0), 2/0(8)	0-3-2-1	0/2(2)	0-5-4-1	1/1(1)
0-5-2	0/0(4), 0/1(0)	0-3-2	2/2(1)	0-1-2	1/1(5)
0-3	0/2(5)	0-1-2-3	1/1(4)	0-5-4-3	2/0(5)
0-3-4	1/0(3), 1/2(0)	0-1-4	0/2(6)	0-5-4	2/1(2)
0-5	1/1(6)	0-3-2-5	2/0(6)	0-1-4-5	0/2(3)
0-0	0/0(1), 0/1(7), 0/2(8), 1/0(2), 1/1(8), 1/2(7), 2/0(7), 2/1(3), 2/2(4)				

VI. EVALUATING POSSIBLE CONFIGURATIONS

In searching for a router configuration that yields a particular set of paths, there are clearly a number of possible port assignments. Any *A* of the *M* input and output ports can be selected for ingress and egress, respectively. Each non-egress output port of a particular router can possibly be connected to any of the non-ingress input ports of any of its neighboring routers. If all routers are configured uniformly, then the number of possible configurations is:

$$\binom{M}{A}^2 (M-A)!\binom{M-A}{C}\binom{M-A-C}{C}\cdots\binom{M-A-(D-1)C}{C}$$

The first term represents the possible assignments of the ingress and egress ports. The second term represents the possible output-port/input-port pairings, where there are (*M-A*) input and output ports that are not designated for ingress and egress. The remaining terms represent the possible ways to partition the ports into *D* groups of size *C*, with each group representing the *C* interconnections with one of the *D* neighbors. The above equation simplifies to:

$$\left[\frac{M!}{A!}\right]^2\left[\frac{1}{C!}\right]^D$$

As the number of router ports increases, the number of possible configurations may become too large for exhaustive search. However, one can use various methods to reduce the search space. First, assume that the router is a standard AWG, such that the rows and columns of the associated Latin square are all shifted versions of the same pattern. Then, if each of the input port assignments is rotated up by α positions (i.e., the assignment of port *j* becomes the assignment of port $j\oplus\alpha$, where $\oplus$ represents modulo *M* addition), the resulting network paths are the same. Similarly, the assignments of the output ports can be *independently* rotated by β positions and still produce the same paths. If a set of assignments is equivalent when rotated, then only one representative configuration from that set needs to be considered.

Another reduction method, which holds for any router, is based on the observation that it is possible to evaluate whether a particular interconnection pattern is capable of producing the desired paths by considering just the output-port/input-port pairings, without designating which neighboring routers are actually involved in the pairing. Consider a 6x6 router where the first two input ports are used for ingress and the first two output ports are used for egress. Assume the network topology is a bi-directional ring with two interconnections between each neighbor (similar to Fig. 2(a)). There are 24 possible configurations of output-port/input-port pairings. For any configuration, consider implementing the output/input pairings on a single router. This is shown in Fig. 8 for one of the possible 24 configurations. Next, consider launching the six wavelengths on the two ingress ports. One can trace the number of times each wavelength passes through the router before it exits on an egress port. This determines the lengths of the paths that are yielded by this interconnection pattern, regardless of the designation of neighbors (because of the assumption that all routers are uniformly configured). From this information, it can be determined whether the interconnection pattern could possibly produce the desired path set. If it can, then the various neighbor assignment possibilities need to be considered. If it cannot, then there is no need to consider the configuration further. As the router size increases, and the desired path sets become more complex, the percentage of the interconnection patterns that are potentially suitable is typically less than 0.1%, which appreciably reduces the design space to explore.

Tracing the paths of the six wavelengths launched on the two ingress ports of Fig. 8, and assuming the router is a standard AWG, yields the following path lengths (ignoring the wavelengths that immediately exit): one path of length one hop, four paths of length two hops, and three paths of length three hops (each transition from an output port to an input port is considered a hop). If the desired result is a diverse pair of paths between every router, then the result must have at least two paths of length one hop, two paths of length two hops, and two paths of length three hops (i.e., 0-1, 0-3, 0-1-2, 0-3-2, 0-1-2-3, 0-3-2-1). The interconnect pattern of Fig. 8 does not satisfy this requirement because it has only one path of length one hop; thus, it does not need to be considered further. (Of course, if the interconnection pattern that was utilized in Fig. 2(a) is implemented on a single router, then it does produce the desired path lengths.)

The design process can take advantage of other symmetries that depend upon the particular topology to reduce the search space further.

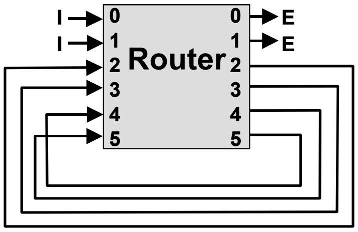


Fig. 8 Output-port/input-port mappings implemented on a single router to test the lengths of the resulting paths.

VII. DESIGNS BASED ON ARBITRARY ROUTERS

If more degrees of freedom are allowed in the architecture, then additional designs can be found. In this section, we consider routers with arbitrary input/output mappings. This added flexibility simplifies the design process. The desired paths are routed and assigned to wavelengths using a standard network planning tool. From the network design, the required input/output mapping can be determined. In general, such a method produces a design with different mappings at each node. One can add further constraints to obtain a uniform routing pattern at each node.

This procedure was used to design a variety of topologies. Here, we focus on the 4,4-bipartite topology, since that topology has not been previously investigated using either standard AWGs or general Latin routers. This topology, comprised of eight routers as shown in Fig. 6(b), provides protection against any three concurrent link or node failures; i.e., there are four diverse paths between any pair of routers.

To achieve this design, 12x12 routers were used, each with four ingress and egress ports. The interconnection pattern is shown in Table 6, where the *W*, *X*, *Y*, and *Z* neighbor designations are indicated in Fig. 6(b). The paths were routed such that diversity on the access fibers was provided as well. Thus, 1+3 protection is supported with the design. (In the interest of space, the paths that were produced are not shown.)

The design was performed such that each router utilized the same mapping. One router input/output mapping that produced the desired paths is shown in Fig. 9. (The mapping is generated by the network design tool, which determines how each wavelength is routed through a node. The search technique of Section VI is not needed.) Entries marked by a dash indicate that the combination of input port and wavelength represented by that entry is not relevant in achieving the desired design. Clearly, this mapping is not a Latin square, as the same entry can appear multiple times in a row.

TABLE 6. PORT CONFIGURATION OF THE NON-STANDARD 12X12 ROUTER USED IN THE TOPOLOGY OF FIG. 6(B)

Port Number	0	1	2	3	4	5	6	7	8	9	10	11
Input Ports	I_0	I_1	I_2	I_3	W_0	W_1	X_0	X_1	Y_0	Y_1	Z_0	Z_1
Output Ports	E_0	E_1	E_2	E_3	W_0	W_1	X_0	X_1	Y_0	Y_1	Z_0	Z_1

Wavelengths

Input Ports	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**
0	5	4	5	7	9	11	11	9	4	5	5	0
1	6	1	-	10	5	-	-	7	7	6	-	5
2	2	8	4	-	7	8	7	-	-	9	9	-
3	9	11	10	3	11	10	5	8	6	10	11	8
4	3	5	8	-	8	-	6	3	5	1	2	1
5	0	0	7	-	4	-	3	4	0	7	8	6
6	10	-	3	-	10	7	2	1	3	4	-	4
7	-	3	0	0	6	3	4	6	11	0	-	-
8	4	10	9	11	1	9	-	5	-	3	0	3
9	8	2	2	-	0	2	-	11	-	11	4	-
10	11	9	11	8	2	6	0	-	-	8	3	-
11	1	7	6	1	3	0	10	0	1	2	10	-

Fig. 9 Input/output mapping of the arbitrary routing device used in the 4,4-bipartite design. The table entries indicate the output ports.

One of the drawbacks of designs based on Latin routers is that the number of paths that originate and immediately terminate on a particular router is A^2, where A is the number of ingress and egress ports. While a small number of such paths are required to accommodate the traffic between end-users that are attached to the same router, the number of these paths can become excessive as A increases. With arbitrary routing devices, the number of such paths can be controlled. For the 4,4–bipartite design, the number of paths starting and ending on any particular router was limited to four. This allows other more ‘useful’ paths to be supported. In the design that was performed, in each period of wavelengths, one set of unprotected paths was provided in addition to the set of 1+3 protected paths (i.e., a total of at least five paths were supported between any two routers). Note that such a path set is not possible with a 12x12 Latin router with A equal to 4, because 16 of the 48 paths originating on each router would exit on that same router (48 paths originate from each router due to 12 wavelengths being launched on each of the four ingress ports). The remaining 32 paths are not sufficient to allow for five paths from a router to each of the other seven routers.

To construct an arbitrary router, one can imagine a device with latching switches that is capable of any routing pattern.

Power could be supplied to the device in order to configure it to have the desired input/output mapping; this mapping would then remain after power is removed, such that the desired passive router is realized.

VIII. CONCLUSIONS

Survivable passive networks can be constructed from a small number of distributed passive routing devices. It was illustrated here that for a router with a given number of ports, non-AWG Latin routers are in some instances capable of producing designs with more useful properties. Furthermore, with complete freedom in selecting the routing matrix of the passive device, networks with even greater survivability can be designed with reasonably sized routers. In this paper, protection against up to three concurrent failures was considered.

This illustrates some of the benefits that can be gained by expanding design processes to passive routing devices other than the standard AWG. The greater routing flexibility would likely be beneficial in other passive applications as well.

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