AWGR-based All-to-all Optical Interconnects using Limited Number of Wavelengths

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***Abstract*—This paper discusses all-to-all interconnections for N nodes using W wavelengths and arrayed waveguide grating routers (AWGRs). This scheme allows for reducing the optical wiring by a factor of $W(N$-1)/2N and isolating the crosstalk.**

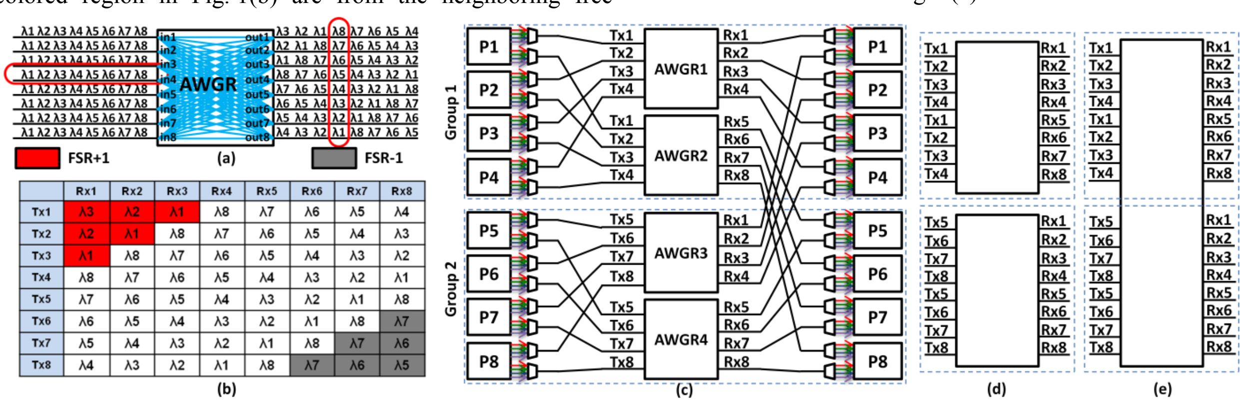
***Index Terms*—Datacenter Networking, Optical Interconnects, All-to-all Communication, AWGR.**

I. Introduction

All-to-all connections, in which every processor sends a unique message to any other processor at any time, is the densest communication pattern that can be imposed on a computing network [1]. However, all-to-all connections are rarely deployed in large scale due to its poor scalability in terms of interconnection wiring. Specifically, in an N-node network, all-to-all connections require a total of $N(N$-1) electrical wires. Wavelength division multiplexing (WDM) technology allows for the frequency domain parallelism. Meanwhile, arrayed waveguide grating router (AWGR) allows for the multiplexed wavelengths in the waveguides being separated and cross-connected. Therefore, it can possibly reduce the $O(N^2)$ wiring complexity to $O(N)$. As shown in Figs. 1(a)(b), N nodes (N=8 in this example) respectively connected to the N input ports of an AWGR can use N wavelengths to reach different output ports simultaneously without interfering with each other. The uniform-loss cyclic-frequency (ULCF) [4] feature of an AWGR guarantees the same set of N wavelengths can be used at each input port, knowing that the wavelengths in the colored region in Fig. 1(b) are from the neighboring free spectrum range (FSR). Therefore, the shuffling of the $O(N^2)$ "optical wires" is confined to a single AWGR (Fig. 1(a)). However, despite the intrinsic merit of dense interconnection in AWGRs, their port count is usually restricted by the size, the fabrication constraints and the inter-channel crosstalk. The difficulties arise mainly from the required critical control on the channel spacing in fabrication as well as accurate wavelength registration for all channels after fabrication [2]. Moreover, in an $N×N$ single AWGR system, the signal-crosstalk beat noises accumulate among the N-1 components [3], which also limit N from being large. Therefore, the need arises for an all-to-all interconnection architecture using AWGRs with limited number of wavelengths. This paper proposes such an interconnection architecture and analyzes the methods for constructing it. The benefits of optical wiring savings and crosstalk reductions are analyzed in detail. The performance improvement using such interconnection architectures is verified by simulation based benchmarking.

II. AWGR All-to-all Interconnects using Limited Number of Wavelengths

The most favorable conditions result from reducing the port count of the AWGR and using smaller number of wavelengths to fulfill the all-to-all connection requirement in a large system. Figs. 1(c)-(e) show such a design in an example of an 8×8 interconnection system. In this example, the number of wavelengths used is reduced from 8 to 4. There are three approaches, including: Fig. 1(c) four 4x4 AWGRs; Fig. 1(d) two 8×8 AWGRs and Fig. 1(e) one 16×16 AWGR for the



	Rx1	Rx2	Rx3	Rx4	Rx5	Rx6	Rx7	Rx8
Tx1	λ3	λ2	λ1	λ8	λ7	λ6	λ5	λ4
Tx2	λ2	λ1	λ8	λ7	λ6	λ5	λ4	λ3
Tx3	λ1	λ8	λ7	λ6	λ5	λ4	λ3	λ2
Tx4	λ8	λ7	λ6	λ5	λ4	λ3	λ2	λ1
Tx5	λ7	λ6	λ5	λ4	λ3	λ2	λ1	λ8
Tx6	λ6	λ5	λ4	λ3	λ2	λ1	λ8	λ7
Tx7	λ5	λ4	λ3	λ2	λ1	λ8	λ7	λ6
Tx8	λ4	λ3	λ2	λ1	λ8	λ7	λ6	λ5

Figure 1. The (a) routing property and (b) routing table of an 8×8 AWGR, the all-to-all connection using 4 wavelengths and (c) four 4×4 AWGRs,(d) two 8×8 AWGRs, (e) one 16×16 AWGR.

all-to-all interconnection. The transmitters for each processor consist of two groups of four fixed lambda lasers, and each group is connected to a separate AWGR input port using a distinguished waveguide.

In a more general case, an N x N all-to-all interconnection system with W ($W < N$) wavelengths requires one of three configurations if N is integer times larger than W:

$$\begin{cases} N^2/W^2 \text{ of } W \times W \text{ AWGRs} & (1) \\ N/W \text{ of } N \times N \text{ AWGRs} & (2) \\ 1 \text{ of } (N^2/W) \times (N^2/W) \text{ AWGR} & (3) \end{cases}$$

Note that a factor of N/W reduction in the number of wavelengths increases the total number of ports in AWGRs by a factor of N/W in return. Eventually, in an $N\times N$ all-to-all system with W wavelengths, a total number of N^2/W ports are required, which can be implemented with either a big AWGR with N^2/W ports or multiple AWGRs with N^2/W total ports.

Table I

	Directly connect	AWGR N WLs	Solution 1	Solution 2	Solution 3
# of nodes	N	N	N	N	N
# of Tx/Rx	N^2	N^2	N^2	N^2	N^2
# of WLs	1	N	W	W	W
AWGR port cnt.	N/A	N	W	N	N^2/W
# of AWGRs	N/A	1	N^2/W^2	N/W	1
# of cross talk components	N/A	N-1	W-1	N-1	N^2/W-1
Total fibers	$N(N$-1)	$2N$	$2N^2/W$	$2N^2/W$	$2N^2/W$
Total I/O ports	N/A	N	N^2/W	N^2/W	N^2/W

Table I summarizes the parameters needed for the different configurations to the all-to-all AWGR interconnection. Note that, the AWGR based interconnection architecture cannot save the N^2 transceivers, but rather saves the optical wiring and isolates the inter-channel crosstalk. As shown in Table I, the number of crosstalk components can be reduced from N-1 to W-1 in approach one. The number of optical wires is determined by the number of total connected ports on the AWGRs, which is N^2/W. Therefore, compared with the $N(N$-1) wires using direct connection, the use of W wavelengths in parallel allows for reducing the optical wiring by a factor of $W(N$-1)/2N no matter which configuration is chosen.

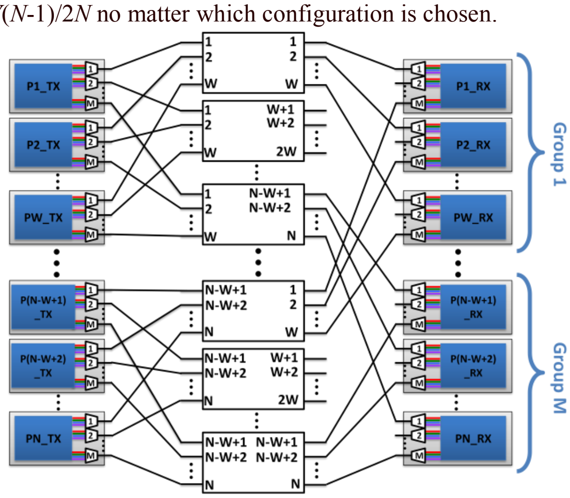


Figure 2. Numbering of the AWGRs' input/output ports

The connection rules for the input ports and the output ports are asymmetric, as shown in Fig. 2. Given N nodes and W wavelengths, the transceivers for each node can be divided into M banks (let $M=N/W$). The AWGRs can be divided into M groups as well, each group containing N total ports (one group can be M $W\times W$ AWGRs, one $N\times N$ AWGR, or N ports of an $NM\times NM$ AWGR). For each connection on the Tx side, the W transmitters in bank j ($1\le j\le M$) of node k ($1\le k\le N$) are connected to the j^{th} input port k in the same group. However, the W receivers in bank j ($1\le j\le M$) of node k ($1\le k\le N$) are connected to the output port k of the AWGR group j. The input ports of the AWGRs are numbered the same as the W nodes in the same group, and are repeated M times in one group, while the output ports of the AWGRs are numbered repetitively from 1 to N for all the M groups. Note that the numbering rules apply in all three configurations.

III. Benchmarking Evaluations

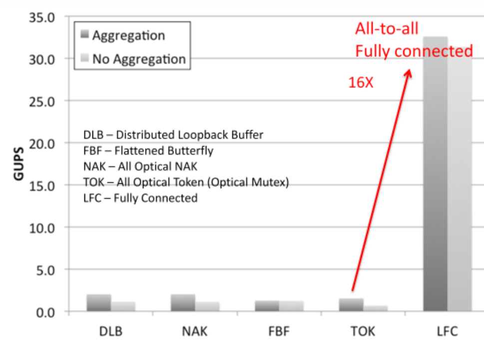


Figure 3. GUPS benchmarking for different interconnects

Figure 3 shows the comparison between the performance of an AWGR based all-to-all fully connected network, that of the AWGR based LIONS switch with three variations [5, 6] (the distributed loopback buffers, the all optical negative acknowledgement (NAC) and the all optical token (TOK)), and that of the electrical flattened butterfly (FBF) [7] switching networks. The giga-updates per second (GUPS) benchmarking [8] for the five networks simulated a 64 node shared memory system. The updates were of 64-bit data values and 1024 outstanding requests were allowed per node. The simulations were run allowing for requests to be aggregated into larger packets and not aggregated. As shown in Fig. 3, the AWGR based all-to-all interconnection results in a 16-fold increase and approaches the theoretical maximum GUPS.

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