# Energy-efficient Optical Broadcast for Nanophotonic Networks-on-Chip

Cheng Li, Mark Browning, Paul V. Gratz and Samuel Palermo

Department of Electrical and Computer Engineering, Texas A&M University
{seulc,mabrowning,pgratz}@tamu.edu, spalermo@mail.ece.tamu.edu

***Abstract*—Broadcast packets are a significant fraction of network-on-chip traffic. Nanophotonics can improve performance for this type of traffic. We present an efficient implementation of broadcast in nanophotonic networks and show it improves performance significantly.**

***Index Terms*—Nanophotonic, NoC, Broadcast Packets**

## I. Introduction

Process technology trends have led to the proliferation of Chip-Multiprocessor (CMP) systems in the pursuit of scalable, power-efficient performance. As CMP systems scale, however, the communication between processor cores becomes critical to the performance of the system as a whole, leading to networks-on-chip (NoCs) as an alternative to traditional bus-based architectures [1]. A CMP is typical organized as a set of $N$ cores, with per-core, lower-level, private caches, interconnected via an NoC to a large shared, last-level cache (LLC). As a result, NoC traffic is typically composed of lower-level cache spills and fills to the LLC, and coherence system traffic to ensure that the lower-level, private caches remain consistent and coherent with each other. Although small, bus-connected, CMPs often use simple, snooping cache coherence systems, snooping's requirement of broadcast messages to multiple listeners for each transaction doesn't practically scale to larger NoC connected CMPs because broadcast requires packet replication, leading to exponential growth in bandwidth utilization as the CMP scales, or requires significant microarchitectural hardware overhead [2]. Nanophotonic-based NoCs composed of ring resonator modulators and filters provide a more natural fit for implementing a broadcast distribution of data, given a mechanism for multiple nodes on a given waveguide to simultaneously listen in on particular packets. In this paper we present a design for limited broadcast (multicast) in Photonic NoCs, and show how it improves performance on workloads with a sub-set of broadcast packets.

Typically, ring filters are tuned to resonate matching a particular source laser wavelength, thereby diverting a maximum amount of photonic energy to the drop port photodetector. This ensures that the optical-electrical interface is as efficient as possible. The side effect of this approach, however, is that very little photonic energy in that wavelength continues on in the waveguide after the tuned ring filter, making broadcast impossible. To enable photonic broadcast, we propose to partially de-tune the ring filters, such that a significant portion of the photonic energy continues on in the waveguide to be absorbed in subsequent filters. To avoid increased bit error rates (BER), we propose a novel receiver design consisting of a ring filter with tunable extinction ratio and a tunable gain-bandwidth transimpedance amplifier (TIA). This tunable gain-bandwidth TIA increases gain and sensitivity for broadcast packets, while maintaining power efficient reception for point-to-point communication. While this design does reduce the power-efficiency of the receiver when receiving broadcast packets and requires a higher laser power, we show that it significantly increases overall system performance. Furthermore, the increased power consumption remains significantly below the power consumption required by a similar electrical interconnect-based solution.

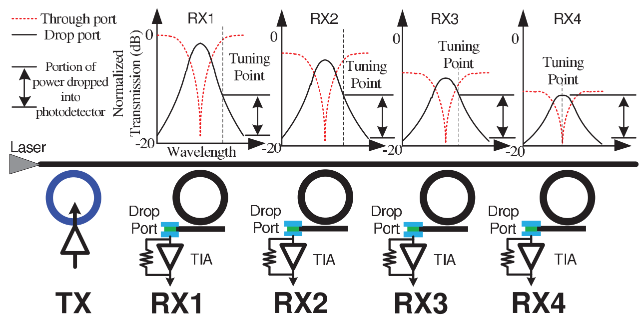


Fig. 1: A 4-node photonic broadcast example. Each ring filter is tuned to designated extinction ratio to ensure equal optical power absorption at waveguide photodetectors

## II. Design Description

Figure 1 shows an example of photonic broadcast with 4 optical ring filters at the receiver side diverting the optical power from the straight waveguide to a drop port for absorption by a waveguide photodetector [4]. In conventional point-to-point optical transmission, a ring filter is tuned to resonate at the source laser wavelength, ensuring the maximum optical power is conveyed to the filter drop port, and achieving the best power efficiency. To implement optical multicast, however, we propose a tuning circuit to tune each ring filter at different resonant wavelngths according to their distance from the transmitting ring modulator, guaranteeing equal optical power is received by the waveguide photodetector. During startup calibration, using the example in Figure 1, the drop port output of the first receiver (RX1) is tuned to the lowest operating point for a given BER in order to ensure a significant portion of the photonic energy continues on in the waveguide to be absorbed in subsequent ring receivers. The last receiver (RX4) is tuned to exactly match the source laser wavelength. In principle, this tuning process guarantee that all the broadcast targets receive equal amount of optical power, thus simplifying the receiver circuit design.

Figure 3 shows the schematic of a potential control loop used to tune a ring filter to the designated operating point. A local monitor circuit is employed to compare the incident optical power with a tunable reference level. The digital control logic takes the comparison result and utilizes thermal tuning as a coarse resonant wavelength control, while a voltage bias DAC finely adjusts the resonator to drop the desired amount of optical power.

To provide reliable data reception under a number of broadcast nodes, a transimpedance amplifier (TIA) with a tunable gain-bandwidth (Figure 2) is proposed and simulated in a 65nm CMOS process. The TIA is based on a common-source architecture with resistive shunt feedback, with the switches implemented as NMOS transistors. As the number of broadcast nodes scales up, the transimpedance gain is increased while maintaining a relatively low noise level to achieve higher receiver sensitivity. TIA bandwidth is also optimized to achieve the best electrical receiver power efficiency at a given broadcast condition.

The optical power loss components used to estimate the photonic

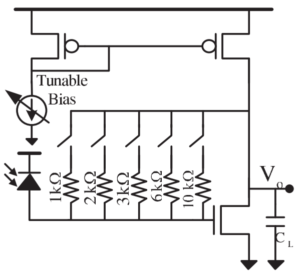


Fig. 2: CMOS switch-gain TIA with integrated waveguide photodetector

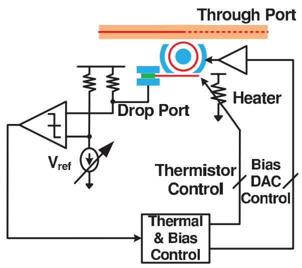


Fig. 3: Ring filter tuning loop based on dual thermal and bias control

| Loss Component | Value | Loss Component | Value |
|---|---|---|---|
| Modulator Insertion | 0.001 dB | Filter Drop | 1.2 dB |
| Waveguide | 1.5 dB/cm | Ring Through | 0.001 dB |
| Photodetector | 0.1 dB | | |

TABLE I: Components of optical loss.

link power budget are listed in Table I [3, 5]. The optical power required for the photonic broadcast is determined by the overall optical power loss in the photonic link, number of broadcast nodes and receiver sensitivity.

Table II lists the configurations of different optical transmission modes under the constraint that the optical power be no more than 3.5× larger than optical power of the design without broadcasting. Therefore, higher receiver sensitivity is required for larger number of broadcast nodes. Note that receiver sensitivity trades off with the bandwidth in a given process. In a 65nm CMOS process, TIA circuit bandwidth is maintained at 10Gbps for up to 3 node multicast, but drops to half for 4- or 5-node multicast. We expect the TIA circuit bandwidth to improve in a more advanced CMOS processes (e.g. 22nm) and support higher multicast levels for a fixed data rate.

## III. Evaluation

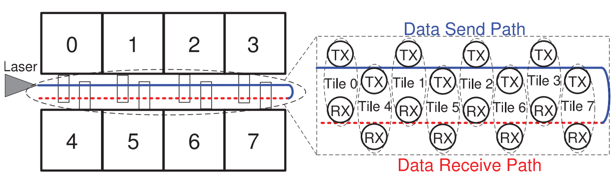


Fig. 4: 8 Node Photonic Network Topology

**Methodology:** To evaluate our multicast design, we model simple, 8-node photonic NoC, shown in Figure 4. This NoC utilizes collision detecting arbitration with exponential back-off. We modified a cycle accurate network simulator to evaluate the photonic network with and without multicast. Simulations were run for 50000 packets. The workload consists of uniform random traffic with bimodal message sizes of 64- and 512-bits to simulate typical CMP NoC traffic. A defined fraction of the 64-bit packets were chosen as multicast packets destined to 2-7 randomly chosen destinations, representing cache coherent multicast packets. In the baseline design, all multicast packets must be sent as a sequence of point-to-point packets. In our multicast design, multicasts of 2-6 destinations are sent as a single packet, multicasts of 7 destinations are split into two packets, one multicast of 3 destinations and one of 4.

**Experimental Evaluation:** Figure 5 shows the load-latency performance comparison between the multicast enabled architecture and a baseline which must serialize and duplicate packets to each destination. Results are shown for 10% and 15% of small packets

| Optical Transmission Mode | Optical Receiver Sensitivity | Optical Power / Wavelength | TIA Gain | TIA Bandwidth | Receiver Circuit Power |
|---|---|---|---|---|---|
| Unicast | -20dBm | 34.1$\mu$W | 1KΩ | 10Gbps | 0.2mW |
| 2-cast | -20dBm | 92.3$\mu$W | 1KΩ | 10Gbps | 0.2mW |
| 3-cast | -22dBm | 118.3$\mu$W | 2KΩ | 10Gbps | 0.7mW |
| 4-cast | -25dBm | 107.9$\mu$W | 3KΩ | 5Gbps | 0.2mW |
| 5-cast | -27dBm | 114.6$\mu$W | 6KΩ | 5Gbps | 0.8mW |
| 6-cast | -29dBm | 117.5$\mu$W | 10KΩ | 2.5Gbps | 0.2mW |

TABLE II: Photonic broadcast configuration

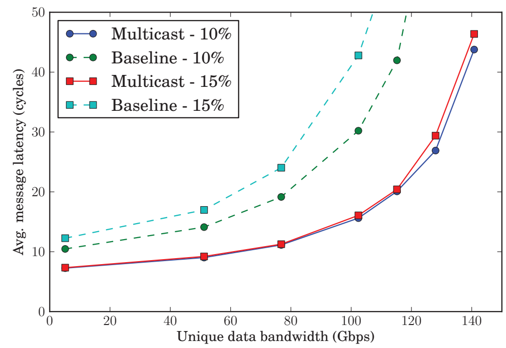


Fig. 5: Multicast to baseline load-latency comparison.

being broadcast. As the offered data rate increases, the latency of an individual message rises due to resource contention and congestion. Because our multicast proposal does not support 7-destination multicast, these packets are split into two packets.

The multicast enabled network achieves significant performance advantage over the baseline with 20% (30%) higher saturation bandwidth for workloads with 10% (15%) multicast packets. Additionally, the multicast enabled network has significantly lower no-load latency, which is more difficult to achieve with design scaling than the higher bandwidth. Multicast packet transmission has the effect of both reducing the effective bandwidth of the workload and hence increasing saturation throughput, because fewer packets are injected for the same unique data transmission; as well as reducing the serialization and arbitration latency, and hence zero-load latency, due to the back-to-back insertion of identical packets to different destinations.

## IV. Conclusions

Multicast forms an important component of CMP interconnect traffic. In this paper, we present a novel technique to implement broadcast in photonic NoCs. Our design relies upon purposeful ring filter de-tuning to allow multiple concurrent reception of photonic frequencies. We also present a switched TIA design to allow variable gain amplification. Together these components provide a significant performance increase for CMP traffic containing multicast packets.

## References


[1] W. J. Dally and B. Towles, "Route Packets, Not Wires: On-Chip Interconnection Networks," in *The 38th International Design Automation Conference (DAC)*, 2001, pp. 684–689.

[2] N. Jerger, L.-S. Peh, and M. Lipasti, "Virtual circuit tree multicasting: A case for on-chip hardware multicast support," in *The 35th International Symposium on Computer Architecture*, june 2008, pp. 229 –240.

[3] A. Joshi, C. Batten, Y.-J. Kwon, S. Beamer, I. Shamim, K. Asanovic, and V. Stojanovic, "Silicon-Photonic Clos Networks for Global On-Chip Communication," in *The 2009 3rd ACM/IEEE International Symposium on Networks-on-Chip (NOCS)*, 2009, pp. 124–133.

[4] K. Shiba, T. Nakata, T. Takeuchi, T. Sasaki, and K. Makita, "10 gbit/s asymmetric waveguide apd with high sensitivity of -30dbm," *ELECTRONICS LETTERS*, vol. 42, no. 20, pp. 1177–1178, Sep 2006.

[5] S. Xiao, M. H. Khan, H. Shen, and M. Qi, "Modeling and measurement of losses in silicon-on-insulator resonators and bends," *Optics Express*, vol. 15, no. 17, pp. 10 553–10 561, 2007.