Improving Crosstalk Resilience with Wavelength Spacing in Photonic Crossbar-based Network-on-Chip Architectures

Sai Vineel Reddy Chittamuru, Sudeep Pasricha
Department of Electrical and Computer Engineering
Colorado State University, Fort Collins, CO, U.S.A.
{sai.chittamuru, sudeep}@colostate.edu

***Abstract*—Crosstalk noise can significantly reduce data transfer reliability in emerging photonic network-on-chip (PNoC) architectures. Undesirable mode coupling between photonic signals at microring resonators (MR) is the main cause of crosstalk in photonic waveguides. As emerging PNoC architectures employ dense wavelength division multiplexing (DWDM) with multiple cascaded MRs, these architectures suffer from high crosstalk levels. In this paper, we propose a novel solution to this problem, by increasing the wavelength spacing between adjacent wavelengths in a DWDM waveguide to reduce crosstalk noise. Experimental results on two photonic crossbar architectures (Corona and Firefly) indicate that our approach improves worst-case signal-to-noise ratio (SNR) by up to 51.7%.**

I. INTRODUCTION

The ever increasing demand for higher performance computing and aggressive technology scaling has driven the trend of integrating an increasing number of processing cores on a single die. In such many-core systems, the efficiency of the communication fabric is as important as the computation efficiency of individual processors. Traditional electrical network-on-chips (NoCs) are expected to reach their limits with increasing core counts, because of high power dissipation and reduced performance due to high congestion [1].

Recent developments in the area of silicon photonics indicate that on-chip photonic interconnects can address the performance and power bottlenecks of electrical NoCs in future many-core systems. On-chip photonic links can support higher bandwidths, lower latency, and lower energy consumption compared to electrical wires, especially at the global level [4]. To enable photonic transfers on a chip, the key photonic components required are: a multi-wavelength laser light source, microring resonator (MR) modulators, photonic waveguides, and MR receivers with photodetectors. The transmission occurs via photonic waveguides that carry multiple wavelengths of light (called dense wavelength division multiplexing or DWDM) allowing multiple streams of data to be transferred simultaneously. Typically an off-chip multi-wavelength laser is used to couple light into the on-chip waveguide. MR modulators are used to modulate electrical signals onto a specific wavelength of light in the waveguide at the source. MRs are also used at the destination as detectors to "drop" the light signal of a specific wavelength from the waveguide to a local photodetector device that converts it to an electrical signal.

A few recent works propose to exploit on-chip photonic links to create PNoC architectures with a crossbar topology [3], [12] that demonstrate improved performance over other topologies. These crossbar-based PNoCs use large numbers of cascaded MRs to support DWDM in their waveguides for parallel data transfers. But crosstalk noise is a major drawback with MRs in these crossbar-based PNoCs, causing severe performance degradation by reducing photonic signal-to-noise ratio (SNR) in the network. Results in [10] show worst-case SNR of the Corona crossbar-based PNoC [12] with 64 DWDM in its data channels is close to 14dB. This SNR value is not sufficient for reliable data communication, as it corresponds to a very high bit error rate (BER), in the order of 10^{-3}.

We observe that for a fixed free spectral range (FSR), increase in DWDM of the waveguide leads to reduction in wavelength spacing between two adjacent wavelengths and this in turn increases crosstalk noise. From transmission spectrums of cascaded MRs shown in figure 1, it can be seen that overlapping region between adjacent wavelengths decreases with increase in the wavelength spacing; this in turn reduces crosstalk noise. Thus SNR in DWDM based photonic crossbars is directly related to the available DWDM in its waveguides. In this paper, we propose novel wavelength spacing (WSP) techniques to increase spacing between adjacent wavelengths in a DWDM waveguide for PNoCs. Our novel contributions are:

- We propose a novel wavelength spacing (WSP) technique and explore varying levels of WSP to reduce crosstalk noise in DWDM-based crossbar PNoC architectures;
- We explore worst-case SNR and performance overheads due to WSP on DWDM-based PNoCs such as Corona [12] and Firefly [3] for real-world multi-threaded PARSEC benchmarks.

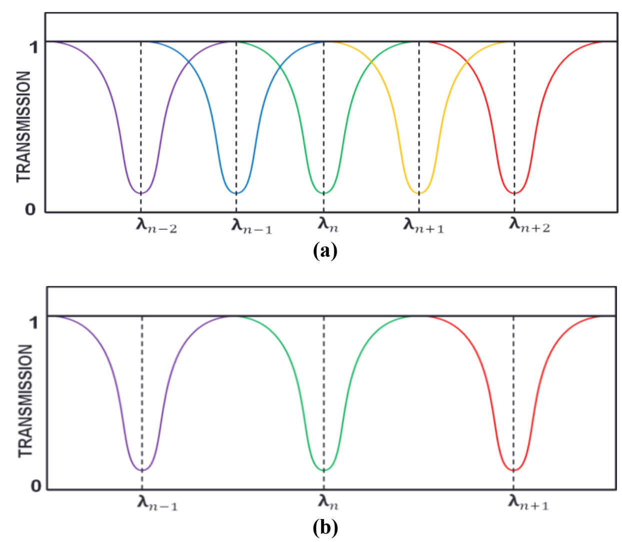


Fig. 1: Transmission spectrum of the cascaded microring modulators when using (a) smaller wavelength spacing (b) larger wavelength spacing.

II. RELATED WORK

Crosstalk is an intrinsic characteristic of MRs and waveguide crossings. Several prior efforts have analyzed the crosstalk behavior of these components. Crosstalk noise in single waveguide crossings is shown to be close to -47.58 dB [6]. A cascaded MR-based modulator is proposed in [8] for low-density DWDM waveguides, with an extinction ratio of 13dB and negligible crosstalk. In the aforementioned works, crosstalk noise appears negligible at the device-level. But at the network-level, aggregate crosstalk due to several photonic devices reduces SNR considerably, creating severe reliability issues. For example, crosstalk analysis of a folded-torus-based PNoC in [7] shows that crosstalk noise power exceeds signal power when network size is equal to or greater than 8×8 nodes. Similar conclusions were drawn from the crosstalk analysis in [10] for the Corona PNoC [12], where its 64 wavelength DWDM data channels are studied and worst-case SNR is estimated to be 14dB, which is too low for reliable data transmission in practice.

Thus, an emphasis on network-level crosstalk is critical in emerging PNoCs, such as Corona [12] and Firefly [3], otherwise such architectures may not be viable for implementation in future chips. Two encoding techniques PCTM5B and PCTM6B are presented in [2] to improve SNR in DWDM-based crossbar architectures. Our goal in this work is to reduce network-level crosstalk via wavelength spacing (WSP) optimizations. We analyze and quantify the worst-case SNR, performance, and energy overheads of using variants of our WSP technique with different levels of wavelength spacing in DWDM-based photonic waveguides used in [12], [3].

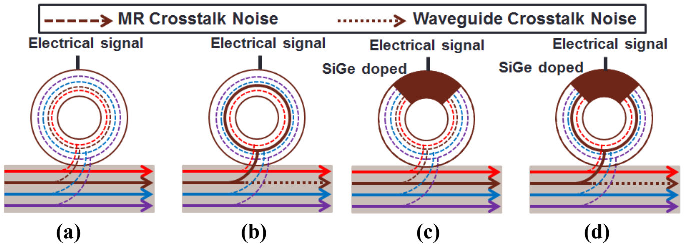


Fig. 2: MR operation modes: (a) modulator in passing (through) mode (b) modulator in modulating mode (c) detector in passing mode (d) detector in detecting mode

III. WAVELENGTH SPACING (WSP) TECHNIQUE

Microring resonators (MRs) in DWDM-based PNoC architectures can be used as either modulators or detectors. An MR modulator can be operated in two modes: modulating and passing. In the modulating mode, the MR is in resonance with the corresponding resonant wavelength in the waveguide and is capable of removing this wavelength from the waveguide. In the passing mode, the MR simply allows all the wavelengths to pass through undisturbed, as the modulator is out of resonance with all the wavelengths. Similarly, MR detectors can be operated in two modes: detecting and passing. In the detecting mode, the MR can remove a corresponding resonant wavelength light pulse from the waveguide, whereas in the passing mode it will permit wavelengths to pass through. Figures 2 (a)-(d) show these different modes of operation for an MR modulator and detector. The figures also show crosstalk noise (as dotted/dashed lines) in the modulator and detector MRs during typical modulation and detection modes in the DWDM-waveguide. Whenever a modulator modulates a '0' or a detector detects a '1' from a particular wavelength by removing the light pulse, there is also crosstalk generated in the waveguide, as shown in Figures 2(a) and 2(d). Thus, MRs generate crosstalk noise, as they not only couple photonic power from their resonance wavelengths but also couple certain portions of photonic power from other wavelengths in the waveguide.

A. Analytical Model for SNR in Corona crossbar-based PNoC

Crossbar-based PNoCs such as Corona [12] use cascaded MRs to modulate and detect data from their multiple writer and single reader (MWSR) waveguides. Corona has 64 nodes and each node consists of four processing cores. Inter-node communication is facilitated via a crossbar network with 64 data channels, where each channel has 4 MWSR waveguides with 64 DWDM in each waveguide. This architecture considers a packet size of 512 bits (cache-line size) and is capable of traversing an entire packet from source node to destination node in a single cycle. Note that we also modeled SNR for the Firefly PNoC [3], but omit its discussion for brevity.

The worst case SNR in the Corona crossbar occurs in the detectors of the last (64^{th}) node traversed by the MWSR data channels. This node is called the maximum power loss node (MPLN). Equation (1) defines SNR(j) of the j^{th} detector at the MPLN as the ratio of $P_{signal}(j)$ to $P_{noise}(j)$ [2]. The signal power ($P_{signal}(j)$) and crosstalk noise power ($P_{noise}(j)$) received at each detector j of MPLN are expressed in equations (2) and (3) [10]. $P_S(i,j)$ in equation (2) and (3) is the signal power of the i^{th} wavelength received before the j^{th} detector. Similarly in equation (4), $P_N(i,j)$ is the crosstalk noise power of the i^{th} wavelength before the j^{th} detector. $\Phi(i,j)$ is the crosstalk coupling factor of the i^{th} wavelength and the j^{th} detector as per equation (4). Q refers to the Q-factor of MR and λ_j is resonance wavelength of MR.

$$SNR(j) = \frac{P_{signal}(j)}{P_{Noise}(j)} \tag{1}$$

$$P_{signal}(j) = L_{DD}\, P_S(j,j) \tag{2}$$

$$P_{noise}(j) = L_{DD}\, P_N(j,j) + \sum_{i=1}^{n} \Phi(i,j)\big(P_S(i,j) + P_N(i,j)\big)\,(i \neq j) \tag{3}$$

$$\Phi(i,j) = \frac{\delta^2}{\left((i-j)\frac{\mathrm{FSR}}{n}\right)^2 + \delta^2}, Here\ \delta = \frac{\lambda_j}{2Q} \tag{4}$$

B. Wavelength spacing (WSP) technique

Crosstalk noise in an MR depends on the gap between its resonant and non-resonant wavelengths. We observe that the coupling factor (Φ) between these wavelengths increases with a decrease in this gap (equation (4)). Therefore, we propose a wavelength spacing (WSP) technique to decrease crosstalk noise at an MR device in DWDM waveguides by increasing spacing between resonant and immediate non-resonant wavelengths. As illustrated in Figure 3, a variable WSP node is added at the beginning of a data waveguide. This node consists of an array of variable-sized MRs capable of switching different spaced wavelengths from a broadband laser source to the data waveguides. To implement the WSP technique in Corona and Firefly, for a fixed FSR, there is a need to decrease DWDM degree in their MWSR and SWMR waveguides. Further due to reduction in DWDM degree, it is not possible to send a packet of 512 bits from source to destination in one cycle, so the packet size need to be decreased to meet the waveguide DWDM requirements. Depending on the degree of WSP used (see Section IV.B), each waveguide is simplified because the number of modulating and detecting MRs is effectively reduced. The reduction in MRs decreases throughput as fewer bits can be transferred in a single cycle. On the other hand fewer MRs also reduce through loss and lower laser power.

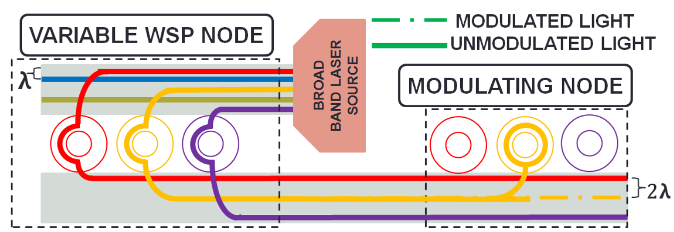


Fig. 3: WSP technique: variable WSP-node increases wavelength spacing by 100% from to 2 in the bottom data waveguide of the PNoC and the modulating node on the waveguide modulates on available wavelengths.

IV. EXPERIMENTS

A. Experimental setup

To evaluate the proposed WSP technique, we implement it on two well-known crossbar PNoC architectures: Corona [12] and Firefly [3]. We modeled and simulated the WSP technique and these PNoCs using a cycle-accurate NoC simulator. We evaluated performance for a 256 core single-chip architecture at a 22nm CMOS node. We used real-world traffic from applications in the PARSEC benchmark suite [5] in our analysis. GEM5 full-system simulation [11] of parallelized PARSEC applications was used to generate traces that were fed into our cycle-accurate NoC simulator. We set a "warm-up" period of 100M instructions and then captured traces for the subsequent 1B instructions. Based on geometric analysis, we estimated the time needed for light to travel from the first to the last node as 8 cycles at 5 GHz in both architectures, for a 20mm×20mm die. We use a packet size of 512 bits, and a DWDM wavelength range is in the C and L bands [9], with a starting wavelength of 1530nm and FSR of 62 nm. We consider Q-factor (Q) of MR as 9000.

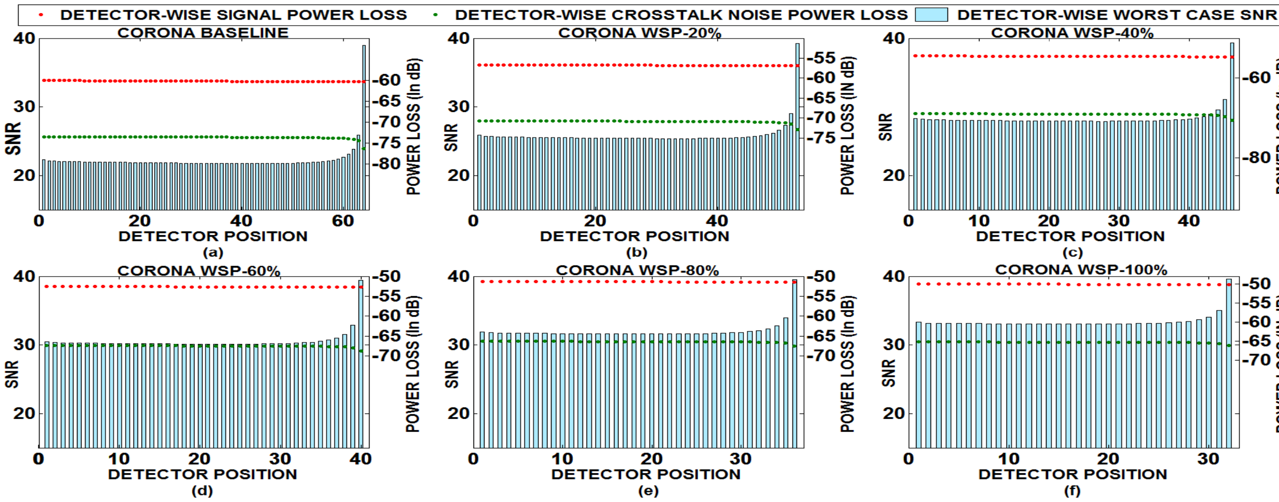


Fig. 4: Detector-wise signal power loss, crosstalk noise power loss and minimum SNR in MPLN for Corona (a) baseline with 64-detectors (b) WSP increased by 20% with 53-detectors (c) WSP increased by 40% with 46-detectors (d) WSP increased by 60% with 40-detectors (e) WSP increased by 80% with 36-detectors (f) WSP increased by 100% (doubled) with 32-detectors.

The static and dynamic energy consumption of NoC routers and concentrators in Corona and Firefly is based on results from the open-source DSENT tool. We estimated power overhead using gate-level analysis and CACTI 6.5 for buffers. For energy consumption of photonic devices, we adopt model parameters from recent work [10], [13], with 0.42pJ/bit for every modulation and detection event and 0.18pJ/bit for the driver circuits of modulators and photodetectors. We used photonic loss for photonic components, as shown in Table I, to determine the photonic laser power budget and correspondingly the electrical laser power.

Table I: Photonic power loss and crosstalk coefficients [10]

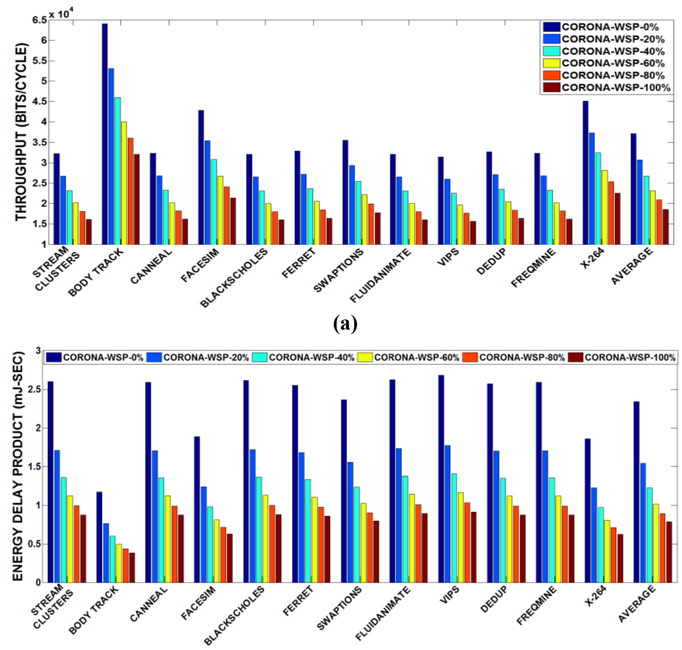
Parameter type	Parameter value (in dB)
Propagation loss	-0.274 per cm
Bending loss	-0.005 per 90°
Inactive modulator through loss	-0.0005
Active modulator power loss	-0.6
Passing detector through loss	-0.0005
Detecting detector power loss	-1.6
Active modulator crosstalk coefficient	-16
Detecting detector crosstalk coefficient	-16

Table II: Worst-case SNR results for Corona and Firefly architectures

Configuration	Waveguide DWDM	Packet Size (in bits)	Worst-case SNR
Corona Baseline	64	512	21.74
Corona WSP_20%	53	424	25.39
Corona WSP_40%	46	368	27.91
Corona WSP_60%	40	320	30.13
Corona WSP_80%	36	288	31.6
Corona WSP_100%	32	256	33.04
Firefly Baseline	64	512	22.55
Firefly WSP_20%	53	424	26.22
Firefly WSP_40%	46	368	28.88
Firefly WSP_60%	40	320	31.23
Firefly WSP_80%	36	288	32.82
Firefly WSP_100%	32	256	34.21

B. Experimental results with Corona and Firefly PNoCs

We compared the baseline Corona PNoC with fair token-slot arbitration [12] and baseline reservation-assisted Firefly PNoC architecture but without any crosstalk-enhancements, with five variants of these architectures corresponding to different degrees of increase in the wavelength spacing: 20% (WSP_20%), 40% (WSP_40%), 60% (WSP_60%) and 100% (WSP_100%). We calculate the received crosstalk noise and photonic SNR at detectors for the MPLN in Corona, which corresponds to the detectors in node 64, using analytical models presented in section III. In a similar manner we also determine the MPLN in Firefly, which is the router 0 of cluster 4. For the Corona and Firefly architectures along with their variants, the worst-case SNR occurs in the MPLN when all the bits of a received data word in a waveguide are 1's.



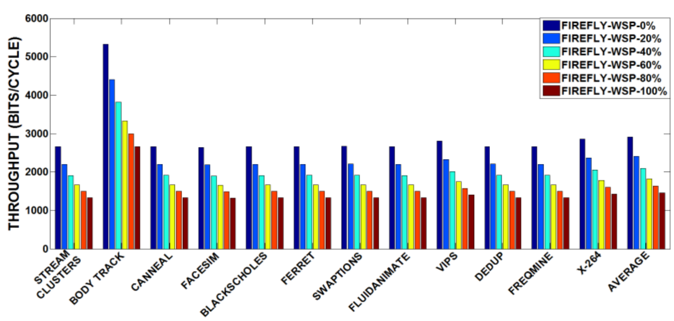
(a)

(b)

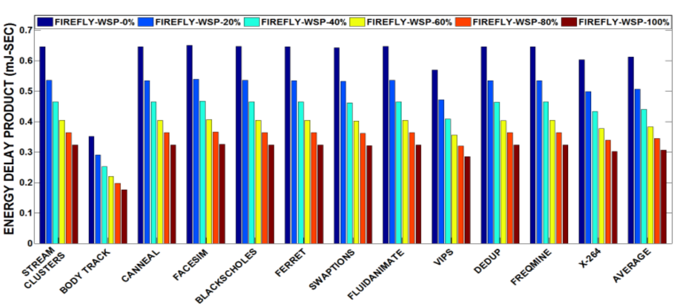
Fig. 5: (a) Throughput, and (b) energy-delay product (EDP) comparison between Corona baseline and Corona configurations with WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100%, for PARSEC suite.

Figure 4 (a)-(f) presents detector signal power loss, crosstalk noise power loss, and SNR corresponding to the detectors in the MPLN for the baseline and five variants of the Corona PNoC. Note that the number of detectors in the node (x-axis) varies across the proposed techniques and depends on the number of data bits transmitted in the data waveguide for each technique, as discussed in Section III. Table II summarizes the worst-case SNR results for all the architectures. The worst-case SNR in both Corona and Firefly architectures is obtained at the 42^{nd} detector of the MPLN in the baseline case; whereas for the WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100% configurations, worst-case SNR occurs at the 33^{th}, 27^{th}, 23^{rd}, 20^{th} and 17^{th} detectors of the WPLN, respectively. From the table it can be surmised that Corona with WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100% shows 16.8%, 28.3%, 38.6%, 45.4% and 49.3% improvements in worst-case SNR compared to the baseline. Furthermore, Firefly with WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100% shows 16.2%, 28%, 38.5%, 45.6% and 51.7% decrease in the worst-case SNR compared to its baseline. Thus our WSP technique reduces crosstalk and improves SNR significantly in both Corona and Firefly PNoCs.

The average throughput and energy-delay product (EDP) for the six configurations of Corona and Firefly architectures are presented in Figures 5 and 6, across 12 multi-threaded PARSEC benchmarks. From Figure 5(a) it can be seen that on average, Corona configurations with WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100% have 17.2%, 28.1%, 37.5%, 43.7% and 50% lower throughput compared to the baseline. Similarly from Figure 6(a) we observe that on average, Firefly configurations with WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100% have 15.2%, 26.4%, 36.5%, 41% and 48.5% lower throughput compared to the baseline. The decrease in throughput with the WSP technique in these architectures is due to the decrease in number of wavelengths in DWDM for data transfer, as shown in Table II. In Corona we observe a higher reduction in the throughput compared to Firefly though DWDM was reduced to same extent in both of these architectures. Corona is an all optical crossbar where all data transfers on the chip traverse the optical waveguides (with reduced DWDM), whereas Firefly is a hybrid network where only a certain portion of the on-chip traffic travels through its photonic links (the remaining traffic traverses through its electrical links). Thus, reduction in DWDM has more impact on throughput for Corona compared to Firefly.



(a)



(b)

Fig. 6: (a) Throughput, and (b) energy-delay product (EDP) comparison between Firefly baseline and Firefly configurations with WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100%, for PARSEC suite.

From the results for EDP shown in the Figure 5(b), on average Corona configurations with WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100% techniques have 34.1%, 47.8%, 56.8%, 61.8% and 66.36% lower EDP compared to the baseline. From Figure 6(b) we observe that on average, Firefly configurations with WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100% have 17.18%, 25.1%, 35.2%, 40.1% and 49.9% lower EDP compared to the baseline. In general, the WSP technique results in a reduction in energy due to an aggregation of several factors. On the one hand, both Corona and Firefly configurations with WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100% in their data waveguides transmit only 53-bits, 46-bits, 40-bits, 36-bits and 32-bits instead of 64-bits in their respective baselines, which reduces the number of MR modulators and detectors on each waveguide by 17%, 28%, 37.5%, 43.8% and 50% respectively. This reduction in MRs on each waveguide minimizes through loss and decreases laser power, while also minimizing static energy consumption in these architectures.

On the other hand, dynamic energy also decreases in all of these configurations compared to its baseline architectures, because fewer bits transverse across data channels, which reduces the energy consumption in modulators, detectors and driver circuits. That is why there is a notable reduction in EDP with the WSP technique.

C. Summary of Results and Observations

From the results presented in the previous subsection, we can summarize that our proposed WSP technique can help to reduce crosstalk noise and improve SNR in DWDM-based PNoC architectures such as Corona and Firefly. The proposed WSP technique very effectively improves both reliability and EDP for these architectures. Comparatively higher improvements in EDP were observed in higher through-loss architectures such as Corona compared to architectures with low through-losses such as Firefly.

V. CONCLUSION

We proposed a WSP technique for the reduction of crosstalk noise in the detectors of dense wavelength division multiplexing (DWDM) based photonic network-on-chip (PNoC) architectures with crossbar topologies. Different WSP configurations (WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100%) of Corona and Firefly show interesting trade-offs between reliability, throughput performance, and energy consumption. Our experimental analysis on the Corona and Firefly PNoCs configurations with WSP_20%, WSP_40%, WSP_60%, WSP_80% and WSP_100% shows improvements in worst-case SNR by up to 51.7%. This translates into an improvement in bit error rates (BER) in these architectures by up to 100×. Thus the WSP technique can notably improve reliability, with some throughput degradation; however it also reduces EDP due to decrease in photonic hardware and through losses.

VI. ACKNOWLEDGMENTS

This research is supported by grants from SRC, NSF (CCF-1252500, CCF-1302693), and AFOSR (FA9550-13-1-0110).

REFERENCES

[1] L. Benini and G. De Micheli, “Networks on chip: A new paradigm for systems on chip design,” in Proc. DATE, 2002, pp. 418–419.
[2] S. V. R. Chittamuru et al., “Crosstalk Mitigation for High-Radix and Low-Diameter Photonic NoC Architectures”, in IEEE D&T, 2015.
[3] Y. Pan et al., “Firefly: Illuminating future network-on-chip with nanophotonics,” in *Proc. ISCA*, 2009.
[4] Y. Xu, S. Pasricha, “Silicon nanophotonics for future multicore architectures: opportunities and challenges”, IEEE Design & Test, 2014.
[5] C. Bienia et al., "The PARSEC Benchmark Suit: Characterization and Architectural Implications," in PACT, Oct. 2008.
[6] C. H. Chen, “Waveguide crossings by use of multimode tapered structures,” in WOCC, 2012, pp. 130–131.
[7] M. Nikdast, et al., “Systematic analysis of crosstalk noise in folded-torus-based optical networks-on-chip,” in IEEE TCAD 33(3), Mar 2014.
[8] Q. Xu, B. Schmidt et al., “Cascaded silicon micro-ring modulators for wdm optical interconnection,” in Opt. Express, vol. 14, no. 20, 2006.
[9] S. Xiao, *et al.*, “Modeling and measurement of losses in silicon-on-insulator resonators and bends,” in Opt. Express, vol.15, no.17, 2007.
[10] L.H.K. Duong et al., “A Case Study of Signal-to-Noise Ratio in Ring-Based Optical Networks-on-Chip,” in IEEE Design and Test, 2014.
[11] N. Binkert et al.,"The gem5 Simulator," in *CA News*, May 2011.
[12] D. Vantrease et al., “Light speed arbitration and flow control for nanophotonic interconnects,” in *Proc. IEEE/ACM MICRO*, Dec. 2009.
[13] P. Grani and S. Bartolini,“Design Options for Optical Ring Interconnect in Future Client Devices,” in *ACM JETC, May, 2014.*