Design Methodology for Optical Interconnect Topologies in NoCs with BER and Transmit Power Constraints

Iphita Datta†, Debasish Datta‡, Senior Member, IEEE and Partha P. Pande*, Senior Member, IEEE

Abstract— Optical Network-on-Chip (ONoC) has emerged as an enabling technology to integrate a large number of processing cores in a single die. In this paper, we review some of the existing optical interconnect topologies for ONoCs and, propose a novel optical topology using multiple-segment buses (MSB) wherein several clusters of cores are interconnected in optical domain using MSB-based multiple optical interconnects. In particular, we analyze the bit-error rate (BER) performance of various ONoC topologies including the proposed MSB topology, taking into account signal losses and crosstalk components along the signal paths. The proposed MSB topology for 16 clusters offers an encouraging BER performance as compared to the other existing topologies, within the acceptable limit of per-wavelength launched power (1.5mW). The BER performance in 16-cluster MSB topology is further improved by incorporating forward error-correcting codes in the communicating clusters. Having studied the 16-cluster MSB topology, the size of the ONoC is scaled up to 64 clusters, wherein the 16-cluster topologies are used as modular MSB units (MUs), which are interconnected by inter-MU buses with optical-electronic-optical conversions at the exit and entry points from and into the communicating MUs. For 64-cluster modular MSB, the impacts of error-correcting codes are also examined. Finally, the paper provides a study on the impact of thermal mistuning of MRRs on the average BER of ONoCs, leading to a requirement of 20MHz laser linewidth to achieve an extinction ratio of 15dB for the ONoC setting considered in the study.

Index Terms— ONoC, BER, 2DFT, Corona, SFB, MSB, WDM, Thermal mistuning, ER, MRR, RS-codes.

I. INTRODUCTION

Low power consumption and support for wavelength-division multiplexing (WDM) in optical network-on-chips (ONoCs) which increase the operational speed manifold with energy-efficient intra-chip communication options, have made optical interconnects a viable choice to realize high-speed intra-chip data exchange in multi-core processors (MCPs). In ONoC-based MCPs, several sets of homogeneous and adjacent cores are grouped into multiple clusters of cores. Optical interconnects, using planar optical waveguides, provide optical interconnections among the clusters to facilitate bulk data transfers (inter-cluster communication), whereas usual electronic interconnections are used in transferring data between the cores within a cluster (intra-cluster communication).

The design of a 2-D folded torus interconnect topology has been realized in ONoCs, with optical circuit-switched connections between the clusters with lasers and modulators/demodulators using micro-ring resonators (MRRs) [1][2]. In [3], Corona, a 3-D multi-cluster interconnect topology has been reported, which comprises of 256 cores, organized in 64 clusters and are interconnected by optical waveguides with WDM, achieved using wavelength-selective MRRs. However, as evident from the ongoing activities, the challenge in designing ONoCs is to incorporate high-speed optical links between clusters using WDM, with an acceptable transmission quality, while meeting the optical power budget. The transmission quality of an optical interconnect topology needs to be assessed in terms of average launched power, inter-cluster speed and bit-error rate (BER). Unlike in long-haul optical fiber communication systems (where the fiber loss is only 0.2dB/km), optical connectivity in ONoCs even beyond a few centimeters becomes challenging, with 1-2dB/cm loss in the silicon-over-insulator (SOI) waveguides used in ONoCs. Very few investigations have so far been reported in the domain of designing topologies, with high inter-cluster speeds and low-transmitted powers for a given BER constraint.

This paper analyses the BER performance of various ONoC topologies, taking into account the signal losses and crosstalk components along the signal path. A novel optical interconnect topology, using multiple-segment buses (MSB), has been proposed (a preliminary version of the work was presented in [4]), which offers an encouraging BER performance within the acceptable limit of per-wavelength launched power (1.5mW) [10]. The paper examines the MSB topologies of varying sizes (4, 16 and 64 clusters). However,

Manuscript received July 14, 2013; revised September 24, 2013; accepted October 28, 2013. This work was supported in part by the Ministry of Human Resource Department, Government of India, and in part by US National Science Foundation (NSF) CAREER grant (CCF-0845504).

†Iphita Datta is currently with Broadcom Communication Pvt. Ltd, Bangalore, Karnataka 560103, India. This work was carried out for her Masters’ thesis (2010-2012) in the Dept. of Electronics & Electrical Communication Engg. at Indian Institute of Technology (IIT), Kharagpur, West Bengal 721302, India (e-mail : ipshitadatta@gmail.com)

‡Debasish Datta is with the Dept. of Electronics and Electrical Communication Engg., IIT, Kharagpur, West Bengal 721302, India (e-mail: ddatta@ece.iitkgp.ernet.in).

*Partha P. Pande is with the School of Electrical Engineering and Computer Science, Washington State University, Pullman 692752, Washington, USA (e-mail: pande@eecs.wsu.edu).
the 64-cluster ONoC is realized by interconnecting four 16-cluster MSB units (MUs) as modules, using longer folded buses through optical-electronic-optical (OEO) conversion at source/destination MUs. The impact of thermal mistuning of MRRs is also examined using a novel analytical model.

Rest of the paper is organized as follows. Section II briefly discusses the enabling technologies, including SOI waveguides, MRR-based modulators, filters, routers and Ge-on-Si photodetectors. Section III reviews the existing topologies and Section IV describes the proposed MSB topology, for 16-cluster MSB and 64-cluster modular MSB formations. Section V presents the BER evaluation model for optical interconnects, used in various ONoC topologies. This section examines the BER performances of 4-, 16- and 64-cluster optical interconnect topologies. Section VI examines the impact of thermal mistuning of MRR on BER performance. Finally, Section VII concludes the paper.

II. ENABLING TECHNOLOGIES

The SOI technology has been able to reduce the cross-sectional area of optical waveguides to sub-micron level, by confining the propagation mode to the silicon core. Submicron SOI waveguides (500nm × 200nm) are designed with high index contrast (HIC) between crystalline silicon core (n = 3.5) and silica cladding (n = 1.45) [5], supporting single-mode propagation over a range of wavelengths (1530-1580nm). MRRs placed beside a SOI waveguide (Fig.1) operate as wavelength-selective optical feedback devices. In this configuration, the lightwave at resonant wavelength, while propagating along the waveguide, gets coupled to the MRR at the MRR-waveguide interface and interferes with the lightwave which has already been coupled from the linear waveguide and moving around the MRR. At on-resonance wavelength, the circumference of the MRR (optical path length) becomes an integer multiple of the resonating wavelength. Thus, the coupled and the propagating lightwaves interfere in the MRR, resulting in a significant absorption of the waveguide power into the MRR. A single MRR, coupled to an optical waveguide, can be viewed as a two-port device as shown in Fig. 1 (the role of the p-n junction used at the base of the MRR is discussed later).

The scattering matrix relating the outgoing optical fields (b0 \text{ and } a'1) with the incoming optical fields (a0 \text{ and } b'1) at the coupling interface of the waveguide (Fig.1) and the MRR is given by [5]

\[
\begin{bmatrix}
  b_0 \\
  a'_1
\end{bmatrix} = \begin{bmatrix}
  t & \kappa \\
  -\kappa* & t^*
\end{bmatrix} \begin{bmatrix}
  a_0 \\
  b'_1
\end{bmatrix}
\]  

(1)

The lightwave propagating along the MRR (b'1) at the coupling interface of the waveguide and the MRR can be expressed as

\[ b'_1 = \alpha a'i e^{i\theta} \]  

(2)

where, t and t* are the complex conjugate transmission coefficients along the main waveguide and MRR respectively, \( \kappa \) and \( \kappa* \) are the complex conjugate coupling coefficients between the MRR and waveguide, \( \alpha \) is the loss encountered by the mode propagating over the circumference of the MRR, \( \theta \) is the phase shift encountered by the propagating mode (\( \theta = 2\pi L/\lambda_{eff} \), where L is the path length (circumference of the MRR)). Assuming that the MRR is conditioned by the law of lossless coupling, one can relate t and \( \kappa \) as

\[ |t|^2 + |\kappa|^2 = 1 \]  

(3)

The design of the MRRs with desirable t, \( \kappa \) and \( \alpha \) (by adjusting the gap between the waveguide and the MRR at the coupling interface) makes the MRR one of the more versatile photonic components in ONoCs. HIC-based SOI MRRs provide high confinement of light in the waveguide core, thereby reducing the minimal bending radius and increasing free-spectral range (FSR).

Using the above expression, i.e., (1) through (3) and \( t = |t|e^{-i\phi_t}, |t| \) is the transmission amplitude and \( \phi_t \) is the transmission phase constant along the main waveguide (as shown in Fig.1), the normalized power at port 2 (Fig. 1) with respect to the incident optical power at port 1 can be expressed as

\[
\frac{|p_0|^2}{|a_0|^2} = \frac{|t|^2 + \alpha^2 - 2\alpha|t| \cos(\theta + \phi_t)}{1 + \alpha^2|t|^2 - 2\alpha|t| \cos(\theta + \phi_t)}
\]  

(4)

A. MRR-Based Modulators

MRRs with electrically controlled p-n junctions at the base use carrier injection/ depletion effects to design high-speed electro-optic modulators. For binary ‘0’, with zero bias across the p-n junction, the path travelled by the lightwave along the MRR circumference length encounters a total phase shift of \( \theta + \phi_t \) as shown in Fig. 1. It is evident from (4) that, when \( \theta + \phi_t = 2m\pi \) and \( |t| = \alpha \), the output power at port \( P_0 \) (port at 2) goes down close to zero, i.e., the MRR absorbs almost the whole power for the corresponding wavelength (\( \lambda_{res} \)), thereby writing a binary ‘0’ on the waveguide (for binary ‘0’ transmission). The governing equation for \( \lambda_{res} \) is given by

\[
\frac{\theta + \phi_t}{\lambda_{eff}} = \frac{2\pi Ln_{eff}}{\lambda_{res}} = 2m\pi
\]  

(5)

with the on-resonance wavelength \( \lambda_{res} \) being decided by \( L (= 2\pi R, R = \text{MRR radius}) \) and effective refractive index \( n_{eff} \) as

\[ \lambda_{res} = \frac{Ln_{eff}}{m} = \frac{2\pi Rn_{eff}}{m} \]  

(6)

The circumference length of the MRR (L) being pre-
determined and fabricated for binary ‘0’ transmission, for a binary ‘1’ transmission to take effect, the effective refractive index \( n_{\text{eff}} \) has to be altered by changing the carrier concentration in the MRR by using a forward bias across the p-n junction. Application of forward bias on p-n junction across the MRR causes a spectral shift in its absorption spectrum, thereby moving away its resonant wavelength from \( \lambda_{\text{res}} \) to \( (\lambda_{\text{res}} + \Delta \lambda) \) by an incremental amount \( \Delta \lambda \), however ensuring that \( (\lambda_{\text{res}} + \Delta \lambda) \) does not interfere with the adjacent transmitted wavelength on the same bus. Thus, binary ‘1’ in the electronic domain is transformed into an increased light output power \( P_l \), say, (because of no absorption at \( \lambda_{\text{res}} \) but at \( \lambda_{\text{res}} + \Delta \lambda \)) at port 2 in the optical domain, attained by detuning the MRR through carrier injection. As reported in [6] and [7], MRR based electro-optic modulators have been designed, fabricated and tested.

B. MRR-Based Routers

Another important device for optical interconnects is the wavelength-selective router from the source to the destination clusters using passive components. The electro-optic routing elements have high traffic switching speeds, but with large device footprint. The use of MRR-based routers (also called as switches) empower the interconnect architecture with high switching speeds [8] and small footprint.

The 2×2 MRR based routing device, as shown in Fig. 2, is called as an inter-segment router (ISR) which couples light at a particular wavelength, selectively between two parallel waveguides. By suitably adjusting the values of \( t_{\text{e}} \), \( k_1 \) and \( \sigma_{l+1} \) (Fig. 2), we can design wavelength-selective ISRs. All these ISRs, being fixed-tuned to respective wavelengths, need no electro-optic tuning and, hence consume no power and operate as a set of passive MRR devices.

C. Ge-on-Si Photodetectors

Si-compatible Ge-photodetectors can be used in optical interconnect systems with MRRs, as direct bandgap in Ge has large absorption coefficients for wavelengths in the near infrared region (i.e., telecom wavelengths in the C band). High speed photodetectors with high sensitivity are designed using the integrated metal-semiconductor-metal configuration [9]. Ge-on-Si photodetectors can be interfaced with the broadband silicon waveguides, carrying information modulated WDM signal.

III. OPTICAL INTERCONNECT TOPOLOGIES

This section presents a brief overview of some of the existing interconnect topologies (followed by the proposed MSB topology in Section IV). In such topologies, optical power is usually derived from an off-chip multi-wavelength laser along with a tapered feed, delivering unmodulated lightwaves through a feeder bus to the optical waveguides serving as interconnects. Prior (static) wavelength assignments are made for WDM-based connections between all cluster pairs. The number of connections for all-to-all connectivity in \( N \)-cluster optical interconnect topology is \( C_N \times 2 \) or \( N(N-1) \).

A. 2-D Folded Torus Topology

A typical 16-cluster (Clusters \( C_{0,15} \)) 2DFT topology is illustrated in Fig. 3 [1][2], wherein the ONoC realizes inter-cluster communication over optical waveguides constituting transport matrix (TM) rings, using wavelength-selective MRR-based switches, viz., gateway switch (GS), injection switch (IS), network switch (NS) and ejection switch (ES). In Fig. 3, the GS routes the signal from the source cluster to the unidirectional TM rings, the IS injects the signal from the unidirectional TM ring to the bi-directional TM rings (using two counter-propagating unidirectional rings), the NS navigates the signal over the bi-directional TM rings and the ES finally routes the signal towards the destination cluster. The communication between a set of clusters is realized by routing modulated signal from the GS of the source cluster (using the IS, assigned to each cluster) into TM rings, where wavelength-specific MRRs in the non-blocking NSs forward the signal to the ES of the destination cluster. At the ES, the modulated signal is photodetected to recover the information (Fig. 3).
Fig. 3, 16 out of $16 \times 2 = 240$ connections can be sourced concurrently. To support higher concurrent connectivities, even with coarse WDM (CWDM) transmission, where $\Delta \lambda = 2.4\text{nm}$ in 50 nm WDM window [10], the design becomes complex to accommodate more MRRs as well as multiple torus rings with larger chips, which in turn increases optical loss and switch crosstalk along the signal pathways, thereby degrading the receiver BER.

B. Corona

Corona is another ONoC realization incorporated into a 3-D chip interconnecting 256 cores arranged in 64 clusters [3]. For the comparison with the proposed MSB topology, a 16-cluster version of Corona (much shorter version of the one presented in [3]) is illustrated in Fig. 4. Each cluster uses a dedicated waveguide (bus) originating from itself, through which it receives a fixed set of wavelengths from the remaining clusters through MRRs as modulators; finally the bus terminates back at the originating cluster forming a broken (incomplete) ring. Corona supports dense WDM (DWDM) (62 wavelengths with $\Delta \lambda = 0.8\text{nm}$ in 50 nm WDM window [10]) on a single bus.

In Corona, the number of waveguides equals the number of clusters ($N$) which traverse long serpentine paths through all the clusters; however, the number of wavelengths (each with 10Gbps rate) multiplexed on a bus ($\Delta$) is $(N-1)$ or $2(N-1)$ or $5(N-1)$ for 10/20/50Gbps inter-cluster speed, respectively. A 4-cluster Corona can support all the 12 inter-cluster connections concurrently with a $\Delta$ of 3/6/15 for 10/20/50Gbps inter-cluster speed, whereas a 16-cluster Corona supports all 240 inter-cluster connections concurrently with a $\Delta$ of 15/30 for 10/20Gbps inter-cluster speed. The geometrical pattern increases waveguide losses and, when DWDM is employed over these waveguides, several MRRs are needed on each waveguide causing high insertion loss and DWDM crosstalk, thereby degrading BER performance.

C. Single Folded Bus (SFB)

A 4-cluster SFB topology using a simplified Corona (single bus) is considered in Fig. 5, wherein all clusters share a single folded bus, composed of inner and outer waveguides traversing each cluster. Each cluster uses a number of MRRs to modulate lightwaves for different wavelengths on the outer waveguide and another set of MRRs on the inner waveguide to receive the desired WDM channels. The SFB topology uses DWDM connectivity on the inner and outer waveguides, at the most with 62 wavelengths on a single bus. However, notwithstanding its simple topology, insertion losses at large number of MRRs and waveguiding losses between cluster pairs contribute to large signal losses, along with DWDM-induced crosstalk components, which in turn can degrade the BER performance significantly with large number of clusters.

In $N$-cluster SFB, $\Delta$ required per bus is $N(N-1)$ or $2N(N-1)$ or $5N(N-1)$ for 10/20/50Gbps inter-cluster speed, respectively. 4-Cluster SFB can support all 12 concurrent connections by multiplexing $\Delta = 12/24/60$ wavelengths for 10/20/50Gbps inter-cluster speed. However, in 16-cluster SFB, $\Delta$ required for 10Gbps inter-cluster connectivity is 240, but the maximum wavelengths available in DWDM are 62; hence 16-cluster SFB cannot be realized for all connections.

IV. MULTIPLE-SEGMENT BUS (MSB) TOPOLOGY

Having discussed the salient features of the above topologies, we propose next a novel interconnect topology [4] (Fig. 6 for 16 clusters), employing shorter multiple-segment buses (MSB), wherein each segment passes through fewer clusters as compared to Corona. In 16-cluster MSB (Fig. 6), two successive rows of clusters (RCs) from the top, i.e., RC(0) and RC(1) are connected by one pair of clockwise (CW) and counter-clockwise (CCW) segmented buses. Similarly, RC(1)-RC(2), RC(2)-RC(3) and RC(3)-RC(0) connectivities are ensured by three more CW-CCW pairs of segmented buses. Generically, this implies that, MSB ensures direct single-bus connectivity ($SB_{sd}$) between an RC-pair (i.e., between a source RC, say RC($s$), and a destination RC, say RC($d$), following the rule given by: $SB_{sd}$ connects RC($s$)-RC($d$), where, $s = i\lceil \log_2(N-1) \rceil$, $d = (i+1)\lceil \log_2(N-1) \rceil$ and $i \in \{0, 1, \ldots, N-1\}$, with $N$ as the number of clusters in a given NoC. However, to provide connectivity between vertically non-adjacent RC pairs, viz., for RC(0)-RC(2) and RC(1)-RC(3), MSB uses ISRs (as discussed earlier in Section II B), enabling lightwaves to switch from one bus to another.

Thus, the inter-cluster communication scenario in MSB can be split into two parts: the first, being direct inter-cluster communication, which is facilitated between clusters connected by a direct waveguide segment, and the second, being the indirect inter-cluster communication which requires a pair of disjoint waveguides and ISRs, with ISRs coupling lightwave at a specific wavelength from one waveguide to another.
In Fig. 6, on bus SB_{01}, each of the 4 clusters in RC(0) \{C_{0,3}\} communicates with the 4 clusters in RC(1) \{C_{4,7}\}, and C_4 communicates with C_{5,7}. C_5 communicates with C_{6,7}, and finally C_6 communicates with C_7. Hence on a bus, \(4 \times 4 + 3 + 2 + 1 = 22\) direct inter-cluster connections are sourced concurrently. A total of \(22 \times 8 = 176\) direct (single bus) inter-cluster connections can be sourced concurrently, on all the 8 segmented waveguides.

However, in Fig. 6, each of the 4 clusters in RC(3) (i.e., from \{C_{12,15}\}), communicates with 2 clusters in RC(1), viz., \{C_{4,5}\} using buses SB_{30} and SB_{01} via the ISR R_1. The clusters \{C_{12,15}\} do not communicate directly with the clusters \{C_{6,7}\}, due to distance constraints and larger number of MRRs on the pathway. Instead the clusters \{C_{12,15}\} communicate with the clusters \{C_{6,7}\} over waveguide segments SB_{12} and SB_{21} using the ISR R_7, thereby supporting 8 indirect connections using multiple buses and ISR. Similarly, on bus SB_{01}, each of the 4 clusters in RC(0) (i.e., \{C_{0,3}\}), communicates with 2 clusters in RC(2), viz., \{C_{10,11}\} over the ISR R_2 and SB_{12}. Also, \{C_{0,3}\} do not communicate directly with \{C_{6,7}\}, due to distance constraints and larger number of MRRs on the pathway. Instead \{C_{0,3}\} communicate with \{C_{6,7}\} over waveguide segments SB_{03} and SB_{52} using the ISR R_5, thereby supporting another 8 indirect connections.

Hence, overall a total of 16 indirect inter-cluster connections can be supported concurrently on 2 pairs of vertically adjacent waveguide segments. There exist a total of 8 pairs of waveguide segments, each supporting 8 indirect inter-cluster connections, totaling \(8 \times 8 = 64\) indirect multiple-bus inter-cluster connections in 16-cluster MSB topology.

### A. 10-Gbps 16-Cluster MSB Topology

Summing up the requirements of 22 direct inter-cluster communications and 16 indirect inter-cluster communications on segmented bus, the total number of wavelengths required on a bus is 38. Since the other waveguides are disjoint from each other, all the 38 wavelengths can be reused independently on each of the other waveguide buses, thereby supporting 176 (direct single-bus connections) + 64 (indirect multiple-bus connections through ISR) = 240 inter-cluster communications with 38 wavelengths at 10Gbps inter-cluster speed. Moreover, with this interconnection scheme, the total number of MRRs on each segmented bus turns out to be 60 and the number of MRR modulators and detectors is 30 per cluster. Thus, the 10Gbps 16-cluster MSB topology achieves load balancing, by distributing the inter-cluster traffic uniformly over all the segmented waveguides. This implies the uniform distribution of MRR-based modulators, detectors and ISRs over all segmented waveguides.

From a generic viewpoint, for \(N\)-Cluster MSB topology, the number of waveguides required is \(N/2\), however the values of \(\Delta\) required is 6/12/30 for 10/20/50Gbps inter-cluster speeds in 4-cluster MSB, 38/60 for 10/20Gbps inter-cluster speeds (20Gbps design with \(\Delta = 60\) discussed later) in 16-cluster MSB. 4- and 16-cluster Corona topologies optimize \(\Delta\) with CWDM conceding marginal WDM crosstalk by increasing the number of waveguides. 4-Cluster SFB, on the other hand, attempts to multiplex multiple wavelengths on a single folded waveguide, which increases the crosstalk. A compromise between Corona and SFB is achieved, by decreasing the number of waveguides in MSB by 50% of that of Corona, which almost doubles \(\Delta\) and increases the crosstalk as compared to Corona. Nevertheless, in 16-cluster Corona, the number of clusters traversed by a signal is always 16, whereas the maximum number of clusters traversed in MSB reduces to 12 with the use of four ISRs (R1 through R4), and to 10 with the use of eight ISRs (R1 through R8). Therefore, as compared to Corona, the signal losses in MSB along the traversed paths decreases significantly due to the lesser path lengths (even with the signal losses due to additional ISRs), thereby relaxing the power budget for a specified BER limit. However, design considerations would change when one wants to have 20Gbps speed for the possible inter-cluster communications on 16-cluster MSB. We consider this aspect in the following.

### B. 20-Gbps 16-Cluster MSB Topology

The finite rise and fall times in MRR response is reflected in the maximum modulation rate that can be achieved. It has been found to date, that the maximum modulation rate of MRR is usually 10Gbps [10]. Therefore, for 20Gbps inter-cluster speed, two wavelengths per inter-cluster communication will be required. The total number of wavelengths required will be double of that required for 10Gbps inter-cluster speed, i.e., \(38 \times 2 = 76\) wavelengths will be required. However, the maximum number of wavelengths available in the DWDM spectrum is 62 [10]. Hence, it is not possible to support all the 240 inter-cluster communications at 20Gbps. To confine the wavelength requirement to 62, all the 22 direct inter-cluster communications on each segmented bus (as mentioned earlier in Sec. IV A) can be made at 20Gbps by extending the wavelength requirement of 22 wavelengths at 10Gbps to 44 wavelengths each operating at 10Gbps. The remaining 16 (i.e., \(38 - 22\)) inter-cluster communications will proceed at 10Gbps, i.e., requiring 16 wavelengths. Hence, combining the wavelength requirements of direct and indirect inter-cluster communication, a total of \(44 + 16 = 60\) wavelengths are required.
Restricting the wavelength requirement to 60 from an initial requirement of 76, sacrifice is made in terms of the number of inter-cluster communication which proceeds at 20Gbps. All the 176 direct inter-cluster communications takes place at 20Gbps, and the rest of the 64 indirect inter-cluster communications take place at 10Gbps. Hence, 73.33% of the inter-cluster communications run at 20Gbps while the rest of the 26.67% inter-cluster communications take place at 10Gbps, with a wavelength requirement of 60. The total number of MRRs per segmented bus turns out to be 104 and the number of MRR modulators and detectors becomes 52 per cluster.

C. 10-Gbps 64-Cluster Modular MSB Topology

The proposed MSB topology (for 10Gbps inter-cluster communication speed), when extended to higher cluster sizes (64-clusters and more), incurs high waveguide losses and DWDM crosstalk, which is expected to degrade BER. Another parameter, which prevents scaling up of MSB topology, is the number of inter-cluster connections which can be supported concurrently, due to the upper limit of 62 wavelengths in DWDM environment. However, one can get around both of these problems by dividing a bigger ONoC into multiple 16-cluster MSB units (MUs) and introducing a modular topology that supports OEO conversion while communicating between a pair of 16-cluster MUs.

The degree of OEO defines the number of times, the signal passes from the optical to the electrical domain, where the signal is retimed, regenerated and refreshed, before passing from the electrical to the optical domain. This aids in refreshing the signal at each OEO hop, and also allows reuse of wavelengths in the MUs. The above proposition leads to dividing the 64-cluster ONoC, into MUs, wherein all connections are established between constituent clusters in optical domain. Each of the clusters in a MU is assigned a set of gateway clusters (GCs), to which it routes traffic destined for another MU. The selection of GCs for clusters in an MU, is made such that none of the GCs are overburdened, and also, the signal loss from the clusters to the GC is minimized. In Fig. 7, the set of GCs, for MU$_0$ are the clusters \{C$_{24-27}$\}, for MU$_1$ the GCs are \{C$_{28-31}$\}, for MU$_2$, the GCs are \{C$_{32-35}$\} and for MU$_3$, the GCs are \{C$_{36-39}$\}. It may be noted that, in the inter-MU connections, if the source and destination clusters are located within one GC, no OEO conversion is needed. The maximum number of OEO conversions (referred hereafter as degree) for a given inter-cluster connection in 64-cluster modular MSB is 2, hence the $^{64}C_2 \times 2 = 4032$ connections can be divided into degree 0, 1 and 2, depending on the respective number of OEO conversions (where degree-0 implies a single-hop all-optical connection without any OEO conversion).

In all 4 MUs, all the $240 \times 4 = 960$ intra-MU connections are setup optically, and communications between the GCs of each MU also proceed ($16 \times 15 = 240$) wholly in the optical domain. Thereby, $960 + 240 = 1200$ inter-cluster connections proceed with degree-0 OEO. The inter-MU communications,
wherein each of the 12 clusters in the source MU (barring the 4 GCs in the source MU), communicates with the GCs of the other MUs with degree-1 OEO. Hence, the total number of inter-cluster connections with degree-1 OEO is 12 (clusters in source MU) × 12 (GCs in destination MU) × 4 (number of MUs) = 576. Out of the 4032 inter-cluster connections, 1776 inter-cluster connections proceed either with degree-0 or degree-1 OEO, the remaining 2256 inter-cluster connections proceed with degree-2 OEO.

However, an upper limit to the number of wavelengths (62) in DWDM connections, which can be multiplexed on an inter-MU bus (IMB), sets an upper threshold to the number of connections between MU pairs. A maximum of 60 connections can be made over one bus; therefore, 60 × 2 = 120 connections can be made over a pair of IMBs. Thus, the number of connections which can be sourced concurrently in 64-cluster modular MSB topology is 960 (intra-MU) + 120 (inter-MU) = 1080 inter-cluster connections. By multiplexing data of multiple connections in the electrical domain, for inter-MU communication, logically higher connections can be established, though at the cost of some queuing delay at GCSs.

V. BER Evaluation in Optical Interconnects

In this section, we present an exhaustive BER evaluation model for ONoC, hitherto not explored much in the literature, which is applicable to all possible interconnect topologies, with varying degrees of losses and crosstalk interference, governed by the topology under consideration [4]. We consider a pair of clusters located at a distance from each other, having inter-cluster lightwave communication between two cores, each core taken from one of the two given clusters. The lightwave received at the destination cluster in presence of crosstalk is expressed as

\[ E_R(t) = \sqrt{2P(b_i)} \cos(2\pi f_s t + \theta_i + \phi_i(t)) + E_{\text{xt}}(t) \] (7)

The first term on the right hand side of (7) describes the signal component received at the destination cluster, \( P(b_i) \) is the bit dependent received signal power taking into account all the losses along the pathway, wherein \( b_i \in \{0, 1\}, f_s \) is the signal frequency, \( \theta_i \) is the initial phase and \( \phi_i(t) \) is the phase noise of the signal component of the lightwave. \( E_{\text{xt}}(t) \) defines the accumulated crosstalk component given by

\[ E_{\text{xt}}(t) = \sum_{j=1}^{W} \sqrt{2P_{sj}} \cos(2\pi f_s t + \theta_j + \phi_j(t)) \] (8)

where \( W \) represents the number of crosstalk components, \( P_{sj} \) is the received power of the \( j^{th} \) crosstalk component, \( f_s \) is the frequency of the \( j^{th} \) crosstalk component, \( \theta_j \) and \( \phi_j(t) \) are the initial phase and phase noise of the \( j^{th} \) crosstalk component. The photocurrent produced at the photodetector output is expressed as

\[ i_p(t) = R_0 < E_R^2(t) > + i_{th}(t) + i_{sh}(t) \] (9)

The first time on the right hand side of (9) defines the square-and-average operation of the photodetector on the received lightwave, with \( R_0 \) as the photodetector responsivity, the second term is the thermal noise of the receiver and the third term represents the signal-dependent (signal as well as crosstalk) shot noise. The first term of right hand side of (9) can be expressed as

\[ R_0 < E_R^2(t) > = i_s(t) + i_{sx}(t) + i_{sx}(t) \] (10)

where \( i_s(t) \) is the signal component of the photocurrent, \( i_{sx}(t) \) and \( i_{sh}(t) \) represent the crosstalk-crosstalk and signal-crosstalk beat noise components. We express \( i_s(t) \), \( i_{sx}(t) \) and \( i_{sh}(t) \) as

\[ i_s(t) = R_0 P_{b_s} = \sum_{j=1}^{W} \sqrt{P_{sj}} \cos(\omega_j t + \theta_j - \Theta_s + \phi_j(t) - \phi_s(t)) \] (11)

\[ i_{sx}(t) = 2R_0 \sum_{j=1}^{W} P_{sj} b_j \cos(\omega_j t + \theta_j - \Theta_j + \phi_j(t) - \phi_j(t)) \] (12)

\[ i_{sh}(t) = 2R_0 \sum_{j=1}^{W} P_{sj} b_j \cos(\omega_j t + \theta_j - \Theta_j + \phi_j(t) - \phi_j(t)) \] (13)

where, \( \omega_j \) = \( \omega_s - \omega_j \) and \( \omega_j \) = \( \omega_j - \omega_k \) represent the respective beat-noise frequencies. The combined electrical noise (shot noise, thermal noise and signal-crosstalk beat noise (crosstalk-crosstalk beat noise ignored)) after photodetection is modeled as a zero-mean Gaussian random process with the variance expressed as

\[ \sigma_{b_s}^2 = \sigma_{sx}^2 + \sigma_{sh}^2 \] (14)

where \( \sigma_{b_s}^2 \) is thermal noise variance with \( R \) as input resistance, \( B_s \) as noise equivalent bandwidth of the optical receiver, \( k \) as Boltzmann’s constant, \( T \) as receiver temperature and, \( \sigma_{sh}^2 \) represents the shot noise variance, given by

\[ \sigma_{sh}^2 = 4kTB_s/R \] (15)

\[ \sigma_{sx}^2 = 2qR_0 [P(b_s) + \sum_{j=1}^{W} P_{sj} B_s] \] (16)

and the worst-case signal-crosstalk beat noise variance \( \sigma_{sx}^2 \) is:

\[ \sigma_{sx}^2 = R_0^2 \sum_{j=1}^{W} P_{sj} P_{b_j} \] (17)

The receiver BER (\( P_b \)) can be evaluated as

\[ \text{BER}(P_b) = P(1)P(0/1) + P(0)P(1/0) \] (18)

where, \( P(0) \) and \( P(1) \) are the transmission probabilities of ‘0’ and ‘1’ and, \( P(1/0) \) and \( P(0/1) \) are the respective conditional error probabilities. Under the Gaussian assumption for the probability density functions, \( P_b \) can be expressed as [13]

\[ P_b = 0.5erfc(Q/\sqrt{2}) \] (19)

where \( Q = R_0[P(1)-P(0)]/(\sigma_t + \sigma_0) \) and the noise variances for the bits \( \{b_i\} \) are given by

\[ \sigma_{b_i}^2 = R_0^2 \sum_{j=1}^{W} P_{sj} / 4kTB_s \] (20)

for \( b_i \in \{0, 1\} \).

A. BER with Error-Correcting Codes

In case of optical interconnect topologies designed for higher cluster sizes, with high waveguide loss and WDM crosstalk, the BER might exceed an acceptable level (assumed as 10^{-3} in our study, as usually desired in optical interconnects to ensure high-speed data transfer in the order of a few Gbps [11][12]) with launched (transmitted) power remaining below 1.5mW per wavelength. Under such circumstances, it becomes imperative to incorporate suitable forward error-correcting
code (FEC) [13][14] to achieve an acceptable transmission quality. The Reed-Solomon (RS) codes are capable of correcting bursty errors, with low implementation overhead. RS \((n, k)\) coding schemes with \(n > k\), provide mapping of \(k\) data symbols to error-resilient \(n\) codeword symbols. The most popular form of conventional RS coding scheme defines \((n, k)\) as

\[
(n,k) = (2^m - 1,2^m - 1 - 2t)
\]  

(21)

where for every \(k \times m\) source data bits, \(n \times m\) encoded bits must be transmitted, to provide for an error correction of \(t\) symbols. Hence this RS coding scheme reduces the transmitted data rate to \(k/n\) times the source data rate, however with a perceptible improvement in the transmission quality. Considering the RS \((n, k)\) code defined by (21), the uncoded symbol error probability \(P_s\) can be expressed in terms of the uncoded BER \(P_b\) as

\[
P_s = 1 - (1 - P_b)^n
\]  

(22)

The RS-coded symbol error probability \((P_s)\) is related to the uncoded symbol error probability \((P_s)\), given by

\[
P_s \approx \frac{1}{n} \sum_{i=1}^{n} C_i P_s^i (1 - P_s)^{n-i}
\]  

(23)

This leads to the RS-coded BER \((P_b)\), expressed as

\[
P_b = 1 - (1 - P_s)^{1/m}
\]  

(24)

**B. Performance Comparison Between ONoC Topologies**

Numerical computations have been carried out to evaluate the BER performance of the above interconnect topologies (chip area: \(20\,\text{mm} \times 20\,\text{mm}\) for 4 and 16-cluster ONoC, \(45\,\text{mm} \times 45\,\text{mm}\) for 64-cluster ONoC). The maximum transmit power per wavelength needs to be limited within 1.5mW to prevent any resonance shift in MRRs [10]. Data rate is assumed to be 10Gbps per wavelength [10] along with the following device parameters: receiver transimpedance \((R) = 316\,\Omega (\equiv 50\,\text{dB} \,\Omega)\), \(R_s =0.75\,\text{A/W}\) [9], MRR modulator extinction ratio = -15dB/-0.1dB (for binary 0/1 transmission) [6], waveguide loss = 2dB/cm, waveguide bending loss = 0.005dB/90\(^\circ\), photodetector loss = 1.5dB [9], MRR pass-through loss = 0.005dB and ISR loss (16-Cluster MSB) = 1dB [1]. In 2DFT [1][2], loss at waveguide crossing (WC) = 0.05dB. loss through an IS = 0.36dB, loss at an IS during injection into the network = 0.55dB, loss through an ES = 0.25dB, loss at an ES during ejection from the network = 0.55dB, loss at a NS = 0.71dB. 2DFT switch crosstalks are assumed negligible, while inter-channel crosstalks (in Corona/SFB/MSB) will depend on wavelength spacing; for closely-spaced wavelengths (DWDM channels), it will vary in 23-30dB range for adjacent and next-adjacent channels. With these physical parameters, we present the results of BER analysis for the four topologies. The total signal loss \((TL)\) along a typical signal path can be calculated as follows from the numbers of MRR modulators/detectors \((N_m\) and \(N_d\) respectively, which contribute to MRR pass-through losses), the number of waveguide bends \((N_b)\), the total waveguiding length \((L_w)\), photo-detector loss \((1.5\,\text{dB})\) and ISR losses \((L_{ISR},\) applicable only to 16-cluster and 64-cluster MSB topology).

\[
TL(dB) = 0.005(N_m + N_d + N_b) + 2L_w + 1.5 + L_{ISR}
\]  

(25)

The issue of large waveguide distances and high crosstalk in SFB compounds the adverse effect on BER, as compared to Corona, where the waveguide distance and crosstalk are lower. A compromise between SFB and Corona is obtained in designing the MSB topology, which effectively halves the waveguides required in Corona by doubling the value of \(\Delta\), however increasing the crosstalk. But, the lower waveguide distances required for the end-to-end connections using
multiple shorter segments and ISRs in MSB cause lesser waveguide losses, with the net effect (of crosstalk increase and loss reduction) eventually decreasing the BER.

In Fig. 9, the BER performance of 16-cluster 2DFT, Corona and MSB is observed for a maximum launched power of 1.5mW per wavelength. The scalability of 2DFT topology to 16-clusters for supporting all-to-all connectivity is limited, due to the heightened complexity of the layout. As discussed in the above section, SFB cannot be scaled to higher cluster sizes due to an upper limit on the Δ. The high waveguide loss (≈ 25dB), though with low crosstalk in 16-cluster Corona, degrades the BER performance. In 16-cluster MSB, comparatively lower signal losses, even with higher crosstalk provides for a better signal quality at the receiver (Pb ≈ 10−7), though this is much above the considered acceptable transmission quality (Pb ≈ 10−10).

| TABLE II PERFORMANCES OF 16-CLUSTER ONOC TOPOLOGIES WITHOUT RS CODING |
|-----------------------------|---------|---------|-------------------|-----------------------------|
| ONoC Topology               | Speed in Gbps | Δ       | Crosstalk         | Signal Loss (dB) | Pb with launched power of 1.5mW |
| 2DFT (24/40 TM rings)       | 10      | -       | Negligible        | 19.17           | ≈ 10−15                      |
| Corona (16 wave-guides)     | 10/15   | 20      | Marginal DWDM     | 25.83dB         | ≈ 10−9                      |
| MSB (8 wave-guide segments) | 10/38   | 20/60   | DWDM              | 17.85           | ≈ 10−9                      |

As evident in Table II, the BER achieved by the 16-cluster ONoC topologies is higher than the acceptable BER. To lower the BER to the acceptable limit of 10−10, RS coding is done. The choice of RS code across source-destination clusters should be optimized so as to keep the implementation complexity of the RS code low, for achieving the desired transmission quality at higher r = k/n ratio (which defines the effective data rate).

In case of 16-cluster Corona, the uncoded BER (Pb) is ≈ 10−2. To improve the transmission quality by lowering the BER to ≈ 10−10, an intensive RS coding is required, which is capable of correcting higher number of symbol errors (t). In 16-cluster Corona, the RS coding scheme used is RS(255,165) for 10Gbps inter-cluster speed, which corrects 45 symbol errors and RS(511,311) for 20Gbps inter-cluster speed, which corrects 100 symbol errors. Thus, the computational overhead of the RS coding scheme turns out to be very high in Corona, and the data rate is lowered due to lower k/n ratio.

On the other hand, 16-cluster MSB has an uncoded BER of ≈ 10−7, which can be lowered to the acceptable BER of 10−10, by using RS(63,61) and RS(31,29) for 10Gbps and 20Gbps inter-cluster speed (Fig.10). In both the cases, the error corrected is 1 symbol per 63/31 codeword symbols for 10/20Gbps inter-cluster speed. As compared to Corona, the effective RS-coded data rate in 16-cluster MSB is higher (higher k/n ratio), with much lower complexity for RS coding scheme.

As evident from Fig. 11, in 64-cluster Modular MSB topology, all the 4032 inter-cluster connections take place with an uncoded BER (Pb) > 10−8; hence RS coding is required in 64-cluster Modular MSB to lower the uncoded BER. For the 240 intra-MU connectivity in 4 MUs, inter-cluster connections are encoded by RS(63,61) for 10Gbps inter-cluster speed.

Table III accounts for the BER range in which the 240 × 4 = 960 inter-cluster connections lie, with RS (63, 61) coding in 16-cluster intra-MU scenario. The inter-MU connection scenario is analyzed in Table IV.

In multi-hop modular MSB environment of 64 clusters with 4 MUs, the BER for all inter-cluster connections is the highest BER path, the signal traverses from the source to the
TABLE III

<table>
<thead>
<tr>
<th>BER Range</th>
<th>Number of intra-MU connections with RS(63,61)</th>
<th>Number for all 4 MUs</th>
</tr>
</thead>
<tbody>
<tr>
<td>10^{-10} - 10^{-11}</td>
<td>16</td>
<td>16 x 4 = 64</td>
</tr>
<tr>
<td>10^{-11} - 10^{-12}</td>
<td>32</td>
<td>32 x 4 = 128</td>
</tr>
<tr>
<td>10^{-12} - 10^{-13}</td>
<td>192</td>
<td>192 x 4 = 768</td>
</tr>
</tbody>
</table>

TABLE IV

<table>
<thead>
<tr>
<th>Source MU - Destination MU (Count of Inter-MU Connection)</th>
<th>Inter-MU signal loss</th>
<th>RS coding</th>
</tr>
</thead>
<tbody>
<tr>
<td>MU1 - MU1, MU2 - MU1, MU3 - MU1, MU4 - MU1, MU5 - MU1, MU6 - MU1, MU7 - MU1, MU8 - MU1, MU9 - MU1, MU10 - MU1, MU11 - MU1, MU12 - MU1</td>
<td>21.1dB</td>
<td>RS(255,247)</td>
</tr>
<tr>
<td>MU1 - MU2, MU3 - MU2, MU4 - MU2, MU5 - MU2, MU6 - MU2, MU7 - MU2, MU8 - MU2, MU9 - MU2, MU10 - MU2, MU11 - MU2, MU12 - MU2</td>
<td>15.95dB</td>
<td>RS(255,253)</td>
</tr>
</tbody>
</table>

destination cluster across MUs. The maximum inter-cluster signal loss in intra-MU 16-cluster 10Gbps MSB topology is 17.645dB. For those 6 inter-MU connections (to carry 6 x 16 x 16 = 1536 inter-cluster connections), where the inter-MU signal loss is 21.1dB (Table IV), the RS(255,247) coding schemes lower the uncoded BER (P_b of ≈ 10^{-6}) to RS-coded BER (P_b of ≈ 10^{-10}). The 4 inter-MU connections, i.e., 4 x 256 = 1024 inter-cluster connections, with a signal loss of 15.95dB between the source and destination MUs, uses RS (255,253) coding to lower the BER to ≈ 10^{-10} (Table IV). Through a detailed study into the remaining 2 inter-MU connections (i.e., 2 x 256 = 512 inter-cluster connections), it is revealed that 120 connections proceed with a BER in the range 10^{-10} - 10^{-11}, while 392 inter-cluster connections proceed with a BER in the range 10^{-11} - 10^{-12}. Summing up the entire 4032 inter-cluster communication scenario (with RS coding wherever necessary, as per Tables III and IV), it is observed that 64 (intra-MU) + (1536 + 1024 + 120) (inter-MU) = 2744 inter-cluster connections proceed with BER in the range 10^{-10} - 10^{-11}, 128(intra-MU) + 392 (inter-MU) = 520 inter-cluster connections proceed with BER in the range 10^{-11} - 10^{-12}, whereas the remaining 768 (intra-MU) inter-cluster connections proceed with a BER in the range 10^{-12} - 10^{-13}.

VI. IMPACT OF THERMAL MISTUNING

Thermal transients due to time-varying voltage biases (from high-speed data streams) applied for electro-optic tuning of MRR-modulators cause mistuning of MRRs (i.e., drift of the MRR resonating frequencies from the desired values, due to thermo-optic effect). The study in this section examines this issue and attempts to assess how it affects the BER values in terms of an MRR parameter, extinction ratio (ER), defined as

\[ ER = 10 \log_{10} \left( \frac{P_1}{P_0} \right) \]  

where P_1 and P_0 represent the output power from the modulator in case of modulating bit ‘1’ or bit ‘0’, respectively. The operation of a detuned MRR-based modulator can be explained using a transfer function model as follows. The spectrum of the transmitted power at the MRR-modulator’s waveguide output port \( P_{out}(f) \) is related to the laser spectrum \( P_{in}(f) \), incident at the ring-waveguide interface on the input side and the shifted MRR transfer function \( G_m(f') \) around \( f' = f - \Delta f \) (with \( j = 0, 1 \)) (with \( \theta = 0, 1 \) for \( P_0 \) and \( P_1 \) respectively, and \( \Delta f \) is the detuned MRR frequency offset for binary ‘1’ transmission) as follows

\[ P_{out}(f) = G_m(f') P_{in}(f) \]  

(27)

The power spectrum of the laser can be assumed to follow a Lorentzian profile, given by

\[ P_{in}(f) = \frac{\lambda^2}{4 \pi^2 N_0} \left[ \frac{1}{(f + f_0)^2 + \left( \frac{1}{N_0} \right)^2} + \frac{1}{(f - f_0)^2 + \left( \frac{1}{N_0} \right)^2} \right] \]  

(28)

where the spectral density of the laser frequency noise, \( N_0 = B_L/(2\pi) \), depends on the 3-dB laser linewidth \( B_L \). In order to find the transfer functions of tuned/detuned MRRs, the term \( \theta + \phi = \theta + \phi \) in (4) can now be expressed as

\[ \theta + \phi = \frac{2\pi}{\lambda} n_{eff}(\lambda')L = \frac{2\pi}{\lambda} n_{eff}(f')L \]  

(29)

where \( \lambda' \) is the resonant wavelength of the MRR (\( f' = c/\lambda' \) with \( c \) as the speed of light in vacuum), \( n_{eff}(\lambda') \) or \( n_{eff}(f') \) is the effective refractive index of the dielectric waveguide which forms the MRR and \( L \) is the path length (as defined in Section II A) encountered by light along the MRR. The MRR transfer function in (4) is accordingly transformed as

\[ G_m(f') = \left( \frac{b_0}{a_0} \right)^2 \left[ \frac{|1 + \alpha^2 - 2\alpha |}{1 + \alpha^2 - 2\alpha} \right] \]  

(30)

For modulating bit ‘1’ and ‘0’, the output power power \( P_{out}(f) \) can be found by detuning the MRR modulator on application of bias as

\[ P_{out}(f) = \int G_m(f - j\Delta f) P_{in}(f) df \]  

(31)

Thus, ER can be found by substituting (31) in (26) for \( j = 0 \) and 1, wherein the limits of integration for (31) varies in the range \( f_{OFF} + j\Delta f - FSR \) to \( f_{OFF} + j\Delta f + FSR \), where \( f_{OFF} \) is the resonant frequency of MRR when its bias is kept off and FSR is the free-spectral range of MRR. It may be noted that, with increase in laser linewidth \( (B_L) \), the input laser power spectrum \( (P_{in}(f)) \) spreads, and the power absorbed by MRR around the resonating frequency decreases, which in turn reduces ER (Table V). In presence of thermal mistuning the resonant frequencies of MRRs \( (f_{OFF}) \) wander around randomly, affecting the ER values, which in turn degrades the BER performance of the optical interconnects. In the following we determine the impact of thermal mistuning on ER and how this affects the BER.

A. ER due to a Given Fixed Mistuning of MRR

The transient thermal changes in ONoC can off-tune an MRR from its resonant frequency \( (f_{OFF}) \) by \( \delta f = \pm a_T \Delta f \) (with \( a_T \) as the coefficient of thermal mistuning), thereby increasing \( P_0 \) to \( P_{OFF} \) however keeping \( P_1 \) practically constant (during \( P_1 \) transmission the MRR remains far off-tuned from the input lightwave spectrum
causing negligible change due to mistuning). Such differential changes of $P_0$ and $P_1$ decrease the value of ER, as governed by

$$ER(\delta f_T) = 10 \log_{10} \left( \frac{P_1}{P_{0T}} \right) \quad (32)$$

Substituting (31) in (32), we get,

$$ER(\delta f_T) = 10 \log_{10} \left( \frac{\int G_m(f_{OFF} - \Delta f') P_m(f) df}{\int G_m(f_{OFF} - \delta f_T) P_m(f) df} \right) \quad (33)$$

The variation of ER for various values of 3dB laser linewidth is illustrated in Table V, where the distance between the peak powers give a tentative idea about the reduction of ER. The variation in $ER(\delta f(T))$ affects the BER, which then becomes a function of frequency shift due to thermal mistuning $(P_a(\delta f(T)))$. The variation of ER and BER with frequency drifts due to fixed thermal mistuning is shown in Fig. 12, considering $\alpha_T = 0.1$. It may be noted that, the frequency offset $(\delta f_T)$ due to thermal mistuning should be much less than the electro-optic detuning frequency offset for transmission of binary '1' (i.e., $\Delta f$). Large mistuning drifts will seriously affect (reduce) ER, thereby causing severe BER degradation. Thus, it would be desirable to have a reasonable control of thermal mistuning (i.e., $\delta f_T \ll \Delta f$, implying $\alpha_T \ll 1$) to ensure reliable transmission performance (Fig. 13).

![Fig. 12: Impact of thermal mistuning of MRR on ER](image)

**TABLE V**

<table>
<thead>
<tr>
<th>$B_L$ (MHz)</th>
<th>ER (dB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>15</td>
<td>15.29</td>
</tr>
<tr>
<td>20</td>
<td>15.00</td>
</tr>
<tr>
<td>25</td>
<td>14.72</td>
</tr>
<tr>
<td>30</td>
<td>14.46</td>
</tr>
<tr>
<td>35</td>
<td>14.22</td>
</tr>
</tbody>
</table>

where, $p(\delta f_T)$ is approximated by a Gaussian distribution with a variance $\sigma_T^2$, given by

$$p(\delta f_T) = \frac{1}{\sigma_T \sqrt{2\pi}} \exp \left( -\frac{\delta f_T^2}{2\sigma_T^2} \right) \quad (35)$$

The impact of MRR mistuning on average BER is shown in Fig. 13, which indicates that with increasing variance of $\delta f_T$, the average BER increases steeply beyond a certain threshold of $\alpha_T$. As evident from Table V, to achieve an extinction ratio of 15dB, the case on which the BER results are based, the 3dB laser linewidth should be 20MHz.

**VII. CONCLUSION**

This paper examines some novel topologies for optical interconnects used in ONoCs with due considerations to BER and transmit power constraints. Having examined the performance of some existing optical interconnects for 4- and 16-cluster ONoCs, we proposed a novel scalable topology employing the MSB configuration with ISRs. Our analysis indicates that MSB can outperform the other topologies for an achievable BER $\approx 10^{-10}$, while satisfying the 1.5mW upper-bound of launched optical power in optical buses for ONoCs with as high as 16 clusters. Subsequently, we explored the scalability of 16-cluster MSB topology for 64 clusters, using 4 modular 16-cluster MSB modules (MUs) interconnected by larger folded buses, employing multihop transmission with OEO regenerations. We also examined the use of RS codes to reduce BERs for the connections having higher BER values. Finally, an analytical model has been proposed to study the impact of thermal mistuning of MRRs in terms of ER and BER values.

**REFERENCES**


Iphita Datta received her Masters’ degree in Fibre Optics and Lightwave Engineering from Dept. of Electronics and Electrical Communication Engg., Indian Institute of Technology, Kharagpur, India. She is currently employed as an engineer in Broadcom Communication Pvt. Ltd., Bangalore, India.

Debasish Datta received his BTech degree in 1973 from Calcutta University, and MTech and PhD degrees from IIT Kharagpur in 1976 and 1986, respectively. Currently he is a Professor in the Department of Electronics and Electrical Communication Engg, at IIT Kharagpur, wherein He has been serving for over thirty-three years. From Kharagpur, he visited Stanford University during 1992-1993, University of California, Davis, during 1997-1999 and Chonbuk National University, South Korea, during 2003-2004 to work on optical communication systems and networking. Currently he is visiting University of Malaya, Kuala Lumpur, since August 2013. Prof. Datta and his group received Sir J. C. Bose Award in 1985 from IERE, UK, and the best paper award in IEEE ANTS 2008 for their work in the area of optical communication systems and networking. He served as Guest Editor for the IEEE JSAC January-2002 Special Issue on WDM-based network architectures. Presently he serves as an Editor for the IEEE Communication Surveys and Tutorials, and had earlier served in the Editorial Board of Elsevier Journal of Optical Switching and Networking. He also served as Track Chair and Technical Program Committee Co-Chair for IEEE ANTS 2009 and 2012, respectively. He also serves in the program committees of various international conferences in his area. His current research interests include wavelength-routed optical networks, passive optical networks and optical interconnects in networks-on-chips.

Partha Pande is an Associate Professor and the holder of the Boeing Centennial chair in Computer Engineering at the School of Electrical Engineering and Computer Science, Washington State University, Pullman. Prof. Pande received the M.S degree in computer science from the National University of Singapore and the Ph.D. degree in electrical and computer engineering from the University of British Columbia, Vancouver, BC, Canada. His current research interests are novel interconnect architectures for multicore chips, on-chip wireless communication networks, and hardware accelerators for biocomputing. Dr. Pande currently serves on the Editorial Board of IEEE Design and Test of Computers, ACM Journal on Emerging technologies in Computing Systems and Sustainable Computing: Informatics and Systems. He also serves in the program committee of many reputed international conferences. He has won the NSF CAREER award in 2009.