Coherent and Incoherent Crosstalk Noise Analyses in Interchip/Intrachip Optical Interconnection Networks

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Abstract—Recently, interchip/intrachip optical interconnection networks have been proposed for ultrahigh-bandwidth and low-latency communications. These networks employ the microresonators (MRs) to modulate, direct, or detect the optical signal. However, utilized MRs suffer from intrinsic crosstalk noise and signal power loss, degrading the network efficiency via the signal-to-noise ratio (SNR). The amount of crosstalk noise and signal power loss may differ from network to network. Hence, there exists a need to systematically analyze the effect of the crosstalk noise and the power loss issues. In this paper, we have developed the analytical models considering both coherent and incoherent crosstalk for both the interchip and intrachip optical networks. The interchip/intrachip optical interconnection networks—the I²CON—are analyzed as a case study. The quantitative results on the individual networks have demonstrated that the architectural design determines the impact of crosstalk on the SNR. We have also demonstrated that the optical interconnection networks with interchip/intrachip interconnects result in better bit error rate (BER) compared with that of only intrachip interconnect. Our analyses of the worst case can be utilized as a platform to compare the realistic performance among different optical interconnection networks via the degradation of SNR/BER and data bandwidth.

Index Terms—Bit error rate, crosstalk noise, intra/inter-chip optical interconnection network, signal-to-noise ratio.

I. INTRODUCTION

The International Technology Roadmap for Semiconductors predicts that CMOS feature size will shrink to 11 nm by 2020 [1]. As such, unprecedented quantities of transistors will allow computer architects to integrate hundreds or even thousands of cores into a single die. With such a large number of cores on a single die, the traditional bus-based interconnects are predicted to face fundamental physical limitations. The emergence of the network-on-chip (NoC) paradigm is expected to provide adequate communication support for future multicores [2]. However, global wire delays and energy costs do not scale down with CMOS technology. Therefore, a pure metallic-based NoC architecture still faces major challenges.

With the increasingly high demand for computational performance, NoCs have been introduced to replace the traditional interconnects. As more applications require higher computation power and, hence, a larger number of processing cores, the metallic interconnects of NoCs could hardly meet the high-bandwidth and low-latency demands. Fortunately, this issue has been addressed by the optical interconnection networks, with the utilization of the wavelength division multiplexing (WDM) technique. By integrating a large number of wavelengths into the network, the ultrahigh-bandwidth data communication can be achieved.

Hence, various optical networks with different topologies have been proposed. Among those topologies, the ring-based optical interconnects [3]–[5] are promising with their on-chip optical crossbars for ultrahigh on-chip bandwidth. These on-chip optical crossbars can improve the network latency because electrical–optical/optical–electrical converters are only needed at the end of the opened ring [3], [6]. More recently, the ring-based optical interconnects have covered not only an intrachip but also an interchip communication. These networks are composed of two different interconnection parts: 1) the optical intrachip for the on-chip communication and 2) the optical interchip is the communication among the chips. Wu et al. [7] have proposed I²CON for such interchip/intrachip optical interconnection networks.

However, one key issue for these WDM interchip/intrachip optical interconnection networks is the crosstalk noise. Crosstalk noise is an intrinsic characteristic of the optical components. Depending on the architecture of the network, the crosstalk noise can be intensified among numerous optical components in various combinations. Moreover, with the presence of a large number of wavelengths in one single waveguide (i.e., WDM-based), crosstalk noise from different wavelengths may affect the detected signal on a wavelength.

Fundamentally, the crosstalk noise can be classified into two types: 1) coherent crosstalk and 2) incoherent crosstalk.
In this paper, we formally provide the analyses of both coherent and incoherent second-order crosstalk noises. Indeed, Duong et al. [8] had given a case study on the crosstalk in ring-based WDM optical NoCs (ONoCs). However, it solely focused on incoherent crosstalk with an analysis of the data channel and the broadcast bus in one ring-based ONoC: the Corona. Another recent work on the crosstalk noise in a WDM-based ONoC is [9], which mainly focus on the incoherent crosstalk in three different topologies: 1) mesh-based; 2) folded-torus based; and 3) fat-tree-based.

In this paper, we present a systematic study on the worst case crosstalk noise for both the interchip and intrachip optical interconnection networks. At the optical-circuit level, we thoroughly model the basic optical elements to analyze the signal power loss and the crosstalk noise. Having these analytical models, we study the worst case situations for the interchip/intrachip optical networks. For the interchip part, we utilize the interchip part of I²CON [7]. Regarding the intrachip interconnect, we analyze and compare the worst case crosstalk noise in the intrachip part of I²CON and another ring-based intrachip optical network: the Corona [3]. With this bottom–up approach, all analytical models at the network level can be translated into initial device-level models for verification.

Finally, numerical values of the parameters used in our analytical equations are applied. Quantitative results of the worst case crosstalk noise, signal power loss, and signal-to-noise ratio (SNR) are presented. It should be noted that our analytical models do not depend on these numerical values. Numerical values are applied, so that we can see the trend as well as the scalability of the interchip/intrachip networks. For the intrachip network, we compare the results of the intrachip of I²CON with the Corona network at the same network size. We also explore more on the trend of the worst case by changing different parameters, such as the Q factors and the passing loss. Regarding the interchip network, we also present the trend of the worst case crosstalk noise and the SNR under different values of the parameters. Based on the worst case SNR results, we also present a comparison between the ideal and real bandwidths, as well as the power needed for sending a bit of data.

The rest of this paper is organized as follows. Section II briefly discusses the state-of-the-art of previous works, while Section III details our models for the basic optical elements. Section IV gives the detailed analyses of the worst case power loss and the crosstalk noise in the interchip and intrachip optical interconnection networks. Section V follows and provides our quantitative results and discussion. Finally, the conclusion is drawn in Section VI.

II. SUMMARY OF RELATED WORKS

At the device level, crosstalk noise has often been considered negligible. For example, the crosstalk noise of −47.4 dB was reported in [10] via a waveguide crossing, which consisted of three cascaded multimode structures. Another work by Tsarév [11] also reported the negligible loss and the crosstalk noise. Xia et al. [12] demonstrated the optical waveguide structures with compact, photonic-wire-based coupled resonators. These structures included up to 16 racetrack resonators on a silicon-on-insulator (SOI) substrate and resulted in a drop-port loss of less than 3 dB. Li et al. [13] designed and fabricated a compact third-order coupled-resonator filter on the SOI platform with focused application for on-chip optical interconnects. In this paper, they obtained a drop-port loss of less than 0.5 dB, an in-band throughput-port extinction of 12 dB, and an out-of-band drop rejection of 18 dB.

In addition, Xiao et al. [14] researched a multiwavelength microring-based structure and reported the losses.

Nonetheless, recently, the crosstalk noise issue has been increasingly investigated because of its negative impact on the network. One of the most recent works on the crosstalk noise in WDM-based ONoCs is [9], which mainly focus on the intrachip optical networks under three different topologies: 1) mesh-based; 2) folded-torus based; and 3) fat-tree-based. In this paper, we present the analyses on the first-order incoherent crosstalk noise. Besides, Duong et al. [8] reported the destructive effect of incoherent crosstalk on the SNR in the data channel and the broadcast bus of Corona ONoC.

III. CROSSTALK NOISE ANALYSES IN OPTICAL ELEMENTS

In the interconnect of Dense Wavelength-Division Multiplexing (DWDM) optical networks, the sets of basic optical devices are placed in order to bridge a source processor with other destination processors. Among those optical devices, splitter and microresonators (MRs) can form different structures for the interconnect. Their function is to perform light modulation, detection, transmission, and division. To analyze the worst case crosstalk noise in a network, we need to first establish the analyses of these MRs and optical splitters.

A. Lorentzian Power Transfer Function

MRs are intensively employed to construct optical interconnects. The MR can be coupled to two waveguides and utilized as a switching element (Fig. 1). The MR can also be coupled to a single waveguide, forming a modulator, or a detector to, respectively, modulate or detect the optical signal (Fig. 2). In general, the MR is approximated as a Lorentzian power transfer function which is peaked at the MR’s resonant wavelength $\lambda_j$ [15], [16]. For an optical signal having wavelength $\lambda_i$, the drop-port power transfer can be expressed as [14]

$$P_{\text{drop}} = \frac{P_{\text{in}}}{\left(\frac{2\kappa_e \kappa_d}{\kappa_e^2 + \kappa_d^2 + \kappa_p^2}\right)^2 \left(\frac{\delta^2}{(\lambda_i - \lambda_j)^2 + \delta^2}\right)}.$$  \hfill (1)

To simplify our analytical equations in the later stages, we define $\Phi(i, j)$ as the ratio of $(P_{\text{drop}}/P_{\text{in}})$ as in (1), where $\lambda_j$ is...
the resonant wavelength of the examined MR, and \( \lambda_i \) is the wavelength of the examined optical signal. In (1), \( \kappa_e^2 \) and \( \kappa_d^2 \) are, respectively, the fraction of the optical power that the input and the drop waveguide coupled into or out of the MR, while \( \kappa_i^2 \) is the fraction of the intrinsic power losses per round-trip in the MR. Based on recent works, for an MR, \( \kappa_e^2 = 0.003 \), \( \kappa_d^2 = 0.001 \), and \( \kappa_i^2 = 0.0025 \) [17]. Moreover, in (1), the \(-3\)-dB bandwidth of \( 2\delta \) is expressed as

\[
2\delta = \frac{\lambda_j}{\bar{Q}}
\]

where \( Q \) is the \( Q \) factor of a particular MR. We also consider the free-spectral range (FSR) of a signal via the difference between \( \lambda_j \) and \( \lambda_i \). This difference is \( \Delta(i, j) = \lambda_j - \lambda_i = (i - j)(\text{FSR}/n) \), where we assume equal spacing between two consecutive wavelengths, and \( n \) is the total number of wavelengths in the network. In this paper, \( Q \) factor is set at 9000 [6] and FSR is assumed to be 62 nm [18].

**B. Crosstalk Noise in the Optical Elements**

In optical interconnects, crosstalk noise is an intrinsic characteristic of photonic devices. It is classified as coherent and incoherent. Basically, we consider the crosstalk incoherent when the optical propagation delay differences in the network exceed the coherent time of the laser. Otherwise, we consider it coherent. Shen et al. [19] have proved that the coherent crosstalk may either contribute to the noise or cause fluctuation in the signal power. In this paper, we show the worst case results of the crosstalk noise, which happens when the coherent crosstalk is treated as noise, not as signal fluctuation. In order to calculate the generated crosstalk noise, we have utilized the Lorentzian-shape power transfer function using the near resonance state of the Lorentzian. In our future works, we will also consider other different methods, such as the matrix model.

To verify the impact of crosstalk noise in the optical interconnects, we utilize SNR, expressed in (3), as the ratio between the received signal and the crosstalk noise power at the detectors. In (3), SNR is indeed independent of the input signal power, since the input power of the signal power and the crosstalk noise power cancels out each other. As mentioned before, the noise power in the denominator includes both the coherent crosstalk and the incoherent crosstalk. Besides this, in order to facilitate the understanding of our analytical equations, Table I provides all the notations and data used in the analyses. The data, which are a projection toward the optical interconnect technology in 2020, are considered from the recent works on Corona and Coronalike interconnection networks [20]–[23]

\[
\text{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}}.
\]

**C. Optical Injectors**

Injectors are the MRs coupled into two waveguides. An injector performs as a switching element to change the light direction. Fig. 1 shows its two stages: 1) the OFF-state and 2) the ON-state. In Fig. 1, the injector is injecting wavelength \( \lambda_j \).

In the OFF-state, when the MR is OFF, the signal travels toward the through port. In this case, the signal power at the through port and the drop port is (4a) and (4c), respectively. Due to the imperfection of the coupling mode, a portion of light from all the wavelengths can be leaked into the drop port. This crosstalk noise power is incoherent and denoted by (4d). Meanwhile, the crosstalk noise power at the through port (4b) is from the signal at the add port. This crosstalk noise is coherent if the signal from the add port and the input port are generated by the same source; otherwise, it is incoherent. Besides, (4e) is the coherent crosstalk also at the through port.

\[
\begin{align*}
P_{s, T, \text{off}}[i] &= L_{i0} P_{\text{in}}[i] \quad (i = 0, 1, \ldots, n - 1) \quad (4a) \\
P_{n, T, \text{off}}[j] &= \left( X_{i0}^2 \right) P_{\text{add}}[j] \quad (4b)
\end{align*}
\]
\( P_{n,D,OFF}[j] = L_d \cdot P_{add}[j] \quad (i = 0, 1, \ldots, n - 1) \quad (4c) \)

\[
P_{n,D,OFF}[i] = \begin{cases} 
0 & (i \neq j) \\
X_i \cdot P_m[i] + \sum_{k=0}^{n-1} \Phi(k, i) \cdot P_m[k] & (k \neq i)
\end{cases} 
\quad (4d)
\]

\( P_{n\rightarrow coh,T,OFF}[i] = (X_i^2) \cdot P_m[i] \quad (i = 0, 1, \ldots, n - 1). \quad (4e) \)

Similarly, we can derive the equations for the injector in the ON-state. In this state, the signal of wavelength \( \lambda_j \) is directed to the drop port. Hence, the signal power and the incoherent noise at the through port are (5a) and (5c), respectively. Other optical signals are directed toward the through port, and their signal power is denoted by (5b). For the drop port, the signal power is (5d), while the noise is from two sources: 1) the noise from other wavelengths (5e) and 2) the noise from the optical signal at the add port (5f)

\[
P_{n,ON,T}[i] = L_i \cdot P_m[i] \quad (i \neq j) 
\quad (5a)
\]

\[
P_{n,ON,T}[j] = L_i \cdot P_m[i] 
\quad (5b)
\]

\[
P_{n,inc,ON,T}[j] = X_i \cdot P_m[i] 
\quad (5c)
\]

\[
P_{n,ON,D,1}[j] = L_i \cdot P_m[i] 
\quad (5d)
\]

\[
P_{n,ON,D,2}[j] = X_i \cdot P_m[i]. 
\quad (5f)
\]

\[
P_{n,ON,1}[j] = \sum_{i=0}^{n-1} \Phi(i, j) \cdot P_m[i] \quad (i \neq j) 
\quad (5e)
\]

\[
P_{n,ON,2}[j] = X_i \cdot P_m[i]. 
\quad (5f)
\]

D. Optical Modulators and Detectors

Similar to injectors, modulators and detectors also follow the Lorentzian transfer function. They are formed by coupling the MRs to a single waveguide. Fig. 2 shows different states of the modulators and the detectors. Similar analyses can be applied, and (6) and (7) are derived for the modulators in the INACTIVE and ACTIVE states, respectively

\[
\begin{align*}
\text{out}[i] &= L_{m0} \cdot P_m[i] \quad (i = 0 \ldots n) \\
P_{\text{OUT},[i]} &= X_{m1} \cdot P_m[i] \\
P_{\text{OUT},[j]} &= L_{m0} \cdot P_m[i] \quad (i \neq j)
\end{align*} 
\quad (6)
\]

\[
\begin{align*}
\text{out}[i] &= L_{d0} \cdot P_m[i] \\
P_{\text{OUT},[i]} &= X_{d1} \cdot P_m[i] + \sum_{i=0}^{n-1} \Phi(i, j) \cdot P_m[i] \quad (i \neq j) \\
P_{\text{OUT},[j]} &= L_{d0} \cdot P_m[i] \quad (i \neq j) \\
P_{\text{SIG}} &= L_{d0} \cdot P_m[i] \\
P_{\text{INC}} &= \sum_{i=0}^{n-1} \Phi(i, j) \cdot P_m[i] \quad (i \neq j) 
\end{align*} 
\quad (7)
\]

Meanwhile, (8a) and (8b) are for photodetectors in the PASSING mode, and (9a)–(9c) are for the detectors in the DETECTING mode

\[
\begin{align*}
\text{out}[i] &= L_{d0} \cdot P_m[i] \quad (i = 0 \ldots n) \\
P_{\text{OUT},[i]} &= X_{d1} \cdot P_m[i] + \sum_{i=0}^{n-1} \Phi(i, j) \cdot P_m[i] \quad (i \neq j) \\
P_{\text{OUT},[j]} &= L_{d0} \cdot P_m[i] \quad (i \neq j) \\
P_{\text{SIG}} &= L_{d0} \cdot P_m[i] \\
P_{\text{INC}} &= \sum_{i=0}^{n-1} \Phi(i, j) \cdot P_m[i] \quad (i \neq j)
\end{align*} 
\quad (8a) \quad (8b) \quad (9a) \quad (9b) \quad (9c)
\]

Regarding the coherent crosstalk, we consider the portion of power which can be leaked out from the leaked-in power of the MR. Equation (10a) is derived for the coherent noise in the INACTIVE-state modulators, while (10b) is for the ACTIVE-state modulators

\[
P_{n\rightarrow coh} = (X_i^2) \cdot P_m[i] + X_{m0} \sum_{i=0}^{n-1} \Phi(i, j) \cdot P_m[i] 
\quad (10a)
\]

\[
P_{n\rightarrow coh} = (X_i^2) \cdot P_m[i] + X_{m1} \sum_{i=0}^{n-1} \Phi(i, j) \cdot P_m[i]. 
\quad (10b)
\]

For the coherent crosstalk noise at the detectors, we derive (11a) and (11b) for PASSING-mode and DETECTING-mode detectors, respectively

\[
P_{n\rightarrow coh} = (X_i^2) \cdot P_m[i] + X_{d0} \sum_{i=0}^{n-1} \Phi(i, j) \cdot P_m[i] 
\quad (11a)
\]

\[
P_{n\rightarrow coh} = (X_i^2) \cdot P_m[i] + X_{d1} \sum_{i=0}^{n-1} \Phi(i, j) \cdot P_m[i]. 
\quad (11b)
\]

E. Optical Splitters

Optical splitters are utilized to allocate portions of signal power from the source to different interconnection paths. For optical interconnects with the presence of off-chip laser source (i.e., the Corona), the optical splitters are extensively exploited. In this paper, we model two common types of splitters, including 1 \( \times 2 \) and 1 \( \times 4 \) power splitters. As can be seen from Fig. 3, the light passes through the splitters and suffers from the loss of \( L_{12} \) or \( L_{14} \). Thus, (12) and (13) are, respectively, the power equations for 1 \( \times 2 \) and 1 \( \times 4 \) splitters

\[
P_{out1} = L_{s12} \cdot P_m(1 - R_{12}) \quad \text{and} \quad P_{out2} = L_{s12} \cdot P_m R_{12} 
\quad (12)
\]

\[
P_{out1} = P_{out2} = P_{out3} = P_{out4} = L_{s14} \cdot P_m R_{14}. 
\quad (13)
\]

For a 1 \( \times 2 \) splitter, we consider different split ratios at two outputs, where output 1 receives \((1 - R_{12})\) and output 2 receives \( R_{12} \) of the power from the input. For a 1 \( \times 4 \) splitter, we consider the same split ratio (i.e., \( R_{14} \)) at all the outputs. Under the scope of this paper, a negligible amount of crosstalk noise introduced by the splitters is considered.
IV. Crosstalk Noise Analyses in Interchip/Intrachip Optical Interconnection Networks

Utilizing our developed analyses on optical elements, we analyze the worst case signal power loss as well as the worst case crosstalk noise in the interchip and intrachip optical interconnection networks. In this paper, I2CON is the interchip/intrachip optical network we have chosen to perform the analyses. I2CON optical interconnect is one of the most recent works, which exploits the property of ultrahigh-bandwidth optical communication on both the interchip (between the chips) and intrachip (within the chips) networks. Regarding the intrachip of I2CON, as it utilizes a ring-based network, we have also analyzed another ring-based network—the Corona—which was one of the first ring-based ONoC in [3].

A. Worst Case Crosstalk Noise in I2CON Interchip Network

In this section, we analyze the intrachip of I2CON. However, before detailing the worst case analyses, we briefly introduce the I2CON optical interconnection network.

1) Overview of I2CON: The interchip/intrachip optical networks for manycore processors, or the so-called I2CON, are the interchip/intrachip optical networks, which utilize high-bandwidth optical communication for both on-chip and among-the-chip networks. The interchip and intrachip networks are both ring-based optical interconnects and are constructed by silicon photonic devices, including modulator [24], photodetector [25], and waveguide [20].

Fig. 4 [7] shows the logical view and the physical view of I2CON, respectively. From Fig. 4(a), it can be seen that I2CON includes an interchip network and multiple intrachip networks. The role of each intrachip network is to connect all the cores (or core clusters) on the same chip plane. Meanwhile, the interchip network is responsible for interconnecting the cores in a third dimension perpendicular to the chip plane. Hence, all the chips (for an interchip network) in I2CON are virtually stacked up, which is similar to a 3-D chip [7]. This is demonstrated in the logical view of I2CON in Fig. 4(b). It is also noted that I2CON utilizes the optical communication for its interchip/intrachip data channels. The control network of I2CON is point-to-point [7]. Hence, in this paper, we will only focus on analyzing the data channels of both the interchip and the intrachip of I2CON. Section IV-A2 will detail our worst case analyses of the I2CON interchip optical interconnection network.

2) I2CON Interchip and Its Worst Case Analyses: The interchip network performs the required communications among different chips. As shown in Fig. 4(a), the interchip network ties the core clusters with the same cluster number in different chips together. For example, the i-th data channel will connect all the i-th cluster in all the chips. Hence, a total of N data channels are formed to fully connect the network with N clusters on each chip. The data channels are identical and parallel to each other without any waveguide crossings. The control for the interchip network of I2CON is bonded by the accompanying control fabrics connected to a central arbiter chip [7]. Hence, the control network for I2CON is point-to-point and will not be analyzed under the scope of this paper. Consequently, as a convention, we will use the term I2CON interchip for the data channel of the I2CON interchip network.

Fig. 5 shows one data channel of the I2CON interchip network. For convenience, we consider the four-chip case of the I2CON interchip, which is similar to what was utilized in [7]. Other cases with different numbers of chips are very similar and can be generalized from our analyses. In Fig. 5, four chips (from 0 to 3) are connected. We denote these chips by cluster(i, j), or C(i, j), with i is the chip number and j is the cluster number. From Fig. 5, it can be seen that a closed-loop waveguide is utilized to interconnect the chips in the interchip network. However, since this waveguide needs to bridge from chip to chip, it is formed by two different sections: 1) on-chip section and 2) off-chip section. The on-chip section utilizes the on-chip silicon waveguide, which is shown in Fig. 5 (green). On the other hand, the off-chip section utilizes the on-board polymer waveguide, as shown in Fig. 5 (orange). Couplers are used to link on-chip silicon waveguide and on-board polymer waveguide. These couplers are shown in Fig. 5 (dark blue). The coupling is achieved by an adiabatic mode transformation [26]. This coupling is indeed listed as the coupling loss $L_c$ in Table I.

Regarding the transceivers of the I2CON interchip, they are composed of VCSELs as on-chip laser sources, on-chip silicon waveguides, injectors, and photodetectors. For each
transceiver, a set of injectors acts as the switching MRs and another set of injectors acts as the bridging MRs. The switching MRs will guide the light source to turn either to the left of the main closed-loop ring or to the right of the main closed-loop ring. Meanwhile, the bridging MRs are those which decide whether or not the light will enter/exit the transceiver.

With this modeling of the closed-loop waveguide and the transceivers, we have taken into consideration all the special properties of the I2CON interchip: 1) the bidirectional transmission and 2) the channel segmentation. Basically, the bidirectional transmission means that a cluster can transmit the signal to another cluster in two different ways: 1) to the left of the ring and 2) to the right of the ring. Bidirectional transmission will lead to another property, which is channel segmentation. As shown in Fig. 5, while C(0, j) transmits the signal to C(2, j) using one segment of the closed-loop waveguide (to the right), C(2, j) can use the other segment of the closed-loop waveguide (to the left) to transmit data to either C(0, j) or C(3, j). It is also noted that we utilize 64 wavelengths for the I2CON interchip to make it consistent with the analyses of other structures in the later stage.

Utilizing our developed analytical models for the optical elements, we have analyzed the worst case signal power loss and the worst case crosstalk noise of the I2CON as follows. The worst case signal power loss happens with the communication between a chip and another chip with a distance of half the network size. As an example from Fig. 5, the worst case signal power loss case happens when chip 0 communicates with chip 2. Hence, we can derive the equation for this worst case signal power loss (14). In (14), we have considered the loss on both on-chip silicon waveguide $L_{sw}$ and on-board polymer waveguide $L_{pw}$. We also considered the loss from the coupling, which we denote by $L_c$. Derived from the analytical equations of the optical elements, $i$ is used to denote the wavelength number, or the detector number in the detectors’ series at the end of each transceiver. Wavelength selective is utilized in I2CON and 64 detectors/injectors should be used for 64 wavelengths. In (14) and other analyses’ equations at the later sections, $n_b$, $n_c$, $d_{pw}$, and $d_{sw}$ are, respectively, the number of bendings, the number of couplings, the distance traveled on polymer waveguide, and the distance traveled on silicon waveguide. For ease of understanding, same notations are used throughout our analyses. The exact numbers of these parameters can be derived from the architectures of each interconnection networks

$$P_{signal[i]} = (L_b)^{n_b} (L_c)^{n_c} (L_{pw})^{d_{pw}} (L_{sw})^{d_{sw}} (L_{Li})^{63} (L_{Lo})^{63 \times 2} \\ \times (L_{Ld})^{64 \times 1} (L_{Lo})^{1} (L_{Li})^{1} P_{VCSELs[i]} \text{.}$$

(14)

The communication between a chip and another chip with a distance of half of the network size suffers from the worst case signal power loss. Considering an example where C(0, j) communicates with C(3, j). Because of the bidirectional property, instead of going through nearly the whole closed-loop waveguide, the light signal can be directed to the left of the closed-loop waveguide. The propagation loss, in this case, is less than that of the worst case signal power loss. In addition, by being directed to the left of the ring, the light signal does not need to pass any series of bridging MRs in between. Hence, the total signal power loss of this sample case must be smaller than the total signal power loss of the worst case. Indeed, our worst case analyses equation can be generalized to any I2CON interchip network of different numbers of chips.

Regarding the worst case crosstalk noise, the crosstalk noise is generated from the four following sources. The first incoherent crosstalk is generated from the signal at the detector series at the end of the receiving chip C(2, j). This crosstalk can be derived from the signal power loss and the detectors of chip 2. Incoherent crosstalk can also be generated by the signal from C(2, j) [C(2, j) can send a signal to C(0, j) at the same time as C(0, j) sends data to C(2, j)]. At the bridging injectors of C(2, j), this signal generates the crosstalk noise, which arrives at the series of detectors of the same chip (i.e., 2) in the second order. This crosstalk is denoted in (15a). Regarding coherent crosstalk, it is generated by the switching MRs of C(0, j) (the sending chip). This first-order coherent crosstalk, denoted in (15b), will travel to the left of the ring and arrive at chip 2 from the right (Fig. 5). Another coherent crosstalk is from the PASSING mode of the detectors of other clusters and is denoted in (15c). For the crosstalk which is generated by the receiving C(2, j), we should add the additional term of propagation loss on polymer waveguide

$$P_{n-inc[i]} = (L_b)^{n_b} (L_{sw})^{d_{sw}} (L_{Li})^{63} (X_{Li})^{63-i} \times (L_{Lo})^{i} (L_{Ld})^{i} (L_{Li})^{1} P_{VCSELs[i]} \text{.}$$

(15a)

$$P_{n-coh1[i]} = (L_b)^{n_b} (L_{X_{Li}})^{61} (L_{sw})^{d_{sw}} (X_{Li})^{2} \times (L_{Lo})^{63 \times 2} (L_{Ld})^{64 \times 1} (L_{Li})^{1} P_{VCSELs[i]} \text{.}$$

(15b)

$$P_{n-coh2[i]} = (L_b)^{n_b} (L_{X_{Li}})^{61} (L_{sw})^{d_{sw}} (X_{Li})^{2} \times (L_{Lo})^{63 \times 2} (L_{Ld})^{64 \times 1} (L_{Li})^{1} P_{VCSELs[i]} \text{.}$$

(15c)

B. Worst Case Crosstalk Noise in the Intrachip Networks

Section IV-A2 has detailed our analyses for the interchip network of I2CON. In this section, we further utilize our developed analytical models to find the worst case signal power loss and the crosstalk noise in the intrachip networks. In order to complete the analyses on I2CON, we analyze its intrachip network. We also perform the analyses on another ring-based intrachip interconnection network, the Corona.

1) I2CON Intrachip and Its Worst Case Analyses: While the I2CON interchip network performs the required communication between the chips, the intrachip network of I2CON is responsible for communications inside a chip. Hence, the intrachip network of I2CON consists of the data channels interconnecting different clusters in the same chip (Fig. 5). Similar to the I2CON interchip, the intrachip network of I2CON also utilizes the on-chip laser source and the optical elements, such as the injectors and the detectors. Another similarity of the intrachip network of I2CON compared with the I2CON interchip is that the control network is also point-to-point. Hence, in this paper, we only analyze the worst case crosstalk noise and the signal power loss among the data channels of the intrachip network. For convenience, the term
I²CON intrachip is used for the data channels of the intrachip network of I²CON.

In I²CON, the intrachip network also follows a ring-based structure, where the data channels are parallel to each other without any waveguide crossing. The I²CON intrachip also shares two special properties, which are the bidirectional transmission and the channel segmentation. However, there exist two major differences between the intrachip and interchip networks. The first difference is that the I²CON intrachip is exposed to another special property: the channel grouping. With this property, the communication between two clusters in the same chip is classified based on its communication distance, or the number of hops between the two clusters. Hence, in one chip, the data channels are parallel but may not be identical to each other. Details of this special property could be found in [7]. Another major difference of the I²CON intrachip is the utilization of only on-chip silicon waveguide. This results from the fact that the I²CON intrachip is responsible for interconnecting the clusters in the same chip.

Taking into considerations all the properties of the I²CON intrachip, we analyze the worst case crosstalk noise and the signal power loss of the intrachip network. In our analyses, we consider an $8 \times 8$-clusters network for a fair comparison with the Corona at the later stage. In both I²CON intrachip and Corona ONoC, each cluster consists of four cores. These 64 clusters are interconnected by a number of waveguides in order to form a closed ring. Table II summarizes the I²CON intrachip’s optical elements. In Table II, we also list the optical elements of the three structures of Corona. The analyses on Corona are detailed later. From Table II, the number of waveguides and MRs in the I²CON intrachip interconnect is both higher than those in Corona. However, this higher number of MRs does not necessarily result in higher signal power loss in I²CON. In addition, from Table II, the number of waveguides between the data channels of the I²CON intrachip and the Corona is quite different. This reflects the special property of channel grouping in I²CON intrachip.

We investigate the worst case signal power loss and the crosstalk noise of the data channel of the intrachip part. Based on the channel grouping property, the data channels of the I²CON intrachip are divided into different channel groups with different communication lengths. It is noted that the channel groups for each chip are identical to each other. Hence, we only need to investigate the worst case situation among all the data channels in one chip (i.e., chip 0). From the analyses of the basic optical elements, it is derived that the data channel group 5 of the I²CON intrachip suffers the most signal power loss. That is, the communication link between cluster $i$ and cluster $(i + 32)$ is mod 64, where $i$ can be any cluster from $C(0, 0)$ to $C(0, 63)$. Fig. 6 shows this link, which is a representative of group 5.

Since it is in channel group 5, only clusters with a 32-hop distance can be a sender. The other clusters can either be receivers or nonreceivers (i.e., the clusters which do not have any detectors detecting an incoming signal). In Fig. 6, when $C(0, 0)$ sends a signal to $C(0, 32)$, the light signal passes through 30 clusters with 64 inactive detectors each, and one cluster, i.e., $C(0, 16)$, with no MR. The signal power loss is expressed in (16). Because there exists no polymer on-board waveguide, (16) does not consist of terms, such as $L_{pw}$ or $L_{c}$.

Based on our analyses of the optical elements, the worst case crosstalk noise also happened in group 5. The crosstalk noise is generated from the four following sources. The first incoherent crosstalk is generated from the signal at the detector series at the end of the receiving cluster (i.e., cluster 32). This crosstalk can be derived from the signal power loss and the detectors of cluster 32. Incoherent crosstalk can also be generated by the signal from cluster 32 (cluster 32 can send a signal to cluster 0 at the same time as cluster 0 sends data to cluster 32). At the bridging injectors of cluster 32, this signal generates the crosstalk noise, which arrives at the series of detectors of the same cluster, 32, in the second order. This crosstalk is denoted in (17a). Regarding coherent crosstalk, it...
is generated by the switching MRs of cluster 0 (the sending cluster). This first-order coherent crosstalk, denoted in (17b), will travel to the left of the ring and arrive at cluster 32 from the right (Fig. 6). Another coherent crosstalk is from the PASSING mode of the detectors of other clusters and is denoted in

\[ P_{n-\text{inc}[i]} = (L_b)^{n_b}(L_{sw})^{d_{sw}}(L_{i_1})(L_{i_0})^{63}(X_{i_1}) \]
\[ \times (L_{i_0})^{63-i}(L_{i_1})(L_{d_0})^{i}(L_{d_1})^{1} P_{\text{VCSELs}[i]} \quad (17a) \]
\[ P_{n-\text{coh1}[i]} = (L_b)^{n_b}(L_{sw})^{d_{sw}}(X_{i_0})(L_{i_1})^{2} \]
\[ \times (L_{i_0})^{63 \times 2 L_{d_0}^{30}}(L_{d_0})^{1}(L_{d_1})^{1} P_{\text{VCSELs}[i]} \] (17b)
\[ P_{n-\text{coh2}[i]} = (L_b)^{n_b}(L_{sw})^{d_{sw}}(X_{d_0}^{2})(L_{i_1})^{2} \]
\[ \times (L_{i_0})^{63 \times 2 L_{d_0}^{30}}(L_{d_0})^{1}(L_{d_1})^{1} P_{\text{VCSELs}[i]} \].

(17c)

2) Corona and Its Worst Case Analyses: In this section, we are going to analyze the worst case situations in another ring-based optical intrachip interconnect, the Corona. Corona consists of 256 general-purpose cores, which are grouped into 64 four-core clusters. Three structures are established: 1) the optical crossbar for data communication; 2) the broadcast bus for multicasting; and 3) the control for arbitration or protocol [3]. As a convention, in this paper, we will use the three terms, such as data channel, broadcast bus, and control, for the three aforementioned structures, respectively. Different from I2CON intrachip, which utilizes the on-chip laser sources, Corona utilizes the off-chip laser. In Corona, the main off-chip laser source is fed into the loop and splits into these different structures. For each optical structure, the sets of MRs perform as modulators, detectors, and injectors. Table II details the optical elements of the three structures of Corona ONoC.

Besides the similarities, there exist differences between the Corona and the I2CON intrachip. In Corona, beside the data channel, another two optical structures exist and should be analyzed: 1) the broadcast bus and 2) the control. Moreover, the 64 clusters of I2CON intrachip are slightly differently arranged compared with Corona ONoC. Furthermore, compared with I2CON on-chip laser sources at every cluster, the Corona ONoC only utilizes an off-chip laser source, providing power to all the three optical structures.

Among the three aforementioned structures, we focus our analyses on the control first. We later analyze the data channel and the broadcast bus, which are similar to each other. In Corona, the control plays a critical role in avoiding congestion in the communication of the optical crossbar and the broadcast bus. In the control, the token ring methodology is utilized [3].

As light pulses are used for token rings, clock propagation is considered with a clockwise movement of the data waveguide [3]. Hence, cluster 0 is the first to inject its token ring into the waveguide, followed by cluster 1, and so on until the last cluster. However, it should be noted that there exists a case where one cluster finishes its communication on almost all clusters and injects those tokens into the waveguide.
different from existing works, we have analyzed both the coherent crosstalk and the incoherent crosstalk in the data channel and the broadcast bus of Corona. As shown in Fig. 8, the incoherent crosstalk in both structures is generated by the ACTIVE-state modulators (i.e., cluster 0 in each structure). These detectors are placed to detect the modulated light coming from the communication source. Meanwhile, the coherent crosstalk is generated by all the INACTIVE-state modulators (i.e., 62 clusters between cluster 0 and cluster 63). Although this is the second-order crosstalk, it can still be accumulated (i.e., 62 clusters between cluster 0 and cluster 63). Although this is the second-order crosstalk, it can still be accumulated due to a huge number of modulators in these two optical structures of Corona.

V. RESULTS AND COMPARISON

Based on our analyses and the data in Table I, we provide and discuss the quantitative results of the \( I^2 \)CON interchip and intrachip optical interconnection networks and the Corona ONoC. By varying the important parameters, such as the MR passing loss, the propagation loss, and the \( Q \) factor, we explore different dimensions of the worst case results. It should be noted that when we change one (or more) parameter(s), we keep the other parameters constant at the values specified in Table I. The die size is 423 mm\(^2\) [3] for Corona, resulting in a chip size of 2.05 cm \( \times \) 2.05 cm. For a fair comparison, we assume the same chip size for \( I^2 \)CON. Moreover, the same network size of 8 \( \times \) 8 is applied for all the comparisons between Corona and \( I^2 \)CON intrachip. For the \( I^2 \)CON interchip, the chip distance is assumed to be 5 cm, so that the thermal density can be reduced effectively [7]. However, it should be noted that our analytical equations are independent of the utilized data, which are only used as an example to indicate several numerical results.

Fig. 9 shows the impact of coherent crosstalk on the worst case SNR in different structures of the Corona and the \( I^2 \)CON intrachip. As can be seen, the coherent crosstalk may significantly affect the worst case SNR in the data channel and the broadcast bus of Corona. In these two structures, the coherent crosstalk noise dominates, since it is generated by the series of INACTIVE-state modulators along the waveguide, while the incoherent crosstalk is only generated by the ACTIVE-state modulators of the first cluster. A similar trend is also applied to the Corona control, where the coherent crosstalk far outweighs the incoherent crosstalk. On the \( I^2 \)CON intrachip network, as the incoherent crosstalk contributes more to the noise (i.e., the incoherent crosstalk from cluster 32), the SNR results are not greatly reduced. Moreover, at a particular \( Q \) factor, the worst case SNR among the structures can differ by up to 50 dB. For example, at \( Q = 9000 \), the worst case SNR of the Corona control is \(-51\) dB, while that of the broadcast bus in Corona is \( 13.4\) dB. Fig. 9 also shows the worst case SNR under varied \( Q \) values. Based on our analytical model, it can be seen that the \( Q \) factor of an MR can significantly affect the SNR. As can be seen from Fig. 9, the smaller \( Q \) values highly damage the SNR (i.e., all the SNRs are negative when \( Q \) is smaller than about 1000). In addition, the larger \( Q \) values than 15 000 may not improve the SNR, since the SNR tends to gradually settle at a value when the \( Q \) factor reaches 14 000.

In order to further investigate the impact of both the incoherent crosstalk and the coherent crosstalk, we also vary the values of the MR passing loss (Fig. 10). According to recent research works, we have increased the MR passing loss from \(-0.001 [27] \) to \(-0.01\) dB [28]. Under different passing losses, the worst case SNR of Corona is more stable, while that of \( I^2 \)CON intrachip decreases deeply. On the one hand, in Corona, by utilizing the off-chip laser with only one laser source, the signal as well as its crosstalk noise in a channel will significantly affect the worst case SNR in the data channel and the broadcast bus of Corona. As shown in Fig. 8, the coherent crosstalk and the incoherent crosstalk in the data channel consists of 1 \( \times \) 2 and 1 \( \times \) 4 splitters, the broadcast bus only consists of 1 \( \times \) 2 splitters.

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Fig. 10. Worst case SNR, signal power loss, and coherent and incoherent crosstalk noises under varied MR passing losses. (a) Worst case SNR. (b) Worst case signal power loss. (c) Worst case coherent crosstalk. (d) Worst case incoherent crosstalk.

Fig. 11. Worst case SNR, signal power loss, and coherent and incoherent crosstalk noise under varied silicon-waveguide propagation loss. (a) Worst case SNR. (b) Worst case signal power loss. (c) Worst case coherent crosstalk. (d) Worst case incoherent crosstalk.

TABLE III

<table>
<thead>
<tr>
<th>Optical structure</th>
<th>Worst-case total power loss</th>
<th>Worst-case total crosstalk noise</th>
<th>Worst-case SNR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Corona data channel</td>
<td>-69.3dB</td>
<td>-80.5dB</td>
<td>10.1dB</td>
</tr>
<tr>
<td>Corona data channel from Ref [8]</td>
<td>-69.3dB</td>
<td>-83.6dB</td>
<td>14.0dB</td>
</tr>
<tr>
<td>Corona broadcast bus</td>
<td>-63.4dB</td>
<td>-76.5dB</td>
<td>13.4dB</td>
</tr>
<tr>
<td>Corona broadcast bus from Ref [8]</td>
<td>-63.4dB</td>
<td>-77.2dB</td>
<td>14.0dB</td>
</tr>
<tr>
<td>Corona control</td>
<td>-66.6dB</td>
<td>-15.6dB</td>
<td>-51dB</td>
</tr>
<tr>
<td>I^2CON intra-chip</td>
<td>-16.8dB</td>
<td>-28.1dB</td>
<td>11.7dB</td>
</tr>
</tbody>
</table>

For a clearer interpretation, we have extracted a table (Table III) for the worst case results among different intrachip interconnects: 1) the Corona data channel; 2) the broadcast bus; 3) the control; and 4) the I^2CON intra-chip. This table is calculated with the parameters mentioned in Table I. In addition, Q is at 9000 [6], and the network size is 8 x 8. Besides, the results from [8] were also given in the table as a comparison. In [8], the Corona data channel and the broadcast bus were analyzed. It should be noted that the total worst case crosstalk noise for [8] is resulted solely from the incoherent crosstalk.

Similar to the comparison of the intrachip networks (i.e., Corona and I^2CON intra-chip), we have also investigated the interchip network of I^2CON under the variation of the propagation losses of silicon and polymer waveguides. Fig. 12 shows the worst case SNR results of different interchip networks of I^2CON under different waveguide propagation losses. The interchip network of I^2CON is featured with two different types of waveguides: 1) the silicon waveguide (on-chip waveguide) and 2) the polymer waveguide (on-board waveguide). Hence, in order to see the impact of these two types of waveguides on the worst case performance, we varied both types of waveguides from −0.2 to −3 dB. In Fig. 12, L_sw and L_pw are, respectively, the propagation losses on silicon waveguide and polymer waveguide. As can be seen from Fig. 12, both types of propagation losses generally have a negative impact on the worst case SNR. The worst case SNR decreases with the propagation losses. In particular, the propagation loss on a polymer waveguide has higher impact on the worst case SNR compared with that of silicon waveguide. For example, when L_sw is kept at −3 dB, the worst case SNRs for two-chip I^2CON interchip vary from about 6 to 20 dB under different L_pw values. Meanwhile, when L_pw is at −3 dB, the worst case SNRs of the two-chip I^2CON interchip change within a little amount. Similar trends are noted for the other two cases: 1) 4-chip I^2CON interchip interconnect and 2) 16-
chip I²CON interchip interconnect. This result has aligned with our analyses, since the incoherent crosstalk from the received cluster is unaffected by the propagation loss on a polymer waveguide. This crosstalk noise is generated by the received cluster and only propagated within the core cluster (within one chip).

In addition to comparing the intrachip of I²CON with Corona ONoC, we have also investigated the scalability of I²CON with interchip and intrachip networks individually. Fig. 13 provides the comparison of interchip/intrachip networks of I²CON in different network sizes. In Fig. 13(a), the scalability interchip network of I²CON is explored. As can be seen from Fig. 13(a), the worst case SNR becomes smaller when we scale the network size. Noticeably, when the network size is 16 chips (4 × 4), the worst case SNR is negative, which results in a higher signal power loss compared with the crosstalk noise power loss (i.e., green and blue columns, respectively). However, when we scale the network from two chips to four chips, the reduction of the worst case SNR is not large. Similarly, Fig. 13(b) shows the worst case results for the intrachip interconnection network of I²CON. The worst case results of SNR, signal power loss, and crosstalk noise power loss also follow the same trend as those of the intrachip network. From these comparisons, it can be seen that there exists a good tradeoff between increasing the number of chips (i.e., a larger interchip network) and increasing the number of clusters (i.e., a larger intrachip network). We will further investigate into this tradeoff point at a later stage in this section.

First, we may need to have a look at the performance of the intrachip interconnect among the interconnection networks: 1) I²CON intrachip; 2) Corona data channel; and 3) broadcast and control.

Regarding the performance of intrachip networks of I²CON and Corona ONoC, we have calculated the results of the ideal/real bandwidths and power consumption per data bit in Table IV. For the ideal case, a modulation rate of 10 Gb/s is assumed [3], [7]. The worst case bandwidth results from the worst case SNR of each structure. For the Corona control, the worst case SNR is considerably negative (i.e., −51 dB), so the corresponding bit error rate (BER) value and the worst case bandwidth are not applicable. In this paper, two sets of the worst case bandwidth have been calculated. The first set, based on the Shannon limit (20), is the maximum theoretical bandwidth, which can be achieved under the constraint of crosstalk noise. The second set is the bandwidth, which is achieved by Reed–Solomon (RS) error correction coding. The input BER, expressed by (21), is achieved from the worst case SNR [29], and RS(255,149) is chosen to reduce this BER of $10^{-2}$ to an output BER of $10^{-12}$. In the worst case energy consumption, the overhead of the error correction coding is not considered.

We have demonstrated that our analyses of the worst case SNR can be a platform to compare the performance of different structures. The results have indicated that in the real situation, several structures may work, but several may not. Due to the accumulation of coherent crosstalk on the receiver, the Corona control apparently demonstrates an extremely low SNR value, and hence very high BER value

$$C = \frac{\text{BW} \times \log_2 \left(1 + \frac{\text{Signal}}{\text{Noise}}\right)}{2} \tag{20}$$

$$\text{BER} = \frac{1}{2} e^{-\frac{\text{SNR}}{10}} \tag{21}$$

Regarding the performance of the complete interchip/intrachip networks of I²CON, it may not be suitable to combine the two SNRs of the interchip and intrachip networks. With a communication, including both interchip and intrachip networks, we compute the SNRs of each network first. We then convert the SNR into BER with (21) and combine the two BERs and arrive at the BER for a communication. This combined BER, using the property of BER for digital communication, is expressed in (22). Table V provides the comparison of various network sizes of I²CON. In Table V,
TABLE IV
IDEAL AND ACTUAL PERFORMANCE: CORONA AND I²CON INTRACHIP

<table>
<thead>
<tr>
<th>Optical structure</th>
<th>Without crosstalk</th>
<th>With crosstalk (Worst-case)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Bandwidth (Th/s)</td>
<td>Energy (pJ/bit)</td>
</tr>
<tr>
<td>I²CON intrachip</td>
<td>160</td>
<td>0.005</td>
</tr>
<tr>
<td>Corona data channel</td>
<td>160</td>
<td>137.50</td>
</tr>
<tr>
<td>Corona broadcast bus</td>
<td>0.64</td>
<td>34.19</td>
</tr>
<tr>
<td>Corona control</td>
<td>0.64</td>
<td>71.62</td>
</tr>
</tbody>
</table>

TABLE V
I²CON WORST CASE BER COMPARISON

<table>
<thead>
<tr>
<th>Number of cores</th>
<th>Intra-chip size</th>
<th>Inter-chip size</th>
<th>Worst-case BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>256</td>
<td>8×8</td>
<td>1 chip</td>
<td>0.03</td>
</tr>
<tr>
<td></td>
<td>8×4</td>
<td>2 chips</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>4×8</td>
<td>2 chips</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>4×4</td>
<td>4 chips</td>
<td>0.01</td>
</tr>
<tr>
<td></td>
<td>16×8</td>
<td>1 chip</td>
<td>0.324</td>
</tr>
<tr>
<td></td>
<td>8×16</td>
<td>1 chip</td>
<td>0.317</td>
</tr>
<tr>
<td></td>
<td>8×8</td>
<td>2 chips</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td>8×4</td>
<td>4 chips</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>4×8</td>
<td>4 chips</td>
<td>0.016</td>
</tr>
<tr>
<td>512</td>
<td>8×4</td>
<td>1 chip</td>
<td>0.008</td>
</tr>
<tr>
<td></td>
<td>8×8</td>
<td>2 chips</td>
<td>0.031</td>
</tr>
<tr>
<td></td>
<td>4×8</td>
<td>4 chips</td>
<td>0.016</td>
</tr>
<tr>
<td></td>
<td>4×4</td>
<td>4 chips</td>
<td>0.016</td>
</tr>
</tbody>
</table>

two different network’s sizes are present: 1) with 256 cores and 2) with 512 cores. With a fixed number of cores, we have varied the size of intrachip and interchip, and the worst case BER results are given. As can be seen from Table V, utilizing higher number of chips rather than using one chip results in better worst case BER. For example, regarding the case of 256 cores, with only one chip, the worst case BER is 0.03, while the worst case BER is significantly reduced with two-chip and four-chip cases. However, when the number of chips increases, the BER will become worse. For 16-chip interchip network, we did not have a resulted BER, since the SNR of the interchip network is already negative. Similar trend can also be observed with the case of 512-core networks. As a result, we have demonstrated that there is a tradeoff in using a higher number of chips (instead of higher number of clusters on chip). Using a single chip is not an optimal solution, while using so many number of chips may degrade the performance of the network.

\[
\text{BER}_{\text{network}} = \text{BER}_{\text{intra-chip}}(1 - \text{BER}_{\text{inter-chip}}) + \text{BER}_{\text{inter-chip}} \quad (22)
\]

VI. CONCLUSION

In this paper, we have developed the analytical models to calculate the signal power loss, the crosstalk noise, and the SNR in the interchip/intrachip optical networks. In our analyses, both the coherent and incoherent crosstalk noises are analyzed. Utilizing our developed models at the device level, we have provided the analyses of the worst case SNR and crosstalk in both interchip and intrachip levels. I²CON and Corona are chosen as two case studies in order to show the numerical comparison results. These quantitative results demonstrate the impact of crosstalk noise on the SNR, the BER, and the network performance. The worst case SNR/BER strongly depends on the network architecture. More importantly, our analyses of the interchip interconnect have shown that we could exploit the tradeoffs between the interchip and intrachip interconnects. Our analyses, therefore, can provide a platform to compare the realistic performance among various optical interconnection networks.

REFERENCES

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