

A Case Study of Signal-to-Noise Ratio in Ring-Based Optical Networks-on-Chip

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Editors' notes:

Crosstalk noise and power loss can reduce signal-to-noise ratio (SNR) and performance of optical on-chip networks. This paper studies and applies an analytical method for modeling crosstalk noise and power loss in large-scale ring-based optical networks such as Corona.

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ultrahigh-bandwidth and low-power energy consuming interconnection networks.

Among the proposed ONoCs interconnect structures, ring-based ONoCs [2], [3], have been introduced due to their advantages of supporting on-chip

■ **WITH THE INCREASINGLY urgent need for higher speed and more powerful computational performance, integrating a large number of cores on a single die has been mainstream for the last few decades. To support these multicore systems, different networks-on-chip (NoCs) structures have been proposed to replace traditional interconnection networks [1]. However, as the number of processing cores on a single die continues to increase, the metallic interconnects in NoCs seem to be falling behind the high-bandwidth and low-latency requirements. This issue has been addressed by the proposed optical networks-on-chip (ONoCs) for**

bandwidth with on-chip optical crossbars. Different from off-chip bandwidth, on-chip bandwidth is not limited by the number of package pins, which is forecast not to considerably increase [4]. Moreover, on-chip crossbars improve network latency with electrical-optical/optical-electrical converters implemented at the end of the ring [2], [4].

Additionally, dense wavelength division multiplexing (DWDM) is inevitable in the future ONoCs [2]. In DWDM, a large number of wavelengths are integrated to provide ultrahigh bandwidth for the network. Nevertheless, one of the major drawbacks of DWDM-based networks is that crosstalk noise is generated and intensified by communications among the components in the network. Regarding this issue, although crosstalk noise due to devices' imperfections might be considered negligible at the device level, crosstalk noise has severe impacts in

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large-scale ONoCs at the network level. This was demonstrated in [5] for single-wavelength ONoCs. In large-scale ONoCs, crosstalk noise accumulates and causes power fluctuations at the receivers, restricting the network scaling. Consequently, the crosstalk noise issue should be more critical in DWDM networks.

In this paper, for the first time, we study the crosstalk noise in a DWDM ring-based ONoC. At the device level, we carefully developed the analytical models based on the optical devices' characteristics reported in fabricated device papers. From those models, we follow a mathematical bottom-up approach to analyze the network components. With this approach, all the analytical models at the network level can be translated into the initial device-level models for verification. As one of the first ring-based DWDM ONoCs, the Corona is chosen to be evaluated. Moreover, utilizing the on-chip optical crossbar, 64 clusters in Corona can independently transmit, resulting in an ultrahigh bandwidth [2]. However, in the ring-based structure, crosstalk noise may accumulate from the first to the last cluster of the open ring.

The Corona ring-based ONoC is a 64 four-core clusters network. Its interconnection is formed by three different structures: the optical crossbar (data channel), the broadcast bus, and the control arbitration. In our study, we focus on the data channel and the broadcast bus. Regarding the existing analytical method in [5], the basic device level's models can be used in any single-wavelength network topology. However, we model the basic optical elements in a DWDM network, which has not been introduced. We also provide analysis up to second-order cross-talk, which is a deeper level compared to [5]. At the network level, the analyses in [5] can only be applied to mesh-based and folded-torus-based ONoCs. In this paper, we utilize our proposed analytical models for ring-based ONoCs using DWDM. Finally, we compare our results of Corona's data channel with those of the aforementioned two ONoCs. In our study, only incoherent crosstalk is considered.

The rest of the paper is organized as follows. The Summary of Related Works section summarizes the state-of-the-art of previous works on the crosstalk noise issue. The Basic Optical Element Analysis section describes the basic optical elements in a general ring-based ONoC, followed by the Corona's Element Analysis section, analyzing different ele-

mentary structures of Corona. The Worst Case Crosstalk Noise Analysis for Corona section details the analysis of Corona's data channel and broadcast bus. Results and discussion are provided in the Result and Discussion section.

Summary of related works

The crosstalk issue has been investigated in several works at both the device level and the network level. On the one hand, at the device level, the amount of crosstalk seems to be negligible. For example, Chen [6] reported an insertion loss and a crosstalk noise value of -0.2 and -47.6 dB, respectively, through a waveguide crossing composed of three cascaded multimode structures. At the network level, on the other hand, crosstalk noise has been noticed due to its negative impact on the SNR. In [5], Nikdast et al. analyzed the crosstalk noise and SNR in folded-torus-based ONoCs and reported that the crosstalk noise power exceeded signal power when the network size was equal to or larger than 8×8 . Nikdast et al. [5] also summarized the findings of crosstalk and SNR in mesh-based ONoCs using two different routers: the optimized-optical crossbar and Crux.

Nonetheless, the aforementioned works focused on single-wavelength ONoCs, where contributed crosstalk originates from only one wavelength. Considering DWDM-based networks, several efforts have been made to analyze the effect of different wavelengths on a given wavelength. Xu et al. [7] presented a four-cascaded microresonator (MR)-based structure and reported an extinction ratio of 13 dB, with negligible crosstalk. In [8], Xiao et al. measured losses in a multiwavelength microring-based structure.

Basic optical elements analysis

DWDM-ONoCs are constructed by a set of basic optical elements that direct light from a source processor toward other destination processors. These elements can also be receivers, detecting and converting light back into electrical signals. In a ring-based ONoC, modulators, injectors, photodetectors, and splitters are utilized to perform the aforementioned tasks. Particularly, modulators are used to modulate the light, while detectors are placed at the end of any communication path to detect the modulated light. Splitters are exploited to distribute power by diverting a fixed portion of the optical

power from one waveguide to another waveguide. Additionally, splitters can be used to split the power into equal portions. Figure 1 shows the basic optical elements of a DWDM-based ONoC.

Figure 1a and b represents a modulator's INACTIVE and ACTIVE states, respectively. Meanwhile, Figure 1c and d are photodetectors in the PASSING and DETECTING states. Two kinds of splitters, which often appear in DWDM networks, are, respectively, modeled in Figure 1e and f: 1 × 2 and 1 × 4 splitters. In the following sections, we further detail our model analysis. To facilitate our study, we provide notations for the utilized parameters in our analytical equations in Table 1. The values for these parameters are from recent device fabrication results [9]–[12]. Several parameters, such as the MR's quality factor (Q-factor) and free spectral range (FSR), are extracted from papers regarding the fabrication of Corona [4], [7].

Modulators and detectors

Modulators and detectors are constructed by MRs which are coupled to a single waveguide. The MR follows a Lorentzian power transfer function peaked at its resonant wavelength λ_{MR} . For an optical signal having wavelength λ_i , the drop-port power transfer can be expressed as [8]

$$\frac{P_{\text{drop}}}{P_{\text{in}}} = \left(\frac{2\kappa_e\kappa_d}{\kappa_e^2 + \kappa_d^2 + \kappa_p^2} \right)^2 \times \left(\frac{\delta^2}{(\lambda_i - \lambda_{\text{MR}})^2 + \delta^2} \right) \quad (1a)$$

where κ_e^2 and κ_d^2 are, respectively, the fraction of optical power that the input and the drop waveguide coupled into or out of the MR, while κ_p^2 is the

fraction of the intrinsic power losses per round-trip in the MR. Indeed, for a normal MR, $\kappa_e^2 \approx \kappa_d^2$ and $\kappa_p^2 \ll \kappa_e^2$, so the first term $2\kappa_e\kappa_d/(\kappa_e^2 + \kappa_d^2 + \kappa_p^2)$ approximates to one. Hence, (1a) can be written as

$$\frac{P_{\text{drop}}}{P_{\text{in}}} = \left(\frac{\delta^2}{(\lambda_i - \lambda_{\text{MR}})^2 + \delta^2} \right) \quad (1b)$$

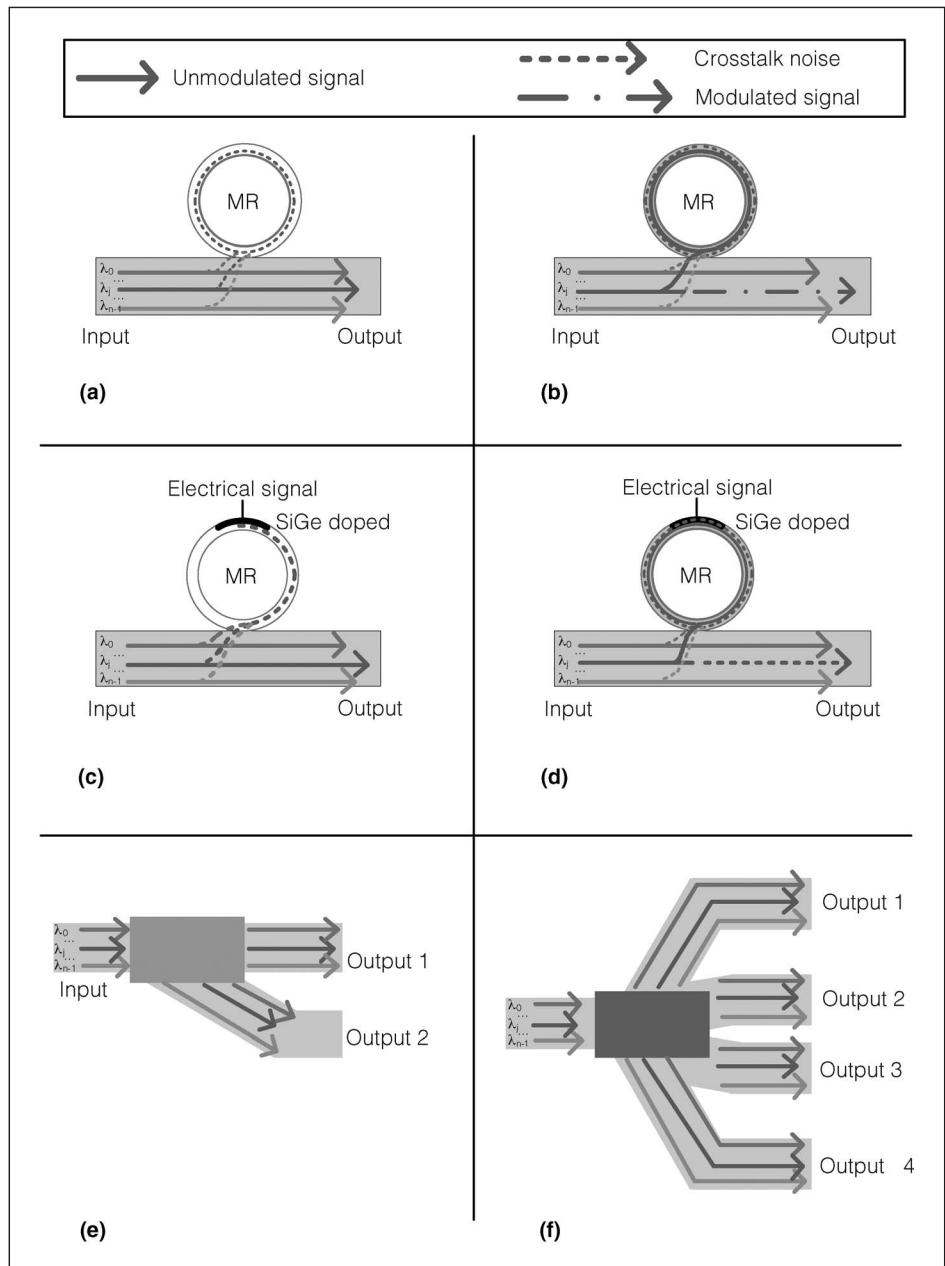


Figure 1. Basic optical elements. (a) INACTIVE-state modulator. (b) ACTIVE-state modulator. (c) PASSING-mode detector. (d) DETECTING-mode detector. (e) 1 × 2 splitter. (f) 1 × 4 splitter.

Table 1 Utilized parameters table.

Parameter	Sym.	Value
Propagation loss	L_p	-0.274dB/cm [9]
Bending loss	L_b	-0.005dB/90° [10]
Power loss: INACTIVE modulator	L_{m_0}	-0.005dB [10]
Power loss: ACTIVE modulator	L_{m_1}	-0.6dB [10]
Power loss: PASSING detector	L_{d_0}	-0.005dB [10]
Power loss: DETECTING detector	L_{d_1}	-1.6dB [10]
Power loss: 1x2 splitter	$L_{s_{12}}$	-0.2dB [11]
Power loss: 1x4 splitter	$L_{s_{14}}$	-0.2dB [11]
Crosstalk coefficient: INACTIVE modulator	X_{m_0}	-0.001dB [10]
Crosstalk coefficient: ACTIVE modulator	X_{m_1}	-16dB [12]
Crosstalk coefficient: PASSING detector	X_{d_0}	-0.001dB [10]
Crosstalk coefficient: DETECTING detector	X_{d_1}	-16dB [12]
Q-factor	Q	9000 [4]
Free-Spectral Range	FSR	62nm [7]

where the -3-dB bandwidth of 2δ is expressed as

$$2\delta = \frac{\lambda_i}{Q} \quad (1c)$$

where Q is the Q -factor of a particular MR.

The FSR of a signal is also taken into account in Figure 1b through the difference between the MR's resonant wavelength λ_{MR} and the examined signal wavelength λ_i . Taking the two wavelengths λ_i and λ_j , for example, we have $\Delta(i,j) = \lambda_i - \lambda_j = (i-j)(\text{FSR}/n)$, where we assume equal spacing between two consecutive wavelengths and n is the total number of wavelengths in the network.

To simplify the equations in the later stages, we define function $\Phi(i,j)$ in

$$\Phi(i,j) = \frac{\delta^2}{(\lambda_i - \lambda_j)^2 + \delta^2}. \quad (2)$$

Modulator. Due to the imperfection of the coupling mode, a portion of the light is coupled into the ring, even when the MR is in the INACTIVE state, which results in a loss in signal power

$$P_{\text{out}}[i] = L_{m_0}P_{\text{in}}[i], \quad i = 0, \dots, n. \quad (3)$$

Regarding a modulator in the ACTIVE state, light will be coupled into the ring, but a portion of the light may pass the modulator, resulting in the modulator's crosstalk. The equation for an ACTIVE state modulator is given in

$$\begin{cases} P_{\text{out}}[j] = X_{m_1}P_{\text{in}}[j] \\ P_{\text{out}}[i] = L_{m_0}P_{\text{in}}[i] \end{cases}, \quad i \neq j. \quad (4)$$

For the general case, the MR is modulating at the resonant wavelength $\lambda_{\text{MR}} = \lambda_j$, where j is the j th wavelength in a waveguide.

Detector. Similar to the modulator, a photodetector is also formed by an MR coupled into a single waveguide. However, different from the modulator, the detector's MR is doped with a Si–Ge layer to detect the incoming optical signal. It needs a converter to convert light into an electrical signal. The detector's models are shown in Figure 1c and 1d for the PASSING and DETECTING modes, respectively.

When the detector is in the PASSING mode, light from all wavelengths passes the detector, but a portion of the light from all of them is coupled into the ring, resulting in an amount of crosstalk noise being detected at the detector. We define this crosstalk noise as the detector's crosstalk. The output and crosstalk noise is, therefore, calculated as in

$$P_{\text{out}}[i] = L_{d_0}P_{\text{in}}[i], \quad i = 0, \dots, n \quad (5a)$$

$$P_{\text{noise}} = X_{d_0}P_{\text{in}}[j] + \sum_{i=0}^{n-1} \Phi(i,j)P_{\text{in}}[i], \quad i \neq j. \quad (5b)$$

When the detector is in the DETECTING mode, the light signal from the wavelength matching the detector's resonant wavelength is coupled into the detector. The output signal power for the light, which passes the detector, is calculated in

$$\begin{cases} P_{\text{out}}[j] = X_{d_1}P_{\text{in}}[j] \\ P_{\text{out}}[i] = L_{d_0}P_{\text{in}}[i] \end{cases}, \quad i \neq j \quad (6)$$

while the detected signal power is given in

$$P_{\text{signal}} = L_{d_1}P_{\text{in}}[j]. \quad (7)$$

However, some portion of the light from other wavelengths may still be coupled into the ring and detected, which is given in

$$P_{\text{noise}} = \sum_{i=0}^{n-1} \Phi(i,j)P_{\text{in}}[i], \quad i \neq j. \quad (8)$$

Splitters

Splitters distribute the power from the source to different interconnection paths. Common types of splitters include 1×2 and 1×4 power splitters. The light passes through the splitters and suffers from loss of L_{12} or L_{14} . The equations for 1×2 and 1×4 splitters are thus given, respectively, in

$$P_{\text{out}_1} = L_{s12} P_{\text{in}} (1 - R_{12}) \quad \text{and} \quad P_{\text{out}_2} = L_{s12} P_{\text{in}} R_{12} \quad (9)$$

$$P_{\text{out}_1} = P_{\text{out}_2} = P_{\text{out}_3} = P_{\text{out}_4} = L_{s14} P_{\text{in}} R_{14}. \quad (10)$$

For a 1×2 splitter, we consider different split ratios at the two outputs, where output 1 receives $(1 - R_{12})$ and output 2 receives R_{12} of the power from the input. For a 1×4 splitter, we consider the same split ratio (i.e., R_{14}) at all the outputs. In this paper, a negligible amount of crosstalk noise introduced by the splitters is considered.

Corona's element analysis

Structure overview

Corona consists of 256 general-purpose cores grouped into 64 four-core clusters. Three structures are established: optical crossbar for data communication, broadcast bus for multicasting, and arbitration for protocol. The main laser source is fed into the loop and split into these different structures. For each optical structure, sets of MRs perform as modulators, detectors, and injectors. In [2], Table 2 summarizes the Corona optical network's optical elements.

Splitter series

In Corona, since only one power waveguide exists, a series of splitters is constructed to split the power from the main source to each processing cluster. Given the analysis of one splitter in the Basic Optical Elements Analysis section, we derive

$$\begin{aligned} P_i &= (L_{s12})^i (1 - R_{12})^i (L_p)^{d_i} (L_b)^{p_i} (L_{s12}) (R_{12}) P_{\text{in}} \\ &= (L_{s12})^{i+1} (1 - R_{12})^i (L_p)^{d_i} (L_b)^{p_i} (R_{12}) P_{\text{in}} \end{aligned} \quad (11)$$

for the power which is split for a particular cluster i . We assume that the split ratio R_{12} is fixed for all clusters, and $(1 - R_{12})$ is the remaining power source after each cluster. 1×4 splitters are not considered in the splitter series because 1×4 splitters equally distribute the power within the cluster or the channel. Figure 2d shows an example of the splitter series via a hierarchical arrangement in the data channel.

In (11), d_i and p_i are, respectively, the distance and the number of bendings from the power source to the i th splitter. From (11), we derive that the larger the channel number, the higher the signal loss that the channel suffers due to the fact that it is further from the main laser source.

Calculating d_i , the distance from the source to the i th splitter.

The total die area for Corona is 423 mm^2 (Penryn based) [2], resulting in $a = 2.05 \text{ cm}$ for each side of the die. For an 8×8 structure, each cluster size is $a/8 = 0.256 \text{ cm}$. We divide these clusters into four 2×8 groups, forming four 16-cluster groups. In each group, the waveguide passes through a two-section L-shape and two 90° bendings. The first section is a , and the second section is approximated to be two clusters, $2a/8 = a/4 = 0.513 \text{ cm}$. The distance between two splitters, considering fair distribution, is $d_{\text{splitter}} = a/16 = 0.128 \text{ cm}$. As a result

$$\begin{aligned} d_i &= (i \bmod 16)d_{\text{splitter}} + \left(a + \frac{a}{4}\right) \left\lfloor \frac{i}{16} \right\rfloor \\ &= (i \bmod 16)d_{\text{splitter}} + \frac{5a}{4} \left\lfloor \frac{i}{16} \right\rfloor \\ &= 2.05 \text{ cm} \\ d_{\text{splitter}} &= 0.128 \text{ cm} \end{aligned} \quad (12)$$

expresses the distance traveled from the source to the current splitter.

Calculating p_i , the number of bendings from the source to the i th splitter.

Similar to the previous calculation for d_i , we formulate the number of bendings from the laser source to the current splitter in

$$p_i = 2 \left\lfloor \frac{i}{16} \right\rfloor. \quad (13)$$

Modulators and detectors series

A series of modulators is constructed by cascading the MRs with different resonant wavelengths. In Corona, 64 MRs are cascaded as one series of modulators. When no communication between cluster X to cluster Y is set up, the modulators of X are INACTIVE, and the output power is expressed in

$$P_{\text{out}}[i] = (L_{m_0})^n P_{\text{in}}[i]. \quad (14)$$

When communication is set up between X and Y , cluster X 's modulators on the communication path

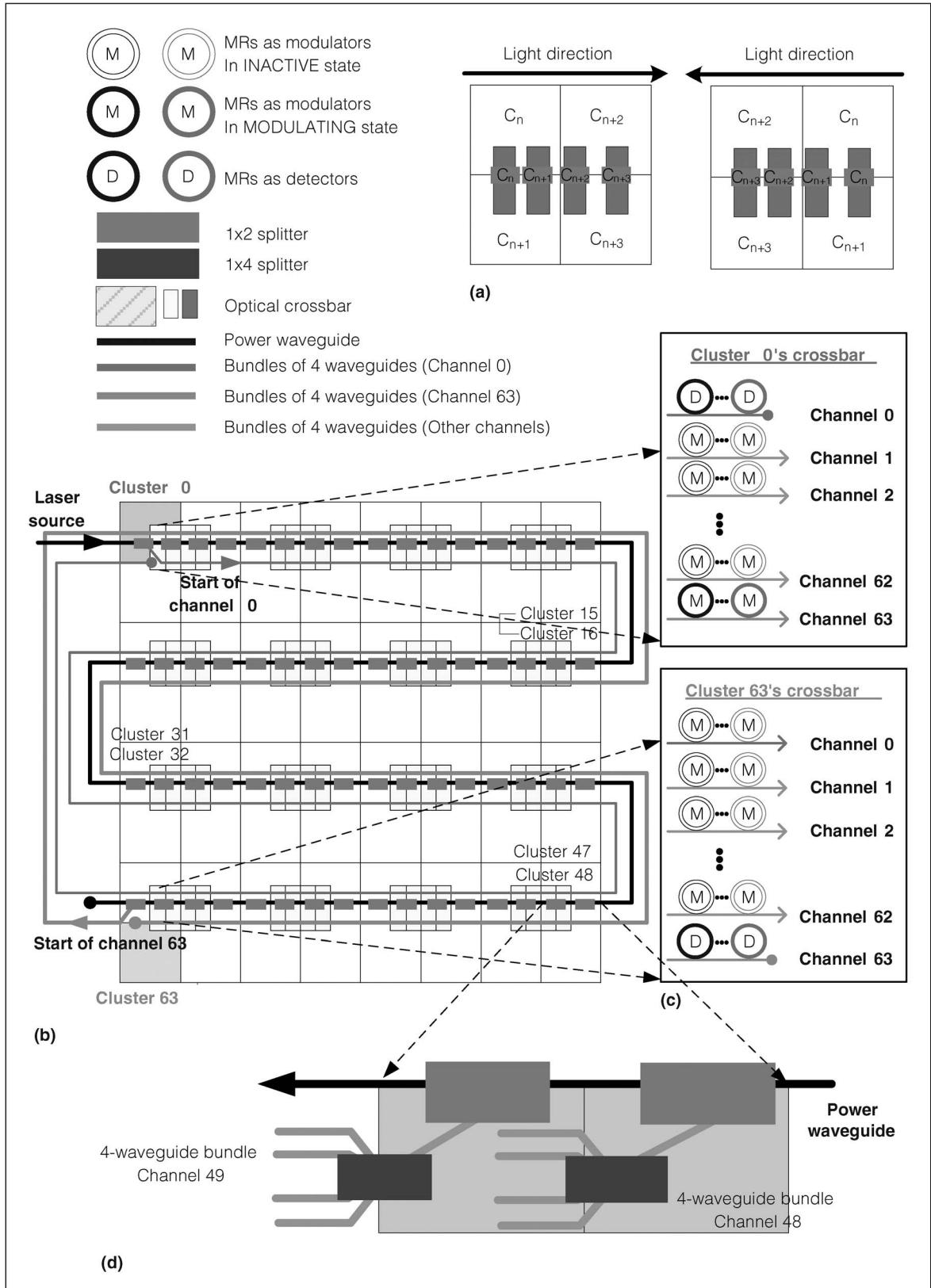


Figure 2. Data channel overview. (a) Light direction notation. (b) Corona data channel structure. (c) Optical crossbars of clusters 0 and 63. (d) Splitter hierarchy.

of cluster Y are MODULATING. For a long time, all these modulators are in the MODULATING state. The output power after this series of modulators is expressed as

$$P_{\text{out}}[i] = (L_{m_0})^{n-1} X_{m_1} P_{\text{in}}[i]. \quad (15)$$

The detectors are always DETECTING the incoming signal. So we arrive at

$$P_{\text{out}_j}[i] = \begin{cases} P_{\text{in}}[i], & j = 0 \\ (X_{d_1}) P_{\text{out}_{j-1}}[i], & j \neq i \text{ and } j - 1 = i \\ (L_{d_0}) P_{\text{out}_{j-1}}[i], & j \neq i \text{ and } j - 1 \neq i \end{cases} \quad (16a)$$

$$P_{\text{out}_j}[i] = \Psi_1(i, j) P_{\text{in}}[i] \quad (16b)$$

$$\Psi_1(i, j) = (X_{d_1})^k (L_{d_0})^{j-k}$$

$$k = 1, \quad \text{if } j - 1 \geq i, \quad k = 0, \text{ otherwise} \quad (16c)$$

defining the received output power before each detector j (from 0 to 63) at the wavelength i (from 0 to 63).

With the defined received power before each detector in (16b), the signal and crosstalk noise power received at each detector j are, respectively

$$P_{\text{signal}_j} = (L_{d_1}) P_{\text{out}_j}[j] \quad (17)$$

$$P_{\text{noise}_j} = \sum_{i=0}^{n-1} \Phi(i, j) P_{\text{out}_j}[i], \quad i \neq j. \quad (18)$$

The worst case crosstalk noise analysis for Corona

Data channel

Corona consists of 64 data channels, and each of them is formed by four waveguides, 64 wavelengths each. A data channel starts from a cluster called the homecluster, traverses other clusters, where a series of modulators can modulate the light, and finally ends at the homecluster again, with a detectors series and an optical terminator. This arrangement results in 64 multiple-writer-single-reader open-ring data paths, where only one cluster can read from its channel and other clusters only manipulate that channel. Figure 2 demonstrates the working principle of the optical crossbar.

In Figure 2, cluster 0's and cluster 63's channels are red and green, respectively. Cluster 0's channel (i.e., channel 0) starts from the first splitter and

channel 63 is split from the last splitter. All the channels make a loop through the ring before ending at their homeclusters. A communication is set up when other clusters manipulate the light with their modulators series on the homecluster.

In Figure 2c, cluster 0 is communicating on channel 63. During the communication, cluster 0's modulators of channel 63 are modulating, while the modulators on the other channels are INACTIVE. Meanwhile, cluster 63's modulators are all INACTIVE, since it does not write to any other clusters. All the detectors of all clusters should be in the DETECTING mode.

With a four-waveguide bundle per data channel, 256 waveguides are required for a complete data path. Hence, a splitter hierarchy consisting of 1×2 and 1×4 splitters is established. Figure 2b shows that the 1×2 splitters are positioned at every channel's beginning to split the source from the power waveguide, and 1×4 splitters are placed after every 1×2 splitter to further divide the power into four waveguides.

The study on the splitter series is given in the Splitter Series section. Instead of P_i , we denote the received power at channel i as $P_{\text{data}-i}$. From (11), the last channel suffers the most signal power loss. Consequently, in the data path, channel 63 suffers the most signal power loss. Figure 3a fully demonstrates a data channel of cluster 63, where cluster 0 desires to communicate with cluster 63. Since every data channel has four waveguides with the same number of detectors and modulators, we can generalize the formula on one waveguide for four waveguides.

In this case, the signal power and the crosstalk noise received at each detector j are expressed in

$$P_{\text{signal}_j} = (L_{d_1}) P_{S_j}[j] \quad (19)$$

$$P_{\text{noise}_j} = (L_{d_1}) P_{N_j}[j] + \sum_{i=0}^{n-1} \Phi(i, j) (P_{S_j}[i] + P_{N_j}[i]),$$

$$i \neq j. \quad (20)$$

P_{S_j} and P_{N_j} are defined in

$$P_{S_j}[i] = \alpha_1 \Psi_1(i, j) P_{\text{data}-N}[i] \quad (21a)$$

$$P_{N_j}[i] = \begin{cases} 0, & j > i \\ \alpha_2 (L_{d_0})^j P_{\text{data}-N}[i], & j \leq i \end{cases} \quad (21b)$$

as the signal and the crosstalk noise power received before each detector j of the channel, respectively.

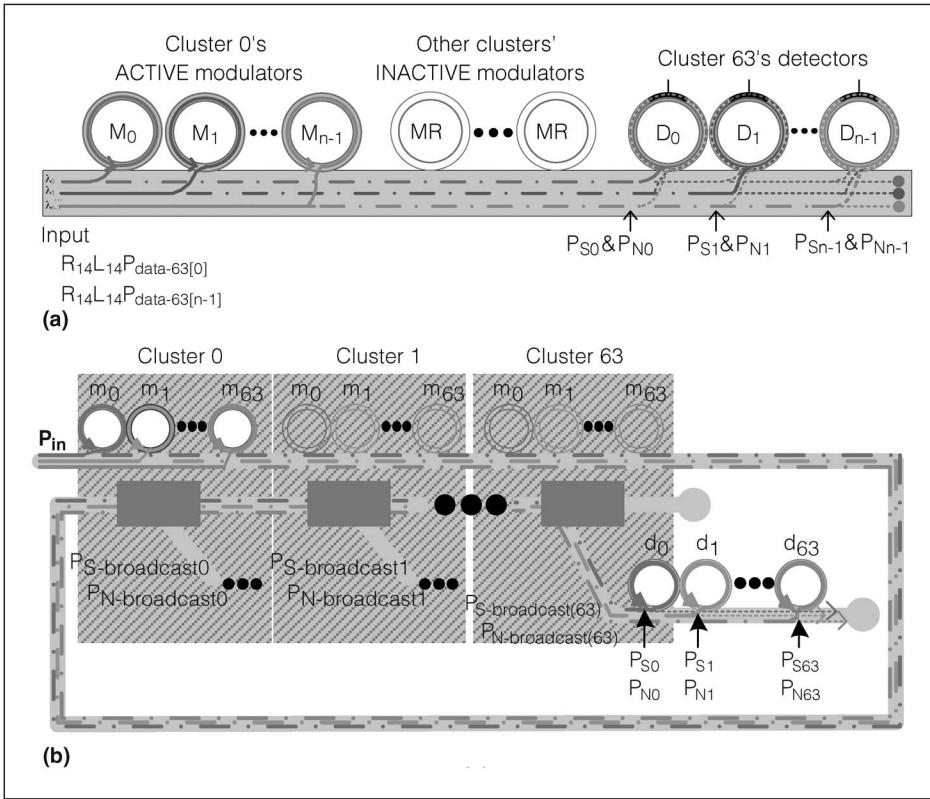


Figure 3. Data channel and broadcast bus. (a) Data channel: Communication between cluster 0 and cluster 63. (b) Broadcast bus: Cluster 63 receives a multicast message from cluster 0.

Also, $\Psi_1(i,j)$ is defined in (16c), where

$$\alpha_1 = (L_{14})(R_{14})(L_p)^D(L_b)^\rho(L_{m_0})^{64 \times 63} \quad (22a)$$

$$\alpha_2 = (L_{14})(R_{14})(L_p)^D(L_b)^\rho(L_{m_0})^{62 \times 64+63}. \quad (22b)$$

Broadcast bus

Similar to the data channel, the broadcast bus utilizes modulators and detectors series. However, for multicasting, the broadcast bus is designated as a single-write–multiple-read channel. Hence, the differences are the waveguide counts and the splitter hierarchy. Using one waveguide, the broadcast bus starts by a series of modulators from all 64 clusters and arrives at a series of 1×2 splitters, splitting the incoming signal message to all the clusters. A series of 64 detectors at the end of each branch detect and receive the multicast message [2]. Figure 3b shows the broadcast bus with notations for the signal power analysis.

In Figure 3b, by modulating the light with its series of modulators, cluster 0 multicasts a message to all other clusters. From Figure 3b, the input power for the broadcast bus first suffers loss from all the modulators of the 64 clusters. Similarly, the crosstalk noise from the MODULATING-state modulators also suffers loss from all the other modulators. These loss values are, respectively, derived in

$$\alpha_3 = (L_p)^D(L_b)^N(L_{m_0})^{64 \times 64} \quad (23a)$$

$$\alpha_4 = (L_p)^D(L_b)^N(L_{m_0})^{64 \times 64-1} \times (X_{m_1}). \quad (23b)$$

where D is the total distance and N is the total number of bendings for a loop.

When the signal and cross-talk noise arrive at cluster x in the broadcast bus, they suffer loss from the splitters series. Propagation and bending loss also accumulate from the first splitter to the x th splitter. This loss is expressed as

$$\beta_1[x] = (L_{S_{12}})^{x+1}(1 - R_{12})^x(R_{12})(L_p)^{d_x}(L_b)^{p_x} \quad (24a)$$

$$\beta_2[x] = (L_{S_{12}})^{x+1}(1 - R_{12})^x(R_{12})(L_p)^{d_x}(L_b)^{p_x} \quad (24b)$$

where d_x and p_x are the distance and number of bendings from $P_{\text{broadcast}}$ to the x th splitter, respectively.

From (23a), (23b), (24a), and (24b), the signal and crosstalk noise power received at cluster x can be expressed in

$$P_{S-\text{broadcast}x}[i] = \alpha_3\beta_1[x]P_{\text{in}}[i] \quad (25)$$

$$P_{N-\text{broadcast}x}[i] = \alpha_4\beta_2[x]P_{\text{in}}[i]. \quad (26)$$

At the end of a cluster's channel, a series of detectors detect both the signal and crosstalk noise. From (16a), (16b), (25), and (26), we derive

$$P_{S_j}[i] = \Psi_3(i,j)P_{S-\text{broadcast}(x)}[i] \quad (27)$$

$$P_{N_j}[i] = \begin{cases} 0, & j > i \\ (L_{d_0})^j P_{N-\text{broadcast}(x)}[i], & j \leq i \end{cases} \quad (28)$$

where $\Psi_1(i,j)$ is defined in (16c).

Further investigating the signal power and crosstalk noise received at each detector, we derive

$$P_{\text{signal}_j} = (L_{d_1}) P_{S_j}[j] \quad (29)$$

$$P_{\text{noise}_j} = (L_{d_1}) P_N[j] + \sum_{i=0}^{n-1} \Phi(i,j) (P_{S_j}[i] + P_N[i]) \quad (30)$$

for the signal and crosstalk noise received at each detector j in the broadcast bus of cluster 63.

Results and discussion

Utilizing the analytical models with the values for the listed parameters, we calculate the crosstalk noise and SNR received at each detector of cluster 63. Equations (19)–(20) and (29)–(30), respectively, represent the signal power and crosstalk noise received at each detector of the data channel and broadcast bus. The SNR is expressed by

$$\text{SNR} = \frac{P_{\text{signal}}}{P_{\text{noise}}}. \quad (31)$$

The SNR is defined as the ratio between the received signal and the crosstalk noise power at the detectors. When substituting (19) and (20) or (29) and (30) into (31), the input power for the signal power in the numerator P_{signal} and that for the crosstalk noise power in the denominator P_{noise} cancel out each other. Hence, the SNR is independent of the input signal power of the network.

Regarding the data channel, the worst case power loss is -69.3 dB at the last detector. The worst case SNR is 14.0 dB at the 43rd detector, where the signal power loss is -69.2 dB. On the broadcast bus, the signal and crosstalk noise at each cluster in the broadcast bus differ in the number of splitters. Following the analysis of the splitter series in the Splitter Series section, the last splitter has the highest power loss. As a result, we calculate the SNR values of cluster 63. Similar to the data channel, the worst case SNR is 14.0 dB at the 43rd detector; the worst case power loss is 63.4 dB at the 63rd detector. Since the broadcast bus does not contain 1×4 splitters, its worst case signal and crosstalk noise power loss are both smaller compared to those of the data channel.

Figure 4a demonstrates the values of the signal power loss, crosstalk noise power loss, and SNR at different detectors of the data channel and the broadcast bus. According to our analytical model, both signal and crosstalk noise suffer from propagation, bending, and passing loss. This reflects

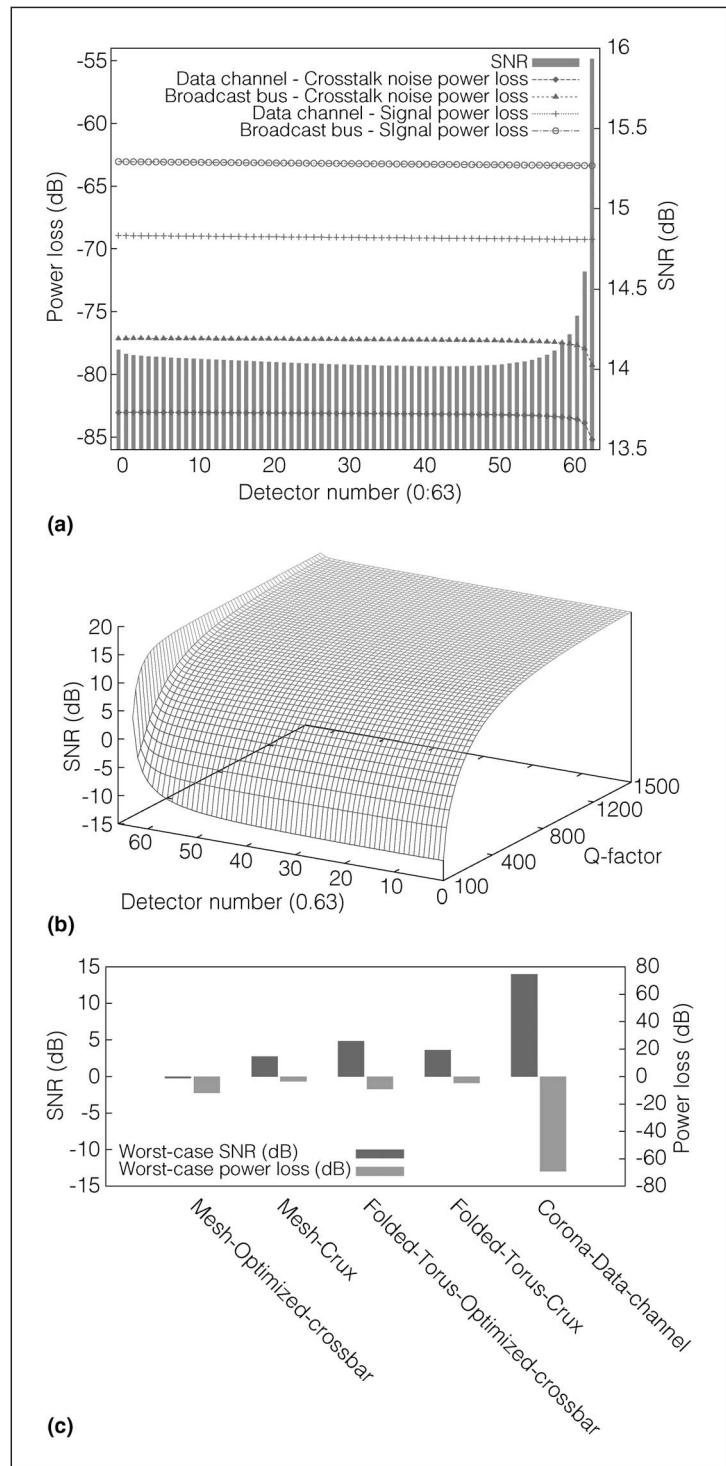


Figure 4. The signal and crosstalk noise power loss and worst case SNR in Corona, and the comparison to mesh and folded-torus ONOCs. (a) Power loss, crosstalk noise and SNR at different detectors ($Q = 9000$). (b) The worst case SNR with different Q-factors. (c) Comparison of the worst case SNR and signal power loss.

the downtrend of both the signal power loss and the crosstalk noise power loss in Figure 4a. However, the results also show that the crosstalk noise power reduces more deeply compared to the signal power. On the one hand, at first, the crosstalk noise power slightly decreases due to the decreasing number of optical signals on different wavelengths that introduce crosstalk noise. Toward the last detectors (i.e., the 60th detector onwards), when only a small number of optical signals contribute to the noise, this crosstalk noise decreases deeply. On the other hand, the signal power decreases more steadily when the detectors' number increases. Consequently, the worst case SNR slightly decreases among the first detectors, reaches its minimum at detector 43, starts to increase, and finally peaks at the last detector.

From our analyses, the Q -factor can substantially affect the SNR. Figure 4b shows the destructive impact of Q . Indeed, the SNR is even negative when Q is smaller than 2000. For example, when $Q = 100$, the worst case SNR is -11.5 dB. A small Q -factor corresponds to the drop port and is different from that of the through port. When Q -factor is fairly small, the crosstalk power exceeds the signal power received at the detectors. Additionally, from Figure 4b, the SNR tends to gradually settle at a value toward a higher Q -factor. Thus, a Q -factor larger than 15 000 may not significantly improve the SNR.

Furthermore, since 64 clusters of Corona are arranged in an 8×8 matrix, we can consider counterpart mesh-based and folded-torus-based ONoCs with a similar clusters' matrix size. Hence, comparison of the worst case SNR and signal power loss is performed for the three ONoCs. The results in the mesh and folded torus are quantitatively simulated in CLAP, an automated crosstalk and loss analysis platform. CLAP can perform the analyses of crosstalk noise, signal power loss, and SNR of single-wavelength ONoCs, using an arbitrary optical router [5]. MATLAB is utilized to simulate Corona's results.

Figure 4c shows the comparison among the three ONoCs. The comparison results indicate that the worst case SNR in Corona is better than that of the mesh-based and folded-torus-based ONoCs. Corona's worst case SNR is 14.0 dB, compared to -0.2 and 3.6 dB in the mesh-based ONoCs, using the optimized-crossbar router and the folded-torus-based ONoCs using the Crux optical router, respectively [5]. However, Corona's worst case power loss is substantially higher, -69.3 dB, compared to

-11.9 and -9 dB in the mesh-based and folded-torus-based ONoCs, respectively.

CROSSTALK NOISE IS an inevitable characteristic of MR-based switches used in constructing ONoCs. At the network level, crosstalk noise accumulates and considerably damages the SNR and scalability of ONoCs. Indeed, the worst case crosstalk noise and SNR analyses in a specific ONoC are profoundly dependent on the specific architectural properties of that network. This paper focuses on the analyses of crosstalk noise in two structures of Corona. However, at the device level, our developed analytical models can be utilized in any other topology using WDM. Utilizing the proposed analytical method, quantitative simulations of the worst case power loss, crosstalk noise, and SNR in Corona are achieved. Results indicate that the worst case SNR in the data network of Corona is 14.0 dB, while the worst case power loss is significantly high: -69.3 dB. Additionally, we compare these worst case SNR, power loss, and crosstalk noise in Corona with those in mesh-based and folded-torus-based ONoCs of the same network size. The comparison shows that Corona's worst case power loss is substantially higher, although it has better worst case SNR. ■

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