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Simulation and Analysis of Typical Wavelength-Routed Optical Networks-on-Chip Routers Based on Optsim

Ingenieurpraxis

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Abstract

Due to the unique wavelength division multiplexing (WDM) technology and ultra-low propagation delay of wavelength-routed optical networks-on-chip (WRONoCs), their advantages in performance over traditional electronic networks-on-chip have emerged. Since the implementation of WRONoCs presents significant challenges, utilizing simulation tools to simulate theoretical WRONoCs is essential in testing their performance in a more realistic environment and finding out the optimization strategy for the design of WRONoCs.

In this study, I have employed the powerful optical simulator from Synopsys, OptSim, to conduct an in-depth simulation on two 4-Input-4-Output WRONoCs: Hash-Router and Generalized Wavelength-Routed Network (GWOR). OptSim is a professional optical circuit simulation tool with powerful modeling and analysis capabilities. It is able to simulate complex optical circuit structures accurately and provide diverse simulation results and analysis tools. This report will show a detailed introduction to my simulation process and the analysis of the simulation results based on OptSim.

Catalog

1. Introduction

In recent years, due to the rapid development of optoelectronic technology and silicon photonics, wavelength-Routed optical networks-on-chip (WRONoCs) have been attracting widespread attention. This new generation of NoCs can not only offer high bandwidth, excellent scalability and low latency due to the wavelength division multiplexing (WDM) technology, but also avoid data collision at design time by distinguishing optical signals carrying different data with different wavelengths of them. Silicon microring resonators (MRRs) have been introduced to route optical signals based on their wavelengths. The MRR is an essential component in WRONoCs since it is able to route optical signals according to their wavelength as well as frequency based on the following principle: when optical signals from one waveguide approach the MRR at the same time, the signals on the MRR resonant frequency (the drop-frequency) will be coupled to the MRR, while the others pass through [1].

One of the typical differences between state-of-the-art WRONoC topologies of the same scale lies in the usage of MRRs. It leads to different MRR tuning powers and different crosstalk noise, which affects the network performance. So the design of state-of-the-art WRONoCs is targeting reducing the usage of MRRs to enhance their performances [1].

Since the expenses to implement WRONoCs and test their performance in reality are considerably high, utilizing powerful simulation tools to test them and obtain more realistic data and the difference between theoretical- and simulated results is essential, which reflects the impact of the environmental factors on their performance and guides the design of WRONoCs. In this project, I have built and simulated two WRONoC routers with 4 transmitter modules and 4 receiver modules (4*4 WRONoCs), and compared their performance.

One of them, based on parallel switching elements (PSEs), is called Hash-Router (shown in Figure 1). PSE is a typical optical switching element (OSE), where only one MRR is built between two parallel waveguides. The optical signal on a specific frequency (the drop-frequency) coupled to the MRR will turn 180 degrees into the other waveguide. In a 4*4 Hash-Router, the usage of MRR is 4 [1].

Another one (shown in Figure 2) is GWOR designed with crossing switching elements (CSEs). Comparing with the PSEs, two MRRs are placed close to the waveguide crossings in CSEs. Therefore, optical signals of drop-frequency from any of the two intersecting waveguides can accordingly be turned 90 degrees. 8 MRRs are used in a 4*4 GWOR [3].

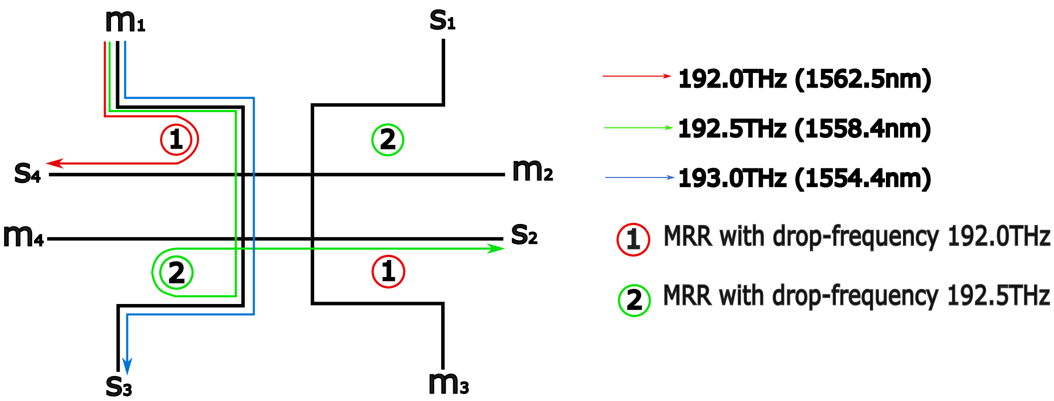


Figure 1: A 4*4 Hash-Router

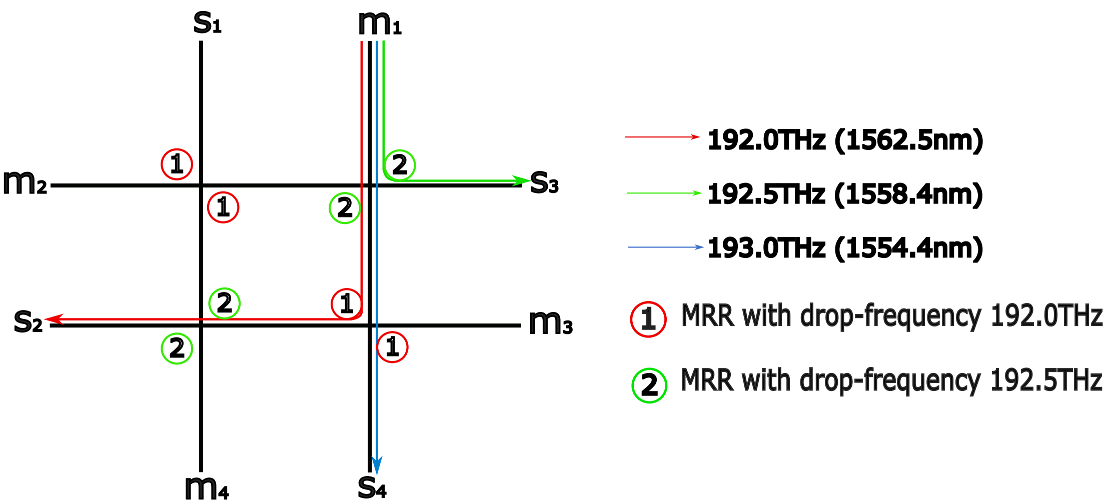


Figure 2: A 4*4 GWOR

The reason why I chose to simulate and compare these two WRONoCs is that these two WRONoCs have similar structures: each transmitter module is paired with a corresponding, very nearby receiver module to form an IP-core, which is an optical transceiver both transmitting and receiving signals, and the communications within an IP-core is implemented by using electrical links. Therefore, in the optical circuit simulation, there are only 4*3=12 optical paths instead of 4*4=16 without considering the electrical signal communication within the IP-Core [1, 3].

OptSim simulator under Synopsys is one of the powerful simulation software in the simulation of optical circuits. There are many built-in optical and electrical components and modules as well as measuring tools, whose parameters can be freely customized, which greatly facilitates the simulation process.

After the whole simulation, I have found that both WRONoCs can transmit the optical signals properly through comparing the generated logical signals input to the transmitters with the digital signals received by the receivers. Besides, under the same conditions, Hash-Router has better transmission efficiency and better performance than GWOR.

2. Introduction to OptSim

As a powerful simulation software in the field of optical circuits, OptSim provides two simulation techniques: Spectral Propagation Technique (SPT) and Variable Bandwidth Simulation Technique (VBS).

SPT Technique is a spectral domain simulation where optical signals are propagated as power spectra. It does not consider phase distortion or non-linearities. Only the optical components are simulated in the SPT, while electrical and logical components are not taken into account.

The VBS technique is a time-domain simulation where signals are propagated along the network as samples in the time domain. It is used to simulate linear and non-linear behavior for both optical and electrical components and can provide complete simulation results. The VBS Technique can be further subdivided into 3 categories: loss-only fiber VBS, linear fiber VBS and full VBS, whose difference lies in different simulation accuracies caused by different extents of inclusion of fiber propagation effect.

Since my purpose is to simulate two WRONoCs, which contain no fibers, I have chosen full VBS during my simulation process.

In addition, there are the built-in optical and electrical components in OptSim:

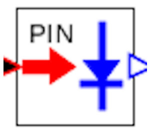
Optical Spectrum Analyzer (OSA): it can display the spectrum diagram of optical signals.

Electrical Scope: it can display the electrical signal diagram and Eye-diagram.

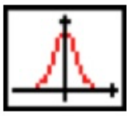
Logica Signal Display: it can display the logical signal diagram from Digital Data Source.

Q-Estimator: it can show the Quality Factor of an electrical signal.

Electrical Power Meter: it can show the electrical power in 10*log(a.u.) of an electrical signal.

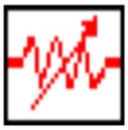


Photodiode: it can transfer the optical signal to electrical signal.



Optical Filter: when it is set as a bandpass filter, it can allow optical signals on specific frequency to pass through; when it is set as a notch filter, it can filter out the optical signal on specific frequency. The specific frequency can be user-difined.

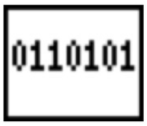
Electrical Filter: it can filter and process the electrical signals.



Optical Attenuator: it can attenuate the optical signals by a specific customized percentage.

Laser: it can transmit optical signals on specific frequency.

Amplitude Modulator: It can change the amplitude of the optical signals according to the change of the input electrical signal.



Digital Data Source: it can generate and output logical signals.

Electrical Driver: it can transfer logical signals to electrical signals.

These components above will be used to build the two WRONoCs.

3. Simulation Process

In order to simulate both the Hash-Router and GWOR, I first built the optical signal transmitter module and the optical signal receiver module. Both routers share the same transmitter and receiver modules.

3.1 3-Channel Optical Signal Transmitter Module

A 3-channel optical signal transmitter module contains 3 single-channel transmitters that can modulate optical signals on different frequencies. The whole module can emit these optical signals into the same waveguide.

A single channel transmitter consists of four components: digital data source, electrical driver, laser, and amplitude modulator.

The digital data source outputs the logic signals, which contain the data to be carried by optical signals, to the Electrical Driver. An Electrical Driver will convert those logical signals into electrical signals and transmit them to the electrical input port of the Amplitude Modulator. Meanwhile, the Laser component emits optical signals on a single frequency to the optical input port of the same Amplitude Modulator, which eventually changes the amplitude of the optical signals according to the change of the input electrical signal, so that the whole transmitter module can transmit 3 optical signals of different frequencies, each of which also contain different logical data information.

In OptSim, I chose the following four built-in components to form a single-channel transmitter: Datasource, NRZ Raised Cosine Driver, CW Lorenzian Laser, and Sin^2 Amplitude Modulator. The Laser_power of the TX_Laser has been set to 30dB and I left the rest of the parameters at default, which can be found in Appendix. In addition, I have also added a Logical Signal display to observe the waveform of the logical signal. All the components are connected as shown in Figure 3:

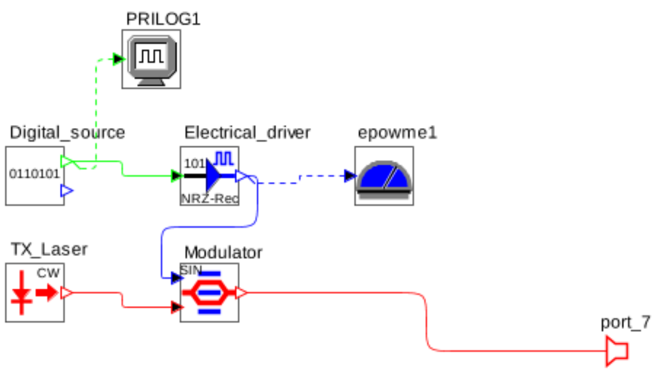


Figure 3: The single channel transmitter

And a whole transmitter module, which contains 3 single optical transmitters, is shown in Figure 4:

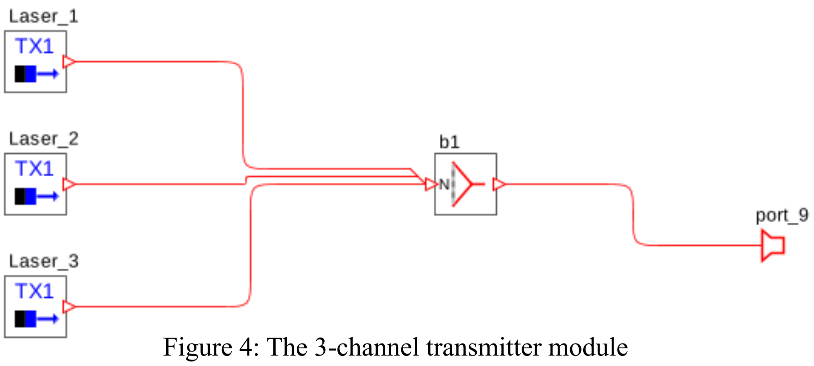


Figure 4: The 3-channel transmitter module

I set the laser-frequency values of the Laser in the three single channel transmitters to 192.0 THz, 192.5 THz and 193.0 THz, and named the three transmitters as *m_1920, m_1925, m_1930*.

3.2 3-Channel Optical Signal Receiver Module

Similar to the transmitter module, the receiver module consists of 3 single-channel receivers that receive only one optical signal on a specific frequency. It is designed to receive 3 different optical signals of different frequencies at the same time.

A typical single-channel receiver contains an optical filter, a photodiode, an electrical filter, and an electrical scope connected in sequence.

The principle is: the optical filter allows optical signals at a specific frequency to pass through, while the Photodiode converts the input optical signal into an electrical signal. The electrical filter, which is set to its low-pass mode, is used to filter out the high-frequency noise signals and enhance the quality of electrical signals at the receivers. The electrical scope is used for displaying and analyzing the electrical signals that have been already processed by the Electrical filter [1].

I connected the built-in Raised Cosine Optical filter, ideal Photodiode, Bessel Electrical filter, and Electrical Scope components in series to form a single-channel receiver, as shown in Figure 5:

Figure 5: The single channel receiver

A whole 3-channel Receiver containing 3 single channel receivers is connected as shown in Figure 6:

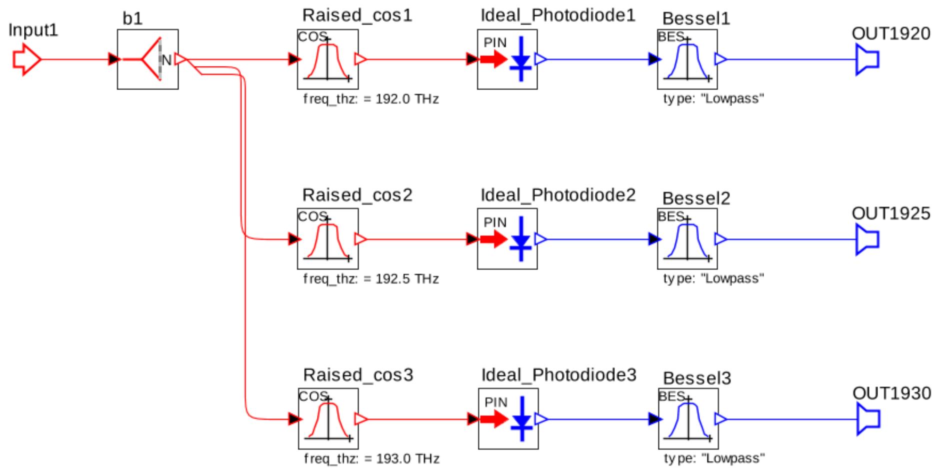


Figure 6: The 3-channel receiver module

I set the center-frequency parameter of the three raised cosine optical filter components in the receiver module to 192.0THz, 192.5THz, and 193.0 THz to match the three laser-frequencies in the transmitter module, named the three receivers as *s_1920, s_1925, s_1930.*

In the following two sub-sections, I introduced the model of a PSE and a CSE.

3.3.1 PSE-Module and Hash-Router

The PSE module, whose schematic is shown in Figure 7, is the most important part of the Hash-Router, and the whole module has two optical signal inputs: the "input port" and the "add port", as well as two optical signal outputs: the "through port" and the "drop port".

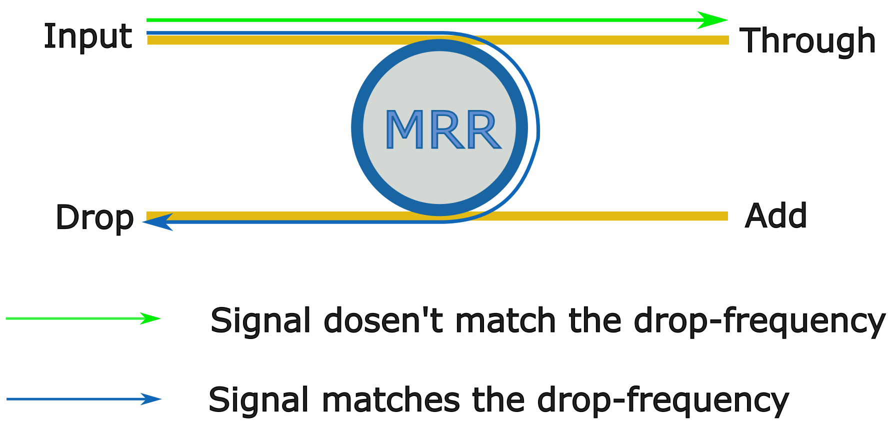


Figure 7: PSE schematic

It can achieve the following functions: the input optical signal on the resonate frequency (drop-frequency) will be turned 180 degrees into another waveguide and then emitted from the "drop port", while the signals on other frequencies are not affected and emit from another output port. The added optical signals are processed in the same way [1].

While building the PSE Module in OptSim, I have introduced two new in-built components: Optical Splitter and Optical Combiner, which can make an optical signal split into several identical optical signals or combine different optical signals together. To change the direction of the specific optical signal while maintaining the transmission direction of the other optical signals, the input optical signal must pass through the optical splitter at first in order to be split into two identical signals. Taking the optical signal input from the "input port" of a PSE as an example, one of the two identical signals split from it should then pass through the "bandpass filter", so that a specific optical signal on drop-frequency is screened out, while another should pass through the "notch filter" to filter out the signal on the same drop-frequency. Signals from Add port will also be processed in the same way. Figure 8 shows a basic PSE Module without loss and crosstalk noise:

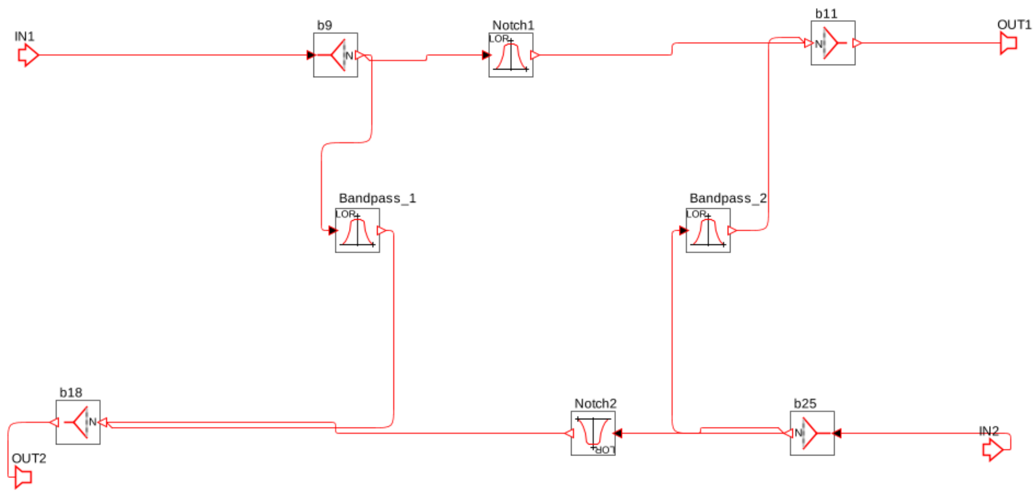


Figure 8: The ideal PSE without loss and crosstalk noise

The Hash-router with the ideal PSE is shown in Figure 9:

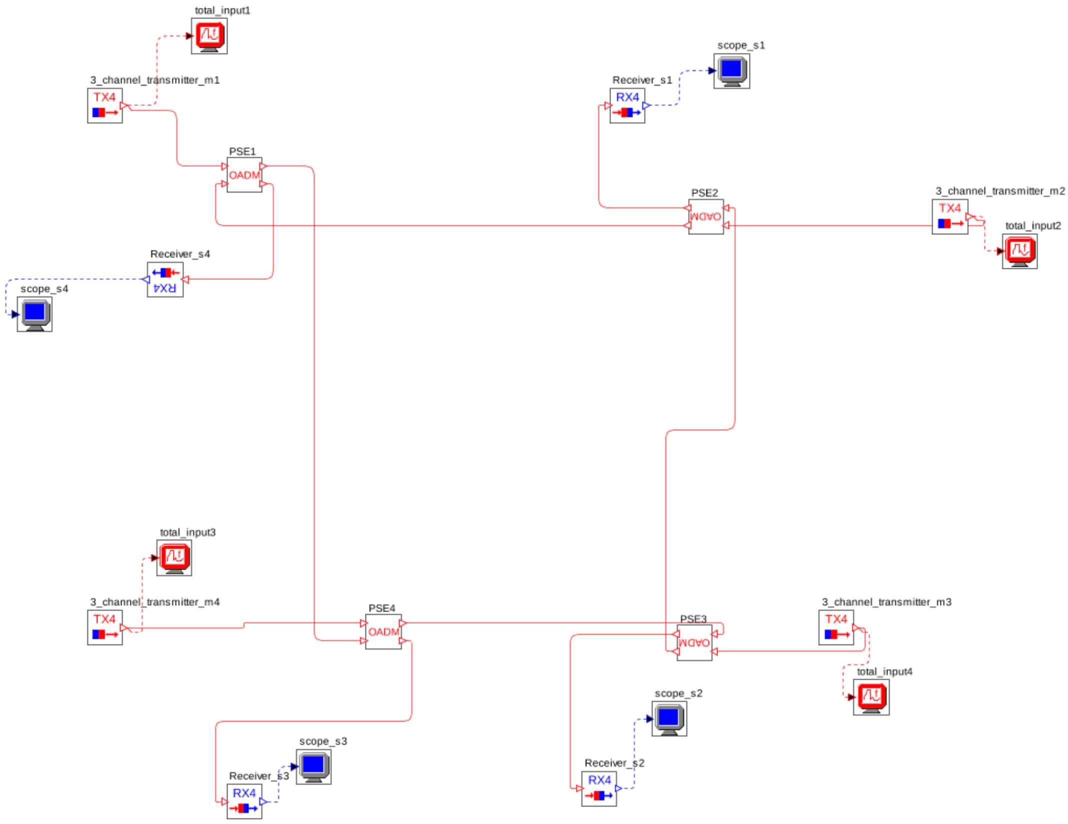


Figure 9: The ideal Hash-Router

The drop-frequency of PSE1 and PSE3 has the same value: 192.0THz, while the drop-frequency of PSE2 and PSE4 is 192.5THz.

However, OptSim reported an Error (Figure 10) before the simulation program started:

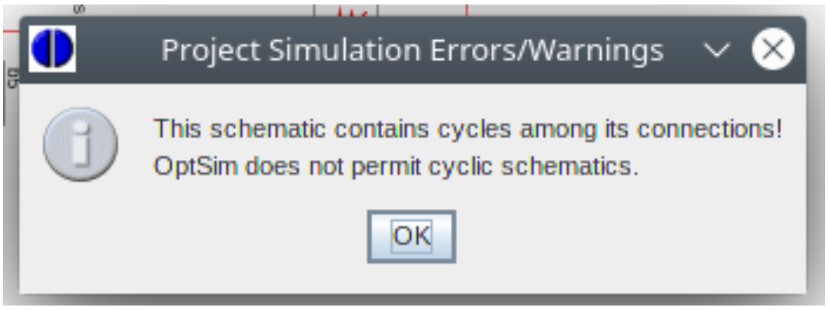


Figure 10: Error Info

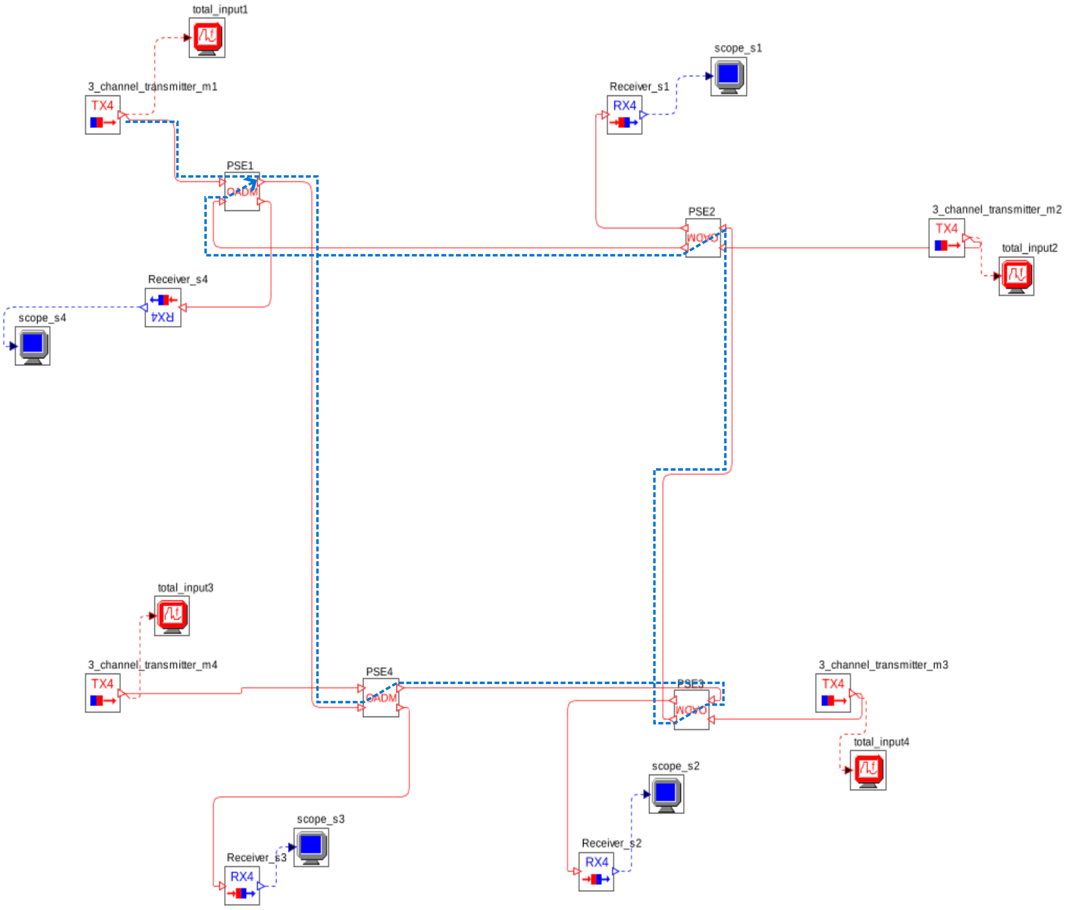


Figure 11: A typical cycle in Hash-Router

Since OptSim does not permit the existence of cycle circuits shown in Figure 11, which appear when all the modules were connected, the simulation program cannot be started, even though the optical signals will never pass along this cycle. For this reason, I redesigned the the PSE module and also added the corresponding loss and crosstalk noise. The completed PSE module is shown in Figure 12:

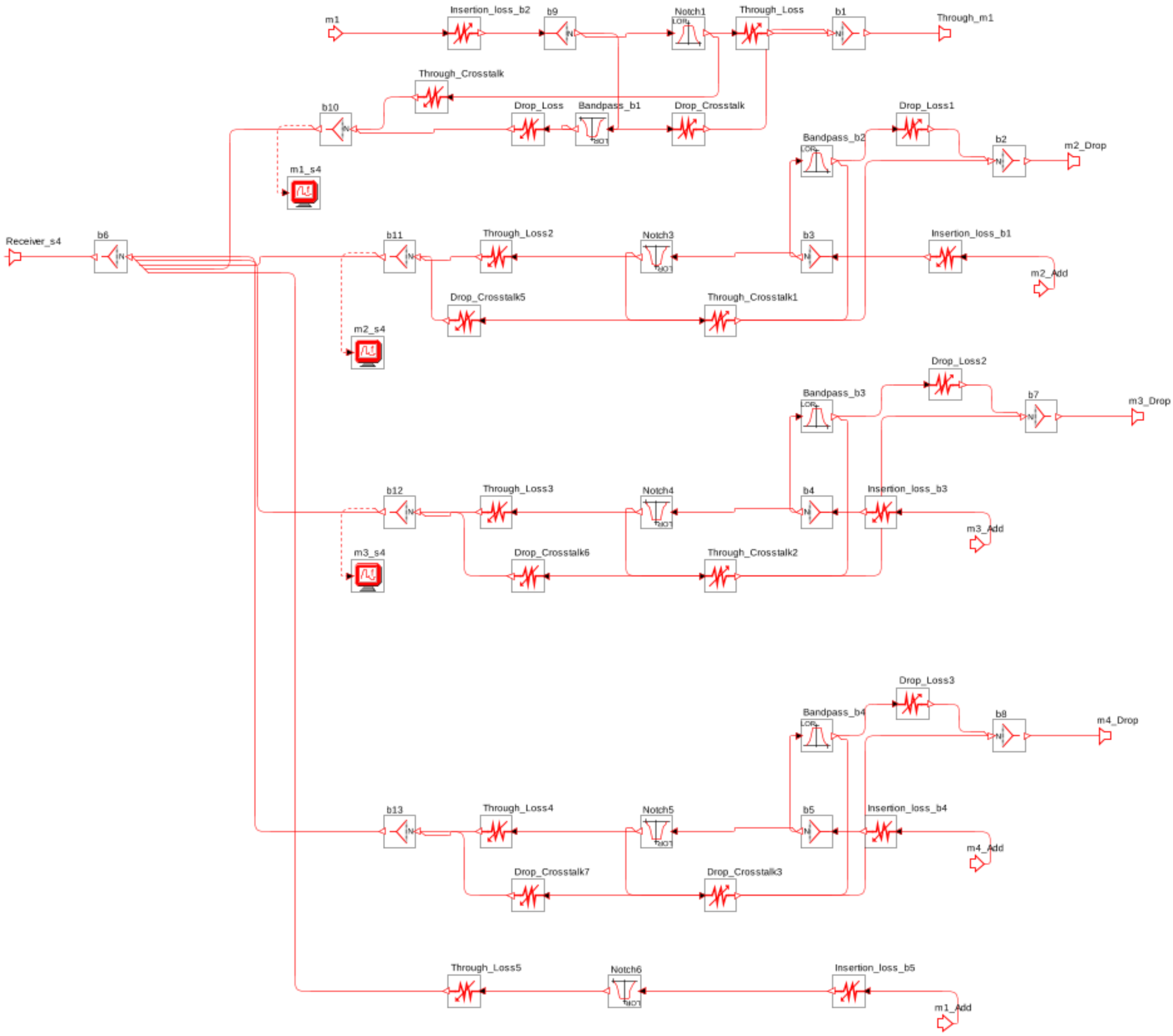


Figure 12: The redesigned PSE module

The basic logic of cycle removing is to prevent the two ends of each cycle from closing, so that the cycle circuits would disappear.

And the principles of loss- and crosstalk generation is as follows: When an optical signal, whose frequency doesn't match the resonate frequency of an MRR from the "input port", for example, passes through the MRR, there will be a through loss of about 0.01 dB, which means the power of the optical signal output from the "through port" will be about 0.01 dB (through loss) weaker than that of the input original signal. Meanwhile, a noise signal called crosstalk per MRR, which is about 50dB weaker than the original signal, will exist and be output from the "drop port". When the frequency of an input optical signal matches the drop-frequency and its transmission direction is changed by 180 degrees, there will be a drop loss of about 1 dB, while a same crosstalk per MRR will exist at the same time and be output from the "through port". The same is true for the optical signal input from the Add port [1].

The schematic of the mentioned principle is shown in Figure 13.

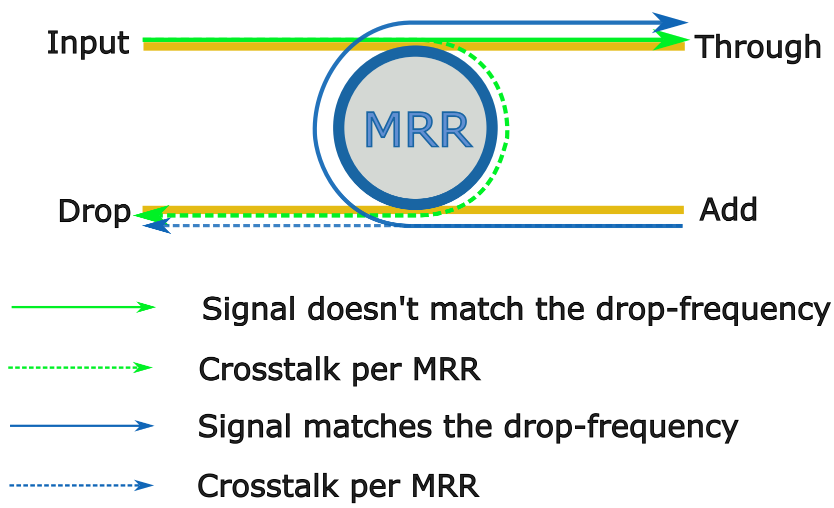


Figure 13: Crosstalk noises in a PSE module

I model the crosstalk noise by choosing the optical attenuator as the component that generates the loss and crosstalk noise, as it will attenuate the power of the passing optical signal by a specified value of decibels. The optical combiners are also necessary to combine the optical signal with the crosstalk noise, which should be output from the same output port.

Finally, I connected all the above modules one by one and added some measurements such as optical spectrum analyzer, logical signal display, and electrical scope in order to visualize the simulation results, so that I can analyze the function and performance of the whole Hash-Router. The complete Hash-Router circuit diagram is shown in Figure 14:

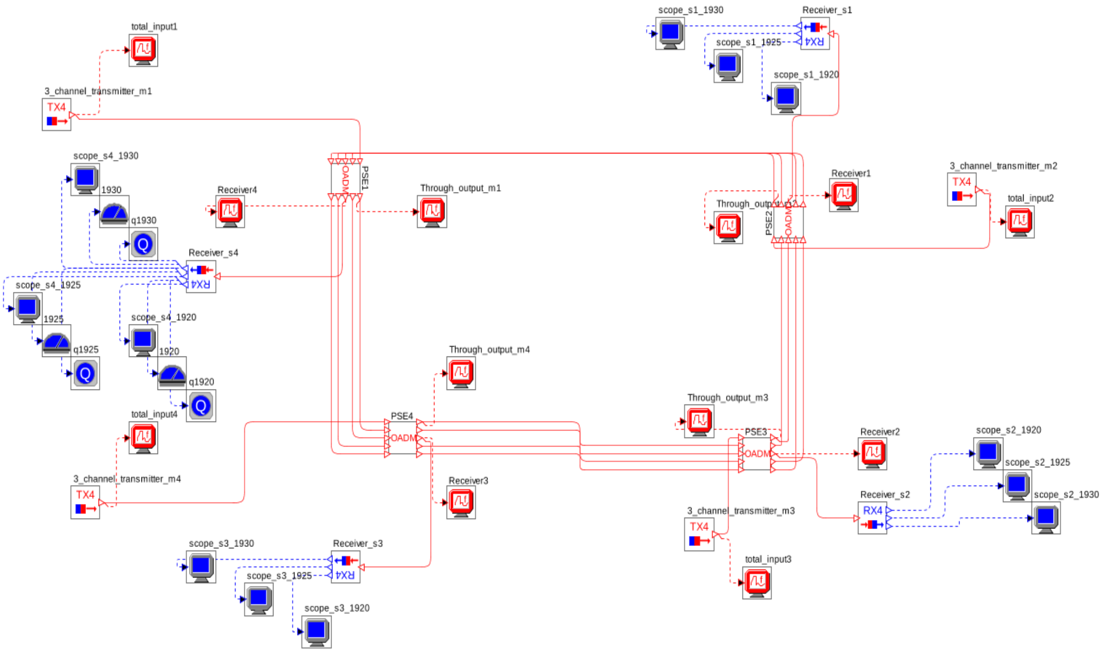


Figure 14: A 4*4 Hash-Router

The drop-frequency of PSE1 and PSE3 has the same value: 192.0THz, while the drop-frequency of PSE2 and PSE4 is 192.5THz.

3.3.2 CSE-Module and GWOR

The CSE module also has two inputs and two outputs, but unlike the PSE module, it consists of two crossed waveguides and two identical MRRs placed next to the waveguide crossing. The schematic diagram is shown in Figure 15:

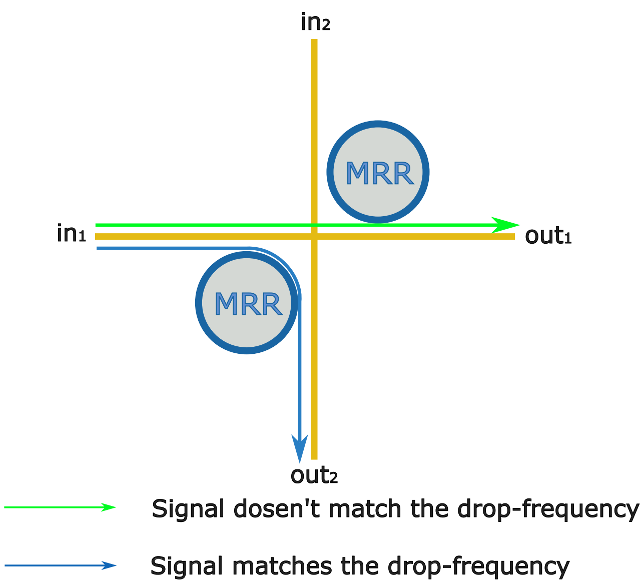


Figure 15: CSE Schematic

In comparison to the PSE Module, the input optical signal on resonate frequency (drop-frequency) will turn 90 degrees when approaching the MRR, while the rest will pass through.

Loss and crosstalk noise can also be generated in the CSE Module, whose schematic is shown in Figure 16:

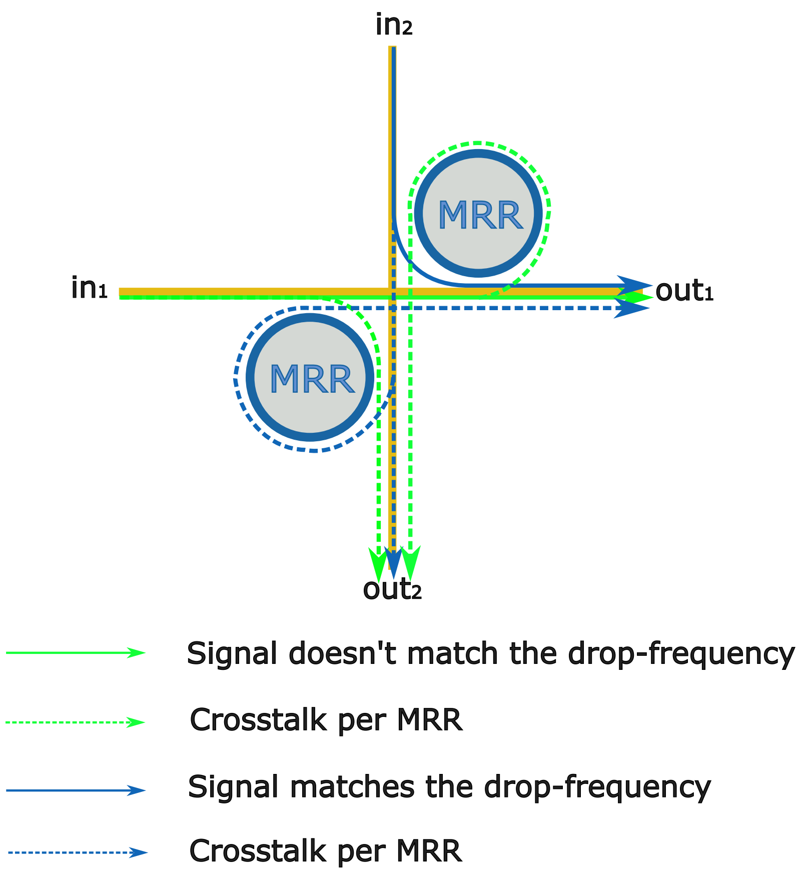


Figure 16: Crosstalk noise in a CSE module

However, since a CSE Module contains 2 MRRs, the through loss will occur two times when an optical signal which doesn't match the MRR resonate frequency (drop-frequency) passes through the two MRRs. As a result, the crosstalk per MRR turned 90 degrees and another crosstalk per MRR turned 270 degrees will be generated separately. The power of both noises is 50 dB smaller than the original signal. On the other hand, the power of the optical signal on drop-frequency will also attenuate 1dB (drop loss) after its transmission direction has been changed at the first MRR. The generated crosstalk per MRR, which is also 50dB weaker than the original optical signal, will be turned again when approaching the second MRR, resulting in the same drop loss and crosstalk per MRR [1, 2].

Figure 17 shows the whole CSE module and the completed GWOR is shown in Figure 18:

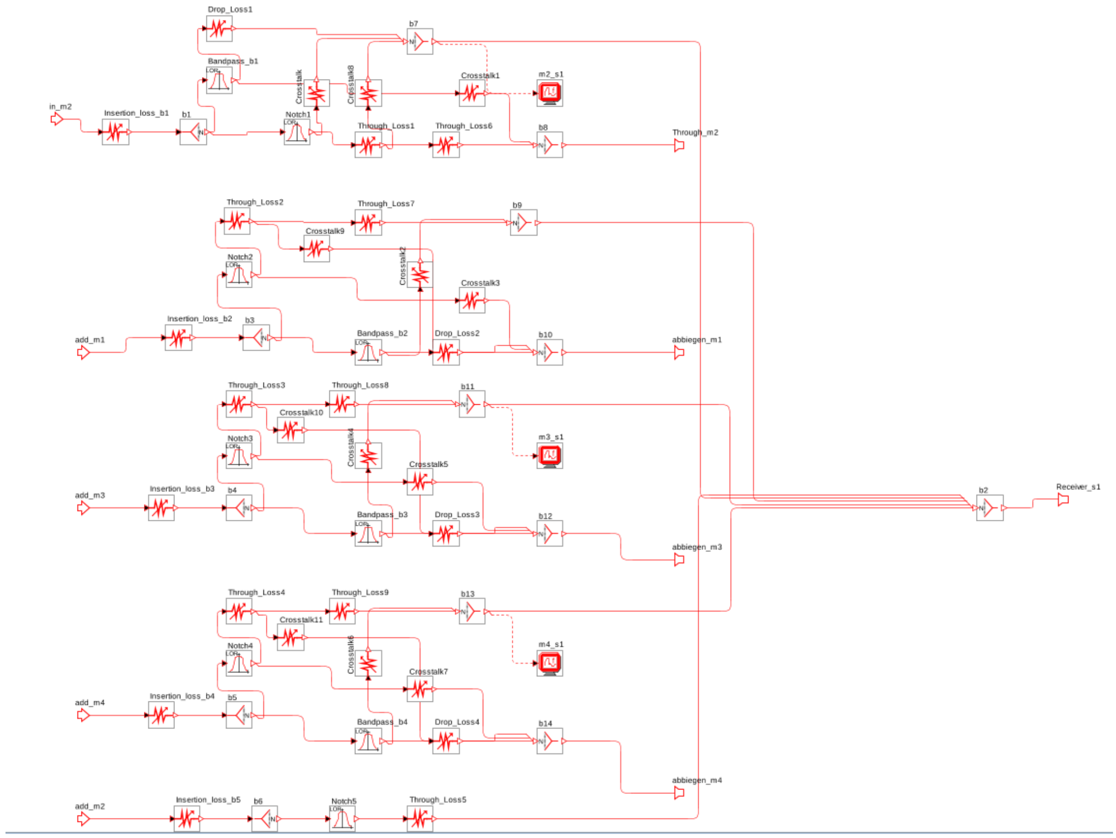


Figure 17: The CSE module

The schematic of a 4*4 GWOR is shown in Figure 18:

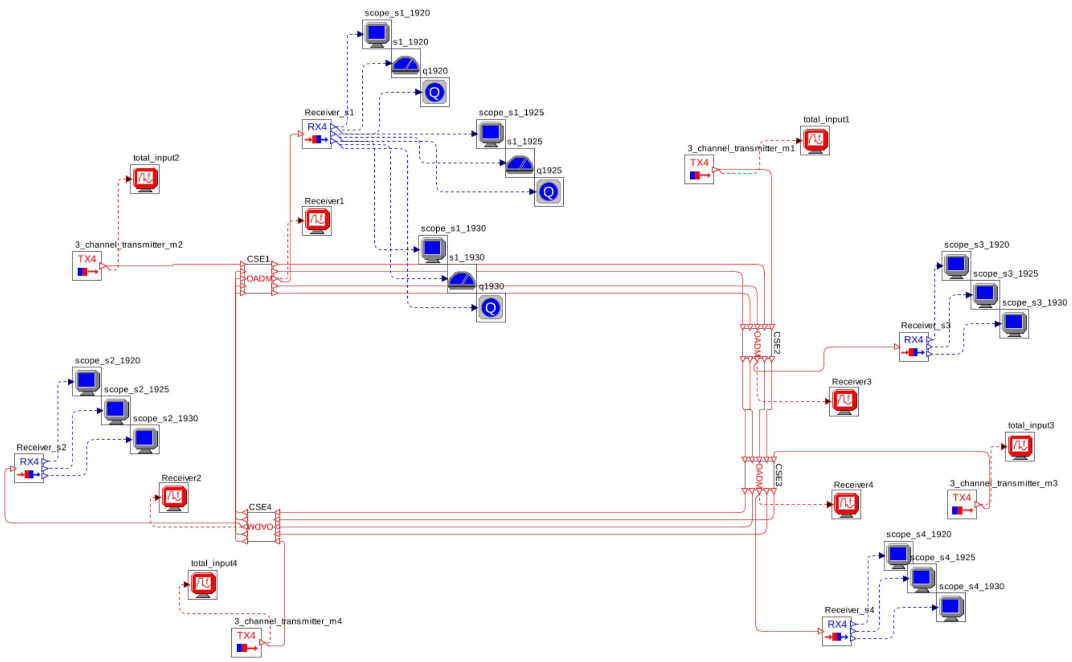


Figure 18: A 4*4 GWOR

As in the Hash-Router, the drop-frequency parameter is 192.0THz for CSE1 and CSE3, 192.5THz for CSE2 and CSE4 [3].

Now, both WRONoC routers were built, where all the transmitter modules will emit three optical signals of 192.0THz, 192.5Thz and 193.0THz containing different logical data. I started a Full VBS Simulation for each of them, with the optical noise and electrical noise options set to “Yes”. I will describe the simulation results in detail in the next section.

4. Simulation Results

In the following text, I have chosen receiver module s4 in Hash-Router and receiver module s1 in GWOR as the subjects of observation to measure and analyze the simulation results. The reason is: for each optical signal transmitted to any one of the receiver modules, I can find a corresponding optical signal transmitted to each of the other three receiver modules which has experienced the same loss and contains the same strength of crosstalk noise due to the symmetry design of both routers. The simulation results at any one of the receiver modules, therefore, can represent the results at all receiver modules.

4.1 Verification of Hash's and GWOR's Functionality

It is important to verify the correctness of data transmission of both WRONoCs at first.

The data transmission is considered as correct if optical signals emitted from any transmitter module in that router can reach the corresponding receiver modules.

For Hash-Router and GWOR, the relationship between the frequency of the optical signal, the transmitter module and the receiver module is:

The following tables show the frequency of the optical signal used by each transmitter to communicate with its corresponding receiver:

Table I: Transmission principle in Hash-Router

	m_1	m_2	m_3	m_4
s_1	X	192.5THz	193.0THz	192.0THz
s_2	192.5THz	X	192.0THz	193.0THz
s_3	193.0THz	192.0THz	X	192.5THz
s_4	192.0THz	193.0THz	192.5THz	X

Table II: Transmission principle in GWOR

	m_1	m_2	m_3	m_4
s_1	X	192.0THz	192.5THz	193.0THz
s_2	192.0THz	X	193.0THz	192.5THz
s_3	192.5THz	193.0THz	X	192.0THz
s_4	193.0THz	192.5THz	192.0THz	X

When the electrical signal waveform displayed by the electrical scope in a single-channel receiver matches the logical signal waveform from a single-channel transmitter, it can be considered that the single-channel receiver has received the optical signal from the corresponding single-channel transmitter.

According to the simulation results of the Hash-Router shown in Figure 19, the waveforms of the electrical signal at s4_1920, s4_1925 and s4_1930 match the waveforms of the logical signal in m1_1920, m3_1925 and m2_1930 respectively.

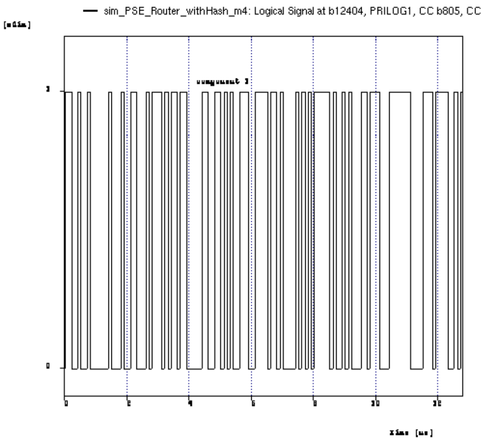


Figure 19(a): Logical signal at m1_1920

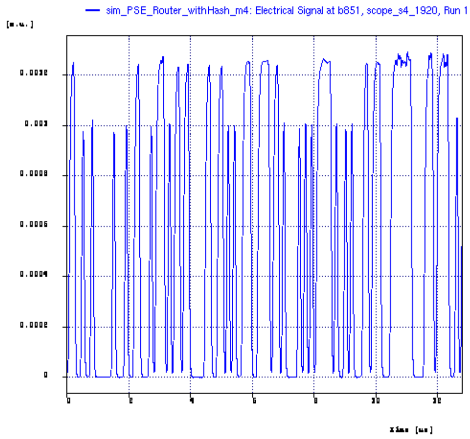


Figure 19(b): Electrical signal at s4_1920

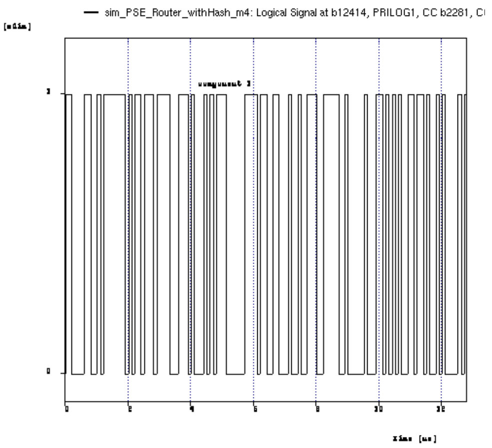


Figure 19(c): Logical signal at m3_1925

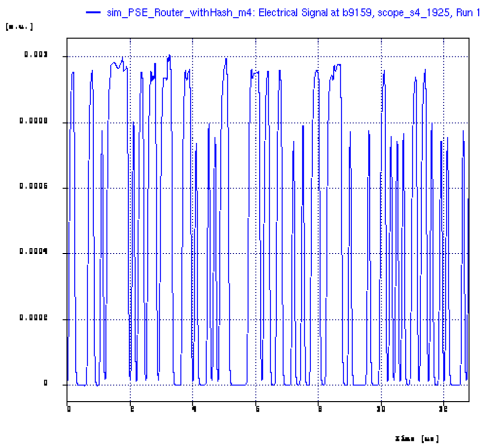


Figure 19(d): Electrical signal at s4_1925

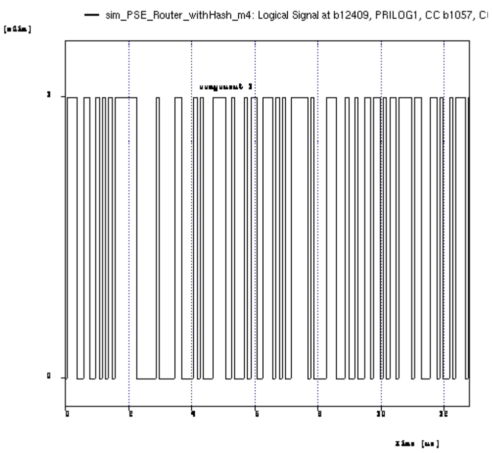


Figure 19(e): Logical signal at m2_1930

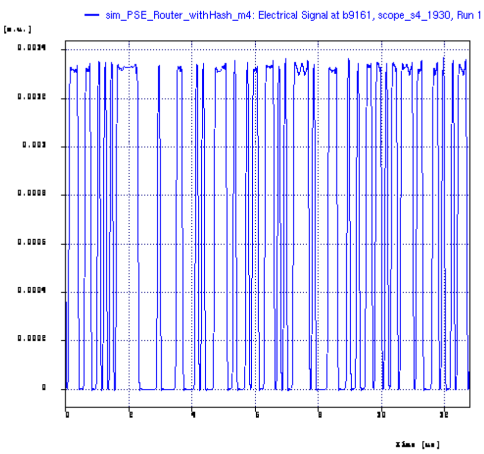


Figure 19(f): Electrical signal at s4_1930

The simulation results of the GWOR shown in Figure 20 are also the same:

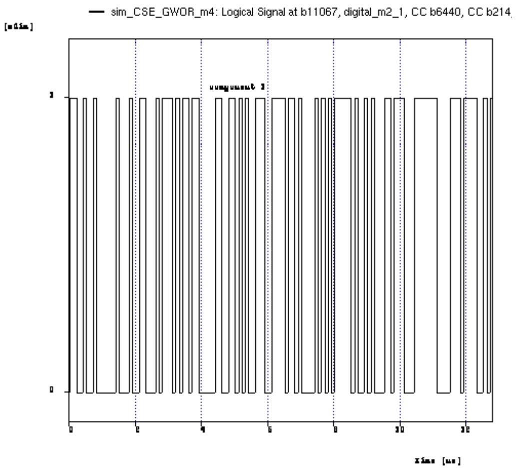


Figure 20(a): Logical signal at m2_1920

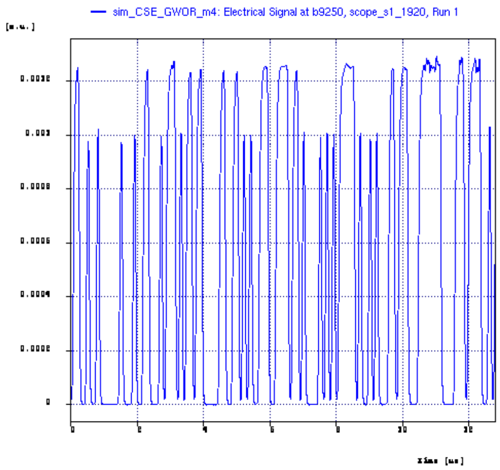


Figure 20(b): Electrical signal at s1_1920

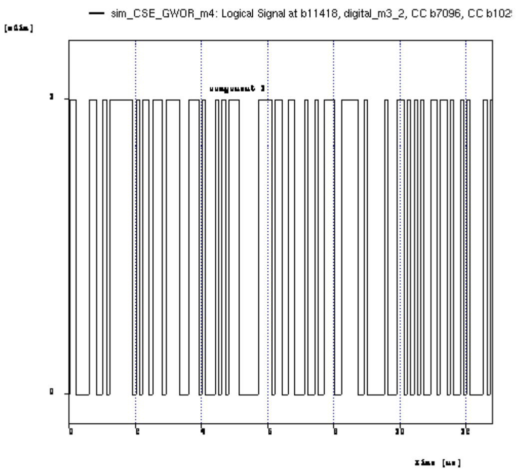


Figure 20(c): Logical signal at m3_1925

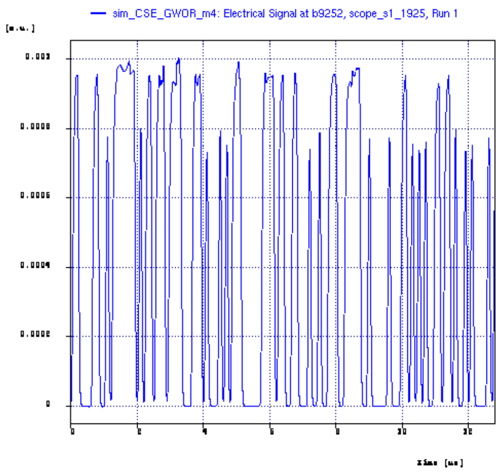


Figure 20(d): Electrical signal at s1_1925

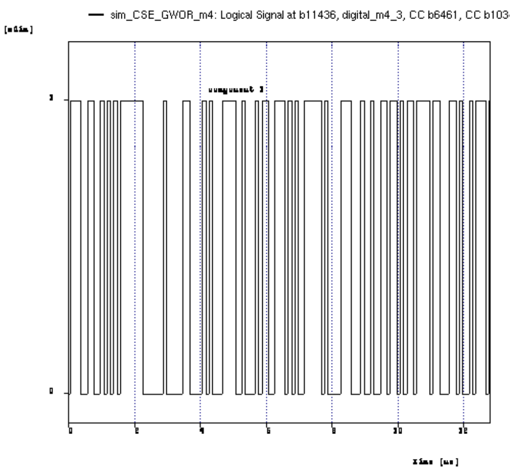


Figure 20(e): Logical signal at m1_1930

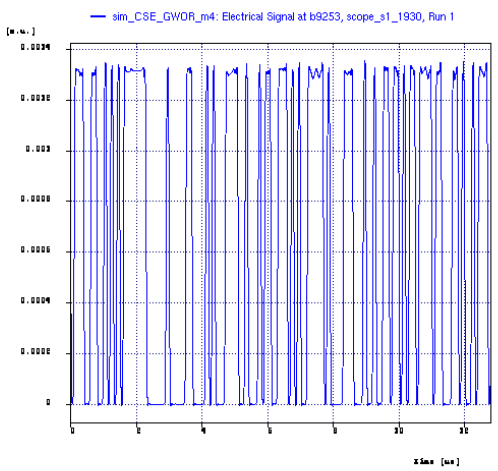


Figure 20(f): Electrical signal at s1_1930

We could see that the peaks and the troughs of the electrical signals at the receiver modules align with those of the logical signals, although they are affected by the noise signals. So, it is proved that the data transmission of both routers is correct.

4.2 Analysis and Comparison

4.2.1 Electrical Signal Power (ESP) in both WRONoCs

With the same electrical signal power (ESP) at all the transmitters, I measured and compared the electrical signal power at the single receiver channels of one receiver module in two WRONoCs respectively. The result can directly illustrate:
(1) the impact of MRR usage on the electrical signal power at the receivers in a WRONoC; (2) the difference of impact caused by different usage of MRRs in both WRONoCs.

For Hash-Router, I measured the ESP of the receiver channels in Receiver module s4. The schematic of the Hash-Router with optical signals transmitted to receiver module s4 and the simulation results are shown in Figure 21 and Figure 22:

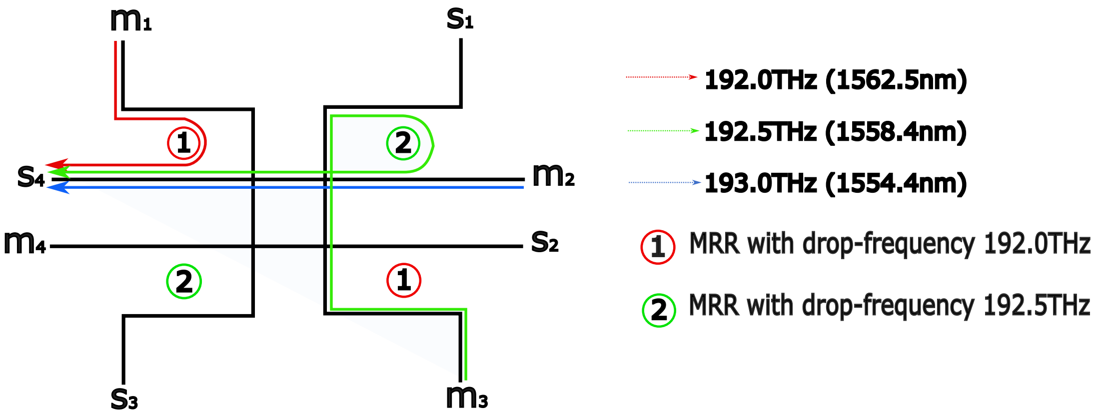


Figure 21: Schematic of Hash-Router with optical Signals transmitted to s4

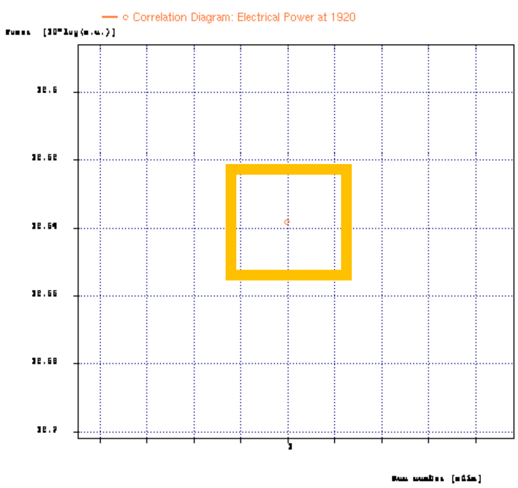


Figure 22(a): Electrical signal power at s4_1920

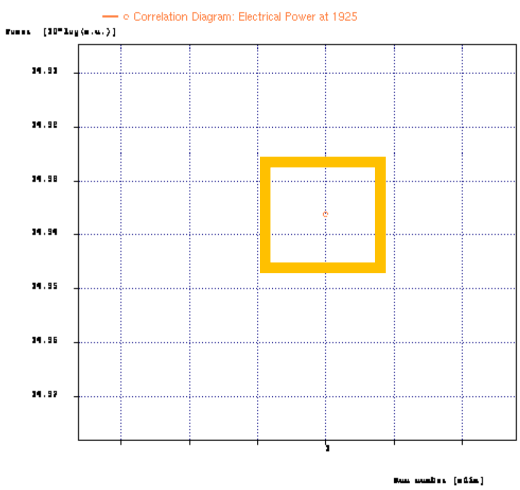


Figure 22(b): Electrical signal power at s4_1925

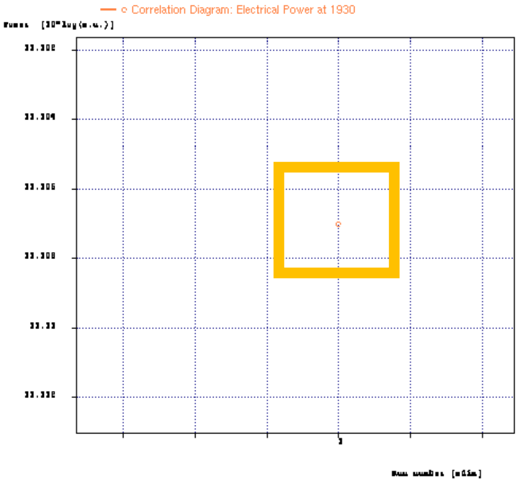


Figure 22(c): Electrical signal power at s4_1930

We could see that the ESP at s4_1920 is -12.638; the ESP at s4_1925 is -14.936; and the ESP at s4_1930 is -11.107, all in the unit of 10*log(a.u.).

The optical signal on 193.0THz transmitted from m2_1930 to s4_1930 only experienced two through losses because its direction could not be changed by the MRRs. Therefore, the corresponding ESP at s4_1930 is indeed the largest, which is -11.107 (10*log(a.u.)). In comparison, there are two through losses and a drop loss occurring to the optical signal on 192.5THz transmitted from m3_1925 to s4_1925, so the ESP at s4_1925 is the smallest, which is -14.936 (10*log(a.u.)). And the optical signal on 192.0THz from m1_1920 to s4_1920 has only experienced a Drop loss, thus the ESP is -12.638 (10*log(a.u.)).

The situation is similar in the Receiver module s1 in GWOR:

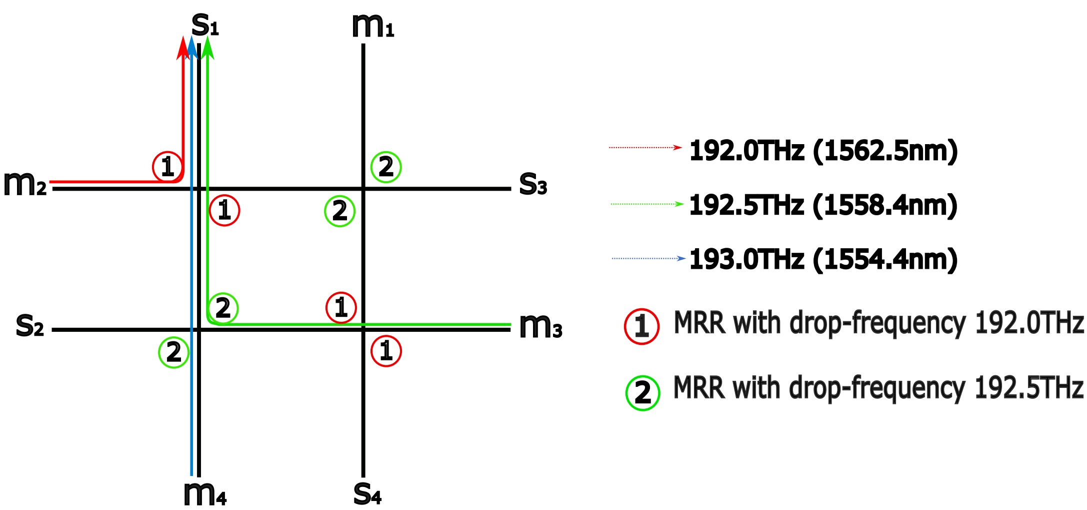


Figure 23: Schematic of GWOR with optical Signals transmitted to s1

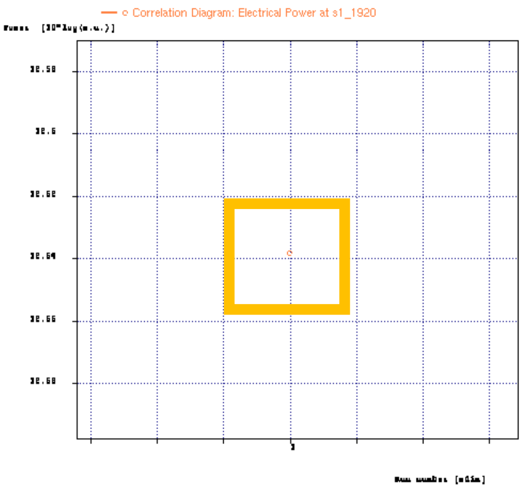


Figure 24(a): Electrical signal power at s1_1920

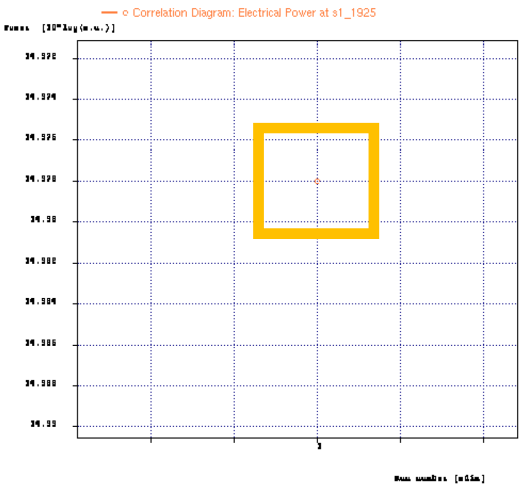


Figure 24(b): Electrical signal power at s1_1925

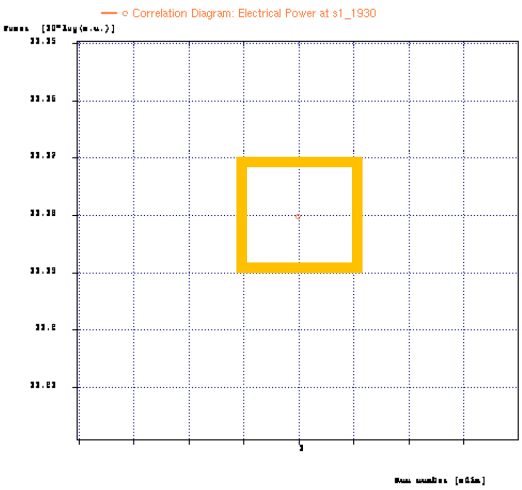


Figure 24(c): Electrical signal power at s1_1930

As shown in Figure 24, the ESP at s1_1920 is -12.638 (10*log(a.u.)) because the optical signal on 192.0THz from m2_1920 experienced 1 Drop loss caused by CSE1; the ESP at s1_1925 is -14.978 (10*log(a.u.)) because of the 4 through loss and one Drop loss occurring to the optical signal from m3_1925; ESP at s1_1930 is -11.180 (10*log(a.u.)) only due to the 4 times through loss of the optical signal from m4_1930.

Table III: ESPs of both receiver modules

	s_1920	s_1925	s_1930
ESPs at receiver module s4 in Hash-Router /10*log(a.u.)	-12.638	-14.936	-11.107
ESPs at receiver module s1 in GWOR /10*log(a.u.)	-12.638	-14.978	-11.180

By comparing the two sets of simulation data, I've found that the ESP at each single channel receiver in the Hash-Router is bigger than that in the GWOR under the same setting of parameters and the same simulation environment. Therefore, the Hash-Router, which contains fewer MRRs than GWOR, has a slightly better transmission efficiency.

4.2.2 Eye-Diagrams analysis

Except for the ESP, it's also important to measure the quality of the electrical signal at the receivers, which is an important performance for WRONoCs. And the quality of an electrical signal is closely related to its Eye-Diagram and Quality-Factor.

4.2.2.1 Eye-Diagrams of the electrical signals in both receiver modules

In OptSim, I can directly obtain the Eye-Diagrams of the electrical signals at the receivers through the connected electrical scopes:

(1) Eye-Diagrams from receiver module s4 in Hash-Router (shown in Figure 25):

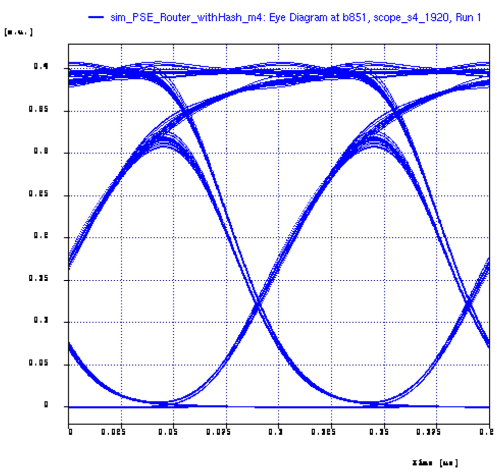


Figure 25(a): Eye-Diagram at s4_1920

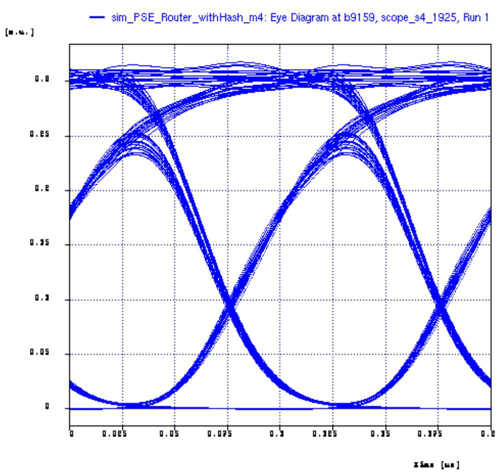


Figure 25(b): Eye-Diagram at s4_1925

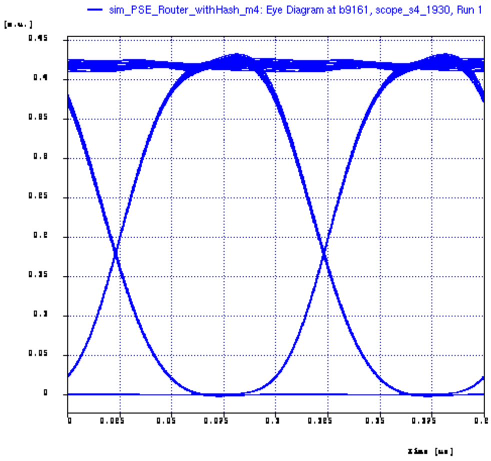


Figure 25(c): Eye-Diagram at s4_1930

(2) Eye-Diagrams from receiver module s1 in GWOR (shown in Figure 26):

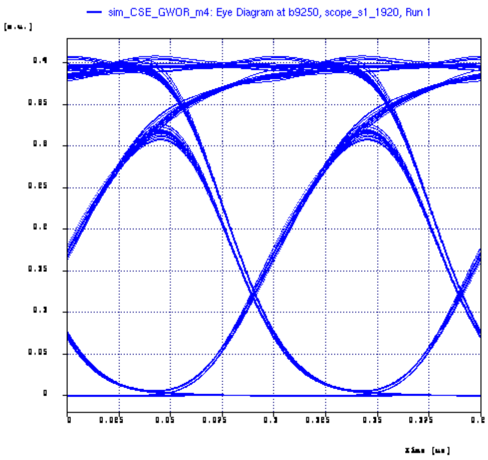


Figure 26(a): Eye-Diagram at s1_1920

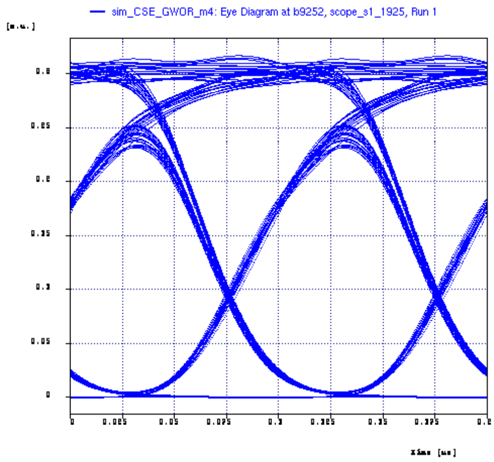


Figure 26(b): Eye-Diagram at s1_1925

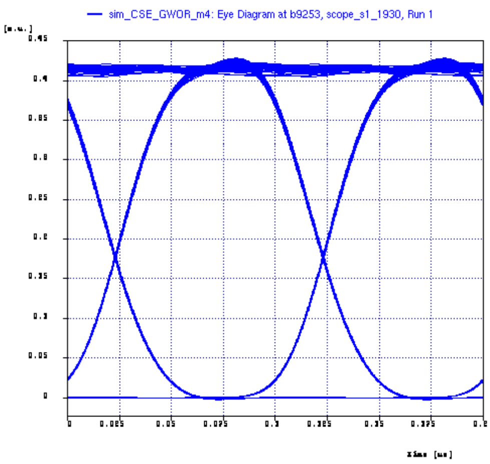


Figure 26(c): Eye-Diagram at s1_1930

It can be seen at first that the Eye-Diagrams from the 193.0THz receiving channels in both receiver modules have the best shape in comparison with those from the 192.0 THz and 192.5THz receiving channels.

Theoretically, in GWOR for example, the optical signal on 193.0THz from transmitter module m4 to receiver module s1 is strongest among the three optical signals shown in Figure 23, since its frequency does not match the drop-frequency of all the CSEs and therefore has only experienced four times 0.01dB through loss rather than the 1dB drop loss. But the noise signal on 193.0THz is relatively much stronger than those of the other two frequencies: two times crosstalk per MRR will be generated when the optical signal on 193.0THz transmitted by m2 passes through the upper left waveguides crossing, whose power is 50dB weaker than the original signal; and the signal on the same frequency from m3 also causes two times crosstalk per MRR when passing through lower left waveguides crossing. Therefore, four times crosstalk per MRR of 193.0THz has been transmitted to receiver module s1 and the strength of the total noise signal would be around 12.04dB bigger than that of only one crosstalk per MRR generated by the original signal, which is 50dB weaker than the original signal, because 20*log4=12.04dB. Meanwhile, the transmission directions of both the optical signals of 192.0THz and 192.5THz respectively from m2 to s1 and from m3 to s1 have been changed by MRRs, so their signal strength at s1 would be around 1dB weaker than that of the signal on 193.0THz. But the noise signal on 192.0THz to s1 generated by the signal on the same frequency from m4 to s1 would be around 100dB weaker than the original signal after being affected by the two MRRs with the drop-frequency of 192.0THz at the upper left waveguides crossing, which could even be neglected. Another noise signal on 192.0THz to s1 generated by the signal from m3 to s1 could also be ignored because it would be 250dB weaker than the original signal after being affected by five MRRs. The noise signal on 192.5THz is respectively generated by the signal on the same frequency from m2 to s1 and from m4 to s1. The former would experience two times crosstalk per MRR when passing through the two MRRs at the upper left crossing, while the latter would cause a noise signal which is 100dB weaker than the original signal and could therefore be ignored after being affected by the two MRRs with the drop-frequency of 192.5THz at the lower left crossing. So, the total strength of the 192.5THz noise signal is around 6.02dB bigger than that of only one crosstalk per MRR caused by the original signal because 20*log2=6.02. The situation in Hash-Router is similar, the noise signals of 192.5THz and 193.0THz would be around two times as strong as the crosstalk per MRR caused by the original signal, which is also 6.02dB stronger than only one crosstalk per MRR caused by the original signal, and the noise signal on 192.0THz, which is around 50dB weaker than the original signal, would almost completely generated by the signal on the same frequency from m2 to s4 when it passes through the upper left MRR with the drop-frequency of 192.0THz because the 192.0THz signal from m3 would be affected by three MRRs and around 150dB weaker than the original signal. Meanwhile, the optical signals of 192.0THz and 192.5THz at s4 are around 1dB weaker than the original signal, and the optical signal on 193.0THz is only around 0.02dB weaker than the original signal.

Therefore, the Eye-Diagram form of the signal on 193.0THz at both receiver modules cannot be the best in theory. In order to find out what has occurred, I have added some optical spectrum analyzers in PSE1 and CSE1, as shown in Figure 12 and Figure 17, to obtain spectrum diagrams and analyze the signals from specific transmitters transmitted to both receiver modules.

4.2.2.2 Spectrum Diagrams of the optical signals from specific transmitter modules to both receiver modules

Firstly, the spectrum diagram of "total input" is shown in Figure 27, which contains all the original optical signals transmitted from the transmitter modules in both routers.

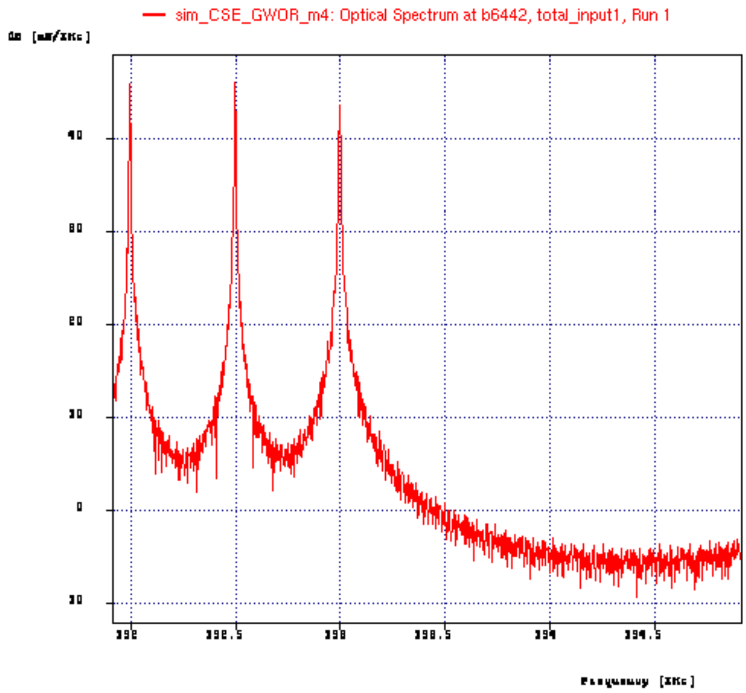


Figure 27: total input signals from a transmitter module

Due to the non-ideality of the transmitter modules, the waveform exhibits jagged edges caused by optical noises.

To find out the strength of optical signals and crosstalk noises, I have also utilized the spectrum diagram of the signals from specific transmitter modules to the two receiver modules s4 and s1 in Hash-Router and GWOR, as shown in Figure 28 and 29.

The receiver modules s4 in Hash-Router can only receive the optical signals from transmitter modules m1, m2 and m3:

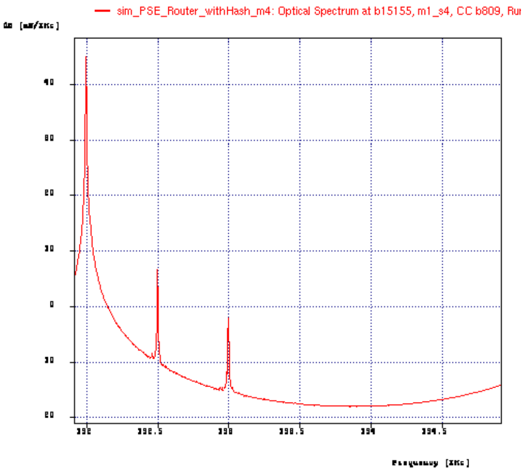


Figure 28(a): optical signals from m1 to s4

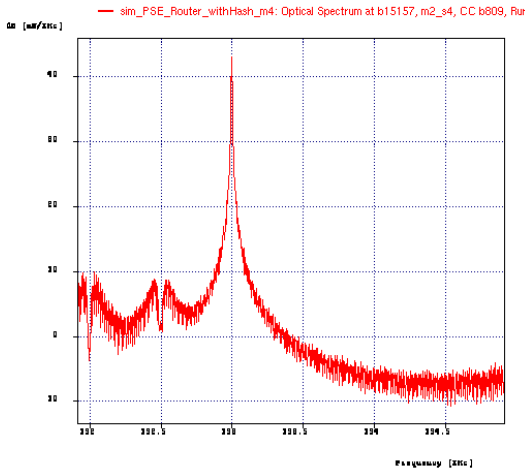


Figure 28(b): optical signals from m2 to s4

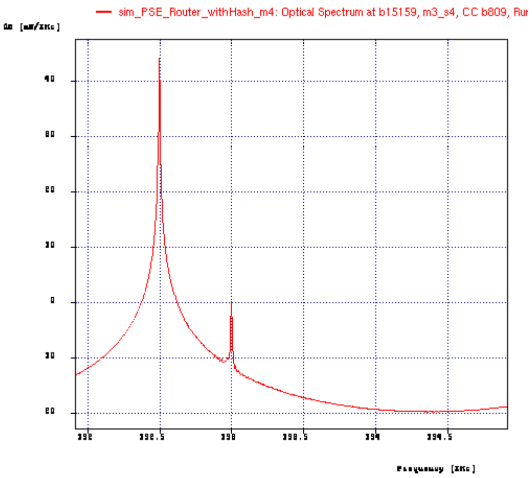


Figure 28(c): optical signals from m3 to s4

The receiver modules s1 in GWOR can only receive the optical signals from transmitter modules m2, m3 and m4:

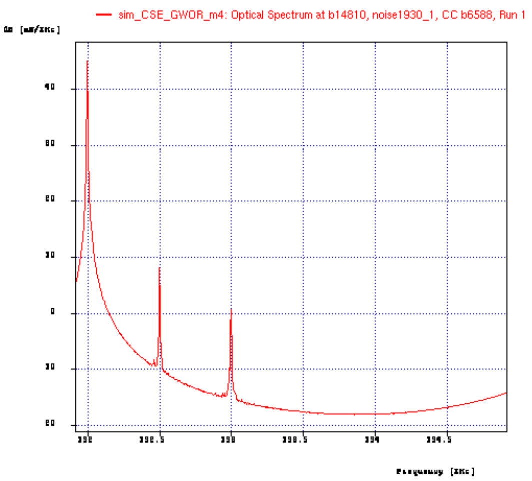


Figure 29(a): optical signals from m2 to s1

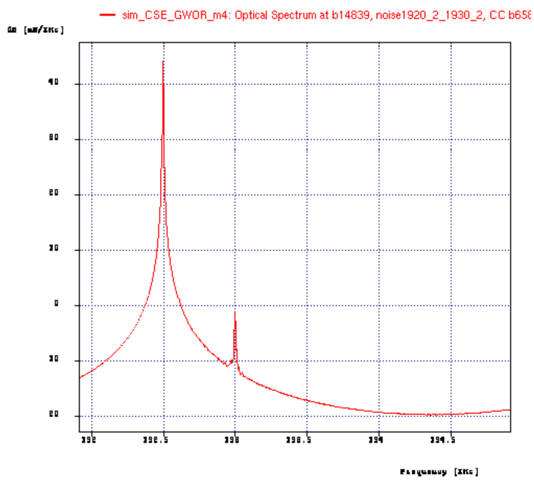


Figure 29(b): optical signals from m3 to s1

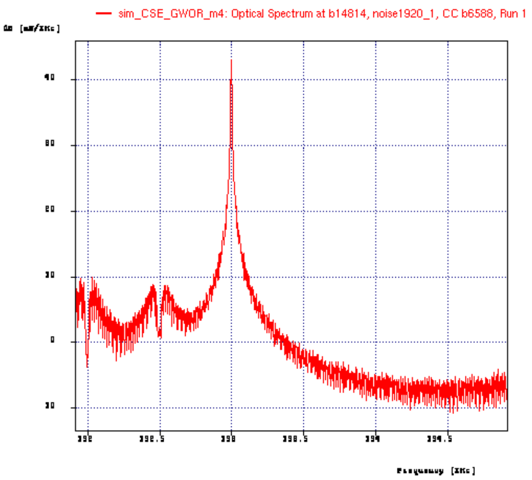


Figure 29(c): optical signals from m4 to s1

As shown in the figures above, only one spectrum diagram exhibiting jagged edges could be found at each receiver module: signals from m2 to s4 in Hash-Router and signals from m4 to s1 in GWOR, both of which contain the optical signals of 193.0THz, because optical signals from m2 to s4 in Hash-Router and optical signals from m4 to s1 in GWOR have only passed through several optical notch filters with central frequencies of 192.0THz and 192,5THz rather than the optical bandpass filters, so that only the signals with a very narrowed bandwidth which is 10GHz (shown in Figure 30) centered at these two frequencies would be filtered out, while the noise signals adjacent to these two filtered signals with a power of around 10dB (mW/THz) is retained. Since the -3dB bandwidth of the optical bandpass filters at the receivers is 40GHz, much wider than 10GHz, as shown in Figure 31, these noise signals with a power of 10dB (mW/THz) have passed through, at least partially passed through the filters and been treated as noise signals when Eye-Diagrams are generated.

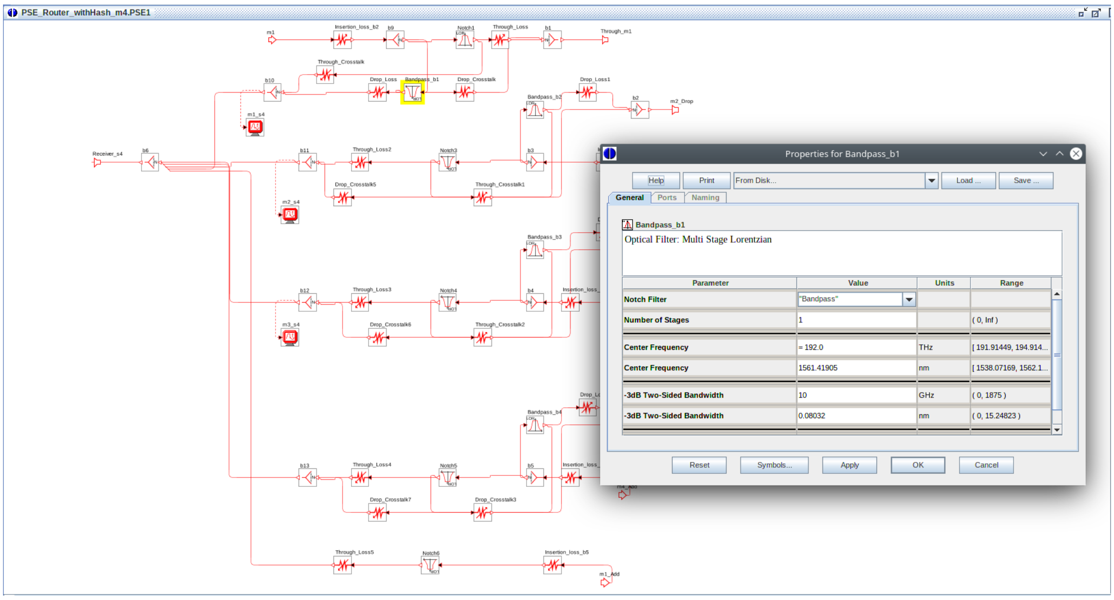


Figure 30: Parameters of the optical bandpass filters in PSE/CSE

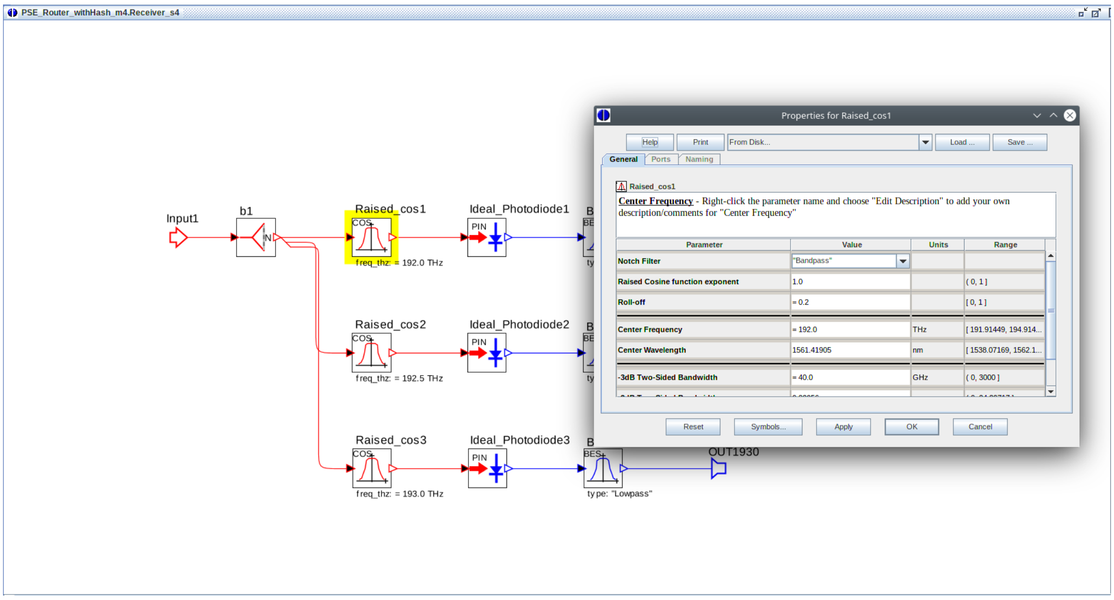


Figure 31: Parameters of the optical bandpass filters in receiver modules

Then we could compare the strength of all the optical noise signals at both receiver modules by simply adding them up separately. According to Figure 28 and Figure 29, it's obvious that the noise signals of 192.5THz are the strongest, whose power is between 10dB and 20dB (mW/THz), while those of 193.0THz is the weakest, whose power is only around 20*log2+0=6.02dB (mW/THz). And the power of noise signals of 192.0THz is around 10dB (mW/THz).

As a result, the form of the 193.0THz Eye-Diagrams is the best while that of the 192.5THz Eye-Diagrams is the worst under the fact that the strengths of the three optical signals are very close.

Since both the two WRONoC routers are designed with the MRR, which is a unique component with specific functions and characteristics, it's impossible to achieve all its characteristics only by utilizing optical bandpass- and notch filters to build PSE/CSE modules. But when the -3dB bandwidth of the optical bandpass filters at the receiver modules was set to be equal to that of the optical filters in the PSE/CSE modules, extra noises due to incomplete filtering by notch filters could be filtered out and prevented to affect the form of Eye-Diagrams.

5 Conclusion

In this project, I performed simulation for two kinds of 4*4 WRONoC routers: 4*4 Hash-Router and 4*4 GWOR. Specifically, I have built circuits on a simulation tool, OptSim, and added noise- and loss components with corresponding attenuations. After simulating them separately, I have also compared the waveforms of the logical signals at the transmitters with that of the electrical signals at the receivers to verify the correctness of the data transmission of both WRONoC routers. Additionally, I evaluated and compared the electrical signal power (ESP), and analyzed the Eye-Diagrams of the electrical signals at the receivers from both WRONoC routers.

The following conclusions are drawn: both WRONoC routers can transmit data correctly, but the Hash-Router with less MRR usage has stronger electrical signals at the receivers. In addition, if the -3dB bandwidth of the optical bandpass filters at receiver modules was set narrower to 10GHz, which is equal to the -3dB bandwidth in the PSE/CSE modules, it could be prevented that too much noise signals of 192.0THz and 192.5THz passed through the bandpass filter at the receivers and the accuracy of the Eye-Diagrams could be enhanced.

6 Reference

[1] Z. Zheng et al. 2021. Light: A Scalable and Efficient Wavelength-Routed Optical Networks-On-Chip Topology.

[2] M. Nikdast et al. 2015. Crosstalk Noise in WDM-Based Optical Networks-on-Chips: A Formal Study and Comparison.

[3] X. Tan et al. 2011. On a Scalable, Non-Blocking Optical Router for Photonic Networks-on-Chip Designs.

7 Appendix

Parameters of the optical transmitter module:

Modulator_extinction_ratio	Modulator_extinction...	30.0
Modulator_chirp_factor	Modulator_chirp_factor	0.0
Modulator_excess_loss	Modulator_excess_lo...	3.0
Laser_power_dBm	Laser_power_dBm	5
Laser_linewidth	Laser_linewidth	10.0
Laser_frequency	Center_frequency+5*...	193.0
Bit_rate	Bit_rate	10.0

Figure 32: Parameters of the optical transmitter module in receiver