OEIL Manual

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https://eexu.home.ece.ust.hk/OEIL.html

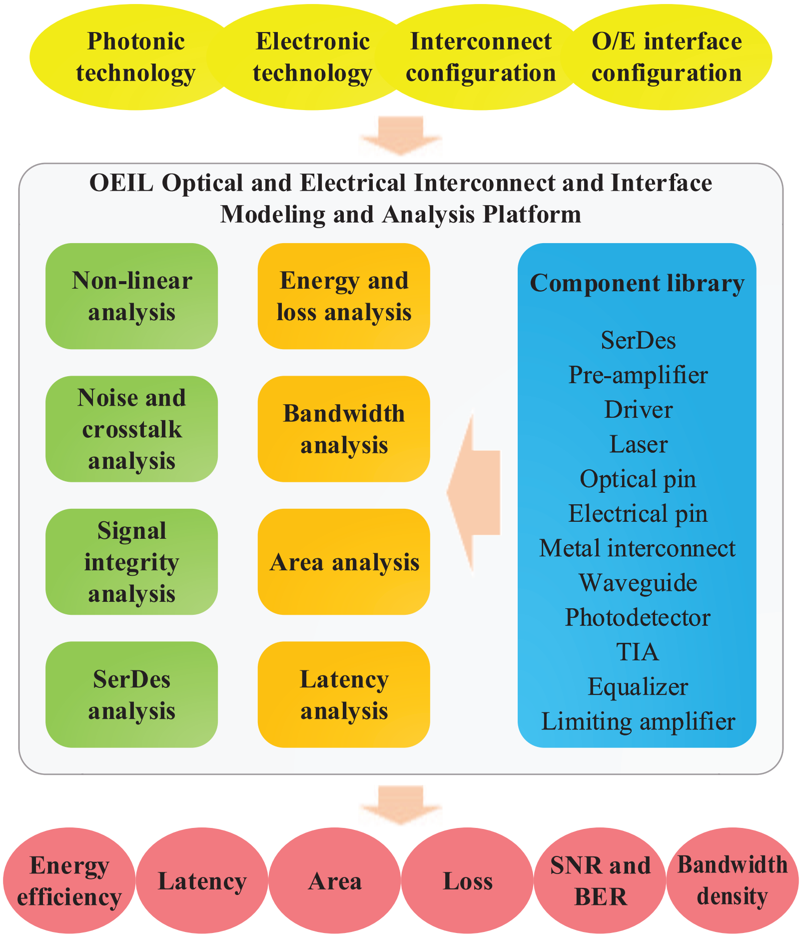

Figure 1: The flow chart of OEIL simulator.

CONTENTS

1 INTRODUCTION

OEIL is an analysis tool for optical and electrical interfaces and links. Fig. 1 illustrates the internal structure of OEIL. The publicly released OEIL is implemented in C code, and it is available online with documentation at [1]. OEIL has a complete library of devices for inter-chip interconnects. It analyzes power consumptions, energy efficiencies, bandwidths, bandwidth densities and latencies of optical and electrical inter-chip interconnects. As can be seen from the figure, the main body of OEIL includes models for crosstalk noises, attenuations, receiver sensitivities, power consumptions, bandwidths and latencies. This tool is designed based on the proposed analytical models in previous sections. The input files of tool OEIL include *interconnect configurations* and *device parameters*, and the output results are written in *output*. The configurations of interconnects such as data rate, interconnect length and number of parallel interconnects are described in file *interconnect configurations*. The parameters of board, microresonator, trace, waveguide, transmitter and receiver can be found in file *device parameters*. Those files have two versions, which are differed by key words *electrical* and *optical*. In additional to the above results, OEIL also generates the intermediate results of analytical models such as crosstalk talk coefficients, attenuations, and receiver sensitivities.

OEIL evaluates the performance of inter-chip interconnects from end to end, which consists of on-chip interconnect, off-chip interconnect and interfaces between them [2]. For electrical interconnects, the device library includes parameters of wires on chip, traces on board as well as electrical copper pins. For optical interconnects, the device library includes parameters of silicon waveguides on chip, polymer waveguides on board, and optical lens or couplers. Additionally, OEIL is also able to evaluate the performance of interconnects, which connect 2.5D or 3D chips. The device library includes parameters of through-silicon vias (TSVs) and bumps among stacked dies. Configurations of the 2.5D or 3D chip can be defined on the configuration file. This tool OEIL is able to not only analyze the performance of inter-chip interconnects but also provide necessary parameters for system simulators. The configuration file is able to describe all kinds of interconnects in a network. OEIL is verified by data from previous published technical reports. It shows good fitting between OEIL and the collected data. The verification will be discussed with more details in next subsection. By updating the device library, OEIL is able to follow the development of technologies.

The optical transmission systems are promising candidates for high speed inter-chip interconnects, and have been implemented in various prototypes. In optical interconnect, signals at different wavelengths will not interfere with each other, the wavelength-division multiplexing (WDM) technology are used, which multiplexes a number of signals at different wavelengths in a single optical waveguide. This technology could effectively increase the total bandwidth of optical interconnects. We mathematically build models for their crosstalk noises, attenuations and receiver sensitivities, and use three parameters to compare the performance of inter-chip interconnects: energy consumption, bandwidth density and latency. In our input files, we make assumptions of various parameters based on the state-of-the-art technologies. They could also be modified according to the real systems configured by users. The output file of this simulator covers the most important information of optical interconnects.

2 HOW TO USE OEIL

Before running this simulator, users could modify the parameter file and configuration file in the input folder. Please follow the instructions in this chapter, compile and run the software. The calculated results could be obtained from the result file in the output folder.

2.1 USAGE INSTRUCTIONS

Enter the directory

```
mkdir build
cd build
```

Compile the software

```
cmake ..
make
```

Run the software

```
» ./OEIL
```

2.2 THE PARAMETER FILE

The program would load the parameter file in order to build models for optical devices. The relationship between parameters and notations are listed in Table 1. The parameter file includes optical and electrical sections.

File path:`./source/parameter_optical.txt`

```
#transmitter#
 0.2     laser_slope_efficiency  n/a       //slope efficiency of laser
 1       laser_threshold_current mA        //threshold current of laser
 0.1     laser_extinction_ratio  n/a       //extinction ratio of laser
 900     laser_area              um^2      //area of laser
 3       laser_voltage           V         //supply voltage of laser
 1.5     driver_voltage          V         //supply voltage of driver
#waveguide#
 0.35    optical_pin_loss        n/a       //coupling efficiency of pin
 250     optical_pin_height      um        //height size of pin
 250     optical_pin_width       um        //width size of pin
 0.0276  propagation_loss        cm^-1     //propagation loss of pin
 1.55    wg_refractive_index     n/a       //refractive index of waveguide
 62.5    wg_pitch                um        //The pitch of waveguide

#waveguide-nonlinear-loss-model#
 4e-9      carrier_lifetime      s         //lifetime of the carrier
 8e-10     TPA_coefficient       cm\W      //coefficient of TPA
 1.45e-17  FCA_coefficient       cm^2      //coefficient of FCA
#receiver#
 14.1    signal_to_noise_ratio   n/a       //signal to noise ratio
 10      tia_noise_density       pA√Hz     //noise density of TIA
 1       tia_transimpendance     kΩ        //transimpendance of TIA
 10      la_voltage_threshold    mV        //threshold voltage of LA
 1       pd_responsity           A/W       //responsity of PD
 60      pd_capacitance          fF        //input capacitance of PD
```

```
#microresonator#
 10      mr_radius_range          um      //estimated radius of MR
 0.9993  mr_attenuation           n/a     //round trip attenuation of ring
 0.3     mr_power_split_k         n/a     //power split ratio into ring
 2.65    mr_refractive_index      n/a     //refractive index of ring
 0.05  mr_tuning_power            mW        //tuning power of MR
 0.12  mr_static_power            mW        //static power of MR
 0.12  mr_dynamic_power           mW/Gbps   //dynamic power of MR
 125   mr_area                    um^2      //area of MR
#serdes#
 0.1     serdes_cur_optical       mA/Gbps   //unit current of SerDes circuit
 40      serdes_area_optical      um^2/Gbps //unit area of SerDes circuit
#encoder-decoder&pll#
 0.5     pll_energy_optical       pJ/bit    //energy efficiency of pll
 18      pll_area_optical         um^2/Gbps //unit area of pll
 0.5     coder_energy_optical     pJ/bit    //energy efficiency of en-decoder
 25      coder_area_optical       um^2/Gbps //unit area of en-decoder
```

File path: `./source/parameter_electrical.txt`

```
#board#
 17.4    pcb_layer_height         mil       //height of pcb layer
 4       pcb_trace_width          mil       //width of pcb trace
 1.4     pcb_trace_height         mil       //height of pcb trace
 24.0    pcb_trace_pair_pitch     mil       //pitch of pcb trace pair
 0.0027  pcb_trace_loss_tangent   n/a       //loss tangent of pcb trace
 3.6     pcb_dielectric           n/a       //dielectric of pcb material
 1       package_pin_pitch        n/a       //pitch of package pin
#trace#
 13.8    trace_half_depth_f       MHz       //half depth frequency of trace
 64.4    trace_characteristic_z   Ohm       //characteristic res. of trace
 0.9897  trace_unit_length_c      pF/cm     //unit length cap. of trace
 0.0797  trace_direct_current_r   Ohm       //direct current res. of trace
 104     trace_input_impendance   Ohm       //input impendance of trace
 1       electrical_pin_load_c    pF        //cap. of electrical pin load
#transceiver#
 10      la_threshold_voltage     mV        //threshold voltage of amplifier
 0.05    la_offset_coefficent     n/a       //offset coefficient of amplifier
 0.01    la_coefficent_margin     n/a       //coefficent margin of amplifier
 1.5     circuit_voltage          V         //supply voltage of circuit
#serdes#
 0.1     serdes_cur_electrical    mA/Gbps   //unit current of SerDes circuit
 40      serdes_area_electrical   um^2/Gbps //unit area of SerDes circuit
#encoder-decoder&pll#
 0.5     pll_energy_electrical    pJ/bit    //energy efficiency of pll
 18      pll_area_electrical      um^2/Gbps //unit area of pll
 0.5     coder_energy_electrical  pJ/bit    //energy efficiency of en-decoder
 25      coder_area_electrical    um^2/Gbps //unit area of en-decoder
```

2.3 THE CONFIGURATION FILE

The program would load the configuration file in order to build models for optical devices. The relationship between configurations and notations are listed in Table 1.

File path: `./source/configuration_optical.txt`

```
10       data_rate_optical           GHz       //bandwidth of one opti. signal
25       length_optical              cm        //length of opti. interconnect
8        serdes_ratio_optical        n/a       //serdes ratio of serdes
8        number_of_wavelengths       n/a       //number of wavelengths
1550     laser_wavelength            nm        //laser working wavelength
0        is_direct_modulation        n/a       //if it is directly modulated
0        is_embedded_optical         n/a       //if embedded clock is used
8        ahared_clk_optical          n/a       //number of shared interconnects
1        is_nonlinear_model_enabled  n/a       //1: enable nonlinear loss model
1e-8     effective_mode_area         cm^2      //This depends on the geometry
0.5      laser2modular_distance      cm        //Distance from laser to modular
0.5      modular2coupler_distance    cm        //Distance from modular to coupler
0.5      coupler2receiver_distance   cm        //Distance from coupler to receiver
```

File path: `./source/configuration_electrical.txt`

```
10       data_rate_electrical        Gbps      //bandwidth of one elec. signal
40       length_electrical           cm        //length of elec. interconnect
8        serdes_ratio_electrical     n/a       //serdes ratio of serdes
8        number_of_pairs             n/a       //number of trace pairs
0        is_embedded_electrical      n/a       //if embedded clock is used
8        ahared_clk_electrical       n/a       //number of shared interconnects
```

2.4 THE OUTPUT FILE

The program would output the result file after calculation. The file includes both the intermediate results as well as the final results obtained from our models.

File path: `./source/output_optical.txt`

```
 sensitivity_oma        0.029970      mW        //receiver sensitivity
 crosstalk_coefficient  0.048546      n/a       //crosstalk noise coefficient
 total_attenuation      0.036274      n/a
                        14.404009     dB        //total attenuation
 energy_consumption     6.085665      pJ/bit    //energy consumption
 area_density           1280.000000   Gbps/mm²  //area bandwidth density
 linear_density         1280.000000   Gbps/mm   //linear bandwidth density
 area                   0.011950      mm²       //area
 latency                3.566667      ns        //latency
 optical_SNR            13.138508     dB        //optical signal to noise ratio
 BER_optical            2.900266e-03  N/A       //bit error rate
```

File path: `./source/output_electrical.txt`

```
 sensitivity_la         10.000000    mW        //receiver sensitivity
 crosstalk_coefficient  0.142492     n/a       //crosstalk noise coefficient
 total_attenuation      0.326181     n/a
                        4.865413     dB        //total attenuation
 energy_consumption     4.706541     pJ/bit    //energy consumption
 area_density           7.200000     Gbps/mm²  //area bandwidth density
 linear_density         23.622047    Gbps/mm   //linear bandwidth density
 area                   0.010800     mm²       //area
 latency                4.029822     ns        //latency
```

3 MODELS FOR OPTICAL INTERCONNECT

We build models for the crosstalk noise, attenuation and receiver sensitivity of optical interconnect, and analyze its performance from the aspects of energy consumption, bandwidth density and latency. All the formulations are general to different technologies.

3.1 CROSSTALK NOISE

The micro-resonator (MR) is an important device in optical interconnect. r^2 and k^2 are the power splitting ratios of the coupler between the ring and waveguide. We assume $r^2 + k^2 = 1$. Besides, a is the round trip attenuation of the ring. The ratio of the drop port power to the input port power is the function of light wavelength, and is expressed in Equation 1.

$$T_d(\lambda) = \frac{(1-r^2)^2 a}{1-2r^2 a\cos\theta(\lambda) + r^4 a^2} \tag{1}$$

Here phase shift $\theta(\lambda)$ is the function of working frequency λ, which is expressed in Equation 2. Besides, n_e is the effective refractive index of the ring, and R is the radius of the ring.

$$\theta(\lambda) = 4\pi^2 n_e R/\lambda \tag{2}$$

At resonance wavelength λ_n, the value of T_d is maximized, and we use this property to filter signal λ_n out of multiple signals in one waveguide. However, there will be small fraction of other signals appearing on drop port. The crosstalk noise coefficient in optical interconnect is the summation of these signals, and is expressed in Equation 3.

$$\varepsilon_o = \ldots + T_d(\lambda_{n-1}) + T_d(\lambda_{n+1}) + T_d(\lambda_{n+2}) + \ldots \tag{3}$$

Suppose there are m different wavelengths in the WDM optical system. The spacing between two neighboring wavelengths is $\Delta\lambda$. In worst case, n equals to $\lceil m/2 \rceil$, and the maximum crosstalk coefficient is expressed in Equation 4.

$$\varepsilon_o = 2\sum_{i=1}^{\lfloor m_o/2 \rfloor} T_d(\lambda_n + i\Delta\lambda) \tag{4}$$

3.2 ATTENUATION

The attenuation A is the ratio of the received optical power to the transmitted power. It mainly includes the coupling loss of optical pins, the passing by and insertion loss of micro-resonators, and the attenuation of waveguides or fibers. In most cases, a multiplication of the losses each should give good enough an approximation to the overall attenuation across the interconnect. This is expressed in Equation (5). In case of a high laser power intensity being pumped into the waveguide, which usually happens when an aggressively large amount of wavelengths is coupled into too thin a waveguide, a nonlinear loss appears as an extra source of attenuation. The nonlinear loss effect is captured by Equations (8) (9) and will be discussed by the end of this section.

$$A_o = \eta_o^2 e^{-\alpha_o L} L_p^2 (m_o - 1) T_d^2(\lambda_n) \tag{5}$$

Here η is the coupling efficiency of each optical pin. α is the attenuation coefficient of waveguide, and L is the interconnect length. Besides, $L_p(n)$ is the passing by loss, and $T_d(\lambda)$ is the insertion loss of one micro-resonator. There is one micro-resonator inserted after the laser and another one before the photodetector. Optical signals will be attenuated if they pass by micro-resonators. Signal λ_n will be attenuated by a sequence of micro-resonators, whose resonance wavelength ranges from λ_0 to λ_{n-1}. The ratio of the pass port power to the input port power is the function of light wavelength, and is expressed in Equation (6).

$$T_p(\lambda) = \frac{r^2a^2 - 2r^2acos\theta + r^2}{1 - 2r^2a\cos\theta(\lambda) + r^4a^2} \tag{6}$$

At their resonance wavelength, the value of T_p is minimized. At other wavelength, the attenuation factor is close to one. $T_p(\lambda)$ is the frequency spectrum of micro-resonator with resonance wavelength λ_n, and $\Delta\lambda$ is the spacing between two neighboring wavelengths. The total passing by loss is expressed in Equation (7). In worst case, n equals to $m-1$.

$$L_p(n) = \prod_{i=1}^{n} T_p(\lambda_n + i\Delta\lambda) \tag{7}$$

With nonlinear loss being considered, the optical intensity $I(z)$ along the propagation direction z is captured by a first-order differential Equation (8).

$$\frac{dI(z)}{dz} = -\alpha_o I(z) - \beta_{TPA} I^2(z) - \frac{\tau_c \cdot \sigma_{FCA} \cdot \beta_{TPA}}{2hv} I^3(z) \tag{8}$$

$$\sigma_{FCA} = \sigma_{1550nm} \cdot (\frac{\lambda_e}{1550nm})^2 \tag{9}$$

Here α_0 is the propagation loss coefficient same as the one in Equation (5). β_{TPA} is the two photon absorption (TPA) coefficient that governs how many free carriers are generated by absorbing photons. Besides, a combination of the free carrier lifetime, τ_c, free carrier absorption (FCA) coefficient, σ_{FCA} and photon energy, hv describe the light absorption by free carriers. The extra nonlinear attenuation across a distance L_0, $A_{nonlinear}$, is therefore written as Equation (10)

$$A_{nonlinear} = \frac{I(L_0)}{I(0) \cdot e^{-\alpha_o L_0}} \tag{10}$$

Apparently, by considering nonlinear losses, more design parameters, including the waveguide sizing and transceiver placement should be carefully dealt with. But before a fine tune, the reader can simply turn on the nonlinear loss model with all parameters default to see roughly how large the impact could be.

3.3 RECEIVER SENSITIVITY

The sensitivity of optical receiver is the minimum optical modulation amplitude (OMA) required in the receiver end. Suppose the noise is Gaussian distributed with standard deviations σ. If the signal to noise ratio equals to SNR, the logic 1 and logic 0 voltage levels are $\pm\frac{1}{2}\text{SNR}\cdot\sigma$ away from the theoretical decision point in the middle. We open the theoretical decision point by at least double the threshold voltage V_{th} of the limiting amplifier (LA). The OMA is expressed in Equation (11). Here i_n is the input referred RMS noise density of the transimpedance amplifier (TIA), f is the frequency of optical modulated signal, Z_{tia} is the transimpedance, and ρ is the responsivity of photodetector (PD).

$$\text{OMA} = \frac{i_n f^{0.5} \cdot \text{SNR} + 2V_{th} Z_{tia}^{-1}}{\rho} \tag{11}$$

3.4 ENERGY CONSUMPTION

The total power consumption can be expressed in Equation (12). Here I_{mod} and I_{bias} are the supply current and bias current of laser driver, I_{tia} and I_{la} are the supply current of the transimpedance amplifier and the limiting amplifier. We use two different supply voltages. V_l and V_c are the supply voltage of lasers and electrical circuits.

$$P_o = (I_{mod} + I_{bias})V_l + (I_{tia} + I_{la})V_c \tag{12}$$

Parameter ε is the crosstalk noise coefficient. Extinction ratio r_e is defined as the power ratio between logic level 0 and logic level 1. The minimum required eye amplitude in optical interconnect is 1 - ε - r_e, which corresponds to OMA, the sensitivity of optical receiver. The maximum driving current required from the laser is the summation of supply current and bias current, and it is expressed in Equation (13). Here A is the attenuation of the entire optical interconnect. η_s and I_{th} are the slope efficiency and threshold current of laser diode.

$$I_{mod} + I_{bias} = \frac{\text{OMA}}{A_o(1 - \varepsilon_o - r_e)\eta_s} + I_{th} \tag{13}$$

The supply current of transimpedance amplifier is proportional to the input pole of the transimpedance amplifier, and it is expressed in Equation (14). Here f is the working frequency of the transimpedance amplifier, C_{pd} is the capacitance of photodetector, and ΔV is the saturation voltage of the transistor in transimpedance amplifier.

$$I_{tia} \approx \pi f C_{pd} \Delta V \tag{14}$$

We evaluate the energy consumption, which is defined as the energy consumed by the interconnects when they transmit unit bits of information. It is expressed in Equation (15). Here P is the power consumption of optical signal. The signal bandwidth is $2f$. Each signal does not interfere with other signals in the same waveguide.

$$\text{Energy Consumption} = \frac{\text{Power } P}{2 \cdot \text{Frequency } f} \tag{15}$$

3.5 BANDWIDTH DENSITY

The number of signals in one interconnect equals the free spectral range (FSR) divided by the spacing between two neighboring wavelengths. FSR is defined as the spacing between two successive resonance peaks in drop port spectrum, and its value is expressed in Equation (16).

Here λ is the optical signal wavelength. R is the radius of micro-resonator, and n_e is the effective refractive index of the waveguide in the micro-resonator.

$$\text{FSR} = \frac{\lambda^2}{2\pi n_e R} \tag{16}$$

The bandwidth of each optical interconnect equals the transmission bandwidth of one optical signal multiplied by the number of signals in one interconnect, and it is expressed in Equation (17). Here $\Delta\lambda$ is the wavelength spacing between two neighboring signals. f is the modulation frequency of the optical signal so that the bandwidth is $2f$.

$$\text{B}_o = 2\lfloor\frac{\text{FSR}}{\Delta\lambda}\rfloor f \tag{17}$$

At the bottom of the package, there are a grid of pins. The area bandwidth density is defined as the maximum bandwidth in unit area, and is expressed in Equation (18). Here B is the bandwidth of a single interconnect, and $S = l_h \times l_w$ is the area of the optical pin.

$$\text{Area Density} = \frac{\text{Bandwidth } B}{\text{Area } S} \tag{18}$$

At each layer of the board, there are parallel interconnects. The linear bandwidth density is defined as the maximum bandwidth in unit width, and is expressed in Equation (19). Here B is the bandwidth of each interconnect, and p is the interconnect pitch.

$$\text{Linear Density} = \frac{\text{Bandwidth } B}{\text{Pitch } p} \tag{19}$$

3.6 LATENCY

We assume that the signal has a long pulse with narrow bandwidth, and ignore its nonlinear effects. The speed of optical signal is hence determined by its group velocity, with which the envelope of a pulse propagates in the optical medium. The latency is expressed in Equation (20). Here c is the light speed in vacuum. n_g is the group reflection index.

$$v_o = \frac{c}{n_g} \tag{20}$$

In addition to the propagation delay, the parasitic capacitances of these electrical modules will also generate RC delays, whose values could not exceed one bit period $1/2f$. The interconnect latency is expressed in Equation (21). Here L is the interconnect length, v is the signal propagation speed, and τ_{RC} is the RC delay of electrical modules.

$$\text{Latency} = \frac{\text{Length } L}{\text{Speed } v} + \text{Delay } \tau_{RC} \tag{21}$$

3.7 SIGNAL TO NOISE RATIO (SNR) AND BIT ERROR RATE (BER)

The optical signal to noise ratio is expressed (OSNR) in Equation (22).

$$OSNR = \frac{1}{\varepsilon_o} \tag{22}$$

Where ε_o is the crosstalk noise coefficient. We can then obtain the bit error rate (BER) based on the optical signal to noise ratio [3]. Their relationship is expressed in Equation (23).

$$BER = \frac{1}{2}e^{-\frac{SONR}{4}} \tag{23}$$

3.8 NOTATION TABLE

The relationship between the notations in this section and the parameter/configuration name in OEIL are listed in Table 1.

`laser_slope_efficiency`	η_s	`laser_threshold_current`	I_{th}
`laser_extinction_ratio`	r_e	`laser_voltage`	V_l
`driver_voltage`	V_c	`optical_pin_loss`	η_o
`optical_pin_height`	l_h	`optical_pin_width`	l_w
`propagation_loss`	α	`wg_refractive_index`	n_g
`wg_pitch`	p_o	`signal_to_noise_ratio`	SNR
`tia_noise_density`	i_n	`tia_transimpendance`	Z_{tia}
`la_voltage_threshold`	V_{th}	`pd_responsity`	ρ
`pd_capacitance`	C_{pd}	`mr_radius_range`	R
`mr_attenuation`	a	`mr_power_split_k`	k
`mr_refractive_index`	n_e		
`data_rate_optical`	$2f$	`length_optical`	L
`number_of_wavelengths`	m_o	`number_of_laser_wavelength`	λ
`laser_wavelength`	λ_e	`optical_intensity`	I
`TPA_coefficient`	β_{TPA}	`laser_wavelength`	σ_{FCA}
`photon_energy`	$h\nu$	`carrier_lifetime`	τ_c

Table 1: The mapping between notations and optical parameter/configuration

4 MODELS FOR ELECTRICAL INTERCONNECT

We build models for the crosstalk noise, attenuation and receiver sensitivity of electrical interconnect, and analyze its performance from the aspects of energy consumption, bandwidth density and latency. All the formulations are general to different technologies.

4.1 CROSSTALK NOISE

In electrical interconnects, the crosstalk coefficient is defined as the ratio of noise amplitude to signal amplitude. Compared with single-ended traces, the crosstalk noise in differential traces is relatively small. The near-end crosstalk noise (NEXT) among parallel traces on board is the main source of crosstalk noise. This is because for properly terminated low-loss striplines, the far-end crosstalk noise (FEXT) is relatively very low. We define $c(d)$ to be the crosstalk coefficient between two parallel traces with distance d, and it is expressed in Equation 24.

$$c(d) = H^2/(4d^2 + H^2) \tag{24}$$

In Equation 24, H is the distance between two metal layers. Parallel differential traces on the PCB board are analyzed. The crosstalk coefficient between the differential pair n and $n+i$ is expressed in Equation 25.

$$N_d(i) = c(|i|p_e - 2w) - 2c(|i|p_e) + c(|i|p_e + 2w) \tag{25}$$

The victim trace pair n has two traces in opposite directions and the aggressor trace pair $n-1$ also has two traces in opposite directions. Therefore, the crosstalk coefficient between two trace pairs is the summation of four terms. Apart from trace pair $n-1$, there are other aggressor trace pairs, such as $n+1$ and $n+2$. The total coefficient ε_e is expressed in Equation 26.

$$\varepsilon_e = \ldots + N_d(-1) + N_d(1) + N_d(2) + \ldots \tag{26}$$

It is assumed that there are m_e parallel trace pairs on the PCB board. The trace pair located in the middle of those trace pairs has the the largest crosstalk noises, and its crosstalk coefficient is expressed in Equation 27.

$$\varepsilon_e = 2 \sum_{i=1}^{\lfloor m_e/2 \rfloor} N_d(i) \tag{27}$$

4.2 ATTENUATION

In electrical interconnects, trace attenuation A_e is the ratio of output signal amplitude to input signal amplitude, and is expressed in Equation (28). α_e is the attenuation coefficient of trace, L is the interconnect length. Additionally, η_e is the attenuation of each electrical pin, and there are two pins in a single electrical interconnect.

$$A_e = \eta_e^2 e^{-\alpha_e L} \tag{28}$$

The attenuation coefficient α_e is expressed in Equation (29), where the first and second terms are called skin effect loss and dielectric loss, respectively. In striplines, w and h are width and height of trace. R_{dc} is the direct current resistance, Z_0 is the characteristic impedance, and C_0 is the capacitance per unit length. $tan\delta_D$ is the loss tangent in dielectric material. Their values will be discussed in Section VI. Additionally, f_s is the frequency when skin depth equals half of trace height h. f is the working frequency of the signal. The attenuation coefficient is increased if f is increased.

$$\alpha_e = \frac{R_{dc}(w+h)}{2Z_0 w}(\frac{f}{f_s})^{0.5} + \pi f C_0 tan\delta_D Z_0 \tag{29}$$

The current in electrical interconnects will drive the electrical pins on both side of the trace. After infinite time, the voltage on the pin will be driven to the full swing voltage. However, for each bit signal, the time to drive the pin is half of the period $1/f$. The ratio of the voltage after that given time to the full swing voltage is defined as the attenuation of each pin η_e, and it is expressed in Equation (30). To drive the pin, current will be attenuated by resistance Z_0 and capacitance C_p of electrical pin.

$$\eta_e = 1 - e^{-\frac{1}{2Z_0 C_p f}} \tag{30}$$

4.3 RECEIVER SENSITIVITY

In electrical interconnects. The driver injects currents through the pair of differential traces, and induces a voltage difference between the two ports of limiting amplifier. Only when this voltage difference is less than $-V_{th}$ or greater than V_{th}, signals can be detected by the limiting amplifier. The sensitivity of electrical receiver is defined as double the threshold voltage V_{th} of limiting amplifier.

4.4 ENERGY CONSUMPTION

The total power consumption is expressed in Equation (31). Current I_0 is the supply current of the driver, I_{la} is the supply current of the limiting amplifier, and V_c is the supply voltage of these two components. The supply voltage is V_c. The value of I_{la} is approximately proportional to the working frequency of limiting amplifier.

$$P_e = (2I_0 + I_{la})V_c \tag{31}$$

The received electrical signal has two voltage levels named V_1 and V_0, which represent logic levels of 1 and 0. A_e and ε_e are the attenuation and crosstalk noise coefficient of electrical interconnect. Their values have been discussed in the previous section. ε_c is called transmitter offset coefficient, which is defined as the ratio of offset amplitude to signal amplitude. The minimum required eye amplitude in electrical interconnects is A_e - ε_e - ε_c, which corresponds to V_{th}, the sensitivity of electrical receivers. The minimum supply current required from the driver is double the current I_0, which is expressed in Equation (32). Z_d is the differential impendence between two inputs of the differential pair.

$$I_0 = \frac{2V_{th}}{(A_e - \varepsilon_e - \varepsilon_c)Z_d} \tag{32}$$

We evaluate the energy consumption, which is defined as the energy consumed by the interconnects when they transmit unit bits of information. It is expressed in Equation (33). Here P is the power consumption of optical signal. The signal bandwidth is $2f$. Each signal does not interfere with other signals in the same waveguide.

$$\text{Energy Consumption} = \frac{\text{Power } P}{2 \cdot \text{Frequency } f} \tag{33}$$

4.5 BANDWIDTH DENSITY

In electrical interconnects, there is only one signal in each differential pair. Therefore, the bandwidth of each electrical interconnect equals double the frequency, $2f$. If the signal frequency is increased, trace attenuation is increased. The value of coefficient margin $\Delta\varepsilon$, expressed in Equation (34), will be decreased. It is possible that these signals will not be detected by receiver because of noises. Every receiver has a minimum required coefficient margin, and the signal frequency of electrical interconnects is limited. Parameters ε_e and ε_c have been discussed in the previous subsection.

$$A - \varepsilon_e - \varepsilon_c = \Delta\varepsilon \tag{34}$$

In Equation (34), $\Delta\varepsilon$ is the coefficient margin, which is assumed to be 0.01 in this model. As mentioned in the previous section, the attenuation coefficient α_e is the function of working frequency f, and this relationship could be expressed as $\alpha_e = \mathscr{A}(f)$. Function $\mathscr{A}$ is a monotonically increasing function, and its inverse function is $\mathscr{A}^{-1}$. The maximum bandwidth of a single electrical interconnect is the function of trace length, which is expressed in Equation (35). It can be seen that if the interconnect length is increased, the bandwidth of electrical interconnects will be decreased.

$$\mathrm{B}_e = 2\mathscr{A}^{-1}\left(-\frac{\ln(\varepsilon_e + \varepsilon_c + \Delta\varepsilon)}{L}\right) \tag{35}$$

At the bottom of the package, there are a grid of pins. The area bandwidth density is defined as the maximum bandwidth in unit area, and is expressed in Equation (36). Here B is the bandwidth of a single interconnect, and $S = l_h \times l_w$ is the area of the optical pin.

$$\text{Area Density} = \frac{\text{Bandwidth } B}{\text{Area } S} \tag{36}$$

At each layer of the board, there are parallel interconnects. The linear bandwidth density is defined as the maximum bandwidth in unit width, and is expressed in Equation (37). Here B is the bandwidth of each interconnect, and p is the interconnect pitch.

$$\text{Linear Density} = \frac{\text{Bandwidth } B}{\text{Pitch } p} \tag{37}$$

4.6 LATENCY

In stripline design, copper traces on the PCB board are surrounded by dielectric material. When an electrical signal propagates along the trace, its speed is determined by the speed of a changing electric and magnetic field, which is in fact the speed of light in the material. The propagation speed of electrical signals is related to the relative dielectric constant of that material, and is expressed in Equation (38). c is the light speed in vacuum, which is about 12 inches per nanosecond. ϵ_r is the relative dielectric constant of the material in the PCB board, and the values of ϵ_r are different in different PCB boards. The signal speed is inversely proportional to the square root of relative dielectric constant.

$$v_e = \frac{c}{\sqrt{\epsilon_r}} \tag{38}$$

In addition to the propagation delay, the parasitic capacitances of these electrical modules will also generate RC delays, whose values could not exceed one bit period $1/2f$. The interconnect latency is expressed in Equation (39). Here L is the interconnect length, v is the signal propagation speed, and τ_{RC} is the RC delay of electrical modules.

$$\text{Latency} = \frac{\text{Length } L}{\text{Speed } v} + \text{Delay } \tau_{RC} \tag{39}$$

4.7 Notation Table

The relationship between the notations in this section and the parameter/configuration name in OEIL are listed in Table 2.

`pcb_layer_height`	H	`pcb_trace_width`	w
`pcb_trace_height`	h	`pcb_trace_pair_pitch`	p_e
`pcb_loss_tangent`	$tan\delta_D$	`pcb_dielectric`	ϵ_r
`package_pin_pitch`	$\sqrt{S_e}$	`trace_half_depth_f`	f_s
`trace_characteristic_z`	Z_0	`trace_unit_length_c`	C_0
`trace_direct_current_r`	R_{dc}	`trace_input_impendance`	Z_d
`electrical_pin_load_c`	C_p	`la_threshold_voltage`	V_{th}
`la_offset_coefficent`	ϵ_c	`la_coefficent_margin`	$\Delta\epsilon$
`circuit_voltage`	V_c		
`data_rate_electrical`	$2f$	`length_electrical`	L
`number_of_pairs`	m_e	`number_of_stack_dies`	m_d

Table 2: The mapping between notations and electrical parameter/configuration

5 Models for Serializers and Deserializers

We build models for the energy efficiency, area and latency of serializers and deserializers. The SerDes models are integrated in both optical interconnects and electrical interconnects. All the formulations are general to different technologies.

5.1 SerDes Modelling

In E-O interfaces(Fig. 2) the multiplexer blocks are important components, which select one of several input signals and forward the data from selected input port to output port. The basic multiplexer block has two inputs and one output. To store the bits of information during each clock cycle, three flip-flops are implemented. Clock signals are used to select input signals. In this design, input 0 is selected when clock signal is low, and input 1 is selected when clock signal is high. Multiplexer blocks in different stages are connected to different frequencies. A 1/2 clock divider is implemented in each stage to provide clock signals with different speeds. An array of microresonators are implemented along the waveguide to modulate N different optical wavelengths. Each microresonator has a unique resonance wavelength, and belongs to one of the E-O interfaces. In a basic multiplexer block, the output signal is delayed.

In O-E interfaces(Fig. 2), the demultiplexer blocks select one of several output signals and forward the data from input port to selected output port. which has one input and two outputs. Similarly, three flip-flops are implemented in demultiplexer blocks to store the bits of information. Clock signals are used to select output signals. In this design, output 0 is selected at the rising clock edge, and output 1 is selected at the falling clock edge. A 1/2 clock divider is implemented in each stage to provide clock signals with different frequencies. In optical WDM systems, each microresonator has a unique resonance wavelength, and belongs to one of the O-E interfaces. In a basic demultiplexer block, one of two parallel output signals is delayed.

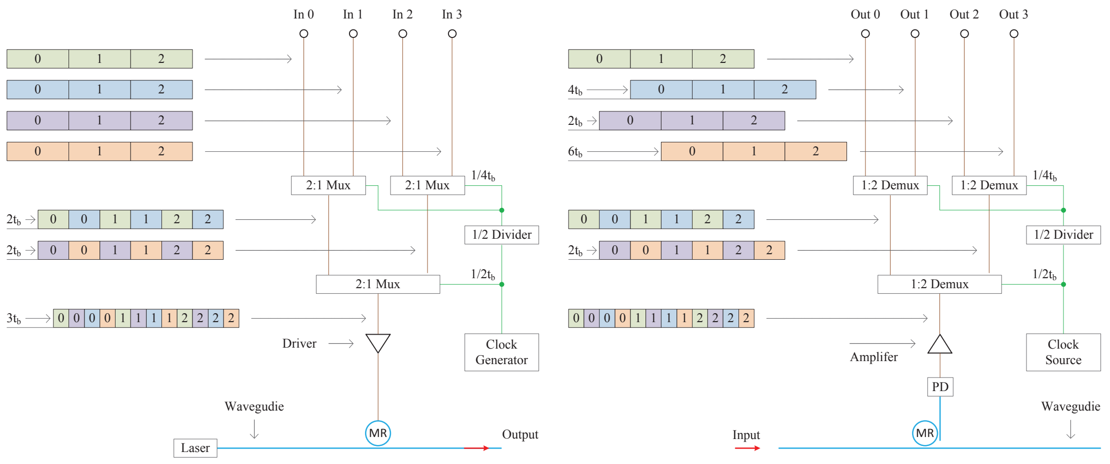

Figure 2: Basic Structures of E-O interface and O-E interface.

5.2 ENERGY EFFICIENCY AND AREA

It is assumed that I_o is the supply current of a single gate running at full clock speed, and the supply currents of other gates are scaled by their working frequencies. Therefore, the supply current of each component in multiplex blocks can be expressed in the unit I_o. Table 3 shows the current breakdown of basic multiplexer blocks. The supply currents of multiplexers, flip-flops, and clock dividers running at full speed are $1I_o$, $1I_o$ and $2I_o$, respectively. In R:1 E-O interface, the total current consumed by multiplexer blocks are about $5\log_2 R \cdot I_o$. Assuming supply voltages are fixed, the power consumption of each component is proportional to the supply current I_o. All of them can be expressed in the unit P_e, which is the power consumption of a single gate. Table 4 shows the current breakdown of basic demultiplexer blocks. In 1:R O-E interface, the total current consumed by demultiplexer blocks are about $4\log_2 R \cdot I_o$.

$$P_e = I_0(2f) \cdot V_{dd} \qquad\qquad S_e = S_0(2f) \tag{40}$$

It is assumed that S_e is the area of a single gate running at full clock speed, and the areas of other gates are scaled by their working frequencies. The area breakdown of multiplexer blocks is similar to current breakdown. In R:1 E-O interface and 1:R O-E interface, the areas are about $5\log_2 R \cdot S_e$ and $4\log_2 R \cdot S_e$, respectively. Power consumptions and areas of multiplexer blocks in both interfaces are summarized in Table 5, where unit power consumption P_e and unit area S_e are expressed in Equation 40.

Component	4:1 Serializer	8:1 Serializer	16:1 Serializer	R:1 Serializer
Multiplexer	2	3	4	log_2R
Flip-flop	6	9	12	$3log_2R$
Clock Divider	2	3	3.5	$4-8/R$
Total (I_0)	10	15	19.5	$\approx 5log_2R$

Table 3: Current Breakdown of Serializer

Component	1:4 Deserializer	1:8 Deserializer	1:16 Deserializer	1:R Deserializer
Flip-flop	6	9	12	$3log_2R$
Clock Divider	2	3	3.5	$4-8/R$
Total (I_0)	8	12	15.5	$\approx 4log_2R$

Table 4: Current Breakdown of Deserializer

	E-O (P_e)	E-O (S_e)	O-E (P_e)	O-E (S_e)
Interface	$5log_2R$	$5log_2R$	$4log_2R$	$4log_2R$

Table 5: Comparison of Power Consumption P_e and Area S_e

Power consumption of driver is denoted as P_d. Each time the voltage level of PN junction is reversed, it is charged or discharged by the driver, where energies are consumed. On the other hand, power consumption of microresonator is denoted as P_m. When voltage level of PN junction is high, it is forward biased, energies are consumed because of the direct current flowing through the PN junction. Power consumptions P_d and P_m are expressed in Equation 41. The dynamic driver power consumption is 1/4. The static microresonator power is 1/2.

$$P_d = 2f \cdot C_m \cdot V_m^2 \qquad\qquad P_m = I_m \cdot V_m \tag{41}$$

P_d is function of data rate f. C_m is the input capacitance of microresonator. V_m is the supply voltage of microresonator. P_m, on the other hand, is not function of data rate f. I_m is the direct current of microresonator. The area of each transmitter module S_m in E-O interface is related to the size of microresonator. Besides, S_l is the area of each on-chip laser.

5.3 LATENCY

The latency of inter-chip interconnects is the amount of time it takes for the head of signals to travel from end to end. It includes three parts: the multiplexer/demultiplexer delay, the RC delay and the propagation delay. It is assumed that the bit time of serial optical signals is t_b and the propagation delay is t_p. Latencies of E-O interface and O-E interface are denoted as T_{eo} and T_{oe}, and expressed in Equation 42. The multiplexer delay in E-O interfaces are (R-1)·t_b. The average demultiplexer delay in O-E interfaces are (R-1)·t_b. On the other hand, the RC delays in all interfaces are assumed to be t_b.

$$T_{eo} = Rt_b + t_p \qquad\qquad T_{oe} = Rt_b + t_p \tag{42}$$

The total latency is the summation of multiplexer/demultiplexer delay, RC delay and propagation delay. t_b is expressed as $1/f$, where f is the data rate of serial optical signals. t_p is expressed as $n\mathrm{L}/c$, where n is the refractive index of optical interconnect. c is the light speed in vacuum, and L is the length of optical waveguide. R is the parallel-to-serial ratio of interfaces.

5.4 NOTATION TABLE

The relationship between the notations in this section and the parameter/configuration name in OEIL are listed in Table 6.

`serdes_ratio_optical`	R	`serdes_ratio_electrical`	R
`serdes_cur_optical`	I_o	`serdes_cur_electrical`	I_o
`serdes_area_optical`	S_0	`serdes_area_electrical`	S_0
`laser_area`	S_l	`mr_area`	S_m
`mr_tuning_power`	P_t	`mr_static_power`	P_m
`mr_dynamic_power`	$P_d/2f$		

Table 6: The mapping between notations and SerDes circuit

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VERSION HISTORY

Revision	**Date**	**Author(s)**	**Description**
1.0	DEC, 2014	Zhehui Wang, Jiang Xu, Peng Yang, Zhifei Wang, Luan Huu Kinh Duong, Xuan Wang, Zhe Wang, Haoran Li, Rafael Kioji Vivas Maeda	Internal released
2.0	AUG, 2015	Zhehui Wang, Jiang Xu, Peng Yang, Zhifei Wang, Luan Huu Kinh Duong, Xuan Wang, Zhe Wang, Haoran Li, Rafael Kioji Vivas Maeda	Basic analytical model
3.0	DEC, 2015	Zhehui Wang, Jiang Xu, Peng Yang, Zhifei Wang, Luan Huu Kinh Duong, Xuan Wang, Zhe Wang, Haoran Li, Rafael Kioji Vivas Maeda	Add SerDes analyses Add area analyses
4.0	AUG, 2019	Zhehui Wang, Shixi Chen, Jiang Xu, Zhifei Wang, Xuanqi Chen, Jun Feng, Jiaxu Zhang, Rafael Kioji Vivas Maeda, Haoran Li, Zhongyuan Tian	Add non-linear models