Study of the capacity of Optical Network On Chip based on MIMO (Multiple Input Multiple Output) system

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***Abstract*—When designing Optical Networks-On-Chip, designers have resorted to make dialogue between emitters (lasers) and receivers (photo-detectors) through a waveguide which is based mainly on optical routers called λ-router. In this paper, we propose a new method based on the Multiple Input Multiple Output concept, and we give a model of the channel propagation, then we study the influence of different parameters in the design of Optical Networks-On-Chip.**

Keywords—λ –router; MIMO channels; capacity; CDMA

I. Introduction

Networks-on-Chip (NoC) have recently become popular as an option for increasing the bandwidth, lowering the latency and reducing the power in chip multiprocessors.

Several network architectures have been presented in the literature to construct efficient photonic networks-on-chip, and this architecture is based on λ-router.

We present here an overview of On-chip optical networks based on (λ-router). The figure below shows an example of a network-on-chip based on an optical waveguide using optical router architecture liabilities (the λ-router) [1,2].

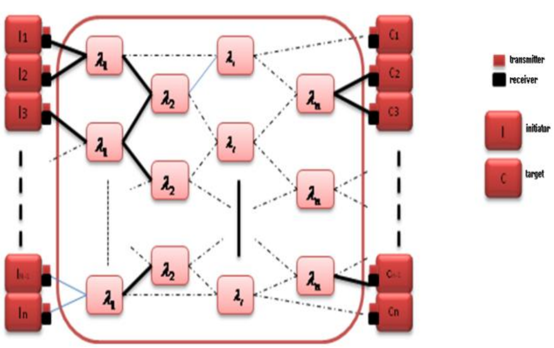

Fig. 1. On-chip optical networks based on λ-router

The basic element of the network is the λ-router [3] which consists of two basic elements:

* Two parallel waveguides.

* A ring cavity, square...

In this paper, we will study and present a novel ONOC (Optical Network On Chip) system based on MIMO technology; we begin in section II by the modeling the propagation's channel of the system which allows us to determine the attenuation between transmitter and receiver. Then in section III, we present the study of ONOC capacity and finally in section IV, numerical results are presented.

II. MIMO Channel Modeling

In this section, we solve Maxwell's equations to determine the electromagnetic field equation that describes the outgoing laser light [4] (channel 1) and we modeling the diffuser (channel 2) which is an important component to diffuse light to all receivers.

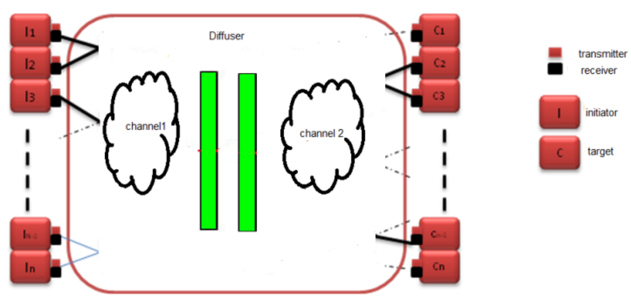

Fig. 2. On-chip optical networks based on MIMO technology

A. Channel 1 modeling

We assume that electromagnetic wave Propagates in a homogeneous medium is subject to Maxwell's equations. Thus, the equation of wave propagation in isotropic medium is:

$$\Delta\vec{E} - \frac{1}{c^2}\frac{\partial^2 \vec{E}}{\partial t^2} = \vec{0} \qquad (1)$$

If we consider the propagation of a monochromatic electromagnetic wave frequency then we have:

$$\Delta E(x,y,z) + k^2 E(x,y,z) = 0 \qquad (2)$$

The solution of this equation is :

$$I(r,z) = I_0(z)\exp(\frac{-2r^2}{w^2(z)}) \quad (3)$$

$w(z) = w_0\sqrt{1+(\frac{z}{z_R})^2}$: Is a measure of the amplitude of Gaussian field with distance from the z-axis.

The percentage of energy F received by the receiver defined by:

$$F = \frac{\int_0^{\rho} I(r)ds}{\int_0^{\infty} I(r)ds} \quad (4)$$

Replacing I(r) by its value at a given point z, s we have after simplification, the function that represent the channel 1:

$$F = 1 - \exp(-2(\frac{\rho}{w})^2) \quad (5)$$

B. Channel 2 modeling

As lasers scatters light linearly, the diffuser appears as a solution to distribute the quantity of light received at the receivers, in this case we say that the diffusion process is done in a Lambertian.

Existing broadcasters are either single surface or double surfaces [5,9].

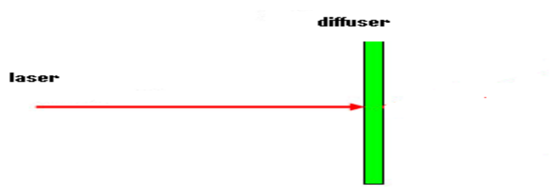

Fig. 3. diagram of a diffuser

The diffuser is an optical component, composed of several different micro-lenses, designed in a manner that each micro-lens arranged to avoid repetition pattern, so that there's control over the distribution of diffusion and intensity profile [8].

For each diffuser:

$$I_0(\theta) = \begin{cases} \cos^p(\frac{\pi}{2}\frac{\theta}{\theta_0}), |\theta| \le \theta_0 \\ 0 \end{cases} \quad (6)$$

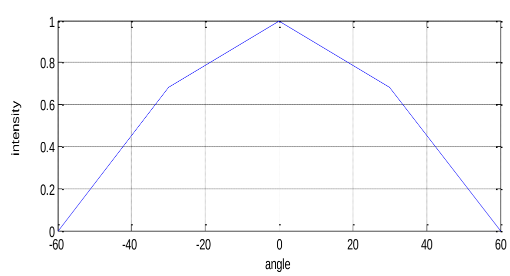

Fig. 4. Response of a diffuser

In our study we choose $\theta_0 = 60°$ and $p = 0.6$.

It is a simple diffuser with low spectral efficiency [5]. In order to increase the spectral efficiency we adopt the use of two broadcasters which are placed one in front of the other as it is shown in the following figure:

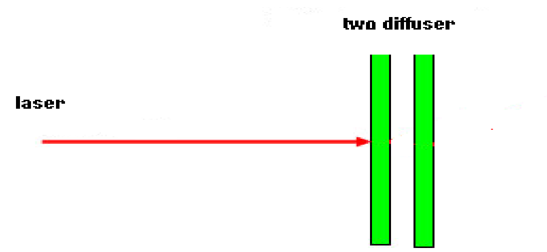

Fig. 5. diagram of two diffusers

The total scattering given by two broadcasters is given by the convolution product:

$$I(\theta) = \int_{-90}^{90} I_0(\varphi)I_0(\theta-\varphi)d\varphi \quad (7)$$

In our study we choose $\theta_0 = 60°$ and $p = 0.6$.

The spectral efficiency is 70% [5] and there is an increasing scattering angle going from 120 ° to 180 °.

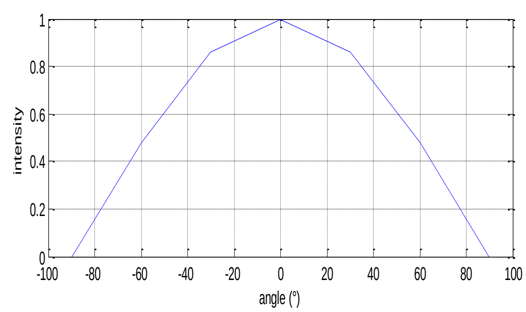

Fig. 6. Response of two diffusers

Then, the channel 2 is represented with:

$$h_{ij} = \frac{A}{d_{ij}^2} I(\theta)\cos(\varphi_{ij})$$

h_{ij} : The coefficient of the MIMO channel.

III. MIMO CHANNEL CAPACITY

To better understand and present the theoretical formulation of the MIMO channel capacity perspective, we introduce the notion of capacity based on the theory of information.

When the channel matrix is known and in reception, it was shown in [7] that the mutual information described above is maximized if $\Phi = \frac{\sigma_e}{Nt}$, σ_e is the variance of the transmitted signal in the case where it follows a normal distribution.

The formula for the ergodic capacity will be given by [6]:

$$C = (\frac{1}{2})E\left[\log_2 \det\left(I_{Nr} + \frac{SNR}{Nt} HH^H\right)\right] \quad (8)$$

With I_{Nr} represents an identity matrix NxN and H is the channel matrix representing the attenuation between each sub-channel.

When the channel is known at both transmitter and receiver, the optimal solution of capacity is a water-filling solution described in 1995 by Telatar [6].

To fully express the ability of this technique, we rewrite the model of the transmission system, to do this we apply the theorem of singular value decomposition of the matrix H which allows us to apply and explain the impact of one of the power allocation techniques of the MIMO system performance. So H will be as follows:

$$H = UDV^H \quad (9)$$

The received signal becomes:

$$Y = HX + N = UDV^H + N \quad (10)$$

We can now write the system as equivalent:

$$\tilde{Y} = D\tilde{X} + \tilde{N} \quad (11)$$

With:

$\tilde{Y} = U^H Y$, $\tilde{X} = V^H X$, $\tilde{N} = U^H N$.

Using Rule determinant, we have:

$$\det\left(I_{Nr} + \frac{SNR}{Nt} H\Phi H^H\right) = \det\left(I_{Nr} + \frac{SNR}{Nt} \Phi H^H H\right) \quad (12)$$

By replacing the expression of H in this last formula we obtain:

$$\det\left(I_{Nr} + \frac{SNR}{Nt} \Phi H^H H\right) = \det\left(I_{Nr} + \frac{SNR}{Nt} \Phi V D^2 V^H\right)$$

Now apply the rule of determining the last formula becomes:

$$\det\left(I_{Nr} + \frac{SNR}{Nt} \Phi V D^2 V^H\right) = \det\left(I_{Nr} + \frac{SNR}{Nt} D V^H \Phi V D\right)$$

Where $\tilde{Q} = V^H \Phi V$ corresponding to the covariance matrix of the equivalent signal, the covariance matrix of the received signal becomes equivalent $A = D\tilde{Q}D$, for A diagonal must $\tilde{Q}$ is also diagonal and in this case the expression of A becomes: $A = \tilde{Q}D^2$.

Using this latter approach of the covariance matrix of the received signal equivalent we can express the MIMO channel capacity using the technique water-filling.

Using the technique of water-filling [7], we seek to optimize the connection between the transmitter and receiver by dividing the total power transmitted on the transmit antennas in order to achieve optimal capacity offered by the system channels MIMO.

To express the optimal capacity, consider the transmission of symbols on a chain of transmission using the technique of Waterfilling such that the matrix $A = \tilde{Q}D^2$ where $\tilde{Q} = diag(a_1, a_2, ..., a_{Nt})$.

In practice, a condition is imposed for power: the total power transmitted on all transmitters is equal to the total power transmitted:

$$\sum_{i=1}^{Nt} P_i = P_t \quad (13)$$

This condition can be written differently as follows:

$$\sum_{i=1}^{Nt} a_i = P_t \quad (14)$$

The formula of the total system capacity allocation technique using a constrained power is as follows:

$$C = (\frac{1}{2})E\left[\sum_{i=1}^{n} \log_2\left(1 + a_i \frac{SNR}{Nt} \lambda_i\right)\right] \quad (15)$$

With $n = \min(Nt, Nr)$ and λ_i is a diagonal matrix D^2. Suppose μ constant to check the power constraint in the case of MIMO system using water-filling technique, we can write the formula for the optimal power allocation as follows:

$$a_i = \frac{Nt}{SNR}\left(\mu - \frac{1}{\lambda_i}\right)^+$$

With the symbol $(Z)^+$ means:

$$(Z)^+ = \begin{cases} Z & si \quad Z > 0 \\ 0 & si\, Z \le 0 \end{cases} \quad (16)$$

Thus, the power output of the transmitter i will be $P_i = \left(\mu - \frac{1}{\lambda_i}\right)^+$ and therefore the water-filling algorithm is optimal power allocation such that :

$$P_i = \left(\mu - \frac{1}{\lambda_i}\right)^+.$$

Water-Filling technique is to have variable power level transmitters. This change is made so that we have an optimization of the channel capacity.

The ability of such a system Water-Filling is given by the following expression:

$$C = (1/2)E\left[\sum_{i=1}^{n} \log_2 (\mu\lambda_i)^+\right] \qquad (17)$$

Or

$$C = (1/2).E\left[\sum_{i=1}^{n} \log_2 (1 + P_i\lambda_i)\right]$$

Since $P_i = \left(\mu - \frac{1}{\lambda_i}\right)^+$

IV. Numerical Results

A. Study of the capacity enhancement with water-filling

We simulate the ability of the capacity previously presented with and without Water-Filling technique to show the contribution of this technique in terms of capacity:

We simulated an optical MIMO transmission system with the use and no use of the Technical Water-Filling knowing that there's direct sight between transmitters and receivers lasers and photodiodes result of this simulation is given by the following figure:

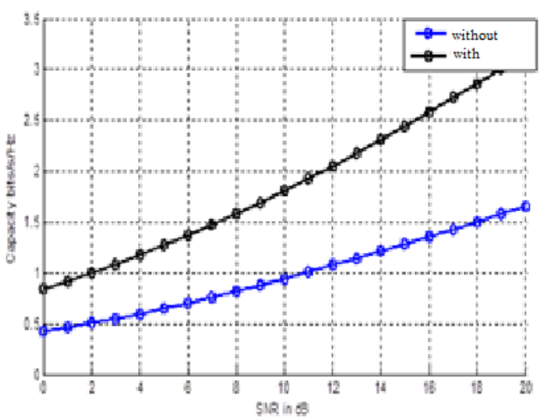

Fig. 7. Capacity = f (SNR) of a MIMO system with or without water-filling technique

This figure shows the improvement carried by Water-Filling technology on the capacity of MIMO channels in the case of sight between transmitters and receivers. Indeed, for low SNR the capacity of the transmission chain using the technique of power allocation Water-Filling is greater than other that does not use it and this increase improves if we increase the SNR more and more. For example if SNR = 12 dB, the ability of the system using the Water-Filling is 2 bits / s / Hz. However, the ability of the chain without using this technique is 1 bit / s / Hz. For large values of SNR the effect is remarkable, there's an increase of the capacity in the area between the two curves.

We also simulated a chain of MIMO transmission in the absence of optical diffusers knowing that there's a direct sight between the transmitters and receivers.

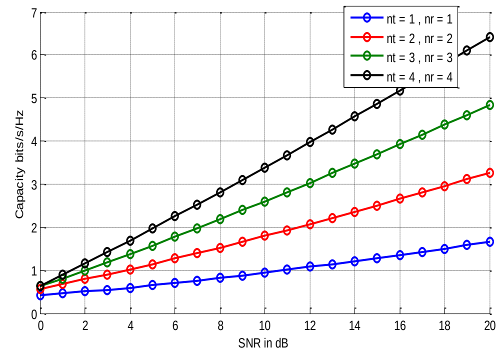

Fig. 8. Comparison of MIMO capacity without Water-Filling

This figure shows the improvement achieved by the addition of a laser on the capacity of MIMO channels in the case of sight between transmitters and receivers. Indeed, for low SNR the capacity of the transmission chain of the various systems are very close but if we increase the SNR, it gives a duplication of bit rate and this is a logical result considering that there is no overlap of data between sub-channels. For SNR = 12 dB, for example the ability of the SISO system is 1 bit / s / Hz, 2x2 MIMO system is 2 bits / s / Hz, 3x3 MIMO system is 3 bits / s / Hz, the system MIMO 4x4 is 4 bits / s / Hz.

B. Parametrics analysis of an ONOC design

We assume that we have a MIMO system as shown

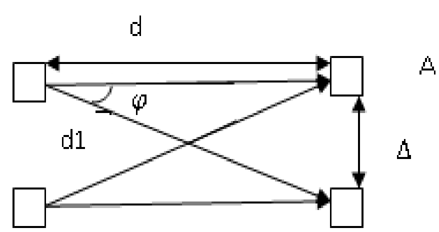

Fig. 9. Schematic of 2 x 2 MIMO systems

In our study we choose:

$\theta_0 = 60°$ and $p = 0.6$.

The coefficient of the MIMO channel is given by h_{ij}

$$h_{ij} = \frac{A}{d_{ij}^2} I(\theta)\cos(\varphi_{ij})$$

From the diagram above, we have: $\begin{cases} d^2 + \Delta^2 = d_1^2 \\ tg(\varphi) = \frac{\Delta}{d} \end{cases}$

A: the surface of the photo-detector is equal to $0.025mm^2$.

We assume the 2x2 MIMO system before, then we set the distance d = 1mm between lasers and photo-detectors and we change different positions of photo-detectors.

We assume that all other parameters are fixed. Under the same conditions we get the following results:

$$\begin{cases} h_{11} = h_{22} \\ h_{12} = h_{21} \end{cases}$$

We simulated a 2x2 MIMO system and the result is represented by the following figure:

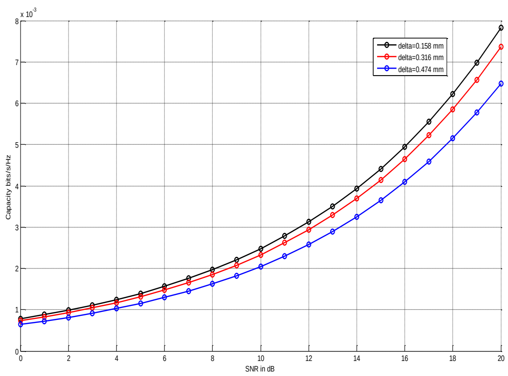

Fig. 10. Capacity = f (SNR) of a 2x2 MIMO system with variation of the result Δ

From the figure above we can see the degradation of the capacity, if we increase the distance between the photo-detector which is an expected result because when the light reaches the diffuser we find that a quantity of light is lost because spectral efficiency diffuser is 70%. As the two photo-detectors are close and there is no distance between them, we find the optimal capacity with a delta value equal to 0.158 mm, which corresponds to two photo-detectors just one after another.

We simulated a 2x2 MIMO system and we vary the distance D, we obtain the following figure:

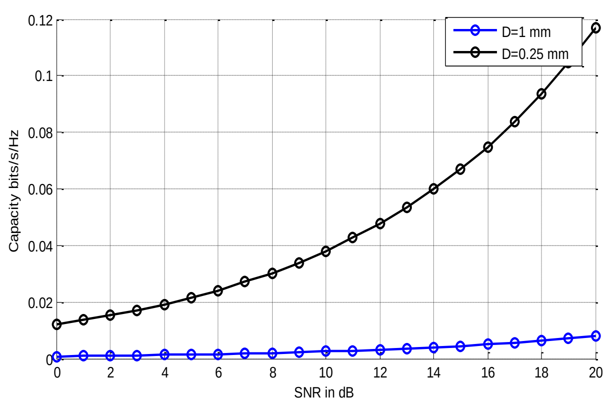

Fig. 11. Capacity = f (SNR) of a 2x2 MIMO system with variations of distance d

From the figure above we observe the degradation of the capacity if we increase the distance between the lasers and photo-detectors which is an expected result.

This figure below shows the improvement achieved by the addition of a laser on the capacity of MIMO channels. Indeed, for low SNR the capacities of the transmission chain of the various systems are very close but if we increase the SNR, there is duplication in the capacity.

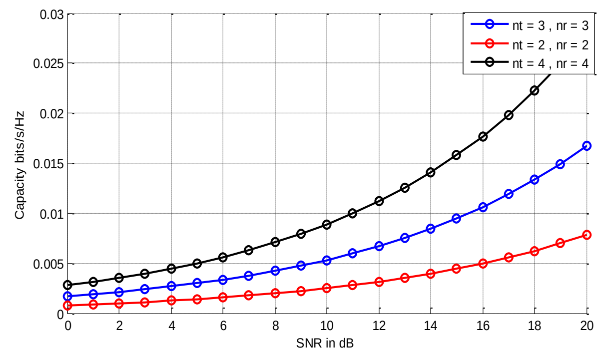

Fig. 12. Capacity = f (SNR) of the MIMO system with different technology water-filling

V. CONCLUSION

We detailed in this paper MIMO channel modeling of ONOC system based on the MIMO technologies. Then we studied the capacity with knowledge of transmission channel for both transmission and reception where we have very detailed Water-Filling technology that allows us to optimize the capacity of MIMO channels and finally we show the important parameters which enhance the capacity of ONOC system design.

After system design, we work now on the performance evaluation of this system with Code Division Multiplexing Acces code.

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