Performance survey of classic and Optic network-on-chip

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Abstract
A system on chip is composed of a large number of intellectual property (IP) blocks on the same silicon. However, as the number of IP blocks on a single chip and their performance continue to increase, a shift from those classic interconnections to optical ones becomes mandatory. This article presents a survey and comparison between an optical link and classic one. Measurable metrics such as, power consumption, latency, throughput and noise effects which are the main parameters describing the quality of the data link to compare the quality of different systems for data transmission are theoretically investigated. Numerical simulations have shown a noticeable improvement of the optical system compared to the electrical network on chip.

1 | INTRODUCTION

It is often taken for granted that the performance of electronic systems increases including speed and density improvements. Currently, Moore’s Law is not able to meet the requirements of these systems, in particular, of the very large-scale system on chip (SoC) with thousands of intellectual properties (IPs). The optimization objective in SoC can be the Network-on-Chip (NoC) performances, such as Quality of Service (QoS), scalability and simplicity. Reaching high performances, consists of proposing a simple NoC architecture to reduce the number of hardware resources required for its implementation, minimizing the latency which characterizes the information transfer delay, and ensuring scalability by introducing resonant structures in transmitter and receiver photonic link [1]. NoC is one key contributor to the system power consumption and is one of the major limiters of performance. Power budgeting has been suggested in [2], exploring circuit techniques for NoC. A network-wide power management scheme has been introduced in [3], which is a technique of a wavelength selection to identify and activate the just needed laser wavelengths of a bandwidth’s application. However, all these approaches cannot guarantee good performance at such lower latencies. The worst-case latency model is presented in [4, 5]. To address NoC performance challenges, a scheme of two steps is proposed in [6]: the first is the estimation of network performance and the second step is the power budgeting.

New applications constantly pushed the boundaries, of conventional wired on-chip interconnects, moreover, electronic routers become a performance bottleneck due to the limited bandwidth, large area, high energy consumption, and crosstalk noise [7]. The classical electronic on-chip network (NoC) has poor scalability, large power consumption, relatively high latency, and signal integrity problems. Therefore optical on-chip networks have been proposed for the next-generation on-chip network [8–10] which are characterized by high speed and less power consumption. Research has been done on integrated optical network on chip (IONoC) [11, 12], suggesting these as solutions to meet the demands of system-on-chip (SoC) new generations. The integration of optical interconnects reduces the stresses on the global wires interconnections, reduces latency, power consumption and ensures the integrity of the transmitted signal. An on-chip multiprocessor (MPSoC) system using multiple processors is used by platforms that contain heterogeneous processing elements with specific characteristics that justify the need to provide optical NoCs. According to [3], modulator, photodetector (receiver), and tuning are three main factors of optical NoC power consumption.

Without taking the noise into consideration, the receiver makes a decision level whether a ‘0’ or ‘1’ is detected. However, noise in digital signals can cause errors at the decision level. The bit error rate, BER, quoted for communications systems to predict its performances, is a key...
parameter used in determining what quality of the transmitter/receiver system should be used, taking into consideration factors such as noise, attenuation, power, and modulation type. A BER of $10^{-9}$ is often considered the minimum acceptable BER for telecommunication applications. The BER is the most significant performance parameter of any digital communications system [13, 14]. It is a measure of the probability that any given bit will have been received in error. The BER depends primarily on the signal-to-noise rate (SNR) of the received signal which in turn is determined by the transmitted power, the attenuation and dispersion of the link, and the receiver noise. The effects of noise and other signal degradation processes can be investigated qualitatively.

The article claims a comparison between electronic networks-on-chip versus optical ones. The optical NoC considered here is a hybrid NoC, with an electronic control network and an optical data path.

The objectives of this article are to explore, investigate and interpret the main characteristics of the communications system, that is, the source transmitter, the channel (attenuation, dispersion, pulse spreading etc.) and the receiver. The overall system performance is limited by latency, power budgets, scalability, global synchronization, BER constraints and noise effect. In this work we will carry out a comparative study of performances between an optical link and communication bus. Furthermore, since performance of a link channel is commonly characterized by BER [13, 14], we consider the noise modelling of interconnections in on-chip communication.

This article is organized as follows. The classic NoC performances are defined and reviewed in Section 2. Section 3 presents numerical results such as BER and crosstalk coefficient. Finally, Section 4 concludes the paper.

2 CHARACTERISTICS OF AN NoC

Measurable metrics for an NoC are its area, power consumption, latency and data rate (throughput).

Our work consists of proposing metrics to characterize and compare the interconnection architectures. We will define the notions of load, and latency. Then, we will mainly interest in energy consumption and the effects of noise on network performance and their influence on the metrics of classical and optical NoC.

2.1 The network throughput

As the network load increases, there is more congestion and packets are delayed in the routers’ buffers until the conflicts are resolved. If the interval between two packets is less than this expectation, the next packets are affected by this delay. The network saturates when many packets are affected by a delay in the network. When the reception of the data in the network is slowed because of the contentions, the FIFO is filled, because the writing of the data continues regularly. After a while, the master IP can no longer write to the FIFO because it is full and the network is saturated. In NoC interconnection architecture, there is a saturation threshold, appearing when too many initiators are trying to generate too much traffic. We define the load $I_C$ of a channel $c$, as

$$I_C = \frac{\text{bandwidth demanded from channel } c}{\text{bandwidth of the input ports}}$$

It represents the amount of traffic that must cross the channel $c$ if each input injects one unit of traffic. The maximum channel load $I_{max}$ depends on the network topology; in fact a mesh topology allows different data paths, which makes it possible to avoid bottlenecks in the case of a maximum load. However, the CDMA access technique offers a single data path and therefore the maximum load $I_{max} = \max I_c$ becomes a vital parameter of the network. Let us remember that bandwidth is the maximum amount of data that can travel through a channel, while throughput is the amount of data that actually does travel through a channel successfully. Having a high bandwidth does not guarantee a high network performance, if throughput in the network is being affected by latency, packet loss and noise. The impact of latency on network throughput can be temporary or persistent depending on the source of the delays. When the traffic reaches the throughput $D$ of the network, the load on the bottleneck channel will be equal to the channel bandwidth $b$ (We suppose for simplicity that all the channels bandwidths are $b$), and any additional traffic would overload this channel. The ideal throughput $D_{\text{ideal}}$ given in Equation (1), is the input bandwidth that saturates the bottleneck channel.

$$D_{\text{ideal}} = \frac{b}{I_{max}}$$ (1)

The bandwidth is given by the width of the link (octets) multiplied by the frequency (Hz). To increase the ideal throughput, it is enough to widen the link or to pass at higher frequencies. For classic NoCs, broadening a link means increasing the number of wires on a bus (128-bit, 256-bit, 512-bit given in AMBA5 CHI [15]), which inevitably means more power consumption, more silicon surface and overall cost higher. For optical NoC, the problem does not arise, since the optical link is provided by a VCSEL diode whose bandwidth is quite high (10 GHz). The network throughput of the optical mesh NoC is 340 Gbps for 128-bit packets. In [16], a novel on-chip optical interconnect named CHAMELEON is proposed. It has the potential to deliver 1.92 Tbit/s bandwidth.

2.2 Latency

The latency is the time required for a packet to traverse the network; it depends on routing flow and topology.

The common contributing components for system latency are as follows:
Propagation delay $T_{p}$; it represents the time required for the packet to travel from the sender to receiver, which is a function of distance over speed of signal. In free space (vacuum), light travels at 299.792 m per microsecond (μs).

On the other hand, the packet travelling through a medium such as a copper wire will have a slower signal speed. It is obvious to note that propagation delay for an optical signal is smaller than the one for an electrical signal.

Transmission delay $T_{d}$; it represents the time required to push a packet into the link, which is the function of packet's length and bandwidth. The latency $T_{L}$ to transmit the payload data of packet of length $L$ to cross a channel with bandwidth $b$ is calculated by Equation (2).

$$T_{d} = \frac{L}{b} \quad (2)$$

One can note that, more the bandwidth is higher, less is the latency.

Processing delay $T_{pC}$; it represents the time required to process the packet header and determine the next destination. Much of this processing is done in hardware, so delays, although existing, are too small. Assuming that processing delay is independent of the physical nature (electrical/optical) of the signal, $T_{pC}$ can be considered the same for classical NoC and optical-NoC.

Queueing delay $T_{Q}$; it represents the time waiting of packet in the queue to be processed. It is important to note that, the higher the load of traffic, the higher will be the likelihood of a packet being delayed inside an incoming buffer. From queuing theory Queue-Size = Throughput × Latency. So, for a fixed queue-size, latency and throughput are inversely proportional to each other.

The total latency $T$ is the sum of all delays:

$$T = T_{P} + T_{d} + T_{pC} + T_{Q}$$

Following the analyses made above, we can conclude that the total latency for optical links is smaller than that of the links based on conductive wires.

2.3 Energy consumption

Nowadays, managing the energy consumption of complex SoCs has been a prime design consideration.

2.3.1 Classical NoC

Interconnect wires are responsible for an ever-increasing fraction of energy consumption in the network on chip. Most of this increase is due to global wires, such as busses and routers. The energy consumed when transmitting a short fixed-length segment of a packet (flit) is [17]

$$E_{\text{flit}} = E_{g}H + E_{\text{wire}}D \quad (3)$$

where $E_{g}$ is average router energy, $E_{\text{wire}}$ is average link wire transmission energy per unit length, $H$ is the number of hops traversed by a flit and $D$ is the distance between source and destination. Wires link losses are significant in an electrical network, so the node-to-node links consume larger energy when the hop count becomes larger. To perform the routing lookup, the NoC requires only the packet header which is the first flit.

Several avenues can be taken into account for reducing energy consumption such as router energy, wire energy and hop count. The low-swing signalling technique [18] has been proposed to reduce wire energy $E_{\text{wire}}$. A wire interconnect scheme can be illustrated as in Figure 1.

The dynamic switching energy of the wire for a full switching is

$$E_{\text{wire}} = C_{L}V_{DD}V_{\text{swing}} \quad (4)$$

where $C_{L}$ is the capacitive load distributed along the wire, $V_{DD}$ is the voltage supply, $V_{\text{swing}}$ is the interconnect voltage swing of the signal on a wire.

The short-circuit current and leakage current are no longer relatively less important compared to the dominant switching energy for a technology under 65 μm, so it must be also under consideration [19, 20].

Power consumption in a circuit is divided into dynamic, static (or leakage) and short circuit power consumption (Equation (5)). Dynamic (switching) power consumption occurs when signals change their logic state. Short circuit power consumption occurs for a short amount of time. Leakage power consumption mainly is the power consumed by the sub-threshold currents.

$$P_{\text{average}} = aC_{L}V_{DD}^{2}f_{clk} + V_{DD}I_{DD} + V_{DD}I_{\text{leak}} \quad (5)$$

In order to minimize the dynamic power dissipation not only the clock frequency ($f_{clk}$) should be lowered but also the switching activity ($a$) and where possible the supply voltage ($V_{DD}$) should be reduced too. A method proposed in [21] aims at characterizing the bit-level switching activity in a signal. In order to design circuits for low power, accurate estimation of power at different design stages has become important.

The modulator (Figure 2) translates the electrical signals into modulated optical signals. Owing to their low operating voltage and compact size, optical resonator-based modulators are preferred for the most recent integrated circuit design, which has a significant impact on optical interconnect

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**FIGURE 1** Interconnect circuit
bandwidth, latency, and area. Micro-ring resonators (MR) have a wide range of applications including signal processing filters, sensors, and lasers modulators. At direct modulation, the modulated optical power from the diode laser is proportional to the current intensity which flows through it, and the inverse versa for the photo-detector. The optical receiver performs the optical-to-electrical conversion of the light signal. It comprises a photo-detector and a trans-impedance amplifier (TIA). The receiver converts small photocurrents into the CMOS-level voltages and must trade-off energy consumption, performance and SNR against each other.

The optical Transmitter/Receiver module was electrically contacted to the NoC. The Transmitter module has a 850-nm VCSEL, and the Receiver module is performed by a PIN photo-detector.

The advantage of VCSEL compared to other laser devices is a high-modulation bandwidth at low current intensity, so it has low power consumption. It can also provide high efficiency at low output power (mW), high reliability and a high temperature operational range. The VCSEL device has the ability to be directly modulated at signal rate of 15 Gb/s and the optical power dissipation had three major contributors: optical receiver, VCSEL and the routing [22].

For the hybrid optical NoC, the communications power consumption $E_{\text{pkt}}$ of each packet is calculated by Equation (6).

$$E_{\text{pkt}} = E_{\text{payload}} + E_{\text{ctrl}}$$

$E_{\text{payload}}$ is the energy consumed to transmit the payload data. $E_{\text{ctrl}}$ is the energy consumed by the associated control packets. An analysis of a typical wireless optical network on-chip is presented, so that $E_{\text{payload}}$ is calculated by Equation (7).

$$E_{\text{payload}} = t_{\text{on}}E_{\text{mr}}L_{\text{payload}} + E_{\text{oe-co}}L_{\text{payload}}$$

$E_{\text{rise}}$ is the average energy consumed by a MR when it is in the on-state whose value is about $5.10^{-4}$ pJ/b [23]. $L_{\text{payload}}$ is the payload packet size. $E_{\text{oe-co}}$ is the energy consumed for 1-bit O/E and E/O conversions, which mainly come from VCSEL driver, VCSEL diode, photo-detector, trans-impedance amplifiers/limiting amplifiers (TIA-LA) circuits, and serializer/deserializer [24]. The power consumption of the VCSEL driver and TIA-LA circuits is 0.82 pJ/b in 80-nm CMOS [25]. The power consumption of the serializer and deserializer is 0.576 pJ/b in 90-nm CMOS [26].

$E_{\text{ctrl}}$ is calculated from Equation (3) by introducing more details about the interconnection (Equation (8)):

$$E_{\text{ctrl}} = (E_{\text{router}} + E_{\text{local_interconnect}}) L_{\text{ctrl}} + E_{\text{global_interconnect}} h L_{\text{ctrl}}$$

$E_{\text{router}}$ is the average energy required to transfer a single bit through a router, it represents the main energy cost when the packets are stored and processed whose value is about 0.87 pJ/b. $E_{\text{local_interconnect}}$ is the average energy required to transfer a single bit through a metallic interconnect between a core and a router. $L_{\text{ctrl}}$ is the packet control size in the electronic NoC. $E_{\text{global_interconnect}}$ is the average energy required to transfer a single bit through a metallic interconnect between routers. Both local and global interconnect energies correspond to wire energy $E_{\text{wire}}$ presented in previous section. $L_{\text{ctrl}}$ is the control packet size, and $h$ is the number of hops.

### 2.4 Noise effects

#### 2.4.1 Wire link noise

In our previous article [27], we discussed the noise effect in classic NoC extracting the BER of wires interconnect and concluded that energy consumption arising when increasing noise. The main reason of this degradation is because of the strong inductive coupling exists between wires. Let us remember that the bus is considered as an analytical RLCG transmission line which takes into account crosstalk noise between wires. Crosstalk noise on-chip primarily comes from capacitive coupling of nearby signals (Figure 3). The crosstalk coupling coefficient $K_C = \frac{C_C}{C_C + C_B}$ is derived from the ratio between coupling capacitance $C_C$ and wire load capacitance $C_B$ [18].

In the case of coupled wires, driven with an output impedance $R$, the transient on victim wire caused by an aggressor will decay with a time constant, $\tau = R(C_C + C_B)$ as shown in Figure 3. In the literature, the capacity of an air capacitor is increased when the distance between its armatures decreases. Integrated circuits do not stop integrating more IPs, without increasing the surface of the silicon, which leads to a decrease in the distance between IPs and especially the distance
between the bus wires to provide enough coupling effect, therefore the coupling capacitor \( C_C \) and \( K_C \) coefficient will increase accordingly. The BER of the wire interconnect is the probability that the noise amplitude exceeds a logic threshold, given by Equation (9) [28].

\[
BER = \int_{-\infty}^{\infty} p(\nu) d\nu
\]  

(9)

where \( p(\nu) = \frac{1}{\sigma_N \sqrt{2\pi}} e^{-\frac{\nu^2}{2\sigma_N^2}} \), \( \nu_N \) is noise voltage which has a normal distribution with a variance of \( \sigma_N^2 \), given by the Gaussian probability density function (\( \sigma_N = 0.2 \)).

### 2.4.2 | Optical link noise

Optical signal-to-noise ratio is used to quantify the degree of optical noise interference on optical signals. In binary optical communication systems, there are two signals levels, each of them may have an error probability associated with \( \{p_0, p_1\} \), therefore a signal-to-noise ratio for each. To calculate the overall probability of bit error, both \( p_0 \) and \( p_1 \) are taken into account. The two SNRs associated with high and low levels into the overall system SNR can be combined into a single quantity called the Q-factor to provide a convenient measure of overall system quality.

\[
Q = \frac{\eta_e}{\sqrt{IRIN}}
\]  

(10)

where \( IRIN = \int_{0}^{\Delta\nu} RIN(\nu) d\nu \)

where \( IRIN \) is the spectral relative intensity noise (RIN) over the system bandwidth \( \Delta\nu \). \( \eta_e \) represents the extinction efficiency of the optical signal.

Q-factor indirectly reflects the BER and can provide a warning of potential BER deterioration. The BER is expressed as a function of Q-factor through Equation (11).

\[
BER \approx \frac{1}{\sqrt{2\pi Q}} \exp\left\{ -\frac{Q^2}{2} \right\} \left( 1 - \frac{1}{Q^2} \right)
\]  

(11)

For \( Q \gg 1 \) we can get a relationship between the BER and the intensity noise (Equation (12)):

\[
BER \approx \frac{1}{\eta_e} \sqrt{\frac{IRIN}{2\pi}} \exp\left\{ -\frac{\eta_e^2}{2IRIN} \right\}
\]  

(12)

### 3 | NUMERICAL RESULTS OF PERFORMANCES

The interconnect line is a metal wire with a length of 10 mm, modelled by a distributed RC model with an extra capacitive load \( C_L \) distributed along the wire, as shown in Figure 1. In our simulation, \( C_L \) is set at 1 pF and \( V_{DD} \) is set at 2 V.

From Equation (5), we plot the power consumption, while the frequency is swept from 100 MHz to 1 GHz depending on switching activity \( \alpha \). The simulation results of power consumption are shown in Figure 4, with different slopes for different \( \alpha \).
It can be observed that the power consumed by interconnections increases considerably with the switching activity and frequency. To estimate the power consumption, one has to calculate the switching activity factors of NoC interconnect. This phenomenon can be worse due to the known Lentz effect ($\frac{Ldi}{dt}$) explained in [27], which is caused by the inductive properties of currents flowing through the on-chip power grid. Thus, the payload information may change its logic state and generate errors. Basically, NoC traffic flows are unevenly distributed across the network. So, if the overall NoC components have to operate at the same frequency, it obviously will cause excess power consumption for the slower flow [6].

Energy consumption is a critical aspect of NoC design. In order to improve the efficiency the performance in NoC, the
TABLE 1 Energy parameters [19, 20, 22, 23]

| Parameters | Values (pJ/bit) |
|------------|----------------|
| \(E_g\) router energy in classical NoC | 6.87 |
| \(E_{local/globalinterconnect}\) energy wire | 11.6 |
| \(E_{net}\) energy consumed by an MR | \(5.10^{-4}\) |
| \(E_{source}\) (optic/electric) (electric/optic) | 0.82 |
| Converter energy consumption | \(0.576\) |
| \(E_{serializer/deserializer}\) serializer/deserializer energy consumption | \(0.87\) |
| \(E_{router}\) router energy in optical NoC | \(0.87\) |

FIGURE 6 Crosstalk versus different values of distance inter-wires

packets are split into flits for the allocation of channel bandwidth. Flits are divided into header flit which consists of routing information, body and tail flits. The total energy consumed to transmit a packet given by Equation (3) is depicted in Figure 5a,b, respectively, for electronic and optical NoC depending on packet length for different number of hops. For high-performance NoC, low energy consumption can reduce the cost related with packaging, and system integration. The packets in our simulation consist of N-flits with 40 bits width. \(N\) is an integer. The system parameters used in this simulation are tabulated in Table 1.

Simulations and analysis results in Figure 5a,b show that the energy dissipation on the global interconnect to transmit a flit increases with the flit size and hops number. To achieve lower energy consumption, it is necessary to use less number of hops for communications and shorter flits sizes. Simulation results predict energy savings, for example in Figure 5a, while the NoC interconnects consumes almost 3.2 pJ/bit to transmit 256-bit flits through 64 hops only consumes 1.5 pJ/bit, for 32 hops which is 46% lower. Figure 5b shows the comparison of optical energy consumption per bit of a packet ONoC, from which it consumes the least energy. It can be estimated that as the size of the networks becomes larger, the average number of hops in ONoC becomes more obvious, which explains why the energy performance per bit will become less sensitive to the number of hops. When data packets are transferred to different receivers or to the same receiver via different routes in the network, a multi-hop point-to-point connection scheme packet switched network is applies, the packet transfer latency will vary largely and energy arise considerably as shown in Figure 5a,b. This result may encourage us to propose NoC using CDMA or OCDMA technique on-chip, for the main reason that the network node of the CDMA NoC does not need to handle any packet routing issues because of its one-hop data transfer scheme. Overall, the energy consumed by a conventional NoC in some cases is higher than that consumed by an optical NoC. For example, for packet of 2000 bits and 8 hops, the energy consumed by an electronic NoC interconnects is \(2.227 \times 10^{-7}\) J,
however it about $7.003 \times 10^{-9}$ J in optical NoC. The topology of an on-chip network considering the CDMA access technique can reduce the energy consumption since the omission of the routing part. Indeed, the on-chip CDMA with one hop size, reduces the energy consumption to the minimum compared to topologies such as mesh ones. Moreover, the optical links based
on micro-ring resonators provide minimized energy efficiencies at given throughput communications, while VCSELs provide few dozen of mW output power from small-area chips, which consumes less power by wire links in classic NoC. In [1], we showed that an optical link under electronics circuitry can provide less 1 Tbps/s, which is in agreement with our survey. That indicates encouraging results to overcome challenges such as optical links energy consumption for a given throughput, which makes optical NoC a promising alternative for electronics ones.

In Figure 6 we consider two 5-mm-length on-chip coupled lines with frequency-dependent which equivalent circuit scheme is given by Figure 3.

From the Figure 6, one can note that the crosstalk coupling values increase almost linearly when distances inter-wires decrease. Crosstalk coupling effects can induce large voltage fault on victim wires which causes transient errors. The increase in the coupling capacitor $C_C$ values can cause spatial burst errors, which occur at a bus interconnect. The main part of the power in CMOS circuits is consumed during charging and discharging of the load capacitance.

As expressed in Equation (11), the BER depend on Q-Factor which allows simplified analysis of system performance. The Q-factor is useful as an intuitive figure of merit that is directly tied to the BER as depicted in Figure 7. These results are simulated for an optical link composed of a VCSEL diode modulated directly by a pseudorandom bit sequence coded by the Non-Return to Zero (NRZ) format, because of its simplicity for this application, a free optical space lossy link, and a PIN photo-detector, since they are the main factors of optical-NoC noise effects. The typical system parameters used in this simulation are tabulated in Table 2.

Figure 7 illustrates the relation between the BER and the Q factor that has been simulated using parameters in Table 1. The higher the Q factor, the lower the BER values, consequently, the better the performance. The BER can be improved by either increasing the difference between the high and low levels in the numerator of the Q-factor or decreasing the noise terms in the denominator of the Q-factor.

### 4 CONCLUSIONS

The various challenges faced by researchers in systems-on-a-chip design have given rise to new trends paving the way for optical network-on-chips. In this article, the NoC performance metrics problem was formulated as to theoretically investigate the overall network performance such as latency, energy consumption, and noise effects over classical and optical NoCs. Besides high latency penalty, the classic NoC also introduces a crosstalk coupling coefficient which increases the whole NoC energy dissipated and the probability of errors, rendering the optical NoC as suitable for power budgeting in future NoC. Indeed, the optical link exhibits excellent robustness properties with regard to noise behaviour. The given analysis provides some keys for optimizing NoC performance. We can conclude that the optical NoC shows good results in terms of latency, energy consumption and the BER with regard to the electronic NoC.

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How to cite this article: Balti M, JEMAI A.
Performance survey of classic and Optic network-on-chip. IET Circuits Devices Syst. 2021;15:393–402.
https://doi.org/10.1049/cds.12025