

Design Technology for Fault-Free and Maximally-Parallel Wavelength-Routed Optical Networks-on-Chip

Andrea Peano
University of Ferrara - Via
Saragat 1, 44121 Ferrara, Italy
andrea.peano@unife.it

Luca Ramini
University of Ferrara - Via
Saragat 1, 44121 Ferrara, Italy
luca.ramini@unife.it

Marco Gavanelli
University of Ferrara - Via
Saragat 1, 44121 Ferrara, Italy
marco.gavanelli@unife.it

Maddalena Nonato
University of Ferrara - Via
Saragat 1, 44121 Ferrara, Italy
maddalena.nonato@unife.it

Davide Bertozzi
University of Ferrara - Via
Saragat 1, 44121 Ferrara, Italy
davide.bertozzi@unife.it

ABSTRACT

The recent interest in emerging interconnect technologies is bringing the issue of a proper EDA support for them to the forefront, so to tackle the design complexity. A relevant case study is provided by wavelength-routed optical NoCs (WRONoCs), which add communication performance guarantees to the typical latency, throughput and power benefits of an optical link, thus providing an appealing technology for the photonic integration of high-end embedded systems. Typically, only abstract WRONoC models are considered to figure out architecture-level performance, and logic connectivity patterns for the quantification of the required signal strength (i.e., static power). However, this design practice overlooks the needed refinement step, where key physical parameters are assigned such as wavelengths of the optical channels, and size of the optical filters. This step is unfortunately not decoupled from the architectural evaluation, since its main constraint (i.e., avoiding routing faults) turns out to be a key limiter for both the network scale and the achievable communication parallelism. By proposing a formal methodology to select WRONoC parameters while avoiding the routing fault concern, this paper aims at maximizing the levels of connectivity and/or of bit parallelism that WRONoCs can achieve, while relating their upper bounds to the uncertainty of the manufacturing process.

Categories and Subject Descriptors

B.8.2 [PERFORMANCE AND RELIABILITY]: Performance Analysis and Design Aids; G.1.6 [NUMERICAL ANALYSIS]: Optimization—*Constrained optimization*

Keywords

WRONoC, Parallelism, Answer Set Programming

Permission to make digital or hard copies of all or part of this work for personal or classroom use is granted without fee provided that copies are not made or distributed for profit or commercial advantage and that copies bear this notice and the full citation on the first page. Copyrights for components of this work owned by others than ACM must be honored. Abstracting with credit is permitted. To copy otherwise, or republish, to post on servers or to redistribute to lists, requires prior specific permission and/or a fee. Request permissions from permissions@acm.org.

ICCAD '16, November 07-10, 2016, Austin, TX, USA

© 2016 ACM. ISBN 978-1-4503-4466-1/16/11...\$15.00

DOI: <http://dx.doi.org/10.1145/2966986.2967023>

1. INTRODUCTION

Networks-on-chip (NoCs) are today the mainstream communication architecture for all large-scale systems-on-chip (SoCs) in 45nm and below [5]. However, the uptake of the networking paradigm for on-chip communication started only when proper EDA support enabled to tackle the complexity challenge. This resulted in tools and methodologies that enabled design, verification and test of NoCs across multiple levels of abstraction and complexity [1]. After a decade of research, NoC toolflows became capable of automatically transforming a high-level functional description of a NoC into a detailed geometric description [18].

Today, methodologies and tools for designing chip-level communication architectures are again on the rise. The reason is that industry is urgently exploring beyond-silicon and beyond-CMOS device, interconnect and memory options, as well as heterogeneous, "More-than-Moore" integration and packaging technologies, in order to maintain Moore's-Law scaling of integration value. In particular, silicon photonics stands out as the most promising technology to overcome the limitations of electronic interconnects as the system scale increases. The intrinsic capability of light to transport information over large distances at very high data rates and low latency, with minor dynamic power dissipation, holds promise for scalable and power-efficient optical networks-on-chip (ONoCs) to interconnect future many-core system architectures. A relentless research effort is currently underway to improve the maturity of CMOS-compatible silicon photonic technology, especially to cut down on its significant static power overhead.

However, awareness of the historical trend followed by electronic NoCs leads to think that the industrial uptake of ONoCs will be not only an issue of technology maturity. In fact, this will also coincide with a turning point for the Electronic Design Automation (EDA) field, since designing with emerging interconnect technologies calls for (radically?) different abstractions, algorithms, methodologies, and tools drawing from the interdisciplinary work of chemists, device physicists, electrical engineers, computer scientists, applied mathematicians, operations researchers, and optimization experts [8].

A number of ONoC design issues is currently increasing the need for EDA support. On the one hand, the development of automatic synthesis approaches of optical circuits

is still in the early stage, since they need to build on top of the specific basic primitives of the target emerging technology [4]. On the other hand, EDA support is required by the refinement step of abstract ONoC models into their actual implementations, which calls for effective solving strategies for the novel optimization problems that arise [21].

This paper tackles one such novel design challenges that are emerging in the context of the latter category, and which has to do with the refinement step of wavelength-routed optical NoCs (WRONoCs). Among the plethora of proposed protocols for optical on-chip communication, wavelength routing has unique characteristics, since it can deliver contention-free all-to-all connectivity. The key principle consists of allocating a reserved wavelength channel to each initiator-target pair, which selects a deterministic routing path across the network. Since optical technology supports the concurrent propagation of multiple optical channels, tuned to different wavelengths, on the same waveguide (named wavelength division multiplexing, WDM), wavelength routing does not require any form of arbitration nor path selection. The predictable and guaranteed communication performance of WRONoCs comes at the cost of static power overhead, due to the use of multiple laser sources.

WRONoCs currently deal with an unsolved design concern: the selection of their wavelength channels and of the optical filters that build up their optical paths. This is typically and incorrectly viewed as a further refinement step during the implementation flow, since the existence of the above parameters is just taken for granted during the architectural evaluation, which simply assumes the contention-free delivery of optical packets to their destination. Topologies are then differentiated based on their loss of optical power.

Unfortunately, the refinement step which selects the actual network parameters cannot be decoupled from WRONoC performance evaluation for two reasons. On the one hand, parameters of wavelength channels and of the filters that selectively route them to destination should be chosen in such a way that routing faults are avoided. *This constraint limits the level of connectivity that can be achieved, which means that large-scale topologies may turn out not to be feasible under the routing fault-free condition.* On the other hand, even when the connectivity of the target number of nodes is feasible, *the routing fault concern limits the achievable level of communication parallelism. Overall, without proper emphasis on the topology refinement step, system designers may consider WRONoC configurations for their architecture that later turn out to be practically infeasible, in terms of levels of connectivity and/or parallelism.*

Last but not least, WRONoC topology refinement is the first design step where the parameters of the manufacturing process at hand become visible. In fact, a high level of uncertainty in that process forces the designer to conservative design choices to meet the routing fault freedom constraint, which penalizes the quality metrics to a significant extent.

To our knowledge, this paper for the first time proposes a formal methodology to select WRONoC physical parameters while maximizing communication parallelism for a specific level of network connectivity. The paper aims at capturing the dependencies between the characteristics of the manufacturing process and the achievable WRONoC performance, hence resulting in design curves that bridge the gap between the system level designer and the technology provider.

2. RELATED WORK

Among communication protocols, wavelength routing eliminates the need for electrical resource reservation, and the corresponding latency and area overhead. A number of wavelength-routed topologies has been proposed so far. While they all deliver the same performance (contention-free all-to-all connectivity), they have different connectivity patterns, which leads to different physical properties, such as kinds of micro-ring resonators, and optical power losses.

The λ -router [3] resembles multi-stage interconnection networks due to the cascaded stage organization. The GWOR topology [20] is built around a basic and symmetric 4x4 routing fabric, with precise generalization rules. The snake topology [16] exhibits a circuitous pattern inspired by pipes. The topology presented in [2] consists of a wavelength-routed optical ring. Finally, a hierarchical topology featuring regularity, vertex symmetry, and constant node degree is presented in [9].

Wavelength routing has been compared with other methods in terms of performance and power. For 16-node systems, the static power overhead associated with the use of multiple laser sources is still lower than or comparable with the overhead for implementing optical arbitration [17]. For larger system sizes, the static power overhead is the price to pay for performance predictability.

To our knowledge, the refinement step that selects the physical parameters of the above topologies has never been addressed before. Such parameters are typically kept as generic in high-level evaluations (e.g., wavelength channels λ_i , optical filters tuned to λ_i), thus taking for granted that wavelengths in the band 1500-1600nm and the associated micro-ring resonators in the typical range $5 \div 20\mu\text{m}$ exist, and combined together yield topologies that do not incur the routing fault concern presented later. As we prove in this paper, this assumption is not always justified, thus motivating this work, that lowers the abstraction layer for WRONoC design. Wavelength routing design has been brought to this stage only in the context of generic fiber-based optical networks connecting large regions, where the routing and the wavelength assignment problem has been stated, but in completely different terms due to the different target environment [13]. For instance, in that domain wavelength conversion is an affordable option, unlike an on-chip environment.

3. BACKGROUND AND MOTIVATION

3.1 Wavelength-Selective Routing

Wavelength-routed optical NoCs (WRONoCs) rely on the principle of wavelength-selective routing, which associates a wavelength channel to each source-destination pair. In particular, master $M1$ uses n wavelengths λ_1 to λ_n to reach slaves $S1$ to S_n , respectively. However, instead of allocating an additional set of wavelengths for the communications of master $M2$ to all the slaves, the initial set of n wavelengths is reused across masters. This wavelength reuse requirement gives rise to two design constraints for WRONoC topologies, which are engineered to make such reuse feasible:

- Optical channels originating from different masters and tuned to the same carrier wavelength should never overlap in WRONoC waveguides.
- Each slave should receive wavelength channels from

different masters on different carrier wavelengths, in order to avoid any signal conflict at the receiver side.

Overall, wavelength-selective routing ends up delivering contention-free all-to-all connectivity, since signal contention for resources is avoided at design time rather than solved at run time. Therefore, no arbitration of ONoC resources is needed.

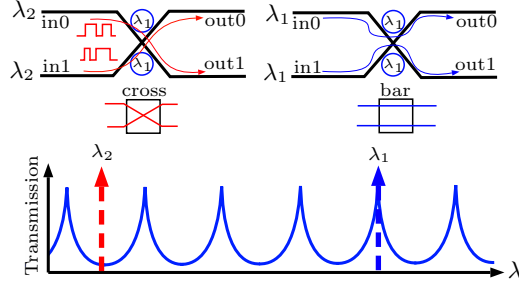


Figure 1: (Top) Optical input signals that are off- vs. on-resonance with the MRRs of an add-drop filter. (Bottom) Transmission characteristic of an MRR.

3.2 Filtering of Wavelength Channels

The building blocks of the most common WRONoC topologies consist of add-drop filters (ADFs). They add or remove narrow-band wavelengths of light from a broader optical signal being carried along a bus waveguide. They use micro-ring resonators (MRR) for this purpose, as illustrated in Fig.1. Essentially, when the input optical signal is on-resonance with the MRR, the signal is deflected (bar function), otherwise it keeps propagating unaffected (cross function). The resonance effect can be achieved by a proper sizing of the MRR radius. In fact, an MRR acts as a wavelength selecting filter with a periodic transmission characteristic, as pictorially illustrated at the bottom of Fig.1. One important parameter is the distance between resonance peaks, which is called the free spectral range (FSR), and gives information about the periodicity of the spectrum. The FSR depends on the ring radius: larger rings have denser peaks, while smaller rings have peaks that are far apart from one another. In order to carry out the bar and cross functions with λ_1 and λ_2 , respectively, we need λ_1 to be on-resonance with the MRRs, and λ_2 to be off-resonance.

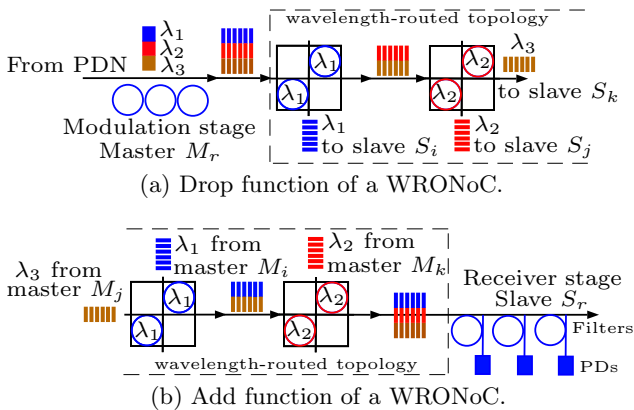


Figure 2: Logical tasks performed by a WRONoC.

3.3 Wavelength Routing Operation

The wavelength-selective routing function fulfilled by each WRONoC can be logically viewed as consisting of two sub-functions:

- **Drop function** (Fig.2a). Each master receives from the power distribution network (PDN) a wavelength-division multiplexed (WDM) optical signal consisting of multiple carriers with wavelengths λ_1 to λ_n . Each carrier is modulated and delivered to the network for routing to a specific and distinct slave. Then, the first task the network should perform consists of resolving the individual wavelength-channels from the multiplexed compound signal, so that each resolved component can be routed to a different destination. In practical terms, this task can be accomplished by using add/drop optical filters, which are tuned to a specific wavelength, and therefore split the associated optical channel from the compound signal.
- **Add function** (Fig.2b). Resolved wavelength channels from the different masters and heading to the same slave should be recombined together into a WDM optical signal propagating onto the output waveguide of that slave. This way, a selective filtering stage can eject the desired wavelength channel and feed it to a photodetector (PD) stage. In practice, this task can be accomplished by using different inputs of add/drop optical filters.

In a WRONoC topology, the add and drop functions are tightly intertwined: as the WDM input signal from a given master propagates down the topology, its wavelength channels are progressively and selectively resolved and coupled with channels tuned on different wavelengths and originating from different masters. This process is illustrated in Figure 3 for the λ -router WRONoC topology case study [14].

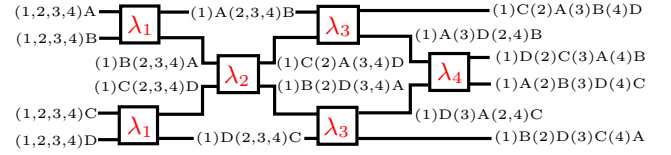


Figure 3: The tightly-intertwined add and drop functions at work in a λ -router WRONoC topology. Numbers refer to wavelength identifiers (IDs), while letters refer to master/slave IDs. Therefore, (1,2)A refers to wavelength channels λ_1 and λ_2 originating from initiator A.

3.4 WRONoC Refinement

A WRONoC topology is ultimately specified by two key design parameters:

- a) the number of wavelength channels used by each initiator;
 - b) the number and kind of add-drop filters in the topology;
- In order to understand the relation between these parameters, let us provide an abstract representation for a generic WRONoC topology.

The topology can be viewed as the combination of basic primitives, which are 1x2 selective filter operators (SFOs), with one input and two outputs. This operator selectively ejects a predefined wavelength channel from one of its outputs, while forwarding the other channels to the other output. In a WRONoC topology, the WDM input signal from

any master undergoes the drop function by going through $n - 1$ SFOs, when assuming the connectivity of n masters with n slaves. This process is pictorially illustrated in a *wavelength resolution graph (WRG)*, reported in Fig.4a for a generic 4x4 WRONoC topology. On each row, properly tuned SFOs eject wavelength channels $\lambda_x, \lambda_y, \lambda_z, \lambda_t$ from the bundle, thus prompting them for the next add phase. The resolution pattern may differ in each row, as illustrated in the figure, therefore the drop order of wavelength channels for master A can be different from that of master B , and so on.

The final topology needs to map the SFOs to real devices. All WRONoC topologies reported in the open literature so far make use of the 2x2 add-drop filters (ADFs) previously illustrated in Fig.1. Therefore, technology mapping implies the pairwise grouping of the 1x2 SFOs into compact 2x2 ADFs. The grouping presented in Fig.4b, completed by the assignment step of the exact ADF resonant wavelengths (Fig.4c), gives rise to the λ -router WRONoC topology of Fig.3. While wavelength assignment can be made based on different criteria, the only (obvious) requirement is that each component of the input WDM signal is filtered only once on each row. Further details on this synthesis process are reported in [19], which proves that by varying the technology mapping and performing a legal wavelength assignment onto it, each WRONoC design point can be materialized.

Overall, the synthesis of an $n \times n$ WRONoC topology requires: a) a number of wavelength channels which is equal to the number of targets n . Each initiator uses a different wavelength channel to reach each target. b) several kinds of ADFs, each tuned to a different resonant wavelength, depending on the wavelength assignment step in Fig.4c.

For what this paper is concerned, it is worth recalling that although the steps in Fig.4b and Fig.4c enable to differentiate a topology with respect to all other ones, the exact value of the wavelength channels λ_i and the exact size and resonant wavelengths of the MRRs inside the ADFs are still specified as symbols, and left unspecified. This is the level of abstraction which is typically used in the literature for WRONoC evaluation, and this is the starting point of this paper.

As a result, this paper moves from the assumption that the topology connectivity pattern has been specified by the system designer, and addresses the further refinement step which is needed for the complete definition of the topology. Therefore, the paper searches for:

a) the exact value of the n wavelengths used by each initiator, which are typically chosen in the frequency band 1500nm-1600nm.

b) the exact radius length of the MRRs inside ADFs, determining the FSR and the periodic resonant wavelengths characteristics.

3.5 The Routing Fault Concern

The two design decisions above are tightly interrelated. In fact, a wavelength channel must be positioned in the frequency band of interest so to be a resonant wavelength of one kind of ADFs, the one that drops (adds) that channel from (to) the input (output) WDM signal. This is pictorially illustrated in Fig.5(a) by means of an example, together with a possible inconvenient. Without lack of generality, wavelength channel λ_2 is placed on one peak of the transmission characteristic of the larger MRR with radius R_2 , while a

smaller MRR with radius R_1 is selected for tuning on the λ_1 channel. The two MRRs have different FSRs, since they depend on the MRR's radius length. Therefore, two resonant peaks from the two MRRs might overlap, as illustrated in the figure. As a consequence, if λ_1 were chosen to coincide with the overlapped peaks, a **routing fault** would occur in the network: *channel λ_1 would incorrectly perform the bar function when entering an ADF tuned to λ_2 , instead of the correct cross function.* While the problem can be easily solved in the example of Fig.5(a) by selecting another resonant wavelength of the small MRR, it can become a serious concern when increasing the network size. In fact, the proliferation of ADFs and of wavelength channels may limit the availability of non-overlapped transmission peaks, which causes the topology to be practically infeasible.

Even for a fixed network size, the routing fault concern turns out to be a fundamental limiter for communication parallelism. In fact, the examples seen so far assume that each initiator sends one bit at a time to each target on a specific wavelength channel. In fact, optical interconnect technology requires serialization of bit-parallel electronic words, which is only partially compensated by the high transmission rates of at least 10 Gbit/s. Communication parallelism could be increased by allocating multiple wavelength channels to each I/O connection, provided that they are allocated to the resonant peaks of the same ADF, in order to properly perform the add and drop functions. Fig.5(b) extends the routing fault concern to a higher communication parallelism. In the figure, the 6 (7) resonances of R_1 (R_2) are shown, however at most 4 bits of parallelism can be guaranteed. Denote by $\Lambda_r = \{\lambda_{r,j}\}$ the resonances of the MRR with radius length R_r (we will also use $\lambda_{r,j}$ for brevity). Since $\lambda_{1,2}$ conflicts with $\lambda_{2,2}$ and $\lambda_{1,6}$ conflicts with $\lambda_{2,7}$, routing fault prevention impedes selecting any of these four; now at most 4 (5) peaks in R_1 (R_2) can be used at the same time. In this case, the minimum parallelism that can be sustained by both wavelength channels is 4.

The above problems are further exacerbated by the uncertainties of both the manufacturing process and of the device parameters (see section 3.6), which cause even resonant peaks that are just close enough not to be available for the routing of any wavelength channel.

This paper tackles the problem of selecting both ADF sizes and wavelength channels in such a way that the connectivity is guaranteed (i.e., all wavelength channels are placed in non-overlapped peaks) and the communication parallelism is maximized, while avoiding routing faults.

The approach proposed hereby is not topology-specific, in the sense that it holds for any generic WRONoC topology.

3.6 The Role of Parameter Uncertainty

This section addresses the effect of two important parameter uncertainties that can not be ignored when designing WRONoCs for routing fault avoidance; this way, we try to capture the fundamental dependency of architecture performance on the manufacturing process.

The first uncertainty is due to the MRRs' fabrication process. Depending on the lithography, up to 10 nm of variation is expected for MRRs using rib-waveguides that underwent a full CMOS process flow [10], i.e., given the tolerance $R_{tol} = 10\text{nm}$ and the nominal radius R_r , the manufactured MRR will be between $R_r^- = R_r - R_{tol}$ and $R_r^+ = R_r + R_{tol}$; R_{tol} identifies the maximum gap between the nominal value

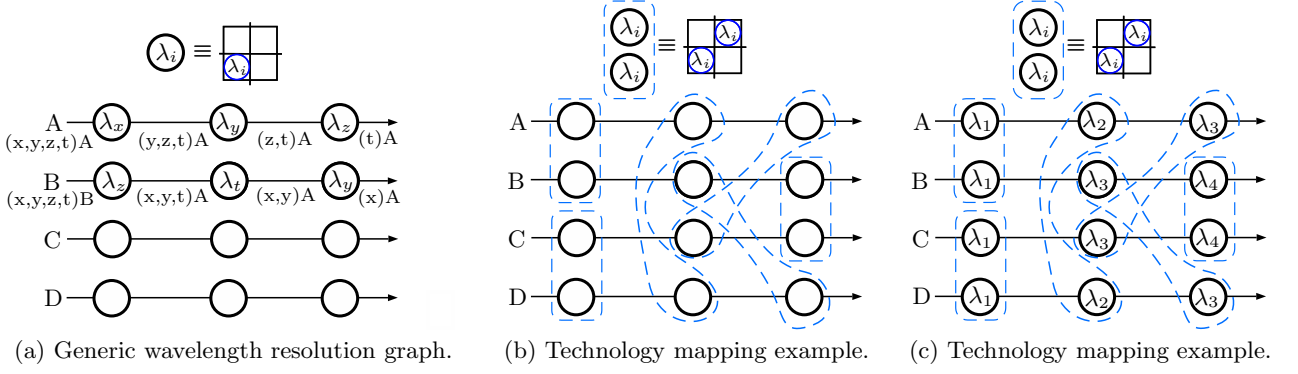


Figure 4: Three-step synthesis methodology of a WRONoC topology.

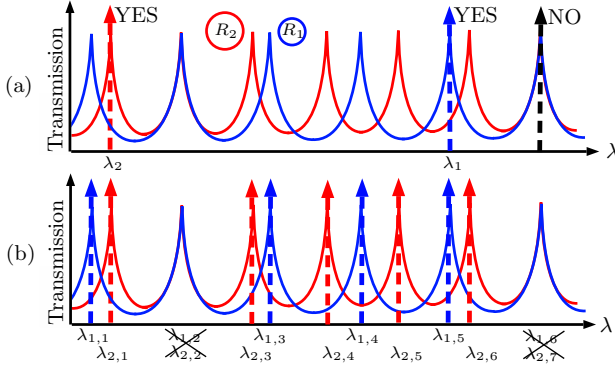


Figure 5: The routing fault concern: (a) constraining wavelength channel selection; (b) limiting parallelism.

at design time and the actual one. The transmission response of the manufactured MRR will vary according to its actual radius. Figure 6 shows the optical spectra for R_1 and its maximum variations, say Λ_1^- , Λ_1 , and Λ_1^+ ; in particular, the most noticeable effect is that the resonances are shifted from the nominal ones to the left (right) for a negative (positive) radius variation. The greatest peak-to-peak

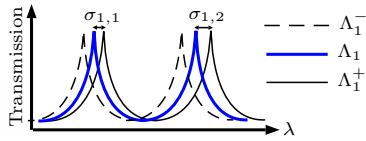


Figure 6: Relation between R_{tol} and σ for a radius R_1 .

distance (nm) between the nominal $\lambda_{1,j}$ and its variations is $\sigma_{1,j}$. Since a small radius variation slightly affects the FSR in general $\sigma_{r,j} \neq \sigma_{r,h}$ for $j \neq h$ ($\sigma_{1,1} \neq \sigma_{1,2}$ in the figure). To translate the variation R_{tol} into the many $\sigma_{r,j}$ we developed a two-step procedure: i) an Electromagnetic Model [15] (EM) computes the three transmission responses Λ_r^- , Λ_r , Λ_r^+ , then ii) the responses are passed to a synthesizer that processes them and returns the σ values. This process is shown within the block I of Figure 7.

The other uncertainty is due to the variation of the central operating wavelength of the laser, caused by variation in temperature and driving current; we set this value to $\Delta\lambda =$

0.5nm^1 . Since laser selectivity is independent from radius variation, $\Delta\lambda$ is considered in addition to σ and accordingly this quantity is processed in the block I of Figure 7.

Given R_1 , R_2 , R_{tol} , and $\Delta\lambda$, the resonances $\lambda_{1,j}$ and $\lambda_{2,h}$ may vary within the intervals

$$I_{1,j} = [\lambda_{1,j} - \sigma_{1,j} - \Delta\lambda, \lambda_{1,j} + \sigma_{1,j} + \Delta\lambda]$$

$$I_{2,h} = [\lambda_{2,h} - \sigma_{2,h} - \Delta\lambda, \lambda_{2,h} + \sigma_{2,h} + \Delta\lambda]$$

In the most conservative hypothesis, $\lambda_{1,j}$ and $\lambda_{2,h}$ should never conflict, i.e., $I_{1,j} \cap I_{2,h} = \emptyset$. Obviously, the larger the intervals, the higher the chance of overlapping, and the lower the number of available off-resonances for other radius values, to the detriment of potential parallelism.

R_{tol} and $\Delta\lambda$ mainly depend on the fabrication technology and the laser selectivity. Section 5 shows how technology improvements can enhance WRONoCs scalability and communication parallelism.

4. PROBLEM FORMULATION

All topologies appear in the form of Figure 4c from which the relevant inputs to our optimization problems can be derived, i.e., the network size $n \times n$ and the number s of ADF types. Notice that the ADF types differ on the MRR's radius length and each ADF can be instantiated multiple times in the topology. The problem is to compute for each ADF type the radius length and its subset of resonances so that the communication parallelism is maximized under the most conservative assumption, i.e., the selected wavelengths never overlap, whatever is the variation scenario.

The choice of the s radius lengths and their wavelength channels is made from a lookup table $\mathcal{T}_{\mathcal{R}}$ where the r -th row contains the resonances $\lambda_{r,j}$ of radius R_r . The radius values are given by the discrete set

$$\mathcal{R} = \{R_{\min} + r * R_{\text{step}}, \forall r \in [0, \dots, \frac{R_{\max} - R_{\min}}{R_{\text{step}}}] \}$$

where the *fabrication options* $R_{\text{opt}} = \{R_{\min}, R_{\text{step}}, R_{\max}\}$ are the minimum radius length, the incremental step, and the maximum radius length, respectively. The resonances and their variations are computed as in block I in Figure 7. Table 1 is built with $R_{\text{opt}} = \{5, 1, 8\}\mu\text{m}$ and reports the σ values along with the resonances, with $R_{tol} = 0.01\mu\text{m}$. $R_{\text{opt}} = \{5, 1, 25\}$ yields 21 rows and about 290 resonances.

¹thorlabs.com/thorcat/21000/SFL1550S-Manual.pdf, p.7

Table 1: $\mathcal{T}_{\mathcal{R}}$ with $R_{\text{opt}} = \{5, 1, 8\} \mu\text{m}$, $R_{\text{tol}} = 0.01 \mu\text{m}$, and $\Delta\lambda = 0.5 \text{ nm}$

r	$R_r [\mu\text{m}]$	$ \{\lambda_{r,j}\} $	$\lambda_{i,1}\langle\sigma_{i,1} + \Delta\lambda\rangle,$	$\lambda_{i,2}\langle\sigma_{i,2} + \Delta\lambda\rangle,$	\dots	[nm]
1	5	5	1496.4(3.5),	1521.3(3.6),	1547.1(3.6), 1573.8(3.6), 1601.4(3.6)	
2	6	6	1500.5(3.0),	1521.3(3.0),	1542.7(3.1), 1564.8(3.1), 1587.5(3.3), 1610.8(3.3)	
3	7	6	1503.4(2.6),	1521.3(2.6),	1539.6(2.7), 1558.4(2.7), 1577.7(2.7), 1597.4(2.8)	
4	8	7	1505.6(2.2),	1521.3(2.2),	1537.3(2.2), 1553.7(2.2), 1570.4(2.0), 1587.5(2.0), 1604.9(2.0)	

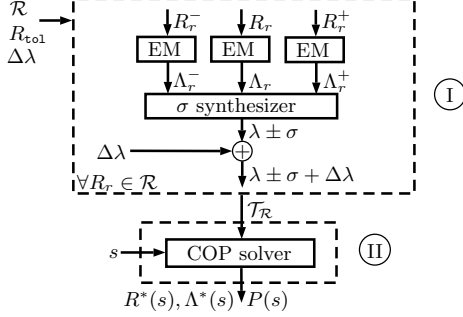


Figure 7: Solving architecture

$R_{\text{opt}} = \{5, 0.25, 30\}$ yields 104 rows and about 1850 resonances (28 in the longest row).

Once $\mathcal{T}_{\mathcal{R}}$ is computed, the optimal sets of radius lengths R^* and of wavelength channels Λ^* are chosen in order to maximize the parallelism. These choices are made on discrete sets; this highlights a *combinatorial* structure of the problem, meaning that the number of possible choices increases exponentially with the table size and the number of resonances. Since not any combination is feasible, due to routing fault prevention, we are faced with a Constrained Optimization Problem (COP).

A COP consists of an input, a set of decision variables, a set of constraints, and an objective function. The inputs are the lookup table $\mathcal{T}_{\mathcal{R}}$ and the number s of ADF types. The core decisions concern which resonances should be selected from $\mathcal{T}_{\mathcal{R}}$. To model this decision we use the boolean variable $x_{r,j} \in \{0, 1\}$ to state whether $\lambda_{r,j}$ is selected. The COP is formally defined as follows:

$$P(s) = \max : \min_{r \in 1..|\mathcal{R}|} \{q_r \mid q_r > 0\} \text{ s.t.} \quad (1)$$

$$q_r = \sum_{\lambda_{r,j} \in \Lambda_r} x_{r,j} \quad \forall r \in 1..|\mathcal{R}| \quad (2)$$

$$s_r = \begin{cases} 0 & q_r = 0 \\ 1 & q_r > 0 \end{cases} \quad \forall r \in 1..|\mathcal{R}| \quad (3)$$

$$\sum_{r \in 1..|\mathcal{R}|} s_r = s \quad (4)$$

The objective function (1) maximizes the parallelism in the selected row (R_r) with the least parallelism, since the global network parallelism is bounded by the channel with lowest parallelism. In practice, we maximize the minimum parallelism that can be sustained by all of the wavelength channels. Constraints (2) define the number q_r of selected elements in row r . Constraints (3) define whether row r (the radius R_r) is selected ($s_r = 1$) or not ($s_r = 0$). Constraints (4) impose to select exactly s rows (ADF's radius lengths). Finally, the following logical constraint is imposed for any $\lambda_{r,j}$

and $r' \neq r$ for which $\lambda_{r,j}$ is conflicting with some elements in row r' ($\exists \lambda_{r',g} \mid I_{r,j} \cap I_{r',g} \neq \emptyset$) and it prevents routing faults:

$$x_{r,j} = 1 \Rightarrow q_{r'} = 0 \quad (5)$$

Constraints (5) either i) allow the non-conflicting elements in rows r and r' to be selected at the same time or ii) prevent any element in row r' to be selected when a conflicting element in row r has already been selected.

The COP (1)–(5) can be reformulated by way of well-known declarative technologies in Operation Research, e.g., Mixed Integer Linear Programming [12], and in Artificial Intelligence, e.g., Answer Set Programming (ASP) [7], and others. The resulting mathematical/logic programs can be solved through off-the-shelf *solvers* (e.g., Clasp [6] for ASP), which either return a provably optimal solution (in our case R^* , Λ^* , and $P(s)$) or prove no solution exists. When non-idealities are involved, the solution consists of those radius lengths and resonances that ensure the parallelism $P(s)$ in whatever post-manufacturing condition.

Given $\mathcal{T}_{\mathcal{R}}$, the scalability analysis is performed for increasing values of s , until $P(s) = 0$; for each s , the COP solver is called, as shown in the block II in Figure 7, and $P(s)$ is returned. Section 5 provides an experimental evaluation about how i) non-idealities, ii) fabrication options, and ii) the network size affect the maximum optical parallelism.

5. RESULTS

We used the optimization framework for WRONoC refinement and parameter selection in Figure 7 to test how the maximum communication parallelism $P(s)$ scales with respect to: i) the number of ADF types s , ii) the fabrication options R_{opt} , iii) the non-idealities R_{tol} and $\Delta\lambda$.

The first test sheds light on the intrinsic scalability of different connectivity patterns, since in general a higher network size requires also a higher number of filter types s , although the exact value of the latter parameter is also topology-specific. As an example, specific configurations of the well-known GWOR and λ -router WRONoC topologies will be considered, by extracting their s requirements. The second and the third tests give some technological drivers to improve the scalability of the topologies.

We programmed the COP in ASP and solved it with Clasp. We solved the ASP programs in the Cineca's Galileo HPC². We used 16 threads and 8GB of RAM in each solver call. The whole experimental platform consisted of about 450 ASP programs (solver calls), the single computing time varied from 0s to 70,000s, for a total of about 58 days of computing time on a single CPU.

For the first test we set $R_{\text{opt}} = \{5, 1, 25\} \mu\text{m}$ [11], and finally $R_{\text{tol}} = 0.01 \mu\text{m}$, $\Delta\lambda = 0.5 \text{ nm}$ to model worst-case variations (see Section 3.6). The ideal manufacturing process is

²www.hpc.cineca.it/hardware/galileo

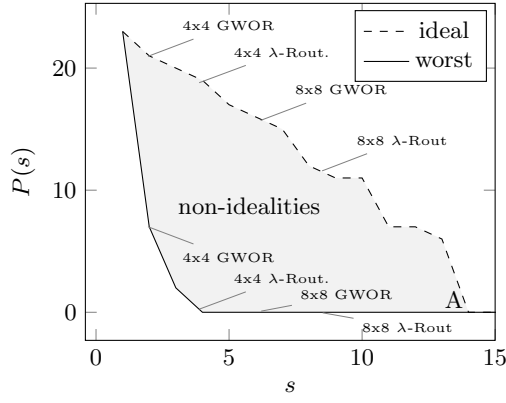


Figure 8: Maximum parallelism $P(s)$ as a function of the number of filter types, with fabrication options $R_{\text{opt}} = \{5, 1, 25\}$

when both R_{tol} and $\Delta\lambda$ are 0.

The chart in Figure 8 shows a first analytical result: the bit parallelism is larger than one ($P(s) > 1$), i.e., wavelength routing is feasible, only for a very limited range of the s parameter (i.e., for overly small network sizes), when worst-case conditions are considered. To make the outcome more tangible, let us associate actual topology configurations to their values of s . In fact, $s = 2$ and $s = 4$ correspond to a 4x4 GWOR and a 4x4 λ -router, respectively, since they use different numbers of MRRs types³. While the GWOR enables 7-bit parallelism, the larger number of MRR types limits the λ -router parallelism to zero, which means the topology is infeasible. Both 8x8 topologies (with $s = 6$ and $s = 8$, respectively) turn out to be infeasible. In the ideal case, the higher number of MRR types of the λ -router is reflected into a relative drop in achievable parallelism by 9.5% for a 4x4 WRONoC, and by 25% for an 8x8 one with respect to GWOR. In this latter case, GWOR has a potential parallelism of 16 bits: the improvement with respect to the worst-case variations is impressive, which denotes the key limiting role played by the non-idealities of the manufacturing process. There is a huge inaccessible “performance” gap (see grey area A) that improvements in fabrication technology and laser selectivity can reduce. This topic is further discussed later on.

Increasing R_{max} , as well as decreasing R_{min} and R_{step} , means to increase the number of the available radius lengths and resonances in $\mathcal{T}_{\mathcal{R}}$, eventually with a benefit on the parallelism. Not necessarily this makes sense from a physical design viewpoint, since a lower ring radius causes a higher sensitivity to process variations, and impairs the manufacturing yield. In contrast, large rings take up more space. Finally, the step parameter depends on the lithography.

In order to express the theoretical bounds, the chart in Figure 9 adds to the chart in 8 the maximum parallelism $P(s)$ curves obtained with $R'_{\text{opt}} = \{5, 1, 30\}$ (ideal) and with $R''_{\text{opt}} = \{5, 0.25, 30\}$ (ideal and worst variation case). In practice, the impact of the lithography resolution is assessed. This chart suggests three main facts:

i) $P(s)$ with R''_{opt} (ideal) is much better than R'_{opt} (ideal), in fact area $C \gg B$, meaning that the resolution R_{step} is

³The ultimate reason is because the λ -router provides self-communication, while the GWOR does not.

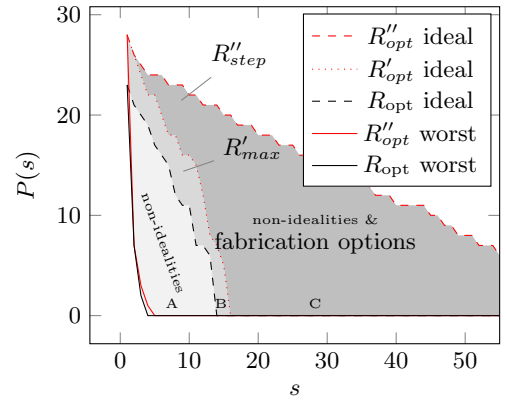


Figure 9: Maximum parallelism achievable with fabrication options $R'_{\text{opt}} = \{5, 1, 30\}$ compared with $R''_{\text{opt}} = \{5, 0.25, 30\}$

a better driver to increase the parallelism with respect to making available more resonant wavelengths through larger rings (the $\mathcal{T}_{\mathcal{R}}$ table in input contains many more radii and wavelengths in the former case than in the latter one).

ii) With R'_{opt} (ideal) $P(s)$ is much higher than with R_{opt} (ideal) and the area $B + C \gg A$, meaning that the combination of multiple fabrication options yields a significant improvement of parallelism and connectivity (especially through the R_{step} parameter;)

iii) In the worst variation case, both R''_{opt} and R_{opt} yield the same parallelism, meaning that WRONoC performance is highly sensitive to the uncertainty of the manufacturing process. In fact, making available multiple wavelength channel selection options is useless if the uncertainty ranges are not reduced accordingly. For instance, with R'_{opt} a 32x32 λ -router yields 14-bit parallelism in the ideal case, which technology maturity can try to materialize over time.

Having fixed $R_{\text{opt}} = \{5, 0.25, 30\}$ and $s = 20$ (roughly 20 interconnected cores with generic topologies), we tested how R_{tol} and $\Delta\lambda$ variations, w.r.t. the state of the art in the literature, can improve the parallelism. This relation is shown in Figure 10. It can be noticed that with common R_{tol} and $\Delta\lambda$ values, in the worst variation case $P(20)$ is pretty much 0, whereas in the ideal case it can peak at 20 bits of parallelism. Lower values of R_{tol} and $\Delta\lambda$, i.e., technological

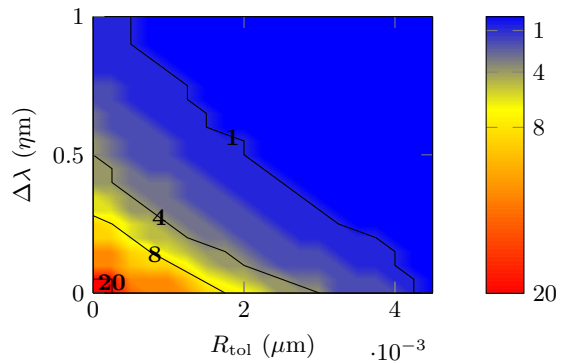


Figure 10: Maximum parallelism $P(20)$ for 20 filter types, expressed as a parameter when varying R_{tol} and $\Delta\lambda$

improvement in the fabrication process and in the laser pre-

cision, can clearly increase the WRONoC parallelism. The engineering curve with $P(20) = 1$ in the chart draws the required values of R_{tol} and $\Delta\lambda$ to guarantee the minimum working parallelism of 1 bit, i.e., the topology is feasible.

6. CONCLUSIONS

In this paper we target the typically overlooked refinement step of WRONoC topologies that completely specifies their physical parameters. This significantly impacts the achieved levels of connectivity and/or communication parallelism, due to the constraint of avoiding routing faults. Our optimization framework demonstrates the huge gap existing between ideal fabrication assumptions and the consideration of worst-case process parameter variations. In principle, even 32x32 WRONoCs can achieve 14-bit parallelism, while in practice worst-case variations limit even the 1-bit parallelism case to WRONoCs smaller than 8 nodes. We show that the resolution in setting the radius of MRRs is the highest-impact technology parameter. Finally, our optimization framework can support the designer in placing uncertainty requirements to the technology provider in order to materialize a predefined level of parallelism. In future work, we will consider statistic distribution of parameter variations in order to limit the severity of process uncertainty and to introduce the notion of yield.

7. ACKNOWLEDGMENTS

We thank the CINECA award under ISCRA (project ISC37), for the availability of HPC resources and support.

8. REFERENCES

- [1] D. Bertozzi, A. Jalabert, S. Murali, R. Tamhankar, S. Stergiou, L. Benini, and G. D. Micheli. Noc synthesis flow for customized domain specific multiprocessor systems-on-chip. *IEEE Transactions on Parallel and Distributed Systems*, 16(2):113–129, 2005.
- [2] S. L. Beux, J. Trajkovic, I. O'Connor, G. Nicolescu, G. Bois, and P. Paulin. Optical ring network-on-chip (ornoc): Architecture and design methodology. In *2011 Design, Automation Test in Europe*, pages 1–6, 2011.
- [3] M. Briere, B. Girodias, Y. Bouchebaba, G. Nicolescu, F. Mieveville, F. Gaffiot, and I. O'Connor. System level assessment of an optical noc in an mpsoc platform. In *2007 Design, Automation Test in Europe Conference Exhibition*, pages 1–6, April 2007.
- [4] A. Deb, R. Wille, O. Keszöcze, S. Hillmich, and R. Drechsler. Gates vs. splitters: Contradictory optimization objectives in the synthesis of optical circuits. *J. Emerg. Technol. Comput. Syst.*, 13(1):11:1–11:13, June 2016.
- [5] J. Flich and D. Bertozzi. *Designing Network On-Chip Architectures in the Nanoscale Era*. Chapman & Hall/CRC, 2010.
- [6] M. Gebser, B. Kaufmann, and T. Schaub. Conflict-driven answer set solving: From theory to practice. *Artificial Intelligence*, 187-188:52–89, 2012.
- [7] M. Gelfond. Answer sets. In F. van Harmelen, V. Lifschitz, and B. Porter, editors, *Handbook of Knowledge Representation*, chapter 7, pages 285–316. Elsevier Science, 2008.
- [8] A. B. Kahng and F. Koushanfar. Evolving eda beyond its e-roots: An overview. In *Proceedings of the IEEE/ACM International Conference on Computer-Aided Design, ICCAD '15*, pages 247–254, Piscataway, NJ, USA, 2015. IEEE Press.
- [9] S. Koohi, M. Abdollahi, and S. Hessabi. All-optical wavelength-routed noc based on a novel hierarchical topology. In *Networks on Chip (NoCS), 2011 Fifth IEEE/ACM International Symposium on*, pages 97–104, May 2011.
- [10] A. V. Krishnamoorthy, X. Zheng, G. Li, J. Yao, T. Pinguet, A. Mekis, H. Thacker, I. Shubin, Y. Luo, K. Raj, and J. E. Cunningham. Exploiting cmos manufacturing to reduce tuning requirements for resonant optical devices. *IEEE Photonics Journal*, 3(3):567–579, June 2011.
- [11] D. Liang and J. E. Bowers. Recent progress in lasers on silicon. *Nat Photon*, 4(8):511–517, Aug 2010.
- [12] R. Martin. *Large Scale Linear and Integer Optimization: A Unified Approach*. Springer US, 1999.
- [13] K. Miliotis, G. Papadimitriou, and A. Pomportsis. Design alternatives for wavelength routing networks. *Optics & Laser Technology*, 35(2):137 – 154, 2003.
- [14] I. O'Connor, M. Brière, E. Drouard, A. Kazmierczak, F. Tissafi-Drissi, D. Navarro, F. Mieveville, J. Dambre, D. Stroobandt, J.-M. Fedeli, Z. Lisik, and F. Gaffiot. Towards reconfigurable optical networks on chip, 2005.
- [15] A. Parini, L. Ramini, G. Bellanca, and D. Bertozzi. Abstract modelling of switching elements for optical networks-on-chip with technology platform awareness. In *Proceedings of the Fifth International Workshop on Interconnection Network Architecture: On-Chip, Multi-Chip, INA-OCMC '11*, pages 31–34, New York, NY, USA, 2011. ACM.
- [16] L. Ramini, P. Grani, S. Bartolini, and D. Bertozzi. Contrasting wavelength-routed optical noc topologies for power-efficient 3d-stacked multicore processors using physical-layer analysis. In *Design, Automation Test in Europe Conference Exhibition (DATE), 2013*, pages 1589–1594, March 2013.
- [17] L. Ramini, M. Tala, and D. Bertozzi. Exploring communication protocols for optical networks-on-chip based on ring topologies. In *Asia Communications and Photonics Conference 2014*, page ATh3A.165. Optical Society of America, 2014.
- [18] Sonics, Inc. SonicsStudio: Next Generation Development Environment. <http://sonicsinc.com/products/development-tools/sonicsstudio-director/>.
- [19] M. Tala, M. Castellari, D. Bertozzi, M. Balboni, and L. Ramini. Populating and exploring the design space of wavelength-routed optical network-on-chip topologies by leveraging the add-drop filtering primitive. In *Int. Network-on-Chip Symposium, 2016*.
- [20] X. Tan, M. Yang, L. Zhang, Y. Jiang, and J. Yang. On a scalable, non-blocking optical router for photonic networks-on-chip designs. In *Symposium on Photonics and Optoelectronics (SOPO)*, pages 1–4, May 2011.
- [21] A. von Beuningen and U. Schlichtmann. Platon: A force-directed placement algorithm for 3d optical networks-on-chip. In *ISPD 2016: 27-34*.