Nanophotonic is a promising solution for on-chip interconnection due to its intrinsic low-latency and low-power features. Future tiled chip multiprocessors (CMPs) for rich client devices can receive energy benefits from this technology but we show that great care has to be put in the integration of the various involved facets to avoid queuing and serialization issues and obtain the rated potential advantages.

We evaluate different management strategies for accessing a simple, shared photonic path (ring), working in conjunctions with a standard electronic mesh or alone, in a tiled CMP. Our results highlight that a careful selection of the most latency-critical messages to be routed in photonics and the use of a conflict-free access scheme is crucial for obtaining performance/power advantages when the available bandwidth is limited.

We identify the design point where all the traffic can be routed on the photonic path and thus the electronic network can be suppressed. At this point, the ring achieves 20-25% speedup and 84% energy consumption improvement over the electronic baseline.

Then we investigate the same tradeoffs when the number of rings is increased up to eight, allowing to raise performance benefits up to 40% or reaching up to 80% energy reduction. We finally explore the effects of deploying a given optical parallelism split between a higher number of waveguides for further improving energy savings.

Categories and Subject Descriptors: C.0 [GENERAL]: System architectures; C.1.2 [Multiple Data Stream Architectures (Multiprocessors)]: Parallel processors; C.1.2 [Multiple Data Stream Architectures (Multiprocessors)]: Interconnection architectures; C.4 [PERFORMANCE OF SYSTEMS]: Design studies.

General Terms: Performance, Design.

1. INTRODUCTION

High-end embedded systems are evolving toward parallel architectures to keep the pace of Moore’s Law and the tiled paradigm is expected to enable design scalability [Ros et al. 2008]. State-of-the-art commercial processors already comprise numerous cores into a single die both in general-purpose (e.g. up to 16 in recent AMD Opteron 6000 models [amd 2013]) and in high-end embedded (e.g. up to 8 in Samsung Exynos

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Octa [Sam 2013]) domains. Intel Polaris [Vangal et al. 2008] prototype reached 1 TFlop some years ago thanks to an 80 cores tiled architecture built around an ad-hoc interconnection network. Ideally, tiled CMP architectures comprise a number of identical tiles, each one having computational capabilities (e.g., a core), some private cache structures (e.g., L1 instruction and data) as well as distributed, shared cache resources. Tiles are tied up with an on-chip interconnection network (NoC) that allows parallel threads to exchange information and to synchronize [Franke et al. 2002; Li et al. 2009; O’Connor and Gaffiot 2004]. This implies a central role of NoCs in future client devices - like smartphones, tablets, set top boxes and embedded PCs - from both performance and power consumption points of view.

Current and future CMPs running modern parallel applications require high-bandwidth and low-latency interconnections for efficiently managing coherence protocol evolution. However, due to the emerging wire delay issues [Kim et al. 2002] and to the increasing number of on-chip cores, traditional electronic NoC designs have troubles in fulfilling these requirements while maintaining an acceptable power consumption [Petracca et al. 2008; ITRS 2011].

On-chip nanophotonics is now considered a promising emerging technology for fulfilling the demand of bandwidth, low-latency and, in particular, low-power consumption of future system, but great care is needed in the design and management of photonic structures to actually take advantage of these features within complex CMPs. As simple photonic topologies are likely to be the first integrated in near future computer systems, and in particular client devices, this paper aims at dissecting the design tradeoffs around the adoption of one, or a few, photonic rings used both in parallel (3D-stacked [Loh 2008]) with a standard electronic NoC, and also alone if sufficient optical bandwidth is deployed.

Therefore, this work can constitute a base design reference for the first tiled CMPs encompassing photonic structures mainly for reaching significant energy reductions, which are extremely important in this domain. As part of the crucial design options, we consider the different behavior of three arbitration techniques [Pan et al. 2009], and associated overhead, to access the shared photonic resources, in conjunction with other design parameters like bandwidth, number of cores as well as various traffic selection strategies in case of hybrid electronic/photonic NoC solutions. The analyzed solutions span from a highly parallel but mutually exclusive and power-hungry one, where only one message at a time flows quickly but needs full arbitration, to low-parallelism conflict-free and more energy efficient ones, where many transmissions can occur in parallel but each one experiences longer transmission time.

In summary, the major contributions of this paper are:

— We single out the performance and energy improvement capabilities of the different points in the bandwidth (wavelength division multiplexing, WDM), access scheme, traffic selection and number of waveguides design space to determine the best trade-offs for the different levels of photonic resources deployed into a high-end embedded tiled CMP. One key novelty of this paper is that it performs this kind of exploration with an analytical approach identifying the best tradeoffs between energy consumption and performance in an integrated fashion, delivering insight on the effects of the various involved facets within small complexity optical networks with one or a few rings.

In particular, results show that the best mix of design choices changes significantly according to the features of the considered cases and, most of all, when energy benefits are mainly pursued;

— In case of hybrid electronic/optical solutions (limited optical resources on-chip), we identify the best design choices, and the corresponding performance and energy ad-
Design Options for Optical Ring Interconnect in Future Client Devices

Fig. 1. Overview of the considered architecture for a 16-core setup. Each tile has access to the optical ring.

advantages, according to the traffic quote that is forwarded onto the optical path(s). In general, given a photonic interconnection setup (bandwidth, topology, access scheme, etc.), up to a certain traffic level diverted to the photonic path, messages experience latency benefits. But beyond a specific point, benefits are eroded, or results get even worse than using the electronic NoC alone, making the case for a carefully integrated design;

Lastly, based on the identified best design points, we investigate along an additional dimension. Depending on the shared medium access strategy, we show how energy consumption can be further reduced employing a higher number of rings (optical paths), each with a lower wavelength parallelism (WDM), aiming at an overall smaller insertion loss which positively affects static power consumption.

The remainder of the paper is organized as follows. In Section 2 we briefly introduce the technologies addressed by the paper. In Section 3 we describe the features of the considered architecture; in Section 4 we discuss state-of-the-art arbitration techniques, while in Section 5 we present the evaluation methodology and discuss the achieved results. In Section 6 we present the related works and, finally, Section 7 concludes.

2. ON-CHIP OPTICAL INTERCONNECTION

In this section we introduce some background about on-chip photonic interconnection technology. On-chip photonics is enabled by the possibility to integrate waveguides, lasers, modulators and photo-detectors into current process technology [Petracca et al. 2008]. The majority of proposals assume to adopt an on-chip optical network (ONoC) on a dedicated layer of a 3D-stacked chip architecture [Petracca et al. 2008; Pasricha and Bahirat 2011]. The communication paradigm, diversely from electronic networks (ENoC), is point-to-point by nature, as light packets cannot be managed in a store-and-forward fashion within the optical domain. Therefore, photonic links can be effectively used to connect communication endpoints directly. This feature determines one of the main benefits of this technology: power consumption of a transmission is, in practice, independent from the on-chip distance. Moreover, end-to-end communication latency is very fast because it is dominated by light propagation speed into silicon\(^1\). The time and energy spent transmitting a message through an electronic mesh instead, varies significantly with the distance between the source and the destination. In a 16-core CMP, sending a message between opposite corners, through a 2D 4x4 ENoC, requires six intermediate hops (switch + link) and transmissions.

Passive [Koohi et al. 2011] and active [Petracca et al. 2008] Photonic Switching Element (PSE) architectures have been proposed for implementing complex network topologies with fixed and reconfigurable end-to-end paths. Passive networks tend to

---

\(^1\)About 66600 km/s \(\rightarrow\) 15 ps/mm.
require more optical modules than active ones to achieve similar connectivity and parallelism. However, active networks require preliminary optical path setup through microring thermal tuning, which induces a significant time overhead. In our proposed architecture, we do not make use of any PSEs to limit network complexity and we aim at tuning the other design parameters as to exploit the positive points of the simple physical topology for performance and, most of all, energy objectives.

3. ANALYZED ARCHITECTURE

Figure 1 shows our baseline tiled architecture for a 16-core setup where each core has private L1 caches and a slice of L2 cache, shared and distributed between all tiles. Directory information is also distributed and is stored along each L2 cache slice. A traditional 2D electronic mesh connects all the tiles. Figure 1 shows also the logical ring-based photonic path (3D-stacked), which is added to the baseline to obtain a photonic enhanced architecture or used in substitution of the electronic mesh. This architecture can be directly scaled down or extended to the other two analyzed architectures with 8 and 32 cores. According to a nomenclature in line with [Batten et al. 2012], we consider optical networks based on ring-shaped waveguides and their logical organizations are Multiple Writers Single Reader (MWSR) nanophotonic crossbar (one bus per destination, every source can write to any bus) and Multiple Writers Multiple Readers (MWMR) photonic arbitrated bus.

We have analyzed different ring-based network configurations. Even if today’s technology is able to put up to 32 lambdas in a single optical channel (WDM degree) [Le Beux et al. 2011], at least 64 wavelengths per waveguide (dense WDM degree - DWDM) are expected to be feasible very soon [Vantrease et al. 2008]. For this reason we have chosen as reference design value around 64 lambdas (64-70 range) but, for completeness, we have also analyzed the more conservative 16 and 32 WDM degrees. Throughout the paper, we indicate one optical ring employing 64-70 wavelengths as the 1-ring configuration. At the same time, when we refer to a N-ring configuration we mean N distinct photonic rings, like the baseline one, used jointly to increase wavelength parallelism in data transmission.

Each ring is independent, therefore the same set of wavelengths can be reused in different waveguides. We assume to use concentric rings in order to limit the number of crossings between waveguides which would increase the overall insertion loss of the optical paths. However also adopting this layout, a limited number of crossings is unavoidable. In fact, using multiple rings, the supply of laser light to an internal waveguide needs to cross the surrounding ones.

At the end of the paper, we investigate also the performance/power effects due to the different number of rings that implement the overall required wavelength parallelism. In fact, for instance, for some access strategy (see Section 5.3), twice the number of rings, each with half wavelengths, can consume less than the baseline with a more aggressive WDM degree. This is due to the nonlinear accumulated insertion loss of the required photonic structures over the optical paths. This effect opens another direction in the design space of the considered optical interconnection.

4. ARBITRATION

Some of the considered communication strategies rely on shared optical resources (i.e., wavelengths in a specific waveguide) and employ a token ring [Smythe 1999] arbitration mechanism. Token ring is a well-known protocol that guarantees starvation free mutual exclusion on an ordered shared medium throughout the utilization of a special frame called token. In our setup the token is a small light packet (just one bit) circulating on the ring. Token acquisition grants the possessor permission to transmit on the

When a node wants to transmit, it waits for the token, removes it from the ring (light detection) and releases it again (token regeneration) after transmitting.

A photonic token reduces the token circulation latency thanks to the quick round trip time in idle conditions (i.e., less than two clock cycles @4 GHz).

In general, an efficient and effective arbitration techniques should allocate the shared medium to the nodes fairly and should allow high channel utilization (high throughput) with low latency and low overhead.

4.1. Arbitration strategies and physical layout implications

We studied three well-known access strategies to the photonic ring [Vantrease et al. 2009; Vantrease et al. 2008; Pan et al. 2009]: Multiple Writers Multiple Readers (MWMR), Single Writer Single Reader (SWSR) and Multiple Writers Single Reader (MWSR). This terminology was proposed by Pan et al. [Pan et al. 2009].

In MWSR strategy, each receiver is associated to a predefined subset of all available colors (e.g., eight lambdas for each receiver in the 8-core, 1-ring setup, DWDM degree (64)). When a sender wants to send a message to a given destination, it waits for the destination-specific token without interfering with other transmissions toward other receivers. For every access scheme, we assume that a receiver can issue a Nack signal toward the sender through the complementary part of the ring using a specific wavelength as soon as it realizes its inability to manage the additional message. In our tested configurations and schemes, Nack messages occur very rarely.

Figure 2 exemplifies the physical organization and optical resources needed for receiving (on the waveguide) and transmitting (before the coupler) messages in the CMP nodes.

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Figure 2 exemplifies the physical organization and optical resources needed for receiving (on the waveguide) and transmitting (before the coupler) a message in case of the MWSR scheme.

In particular, we choose a physical layout where, on the receiver side, we place microring drop filters directly on the main waveguide. Their cascaded insertion loss on the waveguide is a crucial factor for the required laser power. However, their overall number is limited, as it is exactly equal to the considered WDM degree, and for example contributes for about -1.28/-2.5 dB worst case for 64 WDM degree and assuming a microring through loss of -0.02 dB [Vantrease et al. 2009].

Conversely, on the transmission side, we place the microring modulators of each core in a short waveguide trunk that is coupled to the main one, which passes by every core. It would have been practically unfeasible to put such high number of transmission microrings directly on the main waveguide as the overall insertion loss on the worst case path would have been absolutely excessive (i.e., -20 dB if microring through loss is -0.02 dB). In fact, if one node needs to communicate to the node that lays farther from it on the waveguide, modulated light needs to pass by all the other cores (e.g. up to 14 in a 16-core setup) and thus suffers the insertion loss of all the photonic structures on the waveguide for each core. A core can transmit on every wavelength in order to potentially reach every destination, therefore needs one modulator for every core.
Fig. 3. MWMR, physical organization of the optical resources needed for receiving (left) and transmitting (right) messages in the CMP nodes.

wavelength. For example, in a 16-core setup employing 64 DWDM degree, this results in 1024 transmission microrings overall. Employing a waveguide coupler allows limiting the worst and average insertion losses from transmitters to receivers even if the coupler loss itself slightly degrades the best case (i.e., -0.5dB).

SWSR strategy has a single wavelength statically assigned to a sender-receiver pair (e.g., for a total of 56 lambdas for full connectivity in an 8-core CMP) therefore it does not require arbitration at all (no token) and allows concurrent communications between all cores (non-blocking network). The main issue of this scheme is the limited optical parallelism in each communication and scalability, as explained in Section 5.2. We refer to SWSR as the connectivity provided in a ring by the wavelength-routed [O’Connor et al. 2012] technique. Both MWSR and SWSR schemes statically allocate channels (wavelengths) to specific destinations or source-destination pairs, respectively. The drawback of static wavelength allocation is that, on average, the connectivity is overprovisioned in time because the coherency traffic is typically unbalanced, as shown for SPLASH-2 benchmarks [Woo et al. 1995] in [Pan et al. 2010] and as we verified also for the PARSEC 2.1 suite [Bienia et al. 2008], thus reducing the exploitable network throughput. Under this kind of traffic, the use of wider photonic paths only when needed (e.g., MWMR or MWSR), can be more efficient even paying some arbitration overhead and reduced message concurrency.

MWMR strategy improves resource utilization by letting all the network nodes use all available ring wavelengths in mutual exclusion. MWMR uses the token to access the ring and, before sending the message, it needs a receiver-selection phase to ask the destination to get ready for receiving (i.e., tune the microring drop filters). Then, all the available wavelengths in the waveguide are used for message transmission with maximum parallelism and thus minimum latency.

Figure 3 sketches the physical organization of the optical resources needed for receiving (left) and transmitting (right) a message in one node using the MWMR access scheme, given a 1-ring and 16-core configuration. Each node needs 64 microring modulators and, diversely from MWSR, 64 microring drop filters and photo-detectors to transmit and receive on all available colors, respectively. In each node, a splitter is employed to spill a fraction of the light toward the microring drop filters of a node. This way, thanks to splitter tuning, all cores can potentially receive about the same amount of light and the worst case insertion loss is maintained far smaller than applying all microrings directly on the main waveguide. Despite this, the insertion loss of MWMR is still quite higher than in the simpler schemes and thus requires more laser power.

Another drawback of MWMR scheme resides in the high overall number of microrings as every node has to modulate and receive light in all wavelengths. Microrings consume static power for their thermal tuning also when not used.

The relative performance and energy consumption of such techniques are not obvious to predict. In fact going from MWMR to MWSR and SWSR, message concurrency

increases but optical parallelism per transmission decreases, which in turn implies that each communication suffers from longer serialization (transmission) time.

4.2. Arbitration mechanism

In this section we will go into the details of the arbitration mechanism implemented in our ring. When one core wishes to acquire the token (MWMR), or a token (MWSR), two possible cases can happen:

— The shared medium is free and the requestor has only to wait for the token to arrive before transmitting. In our setup (4 GHz, 30 mm ring length), this delay can be at most two cycles for the token to cover the whole ring distance.

— The shared medium is in use, and/or other cores between the token position and the initial requestor will acquire the token for transmitting. Hence, the considered requestor will wait for one or more message transmission times. Is not possible to predict the delay as both the number of conflicting transmissions and their length (control or data message) cannot be known by a core. However, the waiting time is bounded, thus no starvation can occur, because we force each node to release the token after every transmission even if it has more than one message to send. This limits performance of burst transmissions but cache coherence traffic is not very bursty.

In MWMR scheme, a destination-selection phase is needed and we implemented a pipelined mechanism to pursue high channel utilization. We reserve five additional lambdas in order to encode this information (up to 32 cores analyzed) on top of the additional wavelength needed for the token bit.

Another option would be not to encode the destination-selection bits but this would require to transmit them in a separate waveguide because we would need 32 additional bits (wavelengths) to select each possible destination (97 in total). The main advantage of using not encoded destination-selection bits is that a receiver just needs one additional microring to detect if it is selected or not. Otherwise it needs up to five additional microrings for the 32-core setup. We decided to stick to the encoded scheme because it allows avoiding an additional ring and limit static power consumption, which is quite important especially in the MWMR scheme as it will be clear from the next sections.

As further possible improvement we could also reuse the same wavelengths for destination-selection and message transmission. In such a way MWMR scheme would need only 65 wavelengths (64 for data and 1 for the token). However, this would have induced the impossibility to have both destination-selection and message transmission operations active at the same time on the ring, limiting the pipelining of the

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2We rely on a coherence protocol with 8- and 72-byte control and data message lengths, respectively.
different phases and therefore increasing latency. For this reason we opted for using separated wavelengths.

Figure 4 shows an exemplification of our pipelining model for a MWMR strategy. The example shows three transmissions by three different cores: specifically (a) one control message directed to a close destination (within one processor cycle distance on the ring), one (b) data message and (c) one control message to a far destination (two processor cycles). In fact the transmission of a packet needs one or two processor cycles according to the distance toward destination. However, from the sender point of view, the transmission is the same for both close and far destinations. Note that Figure 4 shows the time in optical cycles at the modulation frequency of 10 GHz. In Figure 4 the destination line (Dst-Sel) shows in which cycles the destination-selection phase is performed. The wait state (WS in Figure 4) is the time needed by the destination to switch on its microrings and get ready to receive. During this time the sender accesses the electro/optical (E/O) network interface to prepare itself for the transmission. \(T_{IN}\) is the time at which a sender has acquired the token. \(T_{OUT}\) is the time the token is released. In our pipelined approach, the token is released two optical cycles before the actual end of transmission as it is clear for a data message (e.g., case (b)). Note that this corresponds to one optical cycle before sending a control message (e.g., (a) or (c)), which needs only one 64-bit optical flit. This way the optical channel can reach high exploitation when successive transmissions are performed by different cores.

With this timing, the transmission of a control message requires three optical cycles to be performed. In addition, one to five optical cycles are needed to wait for the token according to its distance from the requestor. Therefore, when the ring is idle, a control message needs a minimum of four to eight optical cycles to be transmitted. This corresponds to two to four processor cycles in our setup (4 GHz).

At the E/O interface, we use a specifically tuned wormhole routing algorithm [Seydim 1998], which starts to transmit optical flits (64 bits in MWMR scheme) as soon as possible according to arbitration. Data messages (72 bytes) require nine optical flits to be transmitted and thus can take benefit from such wormhole approach. In this way, a data message can be transmitted in 11 optical cycles. This leads to a gross minimum transmission time between 12 to 16 optical cycles including token wait, which corresponds to five to seven processor cycles for a complete transmission. We assume to transmit the most significant 64-bit word first so that the receiver node can be unblocked after such first word arrives, while it continues receiving the remaining flits.

Summarizing, in what we call 1-ring configuration, the MWMR scheme uses 64 wavelengths for data transmission, one for the token and up to five for the encoded destination-selection bits. This allows all these three kinds of information to be transmitted at the same time on the ring and avoid “bubbles” (idle optical cycles) in the data wavelengths thanks to the exposed pipelined approach. According to the distance between the two cores that access the ring in succession, bubbles can occur because the second core will have to wait for the token to traverse such distance before starting the signaling. Such idle optical cycles span between zero to five (token round trip time).

Conversely, MWSR requires up to 32 additional lambdas (one token for each possible destination) on top of the 64 data wavelengths. Even if the overall wavelengths number around one hundred is deemed feasible in near future [Chan and Bergman 2012], we conservatively decided to stick to no more than 64/70 wavelengths per waveguide (DWDM degree). Therefore, in MWSR scheme we dedicate a specific ring waveguide for token management, in particular, placed inside the data ring waveguide “circle”.

MWSR timing is almost the same as the one shown in Figure 4 for MWMR, neglecting the transmission of the destination-selection bits. For example, in a 16-core setup, all 64 data wavelengths would be split in 16 slices, each one associated to a destination and four wavelengths wide. Thus, a control message (64 bit) needs 16 optical
Design Options for Optical Ring Interconnect in Future Client Devices

### Table I. Parameters of the simulated architecture.

<table>
<thead>
<tr>
<th>Core</th>
<th>Parameters</th>
</tr>
</thead>
<tbody>
<tr>
<td>Core</td>
<td>8/16/32 cores (64 bit), 4 GHz</td>
</tr>
<tr>
<td>L1 cache</td>
<td>16 kB (I) + 16 kB (D), 2-way, 1 cycle hit time</td>
</tr>
<tr>
<td>L2 cache</td>
<td>16 MB, 8-way, shared and distributed 8x2MB or 16x1MB or 32x512kB banks, 3/12 cycles tag/tag+data</td>
</tr>
<tr>
<td>Directory</td>
<td>MOESI protocol, 8/16/32 slices, 3 cycles</td>
</tr>
<tr>
<td>ENoC</td>
<td>2D-mesh, 4 GHz, 5 cycles/hop, 32 nm, 1 V, 128 bit/flit</td>
</tr>
<tr>
<td>Photonic path</td>
<td>3D, 1-9 parallel waveguides, 30 mm length, 8/16/32 I/O ports, 10 GHz, 64/70 (16 and 32) wavelengths, 460 ps full round</td>
</tr>
<tr>
<td>Losses</td>
<td>microring through 0.02 dB, waveguide propagation 1 dB/cm, waveguide crossing 0.7 dB/cross, waveguide coupler 0.5 dB and splitter 0.5 dB, chip coupling 1 dB</td>
</tr>
<tr>
<td>Main memory</td>
<td>4 GB, 300 cycles</td>
</tr>
</tbody>
</table>

cycles (flits) to be transmitted in the timing of Figure 4. However, up to 16 concurrent transmissions can occur at the same time toward different destinations.

SWSR scheme, being contention free, requires no token arbitration and destination-selection at all and, in case of an 8-core architecture, it needs 56 total lambdas for allowing every possible source-destination 1-bit wide paths in case of full connectivity.

In conclusion, we will analyze SWSR scheme for 8-core architectures, while MWSR and MWMR for 16- and 32-core configurations. The reference network architecture for the various schemes will be referred to as 1-ring configuration, to indicate the number of waveguides carrying the data wavelengths. This corresponds to the total number of waveguides for SWSR and MWMR scheme (encoded destinations), while the 1-ring configuration for MWSR scheme employs an additional ring for token circulation.

Moreover we will refer to 2x, 4x or 8x bandwidth configurations as 2-, 4- or 8-ring, indicating that the number of waveguides dedicated to data flow are two, four or eight.

### 5. RESULTS

In this section we introduce our evaluation methodology and test setup, and discuss the obtained results.

#### 5.1. Methodology and test setup

Table I summarizes the main architectural details and general parameters that have been considered in this work. ENoC dynamic and static energy consumption parameters shown in Table II (left) are derived from ORION 2.0 [Kahng et al. 2012] but they have been verified also with more recent tools (DSENT [Sun et al. 2012]) and obtained using the following formulas:

\[
E_{\text{ENoC static}} = \sum_{i=0}^{n_{\text{switches}}} P_{\text{switch}_i, \text{static}} + \sum_{i=0}^{n_{\text{links}}} P_{\text{link}_i, \text{static}} \times \text{sim time}
\]

\[
E_{\text{ENoC dyn}} = \sum_{i=0}^{n_{\text{switches}}} (E_{\text{switch}_i, \text{dyn}} \times \text{bits}_{\text{switch}_i}) + \sum_{j=0}^{n_{\text{links}}} (E_{\text{link}_j, \text{dyn}} \times \text{bits}_{\text{link}_j})
\]

where \(\text{bits}_{\text{switch}_i}\) and \(\text{bits}_{\text{link}_j}\) are the overall amount of bits that traversed switch \(i\) and link \(j\) and dynamic energies are per bit.

Parameters of the photonic devices shown in Table II (right) and Table III are in line with state-of-the-art proposals [Zheng and al. 2011]. A conservative evaluation of the overall area occupation of our proposed hybrid network, which we assume laying on a dedicated 3D stacked layer, can be derived from the area occupation of the employed photonic elements [Zheng and al. 2011; Biberman and Bergman 2012]. Exact

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occupation is also subject to place and route issues which however are out of the scope of this paper. We recall that mono-modal propagation waveguides have a cross-section width around 500 nm and need to be kept separated by one or a few micrometers when running side by side to limit coupling. Furthermore, bend radii of more than about 6.5-10 µm allow 90° turns with limited loss. Micro-ring modulators and drop filters can be assumed to have a diameter within 3-12 µm range and photodetectors have been demonstrated in about 600 µm² area. Assuming simple templates for the layout organization of photonic ring endpoints, our photonic network based on MWMR access strategy and 9-rings can stay within 25% and 13% chip layer area (assumed 225 mm²) for 32- and 16-core setups, respectively. MWSR strategy on 8-rings can induce less area occupation especially due to photodetector size: about 3% and 2% chip area again for 32- and 16-core configurations. SWSR access strategy for 1 ring, and 8-core setup, can be considered to have a somewhat smaller area footprint than MWSR.

As a function of the architecture (8-, 16- or 32-core) and on the used access strategy (MWMR, MWSR and SWSR technique) we have calculated all the static power dissipated by the lasers, thermal tuning of the microring resonators and the electronic interface circuitry to the photonic medium. More in detail, optical energy calculation was accounted as follows:

\[
E_{ONoC_{\text{static}}} = (P_{\text{MRR,tuning}} + P_{\text{laser}} + P_{\text{logic,static}}) \times \text{sim\_time}
\]

\[
E_{ONoC_{\text{dyn}}} = (E_{\text{modulator}} + E_{\text{photodetector}} + E_{\text{serdes}} + E_{\text{logic,dyn}}) \times N_{\text{O,flits}}^3
\]

where \(P_{\text{MRR,tuning}}\) and \(P_{\text{logic,static}}\) account, respectively, for all micro-ring resonators and all the remaining electronic logic needed to interface toward the optical ring. We are considering to use a low-power and high-frequency logic to access the optical ring. Its dynamic energy consumption is also shown in Table II (\(E_{\text{logic,dyn}}\) parameter) and it has been accounted into the optical dynamic consumption in the presented results.

Table II (right) shows also the DWDM degree of the employed waveguides for the reference 1-ring configuration for the different access schemes. In case of MWSR there is one ring for message transmission and one ring for token management (1 bit/wavelength per destination). Then \(E_{\text{dynamic}}\) is the energy/bit for modulators and photo-detectors, while \(E_{\text{serdes}}\) is the energy/bit for the serializers/deserializers.

Table II. Parameters of the electronic and optical networks.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>DWDM degree (SWSR) [bit]</th>
<th>DWDM degree (MWSR) [bit]</th>
<th>DWDM degree (MWMR) [bit]</th>
</tr>
</thead>
<tbody>
<tr>
<td>(E_{\text{link}}) [pJ/bit]</td>
<td>0.39</td>
<td>56</td>
<td>64 + 16/32</td>
<td>70</td>
</tr>
<tr>
<td>(E_{\text{switch-dyn}}) [pJ/flit] (3-port)</td>
<td>181.92</td>
<td>64</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>(E_{\text{switch-dyn}}) [pJ/flit] (4-port)</td>
<td>266.29</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>(E_{\text{switch-dyn}}) [pJ/flit] (5-port)</td>
<td>338.91</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>(E_{\text{switch-static}}) [mW] (3-port)</td>
<td>63.35</td>
<td>64</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>(E_{\text{switch-static}}) [mW] (4-port)</td>
<td>87.02</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
<tr>
<td>(E_{\text{switch-static}}) [mW] (5-port)</td>
<td>111.21</td>
<td>70</td>
<td>70</td>
<td>70</td>
</tr>
</tbody>
</table>

Performance evaluation are obtained with GEM5 simulator [Binkert et al. 2006], in which we modeled both the all-electronic baseline and photonic enhanced CMP architectures described in Section 3, and we adopted full-system simulation.

Table III shows the static power consumed by the optical network for the considered schemes. It comprises laser power supply, microring thermal tuning and static power of modulators and receivers. Laser power accounts for the insertion loss due to the organization of the different schemes (see Section 3) as enough power is needed at

3This is the overall number of flits flowing on the optical path.

the receiver side for detecting light information correctly. In particular, the overall insertion loss is determined by optical path topology and specific losses, summarized in Table I, due to waveguide propagation, splitters and couplers, microring through losses (for modulators and drop filters) and waveguide crossings.

The first three columns of Table III show 1-ring configurations (1R) for 16\(\lambda\), 32\(\lambda\) and 64\(\lambda\) (wavelengths), while 2-ring (2R), 4-ring (4R) and 8-ring (8R) configurations comprise the highlighted overall data parallelism (e.g., 4R = 256\(\lambda\)), according to our formalism exposed in Section 4.2. For 32-core MWSR scheme, 16\(\lambda\) setup is not available as 16 wavelengths are not enough to be assigned to 32 destinations. For 8-core and SWSR scheme, 16 or 32 overall wavelengths are not enough to cover all possible source-destination pairs (each 1-bit wide) as 56 minimum\(^4\) wavelengths are needed. Furthermore, we did not analyze higher overall WDM degree for SWSR as its poor relative performance in comparison to the required power consumption.

For configurations with more than one ring we have analyzed only MWMR and MWSR strategies as they are the best performing ones. For the MWSR configurations (1- and N-ring) we are considering also the static power due to an additional ring dedicated for managing the multiple tokens. For example, a 4-ring, 16-core, MWSR configuration uses four rings, each 64 wavelengths wide, employing the MWSR access scheme and an additional 16-WDM ring (one per core) using MWMR where each wavelength is modulated independently. Table III shows also the static power consumption of this additional ring (\(P_{\text{TOKEN}}\) entries) and it is interesting to compare its values compared to the overall consumption of the MWSR schemes. For 8 cores it constitutes a limited fraction of the total, especially for multiple ring configurations, e.g., 4R, 8 cores, 45.18 mW (11.9\%) out of 379.91 mW total. While for a higher number of cores its relative weight becomes bigger, e.g., 4R, 32 cores, 1047.70 mW (69.6\%) out of 1505.20 mW. The reason is that the photonic path for token management needs the power-hungry MWMR access scheme, and thus topological organization of modulators and receivers, for allowing all endpoints to potentially transmit and receive every token.

Lastly, from Table III, we can observe that the same token path, e.g., for 8 cores and thus 8 tokens, consumes an increasing static power as the number of rings increases. This is due to the insertion loss originating from light supply waveguide to the token waveguide, which we are assuming to run internally to the data waveguides. For instance, in a 4R MWSR scheme, the token waveguide suffers 4 crossings. For the same reason, in 2R, 4R and 8R, also the internal data paths suffer from increased static power.

### Table III. Static power consumption of the optical network for the considered configurations. [mW]

<table>
<thead>
<tr>
<th></th>
<th>1R (16(\lambda))</th>
<th>1R (32(\lambda))</th>
<th>1R (64(\lambda))</th>
<th>2R (128(\lambda))</th>
<th>4R (256(\lambda))</th>
<th>8R (512(\lambda))</th>
<th>9R (576(\lambda))</th>
</tr>
</thead>
<tbody>
<tr>
<td>(P_{\text{MWMR}}) (8-core)</td>
<td>56.87</td>
<td>142.33</td>
<td>466.52</td>
<td>1011.03</td>
<td>2391.06</td>
<td>-</td>
<td>8512.86</td>
</tr>
<tr>
<td>(P_{\text{MWMR}}) (16-core)</td>
<td>112.23</td>
<td>284.65</td>
<td>933.03</td>
<td>2022.06</td>
<td>4782.11</td>
<td>-</td>
<td>17025.72</td>
</tr>
<tr>
<td>(P_{\text{MWMR}}) (32-core)</td>
<td>224.65</td>
<td>569.29</td>
<td>1866.04</td>
<td>4044.11</td>
<td>9564.23</td>
<td>-</td>
<td>34051.44</td>
</tr>
<tr>
<td>(P_{\text{MWSR}}) (8-core)</td>
<td>34.18</td>
<td>47.24</td>
<td>92.23</td>
<td>177.74</td>
<td>379.91</td>
<td>1014.58</td>
<td>-</td>
</tr>
<tr>
<td>(P_{\text{MWSR}}) (16-core)</td>
<td>123.88</td>
<td>139.47</td>
<td>319.56</td>
<td>635.12</td>
<td>1392.13</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>(P_{\text{MWSR}}) (32-core)</td>
<td>-</td>
<td>606.85</td>
<td>667.25</td>
<td>975.94</td>
<td>1505.20</td>
<td>3135.63</td>
<td>-</td>
</tr>
<tr>
<td>(P_{\text{SWSR}}) (8-core)</td>
<td>-</td>
<td>-</td>
<td>52.85</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

\(^4\)The value is hosted in 64\(\lambda\) column for compactness as a separate column for 56\(\lambda\) would have been needed.
Performance was evaluated for the PARSEC 2.1 benchmark suite, a collection of heterogeneous multithreaded applications spanning different emerging application domains [Bienia et al. 2008; Barrow-Williams et al. 2009]. These benchmarks, comprising artificial visions, media processing, 3D and physical animation, search similarity and featuring parallel algorithms, are representative of the current and near future usage of high-end client devices such as smartphones and tablets [Falaki et al. 2010]. All benchmarks were instantiated with a degree of parallelism of 8, 16 or 32 threads, one per core and we used the medium input-set size to maintain a reasonable simulation time while using a good amount of executed instructions. Benchmarks were modified to enforce that each spawned thread is pinned to a fixed core of the processor (i.e., core affinity). This approach allows avoiding some non-determinism in the parallel benchmark execution. This way, the Linux 2.6.27 operating system, booted on our simulator, assigns each thread to the same core across successive executions so that network performance differences are not influenced by possibly different positioning of threads on the mesh but only by the network itself. Parsec benchmarks are composed of a) a well-defined initialization portion, in which the required threads are spawned, b) the parallel region (called “region of interest”, ROI) and c) the final part in which benchmark resources are released. For performance metric, in line with similar works, we considered the execution time of the entire parallel region (ROI) of each benchmark as representative of the end-user perceived parallel performance. The total dynamic and static energy dissipated by all optical (lasers, modulators, photo-detectors and microring resonators) and electronic modules have been taken into account for evaluating overall consumption.

Results for 32-core architectures will be used to discuss how 16-core results can be scaled toward future high-end embedded architectures for client devices.

5.2. Result discussion
In the following we will discuss the execution time and energy consumption results of the different ring access schemes for various architectures (number of cores) and for different overall available optical bandwidth. We will highlight the cross-interference between all these facets and, in particular, also to the most suitable fraction of the overall traffic that can be fruitfully routed on the photonic path in each considered configuration.

5.2.1. Control message selection (GETS+INV+ACK). At first, we consider the case when only a specific set of latency-critical control messages is forwarded onto the photonic path. This selection encompasses read requests (GETS), invalidations (INV) and invalidation acknowledgements (ACK) and has been shown to be promising for improving execution time performance [Bartolini and Grani 2012] when limited optical bandwidth is available on-chip (1-ring, 56 wavelengths and SWSR access scheme for an 8-core system in case of full connectivity). In such work, the authors highlight that further increasing traffic in photonics induces queuing effects on the optical network interface that degrade performance. Figure 5 confirms that this message selection achieves different execution time improvements for 8- and 16-core configurations and for all access strategies. In particular, SWSR access scheme, which provides contention-free 1-bit wide independent channels, is able to improve performance by 8% on the 8-core setup. For the 16-core configuration MWSR improves 12% over the electronic baseline. Then, this message selection scores up to 23% (8-core) and 18% (16-core) average speedup for MWMR access strategy, with a peak of 41% and 62% improvement for ferret (8-core) and canneal (16-core), respectively. These results confirm the observation that cache coherent traffic is not uniform [Pan et al. 2010] and so benefits more from channel parallelism than transmission concurrency.
The main problem with this message selection resides in energy consumption. *canneal* benchmark shows an improvement of 17% and 34% for MWSR strategy with 8- and 16-core setups, respectively, due to its high degree of fine grain sharing that takes big advantage from the acceleration of some very latency-critical messages. MWMR strategy induces more than 25% energy degradation over the baseline despite scoring good performance (22% and 18% on 8- and 16-core setups, respectively). This is mainly due to two reasons: the first one is that MWMR has high static power consumption (see Section 4.1); the second reason is that selecting such messages, only about 7-8% of the total traffic is forwarded in photonics (Table IV, GETS-INV-ACK row) thus preventing to take significant advantage from the very low-power capabilities of the optical link.

5.2.2. ALL-TRAFFIC-WITH-CLOSE-FAR. Table IV shows the percentage of traffic that use the electronic network or the optical path in the 8-, 16- and 32-core setups with the GETS-INV-ACK and ALL-TRAFFIC-CF traffic selection strategies. With ALL-TRAFFIC-CF (CF stands for close-far), every message is forwarded onto the photonic path unless it needs to travel only one hop, i.e., it is close. In this case, the ENoC is preferred because, in our setup, it is able to manage the transmission with an acceptable latency compared to the ultra low-latency optical path and this, at the same time, maintains the ring free for other farther communications. Indeed in our system
Table IV. Traffic distribution between the electronic and photonic networks for two different message selection rules.

<table>
<thead>
<tr>
<th>Message selection</th>
<th>8-core</th>
<th>16-core</th>
<th>32-core</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>E-traffic</td>
<td>0-traffic</td>
<td>E-traffic</td>
</tr>
<tr>
<td>GETS-INV-ACK</td>
<td>92%</td>
<td>8%</td>
<td>93%</td>
</tr>
<tr>
<td>ALL-TRAFFIC-CF</td>
<td>55%</td>
<td>45%</td>
<td>25%</td>
</tr>
</tbody>
</table>

one hop on the ENoC requires five processor cycles (four for the switch and one for link traversal) versus the best case achievable for a control message (64 bits) optical transmission with MWMR 1-ring, which takes two-four processor cycles as explained in Section 4.1. Furthermore these latency are the best case occurring when the channel is idle. A 1-hop data transmission (576 bits) in the ENoC would require nine processor cycles (four for the switch and five for link traversal (576 (message length) / 128 (flit width) = 4.5 flits hence five cycles)) versus five (best case, token near) or seven (worst one, token far) processor cycles on the 1-ring MWMR scheme. Therefore, in non-idle conditions the transmission time of the ENoC and ONoC in case of just 1-hop are similar. Instead, for instance, in case of a 2-hop ENoC transmission a control message would take 10 processor cycles compared to the same two-four processor cycles of the optical transmission. These observations confirm that close-far routing makes sense.

For the 8-core setup, even in ALL-TRAFFIC-CF, the number of messages traveling 1-hop distances is quite high and for this reason only 45% of the total traffic goes into photonics. While, for bigger meshes (16/32 cores) 1-hop transmissions are less likely and traffic in photonics reaches 75% and 90% for 16- and 32-core setups, respectively.

In terms of execution time, this traffic level makes the relatively narrow-bandwidth SWSR strategy not suitable to seek good performance due to severe serialization and queuing problems. The 8-core configuration (the only considered with this strategy) suffers almost 2x slowdown over the electronic baseline as shown by Figure 6. Considering the 8-core, in SWSR full-connectivity case, each endpoint (tile) needs to have one lambda to transmit toward each of the other endpoints (7), thus requiring $7 \times 8 = 56$ total lambdas. This number scales down to $56 - 20 = 36$, supposing to introduce our close-far routing rule.

In the direction of increased parallelism in message transmission, MWSR strategy reaches 13% average improvement for 8-core setup but it is 15% slower than electronic baseline with 16 cores, indicating that the ring starts to be over-exploited due to increased number of endpoints and traffic intensity.

Then, MWMR scheme achieves an average 23% performance improvement both for 8- and 16-core configurations, with a peak of 59% and 52% for blackscholes and canneal, respectively, on the 16-core setup. This confirms that traffic unbalance [Pan et al. 2010] and high parallelism in message transmission (MWMR) can allow the same photonic resource (i.e., one ring) to deliver better performance than MWSR scheme, even if the ring needs to be used in mutual exclusion.

Summarizing, in comparison to GETS-INV-ACK message selection (Figure 5), the ALL-TRAFFIC-CF (Figure 6) induces some performance degradation for SWSR and MWSR strategies due to traffic queuing on the photonic path. SWSR becomes quite slower than our reference baseline. MWSR still improves for the baseline on the 8-core configuration but gets worse as traffic increases in the 16-core setup. Conversely, MWMR slightly improves the performance advantage thanks to the high transmission parallelism. In general, results show that every scheme is able to provide some performance advantage, especially if working on the most latency-critical messages. The advantage tends to increase as the traffic increases up to the point where the given photonic resource gets saturated and, in an avalanche-effect, messages start spending...
Design Options for Optical Ring Interconnect in Future Client Devices

(a) Time 8-core  
(b) Energy 8-core  
(c) Time 16-core  
(d) Energy 16-core

Fig. 6. Comparison of the access management strategies normalized to the electronic baseline on 8 cores ((a) and (b)) and 16 cores ((c) and (d)) configurations with ALL-TRAFFIC-CF traffic selection rule. In (b) and (d) the four bars have the same meaning as in (a) and (c).

a significant time in waiting. The analysis of the effects of photonic resource increase is addressed in section 5.2.4.

On the energy consumption side, for the 8-core configuration MWSR shows a significant improvement from increasing the traffic on the optical path as more messages can take advantage from the low-energy optical technology. In fact, Figure 6 shows that a significant fraction of the dynamic energy of the baseline mesh is traded for optical dynamic energy, which has a smaller energy/bit cost. Energy reduction compared to all-electronic mesh is about 25% on average, with canneal reaching up to 42%.

The narrower-bandwidth strategy (SWSR) instead suffers from serialization and the consequent slowdown causes a dramatic increase in static energy of both electronic and optical NoC. Overall, this effect reverses the energy advantages of the dynamic component and leads to 1.67x increase in energy consumption.

The best scheme from the execution time point of view (MWMR) equals the baseline mesh consumption because the optical static power is so high that erodes both dynamic energy advantages and ENoC static energy savings due to faster execution. In conclusion, only MWSR scheme is a reasonable solution for the 8-core setup.

Figure 6d shows that for our 16-core setup dynamic energy advantages are eroded by the static energy quotes, both electrical and optical. Both MWSR and MWMR schemes
achieve limited energy advantages (5% and 3% respectively), despite the bigger percentage of messages that can exploit the low energy consumption of the ring, than in the 8-core case (Table IV).

Summarizing, the 16-core setup is very critical as MWMR is able to deliver some execution time advantage but no energy saving, while MWSR incurs in slowdown and no substantial energy advantage or degradation over the full-mesh baseline.

5.2.3. ALL-TRAFFIC. As final step now we want to analyze the behavior of the benchmarks when all the traffic (ALL-TRAFFIC) is forwarded onto the optical ring. In this case the ENoC is no more needed in the chip and, for this reason, its energy quotes are present only in the baseline bars of the following figures.

Figure 7c shows that despite the increase of traffic on the photonic path, the MWMR strategy is still able to sustain it and delivers around 20% execution time improvement for both 8- and 16-core setups. Conversely, MWSR instead is not able to do the same especially for the 16-core setup. Indeed MWSR can still achieve an average 8% improvement for 8-core configuration but suffers 34% slowdown when adopted on a 16-core setup due to queuing issue at the network interfaces.

Considering the results in terms of energy consumption now a huge improvement is possible because all the dynamic and static energy of the electronic part is no more
present. ALL-TRAFFIC rule allows saving more than 65% energy (8-core) for the MWMR strategy and up to 85% for the MWSR one, thus definitely confirming the rated energy advantages of on-chip photonics in the tiled CMP scenario. For the 16-core setup MWMR and MWSR schemes still score very good energy results even if a bit worse than in the 8-core case (59% and 84% reduction, respectively). Static power consumption makes the difference between the considered schemes. MWSR requires far less microring resonators and induces a smaller insertion loss on the waveguide, thus has a smaller static power consumption.

As a general remark, these results highlight that even a simple photonic path, as a ring, can save significant energy over an electronic NoC with both access schemes. However, MWMR is able to deliver both execution time and energy advantages.

We can also notice that now the optical dynamic energy quote is more evident than in previous figures. In fact, now all the CMP traffic is managed by the optical ring and the difference between ENoC and ring dynamic energy reflects the energy/bit difference between the two transmission technologies.

5.2.4. INCREASING BANDWIDTH (RING NUMBER). All previous results were obtained for 1-ring (1R) optical setups, where one ring manages message transmission with a DWDM parallelism (see Section 4.2). But what happens if we try to increase the available bandwidth for the ALL-TRAFFIC routing?

Figure 8 shows average benchmark results for 8- and 16-core architectures (left and right sections of the graphs, respectively) when the available rings for message transmission increase from one to two, four and eight/nine with an overall wavelength parallelism growing up to 512/576. For MWMR scheme we opted to show 9-ring (9R) results instead of 8-ring ones (8R) because our data coherence messages are 72-byte long (576 bits) and in MWMR all wavelengths are used together for message transmission. Thus with 9-ring configuration MWMR needs only one optical aggregated flit, among the nine rings, to transfer a full message. Conversely, MWSR splits the overall aggregated DWDM capability of the rings between the ring endpoints therefore the parallelism of each transmission is far below data message size even with the 8-ring setup.

For completeness, the first two bar groups of Figure 8 show results for 1-ring (1R) with more conservative 16- and 32-wavelength parallelism (WDM), instead of 64/70 (DWDM). The figure shows that MWMR access strategy starts to have problems in
managing the traffic especially for the 16-core setup. More than 20% slowdown for 32-wavelength setup and 2.5x slowdown for the 16-wavelength one. MWMR for the 8-core, 32-wavelength setup still grant an 8% speedup while the narrower configuration slows down by more than 40%. In contrast, MWSR is unusable for these narrower configurations as the available message bandwidth per endpoint is too low (1/2/4 bits) and each transmission suffers very long serialization time.

From the energy point of view the low static consumption of the structures with limited wavelength parallelism allows obtaining good results (more than 80% energy reduction) in all the analyzed cases apart for the 16-lambda, 16-core one with MWSR strategy in which the static consumption of the additional ring necessary to manage the 16 tokens, gives a significant contribution on the overall energy consumption resulting in a more limited 40% energy improvement.

It is very interesting to highlight that going toward inferior wavelength parallelism, MWMR static energy quote becomes smaller than in MWSR for two reasons. First, the latter has a tremendous slowdown that wastes more static power. Second, reducing ring parallelism has a major effect on static power in MWMR scheme than in MWSR one, as shown in Table III.

Instead, going in the direction of increasing parallelism can change the relative performance of the schemes. In fact, the 8-core configuration with double bandwidth (2R-8C histograms) achieves good performance improvements for the MWSR which almost equals MWMR (20% vs 23%). Energy results in Figure 8 for the 8-core setup are very interesting. Indeed, MWSR still provides around the same results as the 1-ring case (considering a little reduction due to the crossing between the two rings) while MWMR scheme requires far more energy and allows only a limited (18%) reduction. Therefore, with almost the same performance results, in this case MWSR scheme is much preferable than MWMR for the 8-core architecture.

For 16-core setup, 2R-16C histograms shows that MWMR scheme induces a similar speedup (20%) as in the 8-core case but MWSR equals the mesh baseline execution time. From the energy point of view, the situation is similar to the 8-core case with MWMR scheme saving about 15% and MWSR up to 82% over the baseline. Summarizing, for 16-core, 2-ring, MWMR scheme allows significant speedup and reasonable energy saving while MWSR equals mesh performance but provides big energy savings.

Further increasing the available bandwidth to 4- or 9/8-ring (nine rings for MWMR and eight for MWSR) doesn’t give significant advantages in the 8-core setup for both MWMR and MWSR schemes, which perform practically the same and show a linear increase in energy consumption as the ring number increases. Conversely, on the 16-core setup, MWMR further improves performance to about 30% for 4- and 9-ring configurations. MWSR reaches 25% improvement for 4-ring setup and saturates to 32% for 8-ring one. The effects on energy consumption is again extremely interesting for putting into perspective the results of the considered schemes and wavelength parallelism. In fact, 4- and 9-ring for MWMR scheme are absolutely bad configurations from the energy point of view, degrading respectively by around 2x and more than 6x over the baseline. The extremely high static power of each MWMR ring is detrimental when many rings are employed.

Conversely, MWSR is far more stable with ring number increase due to the smaller static energy footprint of the required rings. In addition, especially moving from 2- to 4-ring configuration, the small increase in static energy quote is favored by the faster execution time and still scores 62% and 75% reduction for 8- and 16-core setups respectively. In fact, going to 8-ring setup, the static quote raises more evidently as the higher consumption of the required photonic structures is not balanced by a substantial speedup. In practice, execution time speedup saturates at 4-ring configuration.
We can conclude that for the 8-core setup the best design choices can be the MWMR, 1-ring (64 data wavelengths) and the MWSR, 2-ring which deliver near maximum speedup (about 20%) and significant energy saving (68% and 77%, respectively).

Instead, for a 16-core architecture the most profitable design points are the 1- or 2-ring setups, for MWMR scheme and the 4-ring for MWSR one. These allow reaching 20%, 25% and 24% execution time speedup, respectively, with 59%, 15% and 75% energy reduction. Indeed, MWMR 1-ring appears quite flexible for both 8- and 16-core setups while 4-ring MWSR reaches good performance with great energy saving.

5.2.5. SCALABILITY STUDY TO 32 CORES. Previous results show that, according to the number of cores and the access strategy, a minimum bandwidth must be granted to have good execution time. Then, the most suitable mix of photonic resources and access scheme must be chosen with care for seeking also energy reductions.

We analyzed this trend also for a more aggressive 32-core architecture, whose results are shown in Figure 9. Here the contention in accessing the photonic medium is higher than in previous setups. We have summarized into Figure 9 the same three previous message selection configurations, GETS-INV-ACK (CONTROL in figure), ALL-TRAFFIC-CF (ALL-CF in figure) and ALL-TRAFFIC (ALL in figure). For clarity and space reasons we show only the average results across the considered benchmarks.

Results show that one ring, 64 wavelengths wide, is not enough in this setup. The only 1-ring configuration that is able to improve execution time (-18%) is the one with only latency-critical control messages forwarded into the optical ring and MWMR scheme. This is due to the fact that only 5% of the traffic (see Table IV) is routed on the photonic path, thus without clogging it and, consequently, getting transmission speedup. The main issue of this message selection strategy is that the potential very low-energy consumption of the optical path is not exploited at all by the tiny traffic fraction going into it, resulting in more than 20% energy degradation over the baseline for MWMR. MWSR provides just a slight execution time improvement (9%) with a small energy degradation (7%).

We know from previous results that increasing the traffic on the 1-ring setup would help improving energy saving. With 32 network endpoints, the ALL-TRAFFIC-CF allows some reduction (7%) in energy consumption with practically baseline equivalent
execution time and only in case of the MWMR strategy. Actually, the adoption of a hybrid electro/optical network is not justifiable in this case. Conversely, forwarding all the traffic (ALL-TRAFFIC) and using MWMR access scheme, 1-ring, DWDM degree, allows a significant 61% energy reduction at the cost of a 11% slowdown. MWSR would save even 72% but incurring in more than 3x slowdown. Impressively, even a 32-wavelength, 1-ring setup with MWMR would allow 78% energy saving but also 2.2x slowdown.

Summarizing, all traffic on the optical guide requires at least a 2-ring configuration to reach good performance with MWMR scheme. In fact, in this case, 18% execution time improvement are obtained saving 36% of the energy. Increasing ring parallelism cannot deliver better overall solutions for MWMR as with a 4-ring setup execution time reduction reaches 27% but energy consumption gets 50% worse than the baseline. And with 9-ring architecture it is even worse from the energy point of view (5.21x degradation) even if execution time improvement reaches 32%.

Thus, unless the objective is trading energy consumption for higher performance with the MWMR scheme the 2-ring setup appears the best tradeoff.

It is interesting to highlight that increasing the number of available rings is, conversely, very useful for the MWSR scheme. In fact, Figure 9 shows that even if 2-ring configuration hits a 36% slowdown, 4- and 8-ring setups induce execution time improvements of 18% and 40% (best overall), respectively, with a remarkable and very stable energy consumption in all these three configurations (77-80% range). In practice, increasing optical resources with MWSR scheme induces higher static power but its absolute value is more or less compensated by the execution time acceleration.

We can conclude that MWSR strategy is the most convenient when it is possible to integrate numerous rings and give high-bandwidth to each transmission.

5.3. Ring WDM scaling exploration

In this section we analyze the correlation between energy consumption and the number of wavelengths fitted into an optical guide, at a given overall wavelength parallelism. In fact a single waveguide with half WDM degree has a smaller insertion loss and thus a lower static energy consumption. However, to match the overall WDM degree, two similar waveguides are needed and the internal one has to suffer the crossing insertion loss of the supply waveguide. The resulting tradeoff is not obvious and depends on all design choices.

Fig. 10. Energy consumption of optical network normalized to the all-electronic baseline.
We will explore the design space up to 8 concentric rings, which is far below the overall number (some hundreds) of waveguides proposed in some works in literature [Vantrease et al. 2008; Pan et al. 2009; Kurian et al. 2010] and we show that we can still maintain the positive features of the “ring” organization. Naming convention of the considered test cases in Figure 10 are quite self-explanatory: 4R-16WL-MWMR-16C indicates a 4-ring configuration with 16 wavelengths per ring (64 overall) and using a MWMR scheme on a 16-core architecture. We considered the best configurations identified so far for 16- and 32-core setups for both MWMR and MWSR schemes. Table V shows the considered optical static energy (lasers and microrings) values. For reference, each table subset shows in bold also the best configurations selected in the previous discussion. For instance when we need 128 total lambdas, the 2-ring configuration is the considered reference (2R-64λ). To reach the same parallelism we can use four rings with 32 lambdas each or eight rings with 16 lambdas each.

<table>
<thead>
<tr>
<th></th>
<th>(16-core)</th>
<th>(32-core)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>MWMR-64A</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>1Rx64λ</td>
<td>933.03</td>
<td>-</td>
</tr>
<tr>
<td>2Rx32λ</td>
<td>615.45</td>
<td>-</td>
</tr>
<tr>
<td>4Rx16λ</td>
<td>568.20</td>
<td>-</td>
</tr>
<tr>
<td>8Rx8λ</td>
<td>715.22</td>
<td>-</td>
</tr>
<tr>
<td><strong>MWMR-128A</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2Rx64λ</td>
<td>-</td>
<td>4044.11</td>
</tr>
<tr>
<td>4Rx32λ</td>
<td>-</td>
<td>2898.70</td>
</tr>
<tr>
<td>8Rx16λ</td>
<td>-</td>
<td>3227.27</td>
</tr>
<tr>
<td><strong>MWSR-256A</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>4Rx64λ</td>
<td>579.98</td>
<td>1505.20</td>
</tr>
<tr>
<td>8Rx32λ</td>
<td>715.07</td>
<td>2376.00</td>
</tr>
</tbody>
</table>

Table V. Static parameters of the optical network with different WDM degree and waveguide number. [mW]

Figure 10 shows that the decreasing wavelength parallelism inside a single waveguide can be useful to get additional energy consumption benefits until a certain point. On a 16-core setup with MWMR scheme, the usage of two or four rings allows further decreasing energy consumption by another 12% and 14% respectively, over the 59% gain already obtained by the baseline 1-ring, 64 WDM. The usage of eight rings also permits to scale down (67%) the energy consumption compared to the electronic baseline but the achieved benefits are relatively less than using two or four rings. In this case best results are obtained with the four rings setup.

Also for the 32-core architecture, MWMR shows a similar trend. Going from the baseline 2-ring, DWDM configuration to 4-ring one allows reaching the best overall saving of 50%, while, also in this setup, the usage of eight rings slightly degrades the improvement over the baseline to only 45%. Hence also for the 32-core configuration four rings is again the best choice.

Results are different for the MWSR scheme. Indeed, as shown by Figure 10, the previously selected configurations are already the best ones in terms of energy consumption. In fact, for 16-core architecture going from 4- to 8-ring setup causes a degradation of 5% in energy consumption even if still outperforming the electronic baseline by 69%; results are worse also for the 32-core one where the degradation is about 16%, reducing the benefits achieved on the electronic baseline to 55%. The reason is that in the 8-ring configuration insertion loss benefits of a smaller WDM degree per waveguide are surpassed by the insertion loss overheads due to crossings due to internal waveguides.

As last remark on these results, Figure 10 shows that if there are not stringent constraints on the number of photonic structures to be deployed on-chip, the maximum energy saving potential of MWMR and MWSR schemes are more similar than when using the same number of rings, at least for the 16-core setup. Indeed MWSR still maintains more than 20% energy advantage over MWMR for 32-core configuration.
6. RELATED WORK

Recently, a number of photonic-based networks have been studied and several works have been presented to compare electronic and photonic interconnects [Goodman et al. 1984; Shacham et al. 2008; Banerjee et al. 1999].

These solutions span from simple photonic rings that behaves like an optical crossbar-based photonic NoC for on-chip communication like those presented by [Vantrease et al. 2008], [Pan et al. 2009], [Kurian et al. 2010], [Pasricha and Bahirat 2011], [Bahirat and Pasricha 2009] and [Xu et al. 2011], to more articulated ones like [Petracca et al. 2008] and [Shacham et al. 2008], combining different technologies.

Our work instead is focused on one, or a few, photonic rings and then exploiting the best features of nanophotonics while avoiding the negative effects of its shortcomings, with the global objective of decreasing the overall energy consumption in the interconnection. In [Bahirat and Pasricha 2012], the authors present an architecture similar to the one analyzed in this work but with a quite higher number of waveguides (32-256), and different usage. Indeed they use a Particle Swarm Optimization approach in a hybrid photonic-ring/electrical-mesh NoC for defining the programmable photonic regions of influence (PRI), which are interconnected through rings while a standard ENoC is used inside them. Furthermore the authors present a dynamic reconfigurable traffic partitioning technique to balance photonic and electronic traffics.

Specific proposals show quite scalable architectures for high-performance systems that are able to manage up to thousand nodes and some hundreds of optical waveguides, using clustered architectures with a large number of optical resources [Vantrease et al. 2008; Pan et al. 2009; Kurian et al. 2010]. Then, [Xu et al. 2011] are more focused on coherence issues proposing a composite cache coherence protocol that benefits from direct cache-to-cache photonic accesses as in a snoopy protocol.

Our work instead is focused toward rich client systems hence more conservative choices have been considered both in terms of running cores and number of waveguides. In this context, energy consumption becomes the most important concern while not inducing performance slowdown over the electronic counterpart. [Pasricha and Bahirat 2011] proposed a 3D-stacked optical simple architecture that combines multiple photonic rings on various photonic layers with a 3D mesh NoC in active layers. Previously the same authors [Bahirat and Pasricha 2009] explored the usage of only one ring to facilitate global on-chip communication between distant processors and memory cores in high-performance CMPs. In our work, instead, we address one or a few concentric photonic rings on the same optical layer with one endpoint per core with the main target of minimizing energy consumption.

Within proposals with more complex topologies [Petracca et al. 2008; Shacham et al. 2008; Hendry et al. 2009] employ a preliminary optical path setup through a helper electronic networks (active networks). This can potentially limit the latency and energy advantages of photonics depending on the lifespan of optical paths versus setup overhead and due to possible waiting time for contended sub-paths. We focus on a simpler ring-based structure as it can potentially deliver significant latency and energy improvements without investing in more articulated photonic topologies.

Other proposals implement passive wavelength routing [Brière et al. 2007; Koohi et al. 2011; Le Beux et al. 2011], which relies on statically configured optical switches and WDM to obtain conflict-free full connectivity between all network endpoints. All paths connecting every source-destination pair can be used concurrently but the degree of parallelism of each one is limited (e.g., one bit).

[Li et al. 2009] proposed a CMOS-compatible nanophotonic on-chip network with multi-layer design consisting of a WDM multicast sub-network and a throughput-optimized circuit-switching nanophotonic sub-network. In such work, photonic signals
travel over the air, relying on the reflection of light on a specific surface over the wafer itself. In our work we explore the utilization of a 3D-stacked photonic layer with up to a few rings to enhance a standard 2D electronic mesh under multithreaded workloads.

[Bartolini and Grani 2012] evaluated the performance improvements reachable in a 16-core CMP endowed with 2D-mesh assisted by a single ring using SWSR and accelerating a few latency-critical messages. In [Bartolini and Grani 2013] a co-design of a hybrid electronic-optical architecture is proposed, in which the latency-critical traffic is diverted on a single optical ring to enable the usage of a slower and low-power electronic network to seek energy improvements without performance slowdown.

7. CONCLUSIONS
In this paper we addressed the various design choices around the usage of a simple photonic network (ring topology) mainly aimed at reducing energy consumption and, where possible, execution time in high-end tiled CMP embedded systems like smartphones and tablets (i.e., client devices).

Silicon photonics has low-latency and low-energy raw features but photonic interconnection is very different from switched on-chip network and adds a number of new design space directions. For these reasons, only through a comprehensive analysis of such choices, their mutual interaction in the CMP scenario, is possible to exploiting its full potential and, most of all, avoid suboptimal designs.

We investigated 8-, 16- and 32-core setups in order to cover current and near future design requirements. Our focus has been on limited photonic resources (e.g., up to a few rings and no optical switches) and simple organizations as they are more likely to be employed in commercial devices sooner.

We evaluated different access and management strategies of the available bandwidth in one or multiple ring organizations. In fact an access strategy (e.g. MWMR) giving all the available optical parallelism to a communication, induces a very fast message transmission but implies mutual exclusion and requires higher static power consumption. Other ones (e.g., SWSR or MWSR) are more energy-efficient, allow multiple contemporary transmissions but each with narrower parallelism, which in turn can be detrimental for performance and, indirectly, for energy too. Therefore, understanding the best design choices for every configuration is far from obvious. We investigated these aspects for both all-optical and for hybrid electronic/photonic on-chip networks in conjunction with various traffic splitting strategies.

Summarizing, we identified the best mix of design choices for the considered architectures and for each amount of photonic resources and overall bandwidth employed. Specifically, we showed that in hybrid electronic/photonic NoC, the selection of latency-critical control messages can induce performance benefits for all access schemes (up to 22%) and the simpler ones achieve also a marginal energy reduction (5%).

The only way to have significant energy consumption improvements is to increase traffic into optics and, meanwhile, using more aggressive access schemes or increasing photonic parallelism (ring number). We showed that all traffic can be served by one photonic ring with MWMR access scheme achieving 20% and 21% speedup and 68% and 59% energy reduction, respectively for 8- and 16-core systems.

To reach maximum energy saving, the less power-hungry access schemes is needed (MWSR) but with increased optical parallelism so that it can score also performance benefits. We demonstrated that such scheme can reach up to 40% speedup or up to 80% energy reduction using multiple rings.

Lastly we showed that in case of the MWMR strategy, energy consumption can be further reduced if more rings, each with less parallelism, can be employed to obtain the same total optical bandwidth. With this configuration this technique obtains an overall energy reductions of up to 73%.
REFERENCES


Design Options for Optical Ring Interconnect in Future Client Devices


