WAVES: Wavelength Selection for Power-Efficient 2.5D-Integrated Photonic NoCs

Aditya Narayan*, Yvain Thonnart†, Pascal Vivet†, César Fuguet Tortolero† and Ayse K. Coskun*

*Boston University, Boston, MA 02215, USA; E-mail: {adityan, acoskun}@bu.edu
†Université Grenoble Alpes, CEA-Leti, Grenoble, France; E-mail: {first.last}@cea.fr

Abstract—Photonic Network-on-Chips (PNoCs) offer promising benefits over Electrical Network-on-Chips (ENoCs) in manycore systems owing to their lower latencies, higher bandwidth, and lower energy-per-bit communication with negligible data-dependent power. These benefits, however, are limited by a number of challenges. Microring resonators (MRRs) that are used for photonic communication have high sensitivity to process variations and on-chip thermal variations, giving rise to possible resonant wavelength mismatches. State-of-the-art microheaters, which are used to tune the resonant wavelength of MRRs, have poor efficiency resulting in high thermal tuning power. In addition, laser power and high static power consumption of drivers, serializers, comparators, and arbitration logic partially negate the benefits of the sub-pJ operating regime that can be obtained with PNoCs. To reduce PNoC power consumption, this paper introduces WAVES, a wavelength selection technique to identify and activate the minimum number of laser wavelengths needed, depending on an application’s bandwidth requirement. Our results on a simulated 2.5D manycore system with PNoC demonstrate an average of 23% (resp. 38%) reduction in PNoC power with only <1% (resp. <5%) loss in system performance.

I. INTRODUCTION

The core count in manycore systems is increasing to support extremely parallel data-intensive applications with higher compute performance and improved energy efficiency needs [1]. This dense integration of cores results in larger die sizes, which cause lower yield and, as a result, cost challenges. 2.5D integration of smaller chiplets on a large interposer chip has the potential to achieve a higher throughput per watt (or per volume) at a higher manufacturing yield than a large 2D chip [2], [3]. However, with a large core count and longer distances between chiplets, the system performance and energy efficiency is then bottlenecked by the Network-on-Chip (NoC) latencies and bandwidth.

Photonic NoCs (PNoCs) with wavelength-division multiplexing are currently emerging as promising alternatives over Electrical NoCs (ENoCs). In PNoCs, multiple optical signals can be multiplexed onto the same waveguide using microring resonators (MRR), thereby enabling a high internal bandwidth [4]–[6]. Numerous works demonstrating the feasibility of integrating photodiodes [7], low-loss waveguides [8], grating couplers [9], and MRR modulators and filters [10] through slightly adapted or unmodified CMOS process have paved the way for efficient realization of PNoCs.

Figure 1 shows an example PNoC. An off-chip laser source emits multiple optical signals that are coupled onto an on-chip waveguide using grating couplers. MRRs that are fabricated with particular dimensions to resonate at desired laser wavelengths perform data modulation at the transmit site (Tx) as well as data filtering at the receive site (Rx). An MRR modulates the serialized data at Tx onto a laser wavelength, by resonating at the same wavelength as the laser. The optical signal travels through the on-chip waveguide and is filtered at Rx by an MRR that is also resonating at the same wavelength. Based on the intensity of the detected optical signal by the photodetector, a transimpedance amplifier (TIA) feeds the output electrical signal to Rx comparators that deserializes the data.

However, a major factor hampering the maturity of PNoCs is the significant power overhead of the lasers, drivers, serializers, comparators and arbitration logic that increases linearly with the number of laser wavelengths in the system [11], [12]. Furthermore, the MRRs undergo resonant wavelength shifts due to on-chip thermal variations (TV) and manufacturing process variations (PV). The MRRs are typically supplied with heating power to tune them back to desired laser wavelengths and compensate these TV- and PV-induced wavelength shifts. This heating power, however, can get as high as 30% of the system power [11], thereby adversely impacting the promises of sub-pJ advantages of silicon PNoC technology.

Recent design-level innovations show that an analog thermal control loop can remap and lock the MRRs to laser wavelengths compensating for TV- and PV-induced wavelength shifts within 100μs [13]. This thermal tuning interval is greater than the laser power on/off latency (<5ns with <100pm transient error [14]), which enables us to selectively activate laser wavelengths. In our work, we demonstrate that the bandwidth requirements for different applications vary substantially and, therefore, activating all the available laser wavelengths results in increased PNoC power with minimal performance improvement. These observations motivate the need to identify and activate a reduced number of laser wavelengths based on an application’s bandwidth requirements. Since the MRR lock latency dominates laser switching time, our technique provides a low-latency wavelength selection to reduce the PNoC power. Our major contributions are as follows:

1) We design a wavelength selection technique, WAVES, by accounting for the on-chip TV and PV. Based on the bandwidth requirement of an application, WAVES identifies the minimum number of laser wavelengths and activates the best combination resulting in reduced PNoC power consumption with minimal losses in performance.

2) We develop a cross-layer simulation framework to model the system performance and PNoC power (laser, electronics and heating) under different activated laser wavelengths and MRR lock status, which is a strong function of on-chip TV and PV. Through this framework, we explore the optimizations of PNoC power arising from the device-level MRR locking under different system-level constraints (DVFS, thread combinations), based on technology parameters measured on silicon. Our simulation results on a 96-core 2.5D system with PNoC demonstrate 23% (resp. 38%, 42%) reduction in PNoC power with only 1% (resp. 5%, 10%) performance loss.

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II. RELATED WORK

Several prior approaches address the challenge of designing energy-efficient PNoCs. Bahadori et al. explore the tradeoff between an increased number of channels at a high bitrate for maximum aggregated bandwidth and the energy consumption of a PNoC [15]. Luo et al. propose an optimized wavelength allocation by mapping an application task graph onto the system architecture, thereby reducing laser power arising from increased bit error rate [16]. In contrast, our proposed wavelength selection addresses the tradeoff between system performance and PNoC power by activating a sufficient number of laser wavelengths, depending on an application's bandwidth needs.

A primary component of PNoC power is the high heating power overhead required to thermally tune the MRRs to the laser wavelength and to overcome the TV and PV. Major efforts to improve the efficiency of thermal heaters at the device-level include full-FSR tuning range [17], polymer material coating to prototype athermal materials [18], and substrate removal underneath the MRRs for ultralow tuning power [19].

However, most of the efforts focusing on PNoC design is cognizant to the running application or the system architecture, indicating an opportunity for optimization at a system-level. There have been prior efforts to manage thermal gradients around communicating MRRs using temperature-aware thread allocation and migration. RingAware [20] and FreqAlign [21] are workload allocation policies that balance temperature around MRRs to reduce the thermal tuning range. Aurora [22] encompasses a cross-layer approach to reduce thermal tuning power by applying bias current to MRRs to control small TVs, performing DVFS and packet routing around hotter regions and running a scheduling policy for the outer cores.

A common drawback of these techniques is the performance overhead due to thread migration, scheduling or packet-routing. Our wavelength selection technique incurs low latency with minimal storage overhead. To our knowledge, our work is the first to provide a detailed account of PNoC power for a 2.5D manycore system with PNoCs. Our wavelength selection approach, WAVES, is orthogonal to most prior system-level studies and can be combined with them to develop an energy-efficient PNoC.

III. 2.5D MANYCORE SYSTEMS WITH PNoC

In this section, we first present our target 2.5D manycore system with PNoC called Processors On Photonic Silicon inTerposer ARchitecture (POPSTAR) and then provide details on computing the total PNoC power consumption (including laser, drivers, serializers, comparators, TIA and thermal tuning).

A. Architecture overview

POPSTAR is a 2.5D manycore system with a PNoC, consisting of six compute chiplets and eight TxRx chiplets stacked on a photonic interposer as shown in Fig. 2(a). The compute chiplets and the TxRx chiplets are designed using an STMicro C28FDSOI technology, and the photonic interposer uses an optical FEOL technology. An off-chip laser emits up to six wavelengths that are carried by a vertical fiber attachment and coupled onto the waveguides in the interposer via grating couplers.

1) Compute Chiplets: We assume that the 96 cores in POPSTAR are organized in six 3D-ready TSIARLET [3] compute chiplets, with each chiplet consisting of 16 cores, as shown in Fig. 2(a). Each core is a PNoC-based Single-Writer Multiple-Reader (SWMR) link as illustrated in Fig. 2(c). The SWMR topology is mapped onto a U-shaped spiral of waveguides on the interposer. The TxRx chiplets, described in Sec. III-A4, are responsible for the Electrical-to-Optical (E-O) and Optical-to-Electrical (O-E) conversion. Each of the six compute chiplets accesses the PNoC through a TxRx chiplet with a 96-bit wide interface operating at 750MHz. Two TxRx chiplets are used for servicing external IO and DRAM requests. Each wavelength supports a data rate of 12Gbps, resulting in a peak aggregate bandwidth of 576Gb/s.

3) Microring Resonator Group (MRRG): Each TxRx chiplet connects to an MRRG on the interposer. For every MRRG, there is one Tx waveguide and seven Rx waveguides coming from the other MRRGs forming a spiral of SWMR links as depicted in Fig. 2(c). All six wavelengths are evenly spaced in a free spectral range (FSR) of 10.8nm, resulting in a 1.8nm spacing between adjacent laser wavelengths, around a center wavelength of 1310nm. These wavelengths are modulated by Tx MRRs, and the TxRx chiplet filters those signals using six of its 42 Rx MRRs. We assume that all the 48 MRRs in an MRRG are normally maintained slightly off-resonance by the TxRx chiplet so that they are immediately responsive when required for communication [13].

4) TxRx Chiplets: A TxRx chiplet consists of the electronic circuitry for E-O and O-E conversion, as shown in Fig. 2(d). For every Tx MRR in an MRRG, there is a 16:1 serializer and a modulation driver. Similarly, for every Rx MRR in an MRRG, there is a filter bias, a TIA and a comparator. We assume that an analog thermal control loop (as shown in recent work [13]) detects the photodiode current and applies the heating power to thermally tune and lock the MRRs to the nearest laser wavelength. Finally, FIFO queues and multiplexers handle the flow control and communicate with the compute chiplets using local 2.5D passive connections.

B. Power consumption of the PNoC

The power consumption of a PNoC includes laser, serializers, drivers, comparators, TIA, arbitration and flow control, and thermal tuning and control. Table I displays the active and idle power of different elements in a POPSTAR and Table II lists the notations used in our work.

<table>
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<th>Component</th>
<th>Notation</th>
<th>Value (mW)</th>
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<tr>
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<td>$P_{dr, a}$</td>
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</tr>
<tr>
<td>Rx Comparator</td>
<td>$P_{cmp, a}$</td>
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</tr>
<tr>
<td>TIA</td>
<td>$P_{TIA}$</td>
<td>2</td>
</tr>
<tr>
<td>Arbitration and Flow Control</td>
<td>$P_{arb,i}$</td>
<td>32</td>
</tr>
</tbody>
</table>

Table I: Power consumption of different elements [11]
the overall timing control and consume idle power. Depending on a multiplexer handle the arbitration and flow control. The chiplet are active. On the Rx side, active channels are biased all the six serializers and six drivers within all the eight TxRx for transmitting data over the six available laser wavelengths, couplers, filters and modulators. The overall laser power, $P_{\text{laser}}$, can be expressed as:

$$P_{\text{laser}} = P_L \cdot C \cdot \lambda_{\text{act}} \quad (1)$$

The first stage in a PNoC is serialization, where the data is serialized to be modulated onto the MRR. To obtain an acceptable extinction ratio at the MRR, double-rail drivers with high voltage-swings ($> V_{DD}$) are typically used [11]. For transmitting data over the six available laser wavelengths, all the six serializers and six drivers within all the eight TxRx chiplet are active. On the Rx side, active channels are biased to filter the wavelengths. TIA amplifies the detected electrical signal from the photodiode and feeds the value to the Rx comparators, where the data is deserialized. FIFO queues and a multiplexer handle the arbitration and flow control. The serializers, comparators and arbiters are clocked for precise timing control and consume idle power. Depending on $\lambda_{\text{act}}$, the overall electronics power of all TxRx chiplets, $P_{\text{E/OE}}$, is determined as follows:

$$P_{\text{Tx}} = P_{\text{dr}} \cdot \lambda_{\text{act}} + P_{srl,i} \cdot \lambda_{\text{act}} + P_{srl,i} \cdot (\lambda_{\text{tot}} - \lambda_{\text{act}}) \quad (2)$$

$$P_{\text{Rx}} = P_{\text{TIA}} \cdot \lambda_{\text{act}} + P_{\text{comp,a}} \cdot \lambda_{\text{act}} + P_{\text{comp,i}} \cdot (\lambda_{\text{tot}} \cdot C - \lambda_{\text{act}}) \quad (3)$$

$$P_{\text{arb}} = P_{\text{arb,a}} \cdot \frac{\lambda_{\text{act}}}{\lambda_{\text{tot}}} + P_{\text{arb,i}} \cdot \frac{\lambda_{\text{act}}}{\lambda_{\text{tot}}} \quad (4)$$

$$P_{\text{E/OE}} = C \cdot (P_{\text{Tx}} + P_{\text{Rx}} + P_{\text{arb}}) \quad (5)$$

Another major contributor to PNoC power is the thermal tuning power. Since the resonant wavelength of MRRs is highly susceptible to TV and PV, the MRRs experience a wavelength shift from the designed laser wavelength. Therefore, the MRRs need to be thermally tuned to the nearest laser wavelength. This is conventionally achieved by heat injection via Joule effect using resistive heaters inside the MRRs, thereby increasing the MRR wavelength to the nearest laser wavelength. In our system, we assume that the MRRs have a thermal sensitivity ($\frac{\lambda_{\text{act}}}{dT}$) of 78pm/K and the heaters have an efficiency ($\frac{\Delta P}{\Delta T}$) of 120pm/mW [13]. Given the small area footprint of an MRRG, we assume that the steady state temperature over a single MRRG is uniform, so all the MRRs in an MRRG undergo the same TV-induced wavelength shift. However, all the eight MRRGs are possibly at different temperatures, owing to variable chip activity. The overall wavelength shift ($\Delta \lambda_{\text{shift}}$) for an MRRG is given by Eq. (6), where $\Delta T$ is the difference between the MRRG temperature and the ambient temperature and $\Delta \lambda_{\text{shift,PV}}$ is the PV-induced wavelength shift:

$$\Delta \lambda_{\text{shift}} = \frac{\Delta T}{\lambda_{\text{act}}} \cdot \Delta T + \Delta \lambda_{\text{shift,PV}} \quad (6)$$

In a single MRRG, one Tx MRR and seven Rx MRR are heated for every activated laser wavelength. The total heating power, $P_{\text{heat}}$, is calculated by aggregating the heating power of the MRRs over all the MRRGs and is given by Eq. (8), where $\Delta \lambda_{\text{heat}}$ is the required wavelength shift to the nearest laser wavelength for an MRR:

$$\Delta \lambda_{\text{heat}} = \frac{F_{SR}}{\lambda_{\text{act}}} - (\Delta \lambda_{\text{shift}} \ mod \ \frac{F_{SR}}{\lambda_{\text{act}}}) \quad (7)$$

$$P_{\text{heat}} = \sum_{i=1}^{C} \sum_{r=1}^{C} \Delta \lambda_{\text{heat,i,r}} \cdot \frac{\Delta \lambda_{\text{heat}}}{\Delta T} \quad (8)$$

IV. WAVES: WAVELENGTH SELECTION FOR PNOCS

As evident from the previous section, the power consumption ($P_{\text{laser}}, P_{\text{E/OE}}$ and $P_{\text{heat}}$) along a PNoC increases with $\lambda_{\text{act}}$. In this section, we first motivate the need for wavelength selection and then describe how the MRRs lock to the nearest laser wavelength with TV- and PV-induced wavelength shifts.
swaptions evident that the power consumption increases with increasing
shifts and explains the MRR locking mechanism. Section IV-C PV . Section IV-B accounts for only TV-induced wavelength
consume the lowest PNoC power by accounting for TV and
improvements.

(a) Normalized execution time. (b) System power.

Fig. 3: Performance and power breakdown with different $\lambda_{\text{act}}$.

A. Applications’ bandwidth needs

Figure 3(a) illustrates the system performance of selected applications from SPLASH2 [24] and PARSEC [25] benchmark
suites at different inter-chiplet bandwidth settings, i.e., $\lambda_{\text{act}}$. Our simulation framework to run experiments is pre-
icted in Sec. V. We plot the normalized execution time
(normalized to $\lambda_{\text{act}} = 6$) for increasing $\lambda_{\text{act}}$. We observe a
general trend that the system performance tends to saturate at a particular $\lambda_{\text{act}}$. For certain applications such as cholesky and
swaptions, a larger $\lambda_{\text{act}}$ is desirable for high performance. On
the other hand, for applications such as lu.cont and barnes, a
lower $\lambda_{\text{act}}$ provides similar performance as $\lambda_{\text{tot}}$. Figure 3(b)
shows the power breakdown of using different $\lambda_{\text{act}}$. It is
evident that the power consumption increases with increasing
$\lambda_{\text{act}}$. Since the performance saturates at a particular $\lambda_{\text{act}}$, which is dependent on the application’s bandwidth
requirement, activating all the available $\lambda_{\text{tot}}$ laser wavelengths may
increase the power without providing notable performance improvements.

To exploit this observation, we perform a design space exploration (DSE) to determine the minimum required number of
laser wavelengths ($\lambda_{\text{min}}$) that is sufficient to cater to the
bandwidth requirement of an application. We set a perform-
ance loss threshold ($L_{\text{thr}}$) that is deemed acceptable for
a system. For each application, we identify the $\lambda_{act}$ where the system performance loss is under $L_{\text{thr}}$ as compared to
the performance with $\lambda_{tot}$. We define this value of $\lambda_{act}$ as $\lambda_{\text{min}}$. Once we determine the $\lambda_{\text{min}}$, we then need to
activate the best combination of $\lambda_{\text{min}}$ laser wavelengths that
consume the lowest PNoC power by accounting for TV and
PV. Section IV-B accounts for only TV-induced wavelength
shifts and explains the MRR locking mechanism. Section IV-C incorporates PV in addition to TV and activates the best $\lambda_{\text{min}}$
combination that results in the lowest thermal tuning power.

B. Accounting for TV-induced wavelength shifts

Figure 4 illustrates the designed and shifted resonant wave-
length due to TV and PV for six Tx MRRs of an MRRG. In an
ideal case with no PV, the six MRRs resonate at the six laser
wavelengths as seen in Fig. 4(a). From our DSE, we determine the
number of laser wavelengths for an application to be $\lambda_{\text{min}}$(e.g., $\lambda_{\text{act}} = 2$ in Fig. 4). Due to chip activity and the resulting
TV, the resonant wavelength of MRRs shift as illustrated in
Fig. 4(b). Since the MRRs are evenly spaced within the FSR,
this TV-induced resonance shift can be overcome by applying the
same amount of heating at each MRR and, therefore, any
$\lambda_{\text{min}}$ laser wavelengths can be activated. For example, we can
activate the first $\lambda_{\text{min}}$ wavelengths in order to compensate
this TV-induced wavelength shift. The thermal control loop in the
TxRx chiplet supplies heating power to $\lambda_{\text{tot}}$ MRRs until
$\lambda_{\text{min}}$ MRRs lock to the activated laser wavelengths. The other
MRRs, even though heated at maximum, cannot lock, and the
thermal control loop removes their heating power, as shown in
Fig. 4(b). The locked MRRs for Tx and Rx are used for
communication at the activated laser wavelengths. As MRRGs can be at different temperatures due to uneven chip activity, the
set of MRRs locked to the laser wavelengths can be different
among MRRGs. Thus, the $\lambda_{\text{min}}$ selection process is performed
dynamically based on MRR tuning ranges and lock status.

C. Accounting for TV- and PV-induced wavelength shifts

Due to PV, the MRRs do not resonate at the design
wavelength and encounter an additional wavelength shift. We
model the local MRRG PV as a gaussian distribution with a
standard deviation of 100pm.

Figure 4(c) illustrates the combined TV- and PV-induced resonant wavelength shifts of MRRs. These shifts are different for
all the MRRs within an MRRG, and hence not evenly spaced within the FSR. Therefore, all the MRRs in an MRRG
now require variable amount of heating. In this case, activating the first 2 laser wavelengths as claimed in Sec. IV-B results
in a larger tuning range and thereby, a suboptimal activation of
laser wavelengths as depicted in Fig. 4(c). Figure 4(d) demonstrates that activating laser wavelengths $\lambda_3$ and $\lambda_4$
results in a lower tuning range. Hence, the combined TV and
PV effect forces the need to activate the best combination of
$\lambda_{\text{min}}$ for a reduced tuning range and lower heating power.

D. System integration of WAVES

To implement WAVES on a simulated real system prototype
and select the best combination of $\lambda_{\text{min}}$, we implement the following algorithm: (1) store the PV-induced resonant
wavelength shift of all 48 MRRs in all 8 MRRGs as an 8x8x6
100KB so it can be easily stored on-chip. The MRR lock-time to
the laser wavelength is 100µs [13]. We determine the LUT access
time as $\lambda_{\text{int}}/2 \cdot C$ lookups and additions (160 cycles for $C = 8$ and $\lambda_{\text{tot}} = 6$), while laser power-on latency from a cold
state is 5ns [14], hence each takes much less than 100µs. Thus,
the latency overhead of dynamic laser activation is negligible
compared to MRR lock time, and can be run periodically or
every time the MRRs get unlocked due to high temperature
shift. As WAVES does not depend on specific architecture
parameters, our technique is scalable and can be extended to
larger systems with a higher number of MRRs.

V. SIMULATION FRAMEWORK

To evaluate the impact of WAVES, we set up a simulation
framework consisting of a performance simulator, core power
and PNoC power model, and a thermal simulator as shown in
Fig. 5. For performance simulation, we model the POPSTAR
architecture in Sniper [26]. We use multithreaded applications
from SPLASH-2 [24] and PARSEC [25] benchmark suites. We
experiment with two different voltage/frequency (V/f) settings
and four thread combinations for each of the applications. We
activate different $\lambda_{\text{act}}$ to simulate varying internal bandwidth.
Table III details our experiments. For each experiment, we
execute 10 billion instructions in the parallel region or the full
region of interest if it finishes earlier.
We use McPAT [27] to compute the core and cache power consumption. We collect power traces from McPAT simulations and scale the raw power data to the published power values for the Intel SCC cores. We use Equations 1-5 to compute the laser and electronics power depending on λ\text{act}.

We use the 3D extension [28] of HotSpot [29] to determine the steady-state temperature of all the MRRGs. In order to obtain an accurate thermal map, we calibrate HotSpot temperatures to temperatures obtained from Project Sahara [30], which is a sign-off thermal tool from Mentor, a Siemens Business, for simulating detailed 3D circuits within its package and board. We obtain HotSpot temperatures within 2% error margin of Project Sahara on average. Figure 6 illustrates the thermal map in Project Sahara and HotSpot. We assume that the MRRs are designed to resonate at the laser wavelengths at an ambient temperature of 300K.

VI. EXPERIMENTAL RESULTS

To investigate the power savings obtained from WAVES, we conduct experiments on applications with different communication intensities under varying system settings (DVFS and thread combinations) and demonstrate their combined impact on λ\text{min}. Our baseline system activates all the available laser wavelengths (λ\text{act} = λ\text{tot}). We experiment with three different L\text{thr} values (1%, 5% and 10%) to determine the λ\text{min} (λ\text{act} = λ\text{min}). For each L\text{thr}, we compute the PNoC power by activating the first λ\text{min} laser wavelengths (Sec. IV-B) and by activating the best combination of λ\text{min} laser wavelengths (Sec. IV-C). Figure 7 shows the PNoC power savings obtained with WAVES for different applications under varying system settings. We tabulate our average power savings in Table IV. For low\textunderscore comm applications, the system performance saturates for a low λ\text{min}, as seen in Fig. 3(a). As a consequence, even for a 1% L\text{thr}, a lower λ\text{min} is activated and we observe average power savings of 38%. However, for high\textunderscore comm applications, the high network traffic demands higher λ\text{min}, resulting in average power savings of 8% for a 1% L\text{thr}.

Subsequently, we experiment with two DVFS settings to evaluate the effect of compute performance on WAVES. We observe that high_perf (Figs. 7(e)-7(h)) desires a higher λ\text{min} for the same L\text{thr} than low_perf (Figs. 7(a)-7(d)), and therefore, result in lower power savings. On average, we obtain 19% and 26% power savings for high\textunderscore perf and low\textunderscore perf, respectively. The lower power savings in high\textunderscore perf are attributed to the larger on-chip thermal gradient due to increased logic power, giving rise to higher thermal tuning power.

Next, we run applications with different threads counts and combinations to study their effect on WAVES. Figures 7(a)-7(d) and 7(e)-7(h) show the power savings for different applications running with 24, 48, 72 and 96 threads respectively. In most cases, larger thread counts result in increased inter-chiplet network traffic among the communicating threads and result in a higher λ\text{min}. This is evident in high\textunderscore comm applications running 96 threads, particularly canneal and cholesky in Fig. 7(d) and Fig. 7(h), which require all six laser wavelengths to be activated even for an L\text{thr} of 10%.

WAVES achieves 23% (resp. 38%, 42%) average PNoC power savings with only 1% (resp. 5%, 10%) performance loss. In addition, we demonstrate that activating the best combination of these laser wavelengths is feasible with negligible storage and latency overhead.

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<td>23%</td>
<td>38%</td>
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Fig. 7: PNoC power savings when using WAVES under different DVFS settings and thread combinations. The six bars for each application combination of $\lambda_{\text{min}}$, laser wavelengths for three $L_{\text{thr}}$ options. The baseline case (horizontal line) activates all $\lambda_{\text{tot}}$ laser wavelengths.

VII. CONCLUSIONS AND FUTURE WORK

PNoCs are promising alternatives for ENoCs, however, the practical integration of PNoCs in many-core systems is contingent on improving their energy efficiency. MRRs are highly susceptible to on-chip TV and PV, resulting in high PNoC power. Our wavelength selection technique, WAVES, accounts for these variations when selecting a minimum number of laser wavelengths and provides 23% average power savings under 1% loss in system performance. We demonstrate the feasibility of WAVES on a simulated 2.5D-integrated PNoC many-core system with a detailed account of MRR wavelength locking under TV and PV. Our work is orthogonal to most other design or runtime optimization methods for PNoCs and can be applied in tandem. WAVES can be further improved by using an online mechanism based on network and memory accesses to predict the bandwidth requirement for an application.

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