Accelerating the development of secure and reliable photonic and electronic systems

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George Papadimitriou and Dimitris Gizopoulos from the University of Athens discuss the value of simulation frameworks in optimizing the development and integration of photonic and electronic systems

The role of simulation in developing photonic and electronic accelerators

Simulation frameworks are indispensable in modern hardware and computing systems development, enabling researchers to evaluate and optimize complex architectures before physical implementation. These tools facilitate detailed modeling of hardware components, interactions, and performance under various workloads – a broad exploration of the hardware and the software design space. For emerging technologies like photonic accelerators, which promise significant speed and energy efficiency improvements, simulation offers a controlled environment to analyze designs and refine them for real-world applications before expensive physical design takes place.

Photonic neural networks (PNNs) are particularly well-suited for simulation-based research. As these systems integrate novel photonic devices with conventional electronic components like CPUs and memory systems, their design presents unique challenges. Simulations can bridge this gap, enabling the exploration of trade-offs between speed, energy efficiency, reliability, and security in edge computing and other scenarios. Frameworks like gem5, a microarchitecture-level simulator, support such investigations by providing modular environments for configuring and testing system architectures.

Enhancing photonic accelerators through simulation — the NEUROPULS approach

Photonic systems have become increasingly relevant for edge computing systems because they can handle massive data processing tasks with low latency and high energy efficiency (performance per watt). However, ensuring that these systems operate seamlessly within a larger (electronic) computing infrastructure requires careful design and evaluation, which is where full-system simulation frameworks, such as gem5, play a critical role. Such simulation frameworks enable researchers to create and analyze heterogeneous systems that integrate photonic and electronic components.

The full-system support of the gem5 allows for the evaluation of interactions between photonic accelerators and surrounding CPUs or memory hierarchies, ensuring efficient data exchange and workload distribution. Moreover, given the power constraints of edge devices, simulation environments help assess the energy efficiency of photonic accelerators. By incorporating photonics-aware power models into existing simulation tools, it is possible to estimate energy consumption under diverse workloads and optimize designs for minimal power use.

Another important aspect that can be considered is the reliability of such systems. Reliability is crucial for photonic accelerators, particularly in edge environments where hardware must operate autonomously and with minimal maintenance under potentially harsh conditions. Full system, microarchitecture-level simulation allows for the modeling of the majority of fault scenarios. By identifying vulnerabilities, researchers can propose solutions to improve system robustness, ensuring consistent performance even under adverse conditions.

By supporting these activities, simulation tools act as catalysts for advancing photonic accelerators from conceptual designs to practical implementations tailored to the unique demands of edge computing. In NEUROPULS, one of the main contributions is the development of a unified simulation framework based on gem5 to support all these activities.

Addressing security and reliability challenges in photonic systems

The simulation framework built in the context of the NEUROPULS project will enable us to simulate the behavior of the photonic accelerators and their security mechanisms when integrated with low-power, open-source RISC-V processors. It will play a crucial role in examining various scenarios to optimize NEUROPULS hybrid electronic-photonic computing platform, gather key metrics, and forecast performance beyond the capabilities tested in our prototype.

As photonic accelerators are integrated into edge computing systems, addressing their security and reliability becomes paramount. Edge devices often operate in untrusted environments and must be resistant to various physical and software-based threats. Moreover, they must perform reliably in diverse and potentially harsh conditions, where transient and permanent hardware faults and errors can have significant consequences. Although photonic systems offer high computational efficiency, their integration with traditional computing elements can introduce security vulnerabilities.

Simulation tools enable the testing of security measures and services, such as protocols for mutual authentication, software attestation, or cryptographic extensions, in a controlled environment.

Among the various approaches under exploration, hardware primitives like physical unclonable functions (PUFs) are considered effective solutions for mitigating memory-related security threats. PUFs enable the on-demand generation of cryptographic keys, eliminating the need for permanent storage. However, existing electronic-based PUF implementations face significant limitations that hinder their widespread adoption in edge computing systems. In the context of the NEUROPULS project, we are exploring the development of photonic PUFs to build an extensive and concrete simulation framework.

Furthermore, our simulation framework provides the flexibility to analyze trade-offs among security, reliability, performance, and power/energy. By simulating these trade-offs, designers can make informed decisions to achieve the optimal balance for edge computing applications. Simulation-driven insights into security and reliability complement the performance and energy evaluations, enabling the creation of robust photonic accelerators suited to edge environments.

The gem5-based simulation infrastructure built in the context of the NEUROPULS project is critical for developing secure, reliable, and energy-efficient photonic accelerators. The NEUROPULS simulation platform empowers researchers to model intricate system interactions, optimize designs for energy efficiency, and address challenges in reliability and security. By leveraging these capabilities, we bridge the gap between theoretical innovations and practical. For edge computing applications, where constraints are stringent, and performance demands are high, the ability to evaluate and refine photonic systems through simulation is invaluable. As research continues to advance, simulation frameworks will remain critical in enabling the integration of photonic technologies into reliable, secure, and efficient systems for the future of computing.

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