

# NetFPGA SUME: Toward Research Commodity 100Gb/s

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**Abstract**—The demand-led growth of datacenter networks has meant that many constituent technologies are beyond the budget of the research community. In order to make and validate timely and relevant research contributions, the wider research community requires accessible evaluation, experimentation and demonstration environments with specification comparable to the subsystems of the most massive datacenter networks. We present NetFPGA SUME, an FPGA-based PCIe board with I/O capabilities for 100Gb/s operation as NIC, multiport switch, firewall, or test/measurement environment. As a powerful new NetFPGA platform, SUME provides an accessible development environment that both reuses existing codebases and enables new designs.

**Index Terms**—Programmable Hardware, High-Speed, NetFPGA, Networking

## I. INTRODUCTION

**D**ATACENTER growth in size and speed provides a force for change. It motivates the adoption of faster networks, stimulates the connecting of many magnitudes more machines within the datacenter, and inspires new approaches to network-management. Bandwidth aggregates exceeding 100Gb/s to the tens of Tb/s are increasingly common for even modest machine-interconnects.

Datacenter interconnects that are flexible, scalable, and manageable have forced even the most fundamental link-rate to extend well-beyond 100Gb/s. Thus, basic network infrastructure is also pushed beyond 100Gb/s. Such progress creates challenges for research and development; challenges for web-load balancing and denial of service defence, and for intrusion detection at 100Gb/s line-rate with minimum length packets, and challenges for 100Gb/s network-test and capture [1]. Even flexible switching systems such as OpenFlow, and its descendants, will need to adapt to routinely operate with port-speeds of 100Gb/s. Computing challenges also arise as Host Board Adapters (HBA) extend beyond 100Gb/s. Practically, researchers need to prototype new ideas whether that is a lookup or classification algorithm at 100Gb/s or testing larger structures in deployment with prototype platforms capable beyond 100Gb/s.

To deliver this new generation of designs, research prototypes must be designed, prototyped and evaluated, at speeds and scale comparable with those of the deployments in the modern datacenter itself. Practical research-community experience with high-speed datacenter interconnects is limited, often by expense but also by limits in features and inflexibility of current commodity systems.

A researcher may choose two paths: firstly, selecting from among the limited number of reprogrammable commodity high-speed hardware offerings [2], [3], where such projects are built from scratch or with limited reuse. The alternative uses open-source systems, enabling greater collaboration and higher-quality research with reproducible published results.

The NetFPGA project<sup>1</sup> has achieved success as an open-source project. As well as easing collaboration, open-source expedites the design process and permits a robust research approach that enables repeatability and direct comparison of ideas within the wider community. Despite open-source software becoming common de-facto standard, complete open source platforms that include hardware remain scarce, especially for high bandwidth solutions.

Into this setting, we introduce a new NetFPGA open-source platform: NetFPGA SUME. The hardware of NetFPGA SUME is an ideal solution for rapid prototyping of 10Gb/s and 40Gb/s applications, and a technology enabler for 100Gb/s applications, focusing on bandwidth and throughput. Based upon a Virtex-7 FPGA, along with peripherals supporting high-end design: PCI Express (PCIe) Gen.3, multiple memory interfaces and high-speed expansion interfaces. From the outset this card is intended to provide the research and academic community with a low-cost, commodity, device suitable for a range of studies. Users are able to leverage existing open-source designs for this platform thereby enhancing their own experience by permitting them to replace as much or as little of any reference design or to build upon the contributed projects of other users.

Alongside a discussion of a number of use-cases and the manner in which NetFPGA SUME provides resources appropriate in each case, we compare a number of other current FPGA-based solutions and show the advantages over them. We envisage the NetFPGA SUME to see use in research and education but also to provide a platform for rapid prototyping and even a useful deployment under the right circumstances.

## II. MOTIVATION

An ideal platform would be flexible and could be used across a wide range of applications. In network-devices alone, an ideal candidate could be used as both a network-element and an end-host adapter. Open-source hardware is still to achieve the maturity and wide-scale adoption of open-source software, yet it is worthwhile to place the hardware this paper

<sup>1</sup><http://www.netfpga.org>

describes in an open-source framework. It has been our long-standing experience that alongside the active community, an open-source approach stimulates a vibrant and ever-growing library, including reference designs, software and hardware designs.

*Stand-alone device:* A stand-alone computing unit could use commodity or soft-core processes, e.g., [4]. Provided with an appropriate quantity of fast memory, hard disks and, in the case of soft-cores, sufficient resources it can be used to explore a range of modern CPU architecture-alternatives. A suitable device would be a descendent of the RAMP project [5]: an FPGA environment where a practical target frequency of no more than a few hundred MHz is possible, that uses the accuracy of a time-dilated implementation to provide insight into a faster design.

The ideal platform for exploring the datacenter interconnect fulfils the vision of Thacker [6], bringing I/O and network research closer to the CPU-architecture community, with a feature set emphasising I/O capacity.

*PCIe Host Interface:* The PCIe architecture is ubiquitous; even the most adventurous architects see a long life for this interface and a need to accommodate its peculiarities. In common x86 PCIe architectures, processing a few tens of Gb/s of data on a single host while also doing useful work is hard; beyond 100Gb/s of bandwidth this is near-impossible. Even the high-capacity PCIe slots reserved for GPU cards and capable of transfer-rates exceeding 100Gb/s have special-purpose configuration ill-suited to general network traffic.

Modern Network Interface Card (NIC) design already reduces unnecessary data moving from network-interface to host. By providing a combination of high-speed data interface and a flexible development environment, new work in mechanisms of off-load, filtering, and redirection serves to match future network data rates to that of the common PCIe architectures. In the past a reprogrammable NIC has provided a useful environment for supporting prototyping of novel traffic handling (e.g., [7]). In this same way, a flexible platform supporting line-rate experiments would be an ideal platform supporting such HBA or NIC development.

*100Gb/s Switch:* A common restriction among researchers is the extreme price of commodity equipment for high-speed interfaces. While 10Gb/s has become commodity and 40Gb/s is provisioned on many *Top of Rack* switches. In part this is because there are a variety of physical standards for 100Gb/s, no alternative having benefited from marginal cost drops due to economies of scale. Thus a research platform must express flexibility.

A past example of a flexible architecture element [8] permitted a multitude of switch architectures using single-port interface-cards interconnected by a high-speed backplane. Such a fundamental unit permitted several switch designs including those based on cross-bar arrangements and a number of oversubscribed aggregation trees.

Datacenter interconnects already endure a fine balance between demands for throughput and a need for minimal latency. The construction of high-radix switches necessary in even the most modest datacenter scenario requires balancing 100Gb/s interfaces against cross-element latencies less than  $\approx 200$ ns

(comparable with modern switch silicon) lest any significant arrangement become untenably overloaded in latency.

*Physical-Layer and Media Access Control:* With the variety of 40Gb/s and 100Gb/s physical standards still growing, there is ample need to accommodate new physical interconnects. An approach that has addressed this issue well in the past is to provide an intermediate physical connection such as the GBIC or SFP and its successors. An issue at 100Gb/s is such intermediate standards are still unclear, thus the approach of the FPGA Mezzanine Card (FMC), a physical I/O definition, permits a wide number of current and future interface ideas to be accommodated.

Previously, reconfiguration and replacement of physical-layer and media-access controls has been used to encode a side-channel into Ethernet pauses [9] and to provide a prototyping environment for energy-efficient physical-layer systems [10].

### III. THE NETFPGA PROJECT

The context of our solution is the NetFPGA project which provides software, hardware and community as a basic infrastructure to simplify design, simulation and testing, all around an open-source high-speed networking platform. Designed specifically for the research and education communities, the first public NetFPGA platform, NetFPGA-1G [11], was a low cost board designed around Xilinx Virtex-II Pro 50. The successor introduced in 2010, NetFPGA-10G [12], expanded the original platform with a 40Gb/s, PCIe Gen. 1, interface card based upon a Xilinx Virtex-5 FPGA. Current NetFPGA work is licensed under LGPL 2.1.

Beyond the hardware and software, the NetFPGA project is backed by community resources that include online forums, tutorials, summer camp events and developer workshops all supported by the NetFPGA project team. As all the (reference) projects developed under the NetFPGA project are open-source, by reusing building blocks across projects users compare design utilization and performance. Reference projects, included in all NetFPGA distributions, are a NIC, a switch and an IPv4 router. Past experience has shown that both reference and contributed NetFPGA projects are regularly enhanced by community members, redistributed and encouraging a virtuous circle.

### IV. NETFPGA SUME: HIGH LEVEL ARCHITECTURE

The NetFPGA SUME design aims to create a low-cost, PCIe host adapter card able to support 40Gb/s and 100Gb/s applications. The NetFPGA SUME uses a large FPGA, supporting high-speed serial interfaces of 10Gb/s or more presented both in standard interfaces (SFP+) and in a format that permits easy user-expansion, a large and extensible quantity of high-speed DRAM, alongside a quantity of high-throughput SRAM, and all this constrained by a desire for low cost to enable access by the wider research and academic communities. The result of our labours is NetFPGA SUME, shown in Figure 1(a).

The board is a PCIe adapter card with a large FPGA fabric, manufactured by Digilent Inc.<sup>2</sup>. At the core of the

<sup>2</sup><http://www.digilentinc.com>

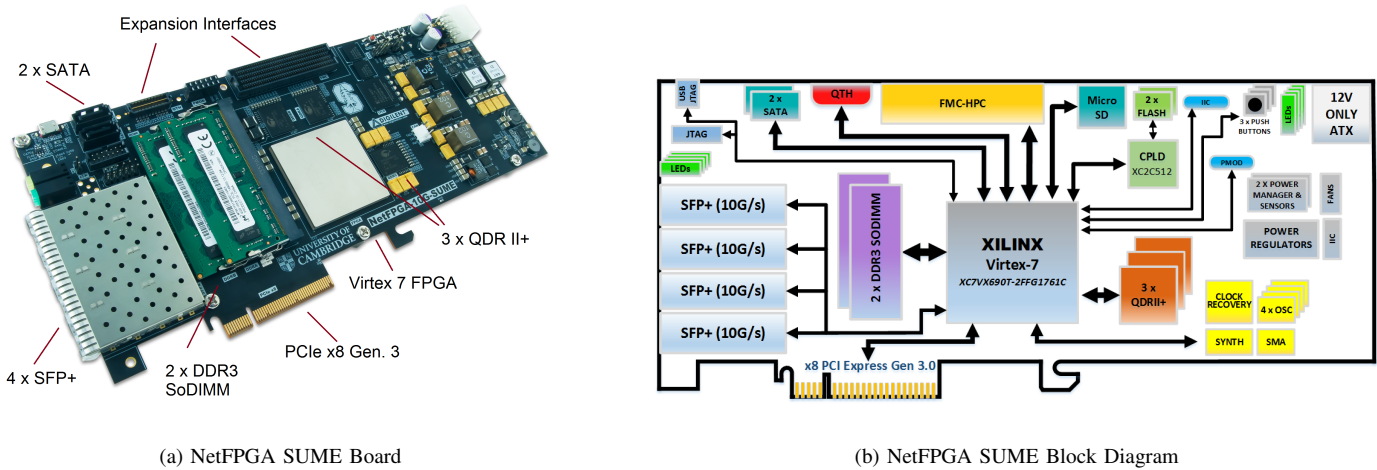


Fig. 1. NetFPGA SUME Board and Block Diagram

board is a Xilinx Virtex-7 690T FPGA device. There are five peripheral subsystems that complement the FPGA. A high-speed serial interfaces subsystem composed of 30 serial links running at up to 13.1Gb/s. These connect four 10Gb/s SFP+ Ethernet interfaces, two expansion connectors and a PCIe edge connector directly to the FPGA. The second subsystem, the latest generation 3.0 of PCIe is used to interface between the card and the host device, allowing both register access and packet transfer between the platform and the motherboard. The memory subsystem combines both SRAM and DRAM devices. SRAM memory is devised from three 36-bit QDRII+ devices, running at 500MHz. In contrast, DRAM memory is composed of two 64-bit DDR3 memory modules running at 933MHz (1866MT/s). Storage subsystems of the design permit both a MicroSD card and external disks through two SATA interfaces. Finally, the FPGA configuration subsystem is concerned with use of the FLASH devices. Additional NetFPGA SUME features support debug, extension and synchronization of the board, as detailed later. A block diagram of the board is provided in Figure 1(b). The board is implemented as a dual-slot, full-size PCIe adapter, that can operate as a standalone unit outside of a PCIe host.

#### A. High-Speed Interfaces Subsystem

The High-Speed Interfaces subsystem is the main enabler of 100Gb/s designs over the NetFPGA SUME board. This subsystem includes 30 serial links connected to Virtex-7 GTH transceivers, which can operate at up to 13.1Gb/s. The serial links are divided into four main groups; while the first group connects four serial links to four SFP+ Ethernet Interfaces, the second one, associates ten serial links to an FMC connector. Additional eight links are connected to a SAMTEC QTH-DP connector and are intended for passing traffic between multiple boards. The last eight links connect to the PCIe subsystem (Section IV-C).

The decision to use an FPGA version that supports only GTH transceivers rather than the one with GTZ transceivers, reaching 28.05Gb/s, arises as a trade-off between transceiver

speed and availability of memory interfaces. An FPGA with GTZ transceivers allows multiple 100Gb/s ports, but lacks the I/O required by memory interfaces, making a packet buffering design of 40Gb/s and above infeasible.

There are also four motives that support our decision to use SFP+ Ethernet ports over CFP. Firstly, as the board is intended to be a commodity board, it is very unlikely that the main users like researchers and academia will be able to afford multiple CFP ports. Secondly, 10Gb/s equipment is far more common than 100Gb/s equipment; this provides a simpler debug environment and allows inter-operability with other commodity equipment (e.g. deployed routers, traffic generation NICs). In addition, SFP+ modules also support 1Gb/s operation. The third, CFP modules protrude the board at over twice the depth of SFP+; CFP use would have required either removing other subsystems from the board or not complying with PCIe adapter cards form factor. Lastly, being an open source platform, NetFPGA is using only open source FPGA cores or the cores available through the Xilinx XUP program. As a CAUI-10 core is currently unavailable, it can not be made the default network interface of the board.

A typical 100Gb/s application can achieve the required bandwidth by assembling an FMC daughter board. For example, the four SFP+ on board together with *Faster Technology's*<sup>3</sup> octal SFP+ board create a 120G system. Alternatively, native 100Gb/s port can be used by assembling a CFP FMC daughter board.

#### B. Memory Subsystem

DRAM memory subsystem contains two SoDIMM modules, supporting up to 16GB<sup>4</sup> of memory running at 1866MT/s. Two 4GB DDR3-SDRAM modules are supplied with the card and are officially supported by Xilinx MIG cores. Users can choose to supplement or replace these with any other SoDIMM

<sup>3</sup><http://www.fastertechnology.com/>

<sup>4</sup>8GB is the maximum density per module defined by JEDEC standard no. 21C-4.20.18-R23B

form-factor modules; although new support cores may also be required.

While DDR4 is the next generation for DRAM devices, it is neither commodity nor supported by the Virtex-7 device; at the time of writing, it was not even available in an appropriate form-factor.

The SRAM subsystem consists of three on-board QDR-II+ components, 72Mb each (total density of 288Mb). The SRAM components are 36-bit wide and operate at 500MHz with a burst-length of 4.

We acknowledge that the performance figures may not be enough to support 100Gb/s line rate when buffering all incoming data: 100Gb/s packet buffering requires both reading and writing to the memory, thus doubling the bandwidth requirement from the memories. Additionally, none-aligned packet sizes lead to additional bandwidth loss.

### C. PCIe Subsystem

Providing adequate PCIe interface resource using the integrated hardcore provided on the Virtex-7 FPGA is one of the greater challenges for a 100Gb/s design; a 3rd generation 8-lane channel, the available Xilinx PCIe hardblock, supports 8GT/s with a maximum bandwidth approaching 64Gb/s. Precise performance is dramatically affected by configuration such as the maximum transmission unit (MTU).

With such a rate mismatch, several solutions may assist in the design of 100Gb/s HBA. For example, one approach would be to use dual-channel PCIe interfaces (via an extension) to provide a pair of PCIe 8-lane Gen.3 channels. Another approach would involve upstreaming through a cascaded second board. Given that the NetFPGA SUME will be an offloading unit for most HBA applications, we believe such approaches to be adequate.

As a further flexible offering, the eight transceivers used for PCIe support may also be allocated directly as a custom interface based upon the eight underlying 13.1GHz GTH transceivers.

### D. Storage Subsystem

The NetFPGA SUME provides storage through either Micro-SD card interface or two SATA interfaces. The Micro-SD provides a non-volatile memory that can serve to supply a file-system, provide a logging location, store operational databases and so on. This makes the NetFPGA SUME an ideal target for prototyping of computer-architectures and structures together with support of applications that combine computing and networking.

### E. Configuration and Debug Subsystem

Additional storage space is provided on board by two NOR FLASH devices. These are connected as a single  $\times 32$  to the FPGA via an intermediate CPLD. Each of the FLASH devices has  $\times 16$  parallel interface and a density of 512Mb. The FLASH memory is intended to primarily store the FPGA's programming file, but remaining space may be used for other purposes. We envisage an initial bootup image stored within the FLASH devices and loaded upon power-up.

The FPGA can be also configured using one of the JTAG interfaces: either a parallel or a USB-coupled one. Once programmed through JTAG, the board may be also reprogrammed via the PCIe interface.

The board contains a number of debug and control capabilities, including a UART interface, I2C interface, LEDs, push buttons and reset, and a PMOD connector.<sup>5</sup>

### F. Additional Features

The capabilities of the NetFPGA SUME can be further extended through on-board VITA-57 compliant FMC connector. The capabilities of 3rd-party FMC cards vary greatly; aside from high-speed I/O breakout interfaces, cards may support exotic serial interfaces, AD/DA conversions, and image processing. Consequently, the features of the platform can be extended too. I/O breakout FMC cards are widely available, supporting multiple 10Gb/s and 40Gb/s ports<sup>6</sup>. 100Gb/s is currently supported using  $8 \times 12.5$ Gb/s channels.

A considerable design effort has been put into the clocking circuits of the platform. Those allow maximal flexibility in setting of the interface's frequency and reduces dependency that often exists among various designs. As the NetFPGA SUME platform is designed with scalability in mind, a clock synchronization mechanism is provided, allowing, for example, a direct support of Synchronous Ethernet. Some of the clocks can also be programmatically configured.

## V. USE CASES

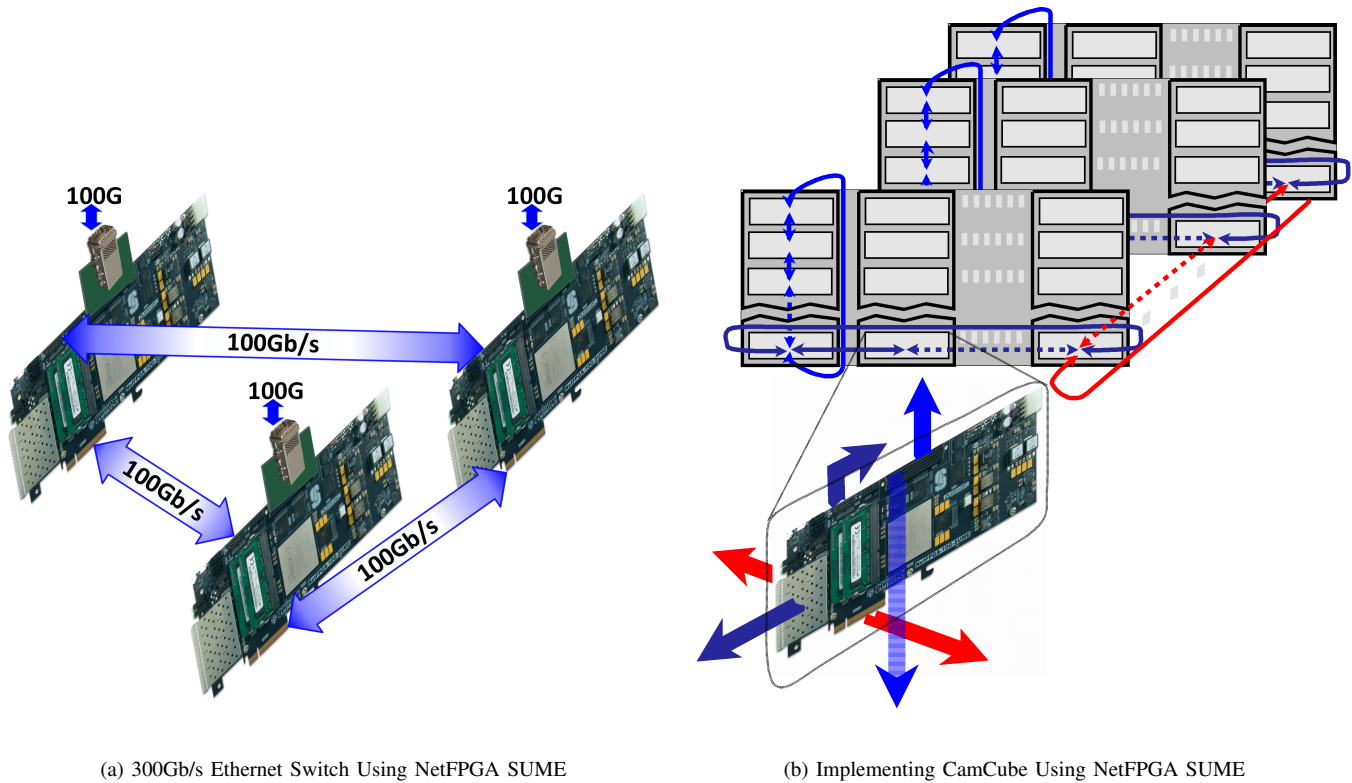
NetFPGA SUME is intended to support a wide range of applications. In network devices alone, the NetFPGA has previously been used as IP Router, switch (both Ethernet and OpenFlow), and NIC. It is also intended to support 10Gb/s and 40Gb/s designs, such as SENIC [13], previously bound by platform resources. The use-cases we describe here extend to the more adventurous, permitting the exploration of new and exotic physical interfaces, providing the building blocks for basic high bandwidth switch research, supporting novel interconnect architectures, and as a formidable stand-alone platform able to explore entirely new host architectures beyond current PCIe-centric restrictions.

*Stand-alone device:* The NetFPGA SUME can operate as a powerful stand-alone computing unit by using a soft-core processor, e.g., [4]. Consider the peripheral devices on board: a local RAM of between 8GB and 16GB running at 1866MT/s, two hard drives connected through SATA (with an appropriate IP core), considerable on-chip memory that can serve for on-chip cache, and numerous communication interfaces. While only offering a practical target frequency of a few hundred MHz, this platform can explore structural choices (cache size and location), novel network-centric extensions and still provide a valuable offload resource.

Alongside being able to meet the growing need for stand alone *bump-in-the-wire* networking units capable of I/O at line-rates independently of any host, NetFPGA SUME is

<sup>5</sup>A Digilent proprietary interface supporting daughterboards.

<sup>6</sup>[http://www.xilinx.com/products/boards\\_kits/fmc.htm](http://www.xilinx.com/products/boards_kits/fmc.htm)



(a) 300Gb/s Ethernet Switch Using NetFPGA SUME

(b) Implementing CamCube Using NetFPGA SUME

Fig. 2. Examples of NetFPGA SUME Use Cases

also suited for implementing networking management and measurement tools, such as [1], that utilize large RAMs to implement tables for counters, lookup strings and so-on.

**PCIe Host Interface:** The NetFPGA SUME supports host-interface development. With the 100Gb/s physical standards still ongoing development, a host-interface capable of 100Gb/s provides the ideal prototyping vehicle for current and future interfaces. Using the uncommitted transceivers in either of the QTH and FMC expansions, permits creating two 8-lane PCIe interfaces to the host: one through the native PCIe interface and one through an expansion interface. The aggregated 128Gb/s capacity to the host (demonstrated successfully by [3]) enables exploring new and as-yet undefined physical termination standards for 100Gb/s networking.

**100Gb/s Switch:** In the past, the NetFPGA provided a fundamental contribution to the success of OpenFlow [14] as the initial reference platform. Switching and routing applications for 100Gb/s is a clear NetFPGA SUME application. A researcher is well placed to explore a variety of architectures in an FPGA prototyping environment. In order to construct a true non-blocking switch solution from NetFPGA SUME cards would require packet-processing at a rate of 150Mp/s for each 100Gb/s port and thus call for either a high core frequency, wide data path or combination of the two. As a result the number of physical ports available on the device is not the rate bounding element.

Using NetFPGA SUME as a true 300Gb/s fully non-blocking un-managed Ethernet switch is shown in Figure 2(a). This architecture uses a high number of high-speed serial links

to deliver the required bandwidth: 100Gb/s connecting every pair of boards and providing an additional 100Gb/s port on each board. An implementation over NetFPGA SUME would use the FMC expansion interface to provide an appropriate interface: either one 100Gb/s CFP port or ten 10Gb/s SFP+ ports. The pair of 100Gb/s constituting the fabric connecting between cards can be achieved by using the transceiver resources of the PCIe connector and the QTH connector; each transceiver operating at 12.5Gb/s to achieve the per-port target bandwidth. The remaining four SFP+ ports might be used to achieve further speedup, improve signal integrity by reducing the required interface frequency, or be used to interface with the FPGA for management functions. Such a set-up might also be managed through low speed UART or I2C. This 300Gb/s switch would cost less than \$5000 yet provide an extraordinary device for datacenter interconnect researchers.

A true non-blocking 300Gb/s switch requires each board to process 200Gb/s of data: 100Gb/s of inbound traffic, and 100Gb/s of outbound traffic, likely on separate datapaths. At 100Gb/s the maximal packet rate is 150Mp/s for 64B packets, however the worst case is presented by non-aligned packet sizes, e.g., 65B. Several design trade-offs exist: frequency vs. utilization vs. latency, and more. One design option may use a single data path, with 32B bus width combined with a clock rate of 450MHz. This will use less resource and will keep the latency low, yet it will pose a timing-closure challenge. An alternative design choice is to use a single data path, but as a proprietary data bus that is 96B wide and a clock rate that is only slightly more than 150MHz. This option has the

disadvantage of considerable FPGA resource utilization, but meeting timing closure would be easier. Alternatively, use multiple data paths, each 32B wide, and keep the clock frequency around 150MHz. This has a high resources utilization, and also requires additional logic for arbitration between the data paths at the output port. Using a NetFPGA SUME reference design, one can select among the options and be able to compare the performance of these three alternatives.

*Physical-Layer and Media Access Control:* The NetFPGA SUME permits on-FPGA reconfiguration and replacement of physical-layer and media-access controls. The expansion interfaces: FMC and QTH, each provide high-speed, standardised interfaces for researchers own daughterboard designs. Such daughter board extensions have been used to good effect for exotic interface design and are common-practice in the photonics community; permitting active and passive optical-component designs closer integration with a standard electronic interface.

Furthermore, with an ever present interest in power consumption of datacenter systems, we have treated the ability to conduct meaningful power and current analysis of a built system of high importance. NetFPGA SUME supports a purpose-specific set of power instrumentation allowing designers to study reducing of power consumption of high-speed interfaces and proving it through field measurements rather than post-synthesis analysis alone.

*Interconnect:* As the last example, we explore not only traditional but novel architectures with line-rate performance. Architectures that are extremely complex or require a large amount of networking equipment tend to be implemented with minimal specialist hardware. By prototyping a complete architecture, researchers can side-step limitations enforced by software-centred implementations or simulation-only studies.

In Figure 2(b) we re-create the CamCube architecture [15]. Originally six 1Gb/s links with software (host) routing; by using NetFPGA SUME could get an order of magnitude improved throughput. Figure 2(b) illustrates how  $N^3$  NetFPGA SUME boards are connected as a  $N \times N \times N$  hyper-cube: each node connects with six other nodes. NetFPGA SUME permits connecting a 40Gb/s channel to each adjacent pair of boards resulting in 240Gb/s of traffic being handled by each node.

## VI. RELATED WORK

Our approach has been to provide flexibility using an FPGA-based platform. Several such FPGA-based network-centric platforms are documented in Table I.

While the price of commercial platforms is high, ranging from \$5000 to \$8000, the price of a board through university affiliation programs is typically less than \$2000. As the table shows, NetFPGA SUME has the most high end features. While the VC709 uses the same FPGA as the NetFPGA SUME board and same DRAM interfaces, it is a non-standard size, lacks SRAM interfaces, and has limited storage capacity. The DE5-Net board has similar DRAM access capabilities as NetFPGA SUME however, the feature set is inflexible with no additional expansion options. The NetFPGA SUME board

has considerably more high-speed serial interfaces than any reference board, making it the ideal fit for high bandwidth designs.

## VII. CONCLUSIONS

We present NetFPGA SUME, an FPGA-based PCIe board supporting an I/O capacity in excess of 100Gb/s provided by  $30 \times 13.1$ GHz transceivers, as well as SRAM and extensible DRAM memory, and a range of other useful interfaces. This is all achieved on a PCIe format board that provides a suitable HBA interface. The hardware is complemented by work done within the NetFPGA project framework providing reference software to enable researcher adoption.

NetFPGA SUME provides an important technology by serving as a platform for novel datacenter interconnect architectures, a building block for basic 100Gb/s end-host and switch research, and as a platform to explore entirely new host architectures beyond current PCIe restrictions. As a stand-alone processing unit it will enable prototype deployments otherwise too complex or too resource-intensive. As a hardware prototyping architecture, researchers are able to side-step the limitations enforced by software-centred implementations and evaluate their designs at the limits of implementation.

We have provided a brief survey of the challenges and opportunities available to researchers using hardware implementation of next generation network designs. The NetFPGA community is now set to adopt the NetFPGA SUME platform, available H2/2014, and everyone is welcome on this journey.

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## REFERENCES

- [1] G. Antichi et al., "OSNT: Open Source Network Tester," *IEEE Network Magazine*, September, 2014.

Platform	NetFPGA SUME	VC709	NetFPGA-10G	DE5-Net
Type	Open Source	Reference	Open Source	Reference
FPGA Type	Virtex-7	Virtex-7	Virtex-5	Stratix-V
Logical Elements	693K Logical Cells	693K Logical Cells	240K Logical Cells	622K Equivalent LEs
PCIe Hard IP	x8 Gen.3	x8 Gen.3	x8 Gen.1	x8 Gen.3
SFP+ Interfaces	4	4	4	4
Additional Serial Links	18×13.1Gb/s	10×13.1Gb/s	20×6.5Gb/s	0
Memory - On Chip	51Mb	51Mb	18Mb	50Mb
Memory - DRAM	2xDDR3 SoDIMM 4GB†, 1866MT/s	2xDDR3 SoDIMM 4GB†, 1866MT/s	4x32b RLDRAM II 576Mb, 800MT/s	2xDDR3 SoDIMM 2GB†, 1600MT/s
Memory - SRAM	27MB QDRII+, 500MHz	None	27MB QDRII, 300MHz	32MB QDRII+, 550MHz
Storage	Micro SD, 2x SATA 128MB FLASH	32MB FLASH	32MB FLASH	4x SATA 256MB FLASH
Additional Features	Expansion interface, clock recovery	Expansion interface, clock recovery		
PCI Form Factor	full-height full-length	Not compliant	full-height 3/4-length	full-height 3/4-length

TABLE I  
COMPARISON BETWEEN FPGA-BASED PLATFORMS. †DENSITY PROVIDED WITH THE BOARD, EACH SUPPORTS 8GB PER SODIMM.

- [2] Arista 7124FX Application Switch, <http://www.aristanetworks.com/>. [Online; accessed March 2014].
- [3] Š. Friedl. et al., “Designing a Card for 100 Gb/s Network Monitoring,” Tech. Rep. 7/2013, CESNET, July, 2013.
- [4] J. Woodruff et al., “The CHERI Capability Model: Revisiting RISC in an Age of Risk,” in *IEEE/ACM ISCA*, June, 2014.
- [5] J. Wawrzyniek et al., “RAMP: Research Accelerator for Multiple Processors,” *IEEE Micro*, vol. 27, pp. 46–57, March, 2007.
- [6] C. P. Thacker, “Improving the Future by Examining the Past: ACM Turing Award Lecture,” in *IEEE/ACM ISCA*, June, 2010.
- [7] I. Pratt et al., “Arsenic: a user-accessible gigabit ethernet interface,” in *IEEE INFOCOM*, April, 2001.
- [8] I. Leslie et al., “Fairisle: An ATM network for the local area,” in *Proceedings of ACM SIGCOMM*, August, 1991.
- [9] K. S. Lee et al., “SoNIC: Precise Realtime Software Access and Control of Wired Networks,” in *NSDI*, pp. 213–225, April, 2013.
- [10] Y. Audzevich et al., “Efficient Photonic Coding: A Considered Revision,” in *ACM SIGCOMM GreenNet workshop*, pp. 13–18, August, 2011.
- [11] J. W. Lockwood et al., “NetFPGA – An Open Platform for Gigabit-Rate Network Switching and Routing,” *IEEE MSE*, June, 2007.
- [12] M. Blott et al., “FPGA Research Design Platform Fuels Network Advances,” *Xilinx Xcell Journal*, September, 2010.
- [13] S. Radhakrishnan et al., “SENIC: Scalable NIC for End-Host Rate Limiting,” in *USENIX NSDI*, pp. 475–488, April, 2014.
- [14] N. McKeown et al., “OpenFlow: Enabling Innovation in Campus Networks,” *ACM SIGCOMM CCR*, vol. 38, no. 2, pp. 69–74, 2008.
- [15] H. Abu-Libdeh et al., “Symbiotic Routing in Future Data Centers,” in *ACM SIGCOMM*, pp. 51–62, ACM, September, 2010.

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