

HEPiX Network Virtualisation WG Update

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HEPiX, October 2019, Amsterdam

This presentation is a summary of the WG [report](#), which is still a work in progress, but feel free to provide your comments, suggestions directly in the document

Motivation

- High Energy Physics (HEP) has significantly benefited from strong relationship with Research and Education (R&E) network providers
 - Thanks to LHCOPN/LHCONE community and NREN contributions, experiments enjoy almost “infinite” capacity at relatively low (or no-direct) cost
 - NRENs have been able to continually expand their capacities to overprovision the networks relative to the experiments needs and use
- Other data intensive sciences are coming online soon (SKA, LSST, etc.)
- Network provisioning will need to evolve
 - Focusing not only on network capacity, but also on other **network capabilities**
- DC networking is evolving in reaction to containers/virtual/cloud resources
- It's important that we **explore new technologies** and evaluate how they could be useful to our future computing models
 - While it's still unclear which technologies will become mainstream, it's already clear that software (software-defined) will play major role in networks in the mid-term

Network Functions Virtualisation WG

Mandate: Identify use cases, survey existing approaches and evaluate whether and how Software Defined Networking (SDN) and Network Functions Virtualisation (NFV) should be deployed in HEP.

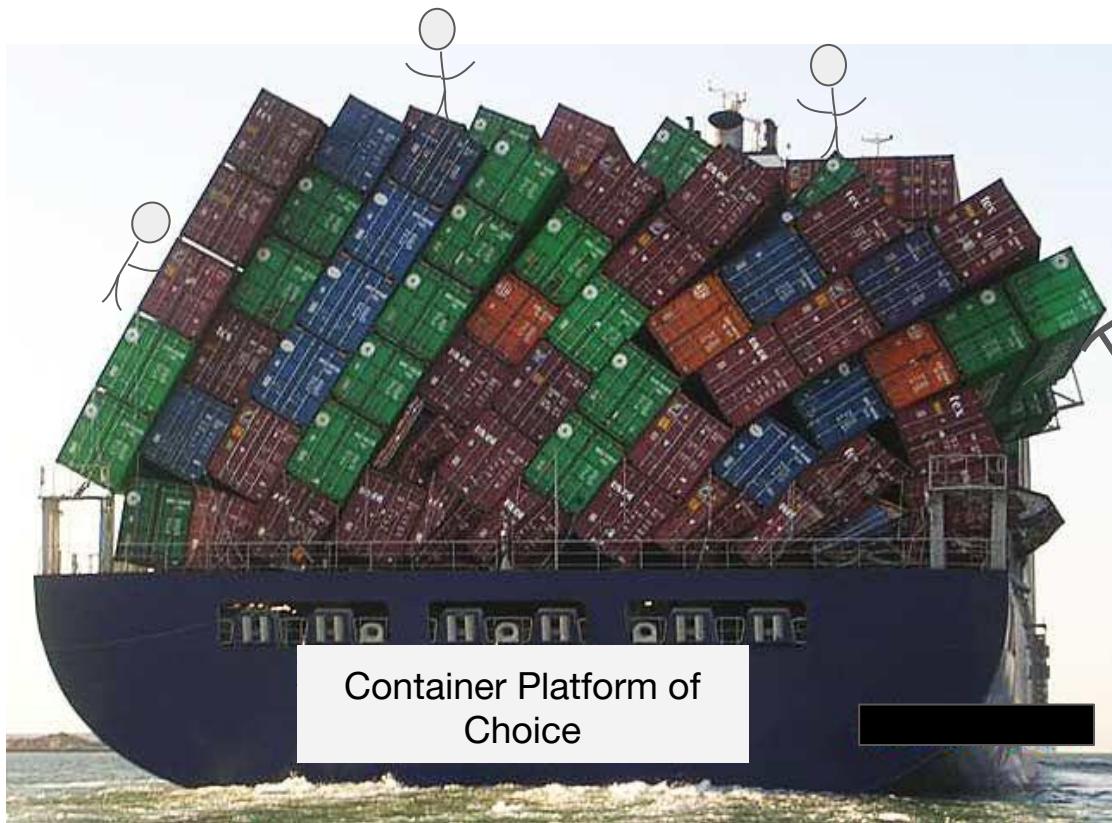
Team: 60 members including **R&Es** (GEANT, ESNet, Internet2, AARNet, Canarie, SURFNet, GARR, JISC, RENATER, NORDUnet) and **sites** (ASGC, PIC, BNL, CNAF, CERN, KIAE, FIU, AGLT2, Caltech, DESY, IHEP, Nikhef)

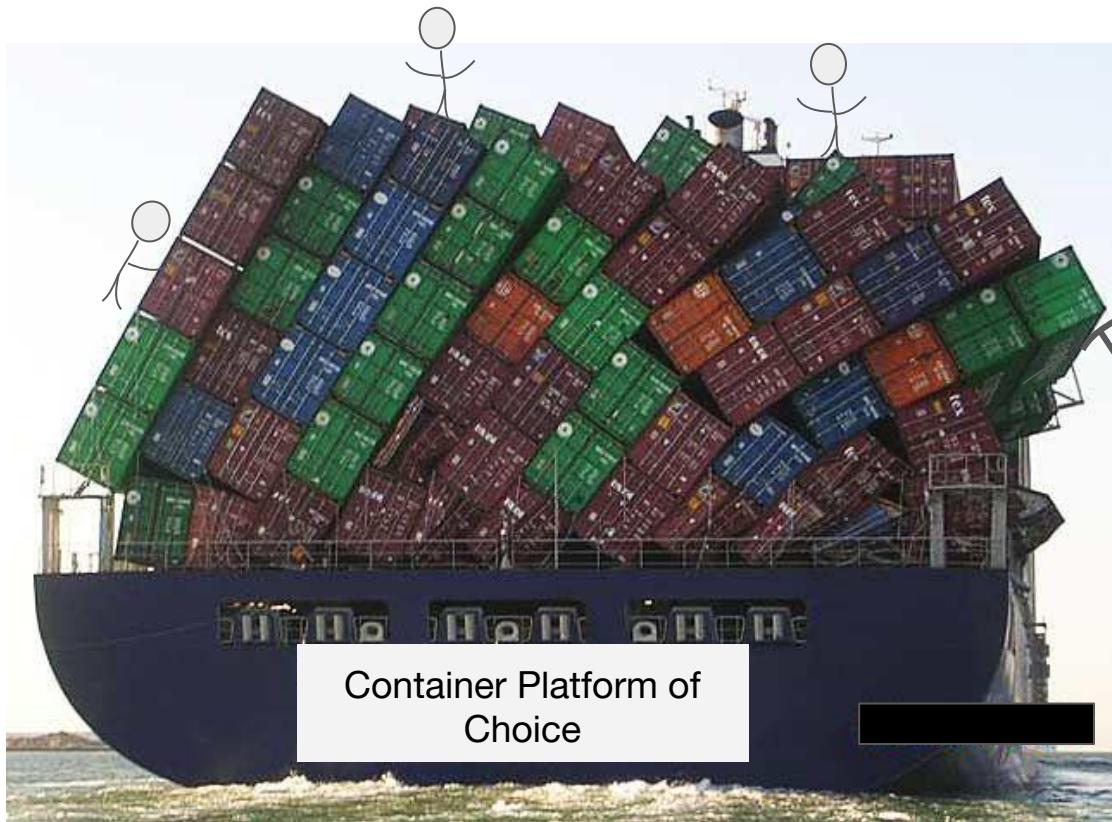
Monthly **meetings** started last year (<https://indico.cern.ch/category/10031/>)

Mailing list: <https://listserv.in2p3.fr/cgi-bin/wa?SUBED1=hepix-nfv-wg>

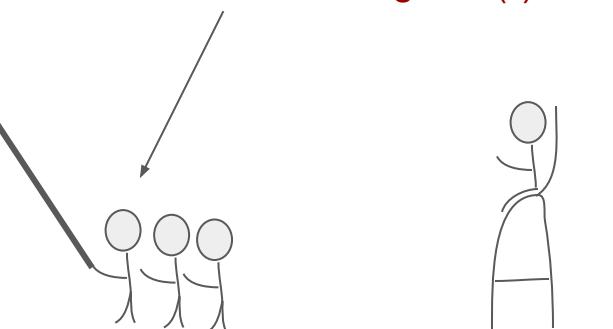
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Network engineer(s) ?



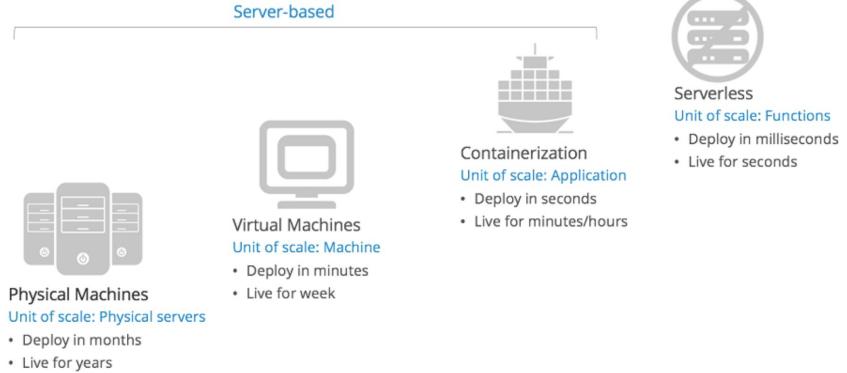
Cloud Native DC Networking

Paradigm Shift in Computing

Moving from static physical machines to very dynamic models with VMs, containers, clusters of containers and federated clusters/serverless

This has major impact on networking requirements in DC

- **Node lifecycle in msecs**
- East-west traffic increases
- **Nodes can migrate** (even across DCs)
- Multiple orchestration methods (stacks) need to co-exist in the DC network
- **Networking across stacks and within needs to perform**

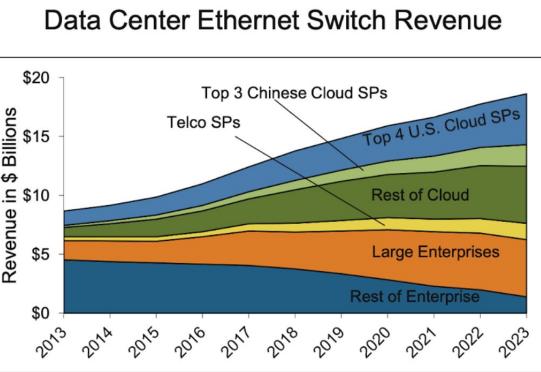
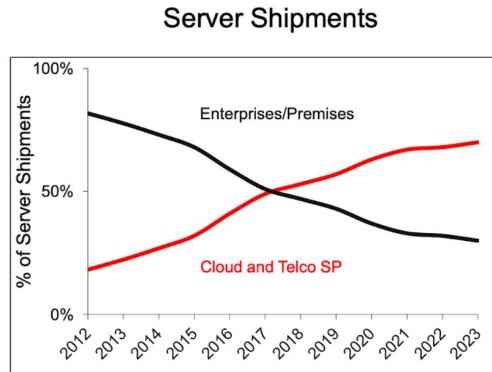


This transition has already started, we already have experiments running payloads in containers and services bundled in K8s pods, physics analysis in K8s has been demoed recently

Cloud Network Opportunity

Paradigm shift most notable in compute, but networking evolution is also pushed by **virtualized storages and GPUs** (wrt. expected throughput and latency)

Network vendors have already started to take note - this will impact future HW



Source: Dell'Oro Group Server Research

Source: Dell'Oro Ethernet Switch Data Center 5 Year Forecast Report January 2019

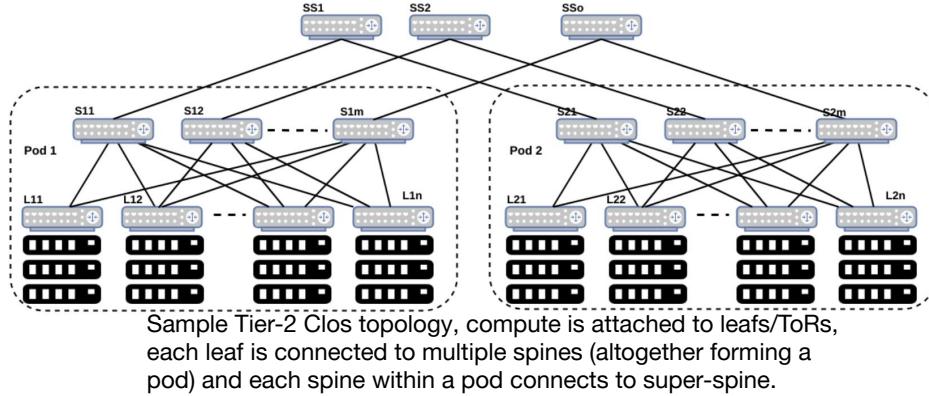
Enterprise workloads are migrating to clouds and hybrid clouds

Emergence of cloud native apps and containers necessitates new architecture

Evolution in DC networking

Clos-topology now de-facto standard

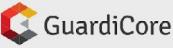
- Homogenous & simple equipment
- Easy to scale and add capacity
- **Routing is the core interconnect technology**
 - Bridging/switching only at the leafs (within a single rack)
 - Connecting across racks relies on network virtualisation
- **Control plane pushed all the way to the leafs (or even directly in servers running software switches)**
- Fine-grained failure domain
- Simple homogenous equipment pushes evolution towards open source
 - Both in software as well as hardware equipment
- Clos is a topic of its own, many different topologies/possibilities exist



Network Virtualisation

Carves a single physical network into multiple, isolated virtual networks

Range of approaches, both open-source (white) and commercial (grey) exist, tracked by the [Cloud Native Computing Foundation](#)

 alcide Addo	 Aporeto Aporeto	 aviatrix Aviatrix Systems	 big switch networks Big Switch Networks	 cilium Isovalent	 CNI Container Network Interface (CNI) Cloud Native Computing Foundation (CNCF)	 Contiv Cisco	 CUMULUS Cumulus Networks	 flannel Red Hat
 GuardiCore GuardiCore	 LIGATO Cisco	 MULTUS Intel	 NSX VMware	 nuagenetworks From Nokia	 OCTARINE Octarine	 Open vSwitch Open vSwitch	 PROJECT CALICO Tigera	 tungstenfabric Tungsten Fabric

In open source there are currently three different lines of thought:

- Hardware switches/NOS - open-source frameworks running on white boxes/ODMs (Cumulus)
- Software switches - running on servers/hypervisors (OVS, Tungsten)
- Linux kernel network extensions - Calico, Contiv, Cilium, etc.

Bare Metal Switches + Network OS

Implement core switching/routing functions directly in Linux kernel and create an open source network OS that can run on bare metal switches.

This approach is followed by **Cumulus** and others

- sometimes with their own equipment (using merchant packet switching silicon)

Free Range Routing (FRR) - IP routing suite for Linux that supports range of routing protocols BGP, OSPF, IS-IS (Linux Foundation project, formerly Quagga).

As this is a platform, different approaches are possible. One particularly interesting approach is to run **eBGP as the only control plane in DC** and use **EVPN/VXLAN** to integrate with compute.

Software switches

An alternative to bare metal/NOS is to have generic **software switch** running directly on the hypervisors/servers

- Good examples of this would be **OVS** and **Tungsten Fabric**

Tungsten/Contrail is a platform to build multi-stack networking DC:

- It has its own software switch running on the servers (vrouter), which uses EVPN/VXLAN to connect them*
- Supports different tunneling protocols (including MPLS)
- Native integration with physical equipment (via BGP or even netconf)

Supports both multi-stack and across-stack (OpenStack, VMware, K8s)

Using BGP/MPLS internally means it's easy to extend network to other DCs

* For comparison btw OVS and vrouter see [OVS talk by Y. Yang](#)
HEPiX Fall 2019, Amsterdam

Network Disaggregation

- Breaks switch/router into hardware and software that can be purchased separately
 - Could have similar impact as server disaggregation had in the past
- This trend has started and is picking up pace due to the following reasons:
 - Clos topology requires small form factor switches with basic features in large quantities
 - Rise of the merchant packet switching silicon (now at the core in most switches)
 - Advances made in the manufacturing of the bare metal switches
 - Technical limitations/cost reduction in building up cloud-native DC with traditional equip.
- This had also significant impact on the progress of the open-source Network Operating Systems (NOS)
 - And in turn on developments in the Linux kernel networking stack and its extensions
- Created pressure for transition into **open environments** (ONIE, [OCP](#), etc.)

Linux Foundation Networking

Additional projects that improve performance, provide alternative controllers, offer programmable off-loading capabilities, etc. are hosted by Linux Foundation



Intel's Data Plane Development Kit (DPDK) - accelerates packet processing workloads running on a wide variety of CPU architectures

P4 - programming language for packet processing - suitable for describing everything from high-performance forwarding ASICs to software switches.

DC Edge

- HEP sites usually require significant north-south bandwidth (btw. DCs)
 - Understanding how to effectively design the DC edge is therefore critical
- DC Edge is going to become very important for number of reasons
 - Advances and affordability of the **Data Centre Interconnect (DCI)** technologies - this includes both hardware-based and software-based approaches (SDN gateways)
 - **Cloud gateways** - connecting DC to the Virtual Private Clouds (VPCs) - extending the networks to one or multiple cloud providers and offer multi-Cloud approaches
 - **SDN gateways** (e.g. Tungsten gateway) offer a possibility to extend networks between DCs and also mix/match traffic to different VPNs - could be very interesting for federated approaches

Programmable Wide-Area Networks

Motivation

Network capabilities in WAN have a number of use cases:

- Traffic engineering
 - Additional capacity exists and can be provisioned by steering traffic via alternate paths
- Network provisioning
 - With DC networking moving towards WAN protocols, there is an opportunity to leverage this to find alternative ways how to organise/manage current L3VPNs/LHCONE (multi-ONE)
- Provide QoS transfers
 - We have been running two dedicated networks (LHCOPN and LHCONE) which mainly differ in QoS provided. Other experiments will likely come up with similar requirements.
- Improve network to storage performance
 - Currently there is often a mismatch between target storage and network performance
- Capacity sharing
 - Network as a resource is becoming likely in the future (like compute/storage today)
- Effective use of HPCs and Clouds

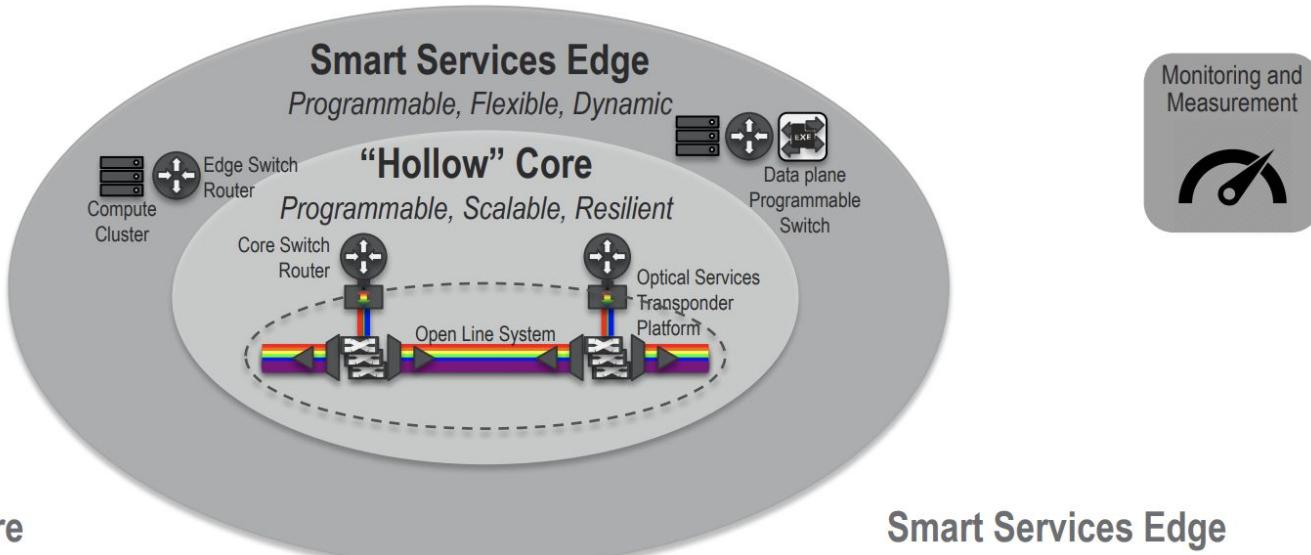
Projects

- Quite different from previous area - only few projects - most of them in R&D stages/prototype, but with very good fit to our use cases
- **Programmable Networks for Data-Intensive Science**
 - **multi-ONE - Traffic separation and VPN provisioning**
 - **SD/WAN**, Software-defined exchanges (**SDX**) and Network Service Interfaces (**NSI**), Data-Centre Interconnects (**DCIs**)
 - SDN for End-to-end Networked Science at the Exascale (**SENSE**)
 - **BigDataExpress** - schedulable, predictable, high performance transfers on top of SENSE
 - **NOTED** - Network-Optimized Transfer of Experimental Data
 - Existing projects also in ATLAS (OVS btw AGLT2/MWT2/KIT), SDN aspects also in NSF-funded SLATE, OSIRIS
- **Network services planned by the R&E providers**

R&E Plans

- R&E network providers have long been working closely with HEP
 - HEP has been representative of the future data intensive science domains
 - Often serving as testbed environment for early prototypes
- Surveying their plans for higher-level services and providing our feedback is critical for future evolution of HEP networking
- Different approaches are being followed - ranging from full SDN capable services (AMLight) up to a range of various low to higher-level edge services (ESNet6)
- Automation and Orchestration of Services in the GÉANT Community
 - Deliverable surveying plans for automation and orchestration of services
- **Our ability to use the programmable edge services will directly impact our ability to effectively use future networks.**

ESnet6 (“Hollow-Core”) Architecture Overview



“Hollow” Core

- **Programmable** – Software driven APIs to allocate core bandwidth as needed, and monitor status and performance.
- **Scalable** – Increased capacity scale and flexibility by leveraging latest technology (e.g. FlexGrid spectral partitioning, tunable wave modulation).
- **Resilient** – Protection and restoration functions using next generation Traffic Engineering (TE) protocols (e.g. Segment Routing (SR)).

Smart Services Edge

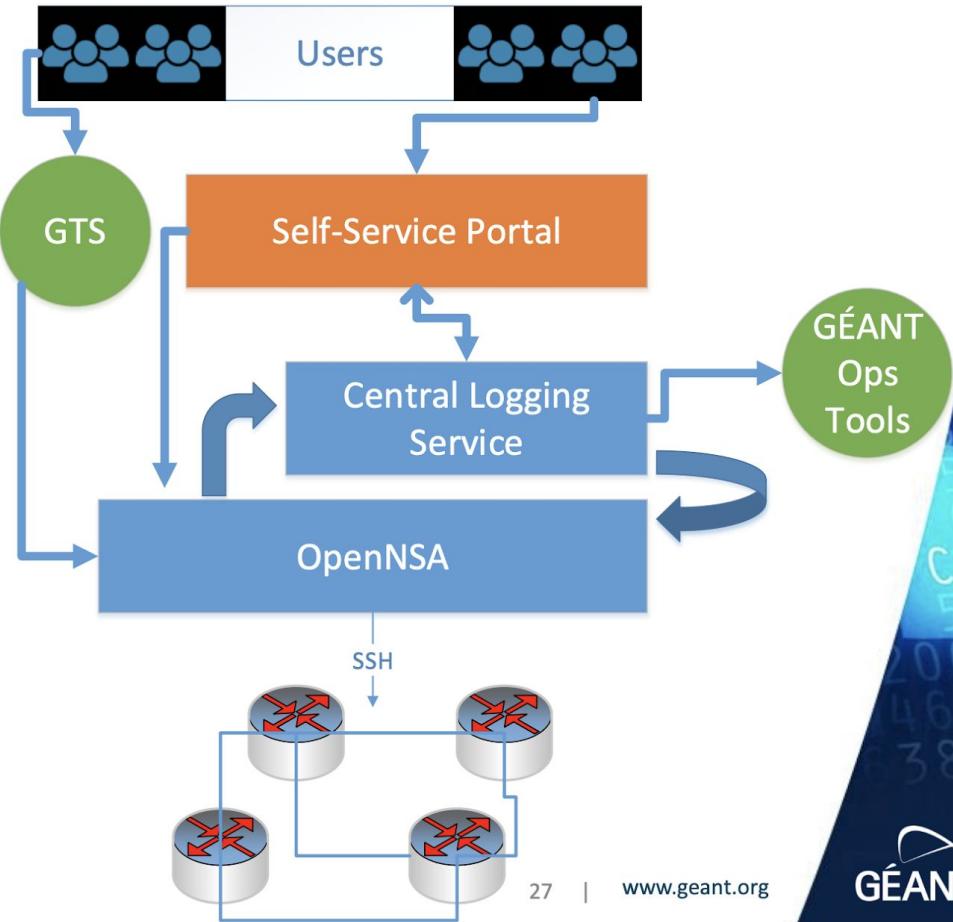
- **Programmable** – Software driven APIs to manage edge router/switch and retrieve telemetry information.
- **Flexible** - Data plane programmable switches (e.g. FPGA, NPU) in conjunction with compute resources to prototype new services (driven by Software Defined Networks (SDN))
- **Dynamic** – Dynamic instantiation of services using SDN paradigms (e.g. Network Function Virtualization (NFV), Virtual Network Functions (VNF), service chaining).

ESnet



Connection Service

- Automated service delivery
- Self service portal
- Open interface (API) for use with 3rd party automated systems and orchestrators
- Automated monitoring and service inventory
- Multi-domain services



Outlook

Working Group Plans

- Finalise report by end of October (next meeting Oct 23rd)
 - Publish and discuss it with the experiments
 - Propose possible areas of further work and understand which of those could be interesting to the experiments
- Decide on Phase II at the LHCOPN/LHCONE in January 2020
 - Networking week at CERN (<https://wiki.geant.org/display/SIGNGN/4th+SIG-NGN+Meeting>)
- Need you help to provide feedback and identify potential areas for further work
 - Cloud native networking DC
 - Performance studies (incl. smartNICs)
 - Programmable Networks Prototypes
 - DCI testing/evaluation
 - etc.
- Always looking for **feedback** and **additional volunteers/sites** for help.

Summary

- **Cloud native DC networking approaches offer ways to build scalable, robust and effective DC networks**
 - They have the potential to radically change the way how DC networking is build up and impact all the other areas
- **Network disaggregation** and open network environments are becoming mainstream at many cloud providers
- SENSE and BigData Express leading projects in **programmable networks** and data transfers, but non-OpenFlow approaches are also being investigated (NOTED)
- NFV WG report surveys the existing approaches and finalises Phase I
- LHCONE/LHCOPN meeting at CERN in January 2020 should provide decision point on Phase II
- **We welcome additional contributions; contact us if you are interested!**

Acknowledgements



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- IRIS-HEP: NSF OAC-1836650

References

WG Report: <https://docs.google.com/document/d/1w7XUPxE23DJXn--j-M3KvXIfXHUnYqsVUhBpKFjyjUQ/edit#>

WG Meetings and Notes: <https://indico.cern.ch/category/10031/>

SDN/NFV Tutorial: <https://indico.cern.ch/event/715631/>

Tungsten Fabric architectural overview:

<https://tungstenfabric.github.io/website/Tungsten-Fabric-Architecture.html>

OVN/OVS overview: <https://www.openvswitch.org/>

2018 IEEE/ACM Innovating the Network for Data-Intensive Science (INDIS) –
<http://conferences.computer.org/scw/2018/#!toc/3>

Cloud native Data Centre (book) -

https://www.amazon.com/Cloud-Native-Data-Center-Networking-Architecture/dp/1492045608/ref=sr_1_2?keywords=cloud+native+data+center+networking&qid=1568122189&s=gateway&sr=8-2

MPLS in the SDN Era (book) -

https://www.amazon.com/MPLS-SDN-Era-Interoperable-Scenarios/dp/149190545X/ref=sr_1_1?keywords=MPLS+in+the+SDN&qid=1568122219&s=gateway&sr=8-1

Backup slides

Use Cases

Data centre networking offering standard cloud compute services

- **Native support for multi-stack**
 - Connecting and integrating multiple orchestration stacks like k8s, OpenStack, etc.
 - Networking and security across legacy, virtualized and containerized applications
- **Network support across-stack**
 - Networking and security across legacy, virtualized and containerized applications
- **Native support for multi-cloud**
 - Extending DC networks to Commercial Clouds and creating federated services spanning DCs
- **Multi-tenancy/isolation**
 - Support for application/experiment level networking (e.g., MultiONE presentation earlier)
- **Network automation**
- **Security and observability**
 - Multistack and across-stack policy control, visibility and analytics

SENSE

SDN for End-to-end Networked Science at the Exascale (SENSE) - U.S.

DOE

Application Workflow Agent

- Transforms the network into a first class resource for workflow planning and optimization
- Allows applications to “query and negotiate” with network
- The SENSE infrastructure is designed to develop these types of services in DevOps manner, and customize for individual application agents.
- Cannot do every computation possible, but can do any computation desired.

BigData Express

U.S DOE funded; FNAL, ESNet, StarLight, KISTI, Univ. of Maryland, ORNL



Our Solution - BigData Express



- BigData Express: a schedulable, predictable, and high-performance data transfer service
 - ✓ – A peer-to-peer, scalable, and extensible data transfer model
 - A visually appealing, easy-to-use web portal
 - ✓ – A high-performance data transfer engine
 - A time-constraint-based scheduler
 - ✓ – On-demand provisioning of end-to-end network paths with guaranteed QoS
 - Robust and flexible error handling
 - CILogon-based security

Existing projects also in ATLAS (OVS btw AGLT2/MWT2/KIT), SDN aspects also in NSF-funded **SLATE**, **OSIRIS** and CERN's **NOTED** project

Network Virtualisation - OpenFlow

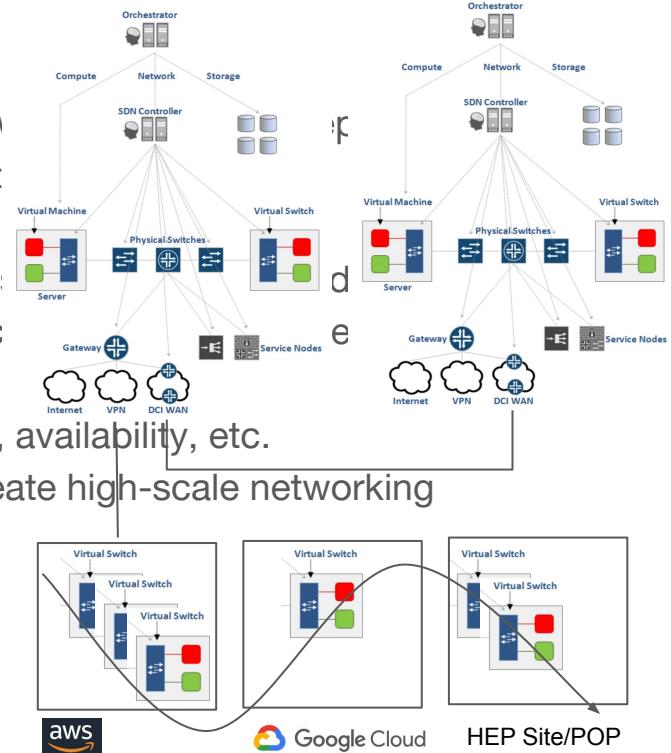
- OpenFlow started with an [influential paper](#) and became a movement in networking R&D
 - The core idea is to use flow tables (available in most packet switching silicon) and use OpenFlow protocol to remotely program the tables (from a centralised controller)
- OpenVSwitch (OVS) is an open source implementation of pure OpenFlow software switch
 - Native controller to program it is Open Virtual Network (OVN) (but others can be used as well)
 - Data plane can use VXLAN, GRE, Geneve; control plane is OpenFlow or native OVSDB
 - Controller supports integration with OpenStack and K8s
- OpenFlow protocol has been updated several times to address its shortcomings and overall didn't live up to its expectations
 - However there are existing production deployments (Google)
 - OpenFlow as such has proven to be very useful in other areas (WAN use cases)
 - Flow tables are still core part of some key network functions (ACLs, NAT, etc.)

SmartNICs

- Now offered from multiple vendors - goal is to maximise capacity while providing full programmability for virtual switching and routing, tunnelling (VXLAN, MPLS), ACLs and security groups, etc.
- Three approaches are being followed:
 - FPGA based - good performance, but difficult to program, workload specific optimisation
 - ASIC based - best price/performance, easy to program but extensibility limited to pre-defined capabilities
 - SOC based - good price/performance, easily programmable, highest flexibility
- Datapath programmability ([tutorial](#))
 - Application level - OpenVSwitch, Tungsten vRouter, etc.
 - Packet movement infrastructure (part of data path) - BPF (Berkeley Packet Filter)/eBPF
 - Full description of data path - P4 language
- FPGA-based SmartNICs broadly deployed in Microsoft Azure
- Tungsten Fabric 5.1 release plans to [support](#) smartNICs
- Good overview provided in [ACM SIGARCH article](#)

DC Edge - Multi-Cloud - DCI/Remote Compute

- SDN-based DC enables other interesting options
- Data Center Interconnect (DCI)**
 - SDN services spanning multiple physical sites, each site has its own SDN Controller
 - Agnostic to the Virtual Infrastructure Manager (Orchestrator)
- Remote Compute**
 - Single SDN deployment extending its services to remote sites to extend VPNs/VMs to another site without running a dedicated SDN controller
- Service chaining (NFV)**
 - Steering traffic between VPNs/VMs according to a policy, availability, etc.
- All the options are complementary** and can be combined to create high-scale networking combining 100s or even 1000s of sites.



Networking Challenges

- Capacity/share for data intensive sciences
 - No issues wrt available technology, however
 - What if N more HEP-scale science domains start competing for the same resources ?
- Remote data access proliferating in the current DDM design
 - Promoted as a way to solve challenges within experiment's DDM
 - Different patterns of network usage emerging
 - Moving from large streams to a mix of large and small frequent event streams
- Integration of Commercial Clouds
 - Impact on funding, usage policies, security, etc.
- Technology evolution
 - Software Defined Networking (SDN)/Network Functions Virtualisation (NFV)

Technology Impact

- Increased importance to oversee network capacities
 - Past and anticipated network usage by the experiments, including details on future workflows
- New technologies will make it easier to transfer vast amounts of data
 - **HEP quite likely no longer the only domain that will need high throughput**
- Sharing the future capacity will require greater interaction with networks
 - While unclear on what technologies will become mainstream (see later), we know that software will play a major role in the networks of the future
 - **We have an opportunity here**
- It's already clear that software will play major role in networks in the mid-term
- Important to understand how we can design, test and develop systems that could enter existing production workflows
 - **While at the same time changing something as fundamental as the network that all sites and experiments rely upon**
 - We need to engage sites, experiments and (N)REN(s) in this effort

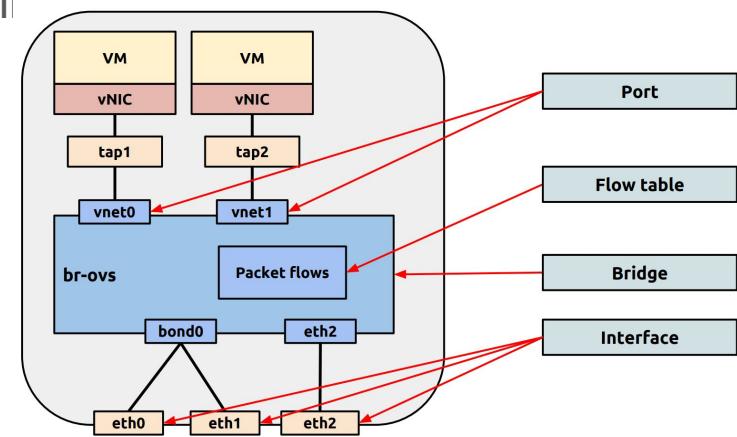
Software Defined Networks (SDN)

- Software Defined Networking (SDN) are a set of new technologies enabling the following use cases:
 - **Automated service delivery** - providing on-demand network services (bandwidth scheduling, dynamic VPN)
 - **Clouds/NFV** - agile service delivery on cloud infrastructures usually delivered via Network Functions
Virtualisation (NFV) - underlays are usually Cloud Compute Technologies, i.e. OpenStack/Kubernetes/Docker
 - **Network Resource Optimisation (NRO)** - dynamically optimising the network based on its load and state.
Optimising the network using near real-time traffic, topology and equipment. This is the core area for improving end-to-end transfers and provide potential backend technology for DataLakes
 - **Visibility and Control** - improve our insights into existing network and provide ways for smarter monitoring and control
- Many different point-to-point efforts and successes reported within LHCOPN/LHCONE
 - **Primary challenge is getting end-to-end!**
- While it's still unclear which technologies will become mainstream, it's already clear that software will play major role in networks in the mid-term
 - Massive network automation is possible - in production and at large-scale
- [HEPiX SDN/NFV Working Group](#) was formed to bring together sites, experiments, (N)RENs and engage them in testing, deploying and evaluating network virtualization technologies

Software Switches

Open vSwitch (OVS) - open source multilayer virtual switch supporting standard interfaces and protocols:

- OpenFlow, STP 802.1d, RSTP,
- Advanced Control, Forwarding, Tunneling
- Primarily motivated to enable VM-to-VM networking, but grew to become the core component in most of the existing open source cloud networking solutions



Runs as any other standard Linux app - user-level controller with kernel-level datapath including HW off-loading (recent) and acceleration (Intel DPDK)

Enables massive network automation ...

Open vSwitch Features

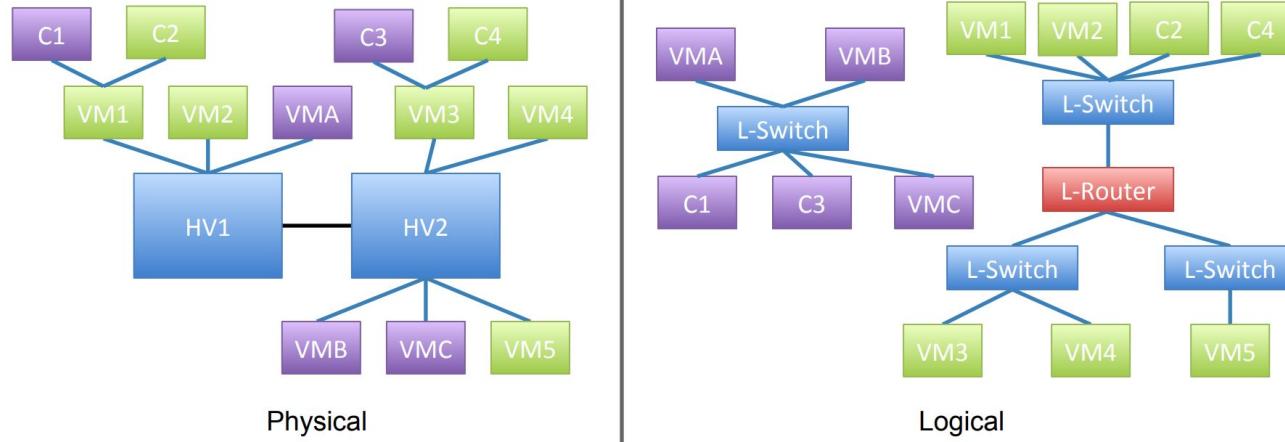
- Visibility into inter-VM communication via NetFlow, sFlow(R), IPFIX, SPAN, RSPAN, and GRE-tunneled mirrors
- LACP (IEEE 802.1AX-2008)
- Standard 802.1Q VLAN model with trunking
- Multicast snooping
- IETF Auto-Attach SPBM and rudimentary required LLDP support
- BFD and 802.1ag link monitoring
- STP (IEEE 802.1D-1998) and RSTP (IEEE 802.1D-2004)
- Fine-grained QoS control
- Support for HFSC qdisc
- Per VM interface traffic policing
- NIC bonding with source-MAC load balancing, active backup, and L4 hashing
- OpenFlow protocol support (including many extensions for virtualization)
- IPv6 support
- Multiple tunneling protocols (GRE, VXLAN, STT, and Geneve, with IPsec support)
- Remote configuration protocol with C and Python bindings
- Kernel and user-space forwarding engine options
- Multi-table forwarding pipeline with flow-caching engine
- Forwarding layer abstraction to ease porting to new software and hardware platforms

Controllers - Open DayLight

- Modular open platform for customizing and automating networks of any size and scale. Core use cases include:
 - **Cloud and NFV** - service delivery on cloud infrastructure in either the enterprise or service provider environment
 - **Network Resource Optimisation** - Dynamically optimizing the network based on load and state; support for variety of southbound protocols (OpenFlow, OVSDB, NETCONF, BGP-LS)
 - Automated Service Delivery - Providing on-demand services that may be controlled by the end user or the service provider, e.g. on-demand bandwidth scheduling, dynamic VPN
 - Visibility and Control - Centralized administration of the network and/or multiple controllers.
- Core component in number of open networking frameworks
 - ONAP, OPNFV, OpenStack, etc.
- Integrated or embedded in more than 50 vendor solutions and apps
- ODL is just one of many controllers that are available:
 - OpenContrail, ONOS, MidoNet, Ryu, etc.

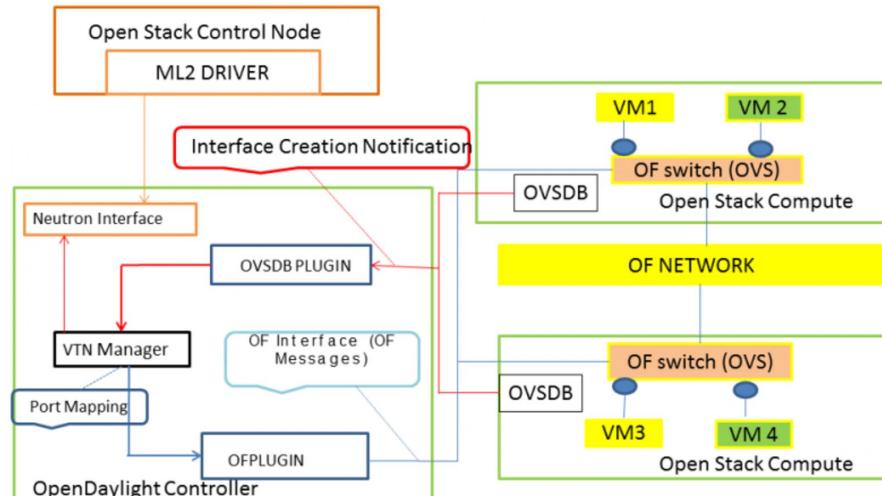
Controllers - Open Virtual Network (OVN)

- Open source logical networking for OVS
- Provides L2/L3 networking
 - Logical Switches; L2/L3/L4 ACLs
 - Logical Routers, Security Groups
 - Multiple Tunnel overlays (Geneve, VXLAN)
 - Top-of-rack-based & software-based physical-to-logical gateways



Cloud Compute - OpenStack Networking

- Cloud stresses networks like never before
 - Massive scale, Multi-tenancy/high density, VM mobility
- OpenStack Neutron offers a plugin technology to enable different (SDN) technologies to work together



Previously mentioned techs together
ML2 driver is what makes
controllers pluggable, so you
can easily replace Neutron
controller with OpenDaylight,
OVN, etc.

Both generic and
vendor-specific plugins are
available

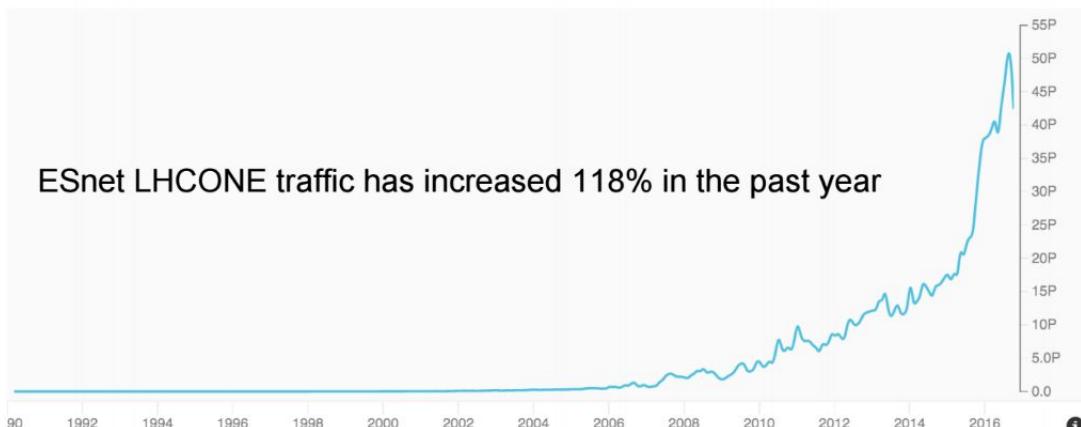
Cumulus Linux

- Alternative to OVS - uses separate apps/kernel functions to program different functionality such as STP/RSTP (mstpd), VXLAN (ifupdown2), VLAN (native linux bridge) etc.
- It does contain OVS to enable integration with controllers:
 - VMware NSX, Midokura Midonet, etc.
- Unlike OVS, Cumulus Linux is not an app, but a distribution, which is certified to run on bare metal switches
 - The list of supported HW is at
<https://cumulusnetworks.com/products/hardware-compatibility-list/>
 - Mainly Broadcom Tomahawk, Trident2/+, Helix4 and Mellanox Spectrum ASICs
- Otherwise runs like standard Linux, which means compute and network “speak the same language”
 - E.g. automation with Ansible, Puppet, Chef, etc.

R&E Traffic Growth Last Year

ESnet Traffic Volumes

LHCONE represents more than 32% of ESnet accepted traffic



◀ August 2016 ▶

	Bytes	Percent of Total	One Month Change	One Year Change
OSCARs	11.22 PB	26.5%	-8.93%	+19.7%
LHCONE	13.7 PB	32.3%	-25.6%	+118%
Normal traffic	17.46 PB	41.2%	-15.1%	+29.7%
Total	42.38 PB		-17.4%	+45.5%

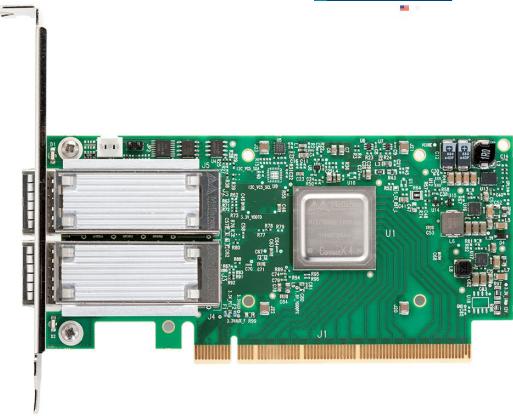
In general, ESNet sees overall traffic grow at factor 10 every 4 years. Recent LHC traffic appears to match this trend.

GEANT reported LHCONE peaks of over 100Gbps with traffic increase of 65% in the last year.

This has caused stresses on the available network capacity due to the LHC performing better than expected, but the situation is unlikely to improve in the long-term.

WAN vs LAN capacity

- Historically WAN capacity has not always had a stable relationship compared to data-centre
 - In recent history WAN technologies grew rapidly and for a while outpaced LAN or even local computing bus capacities
 - Today 100Gbps WAN links are the typical high-performance network speed, but LANs are also getting in the same range
 - List price for 100Gbit dual port card is ~ \$1000, but significant discounts can be found (as low as \$400), list price for 16 port 100Gbit switch is \$9000
- Today it is easy to over-subscribe WAN links
 - in terms of \$ of local hardware at many sites
- Will WAN be able to keep up ? **Likely yes**, however:
 - We did benefit from the fact that 100Gbit was deployed on time for Run2, might not be the case for Run3 and 4
 - By 2020 800 Gbps waves likely available, but at significant cost since those can be only deployed at proportionally shorter distances



Improving Our Use of the Network

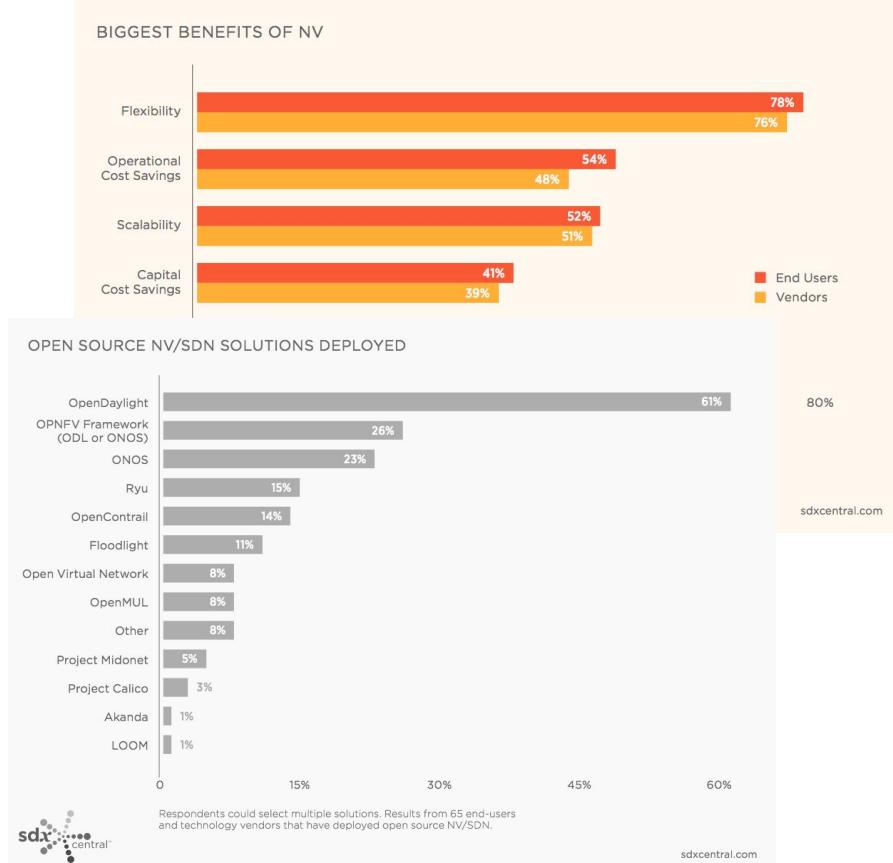
- TCP more stable in CC7, throughput ramp ups much quicker
 - Detailed [report](#) available from Brian Tierney/ESNet
- Fair Queueing Scheduler (FQ) available from kernel 3.11+
 - Even more stable, works better with small buffers
 - Pacing and shaping of traffic reliably to 32Gbps
- Best single flow tests show TCP LAN at 79Gbps, WAN (RTT 92ms) at 49Gbps
 - IPv6 slightly faster on the WAN, slightly slower on the LAN
- **In summary: new enhancements make tuning easier in general**
 - But some previous “tricks” no longer apply
- New TCP congestion algorithm ([TCP BBR](#)) from Google
 - Google reports factor 2-4 performance improvement on path with 1% loss (100ms RTT)
 - Early testing from ESNet less conclusive and questions need answering

R&E Networking

- R&E network providers have long been working closely with HEP community
 - HEP has been representative of the future data intensive science domains
 - Often serving as testbed environment for early prototypes
- Big data analytics requiring high throughput no longer limited to HEP
 - SKA (Square Kilometer Array) plans to operate at data volumes 200x current LHC scale
 - Besides Astronomy there are MANY science domains anticipating data scales beyond LHC, cf. [ESRFI 2016 roadmap](#)
- **What if N more HEP-scale science domains start competing for the same network resources ?**
 - Will HEP continue to enjoy “unlimited” bandwidth and prioritised attention or will we need to compete for the networks with other data intensive science domains ?
 - Will there be **AstroONE**, **BioONE**, etc., soon ?

Tech Trends: Software Defined Networks (SDN)

- SDN is a set of technologies offering solutions for many of the future challenges
 - Current links can handle ~ 6x more traffic if we could avoid peaks and be more efficient
 - SDN driven by commercial efforts
- Many different point-to-point efforts and successes reported within LHCOPN/LHCONE
 - **Primary challenge is getting end-to-end!**
- While it's still unclear which technologies will become mainstream, it's already clear that software will play major role in networks in the mid-term
 - Will experiments have effort to engage in the existing SDN testbeds to determine what impact it will have on their data management and operations ?



Tech Trends: SD-WAN

- Large Network as a Service providers include several well established CSPs such as Amazon, Rackspace, AT&T, Telefonica, etc.
- Recently more niche NaaS providers have appeared offering SD-WAN solutions
 - Aryaka, Cloudgenix, Pertino, VeloCloud, etc.
 - Their offering is currently limited and not suitable for high throughput, but evolving fast
- SD-WAN market is estimated to grow to \$6 billion in 2020 (sdxcentral)
- Will low cost WAN become available in a similar manner we are now buying cloud compute and storage services ?
 - Unlikely, our networks are shared, not easy to separate just LHC traffic
 - Transit within major cloud providers such as Amazon currently not possible and unlikely in the future, limited by regional business model - but great opportunity for NRENs

Tech Trends: Containers

- Recently there has been a strong interest in the container-based systems such as Docker
 - They offer a way to deploy and run distributed applications
 - Containers are lightweight - many of them can run on a single VM or physical host with shared OS
 - Greater portability since application is written to container interface not OS
- Obviously networking is a major limitation to containerization
 - Network virtualization, network programmability and separation between data and control plane are essential
 - Tools such as Flocker or Rancher can be used to create virtual overlay networks to connect containers across hosts and over larger networks (data centers, WAN)
- Containers have great potential to become disruptive in accelerating **SDN** and **merging LAN and WAN**
 - But clearly campus SDNs and WAN SDNs will evolve at different pace

Network Operations

- Deployment of perfSONARs at all WLCG sites made it possible for us to see and debug end-to-end network problems
 - OSG is gathering global perfSONAR data and making it available to WLCG and others
- A group focusing on helping sites and experiments with network issues using perfSONAR was formed - [WLCG Network Throughput](#)
 - Reports of non-performing links are actually quite common (almost on a weekly basis)
 - Most of the end-to-end issues are due to faulty switches or mis-configurations at sites
 - Some cases also due to link saturation (recently in LHCOPN) or issues at NRENs
- Recent network analytics of LHCOPN/LHCONE perfSONAR data also point out some very interesting facts:
 - Packet loss greater than 2% for a period of 3 hours on almost 5% of all LHCONE links
- Network telemetry (real-time network link usage) likely to become available in the mid-term (but likely not from all NRENs at the same time)
- It is increasingly important to focus on site-based network operations