“Grand” Challenges for a Science Mission Network

Chin Guok
ESnet Planning & Architecture Team
Lawrence Berkeley National Laboratory

INDIS 2020
(Virtual Event)
November 12, 2020
Some Background...
History of DOE Office of Science

- **Manhattan Project** (1942 - 1946)
- **Atomic Energy Commission** (1946 - 1974)
- **Energy Research and Development Administration** (1974 - 1977)
- **Department of Energy Office of Science** (1977 - 1998)
- **Department of Energy Office of Energy Research** (1998 - Present)
- **Department of Energy Office of Science** (1998 - Present)
- **Present**
Basic Energy Sciences (BES) supports fundamental research to understand, predict, and ultimately control matter and energy at the electronic, atomic, and molecular levels in order to provide the foundations for new energy technologies and to support DOE missions in energy, environment, and national security.

The mission of the Biological and Environmental Research (BER) program is to support transformative science and scientific user facilities to achieve a predictive understanding of complex biological, earth, and environmental systems for energy and infrastructure security, independence, and prosperity.

The Fusion Energy Sciences (FES) program mission is to expand the fundamental understanding of matter at very high temperatures and densities and to build the scientific foundation needed to develop a fusion energy source.

The mission of the High Energy Physics (HEP) program is to understand how our universe works at its most fundamental level.

The mission of the Nuclear Physics (NP) program is to discover, explore, and understand all forms of nuclear matter.

DOE Office of Science - Largest supporter of basic research in the physical sciences in the US
DOE Office of Science - Uniquely positioned for large scale collaborative science*

*DOE Office of Science facilities also support other collaborations, e.g., LHC, LSST, etc
DOE Office of Science - Uniquely positioned for large scale collaborative science*

This is ESnet

*DOE Office of Science facilities also support other collaborations, e.g., LHC, LSST, etc
An Exabyte Network Today

Yearly aggregate traffic in PB carried by ESnet

1091 PB/year as of CY2019

62% growth year on year
Building our New Network - ESnet6

- **We are here**
- **ESnet5.5 Service Starts**
- **ESnet6 Service Starts**
- **Packet & Low Touch Build**
- **High Touch Build**
- **ESnet6 Project Close-out**

**Timeline:**
- **CY2017**
  - R&D and Design
  - R&D Architecture Review
  - Conceptual Architecture Selection
  - Conceptual Design Review
- **CY2018**
  - Optical Build
  - CD 1/3a IPR
- **CY2019**
  - Optical Build Substantially Complete
  - Colo & Fiber Build Complete
  - OLS Install Starts
- **CY2020**
  - Colocation & Fiber Build Complete
  - OLS Install Starts
- **CY2021**
  - ESnet5 Packet Decom Starts
  - Optical Build Substantially Complete
- **CY2022**

**Additional Notes:**
- Delays Due to COVID-19
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).
“Grand” Challenge #1: Visibility of every packet that enters/exits the network
“Grand” Challenge #1: Visibility of every packet that enters/exits the network

Problem Statement

• **Requirement for high fidelity network monitoring** - WAN network monitoring today provides an aggregate (e.g., SNMP counters), or a sampled (e.g., Netflow/IPFIX) view of the network, which can result in “gut-feel” decisions.

• **Enhancing the user experience** - Performance issues are typically reported by the user with networks responding reactively. Real-time profiling of data transfer performance can be used to proactively address issues.

• **Improving network security** - Comprehensive network information can provide a complete picture for real-time or post-mortem analysis, e.g., complete information of every packet source/destination pair.
ESnet6 High-Touch Architecture Overview

1. Mirror Service - Allows selective flows in the dataplane to be duplicated and sent to the SmartNIC for processing.
2. Programmable Dataplane - Appends meta-data, timestamps and repackages packet for transmission to Platform code.
3. Telemetry Data L2VPN - Provides option to connect SmartNIC and Platform and bypass PCIe bus if needed.
4. Platform - Reads telemetry packets from the network and distributes information to High Touch Services.
5. Management Plane Base Routing Table - Provides connectivity to Remote Servers.
7. Service - Reads data from the Platform and performs real-time analysis as well as inserts selected telemetry data into database.
What Programmable “High Touch” Hardware to Use?

- There are a variety of programmable network devices available today: choice depends on use-cases, development effort available, performance requirement, existing tooling etc.

- ESnet was looking for the following:
  - 100Gbit/s port speed and roadmap for higher speeds
  - Timing and performance guarantees
  - Easy programming (P4 style)
  - Established vendor

- We have done extensive evaluation of:
  - Netronome SmartNICs (prototyping platform)
  - Xilinx FPGAs (production platform of choice)
Telemetry Producers

Copy of original packet of a TCP flow

Programmable Data Plane
Transforms packets

High-Touch Telemetry Packet

Payload removed

Ethernet
IPv4
TCP
Payload

Ethernet
IPv6
Destination: collector
UDP

Original IPv4
Original TCP
Precision Timestamps
Aggregate counters

Payload removed

High-Touch Telemetry Record (approximate) ~100 bytes

<table>
<thead>
<tr>
<th>Packet size</th>
<th>Rate</th>
<th>Telemetry Rate</th>
<th>Telemetry Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>1500B</td>
<td>10Gb/s</td>
<td>812K</td>
<td>1,079Mb/s</td>
</tr>
<tr>
<td>1500B</td>
<td>100Gb/s</td>
<td>8,127K</td>
<td>10,790Mb/s</td>
</tr>
<tr>
<td>9000B</td>
<td>10Gb/s</td>
<td>138K</td>
<td>183Mb/s</td>
</tr>
<tr>
<td>9000B</td>
<td>100Gb/s</td>
<td>1,383K</td>
<td>1,833Mb/s</td>
</tr>
</tbody>
</table>

```go
type HighTouchLayer struct {
    Version    string
    SensorID   uint8
    VlanId     uint16
    IngressTimestamp uint64

    // IP header of original packet
    IpSrcAddr    net.IP
    IpDstAddr    net.IP

    // TCP header of original packet
    TcpSrcPort  uint16
    TcpDstPort  uint16
    TcpSeqNo    uint32
    TcpAckNo    uint32

    // Aggregate counters
    FlowPktCount uint64
    FlowByteCount uint64
    FlowId       uint16
    Flags        uint8
}
```
High Touch FPGA Block Diagram

Programmable
- Per flow / Per packet statistics

Flow ID pkt size

Large Tables

16 Gbytes DDR4

Flow Counters

Real Time Histogram

Real Time Histogram

Programmable
- Packet Forwarding / Editing
  Stateful / In order / Multi-threaded
- QoS
  Shaping / Priority
  Buffering / Flow Control

Packet Distribution Chain
In order 150 Mpps
P4 Configurable add / drop / redirect

100G Stateful NPU
100G Stateful NPU
General Purpose NPU
General Purpose NPU

8 Gbytes HBM (1Tbit / s) R/W BW

Flow ID Ethernet HDR
Flow ID IPv4 HDR
Flow ID MPLS HDR
Flow ID Egress HDR

User Defined HW Processor

Eth

P4 Programmable Parser
Flow ID TCAM

Eth
High Touch Processing Platform

TCP rate monitor  |  Finger of blame  |  Packet Loss

Services

Flow #1  |  Kafka cluster  |  Flow #2

Platform

Fastcapa (DPDK)

TX Process #1  |  TX Process #2  |  TX Process #n

Packet ring

Bulk dequeue  |  Burst enqueue

RX Process #1  |  RX Process #2  |  RX Process #n

RX queue #1  |  RX queue #2  |  RX queue #n

Distributor / RSS

Mellanox 100G NIC

Topics deleted after 24hr automatically

Fastcapa runs on multiple cores (each RX and TX process is one core)

Any DPDK-enabled card

Telemetry packets
TCP Rate and Retransmission Tracking

1 Gbps iPerf Flow - 600,000 Packets

Per-packet rates reaching 10 Gbit/s (line rate of the sender)

1 Gbp/s average flow rate (100 pkt window)

Note: Average rate is calculated using a time-weighted average of per-packet rates.
TCP Rate and Retransmission Tracking
1 Gbps iPerf flow - 1% packet drop

Note: only 23 packets were dropped all together, taking bandwidth down to 5 Mb/s from 1 Gb/s.
TCP Rate and Retransmission Tracking
1 Gbps iPerf Flow - 1% Packet Drop

The difference between the lines represents the performance of the data transfer, convergence is good, divergence is bad.

Flow throughput drops when a retransmission happens
Finger of Blame

Upstream Network(s) is experiencing packet loss* - Both Sensor #1 and Sensor #2 see missing SEQ numbers (non-continuous stream has been observed)

ESnet is experiencing packet loss* - No losses seen at Sensor #1, missing seq numbers at Sensor #2

Downstream Network(s) is dropping* - Both Sensor #1 and Sensor #2 see repeated SEQ numbers

*NB: Using unidirectional observation
“Grand” Challenge #2: Predictive reconfiguration of the network
“Grand” Challenge #2: Predictive Reconfiguration of the Network

Problem Statement

• **Improving the user experience** - Avoiding typical best-effort forwarding and predictively routing elephant flows (i.e., large science workflow data) around congestion results in better performance for both elephant and mice flows.

• **Increase bandwidth utilization efficiency** - WANs are typically designed to run at an average utilization of 25-50%. This is because bandwidth is reasonably static and the network is designed to accommodate for link failures as well as transient traffic spikes. Predictive reconfiguration of the network to reduce hotspots could allow the network to run at higher utilization with less packet loss.
Network ‘Self’ Learns to Predict and Reduce Congestion

Too many flows on same path → Congestion → Packet loss

Predict if congestion will occur
Divert traffic to underused path
Requires Gathering and Processing ‘all kinds of network data’

Massive amounts of disparate real-time data:
- Computational processing of real-time data to make reliable learning
How Can We Predict Congestion?

NetPredict: Deep Learning model

Real-time Data
- PerfSonar (Loss, Throughput)
- Traffic: SNMP data
- Flow behavior: Netflow log

Planning your next transfer?

Less busy than usual
NetPredict*: Deep Learning Model for Network Congestion

- Dynamic Graph Neural Network to reduce prediction errors when network will be congested
- Trains on 2 years of data to predict congestion 24-hours ahead

NetPredict Portal
(Linked with ESnet portal)

Deployed on Google Cloud Platform
- Different models can run at the same time to compute least congested paths
- Estimates transfer completion time

Trust dashboard
- Real-time ML performance
- Build engineer’s confidence in predictions
DeepRoute*: Intelligent Traffic Engineering

**Reward Function**
Multi-Objective Optimization
- Min(Packet Loss)
- Min(Flow Time)

DeepRoute Controller

Network Dashboard collects data and feeds to controller

AI provides better results compared to shortest path algorithms, *actively reducing packet loss*

---

Goal Towards Self-Learning Networks

<table>
<thead>
<tr>
<th>Traditional Networking</th>
<th>Self-Learning Network</th>
</tr>
</thead>
<tbody>
<tr>
<td>Static Routing Algorithms (e.g., shortest route/least hops)</td>
<td>Adaptive Routing (e.g., real-time data for routing decisions)</td>
</tr>
<tr>
<td>Reactive Network Configuration</td>
<td>Proactive Network Configuration</td>
</tr>
<tr>
<td>Inefficient utilization (25-50%)</td>
<td>100% utilization with resilience</td>
</tr>
<tr>
<td>Leads to congestion, packet loss</td>
<td>Learns to avoid congestion</td>
</tr>
</tbody>
</table>
“Grand” Challenge #3: Seamless integration of the network with other technology domains
“Grand” Challenge #3: Seamless integration of the network with other technology domains

Problem Statement

- **Decreasing the cost footprint of large science workflows** - Today’s large science workflows are typically broken down into discreet stages along technology boundaries. This results in inefficiencies in terms of duplicate hardware, i.e., primarily storage.

- **Reducing the time-to-results for distributed science workflows** - Instrument and compute resources are typically scheduled and committed, but networking and storage resources are not. This inconsistency, where some resources are guaranteed, whereas others are best-effort, often results in conservative end-to-end workflow designs.
Example of a Traditional Workflow for Large Scale Distributed Science Experiments

Discrete Data Flow

1. Initial data processing on local compute and staged in local storage.
2. Data transfer over WAN and staged in HPC local storage.
3. HPC fetches data from local storage for processing.
4. HPC stages processed data in local storage for transfer.
5. Data transfer over WAN into HPS for long term storage.
Superfacility: A model to integrate experimental, computational, networking, and storage facilities for reproducible science

Enabling new discoveries by coupling experimental science with extreme scale data analysis and simulations
Superfacility Automation

Diagram showing various components of a superfacility automation system, including instrument, local compute/storage, (HPN) network, (Cluster) compute/(HPS) storage, DTN, (HPC) compute, and (HPS) storage. The diagram also highlights connections between these components and mentions CMS, ALICE, ATLAS, and LHC-B. The image includes references to ESnet.
Superfacility Automation

Application Workflow
Superfacility Automation

Application Workflow

Resource Manager

Local Compute / Storage

Resource Manager

(Cluster) Compute / (HPS) Storage

Resource Manager

DTN (HPS) Storage

Resource Manager

(HPN) Network

Resource Manager

(HPC) Compute / (HPS) Storage

Requests, Credentials

Capabilities, Availability, Confirmation, Status

Requests, Credentials

Confirmation, Status

Resource Orchestrator

CMS

ALICE

ATLAS

LHC-B

Resource Manager

Instrument

(HPC) Compute / (HPS) Storage

Instrument

Cluster

Compute

Storage

Resource Manager

Local Compute / Storage

Resource Manager

(HPN) Network

Resource Manager

(HPC) Compute / (HPS) Storage

Resource Manager

DTN (HPS) Storage
Superfacility Automation

Application Workflow

Requests, Credentials

Capabilities, Availability, Confirmation, Status

Requests, Credentials

Confirmation, Status

Resource Orchestrator

Instantiation of a Interconnected Facilities

Resource Manager

Resource Manager

Resource Manager

Resource Manager

Resource Manager

Resource Manager

Resource Manager

Resource Manager

Resource Manager

Resource Manager

Resource Manager
Superfacility Use Case 1 - Fast feedback to adjust experiment parameters

Linac Coherent Light Source (LCLS)

- Ultrafast X-ray pulses from LCLS are used like flashes from a high-speed strobe light, producing stop-action movies of atoms and molecules.
- Both data processing and scientific interpretation demand intensive computational analysis.
- Leverage HPC resources to process initial results to verify proper alignment. Misalignment results in wasted experiment.
Superfacility Use Case 2 - Reduction or elimination of site local compute and storage

National Center for Electron Microscopy (NCEM) - 4D STEM Development

- NCEM is developing a high frame rate (100KHz) 4D detector system to enable fast real-time data analysis of scanning diffraction experiments in scanning transmission electron microscopy (STEM)

- High frame rate development aims to improve scanning diffraction experiments and will be installed on the Transmission Electron Aberration-corrected Microscope (TEAM)

- Direct high speed data transfer of raw image sets from microscope to HPC for online analysis and storage of data.
Superfacility Use Case 3 - Real-time analysis for monitoring and control

ITER (originally International Thermonuclear Experimental Reactor)

- First fusion device to produce net energy and maintain fusion for long periods of time with ten times the plasma volume of largest machine operating today.
- ITER is designed to produce **500 MW** of fusion power from 50 MW of input heating power.
- Real-time analysis and control is needed to flag potentially dangerous issues within the reactor and mitigate accordingly.
SENSE: SDN for End-to-end Networked Science at the Exascale

● Motivation and Objective
Building an intent-driven, multi-domain, orchestration framework to allow distributed science workflows to intuitively provision and manage end-to-end network services including site-edge data caching.

● Significance and Impact
Policy-guided end-to-end orchestration of network resources to enable real time coordination of network, compute, and storage resources -- this allows for science application workflows to interact with the network as a first class resource to drive end-to-end service provisioning, workflow optimization based on end-to-end resource discovery and performance information, and real-time interaction and negotiation based decision making.

● Research Details
○ Model Driven SDN Control with Orchestration.
○ Intent based science application facing APIs with resource discovery and negotiation.
○ Automated end-to-end troubleshooting and debugging.
○ Datification of cyberinfrastructure to enable intelligent services.

This work was supported by the Director, Office of Science. Office of Advanced Scientific Computing Research. Mathematical, Information, and Computational Sciences Division under U.S. Department of Energy Contract No. DE-AC02-05CH11231.
SENSE Automation Prototype

SDN for End-to-End Networking @ Exascale (SENSE)

LCLS Data Transfer Workflow

SENSE Orchestrator

SENSE Network-RM

SENSE DTN-RM

LCLS

Aggregate detector data, EPICS
data, beamline data -
selection and compression

Compressor Nodes

Event builder nodes

FFB Layer
(nVRAM)

Online Monitoring & FFB Nodes

IB

10 GB/s - 1Tb/s

Exascale HPC

Burst Buffer nVRAM: Streaming
Analysis

ExaFEL Data Flow

NGF / Lustre: Offline from HDF/XTC files.

Exascale HSN

42
## Multi-Domain Automated Resource Allocation - Gaps and Lessons Learned

<table>
<thead>
<tr>
<th>Feature</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Resource Models</strong></td>
<td>Needs to be extended to include additional resource types (e.g. HPC, edge computing, etc).</td>
</tr>
<tr>
<td><strong>AuthN/AuthZ Frameworks</strong></td>
<td>Needs to be flexible, and not encumber the Superfacility modeling process.</td>
</tr>
<tr>
<td><strong>Application Programmable Interfaces</strong></td>
<td>Needs to support negotiation and provide the appropriate abstractions at the right level (e.g. descriptive for applications &lt;-&gt; orchestrator, prescriptive for orchestrator &lt;-&gt; resource managers).</td>
</tr>
<tr>
<td><strong>Frameworks to Share Health and Performance Data</strong></td>
<td>Is critical in understanding how the Superfacility model is functioning, as well as for troubleshooting issues.</td>
</tr>
<tr>
<td><strong>Real Time and Proactive Resource Optimization</strong></td>
<td>Is needed to alleviate scheduling conflicts within the multi-domain heterogeneous resource Superfacility environment.</td>
</tr>
<tr>
<td><strong>AI-Based Techniques for Anomaly Detection, Prediction, and Mitigation</strong></td>
<td>Are necessary to advance the Superfacility model beyond human-scale limitations.</td>
</tr>
</tbody>
</table>
Grand Challenge #4: Information Teleportation
Grand Challenge #4: Information Teleportation

Problem Statement

• **How do you make this work??** - For quantum networking to work, multiple problems at different layers have to be solved, e.g., quantum transduction, quantum sensing, quantum memory, quantum repeaters, quantum communication protocols, etc, etc, etc.

• **What are the use cases?** - Understanding the use cases would help shape what is deployed. Some use cases - secure communications (e.g., QKD), distributed quantum computing, clock synchronization, … what else???
Stages in the Development of a Quantum Internet

- Quantum computing
- Few qubit fault tolerant
- Quantum memory
- Entanglement generation
- Prepare and measure
- Trusted repeater

Functionality

- Leader election, fast byzantine agreement, ...
- Clock synchronization, distributed quantum computation, ...
- Blind quantum computing, simple leader election and agreement protocols, ...
- Device independent protocols
- Quantum key distribution, secure identification, ...
- Quantum key distribution (no end-to-end security)

Stage of quantum network
Examples of known applications

mouseup

Stephanie Wehner et al. Science 2018;362:eaam9288
Quantum Networks - The Next Frontier in Networking...

Lab Receives DOE Funding for Quantum Computing

Quantum Internet Workshop Maps Quantum Future

“The construction of the nation’s first Quantum Internet will open new possibilities in science, strengthen our national security, and open a world of opportunities in communications, innovation, and technology.”

– Secretary Dan Brouillette

New Center to Pioneer Quantum Technologies for Science

ESnet to Support New DOE Quantum Internet Blueprint
Acknowledgements

ESnet High-Touch Team

- Chin Guok <chin@es.net>
- Richard Cziva <richard@es.net>
- Yatish Kumar <yak@es.net>
- Bruce Mah <bmah@es.net>
- Brendan White <bmt@es.net>

ESnet AI/ML Team

- Mariam Kiran <mkiran@es.net>
- Bashir Mohammed <bmohammed@lbl.gov>
- Scott Campbell <scottc@es.net>
- Fatima Bannat-Wala <fatemabw@es.net>

ESnet SENSE Team

- Inder Monga <inder@es.net>
- Chin Guok <chin@es.net>
- Tom Lehman <tlehman@es.net>
- John MacAuley <macauley@es.net>
- Alex Sim <asim@lbl.gov>
- Xi Yang <xiyang@es.net>
Questions...