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CI Lunch and Learn / Jan 21st, 2021

In-band Network Telemetry @ AmLight: Lessons Learned after 2 years

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Outline

- In-band Network Telemetry
- AmLight-INT project after 2 years:
  - Original Goals
  - What we are monitoring
  - Challenges
  - Rolling out to production
  - Results
- What happens next?
  - New projects
- Future Challenges
- Team and Opportunities

In-band Network Telemetry (INT)

- INT is a P4 application that records network telemetry information in the packet while the packet traverses a path between two points in the network

- As telemetry is exported directly from the Data Plane, Control Plane is not affected:
  - Translating: *you can track/monitor/evaluate EVERY single packet at line rate and real time.*

- Examples of telemetry information added:
  - Timestamp, ingress port, egress port, queue buffer utilization, sequence #, and many others

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Questions addressed by INT

- *How did this packet get here?*
  - The sequence of network devices a packet visited along its path (Proof-of-Transit).
    - LAG? No problem. ECMP? No problem. Layer 2 network? No problem!
- *Why is this packet here?*
  - The set of rules a packet matched upon at every switch along the way.
- *How long was this packet delayed?*
  - The time a packet spent buffered in every switch, to the nanosecond, from end-to-end.
- *Why was this packet delayed?*
  - Who else was in the buffer that led to an increased delay?

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INT: How does it work?

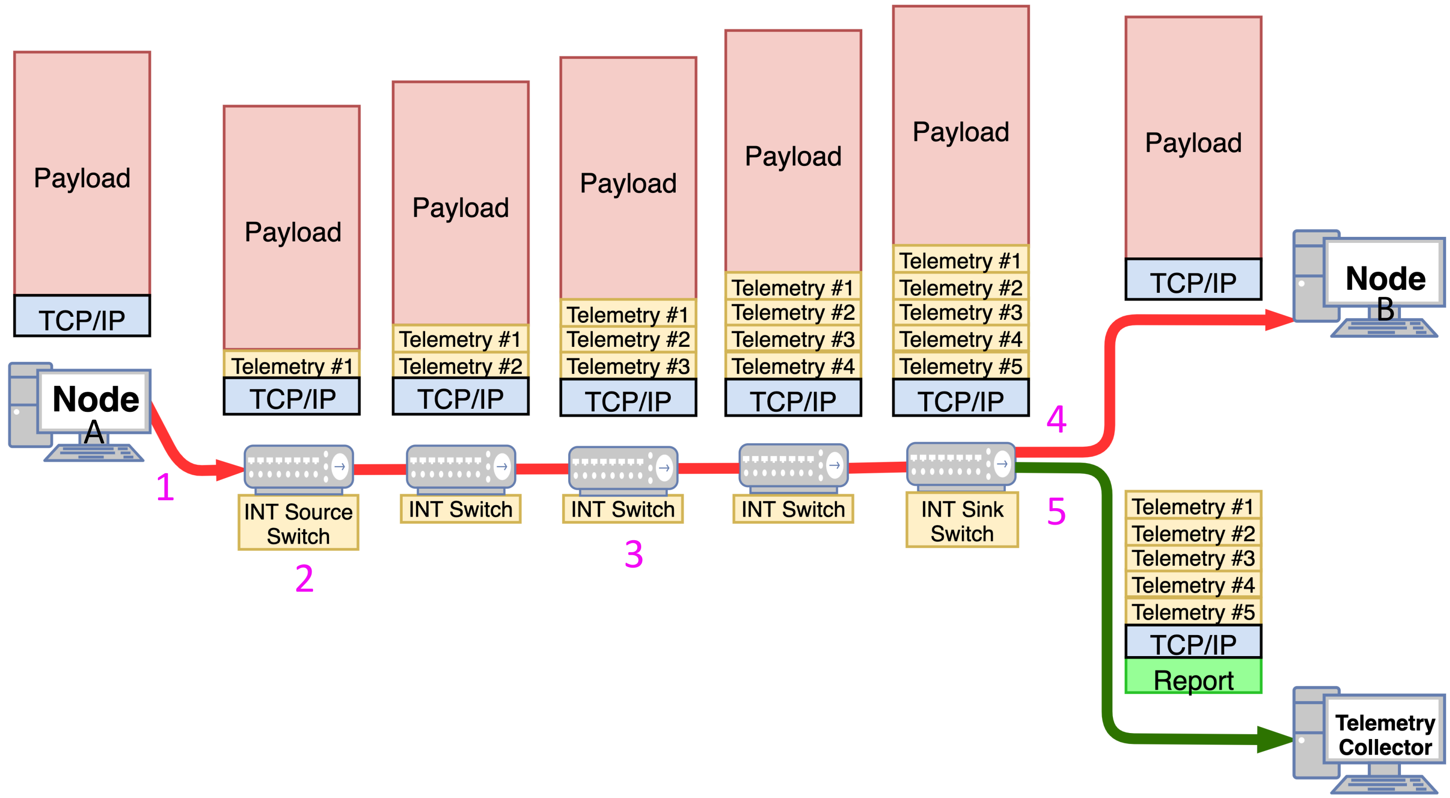
1 – User sends a TCP or UDP packet unaware of INT

2 – First switch (INT Source Switch) pushes an INT header + metadata

3 – Every INT switch pushes its metadata. Non-INT switches just ignore INT content

4 – Last switch (INT Sink Switch) extracts the telemetry and forwards original packet to user

5 – Last switch (INT Sink Switch) forwards the 1:1 telemetry report to the Telemetry Collector



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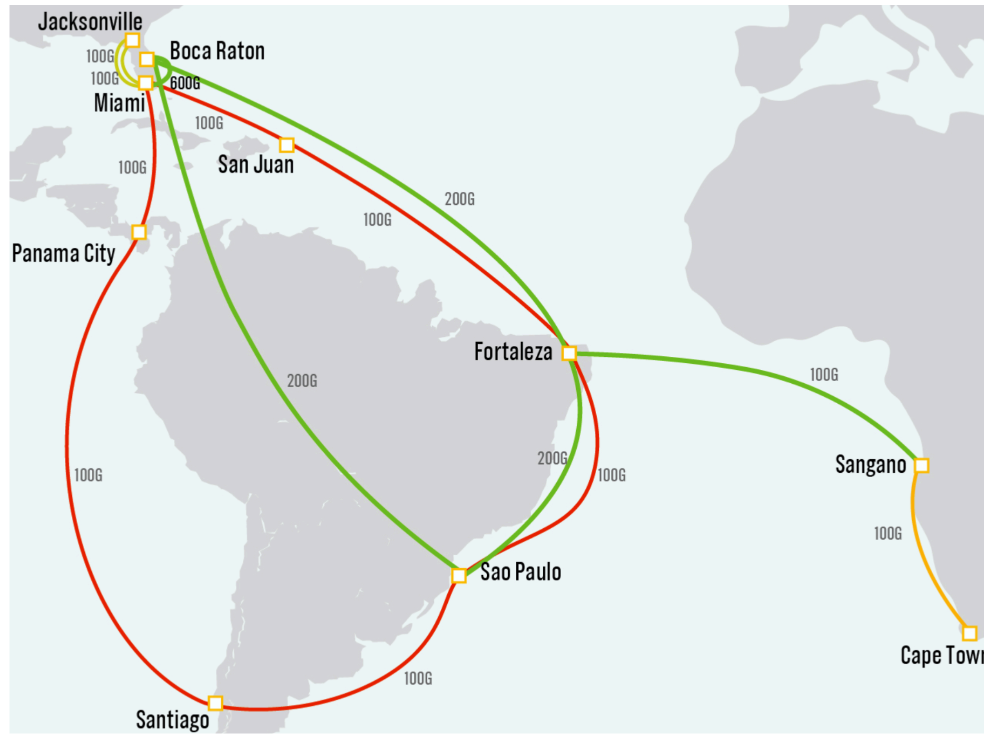
Introduction to AmLight

- AmLight Express and Protect (AmLight-ExP) (NSF International Research Network Connections (IRNC) Award # OAC-2029283)
- 600Gbps of upstream capacity between the U.S. and Latin America, and 100Gbps to Africa
- Production SDN Infrastructure since 2014
  - OpenFlow 1.0, OpenFlow 1.3, and NSI
- NAPs: Florida(2), Brazil(2), Chile, Puerto Rico, Panama, and South Africa
- Driver for deploying INT: The Vera Rubin Observatory's Service Level Agreement (SLA)



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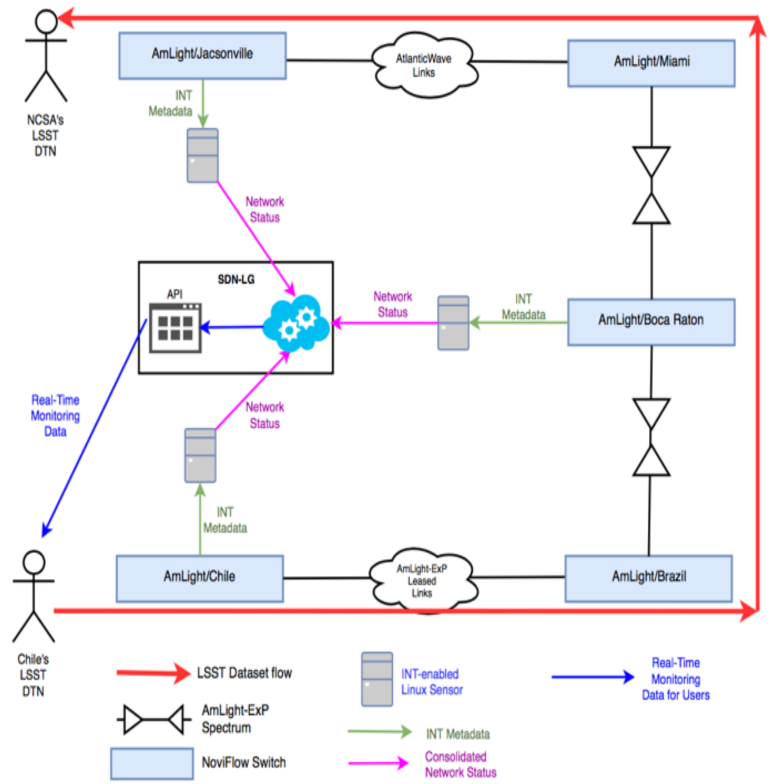
AmLight-INT Project

- NSF IRNC: Backbone: AmLight In-band Network Telemetry (AmLight-INT), Award# OAC-1848746
  - Started in Nov 2018

- AmLight-INT Project Goals:
  - Develop and Deploy INT-capable switches
  - Deploy INT Telemetry Collectors to collect and process telemetry metadata
  - Develop a new methodology to collect and export INT data in real time to feed SDN controllers and users with monitoring information
  - Create a Network Telemetry Design Pattern to be used by other R&E networks



AmLight-INT Project [2]

- Collaboration between FIU and NoviFlow to expand AmLight SDN network towards an INT-capable domain
  - NoviFlow expanded the NoviWare OS to support INT following FIU's requirements
  - FIU developed the telemetry collector and evaluated the NoviFlow switch

- Characteristics of the NoviFlow WB5132 switches @ AmLight:
  - Barefoot Tofino chip:
    - Provides a software-based SDN evolution path to P4Runtime
    - 32 x 100G interfaces (high throughput: 3.2 Tbps)
  - NoviWare supports OpenFlow 1.3 and 1.4 with BFD and LAG (also P4Runtime)

- P4/INT 1.0 specification being followed [1]

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Research challenges ~~being~~ addressed [1]

- *How many high-priority flows can be handled in real-time by the INT Telemetry Collector?*
  - *Currently capable of “processing” 10Mpps* without extra workarounds and nodes.*

- *What is the impact caused by INT in a complex network such as AmLight-ExP?*
  - *Delay: Pushing INT header takes around 450ns. No impact in a long-haul network.*
  - *MTU: Each switch adds 24bytes. Tofino chip has MTU of 10K. Legacy devices in the path have to be considered.*
  - *Colocation: Every AmLight PoP needs colocation for the INT Telemetry Collector (telemetry is processed locally)*

- *How to dynamically enable INT monitoring of specific flows?*
  - *New OpenFlow 1.3 Experimenter Actions created (push_int, add_int_metadata, pop_int, send_report)*
  - *Enables AmLight to be very specific when selecting what to monitor (per-source, per-destination, TCP and UDP, per port, etc.)*

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Research challenges ~~being~~ addressed [2]

- *What is the definition of real-time for the AmLight-INT project?*
  - *Receiving "instructions" from consolidated telemetry reports under 200ms*
    - *Collect telemetry data, process it, send summary to central location, process summaries from multiple telemetry collectors, generate an alert: under 200ms*
    - *Brazil and Chile are 55ms away in propagation delay.*

- *How to store and process multiple Gbps of telemetry data per switch/point of presence?*
  - *Each site has a high-speed management plane with one telemetry collector*
  - *Process: Using eBPF/XDP for processing telemetry data (Challenge 1)*
  - *Store: Waiting for Challenge #1. Not easy.*

- *How to share the network state with the users?*
  - *Summaries and events are stored in a time series database (influxDB)*
  - *Data visualization via Grafana*
  - *gRPC is the goal for users interested in consuming summaries in real time*

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What metadata is being used and how? [1]

- The AmLight INT switches leverage the Tofino chip to collect:
  - Per switch:
    - Switch ID
    - Ingress port
    - Egress port
    - Ingress timestamp
    - Egress timestamp
    - Egress queue ID
    - Egress queue occupancy
  - Per report:
    - Report timestamp
    - Report sequence number
    - Original TCP/IP headers

What metadata is being used and how? [2]

- **Proof of Transit (PoF)** or path taken
  - Metadata used:
    - List of switches
    - Per switch:
      - Switch ID, Ingress port, Egress port, Egress queue ID

- AmLight is capable of path tracing EVERY packet and recording changes
  - Useful for detecting LAG or ECMP hash errors/mismatches
  - Useful for detecting unstable links

- Path taken even indicates *egress queue ID*:
  - Useful for evaluating QoS policies

What metadata is being used and how? [3]

- **Instantaneous Ingress and Egress Interface utilization**
  - Metadata used:
    - List of switches
    - Per switch:
      - Switch ID, Ingress port, Egress port
    - From the user TCP/IP header:
      - IP length

- AmLight's telemetry collector monitors and reports egress/outgoing interface utilization every 50ms*
  - Useful for detecting microbursts and precise bandwidth utilization
  - *50ms can be tuned down for shorter intervals if needed
  - Bandwidth can be monitored per queue

What metadata is being used and how? [4]

- **Instantaneous Egress Interface Queue utilization (or buffer)**
  - Metadata needed:
    - List of switches and their metadata
    - Per switch:
      - Switch ID, Egress port, Egress Queue ID, Queue Occupancy

- AmLight monitors every queue of every interface of every switch:
  - Useful for evaluating QoS policies
  - Useful for detecting sources of packet drops

What metadata is being used and how? [5]

- **Sources of jitter:**
  - Metadata needed:
    - List of switches
    - Per switch:
      - Switch ID, ingress timestamp, egress timestamp

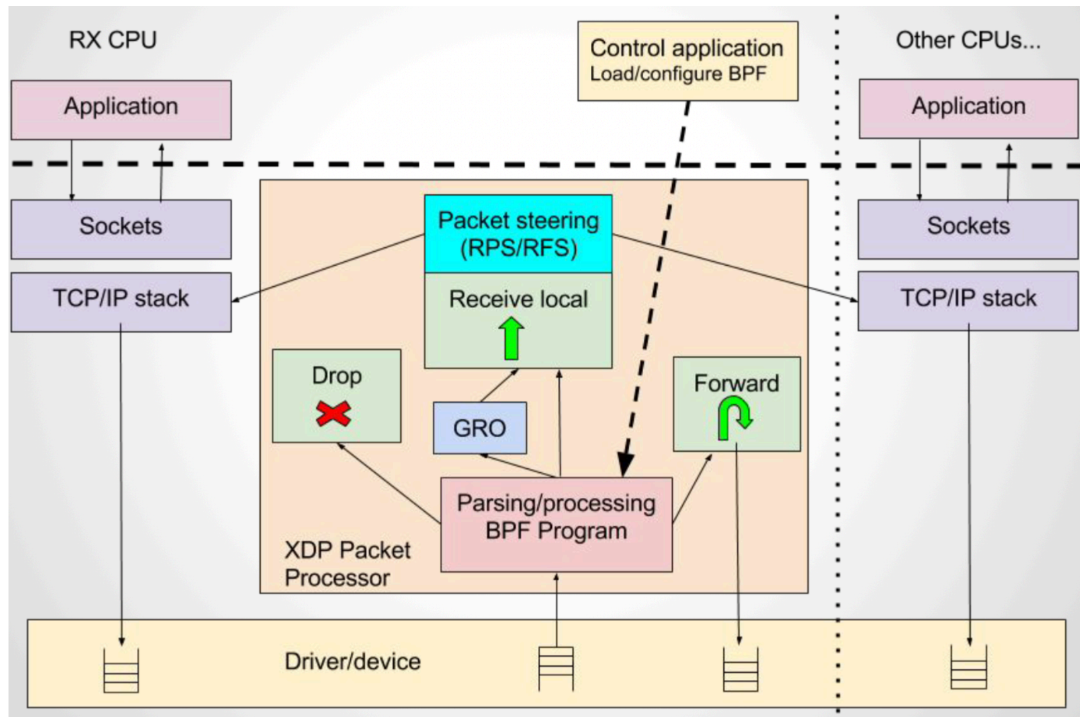
- AmLight monitors per-hop per-packet forwarding delay:
  - Useful for evaluating sources of jitter along the path
  - Useful for mitigating QoS policy issues (underprovisioned buffers)
  - Useful for mitigating traffic engineering issues (underprovisioned links)

Challenge 1: Receiving telemetry reports

- 100Gbps with 9000-Bytes packets ➔ ~1.5M packets per second
- At AmLight, 4-8 switches connect Chile to the U.S.
- Telemetry reports have up to 300 bytes
- Each user packet triggers a telemetry report (1:1)
- 4.5Gbps of telemetry report for each 100Gbps flow
  - Each switch creates a single flow (No hashing possible)
- Solution in place: eBPF/XDP (eXpress Data Path) [4]

XDP - eXpress Data Path

- A thin layer at lowest levels of network stack for incoming packets
  - Not a bypass
- Run-time programmability via “hook”
  - No need to recompile the Kernel
- Comparable to DPDK but simpler
  - No need for dedicated CPUs, huge memory pages, hardware requirements, or licensing)
- Can offload instructions to supported NICs if available
  - Examples: Netronome and Mellanox
- Use by service providers for DDoS mitigation
  - 20Mpps per node documented!
- Performance improvements observed:
  - From 5kpps with Python3 and C (user-space)
  - To 3 Mpps with XDP and one CPU
- Future Lunch and Learn Talk



Source: https://github.com/iovisor/bpf-docs/blob/master/Express_Data_Path.pdf

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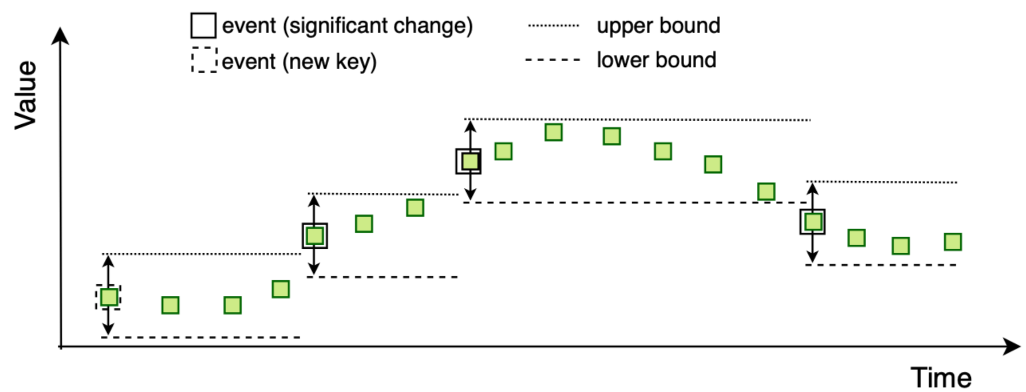
Challenge 2: Storing telemetry reports of interest

- Not feasible to save all telemetry reports (yet)

- Solution: XDP code only “stores” counters that report a change in the traffic behaviour:
  - **A queue that increased/decreased more than 20KBytes**
  - **A flow path that changed**
  - **A hop delay >2 microseconds**
  - **A total delay > 50 microseconds**
  - **An egress interface that is using more than 80Gbps for more than 50ms**

- This data is stored in a time series db
- More granular metrics => more CPU usage

- Result:
  - Good: Close to real time processing
  - Not so good: Not so granular measurements.



[5]

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Challenge 3: Storing all telemetry reports for future research (ML/AI)

- Goal: *Store as many telemetry reports as possible for future research to enable ML/AI researchers to have grounding truth for learning algorithms*

- Each Vera Rubin Telescope (LSST) 5-second 13.6GB data transfer will generate ~337MB of telemetry data.
  - 1,334 observations/night: 450GB of telemetry data/night

- Challenges:
  - How to save Gbps of telemetry reports without increasing OPEX (rack space, power consumption, etc.)
  - How/Where/How long to store such data?
  - How to make it available preserving privacy but without compromising research?
  - What data is really necessary from the telemetry report?
  - What has to be combined with reports to give context? Topology?

- Challenge 3 is wide-open. AmLight is looking for collaborations. *Let me know if you have suggestions!*

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Results and Products

INT Dissector for Wireshark

```
▼ Telemetry Header
  ▼ Telemetry Report Header
      Version: 0x00
      Protocol Number: 0x00
      Drop Bit: False
      Queue Bit: False
      Flow Bit: True
      Telemetry Header Reserved: 0x0000
      Hardware ID: 0x01
      Sequence Number: 0x0003a3b4
      Ingress Timestamp: 0xa474b98e
```

```
▼ Int Shim
    Type: 0x01
    Reserved 1: 0x00
    Length: 14
    Reserved 2: 0x00
▼ Int Metadata
    Version: 0
    Replication Requested: 0
    Copy Bit: False
    Max Hop Count Exceeded: False
    Reserved Bits 1: 0x04
    Instruction Count: 5
    Max Hop Count: 8
    Total Hop Count: 2
    Switch ID Bit: True
    Ingress + Egress Port ID Bit: True
    Hop Latency Bit: False
    Queue ID + Occupancy Bit: True
    Ingress Timestamp: True
    Egress Timestamp: True
    Queue ID + Congestion Status: False
    Egress Port Tx Utilization: False
    Reserved Instruction bits: 0x00
    Reserved Bits 2: 0x497d
```

```
▼ Int Metadata Stack
    Switch ID: 33
    Ingress Port ID: 0
    Egress Port ID: 16
    Queue ID: 0
    Queue Occupancy: 2
    Ingress Timestamp: 1014016357
    Egress Timestamp: 1014016804
▼ Int Metadata Stack
    Switch ID: 35
    Ingress Port ID: 112
    Egress Port ID: 16
    Queue ID: 0
    Queue Occupancy: 2
    Ingress Timestamp: 2267633190
    Egress Timestamp: 2267633728
```


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INT Telemetry Collector: Two Versions

- AmLight-INT Collector Python-edition:
  - Developed using Python 3.7
  - Parses and sends to a RabbitMQ queue to be consumed
  - Saves Telemetry Reports to disk
  - Tracks proof-of-transit
  - QueueTop via CLI
  - Useful for proof of concepts, protocol evaluations, and small testbeds (<5kpps)
  - High visibility, no reports are discarded.
  - Easy to use, upgrade, and install

- AmLight-INT Collector XDP-edition
  - Developed using eBPF/XDP (limited C code)
  - Parses and sends metrics of interest to time-series database
  - Leverages Grafana for visualization of metrics
  - Useful for production environments with more than 5kpps of telemetry reports
  - Harder to upgrade and expand

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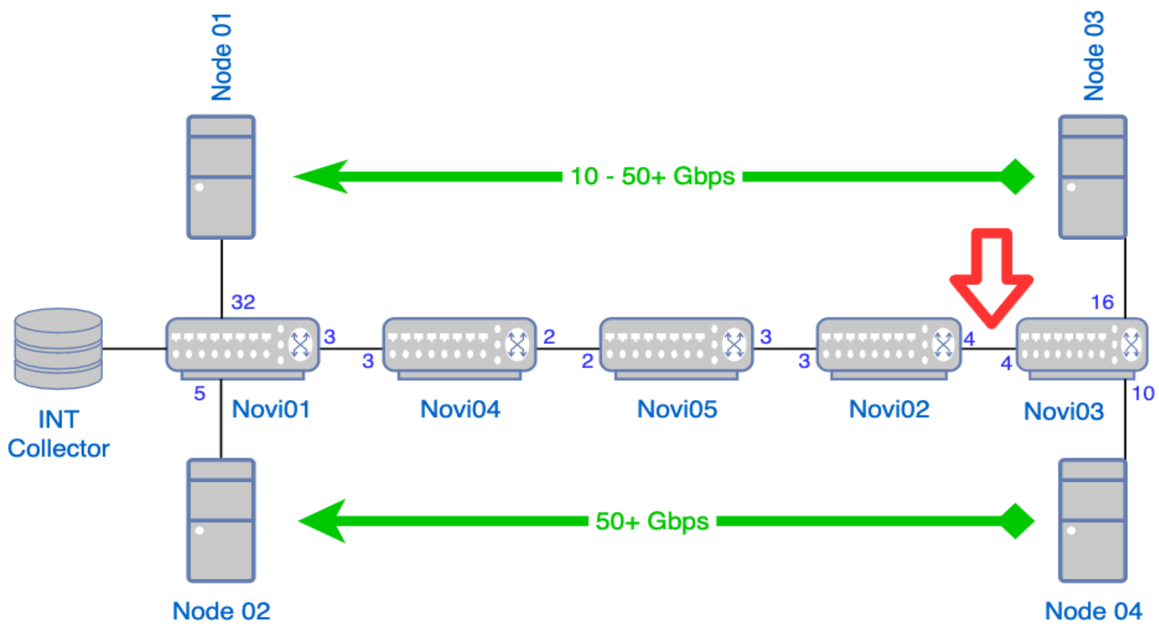
Results

- AmLight-INT Collector's QueueTop application consumes INT data and display realtime monitoring of the network's queues

- Topology on the right created to enable experimentation
  - All links and devices are 100G
  - Novi03 switch port 04 has a bottleneck: Node 03 and Node 04 are sending data to their peers.
  - Let's see what happens next...



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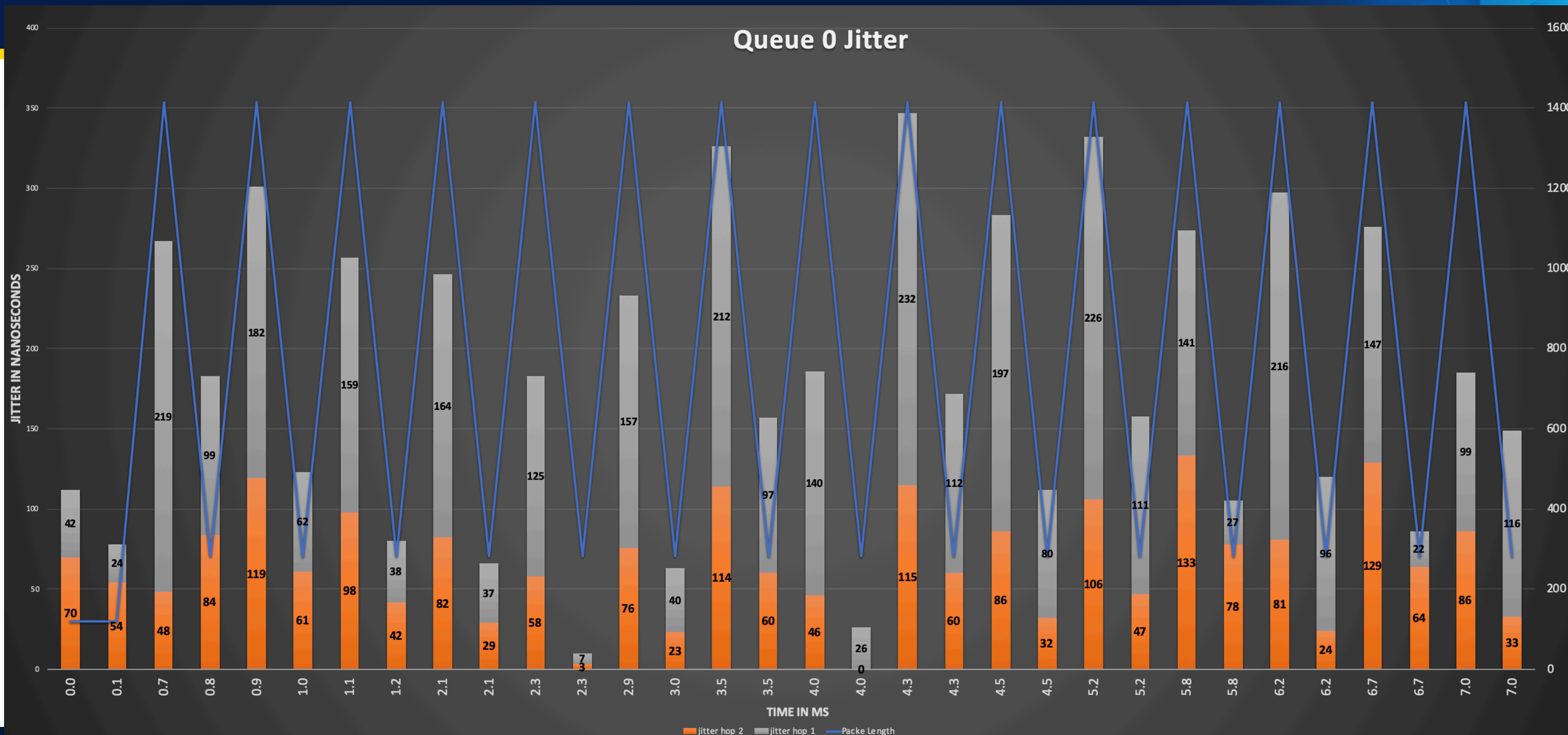
Example of telemetry flow entries

```
[FLOW_ID3]
    Timestamp          = Fri Jan 22 03:12:29 2021
    TableId            = 0
    ofp_version        = 6
    ControllerGroup    = cli
    ControllerId       = cli
    Priority           = 400
    Idle_timeout       = 0
    Hard_timeout       = 0
    Importance         = 0
    Packet_count       = 0
    Byte_count         = 0
    Cookie             = 0
    Send_flow_rem      = false
    Persistent         = false
    [MATCHFIELDS]
        OFPXMT_OFB_IN_PORT = 16
        OFPXMT_OFB_VLAN_VID = 101(OFPVID_PRESENT=1)
    [INSTRUCTIONS]
        [OFPIT_APPLY_ACTIONS]
          [ACTIONS]
            [OFPAT_EXPERIMENTER]
                [PUSH_INT]
```

```
[FLOW_ID18]
    Timestamp          = Fri Jan 22 03:11:05 2021
    TableId            = 0
    ofp_version        = 6
    ControllerGroup    = cli
    ControllerId       = cli
    Priority           = 400
    Idle_timeout       = 0
    Hard_timeout       = 0
    Importance         = 0
    Packet_count       = 0
    Byte_count         = 0
    Cookie             = 0
    Send_flow_rem      = false
    Persistent         = false
    [MATCHFIELDS]
        OFPXMT_OFB_IN_PORT = 18
        OFPXMT_OFB_VLAN_VID = 116(OFPVID_PRESENT=1)
    [INSTRUCTIONS]
        [OFPIT_APPLY_ACTIONS]
          [ACTIONS]
            [OFPAT_EXPERIMENTER]
                [ADD_INT_METADATA]
            [OFPAT_SET_FIELD]
                OFPXMT_OFB_VLAN_VID = 102(OFPVID_PRESENT=1)
            [OFPAT_OUTPUT]
                port = 16
```

Example: Queue 0's Jitter



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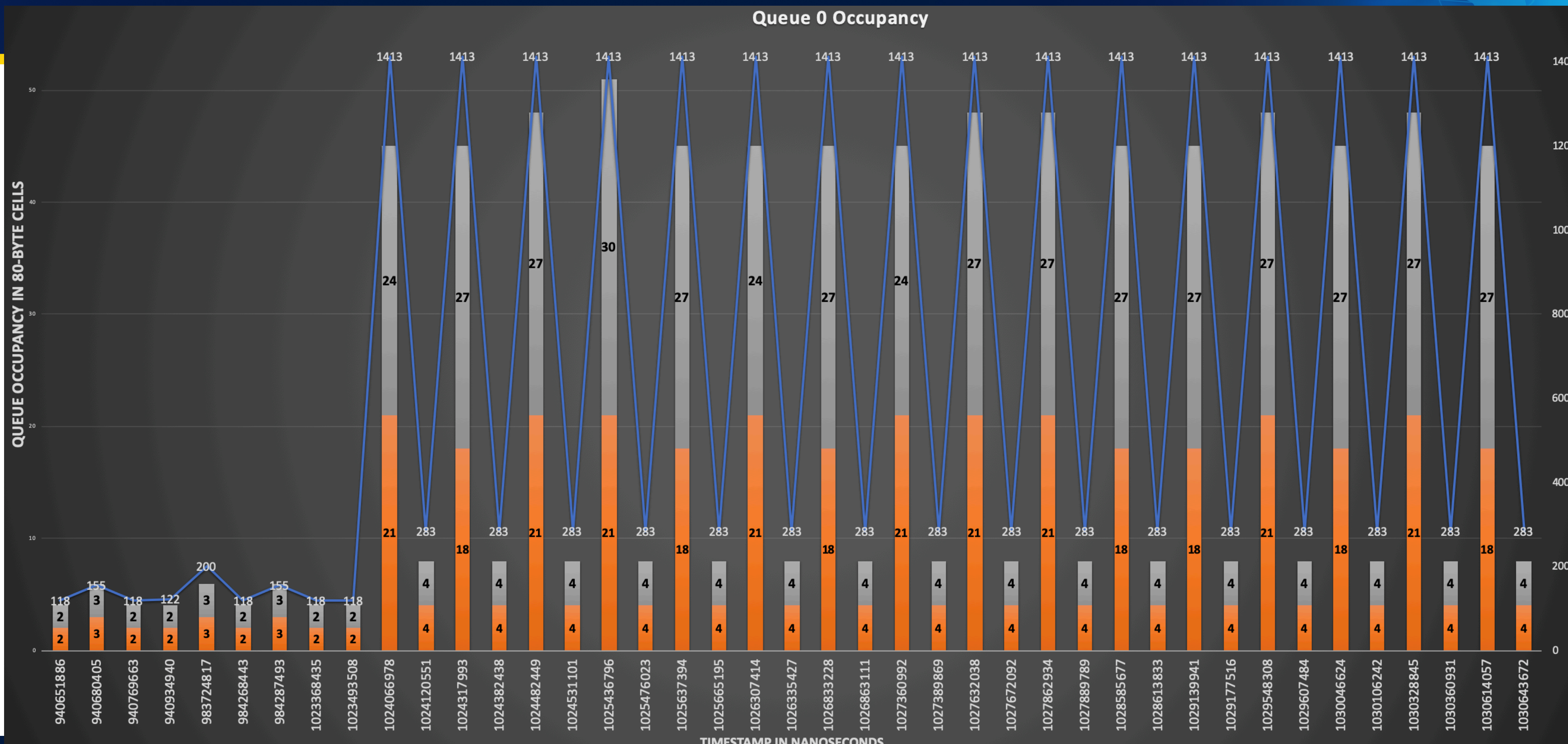
Example: Queue 0’s Occupancy



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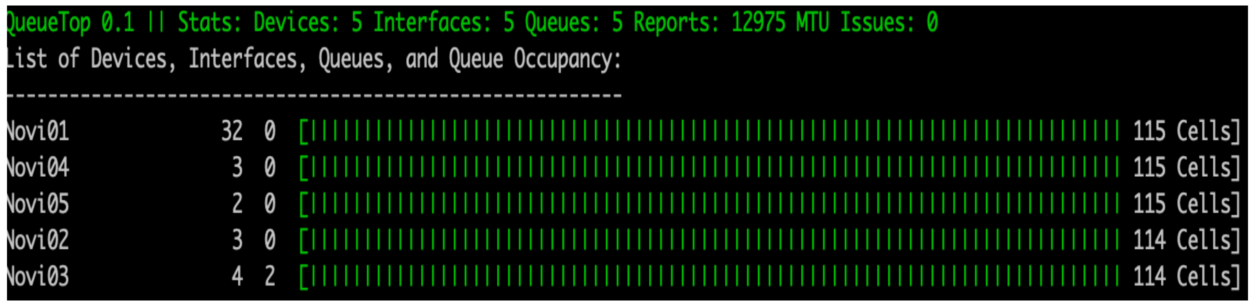
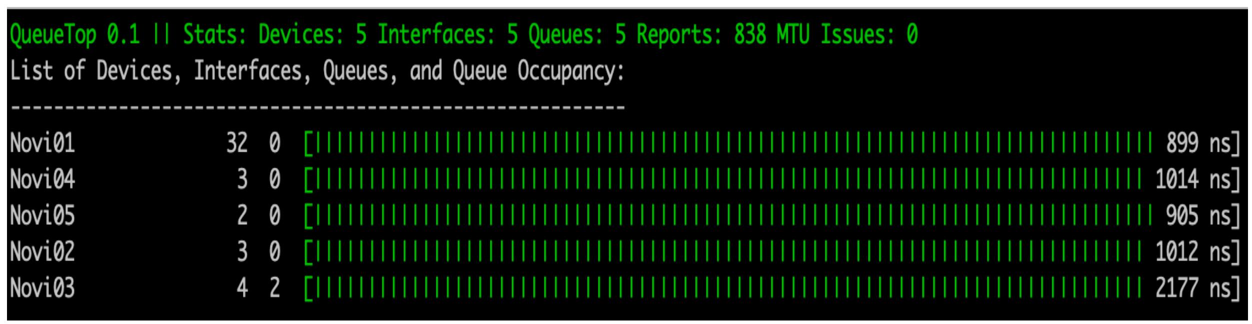
One Source - One Destination - TCP - ~60Gbps

- Node 04 sending data using TCP to Node 02 at ~50Gbps
- No other traffic
- Top:
  - All Queues are using 114-115 cells (or 9K bytes)
- Bottom:
  - Hop Delay around 1 microsend (except for Novi03 that ADDs INT header)





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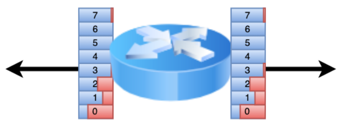
QueueTop – Queue Occupancy Monitor

- Monitors all switches' interfaces' queues in real time




```
QueueTop 0.1 || Stats: Devices: 5 Interfaces: 5 Queues: 5 Reports: 12975 MTU Issues: 0
List of Devices, Interfaces, Queues, and Queue Occupancy:
----------------------------------------------------------
Novi01          32  0  [|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| 115 Cells]
Novi04           3  0  [|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| 115 Cells]
Novi05           2  0  [|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| 115 Cells]
Novi02           3  0  [|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| 114 Cells]
Novi03           4  2  [|||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| 114 Cells]
```

```
QueueTop 0.1 || Stats: Devices: 5 Interfaces: 5 Queues: 5 Reports: 29859 MTU Issues: 0
List of Devices, Interfaces, Queues, and Queue Occupancy:
----------------------------------------------------------
Novi01          32  0  [|||||||||||                                                                           941 ns]
Novi04           3  0  [||||||||||||                                                                         1100 ns]
Novi05           2  0  [|||||||||||                                                                           912 ns]
Novi02           3  0  [||||||||||||                                                                         1088 ns]
Novi03           4  0  [||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||||| 9358 ns]
```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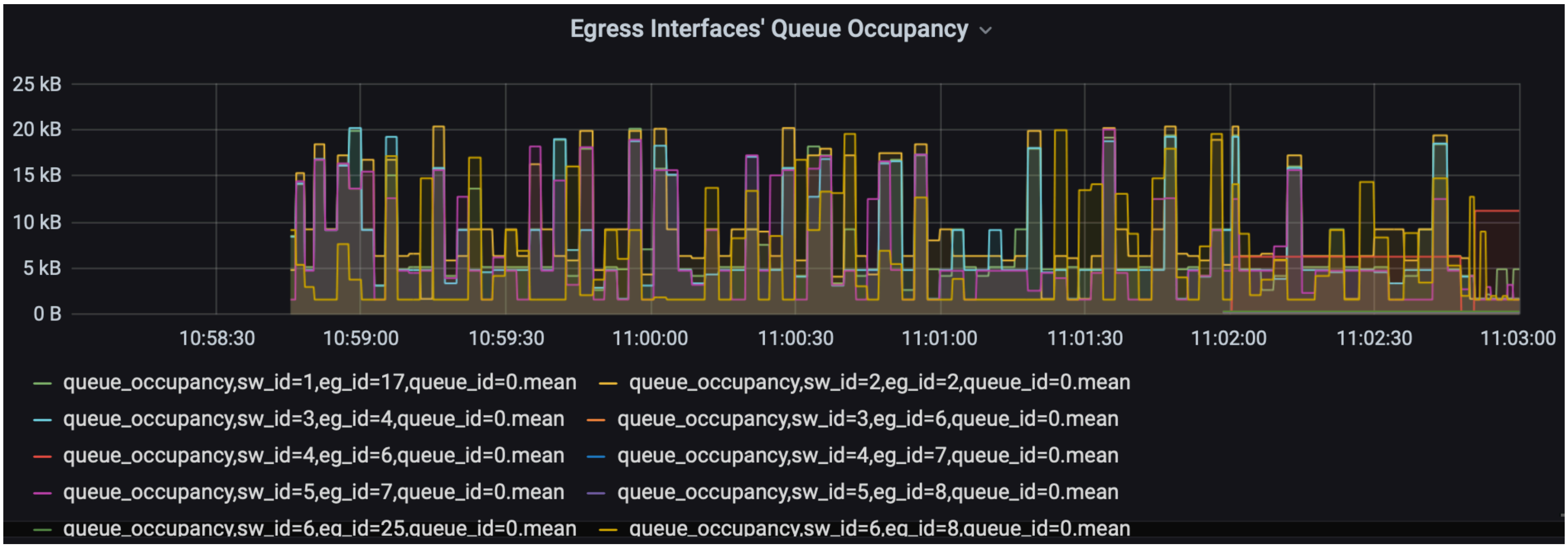
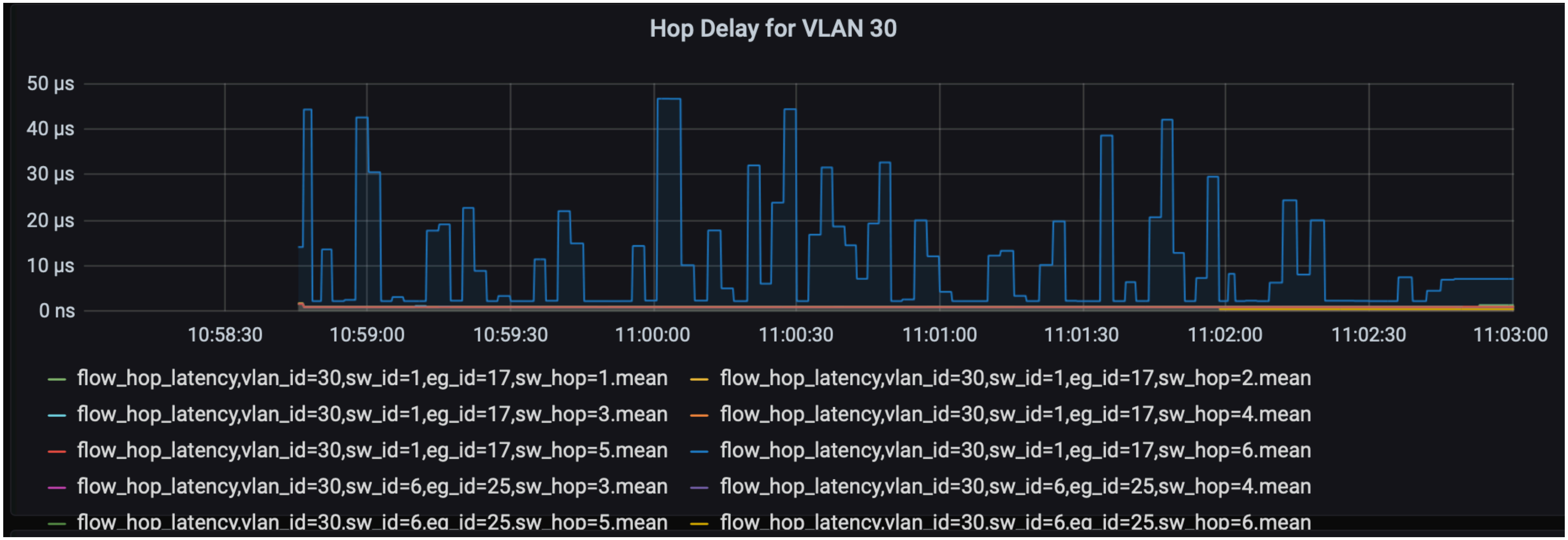
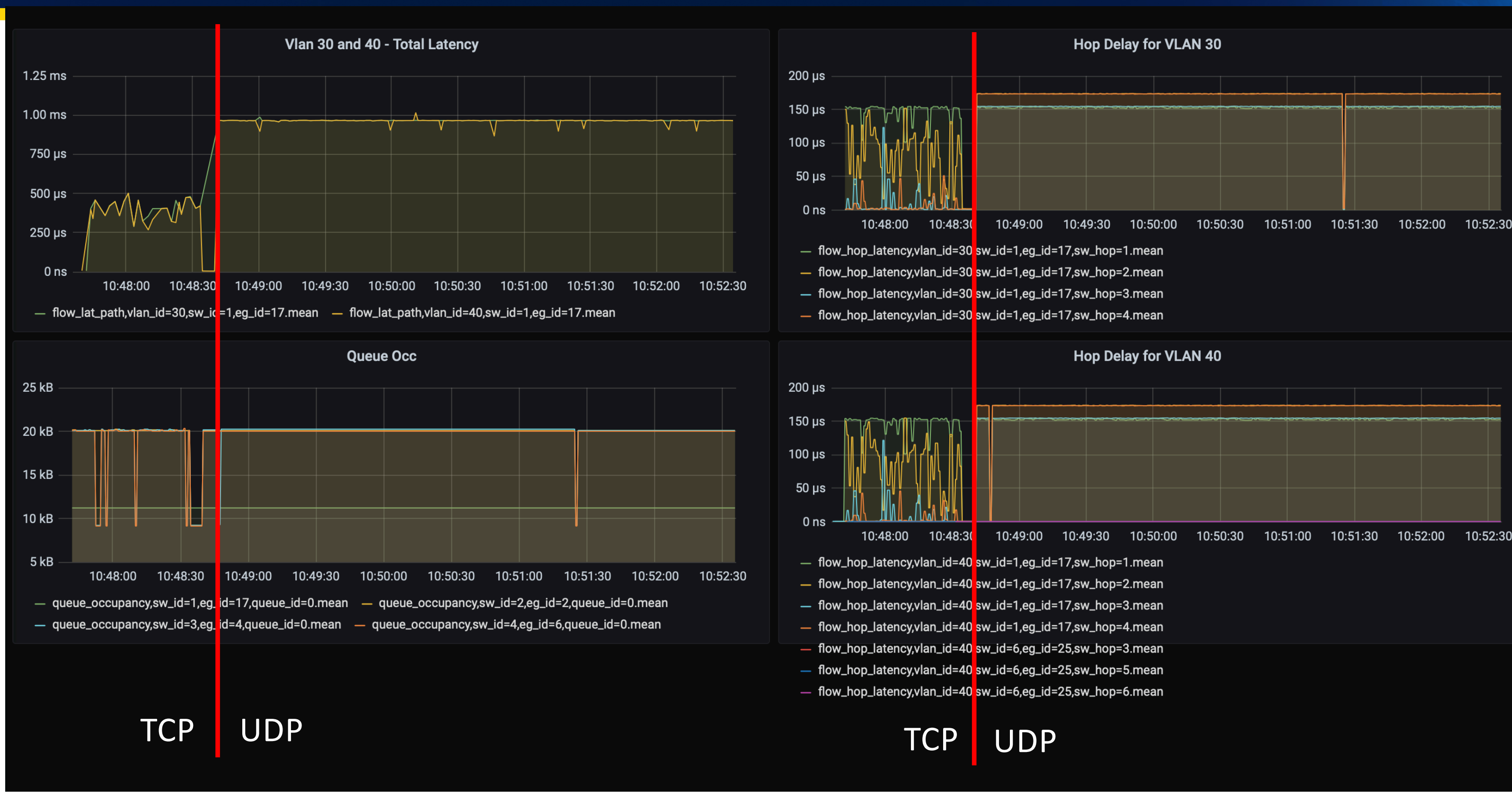
QueueTop + InfluxDB + Grafana



QueueTop + InfluxDB + Grafana

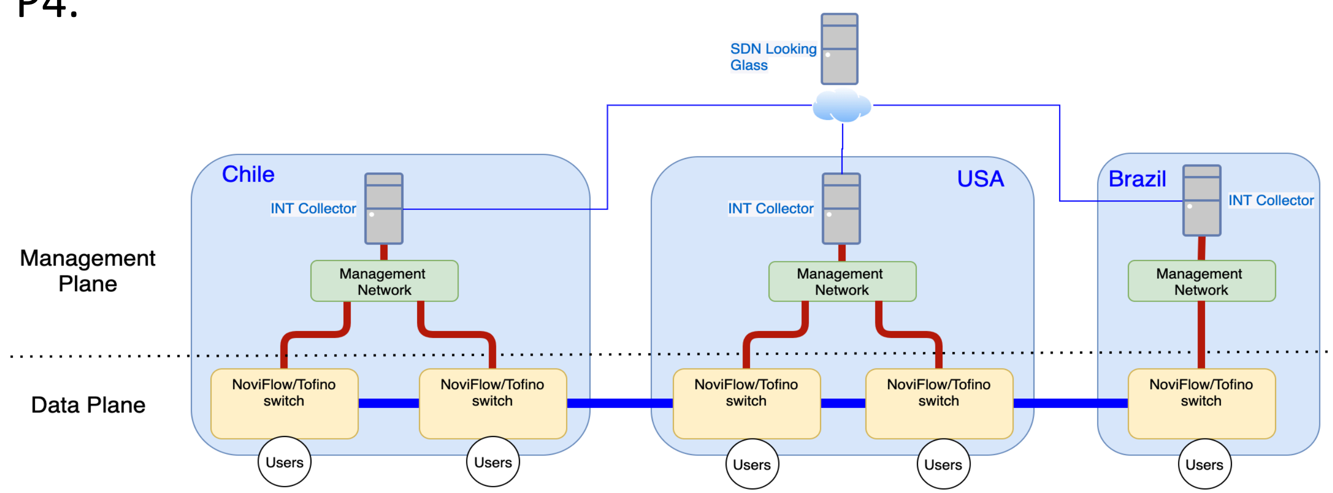


QueueTop + InfluxDB + Grafana



Ongoing Deployment

- At each pop, NoviFlow/Tofino switches are being deployed to replace existing devices
- Each INT pop has a Telemetry Collector gathering Gbps of telemetry and uploading Kbps of network state of the SDN Looking Glass
- A new Control Plane was created to replace the legacy environment using OpenFlow 1.3, gRPC, and P4.



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Conclusions

- Monitoring every and any packet is possible with in-band network telemetry!
- INT has increased the network visibility beyond our expectations
- Combining INT and legacy monitoring tools will enable AmLight to track any performance issue and user complain
- Combining INT with learning tools will enable AmLight to create reliable trends and move towards a closed-loop orchestration SDN network.
- What happens next?

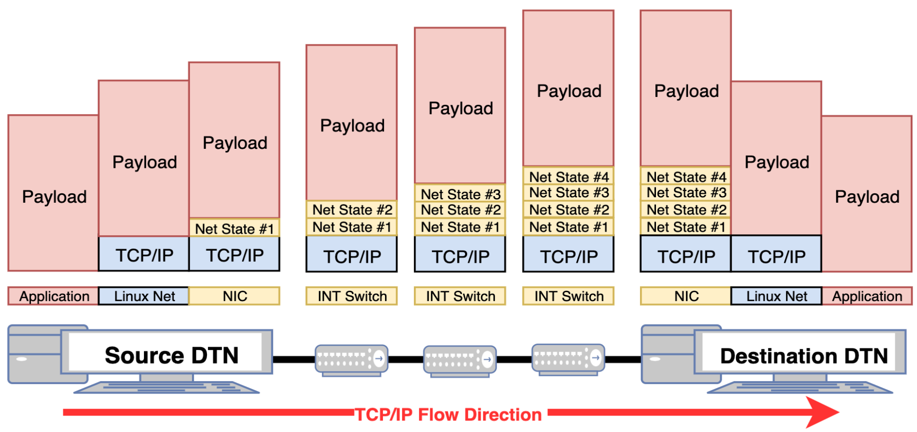
Future

- Maximize the benefits of the current INT substrate:
  - NSF CC* Q-Factor: A Framework to Enable Ultra High-Speed Data Transfer Optimization based on Real-Time Network State Information provided by Programmable Data Planes – Award 2018754
    - FIU and ESnet
    - PI(s): Jeronimo Bezerra, Julio Ibarra, and Richard Cziva
    - Start Date: Oct 15th, 2020 (2 years)
    - Goal: Extending the management plane to high performance DTNs for better visibility
  - NSF IRNC AmLight-ExP: Americas-Africa Lightpaths Express and Protect – Award 2029283
    - FIU, USC, and Vanderbilt
    - PI(s): Julio Ibarra, Heidi L. Morgan, Chip Cox, and Luis Lopez
    - Start Date: Dec 15th, 2020 (5 years)
    - INT Goal: Developing learning systems to consume INT and policies to create a closed-loop orchestration
  - NSF IRNC AtlanticWave-SDX: A Distributed Intercontinental Experimental Software Defined Exchange– Award 2029278
    - FIU, USC, and RENCI
    - PI(s): Julio Ibarra, Heidi L. Morgan, Yufeng Xin, and Jeronimo Bezerra
    - Start Date: Dec 15th, 2020 (5 years)
    - INT Goal: Developing learning and telemetry systems to export different formats of intra-domain telemetry to support inter-domain provisioning and visibility

Q-Factor

- Objective: Improve data transfers over long-haul high-bandwidth programmable networks
- How: Creating an end-to-end framework where endpoints would have network state information to dynamically tune data transfer parameters in real time
  - Bandwidth and resources optimization
- Transformative:
  - Q-Factor will enable endpoints to adapt their data transfers to the network conditions in real time, avoiding packet drops, extra jitter/delays, and excessive memory consumption.

- Summary of proposed activities:
  - Expanding the Management Plane to endpoints
  - Developing a Telemetry Agent to consume network state information and tune endpoints
  - Evaluating tuning at scale over multiple scenarios by leveraging AmLight and Esnet networks and testbeds



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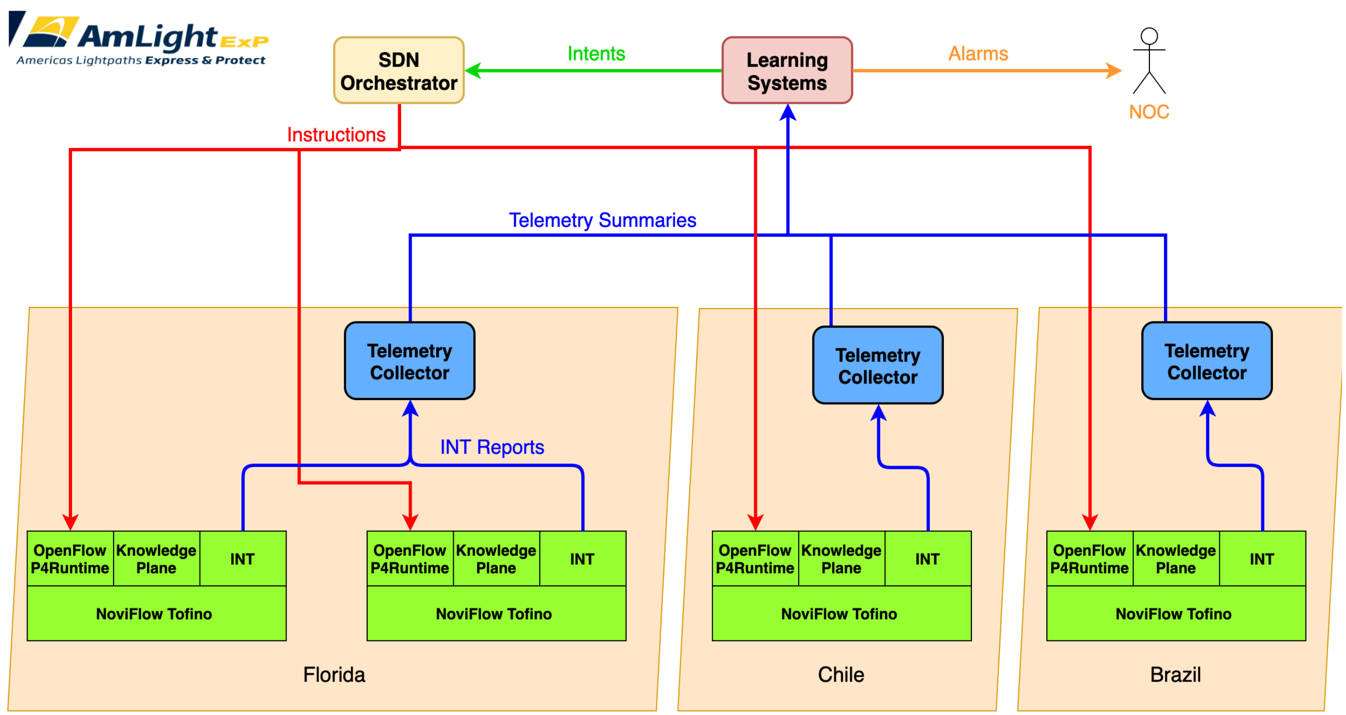
AmLight-ExP

INT-related objective: Closed-loop network orchestration by leveraging telemetry reports from the packet and optical layers, combined with Machine Learning algorithms

Roadmap: Self-Optimizing the network:

- Year 2: < 5 seconds
- Year 3: < 2 seconds
- Year 4: < 1 second
- Year 5: < 500 ms



The Team

- FIU team:
  - Arturo Quintana – Sr. Software Developer
  - Julio Ibarra – PI
  - Italo Valcy – Sr. Network Engineer
  - Jeronimo Bezerra – Chief Network Architect
  - David Ramirez – REU Student

NoviFlow:

Arun Paneri - Director of Engineering
Bryan Kerl - Director, Strategic Accounts
Darrell Irons – Director, Customer Support and Operation

Positions Open! Please share them!

3x Sr. Software Developer (@FIU)

1x Network Engineer (@FIU)

1x Postgrad (@Esnet)

More info at https://careers.amlight.net

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Thank you! Questions?

In-band Network Telemetry @ AmLight: Lessons Learned after 2 years

Jeronimo Bezerra <jab@amlight.net>

References

1. INT Specification: https://p4.org/assets/INT-current-spec.pdf
2. AmLight: http://www.amlight.net
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