A Cloud System for Teaching and Research on P4 Programmable Data Plane

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NSF

Agenda

- Motivation for virtual labs
- Platform
- Libraries
- P4 Tofino Library
- Topologies used by the research community
- Conclusion

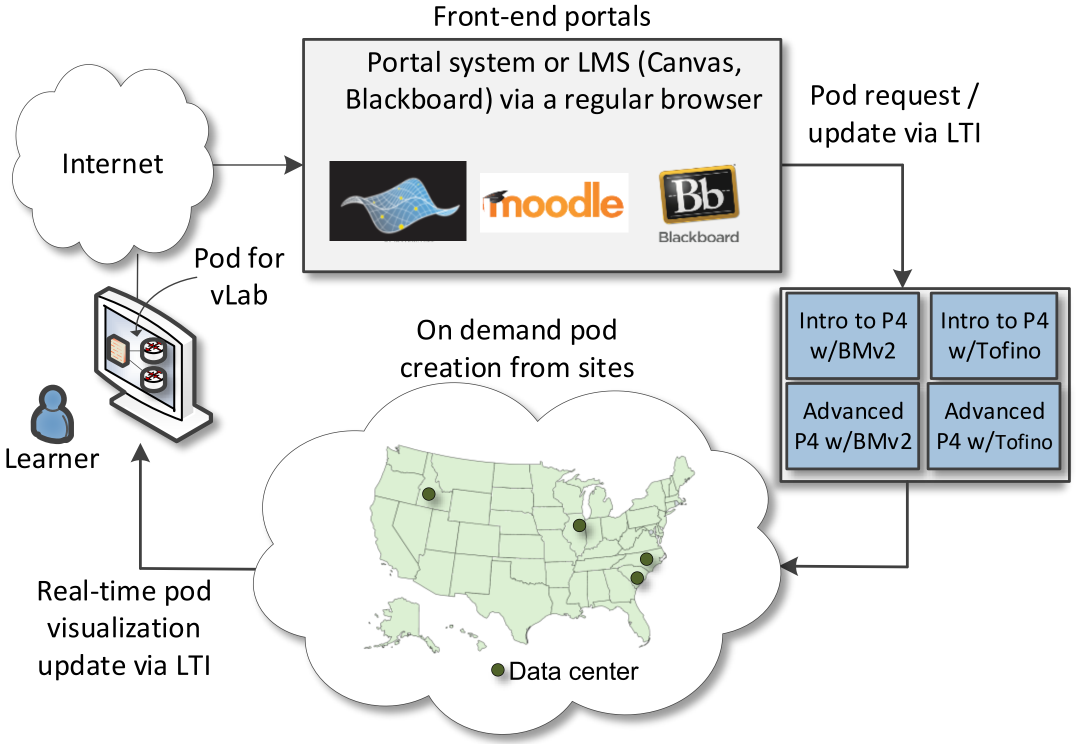
Motivation for Virtual Labs

- IT curriculum should emphasize "learning IT core concepts with authentic practice[1]"
  - "It is not enough to simply attend courses and read books"
- Disadvantages of physical labs
  - Difficult to scale
  - Expensive (space, maintenance, staff)
  - Since COVID-19 emerged, the capacity of labs has been further reduced

1. Information Technology Curricula 2017, ACM/IEEE Joint Committee. Online: https://tinyurl.com/4nqqwa5m.

Motivation for Virtual Labs

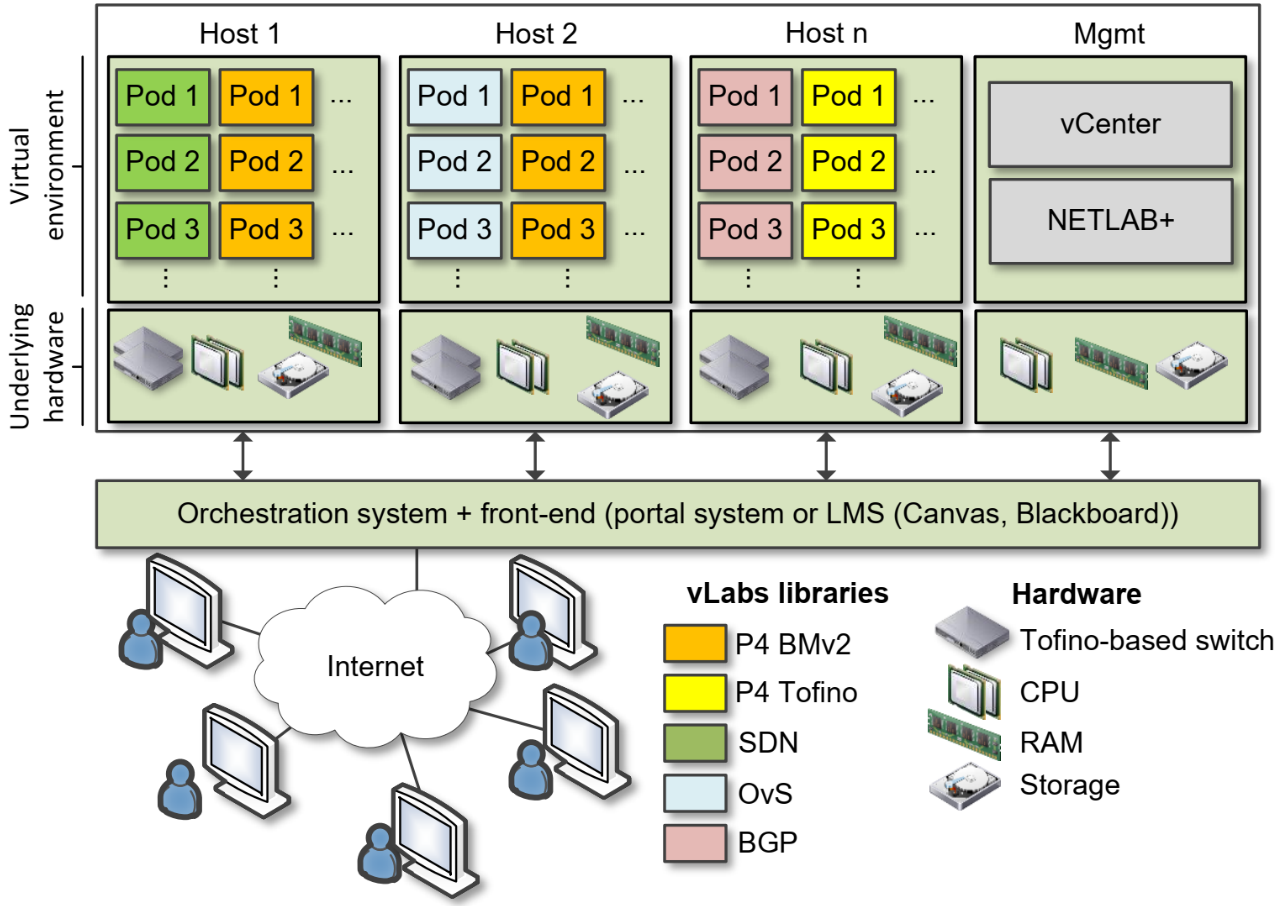
- The University of South Carolina (USC) (SC), the Network Development Group (NDG) (NC), and Stanly Community College (SCC) (NC) have deployed an Academic Cloud
  - Virtual labs on P4, routing, high-speed networks (USC)
  - Remote-access capability to lab equipment via Internet
  - Shared resources (CPU, memory, storage) from four data centers



LMS: Learning Management System. LTI: Learning Tools Interoperability

USC Data Center

- Hosts 1-n store virtual machines (VMs) for virtual labs
- Management server runs vCenter, Management Software (NETLAB+)
- Partnership with Network Development Group (NDG)[1]



1. Network Development Group (NDG). Online: https://netdevgroup.com

Libraries

- A library consists of between 10-20 lab experiments
- Each lab experiment includes a detailed, step by step manual
- Once a learner completes all experiments, the learner acquires significant knowledge and hands-on expertise, and may earn an academic credential or certificate
- Information about libraries are available at http://ce.sc.edu/cyberinfra/cybertraining.html

Library on Introduction to P4 with BMv2

Experiments

- Lab 1: Introduction to Mininet
- Lab 2: Introduction to P4 and BMv2
- Lab 3: P4 Program Building Blocks
- Lab 4: Parser Implementation
- Lab 5: Introduction to Match-action Tables (Part 1)
- Lab 6: Introduction to Match-action Tables (Part 2)
- Lab 7: Populating / Managing Match-action Tables
- Lab 8: Checksum Recalculation and Deparsing

Exercises

- Exercise 1: Building a Basic Topology
- Exercise 2: Compiling and Testing a P4 Program
- Exercise 3: Parsing UDP and RTP
- Exercise 4: Building a Simplified NAT
- Exercise 5: Configuring Tables at Runtime
- Exercise 6: Building a Packet Reflector

Library on P4 Applications, Stateful Elements, and Custom Packet Processing

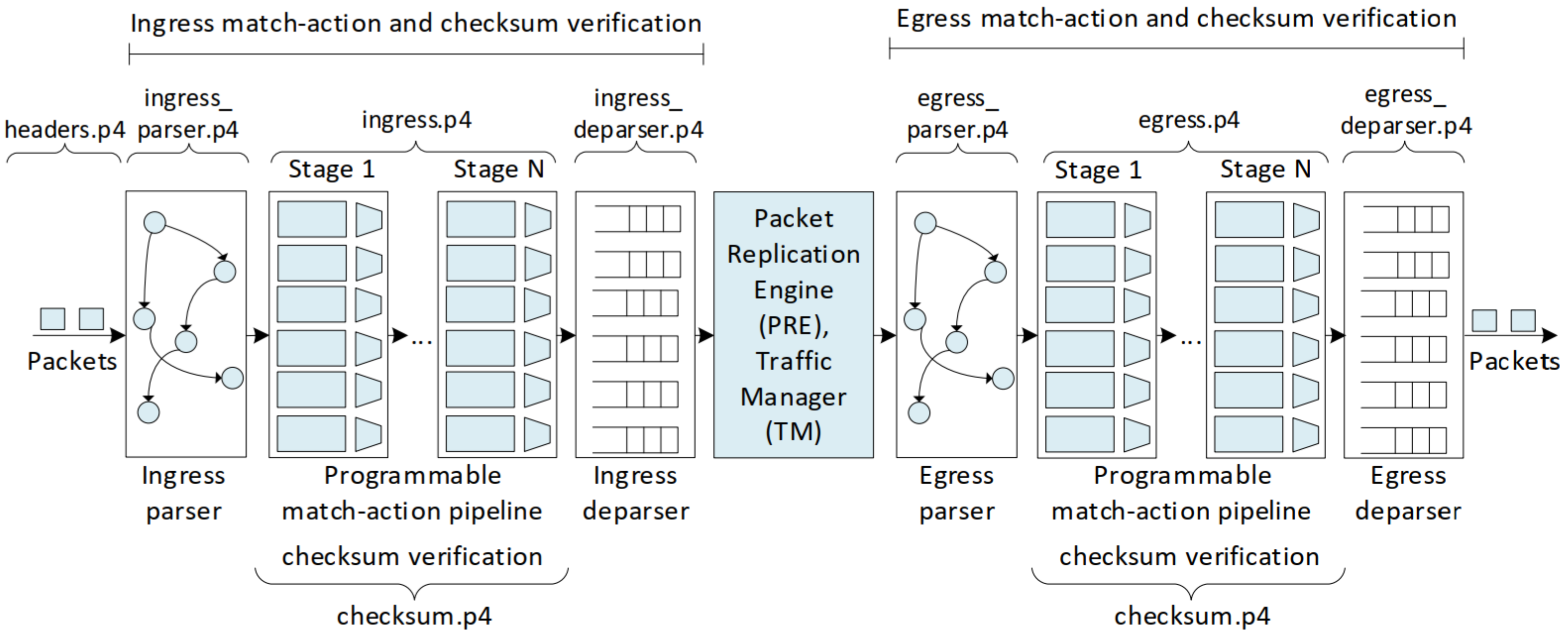
Experiments

- Lab 1: Introduction to Mininet
- Lab 2: Introduction to P4 and BMv2
- Lab 3: P4 Program Building Blocks
- Lab 4: Defining and processing custom headers
- Lab 5: Monitoring the Switch’s Queue using Standard Metadata
- Lab 6: Collecting Queueing Statistics using a Header Stack
- Lab 7: Measuring Flow Statistics using Direct and Indirect Counters
- Lab 8: Rerouting Traffic using Meters
- Lab 9: Storing Arbitrary Data using Registers
- Lab 10: Calculating Packets Interarrival Time w/ Hashes and Registers
- Lab 11: Generating Notification Messages from the Data Plane

Library on P4 Programmable Data Plane with Tofino

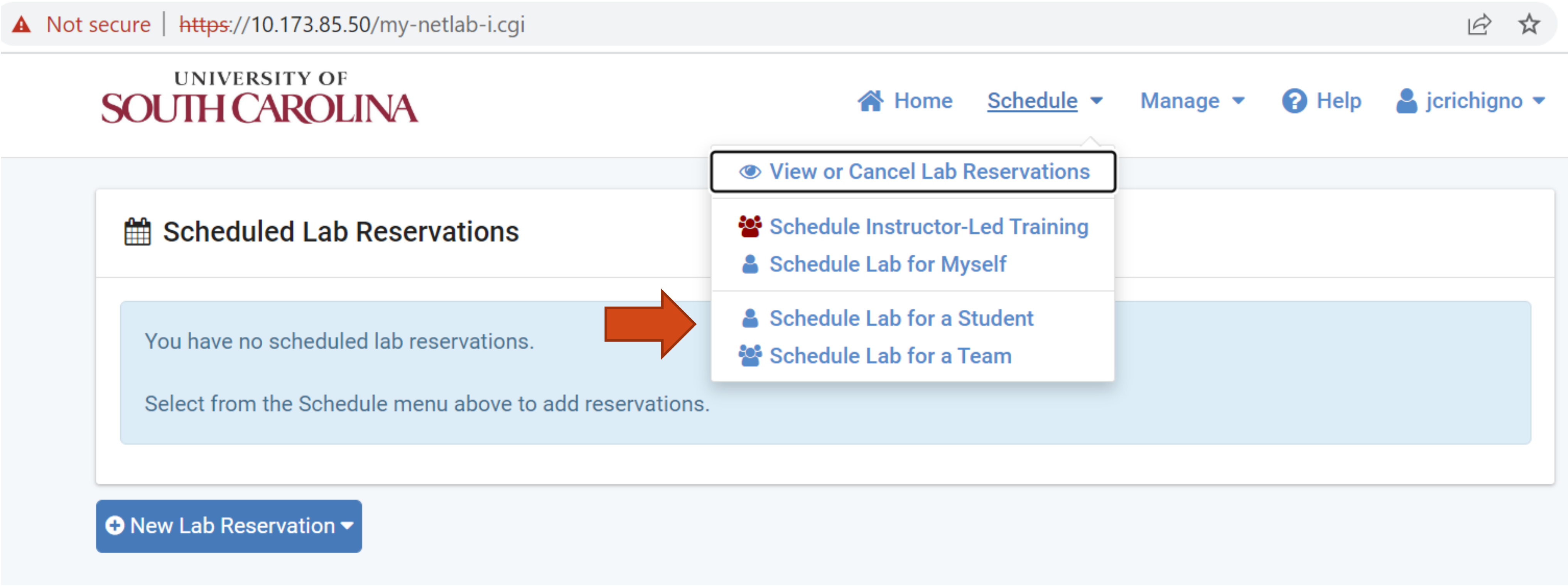
Experiments

- Lab 1: Introduction to P4 and Tofino
- Lab 2: Introduction to P4 Tofino Software Development Environment
- Lab 3: Parser Implementation
- Lab 4: Introduction to Match-Action Tables
- Lab 5: Populating and Managing Match-Action Tables at Runtime
- Lab 6: Checksum Recalculation and Packet Deparsing

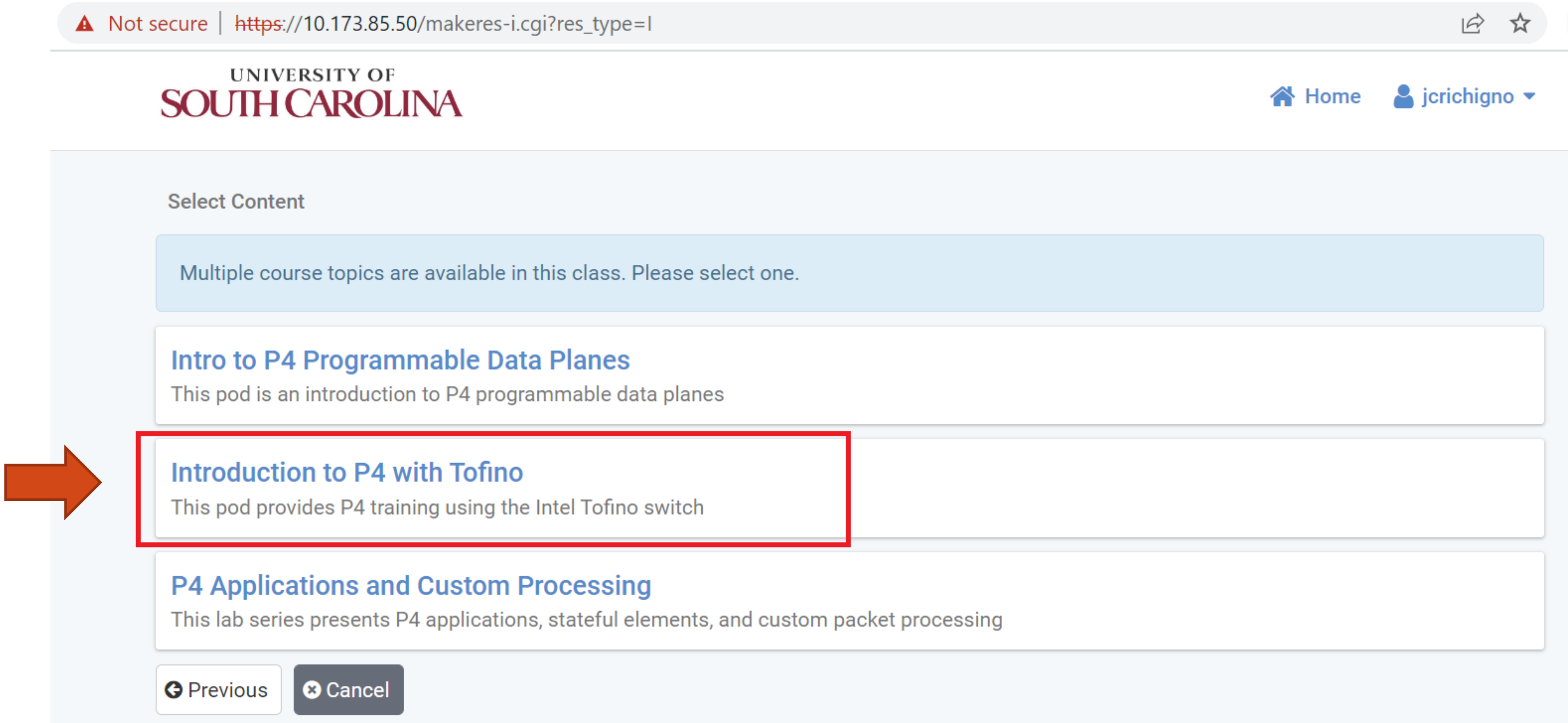


Library on P4 Programmable Data Plane with Tofino

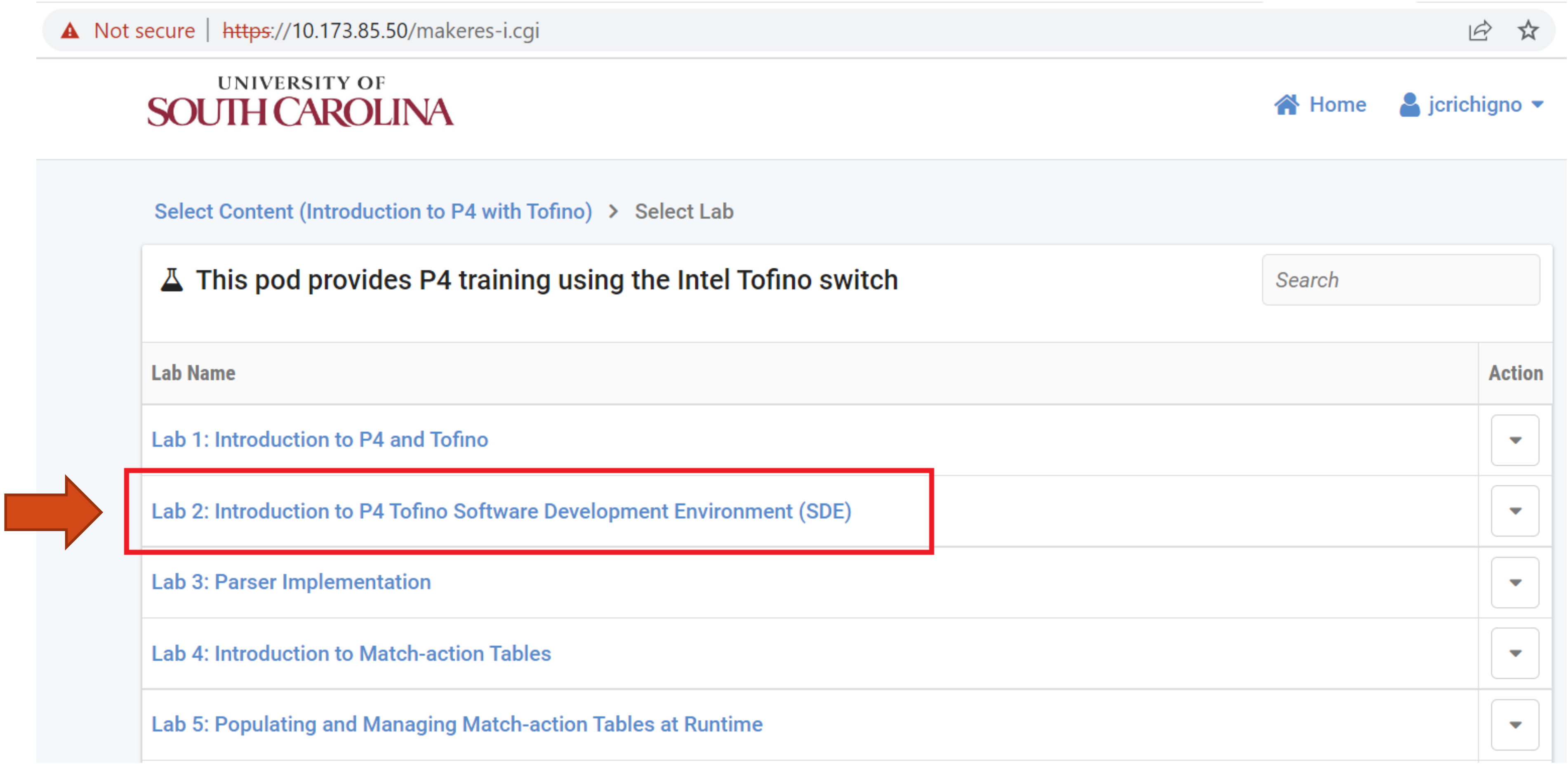
- https://netlab2.cec.sc.edu/



Library on P4 Programmable Data Plane with Tofino



Library on P4 Programmable Data Plane with Tofino



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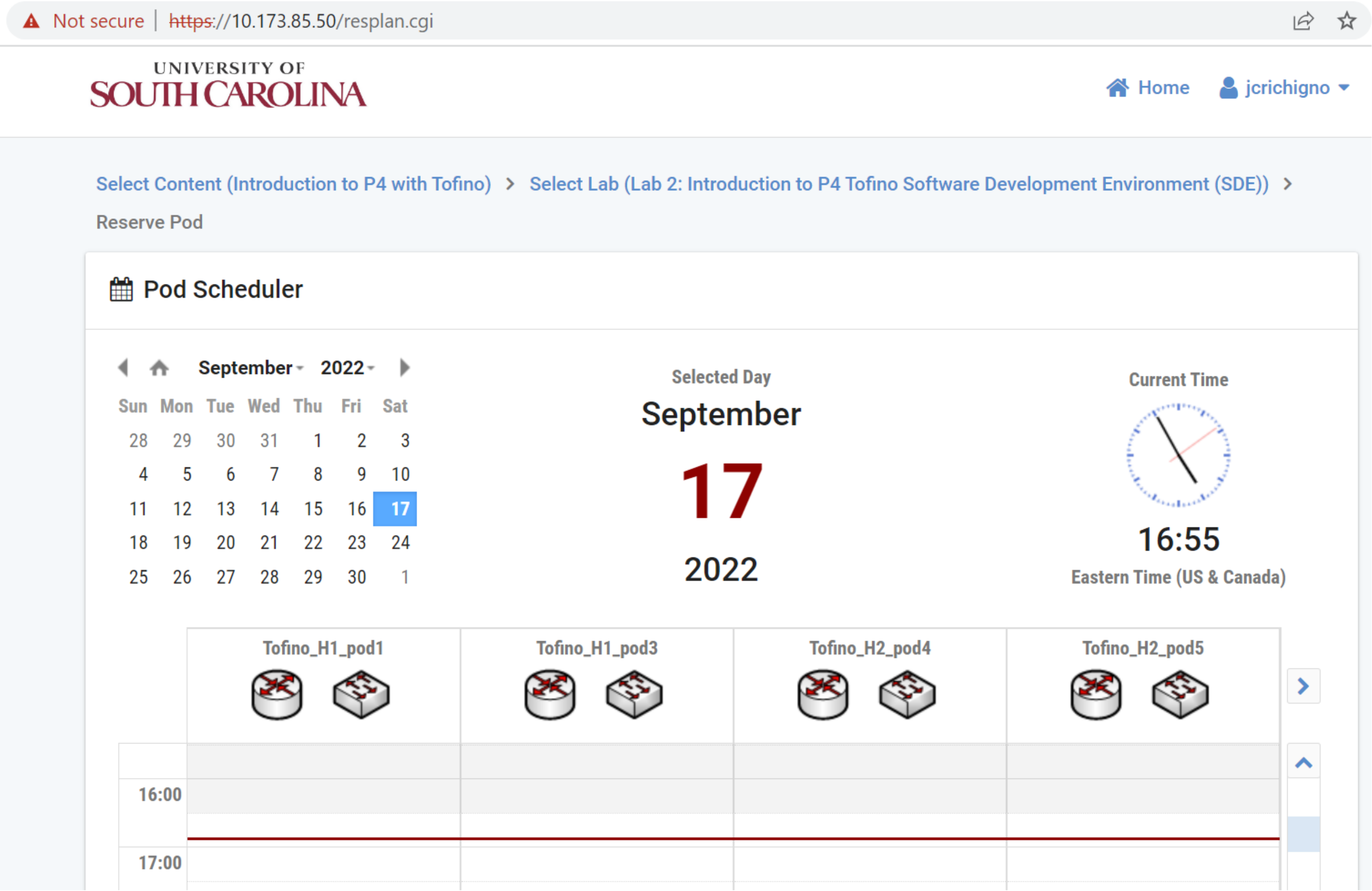

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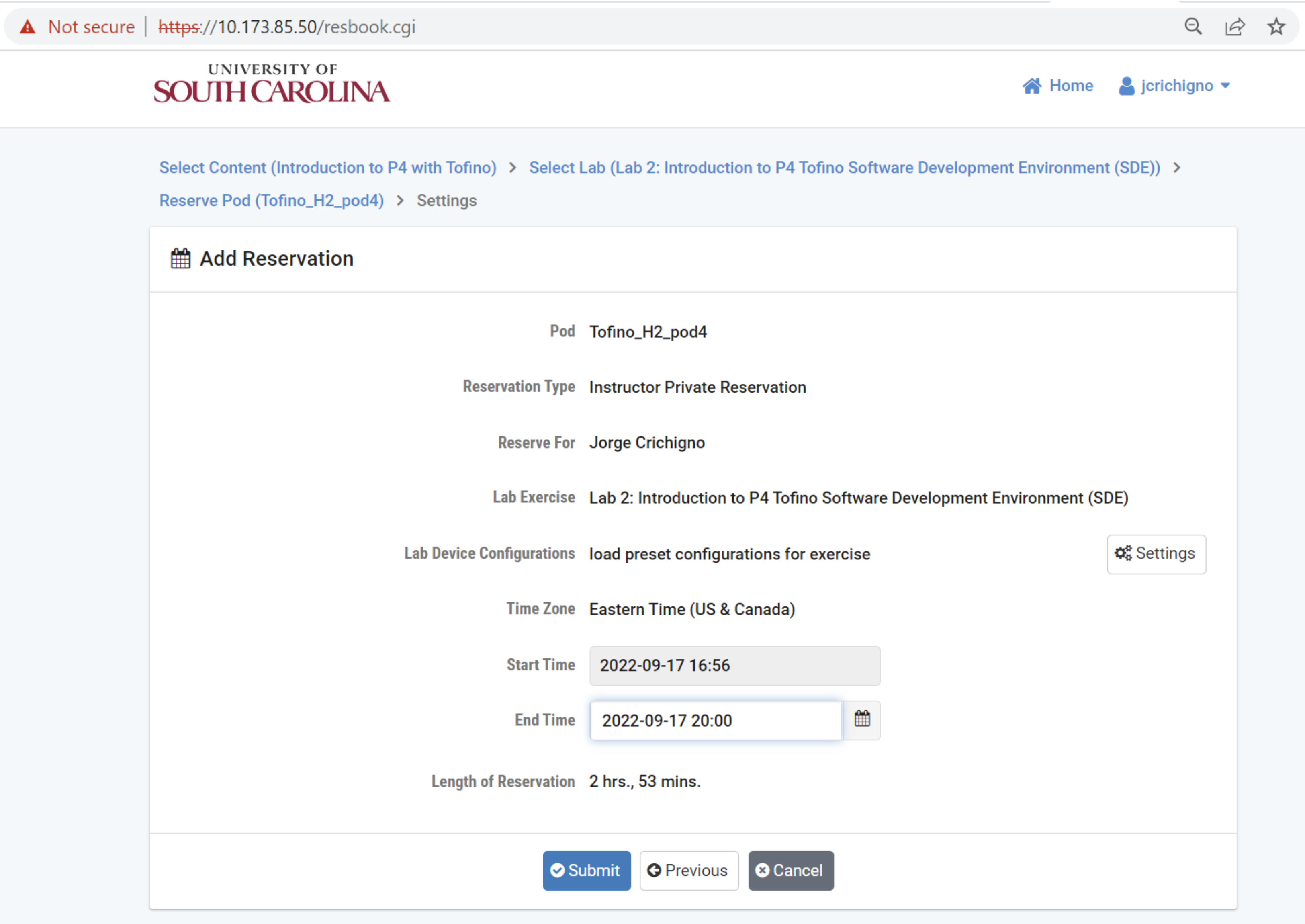
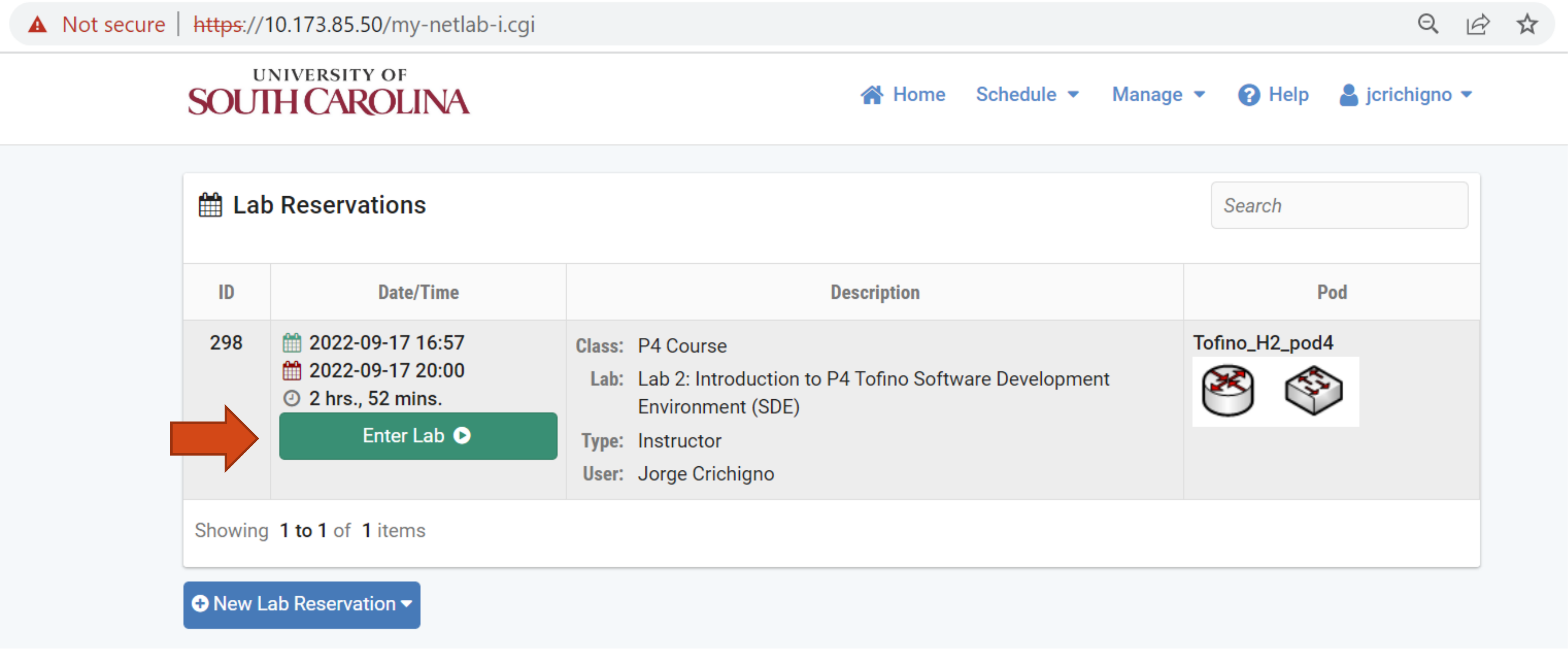


Library on P4 Programmable Data Plane with Tofino



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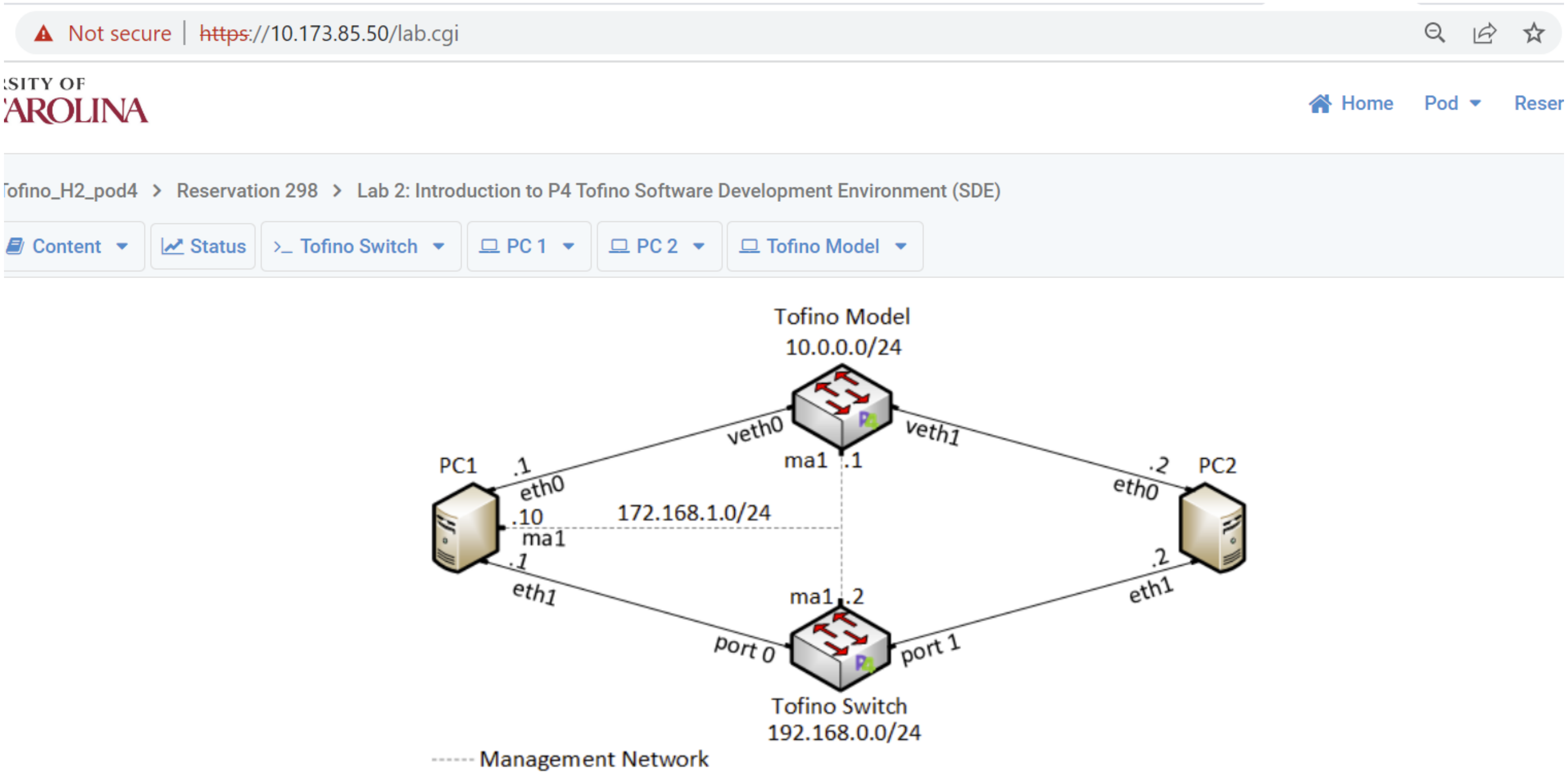
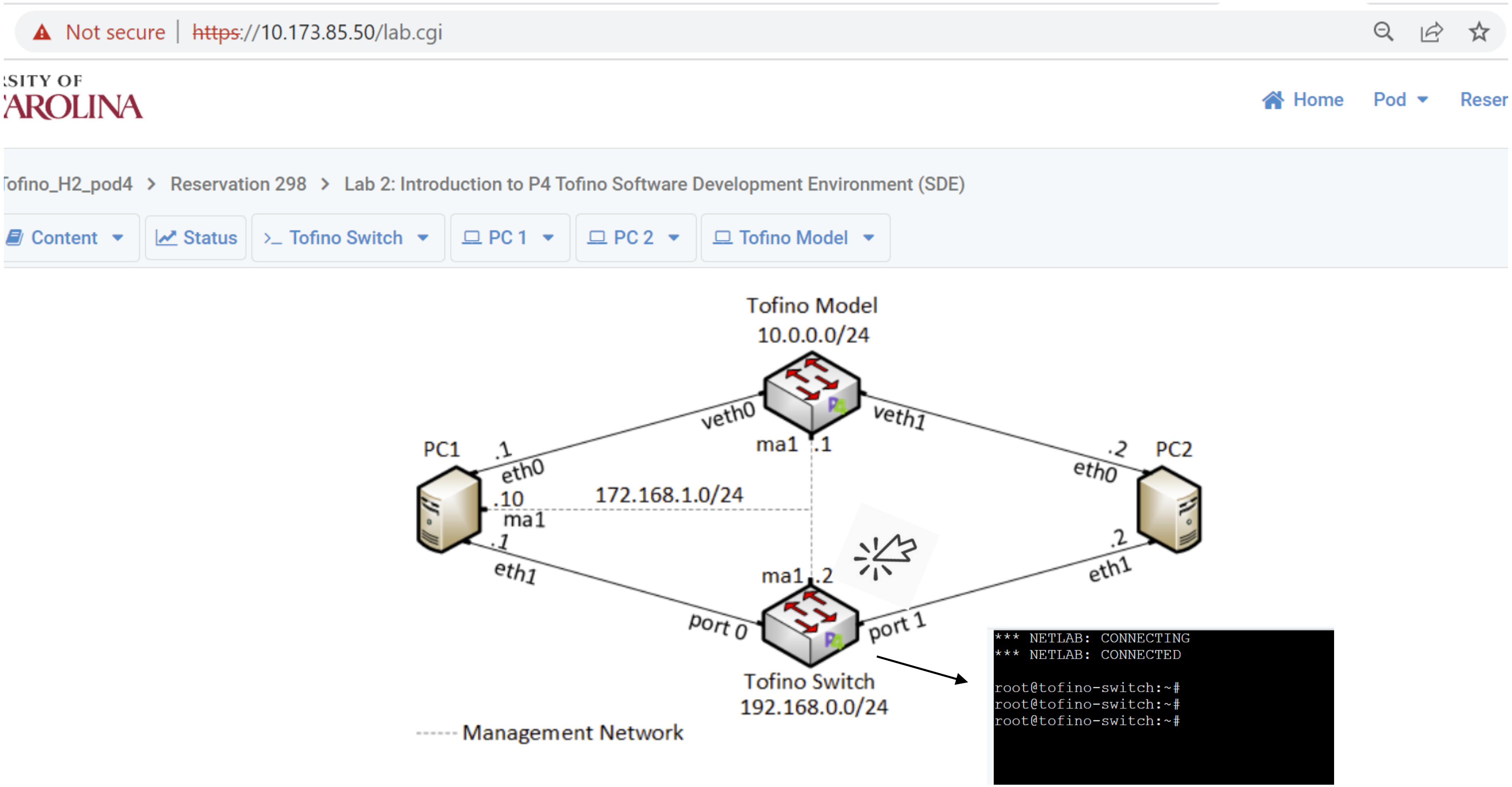


Library on P4 Programmable Data Plane with Tofino



Library on P4 Programmable Data Plane with Tofino

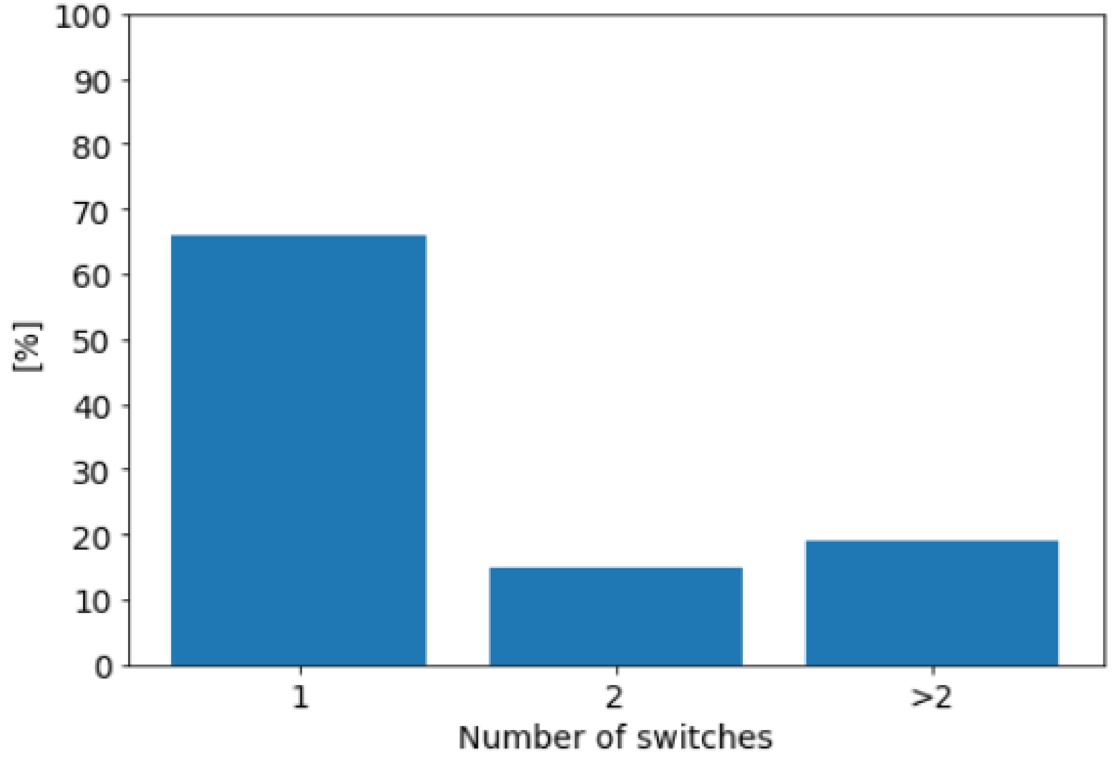
- Topology complexity
  - 6.4 Tbps Tofino programmable switch
  - Tofino model for debugging (trace execution in the data plane)
  - Servers to send/receive data to/from the switch/other servers
  - Multi-mode fiber
  - QSFP28+ transceivers
  - Open Network Linux (ONL) (control plane)
  - Software Development Environment (SDE) from Intel (control plane)
  - Sample P4 codes for each lab (data plane)
  - Laboratory experiments with step-by-step directions (thousands of development hours)
- Logistic challenges
  - NDA with Intel, lawyers' agreement
  - Procurement process
  - Physical hardware, rack space, data center, etc.
  - Software tools, SDE, operating system, etc.

Literature Survey: Topologies used for Research

- 293 papers from 2014 to 2022
- Determine the topologies that are commonly used by experimenters
- Determine the devices that are used

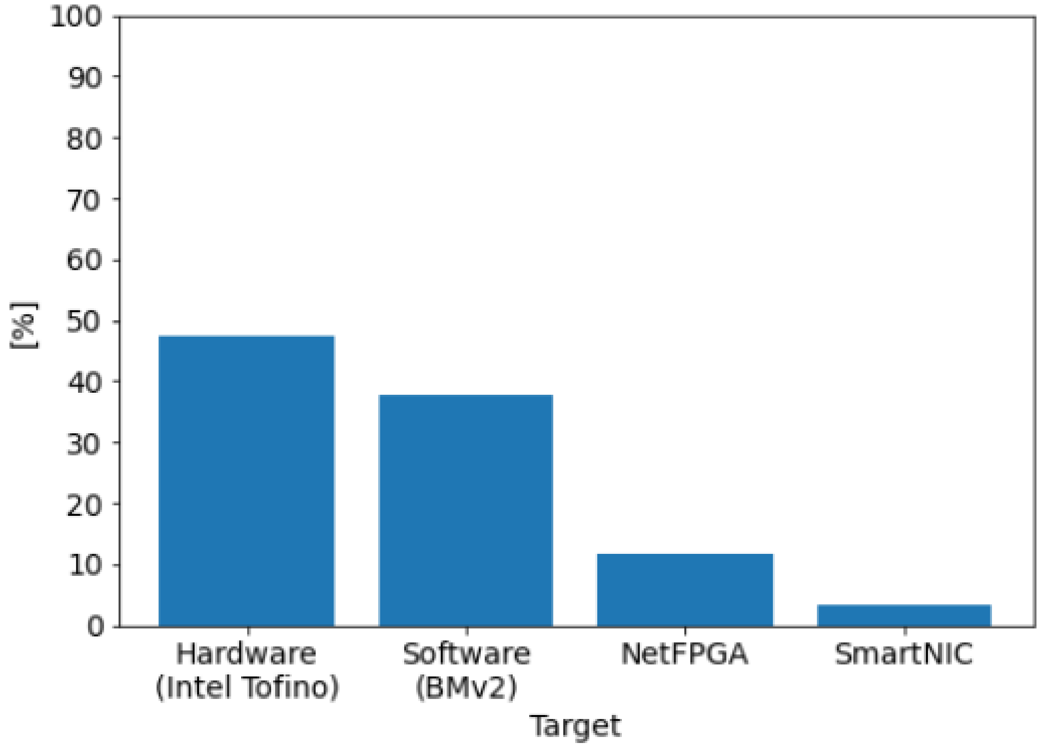
Literature Survey: Topologies used for Research

- Number of switches



Literature Survey: Topologies used for Research

- Targets



Literature Survey: Topologies used for Research

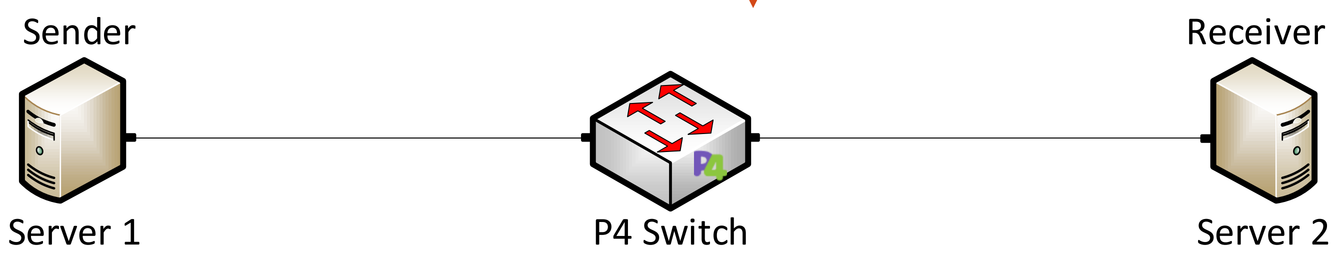
- Number of switches and hosts

		Number of hosts				
Number of switches		0	1	2	3	≥4
	1	8	2	52	7	31
	2	1	2	11	1	8
	3	0	1	0	1	3
	≥4	0	0	4	0	19

Literature Survey: Topologies used for Research

- Papers that use a 2-host, 1-switch topology

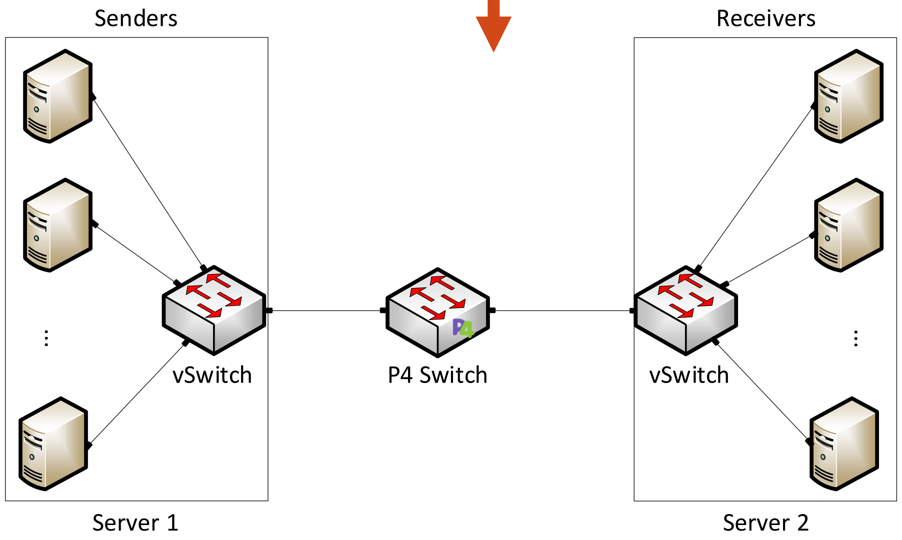
Number of switches \ Number of hosts	0	1	2	3	≥4
1	8	2	52	7	31
2	1	2	11	1	8
3	0	1	0	1	3
≥4	0	0	4	0	19



Literature Survey: Topologies used for Research

- 25% of the papers rely on virtualization to add end devices

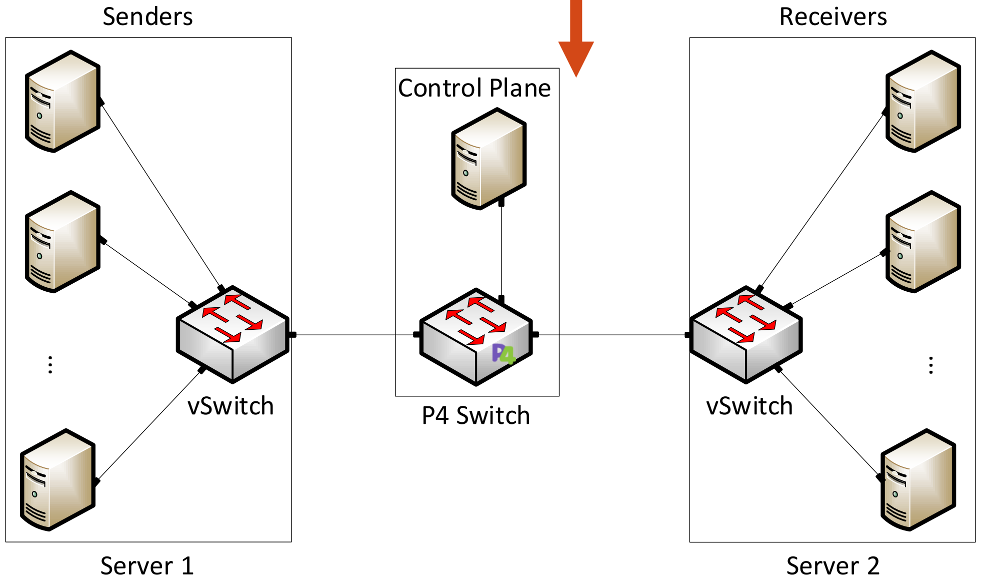
		Number of hosts				
Number of switches		0	1	2	3	≥4
	1	8	2	52	7	31
	2	1	2	11	1	8
	3	0	1	0	1	3
	≥4	0	0	4	0	19



Literature Survey: Topologies used for Research

- Topology supported by the current Tofino pod

Number of switches	Number of hosts: 0	1	2	3	≥4
1	8	2	52	7	31
2	1	2	11	1	8
3	0	1	0	1	3
≥4	0	0	4	0	19



USC, UTSA, USF Research Work

- “INC: In-Network Classification of Botnet Propagation at Line Rate”
- “P4DDPI: Securing P4-Programmable Data Plane Networks via DNS Deep Packet Inspection”
- “Dynamic Router's Buffer Sizing using Passive Measurements and P4 Programmable Switches”
- “On Offloading Network Forensic Analytics to Programmable Data Plane Switches”
- “Coarse Estimation of Bottleneck Router's Buffer Size for Heterogeneous TCP Sources”
- “Offloading Media Traffic to Programmable Data Plane Switches”
- “Towards a Unified In-Network DDoS Detection and Mitigation Strategy”
- “Enabling TCP Pacing using Programmable Data Plane Switches”
- “An Exhaustive Survey on P4 Programmable Data Plane Switches: Taxonomy, Applications, Challenges, and Future Trends”
- “A Survey on TCP Enhancements using P4-programmable Devices”
- “A Survey on Security Applications of P4 Programmable Switches and a STRIDE-based Vulnerability Assessment”

Conclusion

- The primary use is of the platform is for teaching
- The platform is used at USC, UTSA, and USF for research
  - Time to research is shortened
  - Scalable, cost efficient
  - Resources are shared

Home administrator

Admin > Usage > Community Usage > List

Community Usage

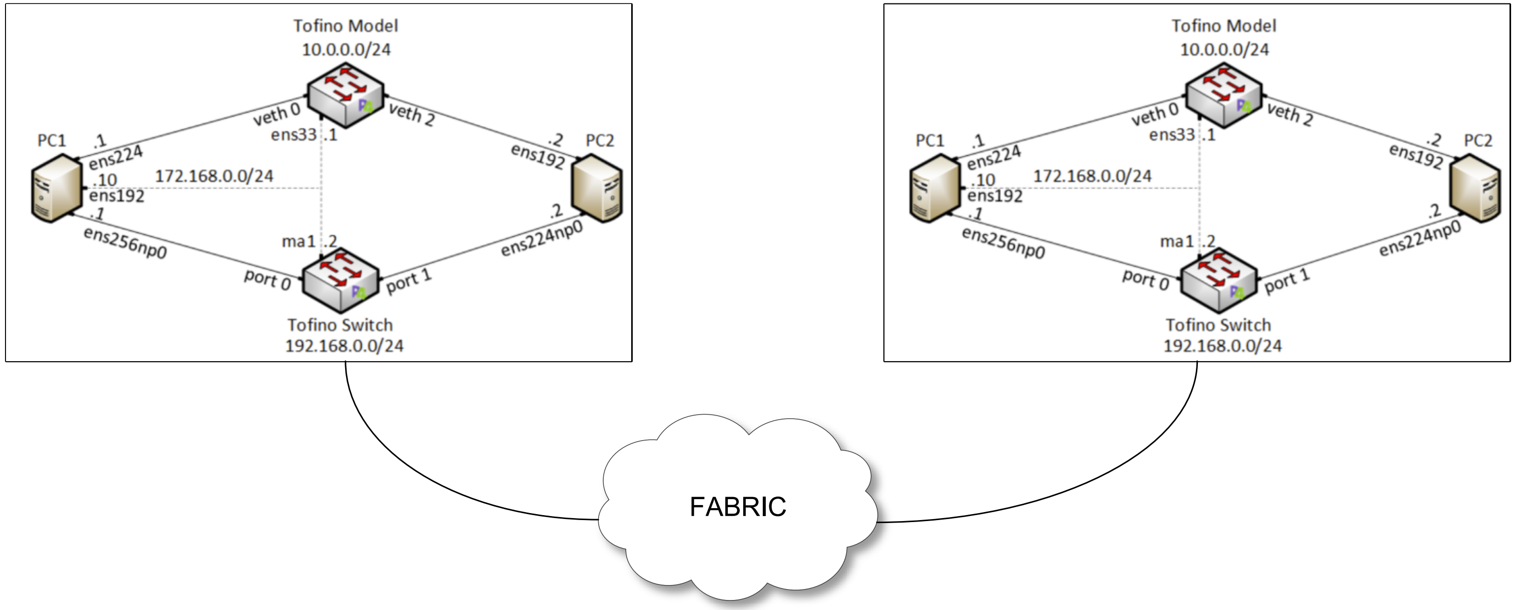
ID	Name	Reservations Made	Labs Attended	Hours Reserved	Hours Attended
1	default	21578	20577	233195.61	105614.35
	Page Total:	21578	20577	233195.61	105614.35
	Table Total:	21578	20577	233195.61	105614.35

Showing 1 to 1 of 1 items

Usage of the cloud by USC courses and research (2019-2022)

Conclusion

- Future work includes exploring potential use cases when pods are connected via a wide-area network
  - Visibility
  - Accurate real-time measurements
  - Data plane processing speed



Conclusion

- Demo, as the time permits
- Application examples in the Poster Presentation session

Thank you

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Platform Features

Feature	Comments
Allocation of resources	Pod granularity
Custom pods	Easy to create custom pods
Cost	Cost-effective when used extensively
Presentation layer for pedagogy	Topology is graphically presented to the learner using a regular browser
Time sharing	Easy to implement time-sharing policies
IP addresses	Pods have the same topology / IP addresses (overlapping addresses w/o conflict)
Functional realism	Virtual labs have the same functionality as real IT hardware in a real deployment
Traffic realism	Devices generate/receive real, interactive network traffic to/from the Internet

Motivation for Virtual Labs

- “The Missing Millions”(NSF report – Oct. 2021. https://tinyurl.com/5awhdazy)
- What can be done to reach out those who are yet to be engaged in STEM workforce?
  - “The present research computing and data ecosystems look impenetrable to many…”
  - “Lower barriers to entry…”
  - “Invest in CI and community laboratories at the edge, enabling broader and more diverse participation”
  - “Explore investments in research computing … that are easily accessible (such as GUIs, …)