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Maturing of OpenFlow and Software-defined Networking through deployments

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ABSTRACT

Software-defined Networking (SDN) has emerged as a new paradigm of networking that enables network operators, owners, vendors, and even third parties to innovate and create new capabilities at a faster pace. The SDN paradigm shows potential for all domains of use, including data centers, cellular providers, service providers, enterprises, and homes. Over a three-year period, we deployed SDN technology at our campus and at several other campuses nation-wide with the help of partners. These deployments included the first-ever SDN prototype in a lab for a (small) global deployment. The four-phased deployments and demonstration of new networking capabilities enabled by SDN played an important role in maturing SDN and its ecosystem. We share our experiences and lessons learned that have to do with demonstration of SDN's potential; its influence on successive versions of OpenFlow specification; evolution of SDN architecture; performance of SDN and various components; and growing the ecosystem.

1. Introduction

Software-defined Networking (SDN) is a new approach to networking that has the potential to enable ongoing network innovation and enable the network as a programmable, pluggable component of the larger cloud infrastructure. Key aspects of SDN include separation of data and control planes; a uniform vendor-agnostic interface, such as *OpenFlow*, between control and data planes; a logically centralized control plane, realized using a network OS, that constructs and presents a logical map of the entire network to services or *network control applications* on top; and slicing and virtualization of the underlying network. With SDN, a researcher, network administrator, or third party can introduce a new capability by writing a software program that simply manipulates the logical map of a slice of the network.

SDN has been gaining momentum in both the research community and industry. Most network operators and owners are actively exploring SDN. For example, Google has switched over to OpenFlow and SDN for its inter-datacenter network [17], and NTT Communications has announced OpenFlow-based Infrastructure as a Service (IaaS) [33]. Similarly, many network vendors have announced OpenFlow-enabled switches as products and have outlined their strategies for SDN [38]. The research community has had several workshops on SDN during the past two years, where diverse SDN research topics have been covered.

In this paper we share our experiences with OpenFlow and SDN deployments over the past three years in four chronological phases.[1] The deployments represent a spec-

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[1] Many people contributed to various aspects of OpenFlow and SDN over the years that our deployments used and relied on. The deployments would not have been possible without the help and contributions of these people. The section on acknowledgements provides a more complete list and details.

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trum from the first-ever laboratory deployment to one that carries both research and production traffic to deployments across the globe, spanning many campuses and a few national networks.

The deployments have demonstrated the key value proposition of SDN and network slicing or virtualization. Our experience shows that deployments that can support both research and production traffic play a critical role in the maturing of the technology and its ecosystem, especially if they also support innovative network experiments or applications. Finally, the deployment experience provided valuable insights into various performance and scalability tradeoffs and provided input to the OpenFlow specifications and evolution of the overall SDN architecture. The following are examples of outcomes and/or insights the rest of the paper will elaborate.

1.1. Performance and trade-offs

For various deployments reported in this paper, a single server of 2010 vintage was sufficient to host the SDN control plane, which includes the network OS and a set of network control and management applications. This confirmed the insight from the earlier Ethane [4] trial at Stanford that a modern server can provide the necessary performance for network control and management of the whole campus.

The flow setup time quickly emerged as an important performance metric for SDN networks, and the CPU subsystem within a switch or router responsible for control traffic is the determining factor until vendors can roll out products with higher-performance CPU subsystems.

The larger national deployment as well as our production deployment in the Stanford CIS building confirmed that the number of flow table entries supported by most commercial switches is a limitation in the short term. Future OpenFlow switches would have to support a much larger number of flow table entries in hardware for performance and scale.

1.2. SDN architecture and OpenFlow specification

Most of early SDN experiments and applications built on NOX [32] would build their own network map and then implement their applications functions as functions on the network map. This pattern suggests that the network OS itself should offer a network map as the abstraction to applications, which represents an important step forward in the evolution of SDN architecture [44].

Our deployment experience combined with various experiments and applications provided valuable input to the OpenFlow specification process in the areas of failover, topology discovery, emergency flow cache, barrier command for synchronization, selective flow table entry expiration, port enumeration, bandwidth limits, and isolated queues for slices, query of individual port statistics, flow cookies, flow duration resolution, and overall clarification of many aspects of OpenFlow specification.

Our deployments also helped build a preliminary version of SDN monitoring and troubleshooting infrastructure, which we used to debug many problems over the years. For this debugging, we used two key architectural features of SDN: (1) OpenFlow switch behavior is essentially decided by its flow table and (2) SDN provides a central vantage point with global visibility. This among other insights shows a way to build an SDN-based automated troubleshooting framework, which would represent a huge step forward for networking [49,28,24,20].

1.3. Paper organization

It is important to note that the paper is about showing how the deployments helped SDN and OpenFlow mature, and it is not about the SDN architecture or how it is superior to other proposed future Internet architectures. The early deployments reported in this paper as well as other SDN developments showcase much of SDN's potential. However, SDN will require sustained research and more diverse deployments to achieve its full potential. This paper simply presents snapshots of the first few years of deployments and by no means represents the final word.

The paper is organized as follows[2]: First, in Section 2, we provide the context that led to OpenFlow and SDN and our plans to take on a trial deployment. We, then, present four phases of deployments: proof of concept (Section 3); slicing for research and production (Section 4); end to end, that is, campus to backbone to campus (Section 5); and production use (Section 6). For each phase, we highlight goals, the state of OpenFlow and SDN components used, infrastructure built, key experiments and demonstrations and lessons learned. We also present how deployments and associated applications influenced the OpenFlow specification, SDN architecture evolution, and rapidly growing SDN ecosystem. We then present how the deployments influenced OpenFlow specifications (Section 7) and evolution of the SDN architecture and components (Section 8) and led to a measurement and debugging system (Section 9). We share our concluding remarks in Section 10.

2. Origins and background

Internet architecture has been a topic of research and exploration since its beginning. There have been government programs and research projects that explored how to make it better or even reinvent it, especially focusing on network programmability. For example, the Defense Advanced Research Projects Agency (DARPA) in the U.S. launched a research program on active networking during the mid-1990s to enable users and network operators to "program" the network elements in the data plane. Subsequently, the EU also launched the Future Active IP Networks (FAIN) program [47,14] with similar goals. Ten years later, researchers proposed the Forwarding and Control Element Separation (ForCES) framework [9] to allow flow-level network programmability using a flexible modeling language for the flow tables and the flow logic. While network programmability seems very appealing, none of

[2] This paper does not provide a HOWTO for deploying OpenFlow. Please refer to [39,8] for an in-depth tutorial on using OpenFlow and for a tutorial on deploying OpenFlow in a production network.

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the ideas has received any kind of adoption in real networks. The U.S. National Science Foundation launched Future Internet Architecture (FIA) to explore next-generation architectures and their experimental evaluation on a nation-wide infrastructure called Global Environment for Network Innovation (GENI) in mid-2000s [19,11]. EU has also launched similar programs such as Future Internet Research and Experimentation (FIRE) [12].

OpenFlow and the larger SDN architecture took shape in 2007 and owe their inheritance to ForCES, SANE [5], Ethane [4], and 4D [18], among others. These earlier projects had also argued for separation of data and control planes and logical centralization of the control and management plane. Ethane demonstrated in 2006 how the approach can be successfully applied to access control for a campus enterprise network requiring sophisticated policies. The SDN architecture generalizes Ethane beyond access control for all control and management functions and aims to provide well-defined abstractions to enable creation of new control and management applications[3] and also help reason about the network behavior in a rigorous way. The control plane is realized using what we call a network OS, which constructs and presents a logical map of the entire network to applications on top.

Early deployment plans for SDN were influenced by the Ethane trial at Stanford University and NSF's GENI. The Ethane trial showed among other findings that experimentation on a campus production network has many advantages. Researchers can more easily use their own campus network and can include their friends as real users, leading to credible results and impacts. Early GENI design and planning argued for a sliceable and programmable networks and servers to enable multiple concurrent experiments on the same physical infrastructure, based on successful Planetlab experience [41]. Therefore, we set the following goals for our SDN deployments:

- Demonstrate SDN architecture generality and its ability to enable innovation.
- Enable at-scale experimentation on campus production networks.
- Enable multiple concurrent experiments using slicing and virtualization on the same physical SDN infrastructure.

NSF's GENI [15] and SDN have enjoyed a synergistic relationship. The GENI initiative has been funding and enabling SDN deployments at Stanford and around the country. On the other hand, SDN deployments now form a major part of GENI's networking substrate and enable network innovations.

SDN deployment for research as well as production use meant that we required vendor-supported commercial OpenFlow switches and robust SDN controllers to serve as the "network operating system." This early reliance on and collaboration with vendors proved invaluable. The synergy with GENI led us to propose *Enterprise-GENI* as an SDN deployment with slicing and programmability on our campus for research and production use. We further proposed to create an Enterprise-GENI kit to help other campuses replicate SDN deployments in subsequent years, and this helped us with SDN growth, especially in the research and education community.[4]

2.1. SDN reference design

Fig. 1 shows an early SDN reference design wherein the data plane and the control plane are decoupled. The data plane (comprised of the simplified switches) is modeled or abstracted as (1) a set of flow table entries that decide how incoming packets matching one or more flow table entries are forwarded and (2) an embedded control processor that interfaces to the control plane and manages the flow table on the switch. The control plane uses the OpenFlow protocol to program the data plane and learn about the date plane state. The control plane is implemented using an OpenFlow controller or a network OS and a set of applications on top. In our design, the controller takes as input the network policies that dictate which subset of the resources is controlled by which control application. This subsection describes the basics of SDN as background for the rest of the paper.

2.1.1. Flow processing logic

When a packet arrives at a switch, the switch inspects whether there is a flow entry (also called a *rule* in the rest of the paper) in its flow table that matches the header fields of the packet. If there is a match, the flow table entry specifies how to forward the packet. If there is no match, the switch generates a *packet_in* message that is sent using the OpenFlow protocol to the controller. The controller passes the *packet_in* event to the appropriate control application(s) based on the policies programmed—which applications see which events. The applications process the events using the network state and their application logic and may send back a message with actions to undertake; the action can involve a *packet_out* (sending out the packet that caused the *packet_in*) or a *flow_mod* (adding or modifying a flow entry), or both.

2.1.2. Control plane operation

The control plane can be *reactive* by handling new flows only after they arrive or *proactive* by inserting flow entries even before the flow arrives, or it can use a combination of the approaches based on specific flows. OpenFlow protocol allows a controller to query the switch through a *stats_request* message and obtain greater visibility into the traffic characteristics. The reactive mode, *stats_request*, and topology-discovery algorithms can together provide the control plane with unprecedented visibility and control over the network dynamics.

[3] Any reference to "application" in the rest of the paper corresponds to *network control and management applications* implemented on an SDN controller. They represent the network service and functions, not computer applications.

[4] Chip Elliott, Director of GPO, encouraged us to think about kits for other campuses.

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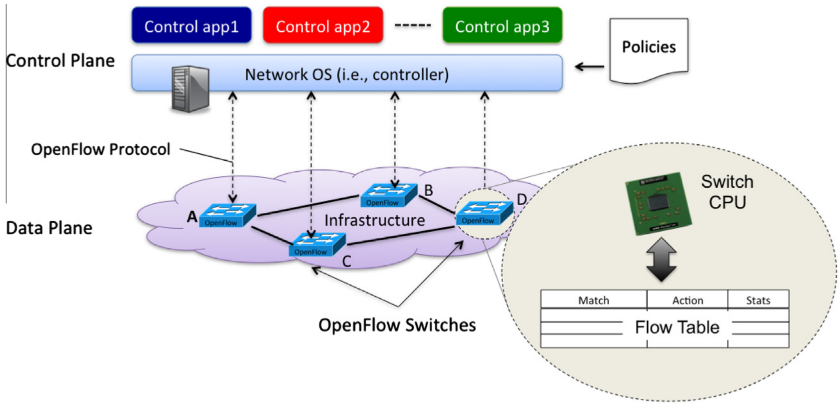

Fig. 1. Early SDN reference design.

2.1.3. Topology discovery

The control plane can behave in a centralized manner and manage a large collection of interconnected switches that make up an *OpenFlow island*. In such a deployment, the controller can use the *packet_out* message to instruct the data plane to send out LLDP packets from switch ports to network links. (Note that an incoming LLDP packet at a switch port will be forwarded to the controller as a packet_in message.) Based on these LLDP *packet_ins*, the control plane can infer the connectivity within the island and construct the network topology. This is the popular approach where no additional support is needed from the switches to infer the topology of the network.

2.2. Performance and scalability

Though the key attributes of SDN architecture offer many important advantages, they obviously have some tradeoffs. For example, separation of the data plane and the control plane suggests performance penalty in terms of additional delay for control operations, especially for flow setup, topology discovery, and failure recovery, and (logical) centralization of the control plane suggests scalability and concerns with a single point of failure. One of our goals with deployments has been to study these performance and scalability implications, and we share our experiences and lessons learned in this regard.

3. Phase 1: Proof of concept

We had simple yet ambitious goals for our proof-of-concept phase, which lasted most of 2008. We wanted to create a small SDN deployment using the first prototypes of OpenFlow-enabled switches and controllers and build sample experiments and applications to show the potential of SDN. Our secondary goals included providing useful input to the OpenFlow specification process and to commercial vendors offering OpenFlow-enabled switches, and getting more researchers, network operators, and vendors to explore and deploy SDN.

One of the key building blocks for this phase of deployment was the first OpenFlow reference implementation, publicly released under the OpenFlow license in Spring 2008. This release enabled early vendors such as HP, NEC, Cisco, and Juniper to build the first set of OpenFlow-enabled hardware switches based on their commercial products with OpenFlow features for only research and experiments. The other key component was NOX [32]—the only controller available at the time. NOX version 0.4 provided a basic platform for parsing the OpenFlow messages and generating events to be handled by different application modules. This version also had the following control applications pre-bundled in the distribution: (1) shortest-path L2 routing, (2) L2 MAC-learning, (3) LLDP-based topology discovery, and (4) switch statistics collection. This served as an ideal platform for experimenters.

In this section we present the infrastructure built, experiments enabled, and key lessons learned in this proof-of-concept phase of deployment.

3.1. Infrastructure built

We started with a small SDN/OpenFlow network testbed in our laboratory at Stanford University, as shown in Fig. 2. The network consisted of prototype OpenFlow switches from HP and Cisco, along with two Wi-Fi access points that each ran an OpenFlow reference software switch developed in our research group. HP and later NEC implemented OpenFlow within the context of a VLAN, i.e., OpenFlow traffic was assigned to pre-specified VLANs and managed by the OpenFlow controller, while all legacy traffic was assigned to other VLANs. We refer to this approach of having OpenFlow VLANs and legacy VLANs co-exist on a switch as a *hybrid model*.[5] This proved to be an important feature in the long run for deploying OpenFlow alongside legacy networks on the same physical infrastructure. Each OpenFlow switch was associated with NOX. The controller had additional modules included based on the exact experiment undertaken in the control plane.

Phase 1 infrastructure grew quickly, as shown in Fig. 3. The Stanford team reprogrammed a group of three

[5] At this time, we did not have a more general solution for slicing and virtualization of SDN networks.

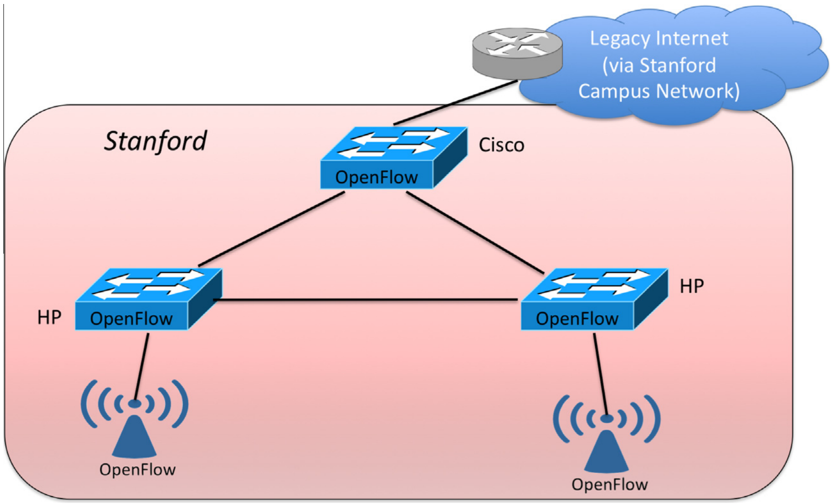

Fig. 2. Phase 1 infrastructure (used for ACM SIGCOMM 2008 demo).

NetFPGA [30] boxes deployed in Internet2 [22] PoPs to be OpenFlow switches and also helped deploy Juniper's OpenFlow-enabled MX switch to create a small SDN island within the Internet2 network. Japan's JGN2plus [23] also deployed OpenFlow-enabled NEC switches and a NetFPGA-based OpenFlow switch in its own network to create another SDN island in Japan. We interconnected these OpenFlow islands by point-to-point tunnels, as shown in Fig. 3, to create an OpenFlow network with a small global footprint spanning Stanford, Internet2, and JGN2plus relatively quickly for research and experimentation.

3.2. Key milestone experiments

With any new technology, it is important to demonstrate innovative applications. In the case of SDN, this meant demonstrating something that is difficult to realize without SDN and would show its overall power. We chose to implement seamless mobility of Virtual Machines (VM) across L2 and L3 network boundaries using SDN's two key features: layer independence of the OpenFlow, wherein a flow can be defined using a combination of L2–L4 headers; and OpenFlow controller's visibility of the global network map. This means when a VM moves, the controller can re-

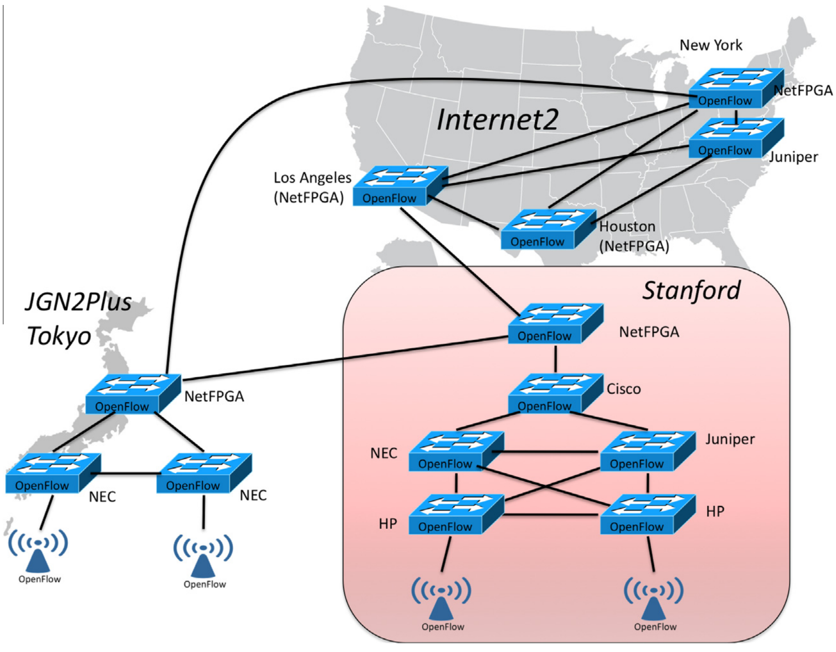

Fig. 3. Extended Phase 1 infrastructure.

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route all its flows to its new location irrespective of its new L2 and L3 locations. We demonstrated the VM mobility capability for a multiplayer game application with mobile VMs to support mobile players without ever interrupting the game. The application was highly visual, and it showcased VM mobility supported by SDN. We were able to provide the least latency between the gaming clients and the backend server either by routing the gaming traffic through routes with the least hop count or by moving the VM hosting the game server closer to the client. This functionality was built using Python scripting within the NOX controller. We built two flavors of the demonstration: one allowing mobility of VMs within Stanford (Fig. 2) and another allowing mobility across the wide-area network (WAN) between Stanford and Japan (Fig. 3) [7]. More importantly, the SDN part of development was trivial to the controller—a small and simple piece of code was needed to reroute flows when a VM moved, demonstrating the power of SDN.

The experiment also allowed using a graphical user interface (GUI) to manage all the traffic in a network, even to the extent that it enabled a network operator to drag and drop flows in arbitrary ways; e.g., the operator could create a flow for fun or demonstration that originates from a client at Stanford, goes to Internet2 New York, goes to Japan, and then ends at a Stanford server; then the operator could arbitrarily change the flow's route by doing drag and drop.

The first set of demonstrations convinced us and the community of the power of SDN, especially to enable innovation. This was the beginning of many organizations wanting to build SDNs for their own research.

3.3. Lessons learned

We summarize a number of important lessons from this phase of deployment. Many seem obvious, especially in retrospect. Still, we had to learn them ourselves, and they served us well in the subsequent years.

3.3.1. Performance and SDN design

Phase 1 infrastructure exposed *flow setup time* as a very important performance metric, at least for the short term. We define *flow setup time* as the time from when the (first) packet (of a flow) arrives at the switch to when the action of forwarding that packet is completed. In reactive control mode, which is typically used in most academic experiments, this indicates the duration each flow needs to wait in an OpenFlow network before traffic can start flowing.[6] This can be a significant overhead for short-lived flows.

We also learned that most current switches have lower performance CPUs for control operations. Since these switches were designed for MAC-learning or destination-IP-based forwarding, their embedded control CPU does not have enough performance to handle a large number of OpenFlow messages. The *stats_requests* and reactive mode of flow setup stress the CPU, leading to increased flow setup times, overall poor response time to control plane messages, and, at times, to network outages. In the short term, the limitation can be mitigated by enforcing a limit on the messages sent over the OpenFlow control channel, aggregating rules, or proactively inserting rules. In the long term, we expect OpenFlow switch vendors to use higher performance CPUs and fine-tune the performance for the OpenFlow use cases—relatively easy for vendors to do going forward.

3.3.2. Living with legacy networks

In the real world legacy networks abound, and it is not possible to have an OpenFlow-only network or a contiguous OpenFlow network. To make OpenFlow and legacy networks interwork, we paid special attention to switch implementations, tunneling mechanisms, LLDP-based topology discovery, overlay routing, and TCP delays.

Through our deployments, we demonstrated the usefulness of the hybrid switch to support both legacy and OpenFlow traffic on the same switch, which has now become the most common model for OpenFlow switches. In the mid to long term we expect the community to adopt OpenFlow-only switches that provide all the necessary functionality for a production network and thus realize all the value of OpenFlow and SDN, including simpler forwarding plane and lower CapEx.

We used tunneling to interconnect the individual OpenFlow islands. Using NetFPGA to encapsulate the dataplane traffic as part of tunneling can at times cause the packet size to exceed the Maximum Transmission Unit (MTU) size at an intermediate router, thereby leading to packet drop. We initially resolved this by tweaking the MTU value at the end servers. We later resolved this by creating a software-based tunneling mechanism that provided Ethernet-over-IP encapsulation (using the *Capsulator* software [3]) and used IP fragmentation to circumvent the MTU issue. Note that software-based tunneling, however, incurs a performance penalty.

For topology discovery of a network that transits non-OpenFlow (i.e., legacy) switches, the controller has to be aware of the relatively common possibility that intermediate legacy switches may drop LLDP packets used for discovering links in the OpenFlow domain. This can be mitigated by using a nonstandard LLDP destination address within the OpenFlow domain.

When we used point-to-point VLANs (in Internet2) to create a virtual link between OpenFlow islands, we had to take caution that the overlay routing performed by the control application did not cause a packet to traverse the same L2 non-OpenFlow link in a different direction; such traversing can cause the L2 learning table of the intermediate non-OpenFlow switch to flap. If the traffic volume is high, the flapping can cause CPU overload and consequently lead to a network outage. This can be resolved in some legacy switches by turning off the MAC-learning feature and in others by re-engineering the topology.

We noticed that the TCP Nagle algorithm, which was enabled by default, interfered with the message exchange between the OpenFlow switch and controller, thereby creating instances when the flow setup time was large. We resolved this issue by disabling Nagle's algorithm (using the

[6] Recall that in the case of proactive mode of operation, the rule is already programmed in the flow table and thus the incoming packet does not have to wait.

TCP socket option) for the OpenFlow control channel because OpenFlow messages are typically only several bytes long and are time critical, and it is not worthwhile to queue packets until the maximum TCP segment size is reached.

4. Phase 2: Slicing and scaling SDN deployment

With the SDN proof of concept and its potential demonstrated, we decided to grow the deployment and add slicing to it with the following goals:

1. to achieve concurrent experiments over the same physical infrastructure;
2. to coexist with production traffic so as to validate the hypothesis that experimentation can occur in everyday networks;
3. to evaluate performance of SDN architecture and components in a real deployment setting; and
4. to improve the software stack and tools available for SDN deployment.

To achieve the above goals, we expanded the topology, added a virtualization layer, created and ran multiple concurrent experiments, and developed orchestration and debugging tools for better analysis and manageability.

This phase of deployment used OpenFlow version 0.8.9, released in December 2008, which included additional features such as (1) vendor extensions to allow vendors to define new actions that are not necessarily standardized, (2) hard timeout for flow rules in the cache, (3) allowing replacement actions of previously inserted flow rules, and (4) providing match capability for ICMP Type and Code fields, and many other minor updates to the existing actions, messages, and protocol formats. The Stanford team again built a reference implementation of OpenFlow version 0.8.9, which helped vendors quickly release new switch firmware and allowed for a more stable OpenFlow-enabled switch ready for the next level of SDN deployments and experimentation.

One of the main requirements for GENI and for our own deployment has been to support multiple concurrent experiments as well as production traffic on the same physical infrastructure. This is achieved by introducing a network virtualization layer in the control plane that creates virtual networks called *slices*; each slice is typically managed by a different OpenFlow controller. The *slicing* implies that actions in one slice do not affect other slices. We implemented SDN network slicing using *FlowVisor* [45], a special purpose OpenFlow controller that acts as a semi-transparent proxy between OpenFlow switches and multiple OpenFlow controllers, as shown in Fig. 4. The FlowVisor isolates the slices based on *flowspace*, a collection of rules that identify the subset of flows managed by a particular slice. With FlowVisor inserted in the middle, all control communication from the switch is classified based on the flowspace, and forwarded to the appropriate controller. In the reverse direction, any message from the controller is validated based on flowspace ownership rules and then forwarded to the switches. With slicing and FlowVisor, we can assign all production traffic to a slice and each experiment to a separate slice. Our deployment in this phase used FlowVisor version 0.3 initially, and then upgraded to version 0.4. In these early versions of FlowVisor, the slice specification and policies governing slice arbitration were specified manually, and remained static through out the complete run.

The rest of the SDN software stack included two types of controllers: NOX version 0.4 for experimentation/research, and SNAC [46] version 0.4 for production OpenFlow traffic. SNAC is a special-purpose open-source controller based on NOX that Nicira [31] released to make it simple for network administrators to specify access-control policies for production OpenFlow traffic. (We defer the discussion of production traffic to Section 6.) Between Phases 1 and 2, the controllers were upgraded to include support for OpenFlow version 0.8.9, as well as fixes to various bugs.

The rest of the section presents the infrastructure built, key experiments enabled, and lessons learned.

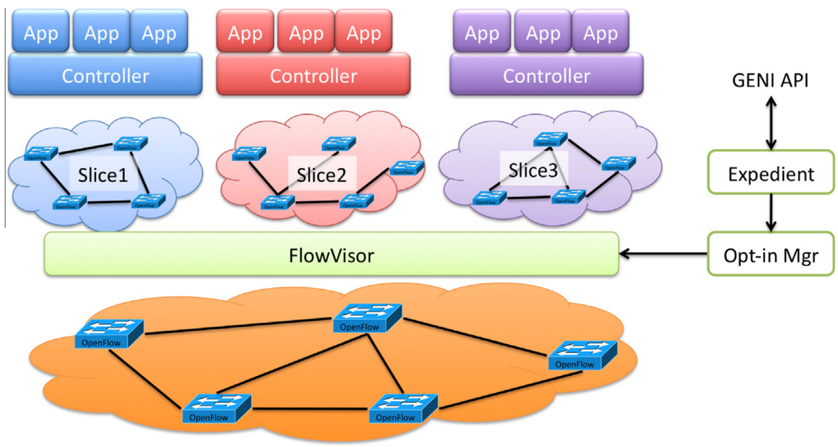

Fig. 4. Slicing-enabled SDN reference design.

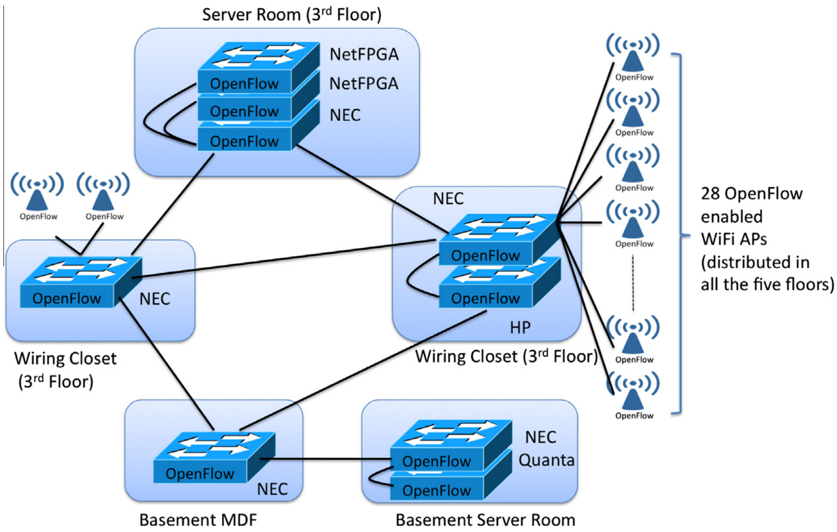

Fig. 5. Phase 2 infrastructure (logical view) in Stanford Gates building.

4.1. Infrastructure built

We expanded our Stanford deployment from the laboratory to within the basement and third floor wiring closets of the Gates building using NEC, HP, and NetFPGA switches running the new firmware for OpenFlow version 0.8.9. The infrastructure had 4 NEC, 2 NetFPGA, and 1 HP OpenFlow-enabled switches. We supported both production network and experimentation network on this infrastructure. Fig. 5 illustrates the interconnection of the network that we deployed. With NEC and HP switches, we used VLANs to create multiple instances of each OpenFlow switch. That is, with one physical switch, we could create multiple VLANs and associate each VLAN with a controller such that the controller thought it was connected to multiple, distinct switches. This was an easy way to emulate a much larger topology than the physical one. All experiments and production traffic used this logical network.

4.2. Key milestone experiments

The most important capability we experimented with was how SDN infrastructure with slicing can support multiple concurrent slices; each slice can support a research experiment, carry production OpenFlow traffic, or carry legacy production traffic. Furthermore, within a slice, SDN retained its core value proposition of making it easy to write innovative applications on top of a controller. In our deployment, the FlowVisor was used to virtualize the infrastructure to support the following experiments within isolated slices, each managed by a different NOX-based controller [43]:

- The *Plug-N-Serve* research project explored the hypothesis that web load-balancing is nothing but smart routing. That is, web requests can be load-balanced across various servers by a smart routing mechanism within the network by routing each request to an appropriate server, taking into account load on each server and congestion on various paths leading to the server. The Plug-N-Serve experiment's slice tested various algorithms for load-balancing web requests in unstructured networks [29]. In this experiment, web queries arriving at a configurable rate were load-balanced by the controller (using its knowledge of the global network state), taking into account both path characteristics and server load. This slice used the flowspace comprised of all HTTP traffic that uses TCP port number 80.
- The *OpenRoads* research project explored the hypothesis that we can create a much better user experience on a mobile device if it can utilize multiple cellular and Wi-Fi networks around it under user/application control. The project used a slice to experiment with and demonstrate loss-less handover between the WiMAX and Wi-Fi wireless nodes [50] for a demanding video streaming application. The OpenRoads slice took control of all traffic generated to or from the Wi-Fi access points.
- The *Aggregation* experiment showcased OpenFlow's ability to define a flow in a very flexible and dynamic way based on a combination of L2, L3, and L4 headers. Furthermore, a set of flows can be easily aggregated as a single flow by reprogramming a flow definition in a table, as sub-flows travel deeper into the network. The specific experiment demonstrated how hundreds of TCP flows are "bundled" into a single flow by re-programming a flow table entry as component flows traverse the network. The aggregation experiment's slice policy was defined based on the MAC address of the hosts dedicated to this experiment.
- The *OpenPipes* demonstrated how hardware designs can be partitions over a physical network. In this experiment, the traffic consisting of video frames was encapsulated in raw ethernet packets and were piped through various video filters running on nodes distributed

across the network [13]. Furthermore, the individual functions could be dynamically moved around in the network. The slice policy was defined based on the ethertype specified in the L2 header.
- The *Production* slice carried all non-experimental traffic and provides the default routing for all users' production traffic.

As in the case of Phase 1, all research experiments in different slices required minimal effort to develop. The SDN part was a simple software application that essentially created the network map in a local data structure, manipulated it for its control logic, and sent flow update events to the NOX. This further validated the power of SDN by enabling innovation and making it easy to create new network capabilities. The successful demonstration of network slicing also proved the viability of SDN to serve as the networking substrate for GENI.

4.3. Lessons learned

By running concurrent experiments, we learned that slicing based on flowspace provides sufficient flexibility to delegate control to different experiments or administrative entities. FlowVisor version 0.3, however, initially did not provide sufficient isolation of the control plane workload across the different control applications. Thus, any increase in flow ingress rate for a particular experiment, such as Plug-N-Serve, caused poor response to flows in the flowspace of a different experiment, such as Aggregation. This was addressed in the next release of FlowVisor—version 0.4—by adding a software rate limit per slice. Despite this feature, it was tricky to enforce the data plane and control plane isolation across slices, especially when the number of slices exceeded the number of data plane queues available.

We also learned that overlapping flowspace is a tricky concept that is poorly understood. The FlowVisor (both version 0.4 and 0.6) allowed overlaps in the flowspace that belonged to each slice. This could be a feature in some cases, and a pitfall in others. FlowVisor version 0.6 provided the possibility of associating priority to slices, so as to specify which controller gets precedence in receiving switch events pertaining to a particular flow. This feature, however, could not prevent two controllers that owned the same flowspace from performing conflicting actions. This was a caveat we tried to share with all experimenters, and still they ended up misusing it and thus getting into trouble.

We obtained a deeper understanding of the performance implications of using SDN: The key metric we tracked was the flow setup time. Our experience suggests 5–10 ms flow setup time for a LAN environment is typical and acceptable. However, our Phase 2 deployments showed flow setup time can be at times greater than 100 ms, too high to have good user experience. Our in-depth analysis revealed that higher flow setup time was often due to the high load in the CPU subsystem at the switch when the SDN deployment was operating in reactive mode. The true reason for this issue, however, was that most switch-embedded CPUs did not have enough power to handle increased load due to OpenFlow.

5. Phase 3: End-to-end deployment with a national footprint

Our Phase 2 deployment and the demonstrations led to significant interest from other universities, especially in the United States and Europe that wanted to deploy and experiment with SDN on their campuses. This led to SDN deployments at eight universities (Clemson University, Georgia Institute of Technology, Indiana University, Princeton University, Rutger University, Stanford University, University of Washington, and University of Wisconsin) with a strong SDN research agenda and willing network administrators and GPO and using Internet2 and NLR as the national backbone networks. We also worked with T-Labs (Deutsche Telekom) and a set of universities in Europe to help them organize a similar project, called OFELIA, with the goal of deploying an end-to-end SDN infrastructure in Europe [26]. These collaborative projects and the increasing interest in SDN led us to the following goals for the next phase of SDN deployments:

- help campuses, GPO, NLR, and Internet2 deploy SDN without requiring heroic effort,
- create a functioning end-to-end SDN infrastructure with slicing and with GENI interface so multiple concurrent slices can be hosted on the same physical infrastructure for experimentation,
- help researchers on campuses to do experimentation and demonstration of their ideas on the local and national SDN infrastructure,
- help mature OpenFlow and SDN components,
- help grow the SDN ecosystem.

For all deployments in this phase, we used the newly released OpenFlow version 1.0 as the default. The main feature added to this version was queue-based slicing, which is a simple QoS mechanism to isolate traffic in OpenFlow networks. Other features added include matching IP addresses in ARP packets, flow cookies to identify flows, selective port statistics, and matching on the ToS bits in the IP header.

Fig. 4 shows the complete SDN stack that was deployed in this phase. The stack comprised OpenFlow-enabled switches running version 1.0 firmware, FlowVisor version 0.6 for slicing individual OpenFlow islands, and NOX version 0.4 for controllers. To scale up experiments and to work with the GENI control framework, we added a policy management framework that was implemented using two additional components, *Expedient* and *Opt-in Manager*.

Expedient [10] is a centralized control framework designed for GENI-like facilities with diverse resources. It centralizes the management of slices and experiments, as well as the authentication and authorization of users. It is designed to support each resource as a pluggable component of the framework and to give each resource its own API for resource allocation and control. This simplifies the addition of new resources into the framework and their management, as each resource can have its own API. For our deployments, Expedient supported PlanetLab API, GENI API, and Opt-in Manager API for OpenFlow networks. Expedient is implemented as a traditional three-tier web server (with a relational database as the backend).

Opt-in Manager [40] is a database and web user interface (UI) that holds information about the flowspace that each user owns and the list of experiments that are running in a network along with the flowspaces that they are interested in controlling. The web UI allows users to opt their traffic into individual experiments. When a user opts into an experiment, the Opt-In manager finds the intersection of that user's flowspace and the experiment's flowspace and pushes it down to FlowVisor, causing the packets matching the intersection to be controlled by the requested experiment's controller. We used version 0.2.4.2.

To support the growing number of SDN deployments around the world, we created several recipes for SDN deployments and posted them on our deployment website [8]. These recipes allowed a group to quickly create an SDN network in software and gain useful experience; deploy a small SDN in a lab; or deploy a network in a building for research and production use with real hardware switches and an SDN software stack. We also tried to create processes for the release and support of SDN components such as NOX, SNAC, FlowVisor, and others.[7]

In the rest of the section, we present the end-to-end infrastructure we built with our collaborators, the key experiments enabled, and the lessons learned.

5.1. Infrastructure built

The nationwide SDN infrastructure comprised 11 individual islands (i.e., 9 campuses, GPO, and NLR)[8] interconnected with each other, as shown in Fig. 7. The infrastructure interconnected virtualizable computing nodes to create a single sliceable and programmable computing and networking facility. Each island deployed an OpenFlow network as well as a few PlanetLab nodes as compute servers to create a local GENI substrate. Fig. 6 presents an illustration of how substrates are stitched to form a large-scale slice using SDN stack (FlowVisor, Opt-in Manager, Expedient, Controller), MyPLC for PlanetLab, and GENI control (Expedient, Omni).

Initially we interconnected the different campus SDN deployments in a star topology, using point-to-point VLANs over the NLR, with the Stanford deployment at the root. For instance, VLAN 3707 was used to interconnect Stanford and Clemson Universities at Layer-2 such that the two islands seemed like just one by routing traffic through MAC-level switching. In a similar manner, we created dedicated VLAN links to each deployment and trunked the traffic at our basement NEC switch, thereby creating a star topology for the national OpenFlow network. Once the NLR SDN deployment became ready for use, each campus deployment set up an additional VLAN connection (VLAN 3716) to the NLR deployment. Most experiments started using this NLR network as the backbone (instead of the Stanford deployment), and it continues to be so even today. Since Princeton University does not directly connect to the NLR, we created a software L3-in-L2 tunnel (using the Capsulator) from a server in the Stanford network to a server at Princeton University. Note that Rutgers University connected to the NLR island through Internet2.

The interconnection among OpenFlow islands was carefully stitched to ensure that the overall infrastructure looked like a single, flat Layer-2 island to the experimenter. In other words, all GENI traffic was carried on a set of VLANs that spanned different segments (including a campus segment, NLR segment, and Internet2 segment) that connected to each other. Although the traffic within each OpenFlow island was processed using flow table entries that included L2–L4 headers as installed by appropriate application controllers (i.e., forwarding within OpenFlow was layer independent and not confined to a single layer such as L2), the interconnects used legacy switches, and we had no control over them.

Experimenters using this global OpenFlow island created a slice of their specification (comprising a list of computing nodes along with the interconnecting network elements) using either a centralized Expedient running at Stanford or a software tool called *Omni* [36]. Both Expedient and Omni interacted with the Expedient Aggregate Manager at each campus to create the slice. Once the slice was created, the local administrator at each campus inspected the slice requirements within the Opt-in Manager and "opted in" the local resources to the experiment. Once opted in, the rules were created in the FlowVisor, thereby mapping the flowspace requested to the experimenter's slice controller. Once a slice was created and flowspace was mapped, the slice (even one that spanned all islands around the country) had one controller to manage it.

5.2. Key milestone experiments

On the large-scale testbed, we conducted the following experiments to showcase the potential of SDN and the capabilities of the nation-wide infrastructure[9]:

- *Aster*x*: A wide-area experiment, based on the earlier Plug-N-Serve system [29], to investigate different algorithms for load-aware server and path selection. The infrastructure used spanned servers and clients located at all SDN/OpenFlow islands (except Rutgers University).
- *Pathlet*: This experiment showcased a highly flexible routing architecture that enabled policy-compliant, scalable, source-controlled routing [16]. This feature was implemented over the OpenFlow controller. Specifically, the experiment demonstrated how edge devices

[7] GPO encouraged us to specify the processes and a release plan and it helped.

[8] Internet2 at the time did not have OpenFlow-enabled switches and provided point-to-point VLANs to interconnect OpenFlow island. Internet2 OpenFlow island was built later [42].

[9] The experiments were publicly demonstrated at the GENI Engineering Conference (GEC) 9 in Washington DC in 2010.

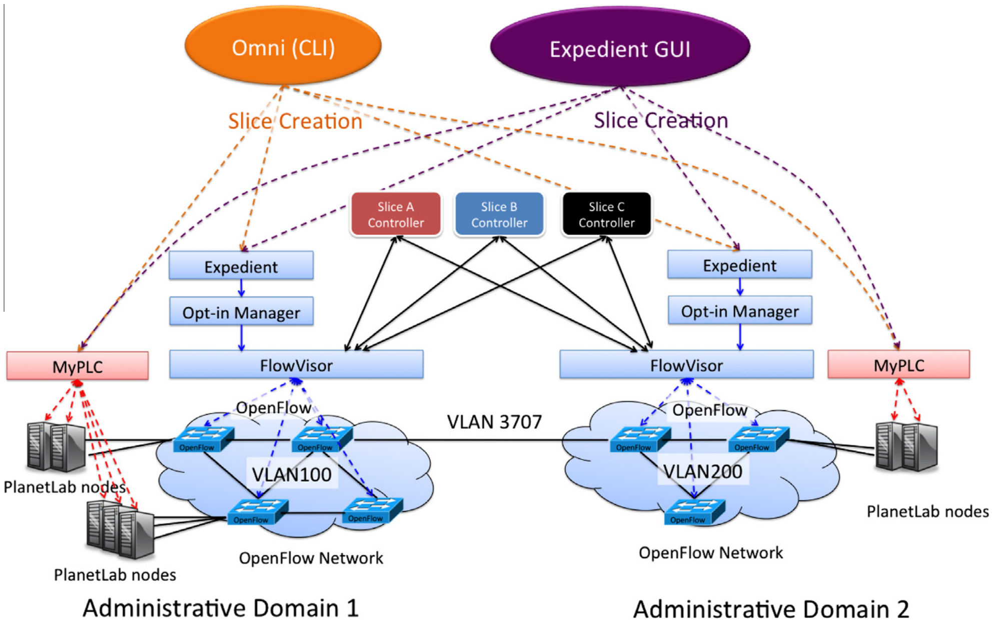

Fig. 6. Wide-area SDN network showing the different software components at each island. A slice request from an experiment was processed by individual island components to form a large-scale stitched slice (with networking and computing).

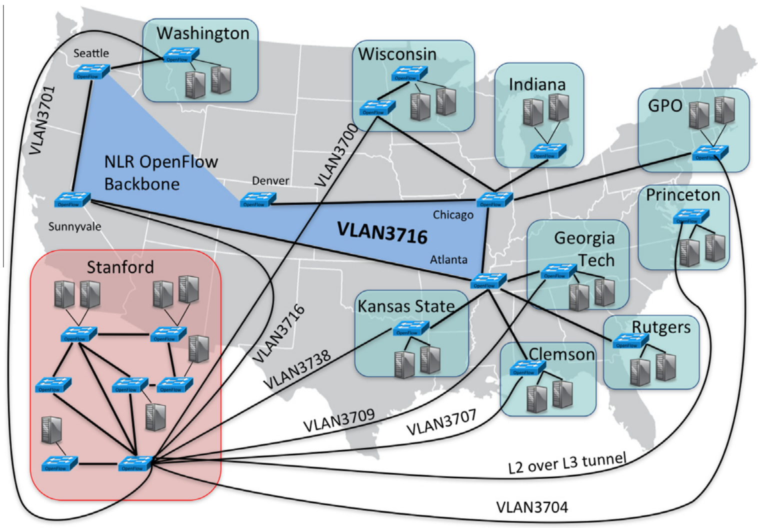

Fig. 7. Phase 3 infrastructure.

can effectively use multi-path routing flexibility in the face of network dynamics via end-to-end performance observations.

- *OpenRoads*: This experiment built on the earlier OpenRoads system and involved a live video stream from a golf cart driving around at 5–10 mph. The experiment showed great user experience for live video if the device is allowed to use multiple wireless networks around it and SDN made it easy to implement handoff between APs and WiMAX base station and tri-casting video stream over both Wi-Fi and WiMAX networks [50].
- *SmartRE*: This demonstration showed how the SmartRE framework allowed both the service and the network capacities to scale by removing redundant content in transmission [1]. The traffic was generated by a popular on-demand video service, and the system used a network-wide coordinated approach to eliminate redundancy in network transfers. The OpenFlow controller and the application made it easy to manage routers with the redundancy elimination feature.

The simultaneous running of all of the above experiments over the same infrastructure yet again confirmed

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that building new applications and capabilities on SDN is relatively easy even if the network spans multiple OpenFlow islands around the country. However, the underlying SDN infrastructure was not as stable or robust. To achieve more stability and predictability, the GPO created an experiment, called the *Plastic Slices project*, that involved running 10 GENI slices continuously for multiple months and monitoring the state. Within each *plastic slice*, the hypothetical experimenter performed a file transfer between pairs of virtual computers in a varying schedule [42]. This experiment helped mature the SDN-based network substrate of GENI.

5.3. Lessons learned

This was at the time when interest in OpenFlow and SDN was growing quickly and many groups around the globe wanted to create their own SDN infrastructure for research and experimentation. Our informal non-scientific estimate based on downloads and email traces suggests there were close to 200 SDN deployments by mid-2011. We supported them in a variety of ways, including offering help and advice on the design of the network; selection of SDN components; and debugging of problems with configuration and deployments; as well as overall hand-holding. Working with these groups around the globe provided invaluable experience and lessons that we summarize in this subsection.

5.3.1. Nation-wide SDN experiments and demonstrations

Creating a single large-scale network by stitching together individual islands is a challenging task for technical and non-technical reasons. Most of the OpenFlow islands were part of CS and EE departments, and they needed to be connected to the campus backbone and then to Internet2 and NLR backbones, which was nontrivial. This involved creating a complete inventory of available network resources, creating figures with network topologies, identifying VLANs available end to end, allocating the VLAN numbers, verifying the connectivity, and coordination with tens of people. GPO did most of this ground work, and without that the nation-wide infrastructure would not have come together.

Our group at Stanford mostly coordinated with the network researchers and administrators directly involved in SDN deployments. Still, the coordination was a balancing act in that we provided SDN tools, support, a blueprint for deployment and guidance to each campus, yet at the same time we wanted each campus to have enough flexibility to be creative and serve its own research and operation goals.

When it came to updating and maintaining the latest software on all campuses, each campus selected a different approach. In some cases, the campuses trusted us (i.e., the deployment team at Stanford University) to configure components such as the MyPLC and the Expedient/Opt-in Manager and upgrade them as necessary. In other cases, each campus assigned a local person. Flexibility and trust on the part of individuals were key to success.

Each of the 11 independent OpenFlow/GENI islands used prototype OpenFlow-enabled switches from different vendors and several prototype software systems that were not tested together. Using this infrastructure to conduct several diverse experiments was an arduous task because the infrastructure was not as stable or predictable. We learned from our experience that conducting the Plastic Slices project first to debug the issues and increase stability should precede any attempts to use the testbed for the large-scale experiments.

Our software release process was complicated because we wanted to ensure that all islands ran the same version of the software stack, and three key software components (FlowVisor, Expedient, and Opt-in manager) were being released for the first time. These components were undergoing active development, debugging, and deployment at the same time, which is not recommended. This required too much of coordination among developers, deployment teams, and campus support staff. While the experiments worked, our experience suggests the university-based developers (students and post docs) and deployment engineers were not well prepared for the challenge, and we cannot recommend doing it again.[10]

5.3.2. Network operation

Through the experimentation and demonstrations, we learned of several issues related to scaling of the infrastructure, controller placement, IP-subnet-based flowspace definition, cross-island interconnection, and network loops.

This phase of the deployment was the largest at the time in terms of the number of OpenFlow islands, switches deployed, slices supported, flow table entries needed, and users. As expected, running over 10 experiments, each having on the order of 1000 rules, stressed the software stack and early versions of OpenFlow switches. For example, the FlowVisor would crash often, and flow setup time was too high in many cases. It took several iterations for the FlowVisor software to mature and become stable. Similarly, the switches were seriously stressed by certain experiments and provided further evidence that their CPU subsystem did not have enough performance for OpenFlow use case. Until switch vendors could provide a higher performance CPU subsystem, we enforced an OpenFlow message rate limit at the switch and a strict usage policy for the data plane workload, so as to keep the load of the switch CPU subsystem below an acceptable threshold.

We learned that a single server hosting a controller for a nation-wide slice spanning 11 islands is sufficient with regards to the load, and the server never became a bottleneck. However, for latency-sensitive experiments (like Aster*x load-balancing), reactive setup of flows in Princeton by a controller in Stanford was sub-optimal. The placement of the controller, thus, became an important consideration for both performance and reliability [21].

We learned that we cannot let each experimenter specify her own flowspace, as this led to flowspace overlap and

[10] After GEC-9, we decided that we could not continue development, deployment, and support of SDN tools and platforms from the university. Instead, we established a separate non-profit organization called Open Networking Laboratory (ON.Lab) that would be responsible for open source SDN tools and platforms and their deployment and support [37].

to flowspace explosion. We learned that it was best to associate experiments with a particular internal IP subnet that spanned the wide-area substrate and allow the experimenter to only control traffic within that subnet (e.g., the subnet 10.42.111.0/24 was dedicated to the Aster*x experiment that stretched to all islands) and all compute servers used by Aster*x sent traffic within that subnet, which was managed by Aster*x's controller. This avoided overlap in flowspace across experiments.

Since the world does not have ubiquitous OpenFlow support, we had to cross legacy switches and networks. This could be tricky because of (1) MAC learning in the legacy network where traffic was overlay routed by OpenFlow switches or where a network uses Q-in-Q could cause perpetual learning and CPU overload and (2) topology discovery errors could potentially arise in the controller when an OpenFlow network was connected at two locations to a legacy network. The first issue is also discussed in the lessons of Phase 1. The second issue was a problem because it caused the controller MAC learning to oscillate and be inconsistent with choosing uplinks for the flows.

Most experimenters wish to have a network topology with loops so as to provide multiple paths to handle their traffic. Having a loop within the OpenFlow network that interconnects with the legacy network is risky because a broadcast storm caused within the OpenFlow network will cause meltdown of even the legacy network. Since the OpenFlow network does not support STP, the legacy network will be unable to identify and block any disruptive loops. In the early GENI network, broadcast storm occurred two times and caused outage in the legacy network: (1) when a loop at BBN was enabled by the experimenter starting their controller before the administrators added safeguards and (2) when a loop across backbones was caused by connecting a campus over both NLR and Internet2 to Stanford. GENI's *Emergency Stop* was required to recover from such a failure when an experiment became disruptive.

6. Phase 4: Production deployment

We had two complementary goals with SDN deployments for production use: to bring OpenFlow and SDN as close to production ready (with network vendors and university network administrators) as a university-based research group can and to demonstrate that SDN with slicing can support both research and production use. The production phase actually overlapped with Phases 2 and 3, and we demonstrated the feasibility of using SDN with slicing for research and production use (for our group) during these phases, as we briefly explained in the previous sections.

As much as our network administrators believed in SDN, they did not want to deploy it for production use until: (1) they could see a production SDN network in operation for 3–6 months with consistent results and (2) they could get SDN components, such as OpenFlow-enabled switches, controllers, and a few core applications, with support from trusted vendors. To meet these expectations we decided on the following plan;

- create an OpenFlow Wi-Fi network that anyone registered with Stanford official Wi-Fi can use as an alternative Wi-Fi for "almost production use",
- create a production SDN infrastructure for our group of approximately 20 people to use,
- create a comprehensive measurement and debugging infrastructure so we can understand and demonstrate performance and stability of our group's production infrastructure on a continuous basis,
- work with hardware and software vendors to achieve the goals listed above.

We had an understanding with our network administrators that if we were able to achieve the goals above, they would deploy SDN in their buildings. In the rest of this section, we present our experiences with the tasks outlined above and how this led our EE department network administrators to do a limited production deployment in two buildings. Though much of the EE production deployment is still ongoing, we present the current snapshot.

6.1. OpenFlow Wi-Fi network

We first built an OpenFlow-based Wi-Fi network (called *ofwifi*) in the Gates building and made it available for any registered user of the Stanford official Wi-Fi network. The OpenFlow Wi-Fi network allowed us to offer "a semi-production service" to guests who do not demand the same level of service as regular users.

As part of Phase 2 deployment, we had deployed 31 OpenFlow-enabled Wi-Fi access points (APs) throughout the 6 floors (including the basement) of the Gates building [51]. Because we have OpenFlow switches in limited wiring closets (1 in the basement and 2 on the third floor), only 4 APs had a direct connection to the OpenFlow switches, and the rest were connected over a software tunnel to one of our OpenFlow-enabled switches.

We opened up the *ofwifi* network for guests, and it quickly attracted many users (approximately 20 users during the busy hour) for their public Internet access. Since users always had the option to switch back to the Stanford Wi-Fi by changing the SSID, extremely high availability was not a critical requirement for the *ofwifi* network. Therefore, we used this network as a place to first deploy new releases of SDN components after testing them in the laboratory. As expected, the network was unstable at the beginning and would suffer many outages. However, by the time we were done with Phase 3 deployment and had conducted several cycles of component improvements and debugging, the *ofwifi* network became quite stable except during the frequent planned outages to upgrade software. Guests used it without realizing that the network was not meant to be production quality.

6.2. Group production network

We, as a group of approximately 20 people spanning 7 rooms in Gates building, decided to use wired SDN for our day-to-day production use with the intent to live the SDN experience ourselves and also use the production net-

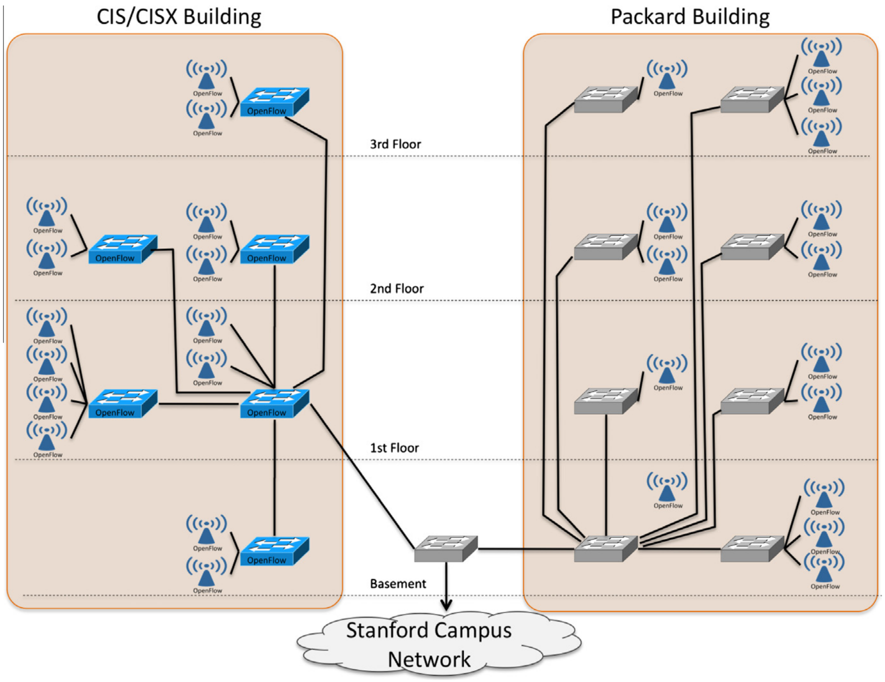

Fig. 8. Phase 4 infrastructure.

work to study and demonstrate performance and stability to our network administrators.

Our production SDN network used NEC, HP, NetFPGA, and Pronto (with Indigo firmware and Pica8 firmware) switches with support for OpenFlow version 1.0.0. We initially used SNAC version 0.4 as the controller, and later replaced it with the BigSwitch commercial controller. Two switches in two different wiring closets on the third floor had direct connections to our 7 office rooms, and both switches were connected to the aggregation switch in the basement. This infrastructure was built as part of Phase 2 deployment, shown in Fig. 5. We deployed various SDN components in this wired production SDN network only after testing them in the lab and in the *ofwifi* network. Thus the wired production network had relatively higher availability.

Both the *ofwifi* and the wired group production networks were instrumented and measured on a continuous basis since 2009, as explained in Section 9. We shared highlights from weekly measurements and analysis with our network administrators. On one hand, the network administrators helped us debug problems, and on the other, they got to see firsthand how the production network was maturing. The section on measurement and debugging elaborates on examples of issues and problems we had to deal with before the network became stable and met all performance metrics.

6.3. Limited production deployment in EE

After two years of close monitoring of SDN evolution in our group's production network, the network administrators of CIS building started enabling OpenFlow capability in their production network with a firmware upgrade from HP switches that had already been deployed. This was an important milestone for SDN deployment, both at Stanford, and in general.

Fig. 8 illustrates the production deployment in the CIS and Packard buildings. We placed 30 OpenFlow capable Wi-Fi access points in each building. At the time of writing this paper, all 6 production switches in the CIS building are OpenFlow-enabled, and they are controlled by a single controller, together with 30 OpenFlow capable APs. The switches in the Packard building are not yet running OpenFlow, and thus the OpenFlow APs in the Packard building are not directly connected to the OpenFlow switches. However, the commercial controller we now use supports multiple OpenFlow islands, and thus, we do not need to create tunnels as we did in the *ofwifi* network.

6.4. Lessons learned

Most Layer-2 switches in a legacy deployment run the Spanning Tree Protocol (STP) to avoid packet broadcast storms due to loops in the network. Since most OpenFlow-enabled switches (e.g., NEC and HP switches) also have an inbuilt legacy stack, it is tempting for some production deployments to use both STP and OpenFlow, wherein STP will prevent any downsides of the loop, and OpenFlow will provide control of all traffic within the safe environment. However, enabling STP on an OpenFlow-enabled VLAN can lead to unpredictable outcomes because the OpenFlow stack has no awareness that a port is "blocked" by STP (port status is "up"). Although this issue is mentioned in OpenFlow specification version 1.1, it has yet to be fully addressed by the hybrid working group of the Open Networking Foundation (ONF). Our deployment does not use STP at this point for this and other reasons.

Even for a small production deployment, OpenFlow switch hardware limitations can be an issue. The first limitation is the flow table size that typically supports a maximum of ≈1500 flow table entries, not large enough for a core switch of a production VLAN within a single building. To mitigate this, controller vendors (e.g., BigSwitch) are using workarounds, such as aggregation of flows through wildcarding of flow-match header fields (e.g., wildcarding the TCP and UDP port numbers). Also, some switch vendors have started to augment the hardware flow table size by a factor of 100. This proved sufficient for our deployment.

The second limitation is the poor upper-limit of the flow-ingress rate (i.e., rate of handing *packet_in*) that made an OpenFlow-enabled switch incapable of being deployed in the core part of the network. This is an artifact of the poor CPU power. This limitation is circumvented in production deployments by breaking a larger network into multiple OpenFlow islands that are physically connected. Controller vendors are offering controllers that can support multiple OpenFlow islands as a default feature for this reason.

7. Input to OpenFlow specification

Our deployment experience provided important input to the OpenFlow specification process, especially early on.[11] As expected, deployments and experimentations exposed a number of ambiguous points and some bugs in the specification, and made the case for a number of new features. In this section, we describe how deployments and experimentation, in part, helped shape the OpenFlow specification.

7.1. Deployment based feedback

Our deployments and demonstrations motivated the inclusion of the following features in the OpenFlow specification:

- Flow modification: allowing quicker (replacement and) modification of existing flow table rules without having to delete and add. This was particularly needed for the handoff of mobile devices from one AP to another, and was included in OpenFlow version 0.8.9.
- ICMP code matching: allowing match of ICMP packets generated by `ping`. This allows the control application to treat the ICMP request differently than the ICMP reply. This was included in OpenFlow version 0.8.9.
- Controller failover: allowing an OpenFlow network to switch the controller if the primary one were to fail, or become unreachable. This has been an important requirement for SDN since the beginning, and became more evident as we got more experience with deployments. This was included in OpenFlow version 0.9, added to the reference implementation, and was picked up by the vendors.
- Emergency flow cache: Our deployment showed the need for managing the dataplane in the event that the switches lose connection to the controller(s) altogether. OpenFlow version 0.9 included the possibility of inserting rules that are to be used, instead of the normal rules, when such a control connectivity outage occurs. Some switch vendors implemented this by having two flow tables: normal and emergency.
- Queue-based slicing: Our early deployments showed a broadcast storm in a slice caused disruption to other slices. To provide better isolation in the dataplane, we asked for queue-based slicing of the network, wherein each slice could be mapped to a different queue in the network. This feature was added in OpenFlow version 1.0.

Aspects experienced during our deployment that are yet to be resolved in the OpenFlow specification still exist. One such prominent is that of inband control. In several deployment scenarios, it is not possible to create an out-of-band network for the control plane communication. This was particularly the case for the early OpenFlow Wi-Fi deployment, where some early commercial products did not allow OpenFlow VLAN and non-OpenFlow VLAN on the same physical port using VLAN tagging. When the only network connectivity available is already part of the dataplane, then the switch needs to provide *inband control*, wherein the switch has to make a special classification as to whether a packet is part of control or general data. Although we requested this feature, the OpenFlow specification team was not able to achieve a consensus on the actual mechanism, and deferred it for later versions.

7.2. Experimentation based feedback

We, along with the experimenters that created interesting SDN applications, provided feedback that also helped shape OpenFlow specifications. The following are some of the main features requested, and added, to OpenFlow version 0.9: (1) *Barrier* command to notify the controller when an OpenFlow message has finished executing on the switch, and is useful to sync the state between controller and the switches; (2) capability to match on the VLAN PCP priority bit field; (3) sending flow expiration (*flow_exp*) message even for controller-requested flow deletions; (4) rewriting IP ToS field with custom value to change prioritization of packets in legacy network; and (5) signaling a switch to check for overlaps when inserting new rules that may possibly conflict with a pre-cached rule. The following are other features requested, and added, to OpenFlow version 1.0: (1) ability to specify a *flow cookie* identifier for each flow to enable the controller to easily track per-flow state; (2) ability to match IP fields in the ARP packets; and (3) switch owner specifiable description of an OpenFlow switch, thus making it easier for the programmer to use it.

[11] The specification process has been receiving input from many sources, especially as more vendors and providers got involved in SDN. All of this input shapes OpenFlow specifications, and not just our input.

8. Input to SDN architecture and components

Our deployments and experimentation also provided useful input to the evolution of the SDN architecture and its components. For example, each experiments or application on NOX typically first builds a network map of its own, and then writes an application logic to work on this map. This insight (among others) led to the realization that it is better for the network operating system to offer the network map as the abstraction as opposed to network events, and that is how the SDN architecture is currently evolving.

8.1. Input to FlowVisor design and implementation

One of the goals of the deployment has been to support multiple concurrent experiments and production traffic on the same physical infrastructure. This led to the concept of slicing and the design of FlowVisor. There are other business motivations for network virtualization, and FlowVisor helps with them, but its original design, and how it fits within the SDN stack, were influenced more by the short term deployment goals. For example, FlowVisor serves as a semi-transparent proxy between the controller and the switches so as to implement slicing. Any control message sent from a slice controller to the switch is intercepted and tweaked to ensure that the slice only manages the flowspace that it controls. This tweaking process may involve replacing the output ports (outports), rewriting match header fields, and altering the actions performed. In the reverse direction, any control message sent from the switch may be routed to the appropriate controller(s) based on the match headers and the input port (inport). This allows each experimenter to own a slice of the flowspace and slice of the network resources, and an end user can opt-into the flowspace.

FlowVisor was conceived, designed, and prototyped in our group at Stanford, and it became a critical component of SDN deployments. As expected deployments and experimentation helped quickly identify bugs, including memory leaks and design limitations of FlowVisor, leading to new versions.

Specifically, we discovered the following bugs: First, we uncovered cases where the FlowVisor translated a FLOOD action from the slice controller into an OUTPUT action among an incorrect list of switch ports [49]—this bug caused the control message to be dropped by the switch; Secondly, we noticed cases when the FlowVisor performed an incorrect demultiplexing of the LLDP *packet_in*s being received, thereby causing the slice controllers to not see the right topology; Lastly, the FlowVisor did not pay attention to topology or port changes, thereby keeping an incorrect list of active ports—this bug caused an incorrect port translation and caused control messages to be dropped by the switch. All of these issues were fixed in the subsequent release of FlowVisor version 0.6.

Based on experimentation, we requested two features: (1) need for a per-slice monitoring system that tracks the rate and number of control plane messages per slice—this will allow us to verify the slice isolation at real-time and (2) need for building safeguards in the FlowVisor to push a default drop rule (for the flowspace) to the switch when the slice's controller is unavailable. They were included in a later release of FlowVisor 0.4.

To make FlowVisor easier to use, we asked for two other features: (1) dynamic rule creation and (2) better user interface. These issues were addressed in a Java-based FlowVisor version 0.6, thereby making it ready for the GENI deployment. Second, this version featured a new set of *fvctl* commands that operated on the state store and provided good visibility into the rule set. Examples of the commands include *createSlice*, *addFlowSpace*, *deleteFlowSpace*, *deleteSlice*, *getSliceInfo*, and *listSlices*. Thirdly, the FlowVisor was built with a new abstraction that made it easier to allow multiple ways to input policies to the FlowVisor, and manage its rule set (e.g., A slice can be created both by the FlowVisor *fvctl* commands, as well as the Opt-in Manager).

Additionally, we provided feedback to solve the FlowVisor rule explosion issue. This explosion occurs when the flowspace requested by an experimenter is expanded into a set of individual internal rules based on the ranges of all the fields, as well as the list of switches and ports. This cross-product can lead to the number of rules of the order 1000 for many experiments.[12] The matter is further complicated when two experiments request an overlapping flowspace (e.g., If slice *A* requests *IP = any, TCP port = 80*, and slice *B* requests *IP = 1.1.1.1, TCP port = any*, then the switch will have to be programmed even before the packets arrive to prevent conflicts, thereby causing an increase in the switch rule set). In some cases, the rule explosion caused the FlowVisor commands to be less responsive because it took too long to install (or delete) all the expanded rules in (or from) FlowVisor memory. During operation, we observed cases where the opt-in step takes as much as a few minutes, which is too long for interactive slice creation. Although this does not affect the management of the flows in the data plane, it proved to be a serious bottleneck for creating slices. This issue continues to be an open issue, as there is no real fix though there are short-term deployment specific optimizations that we, and others, have been using.

8.2. Input to other software components

During the course of the nation-wide GENI deployment, we discovered several issues that had to deal with the consistent state across the full vertical stack, i.e., consistent state of the slice among Expedient, Opt-in Manager and FlowVisor. As each software tool/system was developed by a separate team, inconsistencies should not have been a surprise. Examples include: (1) a slice was instantiated in the Opt-in Manager, but not in the FlowVisor; (2) a slice was deleted at Expedient, but still available in the FlowVisor; and (3) a slice was opted-in at the Opt-in Manager, but the rules were not yet pushed to the FlowVisor. The issues were gradually resolved with deployment and testing, and finally verified by the Plastic Slices project.

[12] Note that the negation rule was discontinued in FlowVisor version 0.6 because expanding to match all other values consumes too much rule table space, e.g., a rule that matches all traffic with *TCP dst port! = 80* may expand to 65,534 rules.

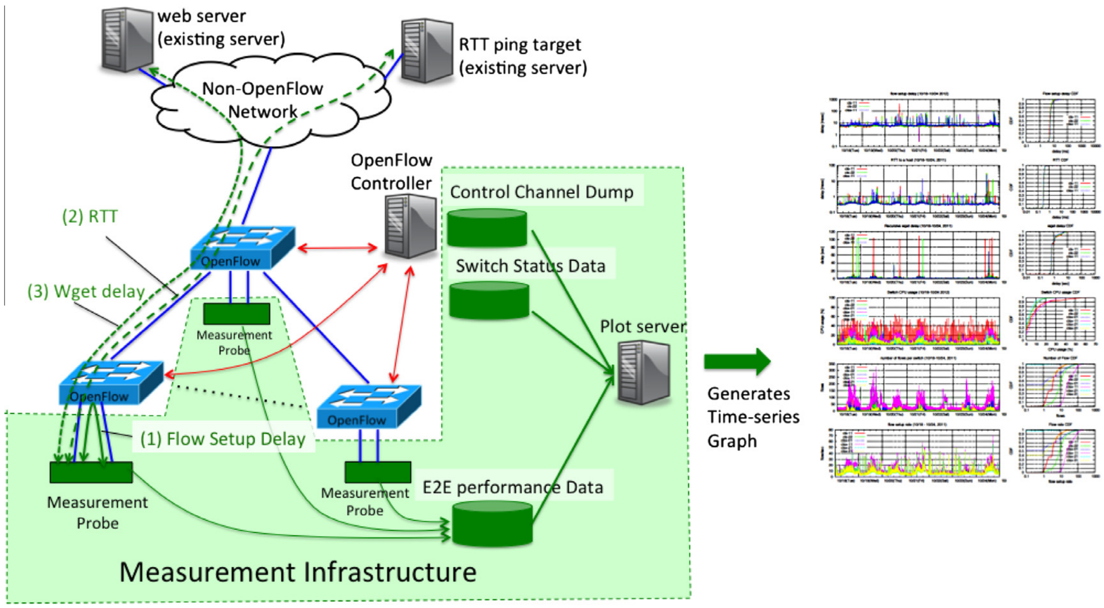

Fig. 9. Measurement infrastructure.

Lastly, our deployment helped provide constant feedback to the controller developers. For instance, we observed that the HP switch in our deployment could not be virtualized based on VLAN to create multiple OpenFlow instances from the same physical switch. We discovered the problem to be with the NOX controller version 0.4, which inaccurately was implemented to only retain the most significant 48 bits of the datapathid (i.e., the switch instance identifier). This caused 2 logical OpenFlow instances within a single HP switch to seem like 1 instance. Similarly, we encountered a bug where the controller (both SNAC [46] and NOX) was not accurately detecting links in the presence of a HP switch. After extensive debugging, we uncovered the issue to be that the LLDP packets generated by the controller's discovery module had a multicast address in the source MAC field. The HP switch, however, is pre-programmed to drop such packets, thereby causing some links to not be discovered. Such issues often manifested as switch problems, and it took significant effort to identify the root case. Based on our feedback, the controller developers resolved the issues in subsequent releases.

9. Monitoring and debugging

As we scaled our SDN deployments, especially production deployments, we had to develop a comprehensive measurement infrastructure to collect, display, and chronologically archive the important network operation metrics. Furthermore, we developed approaches to using this data to monitor and debug the network, as well as to share the performance and stability details with others. In this section, we first describe the measurement infrastructure, and then we present approaches that we adopted for performance analysis and the debugging of SDN deployments.

9.1. Measurement infrastructure and performance metrics

Our objective for the measurement infrastructure was to obtain dataplane measurements to profile the performance as seen by an end-user, as well as to identify issues that are not necessarily visible from the SDN control plane. We deployed several measurement probes in the network that actively measure different metrics to help understand the user experience. Fig. 9 illustrates the measurement infrastructure that we built. As shown, we collected three different data sets, and stored them in a central repository for analysis: (1) control channel dump, passively collected using `tcpdump` of the communication between the switch and the controller; (2) end-to-end performance actively measured by the probes; and (3) switch status metrics actively collected from the controller and switches. The following is a list of end-to-end performance metrics that we use for measuring the end user experience:

Flow setup time. We measure the flow setup time using simple 10-s interval `ping`s between a pair of probes attached to a switch. We use a 10-s interval (which is greater than the typical idle timeout of rules—5 s—inserted by NOX version 0.4) to allow the flow table entry to expire, causing each new ICMP packet to generate a *packet_in* message at the OpenFlow controller. The flow setup delay plot shows the bi-directional flow setup time experienced by the `ping` traffic.
Round-trip time. We measure the roundtrip `ping` delay from the measurement probe to the target host located outside of our OpenFlow network.
Recursive `wget` delay. We measure the delay to download a pre-determined single web page, including its embedded images and links, using the recursive option of the `wget` command. This mimics the web browsing

delay that the end user perceives; the target web page was http://www.stanford.edu/.

The following is a list of switch performance metrics that we collect to understand the overall network behavior:

Switch CPU usage. As we found in the beginning of OpenFlow deployment in Phase 1, when the switch CPU shows a high load, the network is not functional. Since most OpenFlow-enabled switches today use a weak CPU that can be overloaded, we monitor the usage carefully.

Flow table entries used. Today's OpenFlow-enabled switches are often limited by the size of their flow table, making it important to monitor the usage of the flow table. This information also gives an idea of the network usage in the production setup.

Flow arrival rate. Today's OpenFlow-enabled switches, owing to the weak CPU, are not capable of processing a large burst of new flows (in reactive mode, each new flow arrival corresponds to 3 control plane messages). Thus, we track the arrival rate of new flows (i.e., *packet_in*).

9.2. Example performance snapshot

Barring any network problems, we observe that the SDN deployment behaves the same as the legacy one, except for the flow setup time because once the flow actions are cached, packet forwarding works the same with OpenFlow as it does with legacy operation. In Fig. 10, we present a week's snapshot of the performance metrics for the deployment in CIS building. We observe that the metrics are stable, and are within expected limits:

1. *Less than 100-ms flow setup time*: We observe that flow setup time takes approximately 10 ms in our deployment, and most users do not perceive this delay in their network use.
2. *Sub-millisecond round-trip time* as observed from the RTT progression plot .
3. *0% packet loss in network*, as observed from the fact that the CDF of the RTT values reaches 1.
4. *Less than 1 s total delay for 80% of* `wget` *requests to* www.stanford.edu *webpage with over 50 objects*, as observed from the `wget` delay plot.
5. *No CPU overload* as observed from the SNMP-based CPU usage statistics, where the CPU utilization is bound within 70%.

Besides our active monitoring using probes, we also measure and present in Fig. 10 the number of flows and flow setup rates seen by the controller by querying it. We observe an upper-bound of 320 flows that arrive at a maximum rate of 60 flows/s. This is well within the limits of what the HP switch can handle. Lastly, we measure the number of Wi-Fi users by contacting the `hostapd` daemon on the Wi-Fi APs; the count of users exhibits a diurnal pattern, and reaches a maximum of 18 during the busy hours.

Besides the network performance, we also conducted active tests to understand the behavior of the switches.[13] As described in the SDN reference design of Section 2, the flow setup process in SDN deployments is limited by the performance of switch CPU subsystem and suffers from flow setup time overhead. To better understand this aspect, we used a tool similar to `oflops` [34] to evaluate the limitations of switch hardware. The general idea of the tool is to generate new short-lived mice flows (with flow size of just 1 packet), and observing the controller communications as well as the output of the switch. Our evaluation showed that there are several limitations in today's hardware. To illustrate this, we present the behavior of a Broadcom-based OpenFlow switch in Fig. 11. The figure shows that the switch starts dropping new flows after the flow ingress rate crosses 110 flows/s. Once the switch load becomes too high, the flow setup time, packet transmission and flow expiry message generation becomes unpredictable and poor.

9.3. Network performance diagnosis process

In addition to revealing user experience, the time-series plots can be correlated to infer the root cause of the issues for some quick diagnosis of network problems. Here we present some insights or rules-of-thumb to aid future SDN network administrators. Table 1 summarizes how we narrow down the root cause.

If we observe large flow setup times for a prolonged period of time, we first check the RTT plot for the non-OpenFlow network to see if this is really an issue with the OpenFlow network. If RTT of non-OpenFlow network part is normal, then the root cause must be in the OpenFlow part, i.e., processing delay in switch, or the controller processing delay.[14] To identify the exact issues requires looking at the other metrics. For example, as shown in Table 1, if both the switch CPU usage and flow setup rate are low, while the flow setup time is too high, it is likely that the root cause is the slow processing time in the controller (Case #1 in the table).

If the switch CPU is high in spite of the low flow setup rate (Case #2), the switch CPU is overloaded for some processing other than *packet_in*. The root cause can be that the controller is sending too many message to the switch or the switch is busy doing some other job. We need to look into the control channel dump to distinguish these two, but at least we can narrow down the cause and warrant further debugging.

If both the switch CPU and the flow setup rate are high (Case #3), the root cause is likely the high flow setup rate. To see the packet that caused this issue, we look for the *packet_in* message in the control channel dump to see what packets caused the burst of *packet_ins*.

We sometimes observed periods of large round-trip delays while all other metrics were good (Case #6). This indicates that the flow rule is not installed in the switch flow

[13] Previous analyses showed that most controllers (viz., NOX [32], Maestro [27], Beacon [2]) are capable of reactively handling over 40,000 new flows ingressing per sec [48,6]. Thus, for most enterprise deployments, the switch bottlenecks overshadow the controller limitations.

[14] If the legacy network is behaving normally, then the communication delay between the switch and the controller cannot be the root cause.

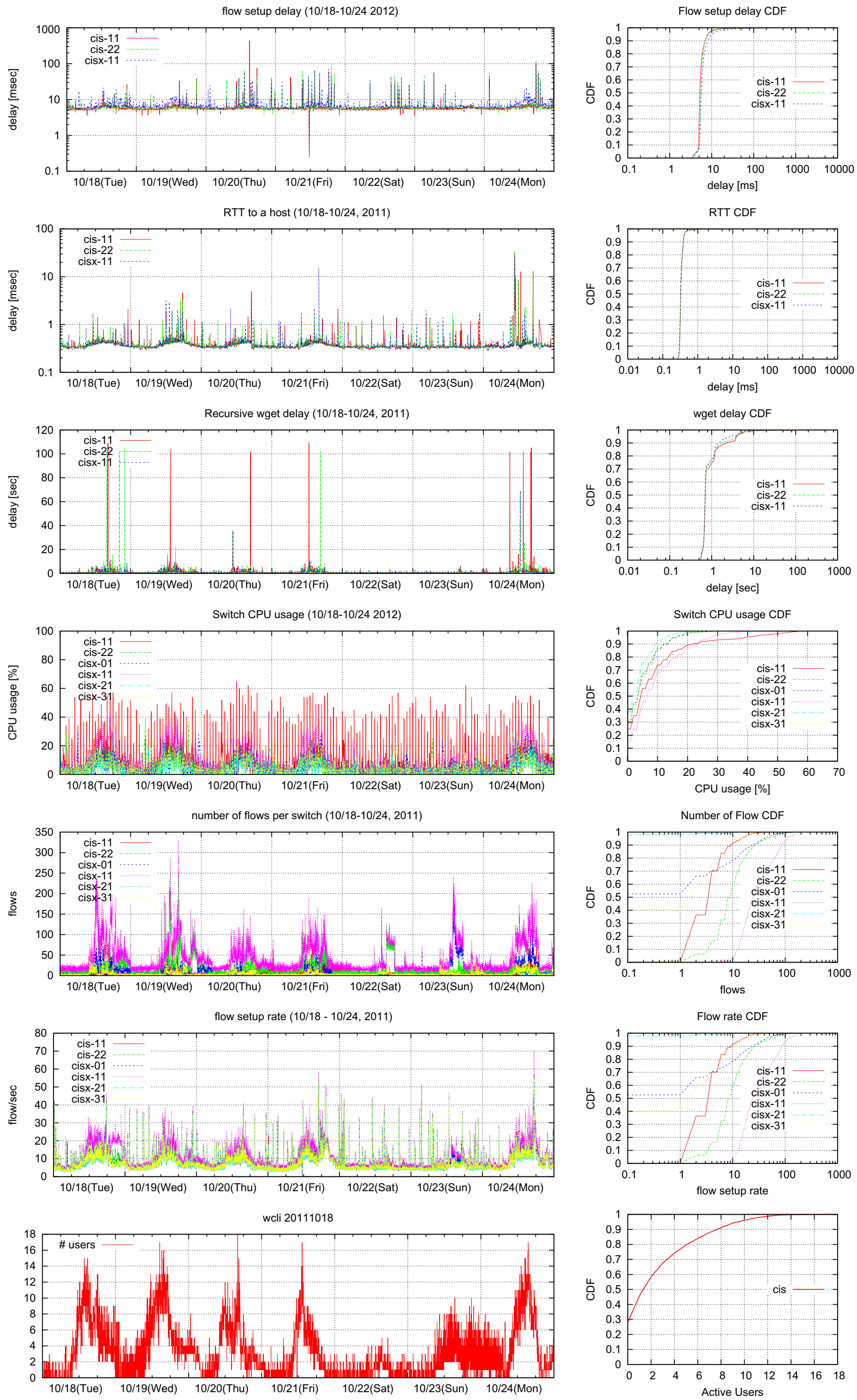

Fig. 10. Measurement data plot for a week (10/18–10/24, 2011). Flow setup time, RTT delay, `wget` delay, CPU usage, number of active flows, flow arrival rate, and number of users are shown (in this order). The left column shows time series, and the right column shows the CDF.

table, or the switch is forwarding packet in software. To distinguish this, we look further into the control channel dump to see whether *flow_mod* (flow table installation) is properly done or not.

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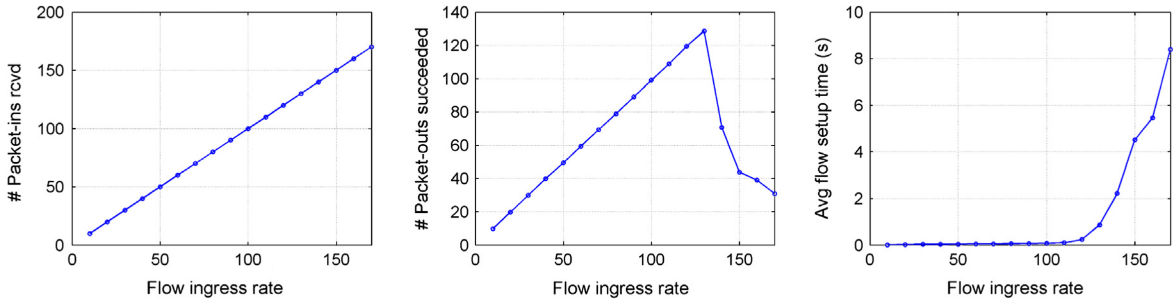

(a) # of packet_in messages received by controller (b) # of packets that were transmitted from buffer (c) Average flow setup time

Fig. 11. Summary of the behavior of a Broadcom-based OpenFlow switch for different ingress flow rates. Comparing the different characteristics of the data plane and the control plane shows where the switch becomes too loaded to handle reactive flow handling. In the above example, the flow setup time grows greater than 100 ms when the flow ingress rate exceeds 110 flows/s. Thus, we recommend using this switch only within that flow ingress rate.

Table 1
Typical symptom and possible root cause.

Case	Symptom					Possible root cause
	FST	RTT	CPU	#Flow	Flow rate	
1	High	*	Low	*	Low	Controller
2	High	Low	High	*	Low	Switch is overloaded
3	High	Low	High	*	High	Burst flow arrival
4	High	Low	Low	*	*	Switch software
5	High	High	*	High	High	Flow table overflow
6	Low	High	*	*	*	Switch software or the controller

Another possible scenario (which is not shown in the table) is when the `wget` delay is too high, while all other metrics are normal. After eliminating the possibility of web server issues (by inspecting the `wget` delay on the non-OpenFlow network), we guessed the reason to be the switch being unable to handle the high flow arrival rate, despite processing pre-cached entries being fine.

In all above examples, though we need to inspect the control channel dump to accurately identify the root cause, correlating the time-series plots helps in shortlisting the possible root causes, and reducing the amount of work in network performance debugging.

9.4. Network debugging

The SDN architecture, with its centralized vantage points, allows for easier debugging and troubleshooting of network problems. The main information that SDN provides, beyond what legacy networks provide, are: (1) the flow-table routing information, (2) the flow-level traffic statistics using *stats_request* command, (3) the sequence of events that occurred in the network based on the control message exchange, and (4) the complete network topology. To make the most of this information, we developed several tools to assist in network debugging [35], such as the OpenFlow plugin for `wireshark`. The tools either collected data through the API that controllers provided, or processed packet dump trace of the communication between the controller and the switches.

The most effective approach for debugging network problems was inspecting the control channel traffic between the controller and the switch using `wireshark`, and correlating this with the observations from the data plane servers or monitors. This debugging approach is well-suited to identify bugs in the control applications, e.g., an incorrect rule that never gets matched, as well as non-OpenFlow issues in the end-device, e.g., an IP address conflict caused by an Apple laptop with state-caching issues.

Since all OpenFlow-enabled commercial switches used in Phase 1 deployment were based on Stanford reference code, interoperability among them did not turn out to be a big issue. Still there were bugs or vendor-dependent behavior, such as the logic behind inserting flow-table entries, that were exposed in a multi-vendor network after extensive use. Our deployment played a significant role in finding these bugs or interoperability issues, and we worked closely with vendors to fix them. We present 2 issues (1 for controller and 1 for switch) that were uncovered by our deployment:

- *Incomplete handover*: When a Wi-Fi Terminal *B* moved from one Wi-Fi AP to another AP while running `ping` to Terminal *A*, the ICMP reply stopped being received by the Wi-Fi Terminal *B*. To debug this issue, we inspected the flow-table of all the involved switches, as well as the control communication between the involved switches and the controller. Fig. 12 illustrates the root cause that we found: After handover to the new AP, the flow table entry in switch *X* and *Y* were not updated for the ICMP reply flow, causing the ICMP reply packet to be sent to the old location of the Wi-Fi Terminal *B*. We fixed this bug by changing the controller logic such that when the controller detected the

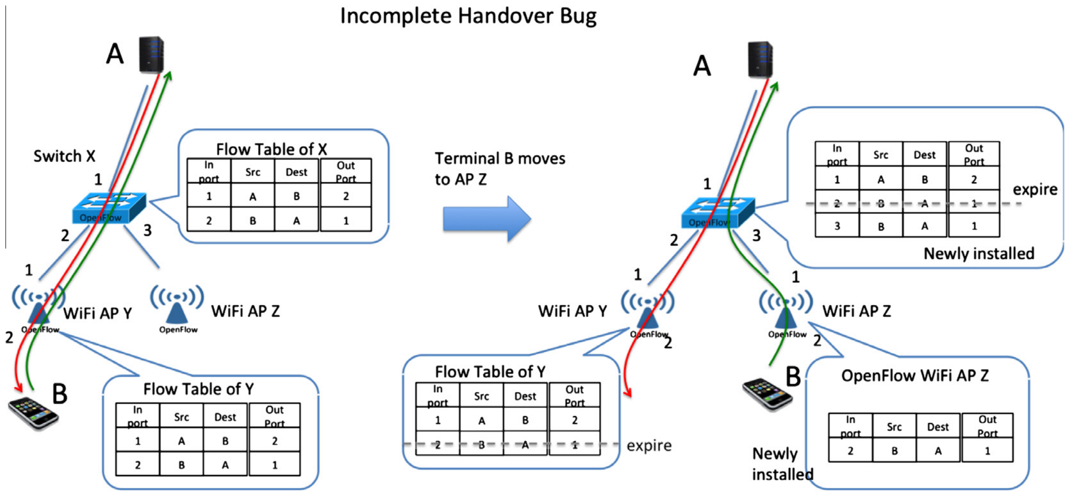

Fig. 12. Debugging packet loss after handover. The left figure illustrates the flow tables before handover, and the right figure shows after handover. Although all switches updated the entries for the ICMP request from Terminal *B*, they did not have the right entry for the ICMP reply from Terminal *A*. The first entry cached in Switch *X*'s flow-table is, thus, the root cause of the loss.

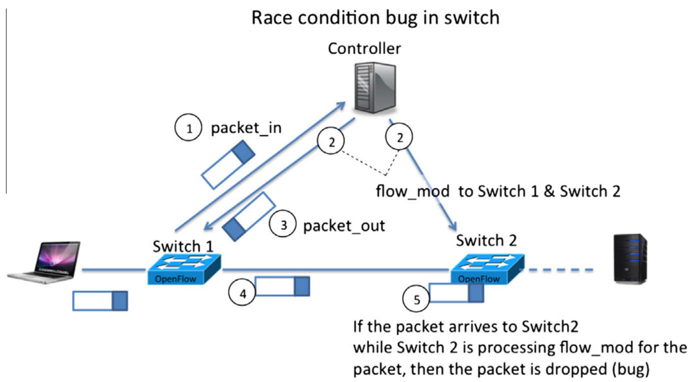

Fig. 13. Debugging non-deterministic loss of TCP SYN/SYN-ACK packets.

change in location of a terminal (through *packet_in* from a new Wi-Fi AP *Z*) it flushed the flow entries related to the reverse direction traffic, and reprogrammed the switches en route.

- *Race condition bug in a switch*: We observed poor web browsing experience in our production network. We debugged that by dumping the TCP SYN and SYN-ACK packets of the HTTP session, at the client-side and server-side, using `tcpdump`, and correlated them with the control plane events observed using `wireshark`. We observed an increased drop rate for the TCP session handshake packets. The correlation, further, revealed that the control plane events were as expected, but the packets were not properly forwarded by the data plane, even though the flow-table of each switch in the network was accurate—this is very intriguing of course. This loss of the TCP handshake packet explained poor user experience for browsing, because the TCP session waits for a prolonged TCP timeout (in the order of seconds). However, the handshake packet loss behavior was not consistent with everything else. So we hypothesized that there was a race condition, as shown in Fig. 13. With this race condition, a packet (the TCP SYN packet) arriving at the second hop switch, while the switch is in the middle of processing a *flow_mod* operation (to insert a new rule), is sometimes dropped. To confirm this, we placed a delay box between the 1st and 2nd switch, and found that the packet is not dropped. That is, if we delay the packet enough (so as to give time to the second switch to finish processing the *flow_mod* message), everything works just fine.

These examples confirm that SDN enables debugging of network problems by inspecting the control channel traffic between the controller and the switch, and correlating this with the observations from the data plane servers or monitors. This approach shows large potential for future automated troubleshooting.

10. Concluding remarks

Software Defined Networking (SDN) has captured the imagination of the network industry and research commu-

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nity. Leading network owners and operators such as Google, Verizon, NTT Communications, Deutsche Telekom, Microsoft, Yahoo!, and others, argue that SDN will help them build networks that would be simpler, easy to customize and program, and also easier to manage. They expect that these attributes of SDN will lead to networks with reduced capital and operational expenses and increased revenues due to new services enabled. They also believe SDN with virtualization would allow the network to be a programmable pluggable component of the emerging cloud infrastructure for multi-tenancy operation. Most network equipment and software vendors are embracing SDN to create products and solutions to meet the expectations of the network owners and operators, and bring new innovations to the market place. The network research community considers SDN an opportunity to help shape the future of networking, and bring new innovations to the market place. In short, SDN has emerged as the new paradigm of networking.

In this paper, we report on early deployments of SDN on university campuses. The deployments, combined with the applications and experimentation, played an important role in demonstrating the SDN potential, and gain the community's mindshare. They also demonstrated the key value proposition of SDN; proved that the physical infrastructure can support multiple concurrent virtual networks for research and production use; revealed a number of performance tradeoffs; provided valuable input to the OpenFlow specification process; and helped vendors and help grow the larger ecosystem. The following is a list of our highlevel takeaways from this experience:

- One of our goals has been to show how SDN infrastructure, with slicing and virtualization, can support both research and production traffic on the same physical infrastructure. We demonstrated feasibility of supporting both research and production traffic on our group's operational infrastructure. However it is not easy to do in the short term. SDN is evolving very rapidly and much effort is required just to create a production deployment. If it has to also support research and experimentation, then getting the whole infrastructure to be stable and useable represents a big challenge. The next round of commercial SDN products, with support for network virtualization, will make it much easier to achieve this important capability.
- The SDN deployments required a new set of measurement and debugging tools and processes. On the other hand, SDN architecture helps in network measurement and debugging because it provides the flow table as an abstraction of a switch, and the controller as a central vantage point for all flow table modifications. We took advantage of these architecture features to debug a few important and difficult network issues, and this shows an important direction for network troubleshooting that is enabled by SDN.
- Visually compelling experiments and demonstrations were critical to showing the power of SDN, and that is, with SDN, a relatively simple software program can create a new network control and management capability. These demonstrations helped win people over including skeptics. Although the value of good demonstrations is well known, it is not easy to practice and many ignore it.
- Deployments and good demonstrations require significant sustained effort over a few years to achieve the impact that is possible. Experimentation on a real deployment with users has several benefits. However, it has limitations: A researcher cannot create arbitrary topologies, cannot scale the network or the number of end users, and cannot experiment with arbitrary traffic mix. Furthermore, a real deployment is time and resource intensive. This led some of our colleagues to develop *Mininet* to help researchers and developers to quickly emulate SDN of an arbitrary topology, scale, and traffic mix. On this emulated network, one can develop and experiment with real SDN control stack that can subsequently be deployed on a physical infrastructure without any changes [25]. We expect the mix of Mininet and real deployments to cover a broader spectrum for research and development.
- These deployments helped create a collaborative and productive relationship between researchers and network administrators on campuses, and between the university and network vendor community. We provided OpenFlow software reference implementations to the vendors, offered to test, profile, use OpenFlow enabled switches and controllers, provided bug reports, and suggested new features to make the products better. For example the universities worked with switch vendors such as Cisco, HP, Juniper, NEC, and Pronto, and controller vendors such as Nicira, NEC, and BigSwitch. HP has been a vendor of choice for the legacy network at Stanford, and it provided OpenFlow-enabled switches very early to be used in our production setting. NEC offered high performance OpenFlow-enabled switches and controllers for our research and experimentation. Pronto provided a very low-cost OpenFlow switch that universities found very attractive for research and experimentation. Nicira participated in all aspects of SDN, and provided open-source SDN controllers, including NOX and SNAC, that played a very important role in early deployments and early success of SDN. Subsequently, BigSwitch provided a controller for the production use. This kind of collaboration between universities and networking vendors has been missing for many years and has been a drag on the field. It is important for both the vendor and university communities to build on the success of SDN deployments, and together help move networking and SDN forward.

Despite all the successes of SDN so far, it is still in an early stage of development. We as a community have completed the first stage of SDN development to demonstrate its potential and articulate an exciting research agenda to realize its full potential for various domains of use, including data centers, service providers, enterprises, and homes. As we, and others, pursue this research agenda for the next several years, we will require many more deployments and much experimentation. The three-year, four-phased deployment effort reported in this paper is just the beginning.

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