OVERCOMING CHALLENGES IN PRACTICAL SDN DEPLOYMENT

A Dissertation

Presented to the Faculty of the Graduate School

of Cornell University

in Partial Fulfillment of the Requirements for the Degree of

Doctor of Philosophy

by

Zhiyuan Teo

August 2016

OVERCOMING CHALLENGES IN PRACTICAL SDN DEPLOYMENT

Zhiyuan Teo, Ph.D.

Cornell University 2016

Performance, reliability and security are important concerns in modern data networks and mission critical systems increasingly depend on them. This thesis investigates these concerns on software-defined networks (SDNs) that are built using Ethernet networking technology. We propose and evaluate some solutions to the problems identified in this process, keeping in mind that our solutions should be simple retrofits as far as possible to minimize change or frustration for the data network user. We then present field findings from a practical deployment of our SDN controller, Ironstack, on an enterprise network setting. Finally, based on this operational experience, we develop a drop-in network switch augmentation that combines our aforementioned solutions and controller into an operator-friendly box, providing a turnkey solution for deploying all the systems described in this thesis.

BIOGRAPHICAL SKETCH

As an undergraduate at the University of Illinois at Urbana-Champaign, Zhiyuan Teo worked with Prof. Klara Nahrstedt's research group to develop network overlay middleware in support of a teleimmersive video technology called TEEVE. Upon graduation, he spent 2 years in Singapore at the Institute of Infocomm Research and worked with Dr. Jo Yew Tham to build peer-to-peer synchronized video delivery software for the Scalable Media Platform (SMP), a scalable video system that has since evolved into the flagship product of a startup company. In 2011, he joined the Computer Science Ph.D. program at Cornell University, where he was co-advised by Professors Ken Birman and Robbert van Renesse in the domain of software-defined networking.

Zhiyuan Teo's research reflect two goals: to advance the science of modern Ethernet networking, while keeping proposed solutions practical and simple for both the user and operator. The latter is a recurring theme in his work and was strongly influenced by his early experience with data networking. His software, Ironstack, is a distributed OpenFlow network controller that emphasizes frustration-free principles. As at print time, Ironstack has driven part of the Cornell Computer Science department's production SDN network continuously for over 15 months.

In the process of pursing his minor in Electrical Engineering, Zhiyuan Teo also became interested in microcontrollers, rapid prototyping and enthusiast automotive engineering. Under the guidance of Professors Francois Guimbretiere and Bruce Land, he built numerous gadgets including a chocolate 3D printer, a department food camera, an FPGA gesture-controlled iPod music dock, a wireless biometric pen drive and a GSM remote vehicle starter. In his spare time, he also enjoys working on his vehicle.

Dedicated to my mother, Jennifer Kim, who endured my long absences from home.

ACKNOWLEDGEMENTS

My brilliant mentors, supportive friends and loving family helped me through this journey. A few names stand out:

- **Ken Birman**. Your supervision, wisdom, encouragement and kindness went way beyond your responsibilities and obligations as an advisor. Thank you for letting me find my own space to innovate. You are a great mentor and I see you as an important fatherly figure in my life. A few sentences is too short to communicate the true magnitude of my gratitude.
- **Robbert van Renesse**. Your calm demeanor, patience, technical ingenuity and occasional humor has helped me navigate out of several tight spots during my time as a graduate student. Thank you for being supportive and giving unselfishly of your time despite your busy schedule.
- **Nate Foster** and **Ao Kevin Tang**. Your deep domain expertise in data networking have been a valuable source of knowledge and experience. You have helped me to become a better researcher and computer scientist.
- **Bruce Land** and **Francois Guimbretiere**. Your classes on microcontrollers, FPGAs, hardware prototyping and rapid prototyping have helped me to realize and integrate creative designs into my day-to-day research as well as my hobbies.
- **Stavros Nikolaou**, **Shrutashi Basu**, **Durgashankar Giridharan**, **Luke Chong**, **Alex Chen** and **Van Nguyen**. People come and go but real friends stay. Thank you for always being there for me. I am very privileged to have your company.
- **Angelin Yang**. Your friendship, unwavering faith and financial support made it possible for me to complete this journey.

- **Jennifer Kim**. As my mother, you are the singularly most important influence in my life. I appreciate everything you have done to raise me and I think about you everyday.

0.1 Special mention

I am deeply grateful to all the staff at Cornell ITSG, who have always been responsive and accomodating to my requests. You are the unsung heroes who have made a large part of my work possible.

Finally, I would like to express my appreciation to A*STAR in Singapore, for sponsoring my university education through graduate school.

0.2 Research funding

Grants from the US Department of Energy ARPA-e GENI Power Grid research program, and the NSF Smart Grids program were used to fund this line of research.

0.3 Additional credits

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CHAPTER 1

INTRODUCTION

The Internet-of-Things (IoT) refers to a recent trend towards the increasing pervasiveness of network connectivity in everyday devices, and is part of a continuing evolution in the automation of everyday tasks. We see examples of these cyber-physical technologies at work in familiar places such as Wifi-enabled TVs, Internet-capable thermostats, network-controlled light bulbs and home security solutions, but the same underlying technology also drives industrial-scale applications such as smart grids, smart city lighting and intelligent traffic control. IoT is rightfully referred to as the "infrastructure of the information society" [18] because the network of IoT sensors and actuators provide the requisite data that form the foundation of any smart initiative.

Because of the implicit dependence of IoT on data networking, we started our line of inquiry by asking ourselves the following question: what features would a modern network need to provide in order to support the emerging needs of today's Internet-Of-Things (IoT) equipment? We were deeply troubled by reports from users about insecure, poorly designed devices [10]. At the same time, we recognize that IoT device demands on bandwidth and latency span the full spectrum, and there is no one-size-fits-all solution that would uniformly work across all applications.

This IoT dilemma is real. Sensors and actuators depend on data networks for connectivity and large-scale coordination, yet the design of these devices and networks lack the necessary performance, reliability and security that are expected in these demanding settings. To illustrate some of these issues, we find it instructive to begin with an example of a critical IoT data network – the power grid.

1.1 Challenges in power grid data networks

Operators of the nationwide power grid use proprietary data networks to monitor and manage their power distribution systems. These purpose-built, wide area communication networks connect a complex array of equipment ranging from Phasor Measurement Units (PMUs) to Supervisory Control And Data Acquisition (SCADA) systems. Collectively, these components form part of an intricate feedback system that ensures the stability of the power grid. In support of this mission, the operational requirements of these networks mandate high performance, reliability, and security.

Present power grid data networks are predominantly run using microwave relays and signal multiplexing on power cables. Connecting to the data center network, a typical power grid operator would have a collection of data collection devices and relay status monitoring devices that have proprietary point to point connectivity to some form of relay device hosted within the data center. Thus the overall architecture has a set of these ″star″ networks, using solutions such as line-of-sight relaying over microwave, specialized communication protocols that run directly on the power lines, etc, that then link into the command center networking infrastructure, with the relay devices functioning as proxies. Although these technologies have proven acceptable over time, the growth of big data in this coming age of smart grid systems means that existing capacity on these data links could be rapidly saturated in the near future. A new and better network technology is needed.

1.2 Evolving the Power Grid

1.2.1 Deficiencies in today's power grid

Much of the national power grid is dependent on a relatively rigid, older style of data networks for command, communications and control (C3). These data networks frequently carry critical information pertaining to the health of the grid, often through sensor readings, that are then used to make decisions for the next stable operating state of the grid. However, a chicken-and-egg cyclic dependency exists between the two: a data network cannot survive without power; conversely, without data, the grid cannot operate in a safe and stable manner. As a consequence, a very rigid, heavily provisioned, heavily protected networking model has emerged, in which today's systems operate over a network that is controlled in a very static manner. An increasingly wide range of features standard in other settings (such as dynamic assignment of host IP addresses) are rejected by power systems operators, and the application layer functionalities such features enable are thus not available.

A further issue is that to a growing extent, OS upgrades and patches have made such features obligatory, hence power systems control networks are becoming costly to support because of their outmoded styles of use of technology.

Apart from physical infrastructure attacks, one of the weakest links in this delicate balancing act is the data network and the software that depend on it. There is emerging consensus that the power grid has numerous vulnerabilities and is susceptible to large scale remote cyberattacks that can result in real, crippling infrastructural damages. As an example, Stuxnet [62] is a well-known malware that quickly spread through data networks and was directly responsible for the destruction of about 1000 nuclear enrichment centrifuges in Iran. It is conceivable that a similar attack could be launched against power grid hardware in the US, with devastating physical and economic effects. Thus, a design objective of future data networks for the power grid should account for security, with a focus on being able to precisely control and audit access to sensitive equipment. Our chapter on EtherSlice investigates security solutions that are relevant in this domain.

Another problem in the concurrent use of data networks to support grid operations is the inherent risk of critical data flow disruptions during network equipment outages. Such failures can occur for many reasons, including wear-and-tear, accidents and uncorrelated power losses. Without access to current data, grid operators are at risk for a cascading chain of failures. This is an important problem that future power grid networks should address, and we tackle this issue in our chapter on RAILS.

1.2.2 Convergence of big energy and big data

Among other characteristics, a smart grid uses digital feedback control to realize improvements and optimizations to the reliability and efficiency of the power distribution network. Part of this smart initiative involves incorporating advanced electrical generation and storage technologies such as renewables and batteries, but the ability to engage in real-time metering and command of equipment is also another key requirement.

Thus, with the emergence of the next generation smart grid, the amount of data that is expected to flow and be processed at control stations will sharply increase. Cisco's surveys [30] have shown that nearly one in four IT managers expect network load to triple over the next two years; the power grid is no exception. In fact, the vision of a smart grid learning, adapting, and controlling the power grid will require big increases in real time data transmission and network load. However, current power grid communications infrastructure uses antiquated technology that will need to be overhauled in order to support such an increase.

Part of the need to support a higher network load comes from the emerging use of Phasor Measurement Units (PMUs), which are sensors designed to measure real-time electrical current, voltage and frequency attributes at distributed locations across the grid. Each of the phasor measurement units timestamps the data that it receives before sending them off to a local Supervisory Control And Data Acquisition (SCADA) system. Time-stamping these measurements allows administrators to have a global view and understanding of the activities on in the grid. Each such device generates 10kb/s or more data, with stringent latency requirements on the links that forward these data to the control centers. As the number of PMUs in the power grid increases, so will real-time data and the need for strong and consistent reliability in the network which is difficult to scale in the current infrastructure.

1.3 Design goals for a next generation power network

The smart elements comprising the power grid is the sum of many interconnected components: meters, sensors, actuators, SCADA systems and operators, all generating or consuming real-time data off a data network in order to provide intelligent behavior. Thus, acknowledging that the smart grid is data-intensive, sensitive to correctness and heavily reliant on a responsive data network, a clear set of design targets emerges: a next generation power network needs to offer high performance, high assurance and high security. Also important, though to a less critical degree, are the pragmatic economic considerations. Ideally, any proposed solution should be incrementally deployable and fully backward-compatible with existing hardware and software on the power grid.

1.4 Thesis contributions

The issues highlighted in the preceding sections are all seen in the smart grid, but are actually universal: they arise to an equal or even greater degree in a modern office complex, an academic campus setting, in a military base, or in almost any environment where a data network might be of interest.

How then can a IoT smart initiative provide security and with high performance leverage sensor deployments that depart from the historical infrastructure standards of the community? Our key insight here is that there are many more IoT devices than there are switching elements in a data network, and it is impractical to require IoT equipment vendors to rearchitect their devices for improved experience. Thus, our model of how IoT becomes smart involves innovation at the level of deployment of such devices, but also in the ways the existing network is managed and perhaps modestly enhanced. Our approach is to pair the sensor with modern functionalities provided by a software-defined network (SDN) that compensate for the sensor (and actuator) limitations. In chapter 3, we describe RAILS, a system that draws on the classic storage coding techniques from RAID [76] and applies these to data networks to transparently improve the performance and reliability of IoT devices over Ethernet networks, without requiring change or modification to the hardware or software of such devices. RAILS was accepted for publication in IEEE SDN-IoT 2016.

RAILS leverages the deployment of an SDN with redundant paths, and also depends on the strategic placement of packet processing elements known as NPUs. This combination provides the necessary infrastructure to retrofit performance and reliability for IoT devices, but does not address security. Security has become a significant issue in modern data networks as users increasingly demand confidentiality and often anonymity in their communications. Confidentiality and anonymity are not merely pertinent as human factors in the post Snowden era, but also represent important building blocks upon which a robust and resilient distributed system can be built. Many power grid sensors and actuators, as well as IoT devices today [11] transmit data in the clear with little regard for the potential consequences. While awareness of such security issues are beginning to percolate equipment owners, there remains an urgent need to address the issues of older hardware that were not designed to meet newer security expectations.

Yet, a clean-slate upgrade of all affected IoT devices is unrealistic because of the staggering time and monetary costs involved. Furthermore, the traditional route of retrofitting security through encryption typically requires public key infrastructure and fails to address anonymity needs. We asked ourselves if we could reuse the same network assumptions and NPU infrastructure designed for RAILS to retrofit confidentiality and anonymity for IoT devices, again without change or modification to end-user devices. The result was EtherSlice, which is described in chapter 4. EtherSlice transparently provides security to network devices while avoiding dependence on encryption, public key infrastructure or even awareness in the protected devices. We are presently working towards a paper submission for EtherSlice.

With prototype systems in hand to address the performance, reliability and security of IoT deployments, the next question that we considered was the practicality of setting up and running an SDN that could be used to drive RAILS or EtherSlice. Indeed, in any kind of data network that might desire RAILS or EtherSlice service, the fundamental assumption was that an SDN would already be in place. What are the factors that could influence a power grid operator to upgrade his data network to something that was RAILS and EtherSlice-ready? Is the deployment of an SDN a simple matter of plug-and-play? Are there special issues that arise that are not seen in traditional data networks? Chapter 5 details our operational experience in deploying an enterprise SDN from scratch, and chronicles some surprising lessons we learnt about SDN and certain controllers. We then incorporate these lessons into the design of our own SDN controller, Ironstack, that mitigate some of the shortcomings inherent to SDNs. We shared a summary of our findings in DSN's DISN 2016.

Finally, we sought to close the loop by considering how we could offer all three systems – RAILS, EtherSlice and Ironstack – in a unified turnkey solution that can be deployed quickly. We reasoned that a drop-in box packaging these systems could be designed as a plug-and-play augmentation to existing SDN switches. We anticipate that the convenience and frustration-free nature of our network switch augmentation would hold universal appeal to infrastructure owners operating or considering the operation of SDNs, which could be the magic recipe to convince data network operators such as the power grid to finally transition over. Chapter 6 describes this network switch augmentation, highlighting the technical and engineering details of putting together these three systems into a single box.

A summary of the thesis contributions are as follows:

- We identify IoT support over data networks as a critical concern in the near future. Present-day IoT data networks are far from suitable for the task. As a challenging example of IoTs, we surveyed performance, assurance and security issues in power grid data networks and identify key objectives for an SDN controller running such a network. Our high-level survey results were published in ToSG 2014, and provided the direction for our research.
- We note that the network offers the most practical route to retrofitting performance, assurance and security for Ethernet devices. This leads us to identify network path redundancy, security and performance objectives, and to suggest that an SDN could respond to the needs if properly configured. We introduce two systems:
    - RAILS, a set of novel network coding techniques adapted from RAID, to transparently improve performance and reliability of net-

work clients. RAILS was published in IEEE NetSoft SDN-IoT 2016. A working RAILS solution would be capable of breaking through present limitations of single path routing to offer improved bandwidth and resilience against network failure.

  - EtherSlice, another set of network coding techniques adapted from Information Slicing, to retrofit confidentiality and anonymity onto Ethernet clients without requiring public key infrastructure. A deployment of EtherSlice could secure devices that are vulnerable today. We are currently working towards a submission on EtherSlice.

- We recognize that a healthy, configurable and user-friendly SDN is a critical prerequisite to deploying RAILS and EtherSlice. This motivates us to investigate the practical issues relevant to the construction, configuration and operation of an SDN, as well as to characterize the performance of a few popular OpenFlow SDN controllers. We detail two major findings:

  - We uncover some surprising findings from our deployment experience and identify several key challenges to adopting OpenFlow in an enterprise setting. For each finding, we propose one recommendation to mitigate the overall impact of these surprises.

  - We survey two OpenFlow SDN controllers and observe that they are slow, buggy and not user-friendly. This motivates us to build and validate Ironstack, a controller that addresses the weaknesses of these SDN controllers.

  Our findings and recommendations were published in IEEE DSN DISN 2016.

- We consider the utility of a unified solution containing RAILS, EtherSlice and Ironstack. This inspires us to design and implement an OpenFlow network switch augmentation that packages all three aforementioned systems into one unified hardware, while remaining convenient and user-friendly. This unified turnkey solution would be an attractive product for managing SDN-based IoT networks that also require RAILS or EtherSlice.
- We draw on our operational experience and examine the challenges of building an SDN controller that provides adequate performance, scalability and user-friendliness. We architect a distributed OpenFlow controller, Ironstack, to provide these features, and disclose its software component design and highlight its critical features. We also compare and contrast the various ways in which the control plane network can be built, and describe how our controller can adapt to these designs.

CHAPTER 2

BACKGROUND AND RELATED WORK

Architecting a new kind of Ethernet data network to address problems introduced by the limitations of existing networks and shortcomings of participatory IoT devices is an involved task requiring deep understanding of the reasons for these issues. Because our approach is to avoid change at the level of the IoT devices, a transparent retrofit will require innovation at the networking layer. In this chapter on background work, we first study the limitations inherent to existing Ethernet networks, then look at how we may circumvent some of these constraints through use of a new kind of programmable networking technology. We also consider existing alternate approaches to tackling the same set of constraints, and reason that existing approaches are insufficient for our goals. From there, we draw inspiration from two main bodies of work accomplished by others to derive a set of network coding schemes suitable for our purposes. We then look at strategies to implement the required hardware and software for these network coding schemes. Finally, we investigated numerous network controller architectures in order to identify the most suitable analogue for our needs, and co-design our own controller taking into consideration the unusual lessons learnt by others from using comparable networking hardware.

2.1 Ethernet Spanning Tree

Ethernet has seen many adaptations since its creation in 1973, and has evolved from a LAN-only networking solution to WAN and beyond. Its cost-effectiveness, flexibility and scalability are the main factors contributing to its popularity. Today, it is the favored link-layer medium for diverse applications ranging from communication carriers to cloud providers to enterprises to regular users, and is projected to continue its evolution to embrace IoT standards in the future [8]. Indeed, recent standards such as the IEEE1588 [17] point to this trend, as they were specifically conceived to meet the timing precision requirements in demanding IoT applications over Ethernet.

Yet, conventional Ethernet is poorly matched to our goal of providing a multipath-capable network for RAILS and EtherSlice because it has an important restriction that mandates a spanning tree topology for correct operation. This spanning tree requirement is not arbitrary; it was designed to connect all participating hosts while eliminating catastrophic network loops. Conventional Ethernet networks perform loop elimination and spanning tree construction by running a distributed algorithm such as the Spanning Tree Protocol (STP) or the improved Rapid Spanning Tree Protocol (RSTP) [14]. In STP and RSTP, Ethernet switches in the same network segment collaborate and agree on which network links to use such that a single spanning tree connects the entire network without any cycles. In the process, STP or RSTP disables links that would otherwise result in loops. All traffic transits the spanning tree, which becomes a network-wide bottleneck. Accordingly, conventional Ethernet networks do not typically feature link redundancies, and where such redundancies exist, they cannot be taken advantage of without special configuration. Worse, failure recovery and redundant link activation typically take between several seconds to half a minute [31], resulting in network hiccups even if no apparent physical partitions have been introduced.

To remove the limitations imposed by a single spanning tree, RSTP was extended to the Multiple Spanning Tree Protocol (MSTP) [15]. MSTP allows concurrent multiple spanning trees to exist within the same network by mapping each spanning tree to a multiple spanning tree instance (MSTI). Each virtual LAN in the network can then be associated with one of the spanning tree instances, thus improving aggregate network availability and reliability when link breakages happen. Bottlenecks are also reduced because the network now distributes its load over a greater number of transit links. However, within an MSTI, participants are still subject to spanning tree outages and repair time. Thus while some VLANs may experience little disruption, other VLANs may be severely impacted. This can seem counterintuitive especially if redundant physical paths do exist in the network and no actual physical partitioning was caused.

Because of the futility in using non-tree topologies, conventional Ethernet networks are infrequently architected with link redundancies, and where such redundancies exist, they cannot be taken advantage of without special configuration. We feel that this is at odds with the plug-and-play vision of Ethernet, where it might intuitively have been expected that additional links introduced between network switching elements should have the effect of automatically and transparently increasing redundancy and performance. Without substantial planning and complex manual configuration, redundant links are typically left unused until primary failures force them into action. Worse, failure recovery and redundant link activation typically take between several seconds to half a minute [31], resulting in network hiccups even if no apparent physical partitions have been introduced.

2.2 Software-Defined Networking

To work around the spanning tree restrictions imposed by Ethernet spanning tree, we use software-defined networking (SDN). SDN is a modern abstraction that allows access to a network switch's routing fabric. In SDN models, the switch's control plane is accessible to an external entity known as a controller, to which all data forwarding decisions are delegated. This control plane has complete command of the data plane, where network packets are transferred between physical and virtual ports on the switch. The control plane is also able to introspect the operational parameters of the data plane, and has a limited capability to transfer packets between the data plane and the control plane at will.

Among SDN standards available today, OpenFlow [68] is the most widely supported specification and is the bedrock upon which our work rests on. OpenFlow is managed by the Open Networking Foundation and has seen significant evolution through multiple versions. The most recent version of OpenFlow is 1.5 [74], although many switches marketed as OpenFlow-capable today support only OpenFlow 1.0. Successive versions of the standard have increased complexity and are not backward-compatible, necessitating independent firmware support for each version of the standard that a switch hardware supports.

On the software end, there are multiple efforts to develop operational OpenFlow controllers, each with varying degrees of programmability, complexity and performance. Some popular controllers include the open-source POX [26] (a generic Python-based system), Floodlight [9] (Java-based), OpenDaylight

[23] and ovs-controller [22] (a C-based reference controller written by Open vSwitch). Commercial closed-source controllers include the Ericsson SDN controller [7] (derived from OpenDaylight), NEC's ProgrammableFlow Controller PF6800 [20] and Big Switch's Big Network Controller [2]. Distributed controllers, such as Onix [58], ONOS [34] and Ravana [54] have also recently become available. The latter few served as principal references for our own distributed controller design, while our experience with some of the former have inspired us to incorporate usability improvements of our own.

2.3 Multipath networking techniques

Our RAILS work depends on multiple disjoint paths to deliver performance and reliability. Multiple paths can be provisioned by OpenFlow SDN techniques. However, before considering the use of SDN, our first inclination was to look into literature for examples where multipath networking is used to accomplish similar improvements. Many multipath networking solutions are variants of a theme designed to reactively address failure through the computation of some backup topology or topologies. For example, Path Splicing [70] is a mechanism that provides multiple paths through a network through the use of multiple statically predetermined routing trees. By allowing traffic to switch routing trees at each forwarding node, the system ensures path reliability during outages, where disjoint path routing may fail. Path splicing has fast recovery time but flows are not redundantly routed and it experiences latency stretch as data traverse non-optimal routes. As a result, the system is able to compensate for failure relatively cheaply, but trades off some performance in the process. By comparison, RAILS is proactive and simultaneously addresses both performance and reliability. In fact, the selection of an appropriate RAIL scheme can simultaneously compensate for failure while also offering performance improvement.

Another example of a reactive, pre-provisioned approach is Multiple Topologies for IP-only Protection Against Network Failures [33]. This solution describes the use of multiple topologies for transparent routing recovery and fault tolerance. Routers precompute some backup topologies and reroutes packets along the backup paths in the event of failures. It performs very well in realistic scenarios even though IP traffic only take single routes at any instance. Again, the approach here is reactive and designed to address failure only. Furthermore, it is an IP-only solution, whereas RAILS is capable of providing performance and assurance for more general classes of traffic as long as they run over Ethernet.

An interesting and pre-provisioned approach is CORONET [56]. CORONET computes link-disjoint paths, similar to RAILS, and implements each disjoint path as a different VLAN. Similar to our network switch augmentation, CORONET also implements a switch configuration module that sets up VLANs. It has a traffic assignment module that assigns host traffic to the VLANs. Thus, instead of relying on point-to-point OpenFlow rules, CORONET uses VLANs to specify paths, and it is claimed to be faster for packet forwarding and failure detection. However, CORONET lacks an evaluation section and it is not clear if the VLAN method of assigning paths is scalable since only 4094 VLAN tags are available.

Other approaches are topology-agnostic and depend on other assumptions for multipath data transport. For example, Multipath TCP [45] works on the L3 network layer and assumes that each IP address owned by the host is homed on a distinct network. The protocol takes a stream of data and distributes it across the multiple owned IP addresses, in the hopes that the underlying physical communication paths taken by each subflow to the destination are actually distinct. This assumption works well in applications such as smartphones, which can leverage both Wifi and over-the-air networks as truly disjoint paths. However over Ethernet deployments, this assumption is less dependable because MPTCP transport over an Ethernet spanning tree could cause subflows to tunnel over the same L2 physical layer links. In comparison, RAILS uses physical network topology information in order to construct truly disjoint network paths.

However, assuming path disjointness exist in a given MPTCP use case, MPTCP enjoys the cost convenience of not needing any modifications on the existing network. However it does require multihoming on devices that wish to take advantage of it. Multihoming may not be possible on many devices that cannot be outfitted with a second network interface card. Furthermore, support for MPTCP is sparse [59] at present, and only caters to the TCP protocol.

Various Ethernet-based multipath or multipath-like approaches also exist. For example, STAR [65] is a spanning tree-compatible protocol that improves QoS routing in an extended LAN. Packets are forwarded over the spanning tree by default but may also take shorter, non-spanning tree alternate paths where they are available. However, unlike RAILS, STAR was developed as a QoS solution, and was not designed to handle failure. Hedera [32] is an example of a dynamic flow scheduler that actively schedules multi-stage switching fabrics in order to improve bisectional bandwidth. It works by collecting flow information from all constituent network switches and maintaining a global view of the network in order to intelligently re-route traffic around bottlenecks.

Reactive, pre-provisioned Ethernet analogues of IP-based multipath also exist, and are somewhat closer to RAILS in terms of their offerings. SPAIN [71] is an Ethernet-based solution that implements redundancy by mapping strategically computed paths to separate VLANs. SPAIN provides increased bisection bandwidth and resistance to network failures. However, its implementation relies on static, pre-installed paths, and does not adapt to substantial network topology changes. Unlike RAILS, SPAIN does not offer a continuum of latency/bandwidth tradeoffs.

Similarly, ECMP [16] is a load-balancing routing strategy that can take advantage of redundancies in a network. Under ECMP, each flow is hashed to a single path from a set of available paths. Although each flow transits only a single path, the aggregate effect is to spread distinct flows across all the available paths, thus load-balancing disjoint paths as a whole. However, because each flow only still uses a single path, individual flows are subject to disruption should a link in their paths fail.

802.1 Ethernet link aggregation [13] combines several physically distinct network links on a switch into a single large logical link, which makes it a special case of RAIL 0. With appropriate failover recovery, Ethernet link aggregation can also improve the resilience of the network against individual link failures. However, only two switching elements may participate in each aggregated link. When a participant switch fails, the entire aggregated link also fails. This is in contrast to RAIL 0, where the link aggregation is the result of multiple paths across multiple switches. If a switch fails in RAIL 0, the aggregated link can continue to exist with reduced bandwidth.

Finally, there are network virtualization techniques that can be used to provision multiple paths. In virtual network embedding services, multipath networking can be elegantly and efficiently provisioned by the underlying substrate. A network virtualization manager presents the view of virtual nodes and logical network links, while the virtualization service manages the mapping of virtual to physical resources. This mapping can aggregate multiple physical links for a single virtual link, thus reaping the performance benefit of having multiple network paths. Substrate Support for Path Splitting and Migration [89] exploits this technique in network embedding, utilizing multiple paths, load-balancing and dynamic path selection.

Although virtual network embedding presents a clean abstraction to network users, it nonetheless passes the problem of multiple paths on to the virtualization layer. At present, many techniques [89] [51] rely on flow hashing to attain efficient use of the available substrate paths while avoiding the problem of packet reordering. Like ECMP, this again has the effect that a physical link failure could disrupt certain flows while leaving others unaffected, and disrupted flows could take substantial time to recover depending on the virtualization manager. Finally, unlike RAILS, the full bandwidth across all the available substrate paths cannot be realized.

SDN-based solutions for robust networking have also been examined. FatTire [77] is a programming language that allows users to specify network redundancy levels, as well as the specific paths that their data packets should transit in a network. The program is then efficiently compiled down to OpenFlow rules that are installed on network switches. This approach naturally facilitates the implementation of seamless network link failovers. However, it requires substantial domain-specific knowledge to operate and program in the language, whereas RAILS is a simple solution that does not require much configuration.

Systems based on forward-error correction schemes similar to RAIL 1 and RAIL 4 also exist. Redundant Packet Transmission (RPT) [48] is a system designed to efficiently and proactively provision for network losses through a content-aware network that contains redundancy eliminating routers. The approach is similar to RAIL scheme 1 in our work, although RPT does not utilize multiple paths and was designed to withstand losses in a single path. RPT differs from forward error correction schemes in that it is more efficient; in the RPT system each original packet in a stream is duplicated, however each duplicate packet beyond the first is compressed or encoded by the RPT router. At each hop of the RPT router, the packets are all decoded or decompressed, and then subject to recompression again after packet drops have been allowed.

2.4 RAILS and RAID

The main body of work that inspired the RAILS system was based on RAID [76]. RAID [76] is the classic work that explores various techniques of storing data on independent disks for the purpose of improving redundancy and performance. Data storage using RAID is largely organized into standardized schemes, with RAID0 corresponding to no redundancy (thus allowing the full utilization of all independent disks), RAID1 corresponding to direct mirroring (simple replication of data across multiple disks) and higher RAID levels corresponding to more complex parity-protected data striping methods. We conjectured that there exists a parallel between independent disks in a RAID system and independent network paths in an SDN, and explored the applicability of such network coding schemes over an SDN. In so doing, we also looked at a number of current multipath techniques.

We conjecture that a parallel exists between disks and network paths as data mediums, so the performance and protection schemes deployed on disks are also applicable in a network. RAID [76] is the classic work that explores various techniques of storing data on a set of independent disks for the purpose of improving redundancy and performance. Data storage using RAID is organized into standardized schemes or levels, each scheme providing a different set of benefits and tradeoffs.

In RAID 0, all constituent disks are aggregated into one large logical disk without redundancy, at the risk of having no protection from failures. RAID 0 allows a user to treat the RAID array as one single large disk, and has the benefit that the multiple read/write heads from the constituent disks can be used to improve read and write efficiency. Similarly, in RAIL 0, the available bandwidth from all constituent network paths are aggregated into one single large logical pipe, which the user sees as a single network path. The individual constituent paths contribute to improved throughput, but like RAID 0, the loss of a single network path will cause the transmission scheme to fail.

On the other end of the efficiency/reliability continuum lies RAID 1. In RAID 1, all data is mirrored across each of the independent disks so that the array can suffer the loss of all but one disk, at the cost of drastically reducing the overall storage efficiency. Similarly, in RAIL 1, network packets are duplicated across every network path, greatly increasing the redundancy of the data, at the cost of very high bandwidth.

RAID levels 2-5 are parity-based improvements upon RAID 0 and 1. The ideas behind RAID 2-5 are similar in spirit. To improve storage efficiency, full mirroring is not used; instead, some variant of forward parity protection is deployed. This is compact and ensures that content can be reconstructed despite the loss of any single disk. By being able to mask a single fault, the resiliency of the disk array is improved against failure. The individual schemes vary only in the granularity and placement of the parity blocks: RAID 2 (bit level parity), RAID 3 (byte level parity), RAID 4 (block level parity) and RAID 5 (block level parity with distributed parity). Because they are all variants on the same parity theme, we implemented RAIL 4, which uses discrete network packets as disk block analogues in RAID.

RAID 6 is essentially a refinement over RAID 5. By adding a second distributed parity block, the disk array can survive two failures instead of one. The construction of the second parity block is substantially more complicated and computationally expensive.

2.5 Network Security

An intelligent SDN controller built to coordinate RAILS and EtherSlice operations require some awareness of data plane network state. For example, an SDN controller should know the bindings of device Ethernet addresses to IP addresses. This knowledge allows the SDN controller to localize a resource, as well as to detect misuse conditions such as IP address spoofing/squatting, ARP poisoning attacks or rogue DHCP attacks. A forward-looking implementation of an SDN controller may even use this knowledge to improve network performance. For example, EtherProxy [44] suppresses network-wide broadcasts when its middleboxes are able to answer DHCP or ARP queries. Ethane [36] extensively uses such knowledge of network state to enforce security policies. Similarly, we use knowledge of the data plane network state to guard against Ethernet address spoofing, ARP poisoning and rogue DHCP attacks in our implementation of EtherSlice.

Many anonymizers are based on Chaum mixes [38], which is public-key encryption-based. In Chaum mixes, a sender constructs a path to the destination through a number of anonymizing hops, and encodes this path using layered cryptography. At each hop, the node decrypts its next forwarding destination, but has no knowledge of other hops or the penultimate source and destination. Nodes also arbitrarily delay or reorder output messages. Anonymizers based on Chaum mixes include popular onion routers such as Tarzan [46], Vuvuzela [85] and Tor [41]. Many of these systems are low-latency, but susceptible to traffic analysis and correlation attacks.

Other variant anonymizer systems are based on Chaum's Dining Cryptographers network (DC-net) [37], which are resistant to traffic analysis, but rely on the construction of a bandwidth-heavy anonymous broadcast channel. These anonymizers provide resistance to traffic analysis by using fixed-length encrypted messages released at time epochs, which remove temporal correlations of transiting messages at the cost of being non-realtime. Systems that improve on the scalability of DC-nets include Herbivore [47], Riposte [39] and Dissent [87].

2.6 Network Processing Units

An OpenFlow SDN featuring multiple paths is one part of the requirement to support RAILS and EtherSlice, since it allows precise control over packet forwarding paths. However OpenFlow itself does not provide facilities to modify packets in arbitrary ways. Recall again that our fundamental operating assumption for IoT devices on our network is that they should not require any change or modification in their hardware or software. Thus, to support RAILS or EtherSlice, packets need to be modified elsewhere other than on the devices and switches themselves. For this purpose, we use Network Processing Units (NPUs).

Network Processing Units (NPUs) are general-purpose packet processors that can arbitrarily modify network datagrams. Technologies such as OpenFlow and P4 [35] support some limited form of packet modification, but they are not truly general in that their modification capabilities are restricted to only the packet header and not to the rest of the packet body. NPUs can be realized in either software or hardware.

On the software end, Marinos et al. [67] proposed an aggressive optimization for certain network applications (such as DNS and static HTTP content servers) by compressing the network stack itself, essentially bypassing latencies that are otherwise introduced by the usual network layers. Their implementation leveraged Netmap [78] to provide low-latency access to network packets in userspace. They then built their own custom Ethernet, TCP/IP and UDP/IP layers to provide socket-like services without incurring substantial system overhead. This is far superior to our initial libpcap approach, and motivated us to try Netmap.

The Netmap [78] provides fast packet I/O that uses various optimizations such as batching and ring buffers to map (hence its name) packets from the NIC directly to user space. Netmap provides very high packet throughput, and by the authors' accounts, were able to sustain line rate packet counting at 10Gb NIC speeds using a modest CPU. Our experience was a little mixed with Netmap as we were not able to attain the same levels of performance on our hardware. Furthermore, our implementation of the RAILS and EtherSlice NPUs required more than just packet counting or header inspection; because of the computation inherent to our work, we were unable to sustain the necessary bandwidth for operation on a dedicated x86 CPU. DPDK [4] and PF_RING [25] are other industrial software alternatives to Netmap that also provide fast direct userspace access to network data packets by bypassing the kernel network stack.

NetSlice [66] is an operating system API that provides line speed (10Gbps) access to network packets through a specialized network stack that is backward compatible with existing socket APIs. NetSlice attains high performance by leveraging dedicated CPU cores, memory and NICs for packet processing, and also uses optimizations such as I/O batching to reduce the cost incurred at kernel traps.

Mekky et al. [69] proposed an extension to Openvswitch that allows application-level packet processing to be efficiently accomplished in the data plane of a software switch, such that they avoid the lengthy detours that application-level packets sometimes take to reach the controller and later reenter the data plane. They do this by intercepting packets before they arrive at

Openvswitch, and were able to demonstrate several network functions implemented in this way. Our implementation of EtherSlice uses the `PACKET_IN` method of receiving packets from Openvswitch, and would have benefited from this method of direct processing in the data plane.

SoftNIC [49] is a hybrid software-hardware system that allows high performance programmability of NIC-like features in software, as opposed to hardware. For example, protocol offloading, packet classification, rate limiting and virtualization, as well as new protocols can be supported. SoftNIC accomplishes this by creating a shim layer between the NIC hardware and network stack, and processes packets in a pipeline using dedicated compute cores. The system is backward compatible.

P4 [35] provides a generalization of the OpenFlow match/action processing by proposing an expressive packet parser that is independent of protocol support baked into the hardware. However, because P4 implementations buffer the packet body separately, they are unable to perform payload-modification operations such as those required to support RAILS or EtherSlice.

The Click Modular Router [57] is a flexible and extensible software architecture to add functionality to routers. At its core, it is a software-driven router, with packets flowing between functional elements in a pipeline. These functional elements are written in C++ and can be tailored to provide standards-compliant routing service, or in fact any arbitrary custom packet processing. Thus the system can be likened to a very early implementation of an NPU.

On the hardware end, Split SDN Data Plane (SSDP) architectures [72] and loadable packet processing modules [73] offer industrial-performance alternatives to the FPGA designs, by integrating the packet processing requirements into an alternate data path that is directly connected to a switch co-processor.

The NetFPGA [21] series of hardware cards provide a development platform for designing, prototyping and testing hardware-based NPUs. FPGA-based NPU designs offer the performance of raw hardware without operating system overhead, and can be designed with traditional hardware synthesis tools. An FPGA implementation of an NPU has the advantage that specialized hardware (such as multiple functional units, parallel computation cores, dedicated packet buffers, etc) can be realized with very low latency. This was the method we chose for building RAILS.

More commodity hardware NPUs include PacketShader [50], which uses off-the-shelf GPUs to implement generic packet-processing functionalities on a regular desktop computer. In PacketShader, network datagrams are moved from the network interface over to the GPU, where a custom shader program performs the required transformations to realize a specific NPU functionality. Because GPUs have many streaming multiprocessors optimized for parallel computation and are better able to cope with the memory access patterns of network packet processing, they perform very well for payload modification tasks that are traditionally taxing on regular x86 processors.

2.7 Controller Design

In building our own OpenFlow controller from scratch, we referenced other designs and sought to incorporate some of the benefits of their approaches.

Google's B4 [53] is an OpenFlow controller used to drive their internal wide area network. The goal of their controller was primarily traffic engineering; they were able to improve inter-datacenter network link utilization from 30-40% to almost full utilization. Although traffic engineering was not a primary goal of our Ironstack controller, the Google B4 deployment informed our controller design and we were able to verify some of the lessons they described. For example, the B4 work noted that the connection between the OFC (OpenFlow controller) and the OFAs (OpenFlow agents, which reside on the switches) were the most constrained and it affected packet IO rates. Their proposed improvement suggested that two channels might be necessary: one for packet IO and another for other control traffic such as link status change and switch programming operations. We took this suggestion and implemented a separate channel for `PACKET_IN` traffic, while retaining complete compatibility with OpenFlow. This is examined in more detail in chapter 6.2.2.

Another feature we drew from Google's B4 and Ethane [36] was the ability for data plane applications to communicate directly with the control plane. This feature is missing from many OpenFlow controllers today. We believe this to be useful as it allows data plane applications to influence controller decisions. For example, Ethane directs network users to authenticate with the controller through a web form before installing appropriate flow rules to bypass the captive portal. B4's Routing Application Proxy (RPA) bridges packets from their Quagga control plane and the switch's data plane. Our RAILS and EtherSlice controllers use this ability to communicate with data plane users for negotiating flow enhancement services. The Ironstack system also uses this feature to implement a simple echo server on the low-level controllers; it is used for monitoring controller liveness from the data plane. The mechanics of bridging the control and data planes vary, but we present two possible implementations in section 5.6.4.

Our experience with centralized SDN controllers show that they perform poorly under load and during initialization. This is in line with our predictions from distributed systems. As a result, we looked for alternatives to centralized SDN controller designs. Onix [58] uses a distributed, replicated network information base (NIB) to improve the scalability, reliability and resilience of network control applications. These network control applications specify their needs for consistency, performance, durability and scalability to Onix. Onix uses a one-hop, eventually consistent, in-memory DHT to store network state. State inconsistency is possible in this system, and it is up to the network control applications to resolve these on their own.

Onix [58] is one of the earliest implementations of a distributed SDN controller. The Onix system is scalable, fault tolerant and has high control plane performance on the basis of its distributed architecture. Yet it is logically centralized, allowing control applications to use a single control platform to implement a range of control functions (such as traffic engineering, routing and access control) in a simple manner. Onix uses a transactional persistent database backed by a replicated state machine for disseminating Network Information Base (NIB) state updates among the distributed Onix instances. However, Onix depends on the control application's assistance to specify consistency requirements, such as the need to prioritize responsiveness over consistency, or vice versa. We note that many control applications can tolerate eventual consistency, and implemented our controllers using a gossip mechanism; an advantage of our gossip mechanism is that our controller does not need to rely on a costly separate control network.

ONOS [34], a distributed network operating system inspired by Onix, uses multiple running instances to manage a large network. Several OpenFlow switches may map to one ONOS instance, and as the network scales, more ONOS instances can be started to manage the load. ONOS provides a logically centralized view of the global network state using a distributed data store. Its final implementation uses RAMCloud [75] as its backing store, and it relies on a publish/subscribe event notification model to exchange state changes between its ONOS instances.

HyperFlow [84] is an implementation of a distributed OpenFlow controller. It assumes a separate network that relies on WheelFS [81] to maintain consistency. HyperFlow uses a publish/subscribe messaging system to synchronize select state across multiple controllers. Each controllers subscribes to three message channels: a data channel, a control channel and its own channel. These channels are represented by directories and the messages are represented by files. The job of managing network state consistency and partition tolerance is delegated to WheelFS. To prevent network loops, flow paths are setup by an authoritative controller, which is the controller managing the flow's source switch.

Elasticon [42] is an elastic distributed OpenFlow controller architecture, which allows for dynamic growth, shrinkage and load balancing of controller instances according to instantaneous load. In Elasticon, an OpenFlow switch connects to multiple SDN controllers. When the master of a switch needs to be reassigned or migrated, an ingenious signalling method is used to provide safety and liveness during a handover. A distributed data store is used to logically centralize data that is shared among all controllers.

A distributed SDN controller offers robustness and scalability, but it also introduces consistency and ordering problems typical in a distributed system. We found it insightful to learn from approaches to these problems. Ravana [54] uses two phase replication protocols to improve on the distributed semantics of control plane operations on an SDN. By introducing a controller runtime and a switch runtime that buffers events into a totally ordered, in-memory log, the system guarantees that events are processed exactly once and without loss. This is a departure from other distributed controller approaches in that it correctly handles state changes during failovers. Ravana also provides a transparent runtime that insulates controller applications from the underlying distributed nature of the system.

Before adopting a distributed approach for our controller, we also looked at the specific impact of such a design on an SDN. Levin et al. [63] investigates the various issues behind distributed SDN control architectures that are logically centralized. A logically centralized architecture retains tradeoffs from its underlying dependence on distributed systems, and they identified two important tradeoffs: between staleness and optimality, and between application logic complexity and robustness to inconsistency. These tradeoffs are relevant to the design of distributed SDN controllers because they affect an SDN application's performance, liveness, robustness and correctness.

2.8 SDN switch quirks

Our experience with quirks in our OpenFlow switches was initially surprising, and suggest that others may have encountered similar issues in other settings. We sought to characterize some of these issues to further enlighten our controller and hardware augmentation design.

Kuzniar et al. [61] performed investigations on a number of OpenFlow switches to characterize the interaction between the control plane and the data plane. The authors uncovered a substantial amount of surprising behavior, including temporal locality behavior in switch updates, performance degradation caused by priority fields, non-atomic rule modifications on a switch and even incorrect OpenFlow barrier behavior. Although their discoveries were made on different switches, we noted some parallels with our hardware, and their work supports our hypothesis that unexpected, standard-deviating behavior is a phenomenon that should be taken seriously by developers.

DevoFlow [40] examines the various causes of latency inherent to OpenFlow and describes the negative impact of flow table size and statistics collection on OpenFlow performance. They then prescribe and verify more efficient methods to install flows and gather statistics by minimizing interactions with the SDN control plane. While their choice of OpenFlow hardware was different, our experiences were largely similar. This reinforced our hypothesis that the abstraction between OpenFlow hardware and software is not clean and decoupled as the specifications may suggest.

Given the heterogeneity of different hardware, we considered how we might build a generic controller that would work well across multiple hardware. As a first step towards this goal, we evaluated the possibility of starting with a reference switch implementation, and then tailoring the reference switch to simulate different hardware. The OFLOPS [79] framework recognizes diversity in the performance and implementation of OpenFlow switch firmware, and characterizes their behavior and performance under a variety of test cases. These characteristics can be used to model switch behavior more accurately than testing on reference implementations of OpenFlow, such as Open vSwitch [22]. Interestingly, their work also uncovered bugs in the implementation of barriers on switches.

Similarly, Danny et al. [52] studied the similar problem of trying to emulate specific vendor performance characteristics with respect to control path delays and flow table usage. They were able to improve the accuracy of switch emulation to a high degree of accuracy across multiple vendors. This work was helpful for our goals since we wanted to build a controller that would work on a variety of hardware platforms, even though we did not have access to the various hardware ourselves.

Our concern about different performance across different hardware led us to search the literature for unifying alternatives. NOSIX [88], an analogue of the POSIX system standard, is a proposed solution to provide better standardization across diverse OpenFlow switch hardware. The authors describe a uniform, portable abstraction layer for SDN controller development through the use of virtual flow tables and vendor-provided switch drivers. Controller developers then specify their requirements for rule processing and make promises about their usage of the virtual flow tables. Unfortunately, NOSIX is not currently in widespread use and few switch vendors have supplied their switch drivers.

Because of the shortage in generic table space on our switches, we looked at alternatives to bridge the gap. Lu et al. [64] describe an implementation of a CPU as a network switch co-processor. They make the observation that modern processors have adequate computing power and have the benefit of access to DRAM, and can thus augment switches with larger forwarding tables and deeper packer buffers. Their system offloads a portion of a network switch's data plane load for processing on a CPU, which then relays the processed packets back to the switch ASIC.

Our experience with configuring and operating SDN switches in pre-OpenFlow mode was tedious and laborious. Thus, while designing our network switch augmentation, we looked into literature to see how others solved similar problems. As it turns out, the problem of initializing and configuring a switch for production use is unavoidably convoluted and manual labor-intensive. The EtherProxy paper [44] echoes this same sentiment: VLANs and subnets need to be created and configured, address assignments need to be managed and routers connecting network segments need to be setup. The process is error-prone and involves a lot of human interaction. Our experience is similar in this aspect; we note from our time working with Cornell's ITSG (Information Technology Support Group) that the setup and configuration phase for hardware is tedious, laborious and often error-prone. In chapter 6, we discuss the design of a serial configurator that takes over the burden of most initialization, allowing an operator to rapidly deploy switches.

CHAPTER 3

RETROFITTING PERFORMANCE AND RELIABILITY OVER ETHERNET

Data networks require a high degree of performance and reliability as mission-critical IoT deployments increasingly depend on them. Although performance and fault tolerance can be individually addressed at all levels of the networking stack, few solutions tackle these challenges in a scalable and easy to configure manner. We propose a redundant array of independent network links (RAILS), adapted from RAID, that combines software-defined networking, disjoint network paths and selective packet processing to improve communications bandwidth and latency while simultaneously providing fault tolerance. Our work shows that the implementation of such a system is feasible without necessitating awareness or changes in the operating systems or hardware of IoT and client devices.

3.1 Introduction

The potential uses of multiple paths in a network have attracted significant attention, and many IETF standards [45] [86] have been finalized or are now being finalized to expose and exploit these capabilities. The reasons for this interest reflect multiple goals: multipath networking provides (1) improved resilience to failures and (2) improved network load-balancing, leading to (3) better data throughput, and hence improved user experience.

The basis for multipath networking is conceptually simple. Multipath networking can be seen as another form of parallelism, with the objective of improving network performance subject to some underlying constraints. These underlying constraints are highly varied, and may not necessarily be bound by engineering or physical limits. For example, one important criteria in MPTCP [45] is flow fairness. Under this criteria, subflows of MPTCP must not use an unfair share of network link bandwidth should they transit the same physical link. This constraint is not imposed by a topology or environmental limit, but is nonetheless required for acceptable deployment. The choice of which constraints to address will determine the optimality of the resultant solution over a broad range of applications.

For our work, we take the position that IoT devices are closed black boxes that are not amenable to modification of any kind, whether in software or hardware. This is a reasonable assumption because many consumer or industrial grade IoT devices are commodity-off-the-shelf components that are generally designed to be tamper-proof and maintenance-free. Critically, this constraint means that any kind of change designed to improve networking experience must be confined to the network switching equipment itself.

In our target setting, we assume that network operators use switched Ethernet and are open to upgrading their switches to OpenFlow [68]-capable models. However, we do not assume that users can or will upgrade their IPv4 networking equipment or software, although they may nonetheless desire the benefits offered by multiple paths in the network. For example, in networks created to support IoT instrumentation of the smart power grid, embedded sensors may not be subject to reprogramming, but could benefit from the resilience offered by a multipath network. Beyond these two assumptions, we do not impose any other limitation, so users are free to run their own protocols and software, oblivious to the underlying network. We believe these assumptions to be valid and powerful, as they cover many existing deployments and have the advantage of frustration-free backward compatibility.

In what follows, we explore a series of building blocks for our work:

- RAIL (Redundant Array of Independent Links), an innovative set of network redundancy schemes adapted from RAID, that collectively provide high speed and reliable packet transportation, while being tunable in terms of latency and bandwidth efficiency.
- The design of dedicated network processing units (NPUs), analogous to RAID controllers, to support RAIL schemes.
- Engineering solutions that require no changes to existing hardware and software beyond network switch upgrades.
- A prototype and microbenchmarks to validate our claims.

Taken together, our work fills an unoccupied niche in computer networking by providing selectable (1) improvements to end-to-end network performance through packet processing and redundant routing and (2) the realization of high-assurance networking through zero-downtime failure recovery, while being (3) a drop-in upgrade that is (4) fully backward-compatible with existing end-host equipment.

3.2 Design and architecture

In order for a network to intelligently address questions about the best paths from a source to destination, it first needs to understand the underlying topology. Whereas regular Ethernet switches make packet forwarding decisions based on local state, we propose an alternative where these switches forward packets based on global state. In this scenario, some or all of the Ethernet switches in the network are replaced by OpenFlow switches. Each OpenFlow switch is driven by a dedicated OpenFlow controller, which is able to exchange state and topology information with all other OpenFlow switches in the network using distributed algorithms. With the topology information, each OpenFlow switch is able to compute disjoint paths between any arbitrary source and destination.

Users of the network continue to see the underlying transport medium as Ethernet, and do not sense substantial differences under regular circumstances; this is the default network forwarding policy. Flows under this policy are subject to disruptions and recovery delay, as with regular Ethernet. However, a user may selectively request enhancement services to treat certain flows differently from regular ones. If admitted by the policy controller on the local OpenFlow switch, some special network processing will confer additional properties on the flow, such as increased bandwidth, additional resilience to failure, transparent encryption or some combination of the above. Policies may be specified reactively or proactively, and either remotely or locally.

Flows that are enhanced are directed to network processing units (NPUs), which then implement policies by processing flow packets. For example, an NPU that is asked to provide tolerance to one link failure on a certain flow may decide to duplicate packets and tag them for delivery along two disjoint paths, de-duplicating the packets just before they arrive at the destination. The exact algorithm selected by the NPU depends on the request and network, but is completely transparent to the network user. Because flow enhancement services consume network capacity and computational resources, they should not be used indiscriminately and the policy admission process should be selective.

Thus, a RAIL network deployment requires several distinct components: (1) OpenFlow-capable switches, driven by (2) distributed OpenFlow controllers supported by (3) network processing units (NPUs), optionally working in tandem with (4) regular Ethernet switches. We describe the implementation of each of these components in the following sections.

3.3 OpenFlow controller design and network topology

For resilience, scalability and backward-compatibility reasons, we propose several design requirements for the OpenFlow controller that will run the RAIL-enabled network: (1) it needs to be distributed to avoid a central slowdown or point of failure, (2) it must communicate in-band with other distributed OpenFlow controllers while being cognizant of non-OpenFlow infrastructure, and (3) it should be capable of performing and delegating potentially intensive network packet processing. Controllers need to exchange topology information among themselves.

3.3.1 Controller-to-controller communication mechanism

Because flow enhancement services can only be offered over OpenFlow-connected segments, the first step in building an intelligent network is to discover the locations of all OpenFlow switches. In particular, every OpenFlow switch needs to learn about other OpenFlow switches directly adjacent to itself. This is not trivial because some OpenFlow switches may be indirectly connected by intermediate hops running regular Ethernet switches. A naively constructed topology discovery packet may be forwarded by intermediate regular Ethernet switches, leading the OpenFlow switches to incorrectly infer that they are directly connected. The challenge is therefore to design a communication mechanism that can carry messages across a single hop, without the danger of further propagation. This is conceptually similar to sending an IP packet with a TTL of 1, although Ethernet does not offer such a TTL facility.

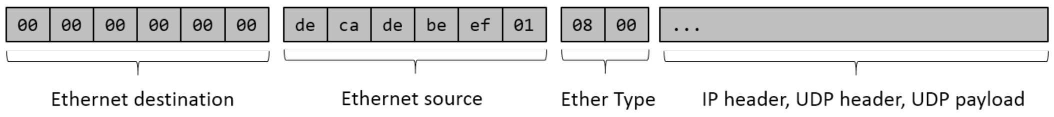


Figure 3.1: OpenFlow-only switches require a communication primitive that will not be forwarded by regular switches.

We accomplish this by making the observation that regular switches will not forward messages with a null (`00:00:00:00:00:00`) Ethernet destination address. However, OpenFlow switches will still see these packets and relay them to its local controller via the `PACKET_IN` OpenFlow event. We refer to this mode of messaging as a single-hop constrained message.

To simplify the structure of controller-to-controller communications and to enable multiple concurrent sessions, we borrow an abstraction from regular networking and wrap the payload of a single-hop constrained message in a UDP packet. Distinct communication sessions between two controllers can then be distinguished by their source and destination port tuple. Thus, direct inter-controller communications use UDP packets, but have the special property that their Ethernet destination field is null. Figure 3.1 shows the structure of a single-hop constrained message.

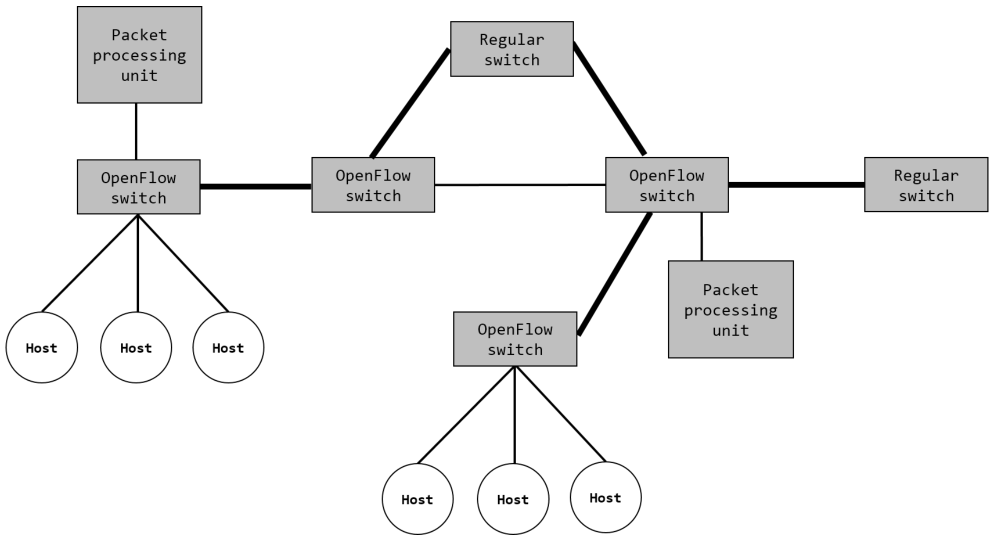


Figure 3.2: Example of an Ironstack deployment. Thick lines represent spanning tree links

3.3.2 Topology discovery and management

With a communications primitive good for single-hop probes, we now describe an implementation for topology exchange among the OpenFlow controllers. The controllers run an automated link-state protocol to discover OpenFlow-enabled network segments. This protocol uses a heartbeat signal to ensure freshness.

OpenFlow switch discovery

Each controller sends a single-hop constrained message on every physical switch port on which it sees a carrier signal. The message contains information about every directly-connected OpenFlow-capable neighbor. The UDP destination port of the message is set to a special value to signal the receiving controller that the message is for topology exchange. Non-OpenFlow switches and end hosts will drop the message because it is addressed to an invalid Ethernet destination. However, an OpenFlow switch will forward the message on to its controller. If the controller was previously unaware of the sender, it will mark its respective switch port as being directly connected to another controller and broadcast a new single-hop constrained message with its updated link state information on every active physical switch port. If the controller has already seen the message, it is silently discarded. This protocol thus performs discovery and propagates link state information to all controllers in the connected OpenFlow segment.

Failure detection and churn

Link state changes on a local OpenFlow switch can be detected through `OFPT_PORT_STATUS` OpenFlow events. This information can be used to update the local topology. Silent failures, such as controller failures, are inferred by heartbeat messages.

Each controller broadcasts a link state message at regular time intervals. When a timeout occurs and no messages have been received from a previously-discovered controller, topology information corresponding to that instance is removed. If the removed instance was a direct neighbor of the local instance, the local instance broadcasts a link-state message with its updated neighbor information. This protocol ensures that failures are promptly propagated throughout the network so controllers have fresh state.

Together with topological discovery, this protocol ensures that the entire distributed system of controllers are self-configuring, self-healing and self-adapting.

End host discovery

To be useful for flow enhancement negotiation, the distributed controllers also need to know the location of end hosts in the network. This is done by snooping on ARP updates. Whenever an end host device emits an ARP message that transits an OpenFlow switch, the controller makes a note of the physical port number from which the message was received before forwarding it. This assists in binding switch ports to end host identities.

Disjoint paths

With the topological information of end hosts and OpenFlow switches known, individual OpenFlow controllers can now answer the question of multiple paths in the network and the best routes from one point in the network to another. Multiple paths between a source and destination can be rapidly calculated by a number of algorithms, for example by computing disjoint paths using the Edmonds-Karp maximum flow algorithm using a unit weight for graph edges.

Although many possibilities for multiple paths may exist between two points in a network, for the purposes of flow fairness and reliability, we consider only fully disjoint paths.

3.4 RAID and RAIL

To restate our goal, we would like the ability for a network user to specify his requirements for a flow, without knowledge or interference in the network. The network then exploits disjoint paths to accomplish the necessary actions to meet these requirements.

We propose a set of user-tunable parameters to improve the performance and/or reliability of a flow. These parameters are conceptually similar to those available in RAID, the set of redundancy schemes used in disk arrays. The analogue of disks in our system are disjoint paths, hence the term redundant array of independent links (RAIL). Because RAID and RAIL primarily differ only in the medium used for data storage, we conjecture and validate that the schemes in RAID are largely applicable to RAIL as well.

In the case of RAIL, the tunable parameters can be seen as a continuum of tradeoffs between latency/reliability and bandwidth efficiency. At one extreme end of the spectrum, each packet in a flow can be replicated onto multiple disjoint paths. The receiving end delivers the first arriving packet to the application and discards the duplicates. Such a scheme minimizes latency and improves the stability of the flow, while also tolerating up to $n - 1$ link or switch failures, at a cost of n times the bandwidth.

On the other extreme end of the spectrum, each disjoint path can be seen as a separate channel through which data can be sent, so each successive packet in a flow can be transferred down whichever path is first available (thus avoiding the problem of sending too many packets down congested paths). In a lightly loaded network, approximately $1/n$ of the packets in a flow can be sent down each path. This scheme maximizes bandwidth efficiency but clearly sacrifices on flow stability and latency, since the entire flow is now dependent on the slowest link. It also does not tolerate link failures since this scheme does not feature any redundancy.

In between these two ends, a parity protection scheme may be used to provide low-cost tolerance to link failure. Alternatively, a simple and more general k out of n scheme may be used to replicate packets such that a flow can tolerate a loss of up to $n - k$ disjoint paths, while providing a lower-bound latency performance of the $n - k + 1$th slowest disjoint path.

Like RAID controllers, RAIL schemes depend on network processing units (NPUs) to handle flow packets, so we present their design first.

3.4.1 Network Processing Unit

The NPU is an abstraction that provides realtime packet processing services. NPUs have been proposed in the past [72] [73] to perform in-line network packet processing. In the context of our work, NPUs need to provide services that include (but are not limited to) automatic packet buffering, re-ordering, rewriting and de-duplication. A concrete implementation of an NPU can assume any of several forms, including an in-controller packet processor that handles OpenFlow `PACKET_IN` events, a dedicated computer directly connected to the switch via a high capacity network link or even purpose-built FPGA hardware. We have experimented with each of these approaches; a summary discussion of these findings can be found in Section VIII.

One of the responsibilities of the NPU in all RAIL schemes (except RAIL 1) is the tagging of ingress packets. The NPU does this by rewriting Ethernet packet headers. Each disjoint path is associated with a destination meta-address, which can be any unique Ethernet MAC address that is not an in-use or reserved address. To designate a packet for transit over a certain disjoint path, its Ethernet destination field is overwritten with the meta-address of the selected path. At the OpenFlow switch, rules are installed to match these special Ethernet addresses, with corresponding actions to forward matching packets down their respective disjoint paths. Tagging packets this way permits efficient forwarding of disjoint path packets as the switch hardware can perform header matching and packet forwarding at line rate.

Tagging packets by modifying their Ethernet destination addresses permits efficient forwarding of the packets when they reach the switch, as OpenFlow rules can be installed to match these special Ethernet addresses and forward the corresponding packets on via their corresponding disjoint paths.

It is important to note that tagged packets do not need to be equally distributed across the selected disjoint paths. This allows the controller to collaborate with the NPU on dynamic traffic shaping strategies. For example, across disjoint network paths that have large bandwidth disparities, the controller may choose to instruct the NPU to tag proportionately more packets (or more aggregate bytes) for higher bandwidth disjoint paths, favoring them over those with lower available capacities.

Tagging packets with their disjoint path meta-addresses is a necessary step, but alone is not sufficient for the functioning of the system. When individual disjoint path latencies are different, it is possible for network packets arrive out of order. The direct delivery of these potentially reordered packets may have unintentional effects on the receiving system. For example, TCP may interpret out-of-order packets as an indication of packet loss and accordingly retransmit the previous packet, while reducing the data transmission rate. This runs counter to our design goal of non-interference with user protocols and systems. Therefore, the NPU also needs to provide some mechanism to preserve packet ordering at the egress switch.

To ensure that packets are delivered in the same sequence as they are received on the ingress switch, some other mechanism must be deployed to ensure ordering. Ordering is particularly relevant for RAIL schemes that feature parity blocks, since the correctness of each emitted packet is critically contingent upon combining the right set of packets.

To introduce packet ordering, some notion of sequencing is required. The intuitive answer to this is to use the sequence information provided by the packet itself. Unfortunately some IPv4 traffic, notably UDP, do not contain a sequence number field. Although it would be relatively straightforward to augment the packet with an extra integer field, in practice this is risky because large packets may be written with no headroom for extra data, and the inclusion of these mere extra few bytes may cause the packet to exceed the network's MTU value. This is disastrous as it would result in that packet being dropped. Thus, the key challenge in including a sequence number is the identification of a non-critical field that can be overwritten for this purpose. In our system, we have chosen to repurpose the 16-bit Ethertype field for sequencing. While this is a reserved field that is used for classifying Ethernet traffic type, we reasoned that the field was safe to hijack because Ethernet forwarding does not depend on the value stored there. Furthermore, because RAIL only handles IPv4 traffic, all network packets encountered by the NPU will effectively have a constant value of `0x0800` in the Ethertype field.

In reality, most Ethernet traffic today are either one of three Ethertypes: IP (type `0x0800`), ARP (type `0x0806`) and VLAN (type `0x8100`). Because our RAIL schemes only concern themselves with non-VLAN IP-based traffic, all network packets encountered by the NPU will effectively have a constant value of `0x0800` in the Ethertype field.

The key challenge in including a sequence number is the identification of a field that can be used for this purpose without substantially modifying the packet itself. Although it would be relatively straightforward to augment the packet with an extra integer field, in practice this is risky because large packets may be written with no headroom for extra data, and the inclusion of merely an extra few bytes may cause the packet to exceed the network's MTU value. This is disastrous as it would likely result in that packet being dropped. Therefore in our system, we have chosen to repurpose the 16-bit Ethertype field for sequencing. While this is a reserved field that is used for classifying Ethernet traffic type, we reasoned that the field was safe to hijack since Ethernet routing does not depend on the value stored there. In reality, most Ethernet traffic today are either one of three Ethertypes: IP (type `0x0800`), ARP (type `0x0806`) and VLAN (type `0x8100`). Because our RAIL schemes only concern themselves with non-VLAN IP-based traffic, all network packets encountered by the NPU will effectively have a constant value of `0x0800` in the Ethertype field.

To ensure that our use of the Ethertype field does not interfere with other network devices that interpret reserved Ethertype values, we picked the IEEE unallocated range [12] `0xB000` to `0xC000`. This gives the system 4096 possible sequence values before wrapping, which is sufficient in our experience.

After flow rules on all involved switches have been set up, the last practical matter pertains to packet reassembly on the NPU at the egress switch. During RAIL service negotiation, the NPU is informed of the set of reserved destination Ethernet addresses corresponding to the original flow, and the original destination Ethernet address for that flow. Incoming packets are then binned according to the original flows they map to. Duplicates are discarded. Whenever sufficient packets have arrived, the original packet is reconstructed and rewritten to reflect its original Ethernet destination address and Ethertype (which is always `0x0800`). The packet is then put into a re-order buffer that maintains the original packet sequence. The re-order buffer releases packets from the NPU as they become available in the correct sequence. The egress switch then forwards the packet along to the true destination.

3.4.2 RAIL 1

We now describe the individual RAIL schemes. Recall that the equivalent scheme in RAID 1 is a simple mirroring process that trades storage capacity for speed and fault tolerance. Analogously, the RAIL 1 scheme replicates data packets across multiple disjoint paths, with the effect that latency and fault tolerance is improved at the cost of bandwidth efficiency. If the disjoint paths have approximately similar end-to-end latencies, RAIL 1 may also reduce latency variance.

For simplicity, we describe the flow rules and actions for a unidirectional data transfer. Bidirectional data transfer can be achieved either by relying on the network's intrinsic backward path over its spanning tree, or by installing another unidirectional RAIL scheme in the opposite direction. Bidirectional data transfers are not required to employ identical RAIL schemes in each direction.

On the ingress switch, a single matching rule for the selected network flow is installed with an action that multicasts packet output to physical ports corresponding to the relevant disjoint physical links. The switch automatically replicates the network packets without further intervention from the controller. Switches along the disjoint paths act as mere waypoints and thus only need one rule each to forward network packets to the next hop. Because the egress switch potentially receives redundant copies of each network packet, de-duplication is required. At this egress switch, the subflows are redirected to an NPU that removes redundant packet copies, before re-emitting the packet back to the switch for delivery to the destination.

3.4.3 RAIL 0

On the other end of the RAID spectrum of tradeoffs is the ability to aggregate multiple storage volumes into one single logical volume. This maximizes the storage efficiency of the scheme, but completely trades away any fault tolerance. In RAIL 0, the available disjoint physical link bandwidths are aggregated together into one logical link. This translates to maximal bandwidth utilization efficiency, but has a statistically greater failure rate than RAIL 1 or even single path connections. RAIL 0 also suffers from higher packet jitter and higher latency, since the latency effects of all links will be evident at the destination.

The RAIL 0 scheme requires support from OpenFlow, but cannot be implemented alone by rules. In this scheme, each ingress flow packet is tagged with some disjoint path meta-address such that the relevant OpenFlow rules will later divert subflows down the respective disjoint paths.

At the ingress switch, several flow rules are required. First, a rule is installed to divert the flow into an NPU that tags each packet with the meta-address of some disjoint path. Another set of rules matches each meta-address and forwards the tagged packets onto their corresponding disjoint path. Switches along the disjoint paths merely forward packets on to their respective next hops, so only one rule is required on each of them.

At the egress switch, a set of rules are installed to forward the tagged packets to a local NPU. This NPU will buffer, reorder and rewrite packets such that emitted packets appear identical in content and sequence to the original flow at the ingress switch. Another rule on the egress switch then takes these packets to the actual destination.

3.4.4 RAIL 3 - 6

RAID levels 3-5 [1] are similar on account of using parity protection to secure data from single failures, with the only differences being the sizes and placements of

[1] We omit the discussion of RAIL 2 because RAID 2 uses Hamming codes and the equivalent network scheme is needlessly complicated without yielding significant benefits.

parity blocks. In RAID 3, this parity block size is one byte while RAID 4 uses a larger block size. Both RAID 3 and RAID 4 use a dedicated parity disk. RAID 5 is similar to RAID 4, except that parity blocks are distributed evenly over all disks. Because these schemes are conceptually identical, we describe RAIL 4. The RAIL 4 scheme has a relatively light traffic footprint while being tolerant of single failures.

At the ingress switch, rules are installed to divert a target flow into the NPU. For each ingress packet, the NPU needs to split the Ethernet payload into $n-1$ disjoint fragments, where n is the number of disjoint paths chosen. If the resultant fragments have uneven sizes, for parity computation purposes the smaller ones are padded to the right with a zero such that all fragments have the same size. A parity fragment is then constructed by computing the XOR of all fragments, essentially assuming the form of forward error correction.

Each of the n fragments are then given an Ethernet header with its original source address, designated disjoint path destination meta-address, and an Ethertype corresponding to the sequence number of the fragment. The synthesized packets are then sent to the switch for transmission along disjoint paths. Padding bytes are not sent with the fragments.

At the egress switch, subflows are sent to the local NPU. Because of the presence of a parity subflow, only $n-1$ packets are required for the reconstruction of an original packet so the flow is able to tolerate the complete loss of one disjoint path. However this reconstruction is tricky: if the excluded fragment had been padded for parity computation, its regeneration will include the padding byte. To fix this problem, the reconstruction process consults the size field in the IPv4 header and checks this against the sum of all fragment sizes. A difference sig-

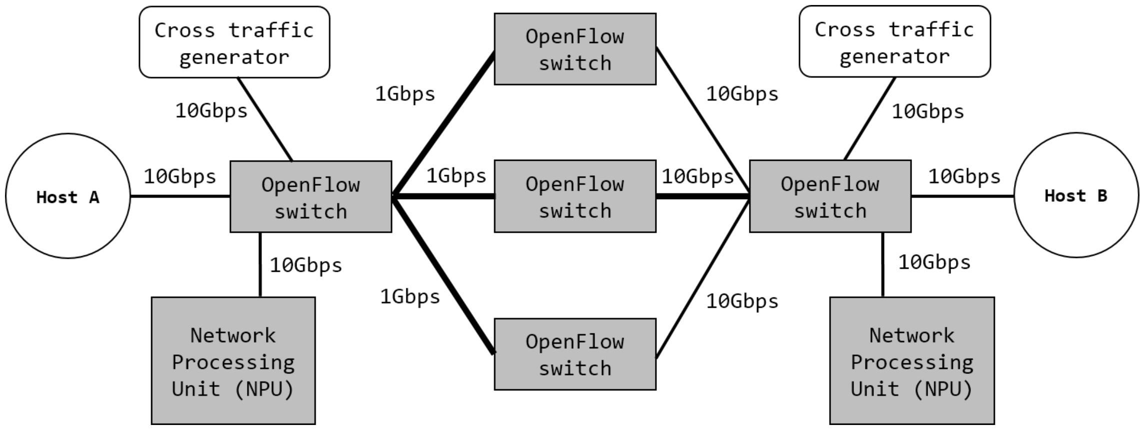


Figure 3.3: The topology used in our evaluation. Bold lines represent spanning tree links.

nifies the presence of the padding byte and it is truncated from the regenerated fragment. The original Ethernet payload can then be recovered by rejoining the fragments in sequence order. Finally, the Ethernet header is prepended to yield the original packet. The NPU then buffers and reorders the packet for appropriate release to the egress switch, which then conveys the packet on to the destination.

RAIL 6 could theoretically improve upon the reliability offered by RAIL 4 to tolerate double losses, although its implementation is significantly more complicated due to the need to construct a computationally-expensive second parity packet.

3.4.5 Generalized *k* of *n* RAIL protection schemes

If the RAIL 0 and RAIL 1 schemes are conceptually at diametrically opposed ends of the tradeoff spectrum, then other alternative schemes can be designed to bridge the gap and provide continuity between the two extremes. We now describe a general scheme that is identical in spirit to hybrid RAID 1 + 0 setups. This scheme is computationally cheap and simple to implement, albeit imperfect in its bandwidth usage.

Given a set of n selected disjoint paths, the paths are first ordered in a ring. Each successive ingress packet is duplicated over the next $k + 1$ paths in the ring. For example, if $n = 3$ and $k = 1$, the first packet in the flow will be sent over paths 1 and 2, the second packet over paths 3 and 1, the third packet over paths 2 and 3. This scheme has the property that the failure of any k paths still allows complete reconstruction of the original flow at egress. Additionally, the ratio of the bandwidth efficiency of this scheme to the maximum possible without duplication is $\frac{1}{k+1}$. Tuning the parameter k therefore allows the user to set the tradeoff between fault tolerance and bandwidth efficiency. When $k = 0$, the algorithm converges to RAIL 0, with maximum bandwidth efficiency but no fault tolerance. On the other hand, when $k = n - 1$, the algorithm converges to RAIL 1, tolerating the failure of all but 1 disjoint path, at the cost of experiencing a $1/n$ bandwidth efficiency ratio. The manner in which packets are tagged and forwarded at the ingress switch, as well as untagged, de-duplicated, reordered and reassembled at the egress switch, is exactly identical to the process described in RAIL 0.

3.5 Modifying a flow in-flight

In general, it is difficult to protect flows a-priori because flow tuples are hard to predict. The reason is that TCP and UDP flows rely on a random source port, and without knowledge of this port, it is impossible to install flow rules before data transmission begins. However, such a requirement is needlessly draconian and we describe a method to set up flow enhancement schemes on-the-fly.

All network flows begin in the non-enhanced mode. We assume that an ARP has been performed earlier so that end hosts know the IP-to-Ethernet address translations, and controllers in the network have learned the Ethernet-address-to-port mappings as per snooping on ARP replies described in section IV.B.3. A regular flow rule is automatically negotiated on all switches in the spanning tree path between the end hosts, if such a rule does not yet exist. From this point on, all packets exchanged between the two systems take place automatically over the single path as provided by the spanning tree.

When a user desires enhanced mode operation on one of its flows, it indicates this as a request to the controller at the immediate OpenFlow switch. The request can be made in many ways, for example through a web site hosted on controller itself, or by running a special utility on the requesting system that negotiates with the controller. In any case, the pertinent flow information is supplied to the OpenFlow controller.

Depending on the RAIL scheme employed, the controller sets up the disjoint forwarding paths by informing remote controllers to install the relevant rules. Installation of rules proceeds backwards from the most distant to the nearest switch, such that the last system to install the rules is the switch immediately adjacent to the requesting host. Since all forwarding rules beyond the first hop have already been set up, installation of the final set of rules will cause the flow to seamlessly switch over from non-enhanced to enhanced mode. Should any flow rule fail to install correctly, the entire procedure is aborted and rolled back, undoing any changes made.

3.6 Scaling the RAIL service

The main bottleneck in a RAIL deployment is the NPU, as real-time packet processing is an intensive operation. A single NPU on an ingress switch may not be sufficient to support all interested clients simultaneously.

To solve this problem, service may be linearly scaled by attaching additional NPUs where they are needed. This is typically as simple as identifying a spare port on the ingress OpenFlow switch and plugging another new NPU into that port; the OpenFlow controller can then register the NPU for immediate use. The controller may also load-balance the local NPUs dynamically by shunting flows to less-loaded units.

If no more spare ports are available, a possible solution would be to spread wire connections on the existing switch over two new switches, effectively spacing out the cables over more switch ports to avail more attachment points for NPUs. The old network topology can be functionally retained by bridging these two switches with a high speed interconnect, for example through a 40Gbps link aggregation switch port.

3.7 NPU implementation

We now describe our experience with different NPU designs.

Using the OpenFlow controller directly as the NPU

Our very first and naive implementation of the NPU used the OpenFlow controller to provide RAIL services. In this implementation, the controller directly processes `PACKET_IN` events corresponding to data from the selected flow, and rewrites these packets before emitting them back onto the switch via `PACKET_OUT` actions. Our intuition was that a controller directly connected to the switch over a dedicated 1Gbps network link should have high speed access to packets that miss flow rules. Although we were not expecting packet transfer rates to saturate the link, we had at least hoped to attain rates that would be high enough to support RAIL schemes over 100Mbps Ethernet links.

Unfortunately, the maximum throughput we could achieve from `PACKET_IN` was 2.56Mbps, far too low to be useful even in deprecated 10Mbps networking. Furthermore, the end-to-end latency using Ethernet spanning tree was 0.18ms. Considering that the added latency of 1.1ms by the switch-to-controller link was an order of magnitude higher, the controller-based NPU would have rendered the performance of all RAIL schemes worse than without enhancement!

In retrospect, poor performance was to have been expected because the OpenFlow hardware needs to extract packets from the data plane into the control plane over a low-speed bus before composing the contents into a `PACKET_IN` message and transmitting it with TCP flow control over another network interface. Nevertheless, it is conceivable that future switch designs [72] [73] may streamline this control-to-data plane path and increase the switch-to-controller bandwidth while also reducing its latency.

Dedicated computer as the NPU

Our second NPU design used high-end Dell Optiplex 990 desktops, featuring Intel Core-i7 processors (8 cores) with 16Gb of RAM, running the latest Ubuntu 14.04 operating system. To ensure bandwidth parity with the switch, each NPU system was equipped with a 10Gbps Myricom Ethernet card.

We attempted several variations of using these commodity computers as NPUs. All approaches worked well for sending packets out of a network interface, and we were easily able to attain 8.5Gbps (line rate based on 536 bytes MTU) egress traffic. However, ingress traffic was more problematic and we could not find a way to reliably receive packets at the same speed. Our implementation using libpcap and later, using packet sockets[2], attained only a maximum initial speed of 7.5Gbps for a few moments before steadily declining. We noticed in both implementations that a lot of packets were being dropped by libpcap and the packet socket after the initial burst of speed, even though the network interface and the driver themselves did not report any packet loss. After some investigation, we deduced that the transfer rate from the network interface card to the userspace packet processing utility was insufficient to keep up with the ingress traffic rate. Profiling the packet processing utility yielded no bottlenecks in the userspace software. Socket buffering only delayed the onset of the problem.

Although we are convinced from simulations that line-rate software packet processing is possible on commodity desktops, our experimental data does not appear to bear this out. We believe that moving the processing code into the ker-

[2]We also attempted to use PF_RING, however our hardware was incompatible with the zero-copy driver so we were unable to attain results any better than our libpcap and packet socket implementations.

nel or network device driver, or using Netslice [66] would dramatically speed up packet handling. That is one objective of our future work.

We designed an FPGA hardware NPU specifically to handle packet processing duties at line speed. For this purpose, we selected a NetFPGA 10G card, which provides four 10-Gigabit Ethernet ports connected to a fully-programmable Xilinx Virtex-5 FPGA. Logic in the FPGA matches packet headers based on predefined rules, rewriting destination MAC addresses to distribute packets evenly for RAIL 0, dropping duplicate packets for RAIL 1, or striping packets for RAIL 4. The card was well-suited for line rate traffic; during experiments, we noticed no dropped packets and the latency cost of forwarding packets through the card was too small to measure. Consequently, we were able to saturate all three disjoint paths in our topology to attain 2.55Gbps aggregate bisectional bandwidth, an almost-perfect 3x speed up.

Like RAID hardware controllers, these findings support our beliefs that a hardware-based NPU is viable. The perfect scaling also suggests that the hardware has ample capacity and would likely cope with higher workloads.

3.8 Evaluation

To evaluate our system, we used a Dell Force10 S4810 switch partitioned by port banks into five OpenFlow instances, in effect simulating five physical OpenFlow switches (Fig 1). The instances were connected in a way to simulate a network topology with three disjoint paths between a source to a destination. All physical links had a capacity of 10Gbps except for one link on each disjoint path, which was deliberately throttled in hardware to 1Gbps. Therefore, the total bandwidth available to any single disjoint path between two end hosts that traversed this network was 1Gbps. Because there were three disjoint paths available, the maximum available bandwidth was 3Gbps. A spanning tree-based path, on account of a singular end-to-end path, therefore had an available capacity of only 1Gbps. Two additional systems were introduced to the edge network switches connecting the two end hosts to inject cross traffic into the spanning tree path.

Two NPUs were connected to the experimental setup. One NPU was located on each virtual switch corresponding to the edge network switches that connected the two end hosts. The NPUs were NetFPGA 10G cards, each providing four 10-Gigabit Ethernet ports connected to a Xilinx Vertex-5 FPGA. Purpose-designed logic in the FPGA performed the various duties of rewriting, reordering and deduplicating packets. The cards were well-suited for line rate traffic; during experiments, we noticed no dropped packets and the latency cost of forwarding packets through the card was too small to measure.

To save on hardware requirements, the OpenFlow controllers were run as separate processes on the same physical machine. One controller was mapped to each OpenFlow switch partition. We deemed this to be a reasonable compromise because the controllers do not consume excessive CPU or memory resources. Moreover, they do not communicate with one another directly – all interprocess communications occur via packets exchanged over the switch. Functionally, it would have been identical to running five controllers on five machines.

Silent failures were simulated by terminating the controllers, while link failures were introduced by physically disconnecting switch cables.

	Ethernet STP	RAIL 0	RAIL 1	RAIL 4
Latency `min/avg/max`	0.122ms 0.152ms 0.185ms	0.126ms 0.166ms 0.196ms	0.125ms 0.160ms 0.210ms	0.125ms 0.158ms 0.184ms
Bandwidth	0.85Gbps	2.55Gbps	0.85Gbps	1.52Gbps
Link failures tolerated	0	0	2	1

Table 3.1: RAILS microbenchmark results, without cross traffic.

	Ethernet STP	RAIL 0	RAIL 1	RAIL 4
Latency `min/avg/max`	4.017ms 11.911ms 17.506ms	0.126ms 3.244ms 13.157ms	0.125ms 0.161ms 0.200ms	0.126ms 0.175ms 0.215ms
Bandwidth	0.51Gbps	2.02Gbps	0.85Gbps	1.52Gbps
Link failures tolerated	0	0	2	1

Table 3.2: RAILS microbenchmark results, with cross traffic.

To benchmark end-to-end bandwidth in our system, we ran `iperf`, a TCP/UDP bandwidth measurement tool to measure aggregate bandwidth between two hosts. Because of a persistent hardware configuration issue in the 10G network interface cards we used, the MTU used in the experiments was 536 bytes. Cross traffic was generated by running bidirectional iperf. End-to-end latencies were measured using the system ping utility and listed respectively in the table as min/avg/max over 100 samples. Our microbenchmark results are shown in tables 3.1 and 3.2.

3.9 Conclusion

We presented the design of a novel solution that provides tunable high performance and reliability for OpenFlow data networks via RAIL schemes that are analogous to RAID. RAIL schemes are supported by network processing units, similar to RAID controllers. Our proposed system is backward-compatible with existing hardware and software. RAIL service capacity can be scaled linearly by adding more NPUs as required. Finally, the evaluation shows that our proposed system is practical and offers real, tangible improvements over existing network setups.

CHAPTER 4

RETROFITTING SECURITY OVER ETHERNET

Confidentiality and anonymity have traditionally been implemented using a combination of encryption and onion routing, both of which require public-key infrastructure (PKI). In recent years, a new PKI-less technique known as Information Slicing was proposed. This technique utilizes disjoint paths and a overlay network in order to realize confidential and anonymous communications over IPv4 networks, but requires special software and some minimum number of peer nodes. Unfortunately the method is ill-suited for direct operation over Ethernet. We adapt Information Slicing to Ethernet software-defined networks, and show that confidentiality and anonymity can be built directly into software-defined networks at the data link layer without necessitating change or awareness in the operating systems or hardware of network clients.

4.1 Introduction

Confidentiality and anonymity have always been user concerns, although networks and protocols were not always designed with these in mind. Today, confidentiality is primarily maintained through the use of cryptography, which transforms plaintext into ciphertext. Ciphertext is unintelligible to eavesdropping parties and the plaintext content may only be recovered with the proper key. Cryptography therefore maintains confidentiality; however, encrypted conversations over the Internet are still subject to other analytical methods. In particular, there is no anonymity at all, as encryption does not protect IP headers so an eavesdropping system can infer the identities of the communicating endpoints even if it cannot recover the contents.

The traditional way of providing anonymity on the Internet is to use anonymizer software such as Tor [41], which relies on a technique known as onion routing. Many variants of anonymizers exist; many of these exploit the large number of peer-to-peer nodes available in a swarm to conceal traffic patterns. Onion routing software depends upon a public key infrastructure and one/some trusted directory node(s) in order to perform layered encryption of message contents.

In recent years, Sachin et al. proposed a method [55] of providing confidentiality and anonymity that does not rely on onion routing or in fact any public key infrastructure at all. The Information Slicing technique relies on the availability of multiple host IP addresses on each peer. Information traversing between peers is subjected to a mathematical treatment that 'slices' each piece of data into multiple fragments that are then sent down each path. Confidentiality is maintained because without a threshold number of slices, the original plaintext cannot be recovered. Anonymity is achieved using an overlay forwarding scheme.

We see a broad need for such solutions. Today, many users rely on some form of enterprise Ethernet network for their connectivity needs. Typical examples include campus networks, office buildings and government intranets. However, vanilla Information Slicing is ill-suited for direct application over regular wired Ethernet intranets. This difficulty stems from several factors:

- Most commodity network hosts are not multihomed, so they are unable to get access to multiple IP addresses.
- In hosts with multihoming or multiple IP addresses, it is quite possible that the physical IP routes are non-vertex disjoint.
- Many network hosts, such as IoT devices, are tamper-proof and cannot be user-retrofitted to provide confidentiality and anonymity.
- There may not be enough, or any peer nodes on the local Ethernet intranet to collaborate with for sufficient anonymity.

Because our new solution overcomes problematic assumptions, it represents a realistic option for such setting. Here, we describe EtherSlice, an adaptation of Information Slicing to Ethernet that (a) avoids the aforementioned problems while (b) being fully backward-compatible with existing hardware and software, (c) without requiring any peer nodes. EtherSlice can be used to retrofit confidentiality and anonymity onto existing networks.

4.2 Information Slicing Primer

Since EtherSlice depends heavily upon Information Slicing [55], we start with a quick overview of the work. The fundamental primitive in Information Slicing makes it possible to transmit a single message confidentially without relying on public or symmetric key encryption. This is done by taking a plaintext m and dividing it into d fragments, where d is a configurable parameter representing the minimum number of slices required for recovery of the plaintext. The fragments are arranged into a rectangular matrix $\overrightarrow{m}$ with d rows and $\lceil \frac{|m|}{d} \rceil$ columns. A full-rank random matrix A of dimensions d'xd is generated, where d' is another configurable parameter dictating the total number of fragments that will be generated after slicing. The random matrix A is then premultiplied to $\overrightarrow{m}$, forming $\overrightarrow{I^*}$, which is a matrix containing d' rows and $\lceil\frac{|m|}{d}\rceil$ columns. Each row $\overrightarrow{I_i^*}$ of this resultant matrix is then concatenated with A_i, the corresponding row of the random matrix A, to form an information slice. Each information slice is sent down a disjoint path. An adversary that collects lesser than the threshold d number of fragments cannot regenerate the plaintext because it is missing some number of information bits. When $d' > d$, the slicing scheme loses some resistance to confidentiality attacks but gains some redundancy in that up to $d' - d$ fragments may be lost without affecting the ability to regenerate the original plaintext.

In the next portion of their work, Sachin et al. note that *anonymity can be built out of confidentiality*. For anonymous communications, a forwarding graph is designed such that $L \times d$ overlay nodes collaborate together over d paths each with L stages. The destination node may be located at any stage within in this graph. For each overlay node, the source confidentially sends each node information about the latter's children nodes, taking care to ensure that the confidential message to setup the forwarding information does not travel through the same node (ie, is vertex disjoint). Because the receiver may be located at any stage in the forwarding graph, it may be required to continue forwarding data on to other children nodes. The receiver knows that it is the destination of the message because the source sends this node a special receiver flag to indicate so. For bidirectional communications, the destination can use a similar procedure to establish a forwarding graph to the source.

Symbol	Definition
m	Original plaintext message.
$\overrightarrow{m}$	Plaintext message arranged into a matrix of d rows and $\lceil \frac{\lvert m \rvert}{d} \rceil$ columns.
d'	Split factor, ie. number of slices a plaintext is transformed to.
d	Threshold slices, ie. minimum number of slices required for plaintext reassembly.
A	A random $d' \times d$ matrix of rank d.
A_i	ith row of the random matrix A.
$\overrightarrow{I^*}$	Presliced version of the transformed message. $\overrightarrow{I^*} = A\overrightarrow{m}$
$\overrightarrow{I_i^*}$	ith row of the presliced, transformed message.
L	Number of stages in an anonymizing path.
N	Total number of nodes used in the anonymizing network, excluding the source node.

Table 4.1: Table of symbols used in the Information Slicing paper.

Table 4.1 presents the list of symbols that are used in the Information Slicing work. For consistency, we use the same notation[1] in this chapter.

4.3 Assumptions and threat model

In our target setting, we assume that the network features a pervasive deployment of OpenFlow switches driven by a controller. Each OpenFlow switch is connected to a network processing unit (NPU), which is a dedicated (possibly lightweight) system used to perform information slicing on network packets, ideally at line rate. The OpenFlow controller, SDN switches and NPUs are trust-

[1]In our work, a node is an NPU-equipped OpenFlow switch. The source node refers to the ingress switch that slices data; conversely the destination node is the egress switch that reassembles data slices.

worthy and non-Byzantine. The network is also suitably wired to permit at least two disjoint paths between any source-destination pair of switches.

We assume an adversary that can snoop on some fraction of the trunk data links, but not the direct links connecting network clients to their immediate switches. We also assume that the adversary cannot snoop on the OpenFlow control network, as it is typically protected by encryption. As in the Information Slicing work, we do not consider an all-powerful adversary that has snooping access to all network links, or an adversary that has access to all disjoint paths in a source-destination pair. Denial-of-service attacks are not considered in our model, so the adversary does not modify data packets or otherwise interfere with data delivery. We believe these are reasonable assumptions because attackers are generally constrained, but have incentive to position themselves where they have snooping access to multiple targets while remaining passive to avoid detection.

Quite critically, we do not impose restrictions on users of the network, so they are free to run their own (possibly insecure) IPv4 software or hardware, oblivious to underlying changes in the network.

4.4 Problems with Information Slicing over Ethernet

In this section, we discuss some problems that hinder the direct deployment of vanilla Information Slicing onto Ethernet networks.

4.4.1 Non-multihomed hosts

The communication model adopted by Information Slicing requires access to multiple IP addresses from a single sender. However, most enterprise Ethernet network users today are non-multihomed in that each host has just one network interface. In many commodity network applications such as IoT-enabled hardware and embedded systems, it may be impractical or physically impossible to augment the hardware or software to support multiple network interfaces. Although it is possible for a device to acquire multiple IP addresses over a single network interface [86], such network setups are uncommon and tedious to configure.

4.4.2 Physical paths may not be disjoint

The dependence of Information Slicing on multiple IP addresses reflects a deeper assumption: the need for vertex disjoint network paths. The premise of confidentiality is completely determined by the ability to transport message slices across vertex-disjoint paths. Confidentiality can be compromised if an adversary gains access to d (i.e. the threshold) number of slices. However, with IP overlay networks, there is no guarantee that the underlying paths taken by the message slices are actually edge or vertex disjoint. In fact, on many Ethernet networks running the Spanning Tree Protocol [14], an overlay network does not provide any path disjointness as all endpoint-to-endpoint traffic traverses common links in the tree. This allows a suitably positioned attacker to gain access to multiple message slices even if the sender was under the impression that the overlay network provided anonymity.

Certain network setups provide multiple distinct Ethernet spanning trees through separate VLANs. In these setups, it is conceivable that some paths between certain source-destination pairs are actually vertex disjoint. However, this is not a generic solution because VLAN tags are a finite resource (up to 4094), and furthermore an attacker can observe and exploit situations in which one client uses different VLANs for reaching certain nodes.

4.4.3 Too few peer nodes

Anonymity over Information Slicing depends on access to peers that can assist with anonymizing traffic. Thus, beyond the physical and hardware requirements, to obtain anonymity within an Ethernet network, a substantial number of active local peers would be required. However, on a small network, the number of available local peers may be too few to provide substantial confidentiality and anonymity.

4.4.4 ARP

Another problem with anonymity arises with intranet IP communications. Normally, when a host wishes to communicate with another host on the same network, an ARP broadcast is performed to resolve the IP to Ethernet address mapping. This is problematic for anonymity because it reveals the anonymizing set on the network itself, even if the exact destination may not be known.

4.5 Operating the EtherSlice network

A high-level overview of operations on the EtherSlice network is presented here; the technical details are in the subsequent sections.

An network user specifies a destination IP or Ethernet address and conveys his desire for a confidential or anonymous flow to his immediate OpenFlow switch, which then forwards the request to the SDN controller. Note that throughout the request, the message only transits trusted channels; as per our assumptions, the attacker can only snoop on the trunk data links. The SDN controller consults its local topological map of the network and computes the disjoint paths for the user. It then installs the OpenFlow rules to forward the user's data flow through the necessary NPUs and disjoint network paths. In operation, after the setup phase, a user may transmit protected data towards the destination without any change or awareness in its application, operating system or hardware; likewise the destination receives the data without any such knowledge. The changes are purely in the data network itself, and the EtherSlice system ensures that packets transiting the trunk data links are appropriately sliced to provide confidentiality or anonymity.

4.6 Implementation

The Ethernet Spanning Tree Protocol and its variants do not permit multiple disjoint paths between source-destination pairs. We can circumvent this restriction using software-defined networking (SDN) techniques. In our setup, all data switches are OpenFlow-based and are controlled by a logically centralized controller. Each data switch is connected to a network processing unit (NPU), which is used to support high-speed packet processing operations in EtherSlice. The SDN controller detects the topology of the entire network and provisions a default spanning tree with L2 learning switches for regular data flows. Thus the network operates and feels like a regular, non-SDN network by default.

For flows requiring confidentiality or anonymity, the controller selects participating switches and computes the necessary disjoint paths among them according to the desired level of confidentiality or anonymity. Each disjoint path between two switches is associated with a meta-address. Meta-addresses can be any unique unused and unreserved Ethernet MAC address, as they serve merely as special destination tags that instruct the SDN controller to forward data outside of the default spanning tree routes.

At each switch that performs information slicing or reassembly, rules are installed to divert ingress data to the local NPU. The ingress data could be plaintext, as in data directly transmitted from an end-host that require slicing, or slices of data from an upstream slicing unit that require reassembly. Depending on the operation required, the NPU performs the relevant transformation and emits the transformed data back into the switch, where the data is forwarded onto disjoint paths or directly to the destination.

The aforementioned steps detail the establishment of a unidirectional flow. For bidirectional communications requiring confidentiality or anonymity, the same procedure above can be repeated with the source and destination roles reversed. However, the disjoint paths and set of switches used may be different.

The following listings outline the various operating algorithms on this network.

Algorithm 1 Network cold start algorithm

```
1: procedure SDNSpanningTree
2:     $S \leftarrow$ set of all switches in the SDN
3:     Wait for all switches to connect to controller.
4:     Flush all rules in all switches.
5:     for each switch $s \in S$ do
6:         for each switch port $p \in s$ do
7:             Send a unique topology probe message on $p$.
8:         end for
9:     end for
10:    for each switch $s \in S$ do
11:        Collect topology probe messages.
12:    end for
13:    Infer network topology.
14:    Compute a spanning tree.
15:    for each switch $s \in S$ do install:
16:        ARP intercept rule.
17:        DHCP snooping rules.
18:        Flow miss rule.
19:    end for
20:    Operate all switches in regular L2 learning mode.
21: end procedure
```

The individual rules are:

ARP intercept rule:

```
Match:  EtherType = 0x0806, Action:  fwd to controller
```

DHCP snooping rule:

```
Match:  UDP packet, port = 66 or 67, Action:  fwd to controller
```

Flow miss rule:

```
Match:  *, priority 1.  Action:  fwd to controller
```

Algorithm 2 Regular learning/forwarding switch

```
procedure LearningSwitch
    $S \leftarrow$ set of all switches in the SDN
    for all switches $s \in S$ do on a flow miss:
        Obtain source mapping information from the flow miss/DHCP packet.
        Update controller's ARP table with this information.
        Lookup Ethernet dest from ARP table.
        if $dest \mapsto \emptyset$ then
            Drop packet.
        else
            Identify the relevant spanning tree port $p$ on $s$.
            Install an L2 rule to forward future packets for this Ethernet destination to $p$.
        end if
    end for
end procedure
```

Algorithm 3 Installing a one-way confidential flow

```
1: function MakeConfidentialFlow
2:     $S \leftarrow$ set of all switches in the SDN
3:     $d' \leftarrow$ total number of slices
4:     $d \leftarrow$ threshold number of slices, $d' \geq d$
5:     $src_{IP} \leftarrow$ IP address of source
6:     $dest_{IP} \leftarrow$ IP address of destination
7:     $src_{Eth} \leftarrow$ Ethernet address of source
8:     $dest_{Eth} \leftarrow$ Ethernet address of destination
9:     Lookup ARP table to obtain $src_{Eth}$ and $dest_{Eth}$ from $src_{IP}$ and $dest_{IP}$.
10:    if $src_{Eth} \mapsto \emptyset$ or $dest_{Eth} \mapsto \emptyset$ then return failure.
11:    end if
12:    $s_{in} \leftarrow$ Ingress switch
13:    $s_{out} \leftarrow$ Egress switch
14:    Compute $R$, the set of disjoint paths between $s_{in}$ and $s_{out}$.
15:    $S_{disjoint} \leftarrow$ all switches in R
16:    if $|R| < d'$ then return failure.
17:    end if
18:    for each path $r_i \in R$ do
19:        Assign an available meta-address $m_i$ to $r_i$, where $p_{s,i}$ is the output port
   for $r_i$ on switch $s$.
20:    end for
21:    for each switch $s \in R$ do
22:        $p_{s,NPU} \leftarrow$ port on switch $s$ connected to the NPU.
23:        if $s \equiv s_{in}$ then
24:            Install rule: forward $src_{Eth}$ to $p_{s,NPU}$.
25:            for each path $r_i \in R$ do
26:                Install rule: forward $m_i$ to port $p_{s,i}$.
27:            end for
28:        else if $s \equiv s_{out}$ then
29:            Install rule: forward $dest_{Eth}$ to the egress port for this Ethernet
   destination.
30:            for each path $p_i \in R$ do
31:                Install rule: forward $m_i$ to port $p_{s,NPU}$.
32:            end for
33:        else
34:            Install passthru rule: forward $m_i$ to port $p_{s,i}$.
35:        end if
36:    end for
37:    Return success.
38: end function
```

Algorithm 4 Installing a one-way anonymous flow

```
1: function MakeAnonymousFlow
2:     $S \leftarrow$ set of all switches in the SDN
3:     $d' \leftarrow$ total number of slices
4:     $d \leftarrow$ threshold number of slices, $d' \geq d$
5:     $src_{IP} \leftarrow$ IP address of source
6:     $dest_{IP} \leftarrow$ IP address of destination
7:     $s_{in} \leftarrow$ Ingress switch
8:     $s_{out} \leftarrow$ Egress switch
9:     $n \leftarrow$ no. of anonymizing switches to use, $n \geq 3$
10:    Construct a list $L$, where $L_0 \equiv s_{in}$ and $s_{out} \in L$. The remaining $n - 2$ items
       are randomly selected switches from $S$ arranged in a random order.
11:    for each switch $s_i \in L, s_i \not\equiv s_{in}$ do
12:        Run MakeConfidentialFlow to provision a confidential flow between
           $s_{in}$ and $s_i$.
13:        Inform $s_i$ of its successor switch $s_{i+1}$ through a confidential message
           from $s_{in}$.
14:        If $s_i$ is the intended destination, send $s_i$ a flag through a confidential
           message from $s_{out}$.
15:        Run MakeConfidentialFlow to provision a confidential flow between
           $s$ and its successor $s_{i+1}$.
16:    end for
17: end function
```

4.7 Adapting the communications model for EtherSlice

In order to retrofit Ethernet for the purposes of transparently providing confidentiality and anonymity to existing network clients, a number of significant changes have to be made, particularly with respect to the ARP discovery process.

The usual first step in establishing IP communications between two hosts on Ethernet is the broadcast of an ARP discovery message. Given a recipient's IP address, the sender attempts to discover the Ethernet address of the recipient through an ARP broadcast. However, in a privacy-preserving setup, this step is problematic because it reveals the identity of the destination endpoint. Keeping in line with our promise not to require changes in the hardware or software of network clients, the challenge here is to satisfy ARP requests without revealing any information.

We make two adaptations in our SDN to accomplish this: a controller-maintained ARP table, and controller-mediated ARP/DHCP replies.

4.7.1 Controller ARP learning

The first change we make is to copy all DHCP and flow-miss messages to the controller. The goal here is for the controller to become aware of the global mappings between Ethernet and IP addresses at the earliest opportunity. These rules are easy to install: at each switch, DHCP-related traffic can be matched by two independent rules that watch UDP ports 67 and 68, while flow-miss messages can be trapped by a single catch-all wildcard rule installed with the lowest priority.

In either case, packets that are forwarded to the controller are inspected for their Ethernet/IP mappings. Acting on this information, the controller maintains an authoritative, up-to-date ARP table for these mappings.

4.7.2 Controller-mediated ARP replies

The second required change modifies the behavior of ARP over Ethernet. Under normal operation, the ARP discovery message is an Ethernet broadcast packet (ie. Ethernet destination address `FF:FF:FF:FF:FF:FF`) containing the IP address whose corresponding Ethernet address a host wishes to look up. This broadcast packet is propagated to every switch and host over the network. However in the EtherSlice system, we suppress the propagation of ARP packets by installing a rule on every switch that redirects all ARP-related traffic to the controller. This is easy because ARP messages have the exclusive EtherType of `0x0806`.

The controller intercepts ARP queries at their ingress switches and replies directly to them by consulting its authoritative internal ARP table. If no mapping exists, the controller does not reply but for safety reasons, it also does not flood the network with the ARP query like a normal network would. Because the controller replies to ARP queries directly at their ingress switches, ARP probes can be satisfied without propagating them over the network. Thus, under our threat model, the attacker cannot learn any information about the intended destination.[2] As a side benefit, this approach also reduces the broadcast load on the network since a substantial portion of broadcast traffic is due to ARP [44].

4.8 Resistance to Attacks

In this section, we detail the resistance of our EtherSlice system to certain attacks that may compromise the confidentiality or anonymity of protected flows on the network.

4.8.1 Ethernet spoofing

A malicious entity operating on the network may attempt to exfiltrate information slices that it is not entitled to by spoofing a target Ethernet address. For example, if Alice and Bob have established a confidential flow, a malicious entity may try to steal information slices by spoofing either Alice or Bob's Ethernet address.

Ethernet address spoofing can be detected from the EtherSlice SDN controller through the installation of appropriate L2 rules. These rules must include the Ethernet source, Ethernet destination and source port. Spoofing can be detected because a flow miss event will be raised when a (address, port) tuple is not matched on a switch.

[2]The controller-mediated ARP system does not work for completely passive hosts that bypass the DHCP system with statically-assigned IP addresses. The controller would be unable to learn ARP mappings without any traffic from these hosts. However, this is usually not a problem because most hosts emit some traffic periodically.

4.8.2 Sybil attacks

Our EtherSlice implementation is resistant to Sybil attacks because the anonymity of communications is provided by the switches, which are part of the trusted network infrastructure, and not by the network users themselves. Thus, while an attacker may try to overwhelm the network through a denial-of-service attack by creating many false Ethernet identities, he cannot coerce switches to deliver him slice data from other network users.

4.8.3 TCAM attacks

Malicious entities that try to cause TCAM overflow attacks can be quickly identified by observing a disproportionate number of Ethernet source addresses coming from a port. This port can be shutdown to prevent more traffic from it. Also, the L2 rules installed for the verified users should never be flushed to make room for new Ethernet addresses.

4.8.4 Rogue DHCP agents

One weakness with our approach of passively snooping on DHCP traffic is that it does not prevent the effects of a rogue DHCP server or client. A malicious DHCP server can compromise information security or cause denial-of-service on the data network. For example, it could award a DHCP lease with a DNS and/or gateway pointed at itself, which would allow the rogue DHCP server to intercept traffic and operate as a man-in-the-middle. It could also cause IP address conflicts by offering an IP address more than once, or by offering an IP address that is invalid for routing within the network.

Rogue DHCP clients can also cause denial-of-service attacks by exhausting all available IP addresses from the DHCP server. This prevents other users from acquiring an IP address for use on the local network.

It is possible to mitigate the effects of both scenarios by relaxing some assumptions about the system. If we permitted the SDN controller to recognize certain systems as safe and trusted, we can authorize them to handle DHCP requests. Another possible method is to integrate the DHCP server functionality directly into the SDN controller. To prevent DHCP exhaustion attacks from clients, we can designate non-switches as endpoints and limit the number of unique DHCP requests that can be issued per such endpoint.

4.8.5 ARP poisoning attacks

ARP poisoning attacks occurs on a network when a client advertises false information about its IP to Ethernet address mapping, and convinces other clients to use the incorrect mapping. ARP poisoning can be used to facilitate man-in-the-middle attacks. The EtherSlice system guards against this by prohibiting client ARP broadcasts or replies from propagating within the network, using an OpenFlow rule designed to suppress the propagation of client ARP traffic. ARP queries are performed by SDN controllers on behalf of network clients, and if an SDN controller observes an ARP advertisement or reply that conflicts with its internal ARP tables, the SDN controller ignores the ARP message. Thus, a

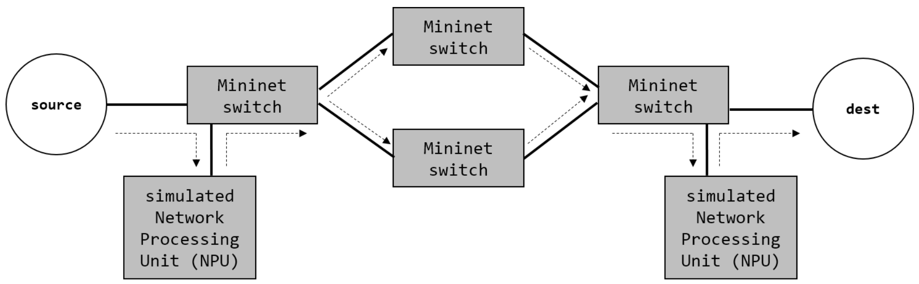


Figure 4.1: Sample workflow in our Mininet setup. Arrows indicate the movement of protected flows.

malicious client cannot use ARP poisoning to convince the SDN controller to route data slices to it, rendering this man-in-the-middle attack impossible.

4.9 Evaluation

To evaluate our system, we simulated various network topologies using Mininet [19]. In order to redirect and process data flows, we wrote a custom lightweight OpenFlow controller. Ordinary data movement across the simulated network was handled by installing regular L2 flows in Mininet, whereas flows that required confidentiality or anonymity were redirected to the controller using the `PACKET_IN` mechanism, effectively using the controller itself as the NPU for slicing/reassembly operations. Packets that require information slicing operations were decapsulated from their OpenFlow headers and processed directly in software using Armadillo [1], a C++ matrix library. Resultant packets were then re-encapsulated and forwarded back to the simulated switch for output. In this way, we were able to completely simulate the NPU packet processor in software. Figure 4.1 shows such a sample workflow.

We tested our system on a variety of network topologies, with varying parameters of disjoint paths and redundancies.

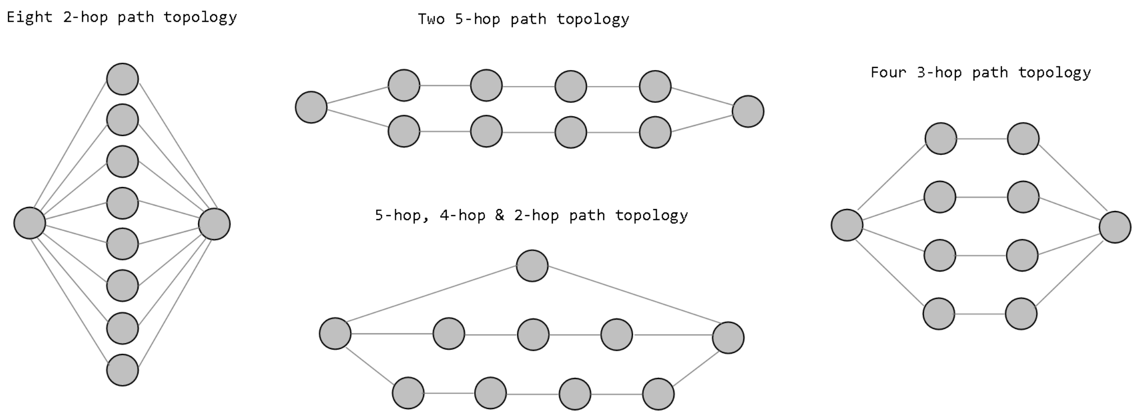


Figure 4.2: Network topologies simulated for our experiments.

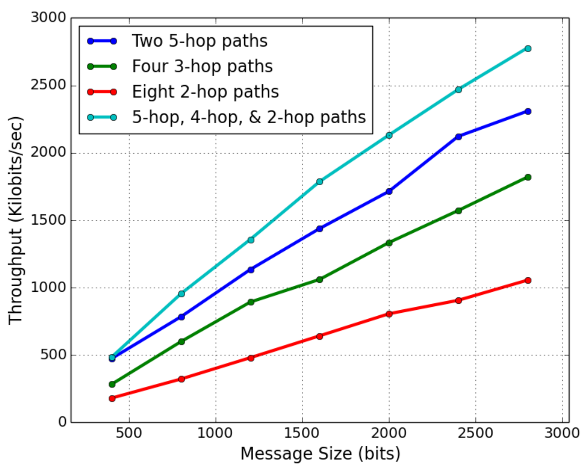


Figure 4.3: Throughput of confidentiality service using varying message sizes and topologies.

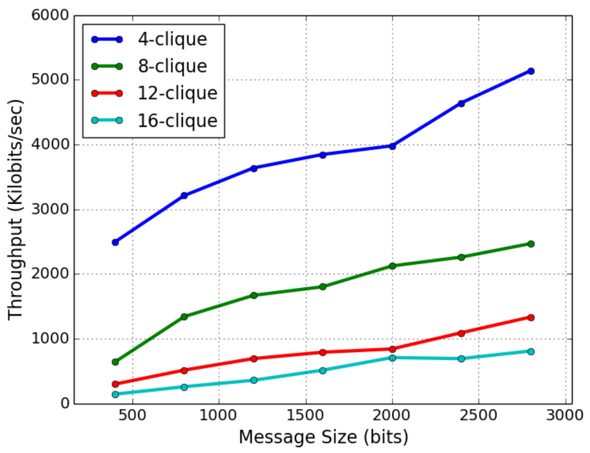


Figure 4.4: Throughput of anonymity service using varying message sizes and topologies.

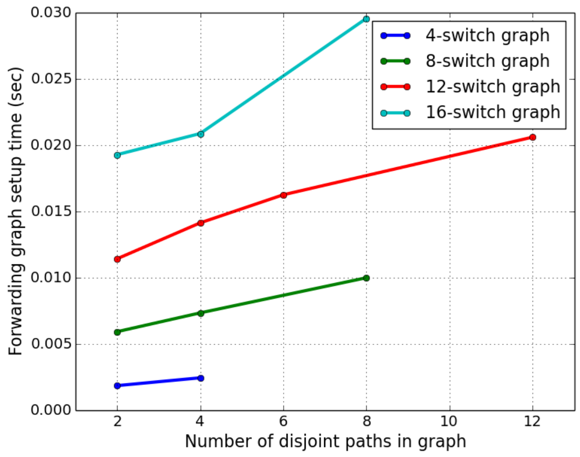


Figure 4.5: Forwarding graph establishment time for anonymity service with varying number of switches and paths in graph. Since graph establishment occurs only once to send many subsequent anonymous messages, millisecond setup times are acceptable.

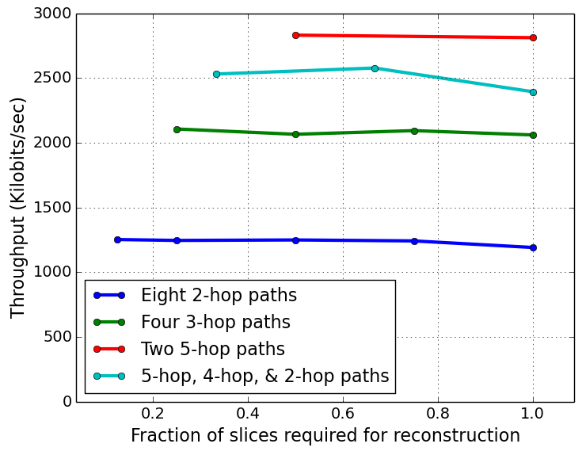


Figure 4.6: Throughput of confidentiality service in different simulated networks when varying the redundancy-to-confidentiality tradeoff (varying d' wrt d). The fraction of slices required for reconstruction is equivalent to the number of information slices that must be received (or intercepted) in order to reconstruct the original message, divided by the total number of information slices sent by the NPU.

To measure end-to-end bandwidth, we used iperf, a TCP/UDP bandwidth measurement tool. Latency was measured using the ping utility.

4.10 Avenues for Improvement

In this section, we discuss some possible modifications to improve the performance or functionality set of the EtherSlice system.

4.10.1 Extension to gateways and DNS

While the EtherSlice system covers communications confidentiality and anonymity within the same Ethernet network, it is possible that users may want to communicate with external network hosts, while preserving confidentiality and anonymity as their data flows through the local Ethernet. This naturally involves the network gateway as an endpoint, and is problematic because an anonymizing set that contains the gateway is very likely to involve communications that exit the network. On a related note, clients that wish to communicate with endpoints outside the network may also consult the local DNS in order to resolve IP addresses. This DNS lookup step can be a dead giveaway that reveals the penultimate destination of a user's data flow.

A simple way to preserve anonymity in situations that require gateways and DNS is to force all anonymizing sets to include the network gateway(s) and DNS. This increases the computational and traffic load on these systems, but can be mitigated by provisioning multiple network gateways and DNS.

4.10.2 NPU improvements

Our prototype implementation of the NPU is software-based and depends on the `PACKET_IN` mechanism in Openvswitch. This method does not provide high packet throughput on real switch hardware. An ideal NPU should be a dedicated system, ASIC hardware or FPGA (such as the NetFPGA) that can process data packets at line rate.

4.11 Conclusion

We presented the design of a practical system to retrofit confidentiality and anonymity to an Ethernet-based network. Our system is completely backward-compatible with existing hardware and software, necessitating no changes with network clients or their operating systems. Finally, the evaluation shows that our prototype is realistic and has reasonable performance.

CHAPTER 5

A CONTROLLER BUILT FROM OPERATIONAL EXPERIENCE

In this section, we chronicle our experience with practical OpenFlow controller design. The design is based on OpenFlow 1.0, although OpenFlow 1.3 is available on the Dell hardware. The reason we selected to use OpenFlow 1.0 instead of 1.3 is because the hardware only supported 1.0 for a long time, and 1.3 did not offer significant new features on the hardware we used. Furthermore, the 1.3 protocol was far more complex.

Interest in OpenFlow and software-defined networks (SDNs) has resulted in a boom in SDN hardware and controller offerings, with varying degrees of maturity, popularity and support. However, few studies have been conducted to investigate the interaction between SDN hardware and software, as well as its impact on controller design and implementation. In this chapter, we chronicle our experience with deploying two commodity SDN controllers and a new system, Ironstack, of our own design in a production enterprise network at Cornell University, and describe the lessons learnt. We also report on several practical limitations of SDN and controller technology, and detail important future challenges for SDN adopters and developers.

5.1 Introduction

The success and excitement surrounding SDNs belies the fact that actual hardware support for OpenFlow spans a wide spectrum. Older OpenFlow-compliant devices often lack the necessary firmware to support some of the more recent versions of OpenFlow. Even among hardware that support the same version of OpenFlow, varying manufacturers, implementations and cost/performance tradeoffs result in different coverage of OpenFlow commands. Furthermore, the OpenFlow specification does not mandate the support of optional commands listed in the standard. Furthermore, some vendors provide non-standard OpenFlow adaptations or extensions [6].

Another issue is that many enterprises do not actually write their own SDN controller software, and view OpenFlow more as a unifying standard than as an opportunity to innovate by creating new specialized control paradigms. Our own research on a new SDN controller we call Ironstack focuses on automating fault-tolerance and security for deployments into challenging settings [82]. But in dialog with potential users we often find that the system owner is less focused on features than on convenience and the level of effort needed to actually deploy and manage the solution. Given an easily deployed, easily operated technology, feature coverage and special properties emerge as a secondary goal. Yet in settings like Cornell, where our networks are managed by an in-house professional team, the fear that SDN might be overwhelmingly complex and suitable only for research and experimentation actually dominates the appeal of standardization. Thus until SDN learns to be a user-friendly turn-key story for the SDN manager, it is unclear how the full potential of the technology could be leveraged.

This chapter first presents our experience in building and operating a small-scale production OpenFlow SDN from scratch, using market-available hardware and off-the-shelf general-purpose OpenFlow controllers. We also discuss limitations of existing commercial options. We then describe the impact of lessons learned and turn these into recommendations. Finally, we discuss some practical challenges that lay ahead for programmable network technology.

5.2 Overview of the Gates Hall SDN

Cornell's Gates Hall SDN comprises 15 high-capacity Dell S4810/S4820 10Gbps switches linking approximately 300 physical hosts over 3 machine rooms and multiple instructional and research labs, providing service to over 1000 students and faculty.

Administratively, the SDN is solely managed by the Information Technology Support Group (ITSG), a team that oversees and supports all engineering IT needs. ITSG does not engage in research, nor in SDN programming as an activity: their role is to ensure that the network operates in a correct, secure, and administratively controlled manner. However, uplink to the general campus network is provided and managed by a different campus-wide organization: Cornell Information Technologies (CIT). CIT requires an L3 isolation router that separates the SDN from the rest of the campus. The L3 isolation router is seen as an emergency kill switch in the event that the SDN interferes with the general campus network. This router is the sole connection to the campus network (by feeding into one of the three main campus routers), and is also responsible for assigning and managing IP addresses for all hosts on the Gates Hall SDN.

Physically, all machines on the SDN share the same switching infrastructure. In order to support Cornell's diverse mix of networking research, the SDN is fragmented into VLANs. Each VLAN is a continuous L2 segment configured with access permissions specific to the usage patterns of its member machines, so membership in a VLAN provides a coarse form of access control. For example, several racks within our datacenter supporting operating systems research require PXE boot and an internal DHCP server within their cluster, yet the cluster itself is not permitted to communicate with the external world. These machines are assigned to a VLAN distinct from the one used to service instructional lab machines which must be accessible remotely over the Internet. Although the principle of VLAN isolation could be considered archaic on an SDN compared to appropriately provisioned rules, it nonetheless provides a convenient point of control at the L3 isolation router, where all SDN VLANs converge.

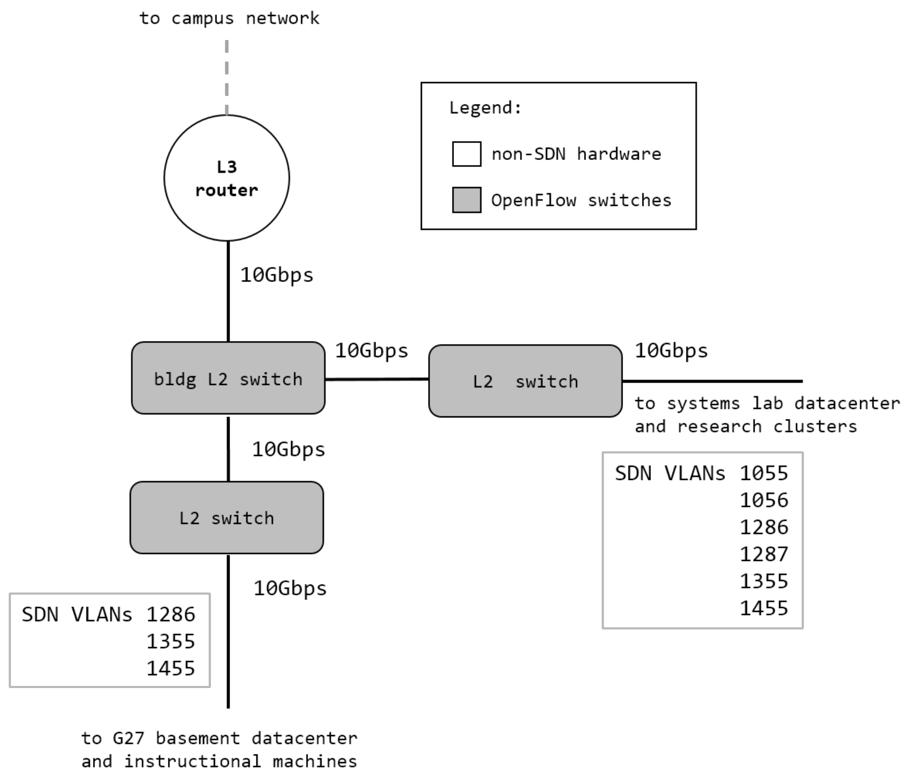


Figure 5.1: Topology of the Gates Hall SDN.

5.3 Hardware slicing

The SDN switches in Gates Hall are a combination of high-capacity Dell S4810 and S4820 switches. These switches are identical except for the physical ports exposed on the front panel: the S4810 switches feature copper SFP (small form-factor pluggable) ports while the S4820 use regular 8P8C (8 position 8 contact) ports. The 8P8C ports are physically more compatible with a wider range of devices, making it substantially easier to connect to commodity Ethernet devices. Both models of switches are capable of being 'sliced'[1] into instances, thereby allowing multiple controllers to operate on logically disjoint portions of the hardware. This is conceptually similar to the virtualization provided by FlowVisor [80], except that the hardware enforces the isolation. Two methods are available for this slicing.

5.3.1 Port-based instances

In port-based slicing, a Dell S4810/20 switch may be arbitrarily partitioned into as many as 8 concurrent instances of disjoint ports. Not all ports have to be assigned to an instance. Each instance can be associated with an independent OpenFlow controller, essentially partitioning the switch physically into multiple smaller switches. Using port-based partitioning, network topologies of up to 8 switches can be simulated using a single piece of hardware. This feature has proven useful in many experiments that we have conducted.

[1]The term 'slice' first appeared in GENI [43] literature and was used in FlowVisor [80] to describe a similar concept.

Port-based isolation has the advantage that it is easy to set up and intuitive from the physical and OpenFlow controller standpoint. We recommend using port-based instancing for developers or researchers beginning in the field.

5.3.2 VLAN-based instances

An S4810/20 switch configured to operate with VLANs in OpenFlow mode can also slice the hardware into instances through VLAN assignments. When operating under this mode, physical ports on the switch are assigned VLAN IDs and marked as tagged or untagged. The tagging status indicates whether a port emits and accepts IEEE 802.1Q frames [83], or regular untagged Ethernet frames. Ports with more than one VLAN ID assignment cannot be marked as untagged.

Up to 8 controller instances may be provisioned this way. Each OpenFlow controller is assigned to manage a set of VLAN IDs, which must be disjoint from other sets of VLAN IDs managed by other controllers. From the OpenFlow controller point of view, the viewable set of physical ports comprise those that are assigned to the VLAN IDs under the instance's control. In addition, ingress traffic on VLAN-tagged physical ports are filtered to retain only packets relevant for the set of VLANs managed by that instance, so a controller for a particular instance will only see tagged VLAN traffic corresponding to its assigned set of VLAN IDs. Other VLAN traffic arriving at the switch is either sent to another relevant managing instance or dropped. The S4810/20 hardware automatically enforces VLAN isolation on a hardware level, and no OpenFlow rules are necessary for this enforcement.

VLAN-based isolation is useful in an environment with multiple VLANs and non-OpenFlow switches, when flow rules need to be conserved and/or some hardware oversight is desired to prevent controllers from making mistakes enforcing VLAN isolation. However, this mode of operation is technically non-compliant with the OpenFlow standard and has behavior that can be confusing for people new to OpenFlow. For example, an administrator wishing to create a layer 2 rule that forwards flows from a tagged to an untagged port should specify a match criteria with an Ethernet destination address and a VLAN ID. However, the action set cannot include a directive to strip the VLAN tag (an `OFPT_BAD_ACTION` error would be returned by the switch), even if it seems logical to do so before outputting the packet to an untagged physical port. Instead, the switch performs tagging and untagging automatically. Other operations in VLAN-based isolation mode, such as a flow rule that copies all packets from one physical port to another, may simply not work without any warning or error.

5.4 Experience with controllers

Our operational experience[2] with OpenFlow SDNs spans about 24 months, of which 4-6 months were spent on hardware familiarization and micro experiments involving isolated switches. With the SDN fully deployed in February 2014, we sliced every switch into 4 VLAN-based instances and ran different controllers on each instance. The first two instances ran production traffic using an open source controller (”Controller A”) and a commercial controller (”Con-

[2]The authors are not affiliated with Dell, the Linux Foundation, or any organization for whose products are mentioned or featured in this chapter. The views expressed herein are subjective and not indicative of any product endorsement or criticism.

troller B") respectively, while the latter two were reserved for research and development purposes and ran our Ironstack controller for the full period of the study. Our switch firmware only supported OpenFlow 1.0 at the time the network went into production (1.3 support arrived in spring 2015) so most of our anecdotal experience is based on the older standard. However, we believe that our insights transcend versions and remain relevant.

5.4.1 Controller A

Controller A is an open source OpenFlow controller that has enjoyed widespread popularity since its initial release a few years ago. The system is designed to operate in a centralized manner, with all OpenFlow switches directly connected to the controller. Because of this centralized mode of operation, the controller maintains an up-to-date view of the SDN topology, as well as all ancillary switch data (such as flows, port statuses and traffic counts). The web interface offered by the controller allows convenient administration of the network through an intuitive webpage accessed from the control network.

We first encountered trouble on the SDN when we grew our network to approximately 200 hosts. At that scale, we started to experience intermittent performance issues caused by discontinuous hardware flow rules on some source-destination paths. These problems would manifest as high-latency (approximately 500-1000ms), lossy flows alongside other flows that perform well. We determined that packets transiting these discontinuities caused flow-missed events to be raised in OpenFlow, which caused these packets to be encapsulated and forwarded to the controller for processing. To ensure delivery, the controller used software forwarding to copy the packets to their destinations. Our investigations also revealed no capacity problems with the switch hardware table, and we concluded that the rules were simply not being installed by the controller despite continuous flow-miss events resulting from the flow discontinuities. We were able to rectify the problem by manually installing the missing rules on the affected switches.

To find out if the missing flow problem was correlated, we restarted the controller multiple times. We found that controller restarts frequently rectify the problem of missing flows in some source-destination paths, but it did not prevent the same problem from recurring on other paths. Furthermore, the controller removes all hardware flows during a software restart, causing a long period of degraded network operation as the controller repopulates its view of the SDN and falls back on software forwarding in the interim. On our 15 switch network, it takes about 10-15 minutes for this controller to recover after a restart.

5.4.2 Controller B

Controller B is a commercially available, proprietary 1U integrated server/OpenFlow controller. It is marketed as a turnkey solution that is simple to use and fast, and the system has received many accolades over the years since it was first available several years ago. The controller is also centralized and provides multiple ways for an administrator to view and manage the network, such as through the command line and over the web. The system is robust and is able to maintain a running view of the operational data and SDN topology.

This controller also experienced scaling issues on our SDN at approximately 200 hosts. Although the controller did not create discontinuous paths, it would sometimes refuse to setup flows for a newly-introduced system. Consequently, the system does not appear on the topological view and does not receive network access. We have also encountered connectivity issues following rapid cycling of a network device's link state: the controller enforces a lockdown period of about 15 minutes before returning the device to active use.

5.4.3 Ironstack

Length limitations prevent a detailed discussion of our Ironstack controller. In brief summary, Ironstack is an open source SDN controller intended to offer a turn-key operator experience while imposing a flexible set of security and reliability guarantees at the fabric level, for example by multiplexing traffic across redundant SDN links and encrypted for protection against intrusion. For our purposes here, the details are not important, because as it turned out, the operator experiences of the ITSG and CIT teams had a far greater role in shaping technology deployment choices than the special features Ironstack was actually created to showcase.

Because ITSG and CIT were unable to successfully deploy controllers A and B in stable configurations, for a period of time ITSG actually only used Ironstack in the full SDN system. Eventually, as campus network security policies evolved, a decision was made to run Ironstack only within our research slices. Thus we have a total of 24 months of experience with Ironstack, of which 10 months included our full production network. When Ironstack was cut back to research-only use, the entire production workload was shifted to the standard (switched Ethernet) CIT network and off of SDN, highlighting the continuing concerns about SDN stability and manageability in production networking environments.

5.5 Lessons learnt

5.5.1 The switch-to-controller pipe is thin

One of the first lessons we verified is that the OpenFlow control connection between the switch and the controller is a serious bottleneck. This corroborates with findings from other prior work [80] [40]. On our Dell S4810/20 hardware with TLS turned off, the control connection rarely exceeded a throughput of 2.54Mbps on a dedicated 1Gbps out-of-band network port. This is a few orders of magnitude lower than the maximum speed of the network port, and could not be explained by slow link activity. We found that the bottleneck was due to an overloaded switch processor. The embedded processor runs the Force10 Operating System, a variant of Linux that provides OpenFlow agent support through an application layer.

Because the switch processor is heavily taxed by other scheduling demands, OpenFlow functionality is prone to slowdowns at high loads. This effect is especially pronounced during times of high `PACKET_IN` throughput. `PACKET_IN` events are most commonly generated in response to flow-misses, where a switch forwards a packet to the controller following a failure to find a matching OpenFlow rule. Even on switches with light network traffic, consecutive flow-miss events can quickly overwhelm the CPU, leading to dropped `PACKET_IN` messages, slow OpenFlow throughput and high latencies processing OpenFlow commands on the switch.

`PACKET_IN` events may also be generated in response to an explicit request for flow traffic to be forwarded or copied to the controller. This is helpful in certain circumstances when a controller wishes to discover network state (for example, by snooping on all ARP and DHCP packets). However, flow-miss events will experience contention and be negatively impacted by `PACKET_IN`s received through this method. To minimize flow-miss packet losses, we advise against explicit copying of flow packets to the controller where possible.

5.5.2 Consider not flushing rules on restart

Many OpenFlow switches today have a fail-secure mode that allows installed flows to remain on a switch and provide limited operational continuity should the controller be disconnected. Our experience with controllers A and B shows that a complete rule removal on controller restarts is often unnecessary, and can be counterproductive in some situations. Apart from occasional flow discontinuities, the controllers typically regenerate the same rules across restarts. However, manually-inserted rules (such as those used to circumvent flow discontinuities) are lost when all flow rules are cleared.

Because complete rule regeneration from a scratch is a time-consuming operation and SDN controllers are unlikely to be adversarial (by installing bogus, broken, or harmful flow rules for its successor), we recommend against the practice of flushing all flow rules during a controller restart unless there is reason to suspect that correctness may be compromised on a large scale. Rules installed by a predecessor represent the product of some computation or planning and should not be wasted. Instead, we suggest that rules be inherited and verified for preservation on controller startup, and an alternate strategy be used for clearing the flows on the switch if needed.

Clearing the flow table instantly and in its entirety is rarely needed as an emergency procedure. If a genuine need to remove flows arises, we suggest that they be removed one at a time or in small quantities batchwise. On OpenFlow 1.0, the controller can do this by first initiating an `OFPT_STATS_REQUEST` with a request of `OFPST_FLOW` to retrieve a list of all flows on the switch, and then issuing staggered `OFPT_FLOW_MOD` requests to remove flows one at a time. The overall effect is to spread out flow deletes that would immediately cause flow-miss events: should the controller remove a flow that was actually active at the time, the resulting flow-miss packets would be less numerous than if multiple flows were generating flow-miss events in response to a bulk removal request. In turn, the switch is less likely to drop flow-miss events, and the controller can establish new flows more expediently.

On the other hand, if the intention of the controller is to prune unneeded rules without disrupting any flow, it could do so in an unintrusive manner. The controller could identify passive flows by sampling the list of all individual flow statistics retrieved from the switch via the `OFPT_FLOW_STATS` request. Flows that have not seen new packets in a certain amount of time can be deemed to be inactive and individually removed to free up entries in the flow table.

5.5.3 Be cognizant of hardware limitations

Although the OpenFlow specification provides a comprehensive array of matching criteria and actions that can be combined in many useful ways, the reality is that these OpenFlow capabilities are limited to what the hardware vendor chooses to support. The OpenFlow switch specification describes the full set of actions that a switch may implement, however switch vendors are only obligated to support actions that are marked as 'required'. In the 1.0 version of the specification, mandatory action support only extends to dropping packets or forwarding to certain ports; useful actions such as packet header field modification and port flooding are optional and may not be available.

Furthermore, even similar actions across different hardware could have various performance characteristics [79] [52]. This non-uniformity of OpenFlow action support and performance can be a source of surprise and frustration to the OpenFlow developer, who may build generic software controllers and support equipment that become functionally degraded or even completely incompatible with real-world hardware. On the other hand, a developer that targets specific hardware may be exposed to vendor lock-in as it is unlikely that all other OpenFlow hardware will provide a similar level of support, let alone behave identically. This point was an especially acute lesson for us because we had been developing early versions of our OpenFlow controller using Open vSwitch [22] as a reference switch. As a result, we committed substantial time to implementing features that worked well under Open vSwitch but were not well-supported in hardware. For example, at the time of our early prototype, our Dell S4810/20 switch did not support the OpenFlow action to strip VLAN tags and we had to emulate this functionality in software, severely degrading the performance of our system.

5.5.4 Equipment-specific features can make a big difference

We attempted to understand the reasons for the scale limits experienced by the controllers we used. The Dell S4810/20 hardware feature multiple forwarding tables. On these switches, flows can be differentiated by types to fall into one of the ACL, L2 or L3 flow classifications. Ordinarily, the multiple forwarding table functionality is disabled and all flows are stored in the ACL (general-purpose) OpenFlow table, which has capacity for only 500 flows. When enabled through an out-of-band command line configuration utility, the switch transparently stores flows matching L2 or L3 classifications into dedicated separate tables. The L2 and L3 flows are particularly compelling because they feature deep tables well-suited for common switching and routing tasks, freeing up valuable ACL table space for more unusual flow rules. Table 1 shows the respective flow table capacities on the S4810/20 switches, while Tables 2 and 3 show the respective syntaxes of the L2 and L3 flows [6].

Table name	Flow capacity
ACL	500
L2	48000
L3	6000

Table 5.1: Flow table capacities on Dell S4810/20 switches.

Our investigation showed that both Controller A and Controller B installed rules that did not fit into either of the L2 or L3 flow classifications. Instead, those flow rules were placed into the ACL table, which prevented the network

Parameter type	Parameters
Match criteria	• `dl_vlan` (input VLAN ID). • `dl_dst` (destination Ethernet address). • all other fields must be wildcarded.
Actions	• `OFPAT_OUTPUT` output to a single physical switch port.

Table 5.2: L2 flow classification.

Parameter type	Parameters
Match criteria	• `dl_dst` must be set to the switch port's Ethernet address. • `dl_type` must be set to 0x0800. • `nw_dst` can be optionally set. • all other fields must be wildcarded.
Actions	• `set_dl_src` must be set to switch port's Ethernet address. • `set_dl_dst` (destination Ethernet address). • `OFPAT_OUTPUT` output to a single physical switch port.

Table 5.3: L3 flow classification.

from scaling once the table was full and no new flows could be created. We discovered that the reason for using ACL entries was because the controllers were unaware of the syntax or availability of the L2 and L3 tables, which prevented them from taking advantage of the deep tables. In contrast, Ironstack did not make substantial use of ACL entries at all because the policies ITSG sought to support were mostly simple enough to be expressed in L2 flows.

5.5.5 Non-standard behavior is standard

Specification-deviating behavior may come as a surprise for developers who assume that hardware marketed as OpenFlow-compliant will exhibit features and functionality exactly as written in the OpenFlow standard. This can be an issue for developers who build their controllers on reference switch implementations (eg. Open vSwitch) and later deploy them on actual OpenFlow hardware.

Non-standard hardware behavior has caught us by surprise on a number of occasions. On our Dell S4810/20 switches, flow priority is only honored within entries in the ACL table; the priority field is completely ignored for flows that fit in the L2 or L3 tables. This posed a problem for our controller, as it had to be aware of these equipment subtleties and install flows into the ACL table if it wished to override specified flows in the L2 or L3 tables.

As another example on our hardware, L2 flows are not instrumented with packet or traffic counters, which limits their utility in network analysis. This forces the developer into a dilemma between the creation of an instrumented ACL flow on a capacity-limited table, or an uninstrumented L2 flow on a large table. To complicate the situation, L2 flows cannot be configured with arbitrary idle timeouts; these flows are either permanent (if the idle timeout value is specified as 0 in the flow rule), or set to some switch preset value (if the specified idle timeout value was non-zero). Since there are no indications of warnings or errors when L2 flows are installed with arbitrary timeouts, an equipment-agnostic controller may mistakenly assume the flow to time itself out accordingly.

On the L3 table, flows are permanent and do not honor any specified idle timeouts. Similar to L2 flows, no information is given by the hardware to indicate that the idle timeout is ignored on an L3 flow.

While these non-standard behavior are generally innocuous quirks, they make it difficult for a developer to write a general-purpose OpenFlow controller that exhibits predictable behavior across different hardware. For example, an OpenFlow controller used to drive a commercial pay-per-use network might rely on L3 flow timeouts to redirect a customer to a captive portal when a lease time expires. Without equipment-specific knowledge of non-standard flow timeout behavior, general-purpose controllers may not correctly enforce customer access policies. In the case of an L2 flow, a software workaround for the idle timeout may not even be possible since it offers no packet counters that can be used to track flow activity.

5.5.6 Configuration tools are just as important as OpenFlow

Although OpenFlow presents a useful interface through which a switch may be controlled, the specifications omit a discussion of equipment configuration tools or utilities because they are often vendor and equipment-specific. Equipment configuration tools provide the means to set up operating parameters that are not necessarily controllable from or related to OpenFlow. For example, the IP address and port number of a controller must be specified to the switch before it can establish an OpenFlow connection to the controller. Other important functionality that are only accessible through equipment configuration tools may include means to power cycle the device, set up VLANs and port tags, as well as enable specific OpenFlow tables or slicing features. On most OpenFlow switches that we are aware of, the configuration tool presents itself as a command line interface physically accessed through the switch's serial (RS232) port. Because OpenFlow switches have their own IP addresses on the control network, they often also support access to the same configuration tool over telnet or SSH.

We take the view that control over these functionalities is just as important as OpenFlow itself in a comprehensive network controller, particularly if the configuration utilities also provide information or indirect control over OpenFlow capability on a switch. As an example relevant to our SDN setup, a network controller should be able to inspect the switch configuration for VLAN or port information pertaining to its slice. It should also be able to control deep table options or reconfigure the IP address and port that the switch seeks a controller at. We are presently unaware of controllers that can perform equipment configuration along with OpenFlow.

5.5.7 Switch misconfiguration can cause confusion

Even with compatible controllers designed to correctly take advantage of the various hardware tables available, it may still not be apparent to the controller that the hardware tables are indeed being used. On the Dell OpenFlow switches, an external configuration utility must be used to manually enable the switch to operate in 'multiple-flow' table mode, and then the individual L2 and L3 flow maps have to be enabled in order for flows specified in the L2/L3 formats to be stored into their high capacity hardware tables. Without the features enabled (which is the default), these flows would be stored in the ACL table.

On our SDN setup, there is no way for a controller to verify that the flows have been stored into the right hardware table, since OpenFlow flow statistics from our Dell hardware do not annotate flows with their flow table IDs. Furthermore, the OpenFlow specification does not provide a way to obtain table capacities, which precludes the ability for a controller to make an informed decision with respect to flow installation. The only way that a controller can tell if a table is full is when the error `OFPMFCTABLEFULL` is generated in response to a flow installation command. By this time, it may be too late for the controller to take remedial action. On the other hand, such table capacities are usually advertised by the vendor or otherwise accessible from the switch configuration utility. We believe that knowledge of table capacities should be propagated to the controller to aid planning purposes.

5.5.8 Isolation is not perfect

Virtualization on an OpenFlow switch provides logical isolation between one controller's traffic from another. Virtualization techniques can be software-based, as in FlowVisor [80], or hardware-based, as is provided directly on the Dell S4810/20 switches. In either case, it is important to note that virtualization does not provide perfect resource isolation between controllers. Resources such as the embedded CPU, forwarding table capacity and bandwidth are shared across all controllers working on the switch.

This is a well-known phenomenon with all virtualization techniques, and is neither a flaw nor bug in the virtualization mechanism. However, controllers should be designed with the assumption that they could be run on virtualized hardware, and thus engage in better cooperative sharing tactics. For example, controllers could minimize flow table wastage by setting an idle timeout on their flows, while also not consuming excessive switch computational power by indiscriminately copying data plane packets to the controller.

5.5.9 No controller-to-data plane communications

One feature that we would have liked to see in a SDN controller is the ability to communicate directly with networking applications that run on the data plane. At present, we are not aware of any controllers that have such a capability, except for Google's B4 [53] Routing Application Proxy, which bridges packets from the Quagga control plane and the switch's data plane. The ability for a network application to communicate directly with the controller opens up substantial development opportunities. For example, the controller can host a HTTP subsystem that serves users statistics about their network usage, or provide a webpage through which network QoS could be requested. A data plane presence on the network also allows the controller to easily implement features such as captive portals.

5.6 Building a controller from ground-up

To validate the applicability of the lessons we learnt, we built our own OpenFlow controller from ground-up, applying the prior experience we gained working with OpenFlow hardware and controllers. Our design is exploratory and unusual, but principled and feasible. The following subsections detail the implementation of our system.

5.6.1 Hierarchical design

A key departure from the architecture used in many other controllers is that our system is hierarchical, rather than centralized and monolithic. In our hierarchical design, every switch is mapped to one low-level controller process. Each low-level controller has full control over its switch, but limited visibility of the entire network. One or more high-level controllers operating on the control network communicate with the individual low-level controller processes via remote procedure calls (RPCs) and coordinate global activity, such as alternate path provisioning and network analysis. We chose a hierarchical design for several reasons:

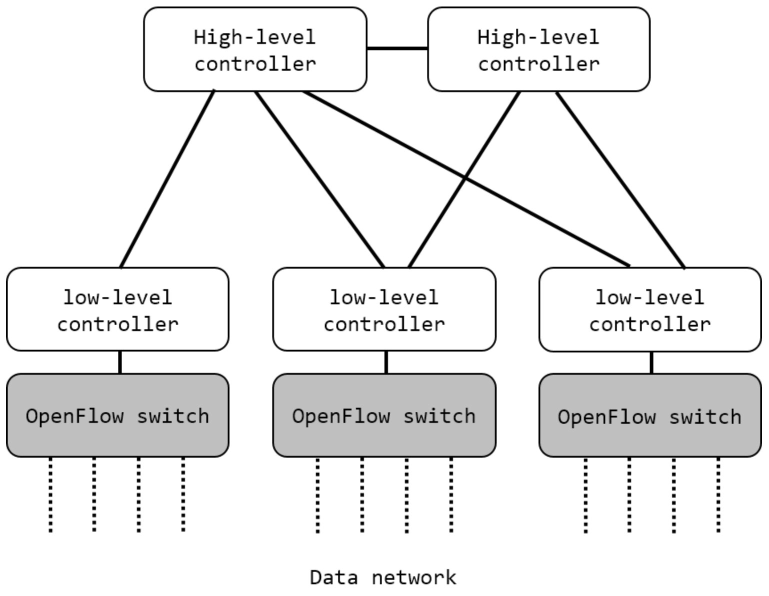


Figure 5.2: Hierarchical controller design. Dotted lines represent network links on the data plane; solid lines are links on the control network. Note that high-level controllers do not need to be connected to every low-level controller. High-level controllers may also run distributed coordination logic amongst themselves.

Faster per-switch tasks

Many OpenFlow tasks do not require a master coordinator or centralized control in order to function correctly. For example, echo requests, which are issued asynchronously by the switch and serve little purpose other than to keep an OpenFlow connection alive, are more expediently processed by the low-level controller. This relieves the high-level controller from unnecessary processing and burden, freeing it up for tasks that are better solved at a higher level.

In fact, even tasks such as basic flow provisioning can be typically performed by low-level controllers, without a need for a complete view of the network. The low-level controller may simply act as a learning switch and install the appropriate flows. The high-level controller may intervene at a later time and instruct the low-level controller to update the flow rules as necessary.

Simpler program logic

A low-level controller designed to attach to a single switch requires less state, concurrency and complexity since it does not need to coordinate multiple switches or perform CPU-intensive global tasks such as determining optimal flow placement. Correspondingly, low-level controller code is more compact and easier to debug. Resource usage on the low-level controller is also light and predictable, with the worst case processing demand caused by heavy OpenFlow traffic on a single switch.

Similarly, with the high-level controller would be simpler to implement as it does not require code to perform low-level switch management. Instead, the code could be focused on issues that are best tackled at a global scale, such as network analysis and flow placement optimization.

Versatile load-balancing

One significant advantage of our hierarchical design lies in the scalability of our controller. While centralized controllers can be scaled to a limited degree by running on a server with higher processing power, the approach is somewhat inflexible and expensive. The hierarchical design allows for considerably more flexibility in the placement of the individual low and high level controllers. On one extreme end, each low-level controller could be made to run on separate physical hardware. This hardware need not be expensive or even computationally powerful. In our experience, a low-level controller is capable of efficient operation on a \$35 single core Raspberry Pi (model B), a low-power, low-performance computer.

On the other extreme end, all low-level controllers could be made to run as individual processes on the same physical machine. This is easily configured by pointing the OpenFlow switches to seek their controllers at different ports on the same IP address. When load becomes a bottleneck on the physical machine, the processes may be spread out over more servers, with only a minor switch reconfiguration required to update the controller IP and/or port.

We anticipate that our approach is more scalable and future-proof: apart from flexible controller placement, it is also conceivable that future switches may offer sufficient on-board computational power or co-processors that enable user-level controllers to be run directly on or in close proximity to the switching hardware.

Resilience to outage

The centralized nature of most OpenFlow controllers is a well-known vulnerability in SDNs [60] [58] [84] [54] [34] [63]. The behavior of an OpenFlow switch under a controller outage depends on whether the secure fail-mode option is available and enabled on the switch. The secure fail-mode feature preserves flows on a switch, allowing some continuity in service, although new flows cannot be established.

Software faults leading to controller failures are common, although control network outages can also cause a switch to lose its connection with a controller. The net effect in both cases are identical: the affected switches go into secure fail-mode, or purge their flows while awaiting successful reconnection with the controller.

In the best possible scenario where all switches on an SDN support secure fail-mode, the impact of a centralized controller outage is the global inability to establish new flows. This effect may be quite noticeable on a large network, where many new flows are created frequently. On the other hand, a hierarchical setup limits the extent of the problem to the switches for which their low-level controllers have failed or become uncontactable. Other low-level controllers can continue to create new flows, reducing service disruption on the global scale.

The advantages of a hierarchical design are more pronounced in the worst-case scenario. If none of the OpenFlow switches in a network utilize secure fail-mode, then all flows are lost on every switch (or on switches that have lost connection to their controller). A centralized controller would face immense load on a restart as it restores flows across numerous switches, leading to poor network performance that can last many minutes. With a hierarchical design, only switches corresponding to failed low-level controllers are affected, and the recovery time can be relatively short since each low-level controller restart has to handle service restoration for just one switch.

Separation of the high-level controller from the low-level controllers also has the advantage of isolating faults that are not directly related to switch management. For example, a flow optimizer unit or third party SDN plugin running on the high-level controller could become unstable during deployment. Under a hierarchial design, the high-level controller crash would not affect the basic functionality of the network, which depends on low-level controllers. An equivalent setup in a centralized controller could result in network outages even though the unstable code had no direct relation to OpenFlow switch management.

Better Performance

Third-party plugins or modules for an OpenFlow controllers is a popular idea due to the extensibility and customization that these plugins provide. However, on monolithic controller architectures, these plugins generally run in the same process and compete for resources that are also used for OpenFlow management. By separating the execution of these plugins from switch management, the high-level controller can perform as much computation as it needs without being concerned about slowdowns with other switch-specific tasks.

5.6.2 Hardware abstraction layers

To abstract away differences between heterogenous hardware, our low-level controller provides generic interfaces to execute common tasks such as provisioning flows or querying the remaining capacity of specific tables. Although we have not built a full driver layer for this purpose, the equipment-specific code to perform these tasks reside in different modules that are selectively activated according to the identity of the attached hardware. The hardware identity can be specified at controller startup time via command line flags, or by automatic detection during the handshake phase of the OpenFlow connection. Automatic detection relies on the data returned by the switch in response to an `OFPST_DESC` stats request, which contains verbose information pertaining to the manufacturer, hardware/software description and even the serial number of the switch.

In the case of the Dell S4810/20 switches, the hardware abstraction layer adapts certain operations to improve their functionality on the hardware. For example, simple flow provisioning requests for a learning switch are translated into more space-efficient L2 table rules before being installed on the hardware, thus keeping the ACL table as lightly loaded as possible. This is in contrast to the hardware abstraction layer for generic OpenFlow switches, which installs a rule with different syntax (that same rule would be installed in the ACL table on the Dell switches).

5.6.3 Built-in switch configuration module

Our low-level controller is designed with a built-in module that is capable of interfacing with the configuration utility on its assigned switch. Prior to accepting an OpenFlow connection from the switch, the low-level controller establishes a telnet or RS232 connection to the switch and queries it for critical bootstrap information. On the Dell S4810/20 hardware that we use, the set of information queried by the configuration utility include the instancing mode (port-based or VLAN-based), the list of pertinent VLAN IDs, as well as the set of each VLAN's tagged and untagged ports. Additionally, the module verifies that the switch will connect to the correct IP address and port for the low-level controller.

The module maintains an open telnet or RS232 connection with the switch even after the OpenFlow control connection is made. This provides the low-level controller access to configuration options and commands that may be invoked remotely by a high-level controller. For example, a high-level controller may reboot the switch remotely by relaying its intention through the low-level controller. Global flow table resource usage is also monitored this way.

5.6.4 Controller data plane presence

An accessible controller presence on the data plane network can be very useful for developing novel solutions that require direct point-to-point communications between data plane applications and the controller. However, in order to avoid being in a chicken-and-egg situation where an SDN controller controls its own connectivity to the switch, most OpenFlow switches require that the controller be present on a logically separate network. This network is known as the control network and is typically dedicated to communications between switches and their controller(s). The logical separation between the two networks present a tricky communications barrier, and we present two solutions to solve this problem.

Low speed data plane presence

Although the OpenFlow protocol does not directly provide support for point-to-point communications between an application on the data plane and the controller, a crude form of communications may be achieved by exploiting the `PACKET_IN` and `PACKET_OUT` functionality to emulate a host presence on the data plane.

This approach relies on the observation that a correctly-functioning packet processing system that appears to send and receive legitimate packets is indistinguishable from any other valid network entity. Thus, if the controller were to assume a valid Ethernet and IP address, and generate traffic or respond to network activity on the data plane in a protocol-correct manner, it would come across as a presence on the data plane.

Achieving basic bidirectional communications is straightforward: to receive packets from network applications on the data plane, the controller sets up a rule to forward all packets with the controller's emulated Ethernet address to the virtual `OFPP_CONTROLLER` OpenFlow port. Thereafter, packets directed at the controller's Ethernet address will be forwarded to the controller via `PACKET_IN` events, along with their ingress port numbers. To send data, the controller encapsulates a packet with the `PACKET_OUT` command along with an output port (or ports) directive, and the switch delivers the packet on the data plane.

However, a bidirectional communications primitive is not sufficient. In order for the controller to operate legitimately on the data plane, it needs a proper Ethernet and IP address. Although Ethernet addresses could be squatted on or fabricated with a low probability of collision, it is considered bad form. A better approach is to use the least significant 48 bits of the datapath ID corresponding to the switch that the controller is acting on. These 48 bits correspond to the switch's Ethernet address, which is likely to be unique since hardware vendors typically issue distinct addresses allocated from their Organizationally Unique Identifer (OUI) blocks [24]. IP addresses could be statically assigned and assumed in the controller, or dynamically requested through DHCP.

One key challenge with building DHCP clients and/or IP-related protocols with the above strategy is that a network stack is typically required in the controller in order to support these communications. The implementation of a network stack is a complicated endeavor that is prone to bugs, and an improperly built network stack may open the controller to security vulnerabilities that can be exploited from malicious entities on the data plane.

Our solution to this problem was to create a custom network device driver that delivers packets between the controller and the data plane. The network driver exposes an Ethernet interface and uses the `ioctl()` function to exchange data between the controller and the device driver. This way, the robust networking code in the Linux kernel performs the relevant packet synthesis and validation steps, greatly reducing the risk of an unsafe network stack implementation.

In addition, server processes such as HTTP servers can run unmodified alongside the controller and be able to communicate with data plane applications.

The advantage of this approach to emulating a host on the data plane is that the controller does not require extra hardware and is thus cost-free to implement. However, this solution is relatively low-speed since it relies on the limited `PACKET_IN` switch resource. In addition, the `PACKET_IN` events corresponding to these communications create contention with other `PACKET_IN` events that may be of higher priority. For example, flow-miss packets may be dropped as a result of HTTP communications between the controller and a data plane network application. This is clearly undesirable, if unavoidable, as it provides an avenue for denial-of-service attacks.

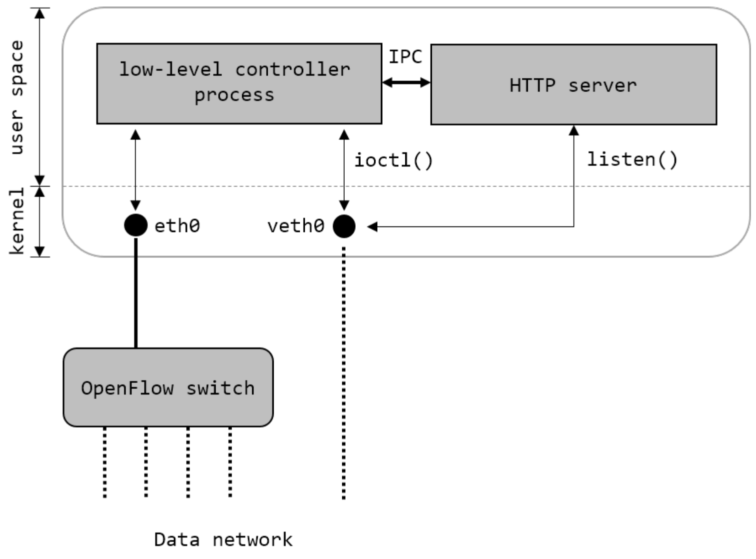


Figure 5.3: Low speed data plane access via veth0, a custom device driver. Dotted lines represent links in the data plane.

High speed data plane presence

If high speeds and high reliability is important from the controller's emulated data plane presence, a better strategy would be to augment or outfit the host machine of the low-level controller with an additional Ethernet card dedicated for this purpose and connect the auxiliary Ethernet port to the data plane. With this setup, the low-level controller would have access to both the control and data plane networks. Configuring the rules in the controller is a matter of simply installing a flow to direct all Ethernet packets destined for the controller to the relevant physical port. The Ethernet address to use for this flow can be directly taken from the auxiliary Ethernet card, and does not need to be fabricated.

The advantage of this approach is that it is relatively hassle-free and does not require substantial code to implement, unlike the device driver solution in the preceding subsection. It also offers the full bandwidth of an Ethernet port, along with the inherent safety provided by the Linux kernel's networking stack. Therefore, it is suited in applications that anticipate sustained or heavy traffic between the controller and data plane network entities. However, this approach is costly and impractical in some cases where an extra Ethernet card cannot be easily added (for example, if an embedded system is used to drive the controller).

5.7 Discussion

In this section, we discuss some potential drawbacks to our controller design.

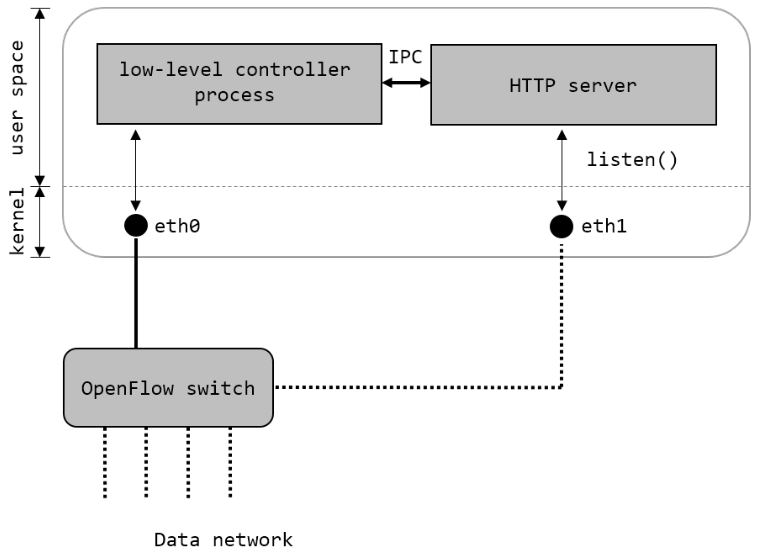


Figure 5.4: High speed data plane access via eth1, a secondary Ethernet interface.

5.7.1 Greater propagation latency

A tradeoff with the hierarchical design we employ is the increased latency between the high-level controller and the actual hardware. This is due to the additional communication and processing overheads associated with proxying commands and data through the low-level controller. As a result, the high-level controller in a hierarchical design is theoretically less nimble than a centralized controller in reacting to constantly-changing network conditions.

5.7.2 Flow startup delays can be significant

Although low-level controllers can effectively emulate regular learning switches without oversight or control from a high-level controller, the process of setting up an end-to-end flow is time consuming, with the setup time increasing linearly in the number of switches that the end-to-end flow spans. This is because at each switch, a slow `PACKET_IN` flow-miss event is generated and must be shipped to the controller for processing and rule installation. On the Dell S4810/20 switches, this overhead can be as much as 100ms. Furthermore, `PACKET_IN` events may be completely dropped during periods of high contention, leading to further delays in end-to-end flow establishment.

In contrast, a centralized controller can outperform the autonomous learning switches, by installing flows in parallel on all switches in the flow path upon receipt of the first `PACKET_IN` event. This would have the effect of reducing the flow startup time to a near-constant latency.

5.7.3 Inefficiencies on a single machine

The hierarchical approach is flexible in the placement of low-level and high-level controllers in the control network; this is the reason for its superior scalability properties. However, for operational or administrative reasons, or for a small scale deployment, it may be desirable to place all low and high-level controllers onto a single machine. This would still yield a correctly-functioning network, however the approach is unwieldy because of the large number of processes running on the machine, and inefficient on account of the substantially increased context switching times. In such scenarios, a centralized controller may offer clearer benefits.

5.8 Performance

SDN performance should be understood as having two complementary aspects. We tend to think about SDN switches and routers in terms of end-to-end flow performance, and in our experience, this aspect of performance was completely satisfactory: Controller A and Controller B both achieved their rated speed and successfully support the Gates Hall use patterns. Less well appreciated is the degree to which controller performance turns out to shape operational experience. Here, our experience has been more complicated.

When working with the vendor-supplied controller software, the many limitations and issues cited earlier combined to make it impractical to actually use them operationally for our scale of use cases. In contrast, we have been successful in operating the Gates Hall SDN configuration using our Ironstack controller. Table 4 summarizes the numbers of active rules and includes some basic performance metrics gleaned from this effort.

Metric	Value
Total rules	280 L2 rules, 4 ACL rules
Peak CPU usage	15.7%
Average CPU usage	1.3%
Reactive rules created/sec (peak)	25
Average switch echo response time (sec)	22ms
Maximum `PACKET_IN` throughput	2.54Mbps

Table 5.4: Micromeasurements of our own controller on a 8-core Intel Xeon E5405 clocked at 2Ghz.

The Gates SDN is an operational network used for Cornells research and teaching, we were not able to isolate the system and conduct stress tests on our controller or the network. However, we do hope to create an isolated research subnetwork in the coming months, which would then permit us to engage in the form of more microbenchmarks that might shed deep light on the scalability of our solution and the potential for deployment of SDN in networking in larger campus configurations. The Gates Hall experience, modulo the difficulties we had with off the shelf controller software, actually encourages us to believe that larger SDN configurations should certainly be feasible, and our hope is to explore that option in future work.

5.9 Challenges ahead for SDN

Going forward with SDN, several important challenges remain to be addressed:

5.9.1 Switch CPU performance

The most immediate concern facing SDN technology is the disparity in computing power between the switch processor and a controller. As our experience shows, the embedded switch processor is typically undersized and is often responsible for the bottleneck between the controller and the switching fabric. This bottleneck becomes more pronounced as successive versions of the OpenFlow standard impose additional complexity upon the embedded processor.

5.9.2 Capacity of rule tables

Another issue facing SDN hardware is its relative scarcity of general-purpose flow entries. Compared to traditional switches, general-purpose 12-tuple OpenFlow rule matching consumes more expensive ternary content address memory

(TCAM) and therefore offers less entries for the same amount of TCAM space. Even with recent advances in OpenFlow TCAM storage efficiencies, the number of available general-purpose entries on most switches today is generally no more than 2000, with many switches offering less than 1000 (see Table 5). This is an order of magnitude lesser than consumers are used to with traditional hardware, and is often perceived to be a limiting factor in scaling a network. The problem is somewhat alleviated by dedicated tables that can be used to soak up commonly-installed flow types, however the shortage of cheap TCAM for general-purpose OpenFlow rules will continue to be an impediment for some time.

OpenFlow switch model	Generic flow capacity	Other tables available
Dell S4810/20	500	L2, L3
Dell N2048	896	L2, VLAN
NEC PF5820	750	L2
Pica8 P3297	8000	L2, L3
Brocade MLX	4000	L2, L3, L23

Table 5.5: OpenFlow table capacities of some equipment.

5.9.3 Non-standard behavior

While non-standard behavior is generally tolerated as vendor differences between hardware companies, the reality is that non-conformance to standards makes it difficult for generic OpenFlow controllers to be written without introducing substantial conditional code or a complete driver layer. The increasing number of OpenFlow hardware vendors, coupled with the growing complexity of OpenFlow standards, increases the risk of emergent vendor-specific behavior that can negatively impact controller development.

5.10 Conclusion

In this chapter, we presented our observations and findings from deploying readily-available OpenFlow controllers on our SDN. Through operation of these controllers, we identified a number of important issues with SDN deployment and OpenFlow controller design. The chapter concluded with some of the challenges that continue to hinder SDN adoption at a larger scale.

CHAPTER 6
A NETWORK SWITCH AUGMENTATION

Our research and operational experience with existing OpenFlow network switches left us wanting for a more sophisticated solution that is more user-friendly. This chapter explores the idea of a *network switch augmentation*, a drop-in hardware solution that can provide improved functionality and usability. Our idealized design is shaped by our operational experience with OpenFlow network management (chapter 5), and is heavily influenced by the desire to support RAILS and EtherSlice (chapters 3 and 4), while being resilient and scalable. Most importantly, the augmentation must be simple to install and use, and should not require hardware modifications to the OpenFlow switch.

6.1 Functional and usability deficiencies

Based on our experience with the Dell S4810 [5] high performance OpenFlow switch, we identified the following functional and usability deficiencies:

- Poor `PACKET_IN` performance.
- Lack of an independent computing unit to run user software.
- Difficulty in configuring the switch outside of OpenFlow.
- Lack of an NPU.

6.1.1 Poor `PACKET_IN` performance

The `PACKET_IN` mechanism is a useful channel for receiving hints about the data plane. Besides receiving notification of flow-misses to generate reactive flows, `PACKET_IN` events can be used to discover underlying network state, such as the mappings between Ethernet and IP addresses of devices. The `PACKET_IN` mechanism can also be combined with `PACKET_OUT` mechanism to simulate a controller plane presence, and can be used to implement functionality when data plane clients need to communicate with their controllers (see chapter 5.6.4).

However, as our operational work in chapter 5 shows, the Dell S4810 switch has poor performance copying packets from the data plane to the control plane, with sustained peak bandwidths of about 2.54Mbps. This is far below the bandwidth capability of the network link between the switch and controller. This bottleneck is due to CPU saturation, and excessive `PACKET_IN` throughput affects responsiveness of other OpenFlow tasks.

6.1.2 Lack of an independent computing unit to run user software

In the process of building the Ironstack controller, we asked ourselves how close we could situate the controller to the actual OpenFlow hardware itself. Our key motivation was to provide a default controller ready to run when the OpenFlow switch was powered up, but we later generalized this desire to include other user applications. In other words, is it possible to treat the switch as a networking equipment that also features a CPU, such that the switch can be used as a server?

The reality was quite grim: existing OpenFlow network switches generally lack a robust processor, and that processor is usually already dedicated to the embedded operating system of the switch. While it is possible to modify or replace a switch's embedded operating system to permit the execution of user programs, in reality most switch embedded operating systems are proprietary and necessary for correct operation of the switch and cannot be replaced arbitrarily. Where it is possible to run user programs under the embedded operating system, performance is usually poor because of the overtaxed embedded processor.

6.1.3 Difficulty in configuring the switch outside of OpenFlow

On many OpenFlow network switches that we are aware of today, the only way to access and modify their initial configurations is through a serial line (RS232) interface. In particular, the Dell S4810 switch requires a lengthy configuration step over the serial interface before the switch can be enabled for OpenFlow use. The procedure is complicated and requires a separate computer outfitted with a RS232 interface. The process of such configuration is usually manual, laborious and often repetitive, yet critical for bringing the switch to an operational state. It would be desirable for the network switch augmentation to allow automatic rapid configuration of the OpenFlow switch with minimal labor, possibly with the aid of human interface devices.

6.1.4 Lack of an NPU

NPUs, particularly FPGA-based units, are extremely flexible and useful for line-rate packet processing. An NPU can accomplish any arbitrary computation on a network packet, and is not constrained by the fixed-function pipelines of OpenFlow or P4 [35]. This makes NPUs well-suited for tasks such as RAILS and EtherSlice (see chapters 3 and 4). NPUs can thus be seen as complementary to OpenFlow, although NPUs themselves are not generally available as built-in components on commercial OpenFlow switches.

6.2 Network switch augmentation design

We now cover the design of our idealized network switch augmentation.

6.2.1 Hardware specifications

Our prototype augmentation is based on the single core Raspberry Pi model B+ microcontroller (RPi) [29] and is fully software and pin-compatible with its more recent, faster multicore replacement models (Raspberry Pi 2 and Raspberry Pi 3). The RPi microcontroller is low cost ($35), compact and has a substantial number of general-purpose I/O (GPIO) pins for interfacing with external peripherals. Its default operating system, Raspbian, is Linux-based and well-supported in the development community, striking parity with other Linux distributions in terms of access to software packages, utilities, modern compilers and toolchains. Moreover, the RPi has decent computing performance and is capable of executing many modern applications that are typically associated with desktop or server-class computing. This makes the RPi an ideal system for running the Ironstack low-level controller. Table 6.1 compares the hardware capabilities of select Raspberry Pi models.

Hardware	Raspberry Pi B+	Raspberry Pi 2	Raspberry Pi 3
SoC	Broadcom BCM2835	Broadcom BCM2836	Broadcom BCM2837
CPU model	ARM1176JZF-S	Cortex-A7	Coretex-A53
Instruction set architecture	32 bit ARMv6	32 bit ARMv7	32/64 bit ARMv8
CPU Frequency	700Mhz	900Mhz	1.2Ghz
Number of cores	1	4	4
RAM	512MB	1GB	1GB
GPIOs	17	17	17
Power rating	600mA (3.0W)	800mA (4.0W)	800mA (4.0W)

Table 6.1: A comparison of pin-compatible Raspberry Pi variants for the prototype network switch augmentation. Sources: [29] [27] [28].

6.2.2 Peripherals

Our network switch augmentation features several peripherals that provide various functionality. These are:

- 2xEthernet network interfaces.
- A USB serial-to-TTL connector.
- Bluetooth BLE4.0 transceiver.
- A capacitive touch screen.
- (Optional) A NetFPGA10G or similar card (or an array of them).

The schematics for the network switch augmentation can be seen in figure 6.1. The following subsections provide an explanation of how the peripherals are used and the utility they provide.

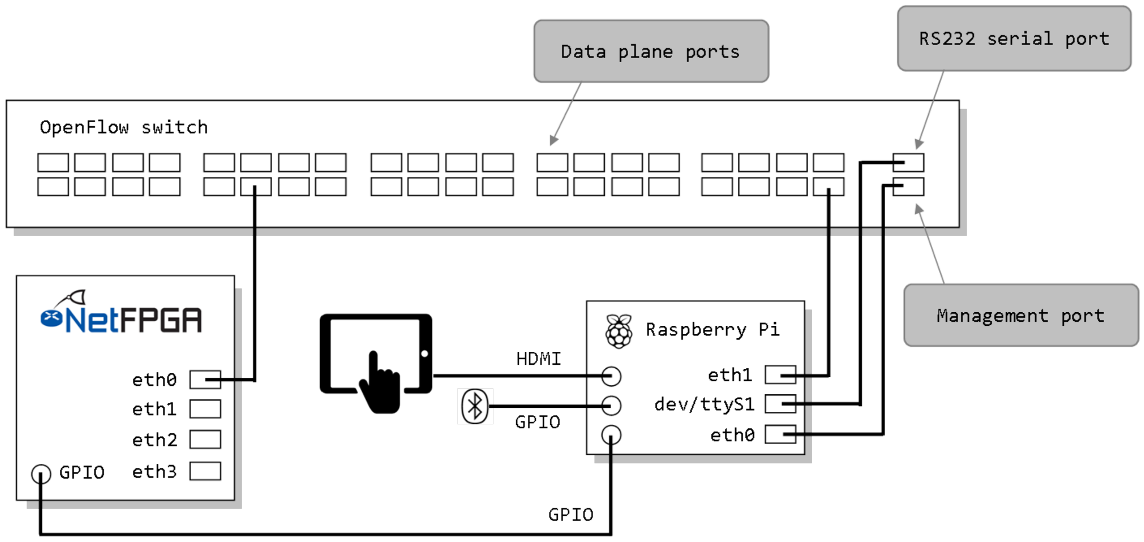


Figure 6.1: Schematic for the network switch augmentation, including connections to the OpenFlow switch.

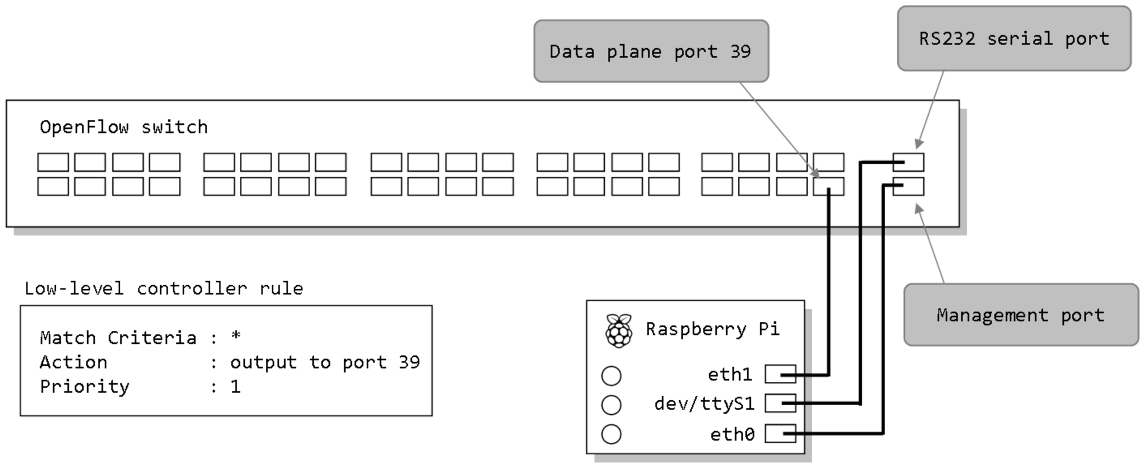
Ethernet network interfaces

The RPi and its successor models are manufactured with one built-in 10/100 Ethernet network interface, addressable as `eth0` in the Raspbian operating system. This primary interface provides the TCP networking connectivity required for the local low-level Ironstack controller(s) to communicate with the OpenFlow hardware, and is ideally connected to the management interface on the OpenFlow hardware. The management interface on an OpenFlow switch provides a dedicated, out-of-band communications channel with the low-level controller. If such a management interface is not available or if a separate control plane network is to be used, then the primary Ethernet interface on the RPi should be connected to the control network. A discussion about the tradeoffs between different control plane designs is explored in section 7.2.

The RPi does not come outfitted with a secondary Ethernet network interface, however this can be provisioned through a USB attachment. The purpose of the secondary Ethernet network interface (`eth1`) is to improve the general responsiveness of the overall controller/switch system. As our operational findings in section 5.5.1 show, reducing the `PACKET_IN` load on the embedded switch CPU frees up cycles that results in better overall OpenFlow responsiveness. Instead of directing flow-miss events through the switch CPU to the controller, `PACKET_IN` events can be avoided entirely by diverting flow-miss packets to the secondary network interface on the RPi. The RPi runs a packet demultiplexer daemon on this promiscuous interface that reads out the packets via an API such as `libpcap` or DPDK and hands them to the appropriate low-level controller via IPC. Figure 6.2 shows the ruleset required to divert flow-miss packets to the secondary RPi network interface, while figure 6.3 shows how flow-miss packets are handled at the RPi switch augmentation after they are copied from the OpenFlow switch.

Serial-to-TTL connector

The OpenFlow specification deliberately elides discussion on the prerequisite configuration steps required to put a switch into OpenFlow mode. At minimum, an OpenFlow switch needs to be configured with a controller IP address and port. This configuration needs to be performed out-of-band, and is typically provided via a Cisco IOS-like [3] command line interface. On the Dell S4810/4820 switches that we built our controllers for, the command line inter-



```
Match Criteria : *
Action         : output to port 39
Priority       : 1
```

Figure 6.2: A low priority rule captures all flow-miss packets and redirects them through a data plane port to `eth1` on the switch augmentation. If VLANs are used on the switch, this data plane port must be a tagged member of all such VLANs.

face can be unconditionally accessed via the 9600 baud RS232 serial port connector.

Our RPi network switch augmentation thus features a serial port connector from the microcontroller to the switch. Because the switch serial port uses the RS232 electrical standard (-12V to +12V signals) and the RPi uses TTL (3.3V and 0V levels), a serial-to-TTL converter is required. For simplicity, we use a USB serial-to-TTL device, which conveniently appears as a file in Raspbian under `/dev/ttyS1`. An additional advantage of our setup is that the USB device we used has a connector that fits the switch's unusual RJ45 serial port.

A serial configurator process on our RPi switch augmentation assumes sole control of the serial port and provides a RPC interface for other processes to query or control the hardware. This process translates RPC commands to the Cisco IOS-like commands that are then sent via serial, and interprets the resulting responses. The process also performs arbitration, notification and mediation for processes that wish to simultaneously control or configure the hardware.

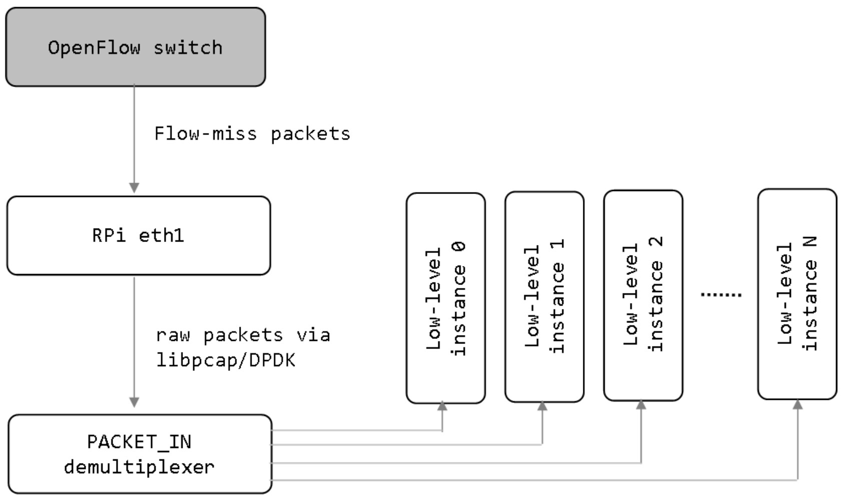


Figure 6.3: Flow miss packets are forwarded to `eth1` on the switch augmentation and demultiplexed to the appropriate low-level controller instance.

Several processes interface with the serial command process. For example, the human interface process converts touchscreen commands to configuration RPC calls. Figure 6.4 shows the relationship between the various processes that interface with the serial configurator. When interfacing with a switch that has been reset to factory settings, the RPi switch augmentation automatically uses the serial configurator to put the switch into a default SDN learning switch with one low-level controller instance. This allows an operator to rapidly deploy an OpenFlow switch by connecting it to the RPi switch augmentation.

Bluetooth BLE4.0 transceiver

While not a critical component, our augmentation also includes a Bluetooth Low Energy transceiver. The transceiver is used to provide out-of-band proximity access to the augmentation and can be used to interface with a Bluetooth-enabled device so the switch may be configured without physically accessing it. Future

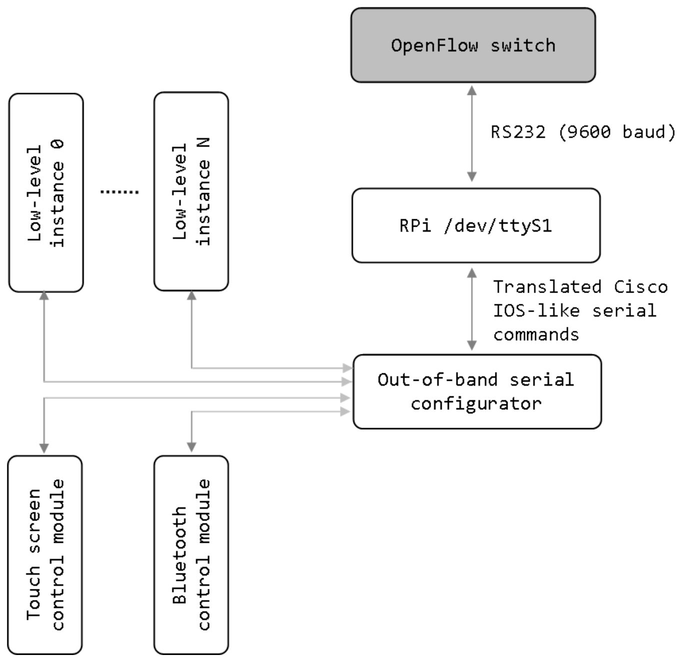


Figure 6.4: The serial configurator process provides arbitration, notification and mediation for actual OpenFlow hardware settings.

work may leverage this device to provide out-of-band mesh connectivity among low-level controllers within the same physical area.

Capacitive touch screen

A key portion of our work aims to provide improved usability. Our augmentation features an integrated capacitive touch panel to provide monitoring and hands-on configuration of the various operating parameters of the local low-level controller(s) and OpenFlow hardware. This removes the need to separately setup and configure the hardware and controller, and relieves the operator of the burden of having to sift through expansive manuals for the Cisco-IOS commands to activate hardware features.

The touch panel screen is also capable of simplifying tasks that were previously laborious. For example, cable tracing in a data center can be rapidly expedited by having the operator indicate on the touch panel the desired switch port whose cable needs to be traced. The touch panel control module issues an RPC to the relevant low-level controller, which then injects a special marker packet out the switch port. On receipt of the marker packet at the remote switch, the remote network switch augmentation can perform a task (such as flashing its screen or an LED) to indicate the trace endpoint.

NetFPGA add-in

Experience from our RAILS and EtherSlice (chapters 3 and 4) work show that the NetFPGA can be a very useful platform for providing reconfigurable NPU operations that are otherwise difficult to perform with OpenFlow, P4 [35] or related fixed-function networking hardware. Our RPi switch augmentation can be optionally augmented with an array of NetFPGA cards. The NetFPGA cards communicate with the RPi via I2C (or CAN), with each NetFPGA card holding a unique I2C/CAN address. The NetFPGA control module on the RPi detects the number and type of FPGA modules available, and coordinates with the low-level controller(s) to determine the appropriate rules to install when NPU support is required. Figure 6.5 shows one way in which an array of NetFPGAs can be attached to the RPi switch augmentation.

With this setup, low-level controllers can reserve/deallocate NetFPGA computation units, assign path meta-addresses, request reorder/deduplication buffers and so on, without manual intervention.

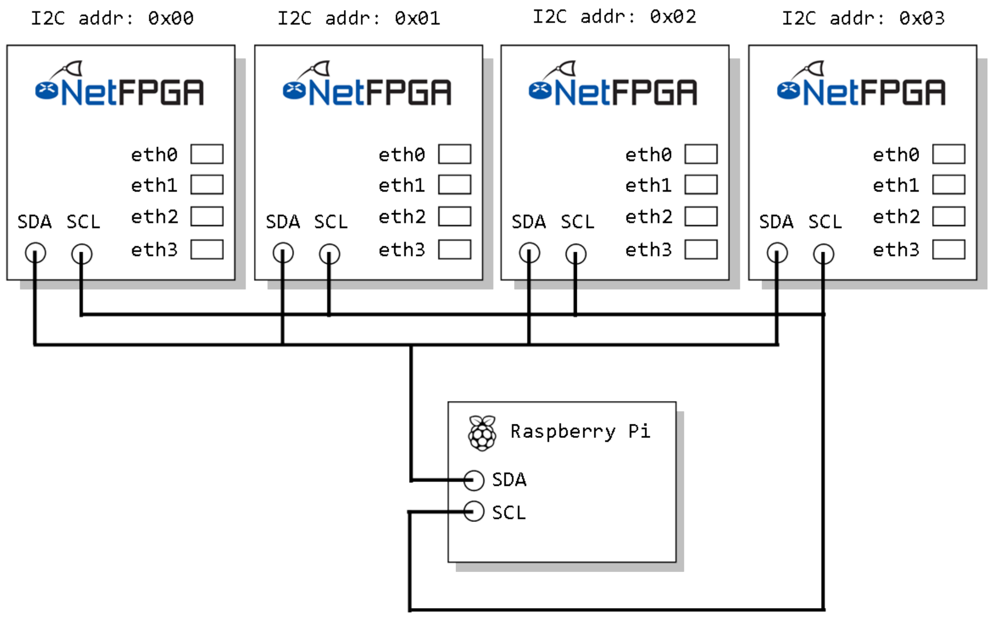


Figure 6.5: An array of NetFPGAs using shared I2C communication lines.

6.3 Integration with a switch

Although designed as an independent external unit, the network switch augmentation can also be built as an integral part of an OpenFlow switch, thus removing the need for additional space, wiring and power for the augmentation itself.

6.4 Conclusion

In this chapter, we unveiled the design and engineering schematics of a network switch augmentation. The network switch augmentation combines many disparate elements in a coherent manner to provide a turnkey solution that offers RAILS, EtherSlice and Ironstack in a single package, while being convenient and user-friendly. Our network switch augmentation can be retrofitted onto existing OpenFlow switches, or built within the switches itself.

CHAPTER 7

IRONSTACK SOFTWARE DESIGN

In this chapter, we describe the design and architecture of our Ironstack OpenFlow controller system. This system was written in C++ and built to meet OpenFlow 1.0 specifications (at system conception, hardware support for OpenFlow 1.3 was not yet available). In the course of our research, we adapted the software several times for various experiments (notably for RAILS and EtherSlice as described in prior chapters). The system presented here represents the 'base' version, which is the generic learning switch controller that was accepted for deployment onto the Gates Hall software-defined network.

As alluded to in section 5.6.1, our OpenFlow controller is hierarchical by design and includes special support hardware. The term 'Ironstack' does not refer to a single entity, computer process or software. Rather, it is an aggregate term that addresses all our proprietary software and hardware solutions deployed to drive an SDN.

7.1 General architectural features

The Ironstack controller can be coarsely broken down into several key components:

- Bootstrap agent
- Hardware abstraction layer (HAL)
- Packet callback chain

- Services (CAM/ARP/flow table, security policy/switch state etc)

Figure 7.1 shows the general architectural features of the Ironstack system.

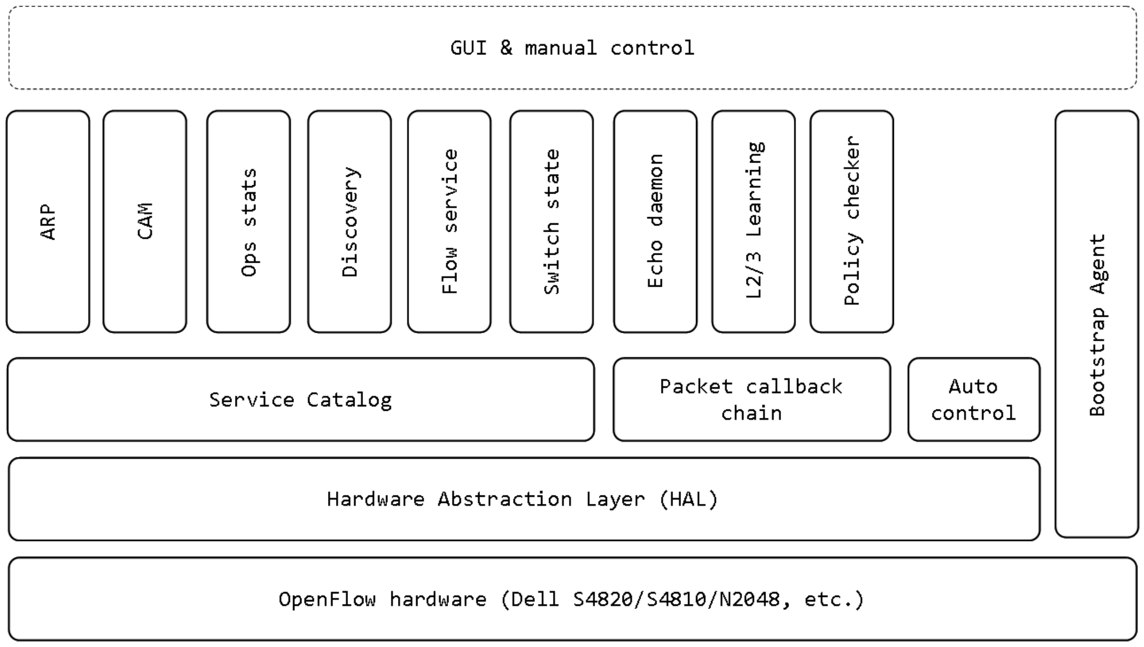


Figure 7.1: Ironstack components.

7.1.1 Bootstrap agent

The bootstrap agent is the first significant module to run in the startup phase of the controller. The role of this module is to discover switch configuration settings that may not be available or discoverable from OpenFlow itself; hence it needs to run before OpenFlow-specific code is started. The bootstrap agent connects to the management system over telnet and downloads its configuration in a read-only manner. In the process, it identifies global switch settings such as the number of OpenFlow instances, their respective controller connection addresses and ports, as well as the VLAN configuration of each individual port in an OpenFlow instance. This information is critical to the correct operation of the OpenFlow controller, since the controller needs the switch to connect at the correct address, and must also know the specific VLANs on the ports of its managed instance.

Apart from low-level configuration detection, the bootstrap agent also provides direct access to switch OS utilities that are not available through OpenFlow. For example, on our Dell S4810 switch, the bootstrap agent is capable of changing OpenFlow-specific settings (such as the port/address, echo/timeout interval) and performing some actions that are not possible from OpenFlow itself (such as configuring ACL table depths, toggling L2/L3 tables and power cycling the switch).

7.1.2 Hardware abstraction layer

The hardware abstraction layer (HAL) represents the lowest layer of the controller and interfaces directly with the switch hardware through the OpenFlow protocol. The HAL is responsible for a number of hardware-specific tasks, including handshaking, heartbeat acknowledgements and filtering of OpenFlow messages for the relevant service modules. It is architected for performance and uses dedicated threads to service the input and output communication queues, as well as two separate threads to handle event callbacks and `PACKET_IN` events. Thus, event or packet processing speeds are independent of I/O and may proceed at separate rates without affecting one another. Figure 7.2 shows the processing pipeline of the HAL.

HAL exposes a publish/subscribe model, and interested subunits can make API calls to it for notifications of an event. For example, the flow service module subscribes to HAL for messages that indicate flow modification or flow deletion, and the operations module subscribes to HAL for messages pertaining to flow statistics. Events are processed sequentially by the dedicated event handling thread, and an event must be fully processed (returned from the callback) before the next event can be considered.

`PACKET_IN` messages are data-plane specific and can be quite numerous at any instant. HAL filters these messages into a separate queue, which is handled by another dedicated thread, so that `PACKET_IN` messages do not affect the processing speed of other switch-related events. `PACKET_IN` messages enter a packet callback chain where they are processed sequentially.

7.1.3 Packet callback chain

Packets may be copied to a Ironstack low-level controller via the `PACKET_IN` mechanism for a variety of reasons, such as on flow miss events or when manually specified by higher-level application logic. For example, the L2/L3 learning unit snoops on received packets to recover Ethernet-to-IP mappings of hosts on the network; an echo daemon may respond to pings, or a controller-based application level TCP module may simulate a TCP communications stack by responding to TCP packets (see section 5.6.4). Raw, unfiltered packets may also arrive at a low-level controller via IPC when conveyed through a packet demultiplexer operating on the secondary Ethernet interface (`eth1`) of the support hardware (see section 6.2.2).

In every use case, it is clear that some principled way of filtering and delivering the packets must be followed. The method used in our Ironstack controller

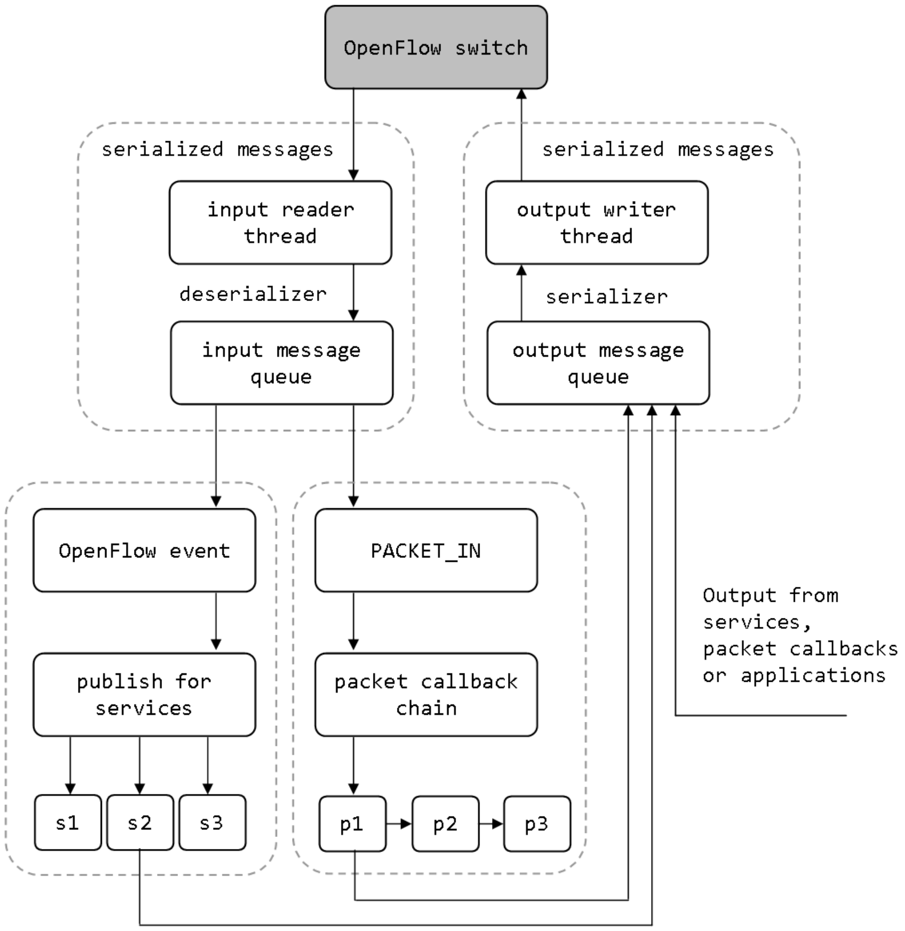


Figure 7.2: HAL processing pipeline. Dotted boxes represent processing boundaries of the various HAL threads.

follows the *chain of responsibility* software design pattern, where multiple listeners can subscribe to callbacks that are activated when a packet is available. Callbacks are registered with HAL together with a priority level. The priority level determines the precedence in which callbacks are activated. When a packet is received, it is sent down the callback chain for consideration by the registered entity with the highest priority. If that callback consumes the packet, the remainder of the callback chain is ignored and they do not receive the packet. Otherwise the packet continues propagation down the callback chain to the entity with the next highest priority. Note that a callback may transparently inspect a packet and take action without consuming the packet; this feature is exploited in L2/L3 learning functionality of the default controller. Packets not consumed by any callback are dropped when they reach the end of the chain. Figure 7.3 gives a pictorial representation of the callback chain.

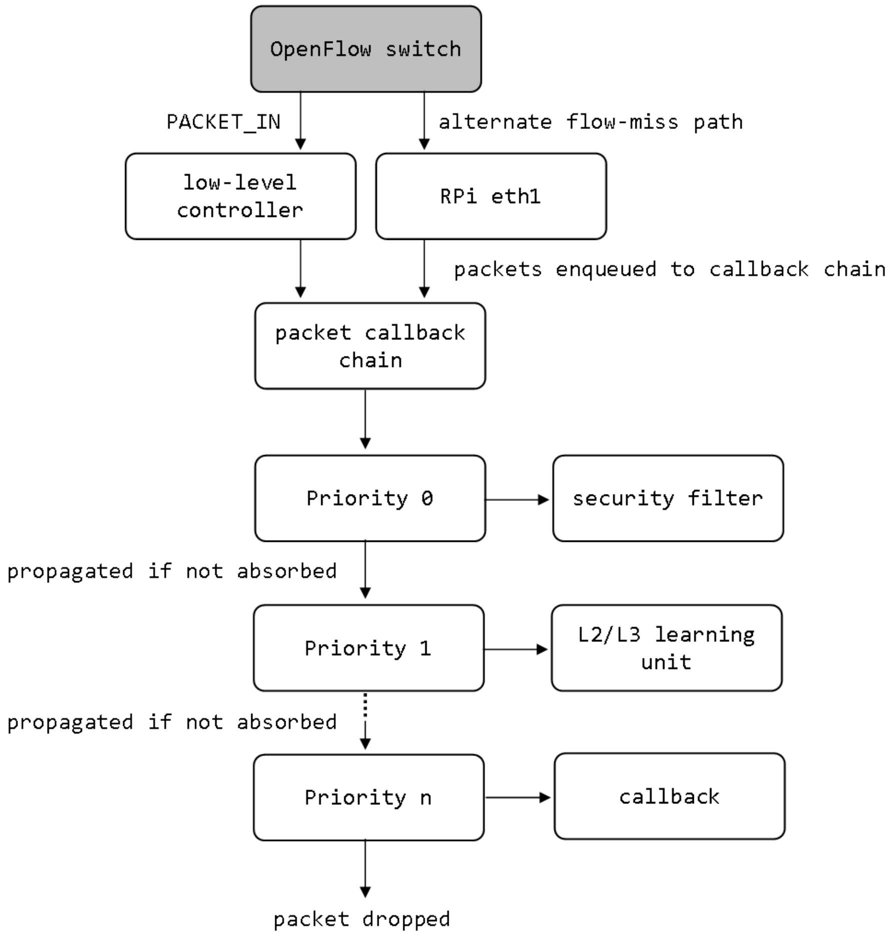


Figure 7.3: Packet callback chain.

7.1.4 Services

Although the HAL is capable of sustaining an OpenFlow connection on its own, the 'controller' aspect of Ironstack arises from its interaction with services. Services represent self-contained, highly specialized logic suited for a narrow set of related tasks, and may subscribe to specific HAL OpenFlow messages. For example, the switch state service subscribes to port modification events, and interacts with HAL to maintain an authoritative view of the local OpenFlow switch. This view includes information about the equipment serial number, per-port link activities, link speeds, VLAN associations and VLAN tagging information. Because it is a service, higher-level application logic can query the switch state module for this information; the HAL does not maintain it.

Services are 'hot-pluggable' and can be attached or detached from the HAL at runtime. A service catalog maintains the necessary smart pointers to these modules.

7.2 Inter-Ironstack communications

To realize the goal of resilience and scalability, the Ironstack low-level controllers are architecturally distributed and non-dependent on a centralized entity. Each low-level controller instance maps to a single OpenFlow switch instance, and is capable of making independent forwarding decisions. Low-level controllers synchronize state via gossip and are also able to requisition flow services from one another, such that a single low-level controller can request end-to-end setup or teardown of flows in a network.

The enabling primitive for this distributed operation is a form of inter-Ironstack communications. Inter-Ironstack communications may be done in-band or out-of-band depending on the architecture of the SDN; each approach has its tradeoffs which are discussed in the following subsections. Table 7.1 summarizes the key points.

7.2.1 Dedicated control network

On many SDN setups, particularly SDNs that are architected for a centralized controller or distributed data store, a dedicated network is provisioned for control plane communications. The Gates Hall SDN follows such a setup. Under this design, the low-level controllers may be located anywhere, possibly on remote machines far away from the physical switch itself. Because the low-level controllers run on a unified network, they may communicate with one another conveniently via control-plane IP addressing, out-of-band from the data plane network. This arrangement is also resource-efficient in that a large number of low-level controllers can be run on a single powerful server, or arbitrarily distributed over multiple machines as the OpenFlow network is scaled.

One disadvantage of such SDN architecture is that the failure or degradation of equipment on the control plane network, such as due to heavy load or an outage of an aggregation switch serving multiple OpenFlow switches, may result in the loss of responsiveness or operation of the affected OpenFlow switches. Such architecture is also incompatible with the efficient `PACKET_IN` handling mechanism discussed in section 6.2.2, as it is infeasible to outfit a server with many spare Ethernet interfaces and cables. By the same reasoning, it is also infeasible to provide the pre-OpenFlow configuration support as discussed in section 6.2.2. NetFPGA support (section 6.2.2) would have to be implemented in a different way, possibly by having the NetFPGA parse instructions received directly from its network ports, as opposed to I2C/CAN communication from a dedicated support hardware.

Figure 7.4 shows an example of an SDN using a separate control plane network.

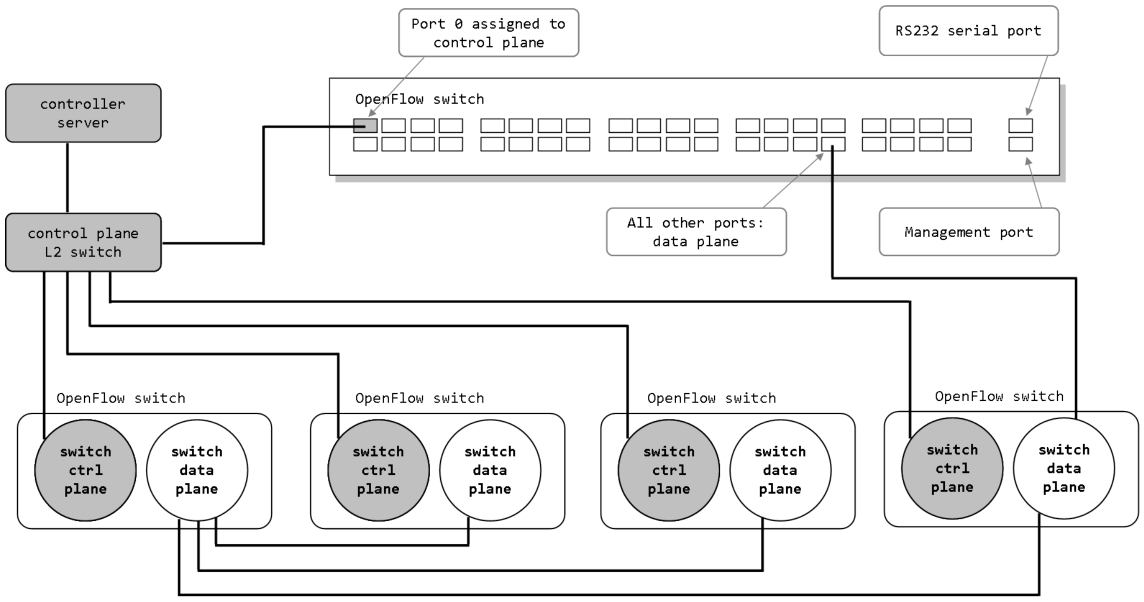


Figure 7.4: An SDN with a separate control plane network. Control plane elements are shaded in gray. One OpenFlow switch has been magnified for clarity.

7.2.2 In-band control network

On large SDN deployments, the cost of the independent control network may become quite substantial as additional separate cabling and switches are needed beyond the SDN data plane requirements. For this reason, it may be more cost-efficient to consider a deployment of low-level controllers as described in section 5.6.1. Such a deployment also lends more naturally to the provision of high efficiency `PACKET_IN` streaming, pre-OpenFlow configuration and NetFPGA support as detailed in section 6. As an advantage, the failure of any single element in the SDN is localized, and non-failed switches continue to operate without disruption. This is in contrast to a separate control network, where the failure of a single control network component can cause multiple disruptions in connectivity between OpenFlow switches and their controllers.

The disadvantage with such a deployment is that multiple independent physical servers are required, one for each switch, even if the servers themselves can be small and cheap. The cost of the servers, as well as their space and power requirements, may mitigate any savings associated with eliminating the control network. It also makes conversion to the out-of-band model impossible, as the underlying infrastructure for the independent control network does not exist. Furthermore, because the low-level controllers are no longer on the same unified control network, it is not possible for them to communicate using regular IP communication primitives. Instead, the low-level controllers have to rely on the underlying data plane to transport control-plane messages, embedding such messages in-band with data plane traffic. A proposed mechanism for doing so is discussed in section 3.3.1.

7.3 Conclusion

In this chapter, we presented the core modular components of our Ironstack controller software in detail, described its bootstrap process, and detailed its distributed operation. We also presented alternative designs for the control network, and compared the tradeoffs inherent to each design. Finally, we described how our Ironstack controller can be adapted to run on these control network designs.

Property	Dedicated control plane network	In-band control plane network
Failure handling	Single failures can cause multiple outages	Single failures cause at most one failure
Effect of congestion	Congestion on control plane network can cause slowdown	Congestion on data plane network can cause slowdown
Controller placement	Flexible; anywhere as long as it is on the control network	Close proximity to OpenFlow switch
Convertibility	Can be converted to in-band control network easily	Costly to convert to dedicated control plane network
Supports centralized controller	Yes	No
Supports distributed controller	Yes	Yes
Support for pre-OpenFlow operations	No	Yes
NetFPGA support	Yes	Yes
High efficiency `PACKET_IN` handling	No	Yes
Cost	Primarily from switches and cables for control plane network	Primarily from distributed server boxes

Table 7.1: SDN control plane architecture tradeoffs.

CHAPTER 8

FUTURE WORK

While our RAILS work investigated the use of multiple paths to improve performance and reliability, it is unclear how our system performs beside other popular multipath techniques such as MPTCP. Specifically, it would be interesting to compare the behavior of regular TCP over RAILS to MPTCP over a similar network setup, and compare their respective behaviors under failure. This is one subject of our future work.

Our current EtherSlice work depends on simulation and uses an inefficient controller-based NPU. We believe that the current processing pipeline does not realize its full performance potential because it is entirely software-based and unaccelerated by any hardware. A better implementation would use a real OpenFlow switch coupled with a hardware-based NPU such as the NetFPGA that we used in RAILS. Alternatively, a hardware OpenFlow switch together with a software-based NPU that combines fast packet I/O (using a framework such as NetMap) with GPU-based matrix computation, might attain a respectable EtherSlice throughput at a fraction of the cost and implementation difficulty of the NetFPGA approach. Both are targets of our future work.

Finally, we note that our Ironstack controller is still a work in progress. While we were able to improve various performance and usability aspects of an SDN to the point where it is capable of driving an operational SDN, it is presently a system with many rough edges and unimplemented features. For example, the Ironstack controller lacks a global coordinating entity, a policy language, and a means to adequately address certain common security concerns that may arise from abuse of an SDN. These are rich targets for future work, and we plan to refine our controller such as is befitting for a commercial setting.

CHAPTER 9

CONCLUSION

In this thesis, we presented a number of engineering solutions designed to address real needs in the IoT space. We showed that problems pertaining to performance, reliability and security can be tackled through a combination of SDN switches, NPUs and appropriate packet processing. RAILS solves the problem of performance and assurance for IoT devices, while EtherSlice retrofits confidentiality and anonymity for devices that are incapable of them.

Because RAILS and EtherSlice depended significantly on the use of an SDN and an SDN controller, we also investigated and presented our experience with configuring, operating and maintaining a real, operational SDN. The lessons learnt enlightened our controller design, and we introduced the design and software architecture of the resulting system.

Finally, drawing on all the lessons we learnt from RAILS, EtherSlice and Ironstack, we engineered a network switch augmentation that combines all three systems into a box that can be quickly and conveniently deployed. It is our hope that our combined solution would be a practical product for IoT network operators such as the power grid.

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