Flexible Software Defined Network

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A thesis submitted for the degree of

Doctor of Philosophy

Yet to be decided

Abstract

This thesis states that the best way currently to evolve computer networks is through the evolution of the control domain of networks. We state that in order to make control more effective in a computer network, we need to evolve control on the edges, and expose an API to users and applications in order to allow them to express their interest more explicitly.

The evolution of human communication needs has been radical in the recent years and Internet has evolved as the main medium. It has become vital from many aspects of society, while Internet accesibility is slowly recognised as a fundamental human right. Network engineering hasn't been fully capable to support this development through sufficient innovatio. Network perfromance requirements are enhanced and modern networks have become highly complex, as well as network performance requirements. Although, link rates have inceased significantly, the complexity of modern networks hardens the optimization task.

In order to

Keeping in accordance with the end-to-end principle of computer networks, a approach would be to develop more efficient protocols. Unfortunately, the requirement for fast connectivity at low cost, has assimilate to the network a number of strong assumtpions, that make it impossible to develop and propose new network protocol that address aforthmentioned problem. An alternative approach to the problem is to provde evolution through the control plane. Such approaches have been explored in the past without a lot of adaption. A recent development in the field is called *SDN* and gains a lot of interest from the comunity.

In my thesis, I will firstly present a set of evaluation platform and results that try to understand the impact of the SDN paradigm, and especially

its popular implementation *OpenFlow*. The result show that the protocol implementation are not yet sufficiently mature to be deployed across the network. Although, software implementations of the protocol are exceptionally efficiently.

This observation drives my exploration on the possibilities of deploying OpenFlow in the edge of the network, close to end-users.

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Chapter 1

Introduction

Internet has become the predominant mode of communication in the modern societies of our times. Currently, 1/3 of earth population is connected to the Internet ITU [2011], while Internet-related business is estimated to account for 3.4% of the global GDP du Rausas et al. [2011]. In paraller, a large fraction of our everyday social life requires network/Internet connectivity. Regardless the vital role of computer networking in our life, its strong backwards compatibility ties create a gap on our ability to evolve functionality in order to fulfil current resource short-term requirements. As a result, although the social setting requires novel functional properties from its global network, it is rather difficult to provide it, without disconnect a portion of it.

My work focuses on the evolvability problem of modern networks. The key idea of this work focuses on ways to evolve computer network functionality through the control plane. In this dissertation we argue the thesis that:

> Computer network should compat the problem of network ossification through context-aware evolved control planes, in order to provide new properties to their inter-connecting fabric. Such novel control plane implentations should focus on the requirements of the deployment environment and customly understand and fit their properties and functionalities. Such approach have to be deployed on the edges in order to obey the end-to-end principle.

For the remainder of this introduction we justify the importance of this thesis. In section 1.1 we present in details some of the limitation that current Internet faces and

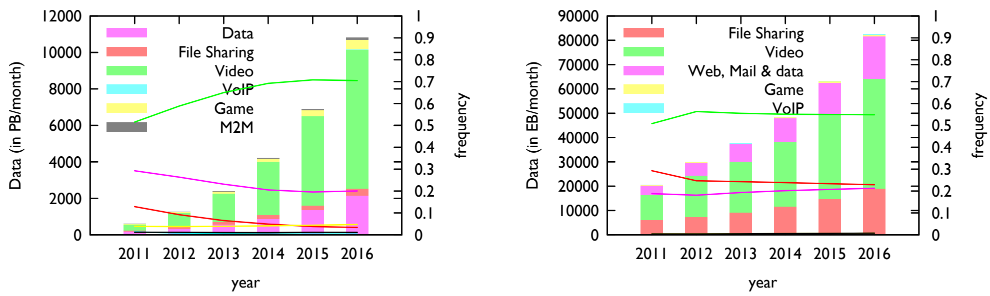
Application	rate	latency	jitter	# connections
web	0	0	0	0
video	0	0	0	0
p2p	0	0	0	0
voip	0	0	0	0
game	0	0	0	0

Table 1.1: Network performance requirement for a set of popular traffic classes.

the inherent limitations of current architecture in terms of evolvability. In section 1.2, we list briefly the main contributions of this thesis and in section 1.3, we present briefly the content of each chapter of the thesis. Finally, in section 1.4 we list the publications relating to the content of this thesis.

1.1 Motivation

Conputer network evolution



(a) global mobile traffic trend

(b) global Internet traffic trend

Figure 1.1: Cisco Visual Network Index reports on global network traffic per application. Subfigure 1.1(a) provides details on the global Internet traffic trends, while Subfigure 1.1(b) focuses on Mobile Internet traffic.

One of the ideas that formed the subjective condition of the digital revolution of our era, was the concept of computer networking. The initial goal of this concept was to develop a new communication architecture that would allow continuous communication over a redundant network, even when a significant number of vertex was destroyed. The main building block of computer networks is the idea of packet-switched networks Licklider [1963]. This idea gave birth to the pioneer of today's Internet, the *ARPANET* Mills and Braun [1987], allowing for the first time in computing history communication between multiple computers over a mess network. The initial set of applications that were standardised where : e-mail Bhushan et al. [1973], ftp Bhushan [1972b] and voice Cohen [1977]. This initial implementation was later replaced by the NSFNET in the 80's, which finally devolved in today's Internet. As part of this transition, the research community developed also the standards for the TCP/IP protocol suite Clark [1988], the default protocol to provide connectivity for the Internet.

Since the time of the ARPANET, computer networks have seen a significant elevation on their role in the social apparatus of our world due to a number of reasons. One of the most important trends, that boost their role, was the radical reduction in cost, size and capabilities of network-enabled personal computers, following Moore's Law model. The low cost factor of personal computers along with the programmable nature of the computer CPU, makes it an elegant platform to develop applications that introduce seamlessly new functionalities. Nowadays, programmable CPUs are integrated in a number of multi-purpose devices such as mobile phones, display devices etc, while the ability of personal computers to transform in size, introduces new computing concepts, such as laptops, tablets and other. As a result, the paradigm of one computer per household of the 90's rapidly shifted to the paradigm of multiple devices per user, replacing a number of everyday single-purpose devices **?**. On one hand, this augmentation in computational devices requires new modes of communication that allow devices to share consistently state, driving a significant development in computer network technologies. A number of network-enabled applications are developed to address these requirements, while new network paradigms are introduced like home networks and hotspots. Existing computer network technologies make this work easy, as they only require a minimal implementation of a protocol and a peer with a forwarding entity in order to establish connectivity with any other device. On the other hand, the elevated role of computer networks and the introduction of the cloud computing paradigm, introduce a number of internet-wide services with a global scope. The important role of computer networks can be further reflected in the government level debate to proclaim Internet connectivity as a fundamental human right Klang and Murray [2005].

In parallel with the development of the personal computer paradigm, computer network are widely adopted as an integral asset for industry. Currently the Internet produces 4,3% of the global GDP. Computer Networking and the Internet, provide the middleware to interconnect modern multinational businesses. In the business domain computer network have become popular and important for two main reasons: computer networks provide a cheap and fast communication medium to interconnect the business logic, and distribute content to users. The adaptation of computer network has further augmented through the utilisation of the cloud as a medium to offload infrastructures to 3rd party cloud providers, reducing to a great extend the cost of running services in house. *add a reference to the value of the cloud industry.*

The wide adaptation of computer networks has introduce a number of new use cases and applications. Computer networking depends to a great extend on the abstraction design pattern in order to support scalability and heterogeneity. The abstraction principle is based to a great extend on the OSI model **??**, which tries to separate network functionality into a number of layers and define the interface provided by each layer. A side effect of this design is that application developers don't have access on the properties of the underlying path. The OSI model or the TCP/IP implementations provide semantics for the interfaces but they don't provide any guarantees on the performance properties. Applications on the other hand, have performance requirement which they try to 'enforce' in the deployed environment. As a result, resource allocation in a network becomes difficult due to the diverse nature of network applications. In order to exemplify the problem, we list in Table 1.1 a number of key traffic properties for popular traffic classes of the Internet. Network applications have diverse properties which becomes difficult to address during network congestion.

Network planning for long term periods is also difficult to address. The main cause of this problem is the high churn in the popularity of network applications. In order to exhibit this trend, we plot in Figure **??** the global prediction on traffic volumes for popular application classes for five years. We use data from cisco visualization index white papers Cisco [2012]; Mobile [2012]. In the histogram we can see that network traffic is expected to increase an order of magnitude for the mobile environment, while the global Internet traffic is expected to increase four times. In parallel, application volumes evolve unevenly between traffic classes. File sharing services are expected to reduce their share of the total volume, replaced by web and video delivery services.

High diversity is also observed on the properties of available mediums for computer networks. The properties of links is defined in the data link and physical layer of the OSI model. Currently, Ethernet is the predominant link layer protocol in the Internet. In the 80s the low cost property of Ethernet implementations establish it as the leader of the market ever since. The protocol has developed standards to run over coper and optical mediums, as well as off-licence radio frequencies, satellite and mobile networks. Although the Ethernet abstraction is persistent among all these mediums, it hides a lot of the performance limitations of the link (e.g. packet loss, hop-by-hop ARQ etc.). Because of this diversity in links, the performance of a computer network can be variable. An example of this property is the Internet. Internet exhibits a 3 layer hierarchy of ASes, which allows it to scale and provide short-length paths between any 2 nodes. Tier 1 and 2 ISPs provide forwarding in an homogeneous and fast manner. Such ISP's are in charge of a relatively small number of network points and thus are able to upgrade network infrastructure with relatively low costs, which can further be offloaded to clients through SLA agreements. For Tier-3 ISPs things are a lot different. This class of ISPs covers a wide range of services. Also because this is the last hop to end users, such networks tend to be large and spread over large geographic distances. For this type of networks, connectivity properties are variable, users SLA have minimum guarantees, performance can be highly dependent on link sharing ratio and can be highly variant due to the heterogeneity of medium types. Additionally, the cost to upgrade such networks is high, while strong market competition makes difficult to offload costs directly to users. A number of measurement studies have described these differences Dischinger et al. [2007]; Huang et al. [2010].

1.1.0.1 Computer network ossification

Although computer networks are highly important for society the adaptability of network technologies to user requirement has not been equal over the years. This mismatch can be ascribed to a number of reasons.

Current network technologies were developed a number of years ago in order to develop standardized and generic mechanisms to interconnect research institutes. Although DARPA funded the idea of computer networks in order to develop new resilient communication mechanisms, the early adopters of the technologies were universities and research facilities. As a result, protocols were developed by computer scientist taking under consideration the properties of such environments. The TCP/IP protocol suite was develop during the transition of the ARPANET to NSFNET. Since then, the TCP/IP protocol suite has been the default standard of the Internet. During the first period of the NSFNET, a number of competitive suites were developed which addressed in their specification the problem of extensibility *find references for OSI TP* protocol and ATM UNI* . Unfortunately, the increased design complexity made it difficult to develop high performance implementations, and they soon were declared obsolete by the network community. The TCP/IP protocol suite provided a fair split between simplicity and extensibility at that time.

Nontheless, in the recent years the limitations of TCP/IP abstraction have become apparent, as a number of fundamental assumptions has changed. Some of the core limitations of the protocol can be described in the following points:

Elevated Role of Security : An important architectural goal for the design of computer network was the minimization of functional requirements from joining hosts, allowing wide adoption of the technology and open accessibility. When the idea of computer networks was first developed, the capabilities of computer hardware were limited and network connectivity should not consuming a significant portion of the computational resources of a node. As a result, the initial security requirements from computer network technologies were minimal. In the recent years, due to the vital role of computer networks in industry, security requirements expanded. A McAfee report from 2009 reports that the cost of cybersecurity is calculated to approximately six hundred million dollars **?**. The threat model lurcking over the Internet is wide and contains a number of threats, from Information interception to denial-of-service attacks. Such costs can be reduced to a great extend if the security was inherent to network protocols, span from the lowest levels of the network abstraction and spread across the network. Attempts to address such problem have been proposed in the protocol community, e.g. IPSEC Kent and Atkinson [1998], but the deployment at the moment is not straighforward.

Network Addressing : When the IP protocol was firstly deployed in the Internet, the size of the network was sufficiently small. Addressing was assigned based on a 32-bit integer space, split in byte aligned classes in order to permit aggregation at the forwarding entities. Within 10 years, the initial assumption over the size of classes was re-established through the classless Inter-domain routing (CIDR), in order to allow better utilisation of the IP space. Within 15 years though the initial assumption over the size of the address space prooved also shortviewed, as IP addresses were not sufficient to cover the needs of hosts. A number of layer violations, like NATs, were widely used within the subsequent years in order to provide connectivity to the increasing number of end-hosts. In order to address this problem within the design of the network protocol, a revised version of IP has been proposed Deering and Hinden [1998] since 1998, but its deployment is slow, as the size of the current Internet makes it extremely difficult to replace IPv4 without significant connectivity problems and costs.

Resource allocation : Internet provides a best-effort forwarding mechanism. This design decision was chosen in order to enforce the end-to-end principle of the Internet Saltzer et al. [1984] and avoid state in the intermediate nodes of the network. Such an approach covered sufficiently the requirements of the networked applications of the time. As new network application became available over the years, more strict performance requirements were introduced. Unfortunately, Internet currently has no mechanism to address these requirement network-wide. Network engineers have tackled this problem through adequate resource provision Teitelbaum and Shalunov [2002]. This approach though becomes inefficient as network rates increase. In a 40gbps link the impact of queueing delays or packet drop becomes significant to the performance of streams. In related literature, a number of approaches has been proposed to address this problem in multiple layers of the network stack Blake et al. [1998]; **?**]; **?**. Unfortunately, such approaches are difficult to deploy across large networks, as they require significant upgrade in network elements, introducing a significant cost.

Bidirectional connectivity : A side-effect of mechanisms addressing the previous two problem is the collapse of a fundamental assumption of computer network design, the ability of two connected nodes to communicate. A node which is behind a traffic inspecting middlebox is not guaranteed to receive incoming connections from any node and thus is not fully interactive. This problem has a direct consequence for users to resolve to 3rd party services in order to establish connectivity, changing as a result the communication mechanism.

A number of problems that we experience with current network functionality can be traced back to the assumptions of the protocols. A number of clean slate approach have been proposed over the years, that address a number of these problems. The process though to deploy a new protocol is not straightforward. Computer networks currently suffer from an effect that is term as {it 'protocol ossification'} in the research community. The protocol hierarchy in the internet currently looks like an hourglass. We currently have a multitude of protocol in the application and link layer, but we only have IP in the network layer and TCP and UDP in the transport layer. The specifications of these protocol define a number of mechanisms that allow protocol designers to develop extensions. Unfortunately, these mechanisms are not guaranteed to be supported across the network, as their support is not critical for functionality and thus can be sacrifices in favour of performance. As a result, the capabilities to evolve protocol in a manner that is compatible with the current Internet infrastructure is impossible. In Bauer et al. [2011] authors report that 80% of popular services doesn't support ECN and 0,6% of destination may drop ECN traffic, while in Honda et al. [2011] authors report a large scale inability of the Internet to cope with TCP traffic that carries unknown option fields.

1.2 Contributions

1.3 Outline

1.4 Publications

As part of my PhD work the following work was published by me:

- Rotsos, C., Van Gael, J., Moore, A. W., & Ghahramani, Z. (2010). Probabilistic graphical models for semi-supervised traffic classification (pp. 752757). Presented at the IWCMC '10: Proceedings of the 6th International Wireless Communications and Mobile Computing Conference.

- Mortier, R., Ben Bedwell, Glover, K., Lodge, T., Rodden, T., Rotsos, C., et al. (2011). Supporting novel home network management interfaces with open-

flow and NOX. Presented at the SIGCOMM '11: Proceedings of the ACM SIGCOMM 2011 conference, ACM. doi:10.1145/2018436.2018523

- Madhavapeddy, A., Mortier, R., Gazagnaire, T., Proust, R., Scott, D., Singh, B., et al. (2011). Constructing a Functional Cloud (Mirage 2011), 110.

- Mortier, R., Rodden, T., Lodge, T., McAuley, D., Rotsos, C., Moore, A. W., et al. (2012). Control and understanding: Owning your home network (pp. 110). doi:10.1109/COMSNETS.2012.6151322

- Rotsos, C., Sarrar, N., Uhlig, S., Sherwood, R., & Moore, A. (2012). Oflops: An open framework for openflow switch evaluation, 8595.

- Chaudhry, A., Madhavapeddy, A., Rotsos, C., Mortier, R., Aucinas, A., Crowcroft, J., et al. (2012). Signposts: end-to-end networking in a world of middleboxes. Presented at the SIGCOMM '12: Proceedings of the ACM SIGCOMM 2012 conference on Applications, technologies, architectures, and protocols for computer communication, ACM.

- Rotsos, C., Mortier, R., Madhavapeddy, A., Singh, B., & Moore, A. W. C. I. 2. I. I. C. O. (n.d.). Cost, performance & flexibility in OpenFlow: Pick three. Presented at the Communications (ICC), 2012 IEEE International Conference on.

- Madhavapeddy, A., Mortier, R., Rotsos, C., Scott, D., Singh, B., Gazagnaire, T., et al. (2013). Unikernels: Library Operating Systems for the Cloud. Proceedings of ASPLOS.

Chapter 2

Background

2.1 Introduction

2.2 Network Control

2.2.1 Distributed optimisation

2.2.2 SDN

2.3 Edge Network CHaracterisation

2.3.1 Network Measurement

2.3.2 Demographics

2.4 Conclusions

Chapter 3

Understanding the capabilities of the OpenFlow protocol

This chapter contains the results of an exhaustive characterisation study of existing SDN technologies. We are trying to understand the capabilities of the SDN paradigm as well as the limitation incurred by current implementation efforts. The work focuses on the functionality of version 1.0 of the OpenFlow protocol. This is the sole standardised instantiation of the SDN paradigm and version 1.0 is the current standard available in hardware switches. OpenFlow functionality is modular, thus the experiments can be reproducible over other future SDN protocol specifications. For this work, we have developed two frameworks: OFLOPS and SDNSIM. OFLOPS is a high precision OpenFlow switch micro-benchmark platform. Using the platform, we develop a set of elementary testing scenario in order to understand the performance limitation of existing OpenFlow switch implementations. SDNSIM is a macro-benchmark platform for OpenFlow architectures. The platform extends the Unikernel abstraction in order to support large scale network simulation and emulation, using the same experiment specification. In this chapter we present the goals of OFLOPS (Section 3.1) and a design overview of the OFLOPS platform (Section 3.2). Further, we select a number of off-the-self OpenFlow implementations (Section 3.3) and present the results of a set of OFLOPS test scenarios over the elemenetary interaction provided by the protocol (Section **??**.

3.1 OFLOPS introduction

Although the short period since the introduction of the SDN paradigm, many novel control architectures have been proposed Handigol et al. [2009]; Sherwood et al. [2010]; Yu et al. [2010]. The deployment of such architectures to production networks isn't straightforward. In **?** authors describe their experience in deploying the first OpenFlow production networks in Stanford University and point out that the initial deployment was highly under-performing and unreliable when a simple reactive control scheme was deployed. The main source of problems relates to firmware and hardware limitations. In order though to make the transition of SDN and OpenFlow from research to industry , developers need to evaluate thoroughly proposed functionality and provide accurate availability and performance guarantees. In order to address this issue we developed OFLOPS [1], a measurement framework that enables rapid development of use-case tests for both hardware and software OpenFlow switch implementations. To better understand the behavior of the tested OpenFlow implementations, OFLOPS combines measurements from the OpenFlow control channel with data-plane measurements. To ensure sub-millisecond-level accuracy of the measurements, we bundle the OFLOPS software with specialized hardware in the form of the NetFPGA platform[2]. Note that if the tests do not require millisecond-level accuracy, commodity hardware can be used instead of the NetFPGA Arlos and Fiedler [2007].

3.2 OFLOPS design

Measuring OpenFlow switch implementations is a challenging task in terms of characterization accuracy, noise suppression and precision. Performance characterization is not trivial as most OpenFlow-enabled devices provide rich functionality but do not disclose implementation details. In order to understand the performance impact of an experiment, multiple input measurements must be monitored concurrently. Further, current controller designs, like SNA [2010]; Gude et al. [2008], target production networks and thus are optimized for throughput maximization and programmability,

[1] OFLOPS is under GPL licence and can be downloaded from `http://www.openflow.org/wk/index.php/Oflops`

[2] `http://www.netfpga.org`

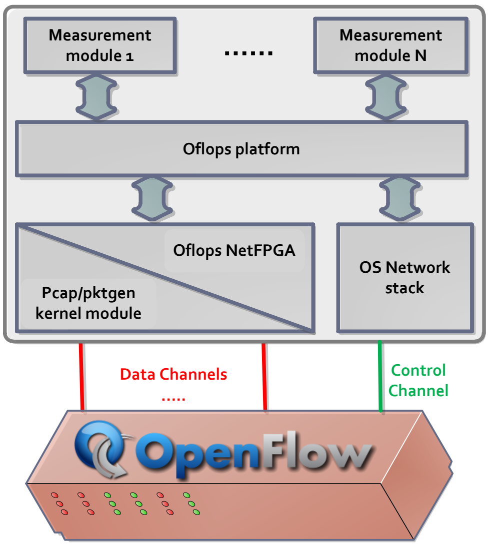


Figure 3.1: OFLOPS design schematic

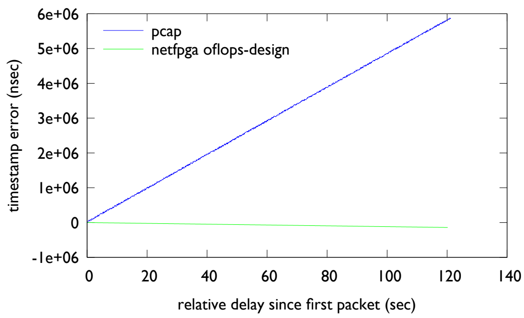


Figure 3.2: Evaluating timestamping precision using a DAG card.

but incur high measurement inaccuracy. Measurement noise suppresion in the control plane requires a new simplified OpenFlow controller library with low processing latency. Finally, high precision measurements after a point are subject to loss due to unobserved parameters of the measurement host, such as OS scheduling and clock drift. The result of these challenges is that meaningful, controlled, repeatable performance tests are non-trivial in an OpenFlow environment.

The OFLOPS design philosophy aims to develop a low overhead abstraction layer that allows interaction with an OpenFlow-enabled device over multiple data channels. The platform provides a unified system that allows developers to control and receive information from multiple control sources: data and control channels as well as SNMP to provide specific switch-state information. For the development of measurement experiments over OFLOPS, the platform provides a rich, event-driven, API that allows developers to handle events programatically in order to implement and measure custom controller functionality. The current version is written predominantly in C. Experiments are compiled as shared libraries and loaded at run-time using a simple configuration language, through which experimental parameters can be defined. A schematic of the platform is presented in Figure 3.1. Details of the OFLOPS programming model can be found in the API manual ofl.

The platform is implemented as a multi-threaded application, to take advantage of modern multicore environments. To reduce latency, our design avoids concurrent access controls: we leave any concurrency-control complexity to individual module implementations. OFLOPS consists of the following five threads, each one serving specific type of events:

1. Data Packet Generation: control of data plane traffic generators.

2. Data Packet Capture: data plane traffic interception.

3. Control Channel: controller events dispatcher.

4. SNMP Channel: SNMP event dispatcher.

5. Time Manager: time events dispatcher.

OFLOPS provides the ability to control concurrently multiple data channels to the switch. Using a tight coupling of the data and control channels, programers can understand the impact of the measurement scenario on the forwarding plane. To enable our platform to run on multiple heterogeneous platforms, we have integrated support for multiple packet generation and capturing mechanisms. For the packet generation functionality, OFLOPS supports three mechanisms: user-space, kernel-space through the pktgen module Olsson [2005], and hardware-accelerated through an extension of the design of the NetFPGA Stanford Packet Generator Covington et al. [2009]. For the packet capturing and timestamping, the platform supports both the pcap library and the modified NetFPGA design. Each approach provides different precisions and different impacts upon the measurement platform.

A comparison of the precision of the traffic capturing mechanisms is presented in Figure 3.2. In this experiment we use a constant rate 100 Mbps probe of small packets for a two minute period. The probe is duplicated, using an optical wiretap with negligible delay, and sent simultaneously to OFLOPS and to a DAG card. In the figure, we plot the differences of the relative timestamp between each OFLOPS timestamping mechanism and the DAG card for each packet. From the figure, we see that the pcap timestamps drift by 6 milliseconds after 2 minutes. On the other hand, the NetFPGA timestamping mechanism has a smaller drift at the level of a few microseconds during the same period.

3.3 Measurement setup

The number of OpenFlow-enabled devices has slowly increased recently, with switch and router vendors providing experimental OpenFlow support such as prototype and evaluation firmware. At the end of 2009, the OpenFlow protocol specification was released in its first stable version 1.0 ope [2009], the first recommended version implemented by vendors for production systems. Consequently, vendors did proceed on maturing their prototype implementations, offering production-ready OpenFlow-enabled switches today. Using OFLOPS, we evaluate OpenFlow-enabled switches from three different switch vendors. Vendor 1 has production-ready OpenFlow support, whereas vendors 2 and 3 at this point only provide experimental OpenFlow support. The set of selected switches provides a representative but not exhaustive sample of available OpenFlow-enabled top-of-rack-style switching hardware. Details regarding the CPU and the size of the flow table of the switches are provided in Table 3.1.

OpenFlow is not limited to hardware. The OpenFlow protocol reference is the software switch, OpenVSwitch Pettit et al. [2010], an important implementation for production environments. Firstly, OpenVSwitch provides a replacement for the poor-performing Linux bridge Bianco et al. [2010], a crucial functionality for virtualised operating systems. Secondly, several hardware switch vendors use OpenVSwitch as the basis for the development of their own OpenFlow-enabled firmware. OpenVSwitch development team has standardised a clean abstraction over the control of the switch silicon (similar to linux HAL), which allows code reuse over any forwarding entity that implements the switch abstraction. Thus, the mature software implementation of the OpenFlow protocol is ported to commercial hardware, making certain implementation bugs less likely to (re)appear. In this paper, we study OpenVSwitch alongside our performance and scalability study of hardware switches. Finally, in our comparison we include the OpenFlow switch design for the NetFPGA platform Naous et al. [2008]. This implementation is based on the OpenFlow reference implementation, extending it with a hardware forwarding design.

In order to conduct our measurements, we setup OFLOPS on a dual-core 2.4GHz Xeon server equipped with a NetFPGA card. For all the experiments we utilize the NetFPGA-based packet generating and capturing mechanism. 1Gbps control and data channels are connected directly to the tested switches. We measure the processing

Switch	CPU	Flow table size
Switch1	PowerPC 500MHz	3072 mixed flows
Switch2	PowerPC 666MHz	1500 mixed flows
Switch3	PowerPC 828MHz	2048 mixed flows
OpenVSwitch	Xeon 3.6GHz	1M mixed flows
NetFPGA	DualCore 2.4GHz	32K exact & 100 wildcard

Table 3.1: OpenFlow switch details.

delay incurred by the NetFPGA-based hardware design to be a near-constant 900 nsec independent of the probe rate.

3.4 Switch Evaluation

As for most networking standards, there are different ways to implement a given protocol based on a paper specification. OpenFlow is not different in this regard. The current reference implementation is defined through OpenVSwitch Pettit et al. [2010]. However, different software and hardware implementations may not implement all features defined in the OpenVSwitch reference, or they may behave in an unexpected way. In order to understand the behaviour of switch OpenFlow implementation, we develop a suite of measurement experiments to benchmark the functionality of the elementary protocol interactions. These tests target (1) the OpenFlow packet processing actions **??**, (2) the packet interception and packet injection functionality of the protocol **??**, (3) the update rate of the OpenFlow flow table along with its impact on the data plane, **??** (4) the monitoring capabilities provided by OpenFlow, and (5) the impact of interactions between different OpenFlow operations.

3.4.1 Packet modifications

The OpenFlow specification ope [2009] defines ten packet modification actions which can be applied on incoming packets. Available actions include modification of MAC, IP, and VLAN values, as well as transport-layer fields. A flow definition can contain any combination of them. The left column of Table 3.2 lists the packet fields that can be modified by an OpenFlow-enabled switch. These actions are used by network devices such as IP routers (e.g., rewriting of source and destination MAC addresses) and NAT (rewriting of IP addresses and ports). Existing network equipment is tailored to perform a subset of these operations, usually in hardware to sustain line rate. On the other hand, how these operations are to be used is yet to be defined for new network primitives and applications, such as network virtualization, mobility support, or flow-based traffic engineering.

To measure the time taken by an OpenFlow implementation to modify a packet field header, we generate from the NetFPGA card UDP packets of 100 bytes at a constant rate of 100Mbps (approx. 125 Kpps). This rate is high enough to give statistically significant results in a short period of time, without causing any packet queuing for any of the switches. The flow table is initialized with a flow that applies a specific action on all probe packets and the processing delay is calculated using the transmission and receipt timestamps, provided by the NetFPGA.

Evaluating individual packet field modification, Table 3.2 reports the median difference between the generation and capture timestamp of the measurement probe along with its standard deviation and percent of lost packets.

We observe significant differences in the performance of the hardware switches due in part to the way each handles packet modifications. Switch1, with its production-grade implementation, handles all modifications in hardware; this explains its low packet processing delay between 3 and 4 microseconds. On the other hand, Switch2 and Switch3 each run experimental firmware providing only partial hardware support for OpenFlow actions. Switch2 uses the switch CPU to perform some of the available field modifications, resulting in two orders of magnitude higher packet processing delay and variance. Switch3 follows a different approach: All packets of flows with actions not supported in hardware are silently discarded. The performance of the OpenVSwitch software implementation lies between Switch1 and the other hardware switches. OpenVSwitch fully implements all OpenFlow actions. However, hardware switches outperform OpenVSwitch when the flow actions are supported in hardware.

We conducted a further series of experiments with variable numbers of packet modifications as flow actions. We observed, that the combined processing time of a set of packet modifications is equal to the highest processing time across all individual actions in the set. Furthermore, we notice that for Switch1 and OpenVSwitch there is a limit of 7 actions, which potentially exposes some relation in the code base.

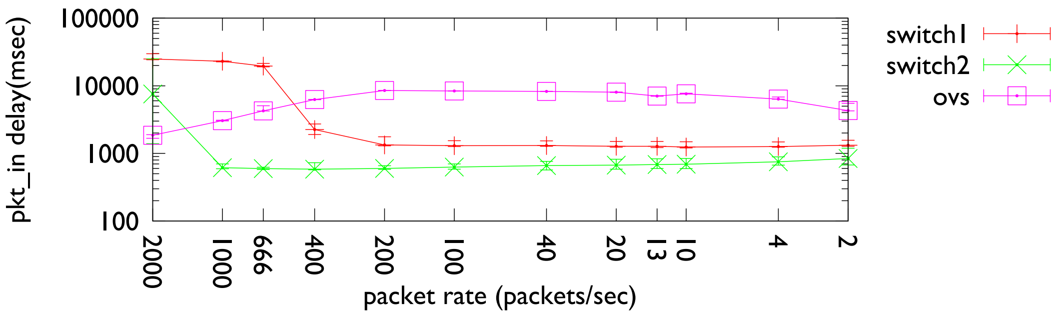
Mod. type	Switch 1			ovs			Switch 2		
	med	sd	loss%	med	sd	loss%	med	sd	loss%
Forward	4	0	0	35	13	0	6	0	0
MAC addr.	4	0	0	35	13	0	302	727	88
IP addr.	3	0	0	36	13	0	302	615	88
IP ToS	3	0	0	36	16	0	6	0	0
L4 port	3	0	0	35	15	0	302	611	88
VLAN pcp	3	0	0	36	20	0	6	0	0
VLAN id	4	0	0	35	17	0	301	610	88
VLAN rem.	4	0	0	35	15	0	335	626	88

Mod. type	Switch 3			NetFPGA		
	med	sd	loss%	med	sd	loss%
Forward	5	0	0	3	0	0
MAC addr.	-	-	100	3	0	0
IP addr.	-	-	100	3	0	0
IP ToS	-	-	100	3	0	0
L4 port	-	-	100	3	0	0
VLAN pcp	5	0	0	3	0	0
VLAN id	5	0	0	3	0	0
VLAN rem.	5	0	0	3	0	0

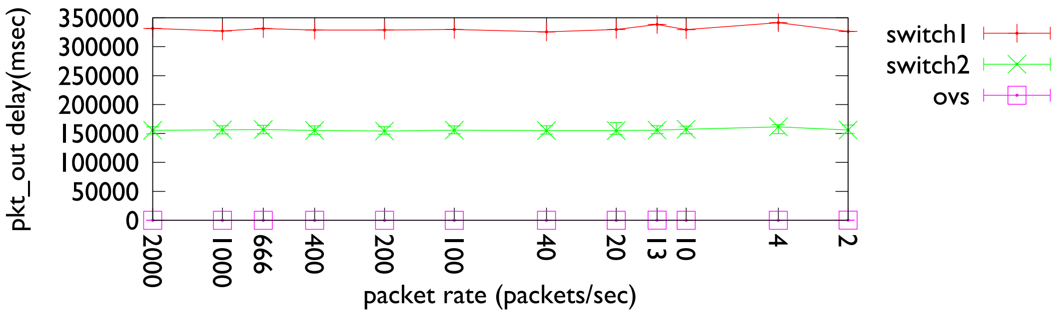
Table 3.2: Time in μs to perform individual packet modifications and packet loss. Processing delay indicates whether the operation is implemented in hardware ($<10\mu$s) or performed by the CPU ($>10\mu$s).

3.4.2 Traffic interception and injection

OpenFlow protocol permits a controller to intercept or inject traffic over the control plane. This functionality allowed in the initial design of the OpenFlow controller to be reactive and handle traffic on a per-flow basis. Packet injection allows the controller to interact with connected network hosts. The interception mechanism in OpenFlow has been reported in the initials deployments of the protocol to cause significant slow-down in the control plane and led to switch disconnection at high data rate Kobayashi et al.. This is a direct consequence of the silicon design in current OpenFlow switches, that develop such functionality as an low-frequency exception mechanism. In order to characterise this functionality, we develop a simple experiment using OFLOPS that sends packets at a specific rate and measure the latency of the switch to process them.



(a) Packet in message latency

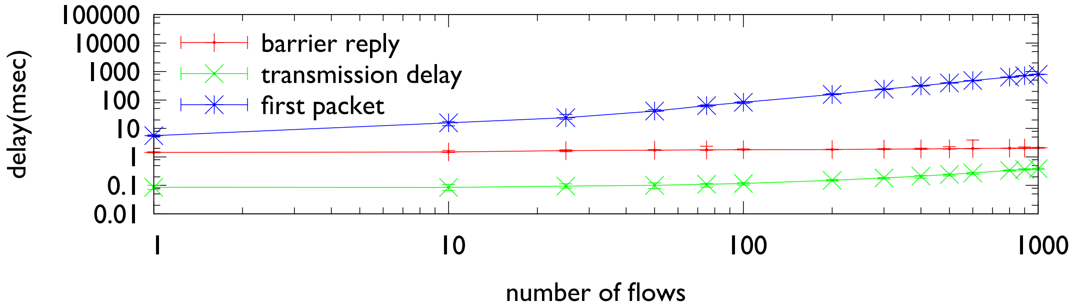


(b) Packet out message latenct

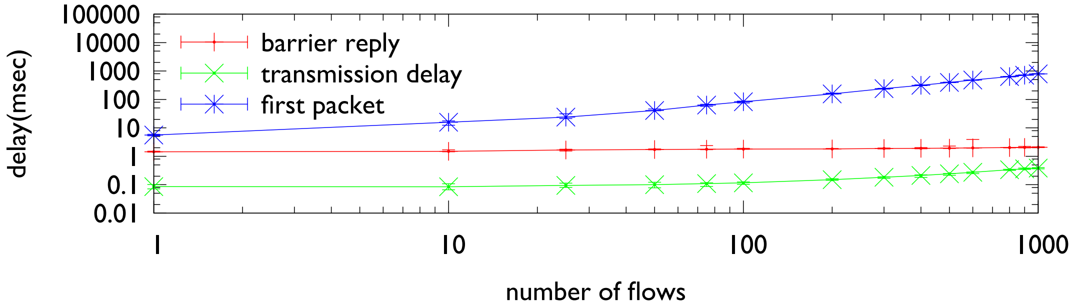
Figure 3.3: Latency to intercept or inject a packet using the OpenFlow protocol

In Figure **?**, we show the latency induced on packets both for Packet_in and Packet_out messages. We omit in this experiment Switch 3 as this functionality maxed out its CPU utilisation and after a few seconds made the switch unresponsive over the control channel. For packet_out messages, the switches rate limit through the tcp connection channel the rate of messages received and as a result they provide a constant performance. For packet_in messages, we observe a diverse behaviour between hardware switches at high packet rates. For Switch 1, packet loss and latency gets high for traffic rates above 400 packets per second. Additionally, we noticed that the switch is able to process a maximum of 500 packets/sec. For Switch 2 latency and packet loss are significantly lower and stable. Switch 2 faced problem to process packet important packet at high rates of 2000 packets per second. OpenVSwitch, has a high but stable latency for any tested data rates.

3.4.3 Flow table update rate



(a) OpenVSwitch (log-log scale)



(b) Switch1 (log-log scale)

Figure 3.4: Flow entry insertion delay: as reported using the `barrier` notification and as observed at the data plane.

The flow table is a central component of an OpenFlow switch and is the equivalent of a Forwarding Information Base (FIB) on routers. Given the importance of FIB updates on commercial routers, e.g., to reduce the impact of control plane dynamics on the data plane, the FIB update processing time of commercial routers provide useful reference points and lower bounds for the time to update a flow entry on an OpenFlow switch. The time to install a new entry on commercial routers has been reported in the range of a few hundreds of microseconds Shaikh and Greenberg [2001].

OpenFlow provides a mechanism to define barriers between sets of commands: the `barrier` command. According to the OpenFlow specification ope [2009], the barrier command is a way to be notified that a set of OpenFlow operations has been completed. Further, the switch has to complete the set of operations issued prior to the barrier before executing any further operation. If the OpenFlow implementations comply with the specification, we expect to receive a barrier notification for a flow modification once the flow table of the switch has been updated, implying that the change can be seen from the data plane.

We check the behavior of the tested OpenFlow implementations, finding variation among them. For OpenVSwitch and Switch1, Figure 3.4 shows the time to install a set of entries in the flow table. The NetFPGA-based switch results (not reported) are similar to those of Switch1, while Switch2 and Switch3 are not reported as this OpenFlow message is not supported by the firmware. For this experiment, OFLOPS relies on a stream of packets of 100 bytes at a constant rate of 10Mbps that targets the newly installed flows in a round-robin manner. The probe achieves sufficiently low inter-packet periods in order to measure accurately the flow insertion time.

In Figure 3.4, we show three different times. The first, *barrier notification*, is derived by measuring the time between when the **first insertion command** is sent by the OFLOPS controller and the time the barrier notification is received by the PC. The second, *transmission delay*, is the time between the first and last flow insertion commands are sent out from the PC running OFLOPS. The third, *first packet*, is the time between the **first insertion command** is issued and a packet has been observed for the last of the (newly) inserted rules. For each configuration, we run the experiment 100 times and Figure 3.4 shows the median result as well as the 10^{th} and 90^{th} percentiles (variations are small and cannot be easily viewed).

From Figure 3.4, we observe that even though the *transmission delay* for sending flow insertion commands increases with their number, this time is negligible when compared with data plane measurements (*first packet*). Notably, the *barrier notification* measurements are almost constant, increasing only as the transmission delay increases (difficult to discern on the log-log plot) and, critically, this operation returns before any *first packet* measurement. This implies that the way the *barrier notification* is implemented does not reflect the time when the hardware flow-table has been updated.

In these results we demonstrate how OFLOPS can compute per-flow overheads. We observe that the flow insertion time for Switch1 starts at 1.8ms for a single entry, but converges toward an approximate overhead of 1ms per inserted entry as the number of insertions grows.

Flow insertion types

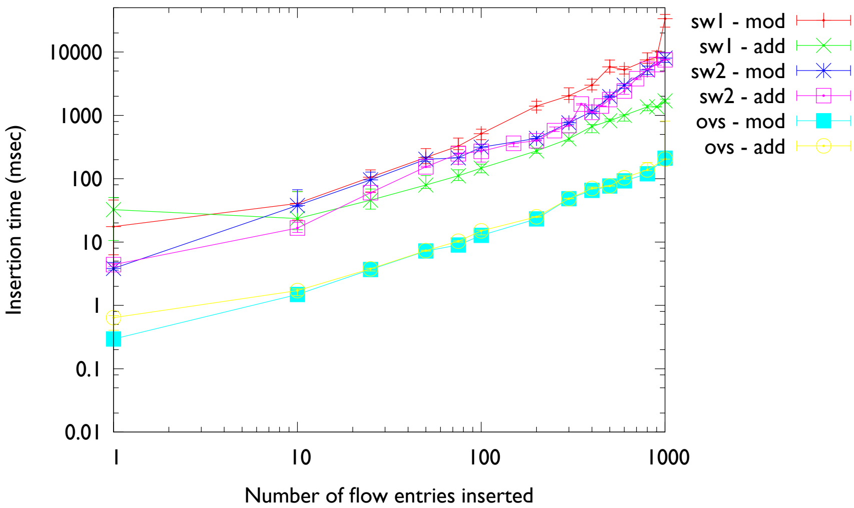


Figure 3.5: Delay of flow insertion and flow modification, as observed from the data plane (log-log scale).

We now distinguish between flow insertions and the modification of existing flows. With OpenFlow, a flow rule may perform exact packet matches or use wild-cards to match a range of values. Figure 3.5 compares the flow insertion delay as a function of the number of inserted entries. This is done for the insertion of new entries and for the modification of existing entries.

These results show that for software switches that keep all entries in memory, the type of entry or insertion does not make a difference in the flow insertion time. Surprisingly, both Switch1 and Switch2 take more time to modify existing flow entries compared to adding new flow entries. For Switch1, this occurs for more than 10 new entries, while for Switch2 this occurs after a few tens of new entries. After discussing this issue with the vendor of Switch2, we came to the following conclusion: as the number of TCAM entries increases, updates become more complex as they typically requires re-ordering of existing entries.

Clearly, the results depend both on the entry type and implementation. For example, exact match entries may be handled through a hardware or software hash table. Whereas, wild-carded entries, requiring support for variable length lookup, must be handled by specialized memory modules, such as TCAM. With such possible choices and range of different experiments, the flow insertion times reported in Figure 3.5 are not generalizable, but rather depend on the type of insertion entry and implementation.

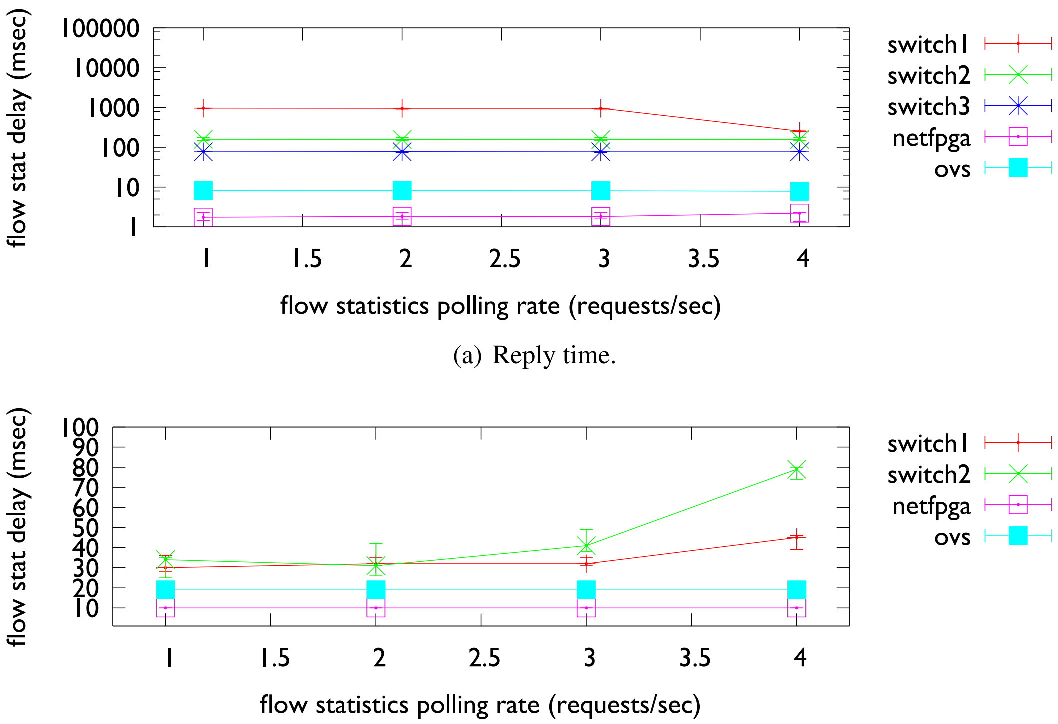
3.4.4 Flow monitoring

The use of OpenFlow as a monitoring platform has already been suggested for the applications of traffic matrix computation Balestra et al. [2010]; Tootoonchian et al. [2010] and identifying large traffic aggregates Jose et al. [2011]. To obtain direct information about the state of the traffic received by an OpenFlow switch, the OpenFlow protocol provides a mechanism to query traffic statistics, either on a per-flow basis or across aggregates matching multiple flows and supports packet and byte counters.

We now test the performance implications of the traffic statistics reporting mechanism of OpenFlow. Using OFLOPS, we install flow entries that match packets sent on the data path. Simultaneously, we start sending flow statistics requests to the switch. Throughout the experiment we record: the delay getting a reply for each query, the amount of packets that the switch sends for each reply and the departure and arrival timestamps of the probe packets.

Figure 3.6 reports the time to receive a flow statistics reply for each switch, as a function of the request rate. Despite the rate of statistics requests being modest, quite high CPU utilization results for even a few queries per second being sent. Figure 3.6 reports the switch-CPU utilization as a function of the flow statistics inter-request time. Statistics are retrieved using SNMP. Switch3 is excluded for lack of SNMP support.

From the flow statistics reply times, we observe that all switches have (near-)constant response delays: the delay itself relates to the type of switch. As expected, software switches have faster response times than hardware switches, reflecting the availability of the information in memory without the need to poll multiple hardware counters. These consistent response times also hide the behavior of the exclusively hardware switches whose CPU time increases proportionally with the rate of requests. We observe two types of behavior from the hardware switches: the switch has a high CPU utilization, answering flow-stats requests as fast as possible (Switch2), or the switch delays responses, avoiding over-loading its CPU (Switch1). Furthermore, for Switch1, we notice that the switch is applying a pacing mechanism on its replies. Specifically, at



(a) Reply time.

(b) CPU utilization.

Figure 3.6: Time to receive a flow statistic (median) and corresponding CPU utilization.

low polling rates the switch splits its answer across multiple TCP segments: each segment containing statistics for a single flow. As the probing rate increases, the switch will aggregate multiple flows into a single segment. This suggests that independent queuing mechanisms are used for handling flow statistics requests. Finally, neither software nor NetFPGA switches see an impact of the flow-stats rate on their CPU, thanks to their significantly more powerful PC CPUs (Table 3.1).

3.4.5 OpenFlow command interaction

An advanced feature of the OpenFlow protocol is its ability to provide applications with, e.g., flow arrival notifications from the network, while simultaneously providing fine-grain control of the forwarding process. This permits applications to adapt in real time to the requirements and load of the network Handigol et al. [2009]; Yap et al.

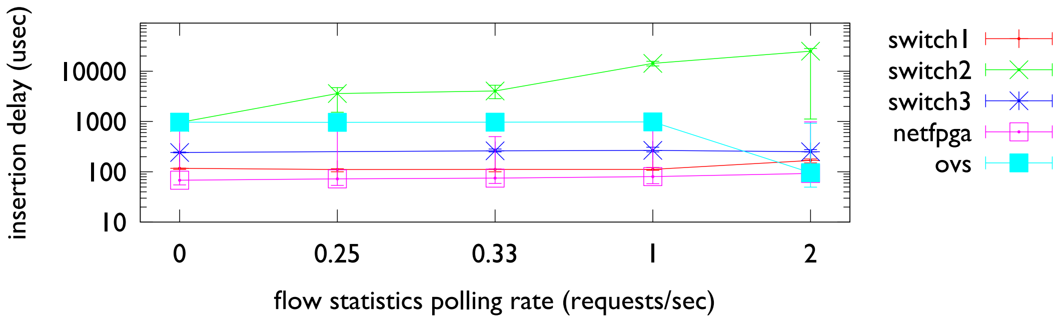


Figure 3.7: Delay when updating flow table while the controller polls for statistics.

[2009]. Under certain OpenFlow usage scenarios, e.g., the simultaneous querying of traffic statistics and modification of the flow table, understanding the behavior of the data and control plane of OpenFlow switches is difficult without advanced measurement instrumentation such as the one provided by OFLOPS.

Through this scenario, we extend Section 3.4.3 to show how the mechanisms of traffic statistics extraction and table manipulation may interact. Specifically, we initialize the flow table with 1024 exact match flows and measure the delay to update a subset of 100 flows. Simultaneously, the measurement module polls the switch for full table statistics at a constant rate. The experiment uses a constant rate 10Mbps packet probe to monitor the data path, and polls every 10 seconds for SNMP CPU values.

In this experiment, we control the probing rate for the flow statistics extraction mechanism, and we plot the time necessary for the modified flows to become active in the flow table. For each probing rate, we repeat the experiment 50 times, plotting the median, 10^{th} and 90^{th} percentile. In Figure 3.7 we can see that, for lower polling rates, implementations have a near-constant insertion delay comparable to the results of Section 3.4.3. For higher probing rates on the other hand, Switch1 and Switch3 do not differ much in their behavior. In contrast, Switch2 exhibits a noteworthy increase in the insertion delay explained by the CPU utilization increase incurred by the flow statistics polling (Figure 3.6(b)). Finally, OpenVSwitch exhibits a marginal decrease in the median insertion delay and at the same time an increase in its variance. We believe this behavior is caused by interactions with the OS scheduling mechanism: the constant polling causes frequent interrupts for the user-space daemon of the switch, which leads to a batched handling of requests.

3.5 SDNSIM introduction

In the SDN paradigm, backward-compatible evolvability of computer networks is achieved through the distribution of control to external programmable units. The protocols provides all required mechanisms in order to allow a remote entity to get sufficient forward plane feedback and control the forwarding process at a very fine level. So far the trend in OpenFlow design is to aggregate control in a single control unit, in order to have a single point of control in the network. This aggregation permits on one hand to achieve higher optimality in forwarding policy, while on the other hand the logic can be developed in richer programming environments, than the embedded systems usually found in current network devices.

The ability to distribute control over multiple functional units, in conjunction with the complex nature of network stacks, as well as the diverse behaviour of OpenFlow switch and controlling platforms, reduces the ability of developers to predict the behaviour of an SDN design. In order to reason on correctness, developers must build realistic small scale experiments, and larger scale experiments in order to reason on performance. In the related literature on network evaluation there have been two main experimental approaches: *realistic testbed* and *simulation*.

In the realistic experimentation approach, scientists try to reconstruct the exact properties of the deployment environment. This approach provides an optimal measurement environment the provides full control of the parameter of the experiment, but has a significant overhead in resources and configuration time. Experimenting with a real datacenter would require a high number of machines that implement full functionality of the target environment, large interconnection planning and careful metrication and analysis of the resulting system. These requirements scale badly as the number of network hosts increases. In order to reduce resource costs, the research community has developed shared testbeds *add some pointers.* . Such testbeds though limit the capability of users to control measurement noise and network topologies.

In the simulation approach, researchers replace some part of the functionality of the system by a simpler model. The goals of such an approach is to reduce the complexity of the experiment, and achieve scalability for large network sizes. This approach has two main drawbacks. Firstly, the fidelity of the results depends extensively on the reality of the assumptions of the model. Secondly, in order to simulate appropriately the network, the users usually need to rewrite the logic of their experiments in order to fit the abstraction of the underlying models. For example, in order to simulate OpenFlow-based network currently there is no off-the-self simulation platform to support the protocol. An OpenFlow architect is required to reimplement its OpenFlow logic in order to experiment with architectural designs.

SDNSIM [1] is a novel framework, that bridges the two domains of experimentation and provides an OpenFlow specific development environment. The framework is written in OcaML, a high performance functional language, and extends the functionality of the Mirage [2] library OS. Developers can implement the required functionality of their network design and at the compilation step select the target experiment type. SDNSIM provides two target options: a simulation target, that runs the Mirage code on top of the ns-3 simulation environment, and a realistic target, that build and deploys each node of the simulation as a DomU VM and configuration resource allocation using xen's API.

3.6 Mirage Library OS

Cloud computing has revolutionized the way the business use IT infrastructures as well as the way we develop distributed computing applications. The abstraction is straightforward. A third party entity takes responsibility to maintain a datacenter. This infrastructure, is partitioned into smaller virtual computational units which clients can rent in order to run their applications. The elegance of this model is based on simplicity of the abstraction that the cloud provider provides to the user and the ability to port existing services running on a personal computer or a server to the cloud platform.

Although the simplicity of the exposed abstraction, the cloud architecture consist of a complex set of processing layers. A single application VM would include: i) the virtualization runtime layer, ii) the guest OS kernel layer, iii) A language runtime layer (POSIX, JVM etc.) iv) user-space thread layer. This layer complexity, although it provides excellent backwards compatibility for existing datacenter applications, it makes the process of optimisation, debugging as well as security difficult, while there

[1] OFLOPS is under GPL licence and can be downloaded from `http://github.com/crotsos/sdnsim/`

[2] *http://openmirage.org*

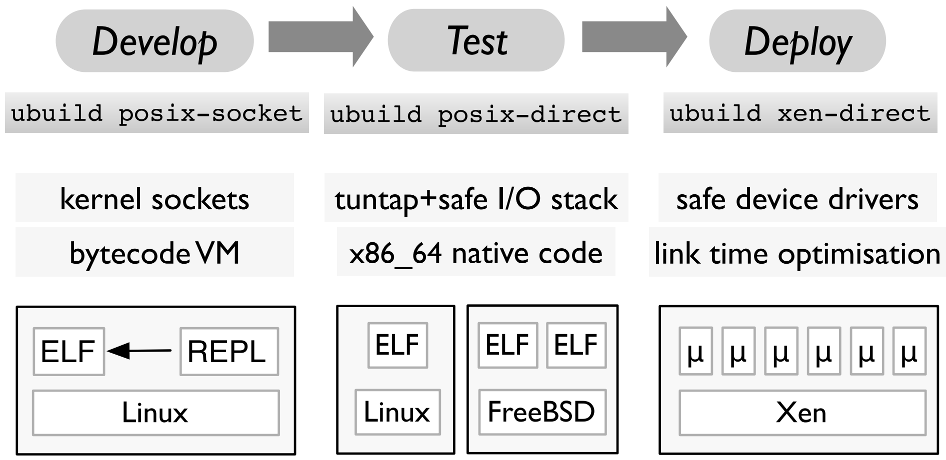


Figure 3.8: Specialising a Mirageapplication through recompilation alone, from interactive UNIX Read-Eval-Print Loop, to reduce dependency on the host kernel, and finally a unikernel VM.

is a significant overlap on the functionality provided by each layer.

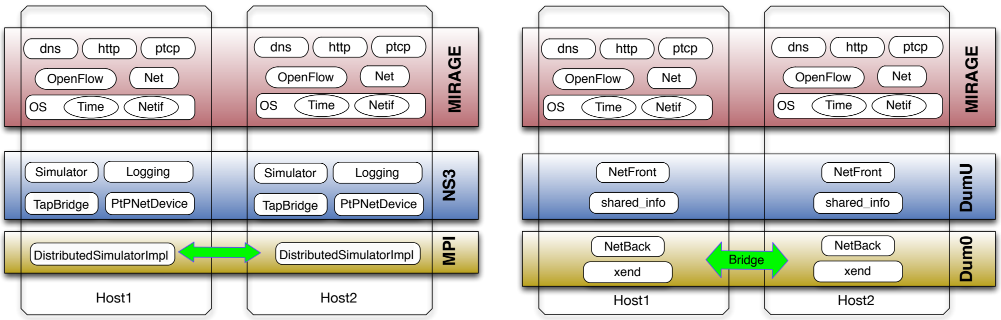
Mirage is a clean-slate application synthesis framework that allows users to compile application to a single bootable VM image. Mirage relies on the idea of library OS; functionality is separated into logical modules which integrates in a resulting binary, only if needed by the code. As a result, Mirage is able to generate small size VM images which additionally are fast to boot. Although, OCaml is a functional language, it is able to generate highly performand binary code and application specific microbenchmarks has shown performance to be compare to c code implementations. In order to minimize processing layers, IO operations are coded on top of the NetFront device abstraction provided by Xen, while the OS is using extensively zero-copy mechanisms and exposes directly the pages of the shared memory ring to application space, over a simple abstraction that enforces memory boundaries.

Mirage executes OCaml code over a specialised language runtime modied in two key areas: memory management and concurrency. Because of the single process nature of Mirage images, the OS uses a single address space, separated between the text and data section of the program and the runtime heap. Because the program code is immutable during runtime, Mirage can lock write access to executable memory space, thus mitigating buffer overflow attacks. Additionally, this mechanism removes the requirement of Address Space Randomization (ASR), which simplifies and makes more efficient memory management. To provide concurrency beyond Xen IO polling function, Mirage integrates the Lwt cooperative threading library **?**. This internally evaluates blocking functions into event descriptors to provide straight-line control ow for the developer. Written in pure OCaml, Lwt threads are heap-allocated values, with only the thread main loop requiring a C binding to poll for external events. Mirage provides an evaluator that uses Xen polling to listen for events and wake up lightweight threads. The VM is thus either executing OCaml code or blocked, with no internal preemption or asynchronous interrupts. The main thread repeatedly executes until it completes or throws an exception, and the domain subsequently shuts down with the VM exit code matching the thread return value. A useful consequence is that most scheduling and thread logic is contained in an application library, and can thus be modified by the developer as they see fit.

In order to provide basic system programming capabilities, Mirage OS provides two core modules, named Net and OS, that implement and expose the required functionality for networking and device management, respectively. The API is similar to the API provided by the Unix model from OCaml; developers can modify their code and compile existing applications to Mirage VMs. Due to the simplicity of the OS and Net modules, Mirage provides the ability to compile code to other target backends, apart from the Xen platform. Specifically, Mirage can generate UNIX binaries, using both the POSIX library network functionality and raw sockets, and even Javascript executables that run in a browser. There is also currently an effort to port Mirage in the FreeBSD kernel as well as the BareboneOS, an assembly written minimum OS. The diverse set of deployment backends, provides to developers an environment to test and optimize code gradually. Developers build initially their core logic over the POSIX backend in order to test the correctness of the code, then they can try their code over the Mirage default network stack, to perform a small scale performance evaliation, and finally they can synthesize the resulting deployable Xen Image 3.8.

3.7 SDNSIM design

```
<?xml version="1.0" encoding="ISO-8859-1"?>
<topology module="Simple_tcp_test" backend="ns3-direct"
```



(a) NS3 (b) Xen

Figure 3.9: SDNSIM host internal architecture: ns3 simulation 3.9(a) and xen real-time emulation 3.9(b).

```
    duration="30">
  <modules>
    <library>lwt</library>
    <library>lwt.syntax</library>
    <library>cstruct</library>
    <library>cstruct.syntax</library>
    <library>mirage</library>
    <library>mirage-net</library>
    <library>pttcp</library>
  </modules>
  <node name="host1" main="host_inner">
    <param>1</param>
  </node>
  <node name="host2" main="host_inner">
    <param>2</param>
  </node>
  <link src="host1" dst="host2" delay="10" rate="100"
    queue_size="100" pcap="false"/>
</topology>
```

Listing 3.1: A sample SDNSIM configuration file interconnecting a server and a client host

For the user perspective, the core of SDNSIM consists on a single executable that works as one more OCaml build system. Developers write their OCaml code in order to define the functionality of network nodes, and use a single xml file in order to describe the network topology and match functionality to network hosts. A sample xml file is presented in Listing 3.1. The configuration describes a simple client (host1) - server (host2) configuration. For an experiment definition, developers needs to define, at minimum, the core code module (topology@module), the target executable (topology@backend) and the duration of the experiment (topology@duration). In order to define a host, SDNSIM uses a host xml entity. For each host users must define the host name (node@name) and the host main function (node@main), while a number of named parameters (node/param) can be passed to the main function. Finally, developers can define links between hosts (link@src, link@dst) along with the device (link@queue_size, link@pcap) and propagation properties (link@rate, link@delay), using the link xml entity. Links can be used also to integrate external network interfaces in the simulation, in order to allow the experiment to interact with entities outside of the experiment scope.

The functionality of a node in the SDNSIM platform can be split in 3 layers. A simple representation of the architecture of an SDNSIM host can be seen in Figure 3.9. At the top layer of the host is the application logic of the host. This layer is defined by the developer, and define the traffic load of the network and its forwarding logic. In order to allow realistic traffic patterns, SDNSIM can reuse all the application protocol libraries supported in the Mirageplatform, namely dns, http, ssh and OpenFlow. Additionally, we have re-implemented in OCaml the pttcp tcp test tool functionality **??**, in order to allow model driven TCP flow generation.

In the middle layer of the host architecture, we reuse the network library and the OS abstraction defined by the Mirage platform. These libraries are mapped in the lower layer of the respective backend. Currently, SDNSIM supports two backends, *NS3* and *Xen*. For each backend a different strategy has been followed in order to match the respective the middle layer abstraction to the model of the environment.

3.7.0.1 NS3

A schematic of the architecture of the platform using the NS3 back end is presented in Figure 3.9(a). Given that the application is primarily network-oriented, the integration requires bridging of two main functionalities tbetween Mirage and NS3 system: the time and network abstraction of the OS. The OS layer of Mirage contains three modules that handle these functionalities: the OS.Netif, the OS.Clock, and OS.Time modules. OS.Netif is responsible for spawning a thread for each network device and propagating the received packet to the Net.Ethif module. The OS.Clock and OS.Time modules provide gettimeofday and sleep functionalities respectively to Mirage applications. The NS3 back end uses a pure event-driven OS design approach. As a result, for each host not using a main loop function to handle the event, only events generated by the NS3 layer are used to execute the operating system. This design pattern is required because the OCaml runtime does not allow multithreaded functionality. However, it also incurs the danger that time-independent events may be suppressed. To avoid long idle periods for the host process, the code injects *idle* events to execute such events.

For the timing aspect of the simulation, the gettimeofday functionality of the OS is coupled with the global Simulator clock of the NS3 platform. Further, when the process executes a sleep system call for a thread, the sleep request is translated into an NS3 time event, idling the requesting thread. Mirage uses Lwt (a popular OCaml library for lightweight threading and asynchronous IO), which allows the thread to cooperate and synchronize when a blocking operation occur.

The networking functionality uses an abstraction primitive of the NS3 platform, PointToPoint channel. This primitive simulates a simple PPP encapsulated link. The main reason for using this connection abstraction is the fact that it is the only abstraction that implements rate limiting on the network device entity and that does not require any state sharing between the two hosts to schedule transmission. Such a model is valid for the case of large datacenters, as the Ethernet links are usually full duplex and the medium is not shared between more that two entities, negating the requirement for CSMA MAC protocols. For the sending functionality, the network device contains a single network queue for each device shared between the OCaml code and the NS3 simulator entity, on which packets can be stored temporarily when the network medium is busy transmitting data. To provide a reliable network device that will not drop packets when the queue is full, during transmission the OS netif module first checks the size of the queue; in case it is full, it defers its packet copy until the queue has an empty slot. To avoid consuming processing cycles from the simulation, the queue also provides a notification mechanism to the OCaml code, which notifies the net module when a slot is available in the queue. As a result, we avoid any unnecessary polling. For packet receipt, the NS3 device allows registering receipt callback to each virtual network device. The packet demuxing callback implements logic to forward packets to the appropriate listening thread.

An important assumption of the current architecture that provides accuracy in simulation time is the blocking nature of the event-handling process. In this way, the virtual clock will not increment while a host is processing an event and all processing complexity of hosts is assumed to incur negligible delays.

Finally, in order to make the simulation scalable, a distributed message passing mechanism has been included that allows each host to run in an independent process and synchronize with other hosts only during network interactions. This layer in the architecture has been included because the OCaml runtime cannot support multithreaded parallel programming in order to make the garbage collection easier and faster. By allowing this process level distribution of the simulation load, we are able to distribute the computation burden across multiple cores in multicore platforms, or even extend the simulation across the network, by deploying hosts in remote machines and notifying the MPI process of their existence. On the other hand, the synchronization relaxation is not significant for the class of operations considered, as the traffic in a datacenter is dominated by the TCP protocol – which by nature bases its rate-adaption capabilities on the synchronization of the participating hosts.

3.7.0.2 Xen

For the Xen back end a lot of the work to integrate the Mirage libraries with the hypervisor was already developed by the Mirage project. There are two main differences on the design of the Xen back end in comparison to the NS3 back end. First, in the Xen case, the emulated host now runs in real time and as a result it has to handle in the OS space the generation of time and network events. To avoid the low-level interaction of the OS code with the hypervisor hardware-software abstraction, the code uses the existing MiniOS code to boot and interact with the network devices. Packet receipt and transmission is handled by a number of ring buffers that can be accessed both by the OCaml code and the MiniOS library. Each VM appropriately handles events through a polling mechanism running within a loop, and waits for either packets to arrive or for sleep requests to time out. The second difference is the fact that, due to the real-time nature of this back end, the experimental measurement results may include high noise and variance, especially when highly computational tasks are implemented in the host space. The Xen back end sacrifices accuracy to provide faster execution times.

Work on the Xen back end over the summer of 2012 focused on developing appropriate bindings for the Topology module in order to generate the appropriate VM binaries as well as configure network requirements. To achieve this, the xen-api library was used. This library provides bindings in various programming languages that allow programmatic allocation of resources and deployment of new VMs. The library uses an XML-based RPC protocol that communicates with a hypervisor server and provides both monitoring and configuration capabilities. Additionally, in order to configure the network environment, I used the OpenVSwitch software switch to provide bridging functionality for the VMs. OpenVSwitch provides a controlling daemon that is responsible for the monitoring and the configuration of the switching functionality in real time. The daemon exposes a JSON RPC mechanism through which users can change aspects of the switching functionality in real time, such as the creation of resource limiting queues and the assignment of flows to queues. This is still an ongoing task without fully functional code.

3.8 SDNSIM evaluation

In order to evaluate the performance of the develop develop a number of small scale microbenchmarks in order to evaluate the performance of the OpenFlow protocol functionality as well as the performance of the NS-3 binding. In **?**, there is an exhaustive analysis of the performance of the Mirageplatform, which we omit from this section. In Section 3.8.1, we use a number of off-the-self benchamrking platforms of the OpenFlow community and benchmark the OpenFlow controller and switch performance and in Section 3.8.2 we test the scalability of the ns3 backend

3.8.1 OpenFlow library performance

Controller

We first benchmark our controller library's performance through a simple baseline comparison against two existing OpenFlow controllers, NOX and Maestro. NOX **?** is one of the first and most mature publicly available OpenFlow controllers; in its original form it provides programmability through a set of Python modules. In our evaluation we compare against both the master branch and the *destiny-fast* branch, a highly optimised version that sacrifices Python integration for better performance. Maestro **?** is an optimised Java-based controller that aims to achieve fairness among switches. We compare these against the Mirage controller targeting two different network backends: *mirage-unix* targets the UNIX Sockets backend and so uses the existing Linux TCP/IP stack, while *mirage-xen* targets the Xen hypervisor and runs as a domU virtual machine using the Mirage TCP/IP stack.

Our benchmark setup uses the *cbench* application from the Oflops benchmarking platform.[1] Each emulated switch simultaneously generates *packet-in* messages and the program measures the throughput of the controller in processing these requests. It provides two modes of operation, both measured in terms of *packet-in* requests processed per second: *latency*, where only a single *packet-in* message is allowed in flight from each switch; and *throughput*, where each switch maintains a full 64 kB buffer of outgoing packet-in messages. The first measures the throughput of the controller when serving connected switches fairly, while the second measures absolute throughput when servicing requests.

We emulate 16 switches concurrently connected to the controller, each serving 100 distinct MAC addresses. We run our experiments on a 16-core AMD server running Debian Wheezy with 40 GB of RAM and each controller configured to use a single thread of execution. We restrict our analysis to the single-threaded case as Mirage does not yet support multi-threading. For each controller we run the experiment for 120 seconds and measure the per-second rate of successful interactions. Table 3.3 reports the average and standard deviation of requests serviced per second.

Unsurprisingly, due to mature, highly optimised code, *NOX fast* shows the highest performance for both experiments. However, we note that the controller exhibits extreme short-term unfairness in the throughput test. *NOX* provides greater fairness in the throughput test, at the cost of significantly reduced performance. Maestro performs as well as NOX for throughput but significantly worse for latency, probably due to the overheads of the Java VM. Finally, Mirage throughput is somewhat reduced from NOX fast but substantially better than both NOX and Maestro with both backends; the Xen backend wins out over the UNIX backend due to reduction of layers in the network stack. In addition, Mirage Xen achieves the best product of performance and fairness

[1] `http://www.openflow.org/wk/index.php/Oflops`

2*Controller	Throughput (kreq/sec)		Latency (kreq/sec)	
	avg	std. dev.	avg	std. dev.
NOX fast	122.6	44.8	27.4	1.4
NOX	13.6	1.2	26.9	5.6
Maestro	13.9	2.8	9.8	2.4
Mirage UNIX	68.1	11.7	21.1	0.2
Mirage Xen	86.5	4.4	20.5	0.0

Table 3.3: OpenFlow controller performance.

among all tested controllers in the throughput test. Comparing latency, both Mirage backends perform much better than Maestro but suffer somewhat in comparison to NOX: we believe this is due to the lack of optimisation in the Mirage TCP/IP stack.

3.8.1.1 Switch

We also use the Oflops benchmark platform **?** to evaluate performance of the Mirage switch implementation. We compare against the Open vSwitch[1] (OVS) kernel implementation, an OpenFlow-enabled software switch implemented as a Linux kernel module. OVS is currently used by many datacenter service providers to enable virtual machines to be bridged in dom0, while its OpenFlow functionality is used by vendors to implement OpenFlow firmware.

For this experiment we use two virtual machines, one running the Oflops code, the other running the OpenFlow switch configured with three interfaces bridged separately in dom0. One interface provides a control channel for the switch, while the other two are used as the switch's data channels. This represents a setup that might be used to enable an application to modify switch functionality without affecting the network functionality in dom0. Using Oflops, we generate packets on one of the data channels and receive traffic on the other, having inserted appropriate flow table entries at the beginning of the test. We run the test for 30 seconds using small packets (100 bytes) and varying the data rate.

Figure 3.10 plots as error boxes the min, median and max of the median processing latency of ten test runs of the experiment. We can see that the Mirage switch's forwarding performance is very close to that of Open vSwitch, even mirroring the high

[1] `http://openvswitch.org`

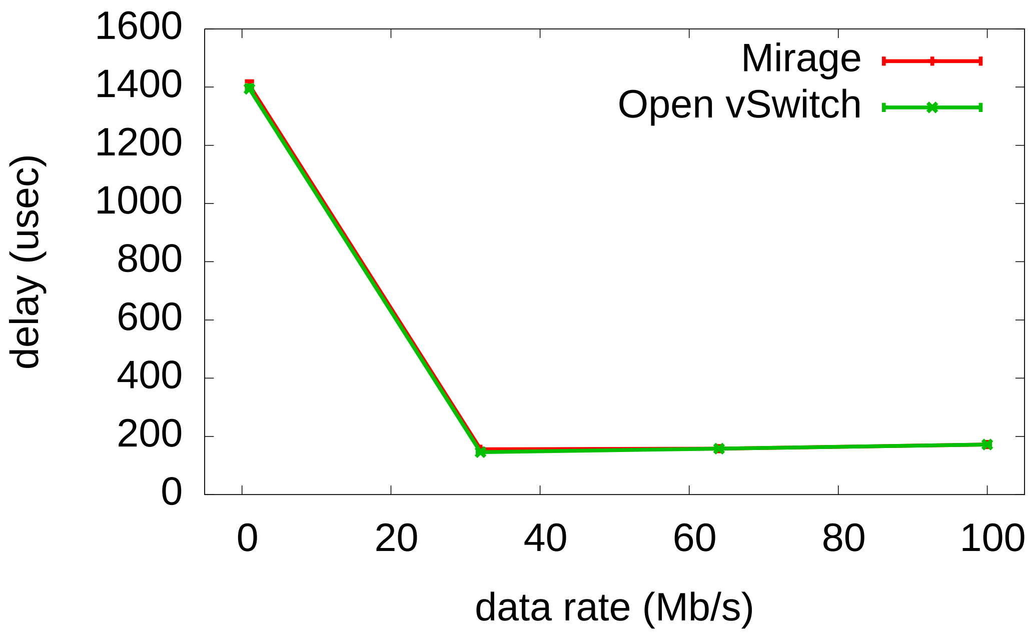


Figure 3.10: Min/max/median delay switching 100 byte packets when running the Mirage switch and Open vSwitch kernel module as domU virtual machines.

per-packet processing latency with a probe rate of 1 Mb/s; we believe this is due to a performance artefact of the underlying dom0 network stack. We omit packet loss due to space constraints, but can report that both implementations suffer similar levels of packet loss. However, the Mirage switch has a memory footprint of just 32 MB compared with the Open vSwitch virtual machine requirement of at least 128 MB. We are currently working toward better integration of the Mirage switch functionality with the Xen network stack to achieve lower switching latency.

3.8.2 NS-3 performance

An initial experiment of the delay incurred by SDNsim involves simulating a simple topology setup. The simulated topology is present in Figure 3.11. The topology consists of a single multi-port switch with a number of connected hosts. The hosts are generated in pairs and are programmed to generate steady-state full-rate TCP traffic from the client to the server. The switch is also connected to an OpenFlow controller that implements the control logic of a learning switch. For this scenario, two variations of the topology exist, one with all hosts connected to the same switch, and a second

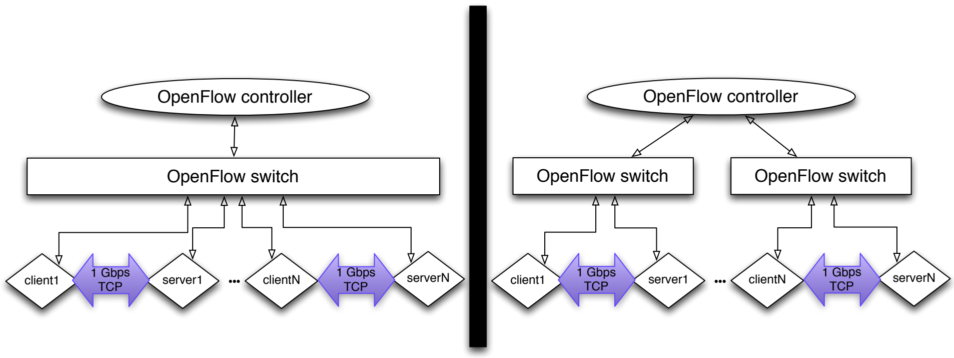


Figure 3.11: Topology of two basic simulation scenarios for the SDNsim platform

Table 3.4: Simulation results

A	B	C	D	E	F	G

one where the hosts are distributed between two switches. This experiment ran for 30 seconds of simulated time.

The results of the simulation process are presented in Table 3.4, which shows the amount of time of real execution time of the simulation, as well as the slowdown factor of the simulation. Although, the simulation platform appears to be extremely slow, the experiment uses steady-state TCP connections that sending traffic at a constant rate of 1 Gbps. This is an unrealistic scenario for datacenters, as the links are not expected to run at full utilization for a long period of time and the delay of the simulation is driven by the amount of network interrupts that occur in the network. Further, a significant gain from the multi-process distribution strategy can be seen by comparing the slowdown factor between the topology using a single switch and the one distributing the load between two switches. In the first scenario, the openflow switch is the bottleneck of the simulation, as it has to process all the events generated in the network sequentially, slowing down the process. In the second example, the network events are distributed between the two hosts of the network, thus allowing simulation parallelization – which reduces the execution time almost in half.

********* LET'S FIX THIS, PLEASE!!! The skeletal table is begun above but commented out.

Delay (in min) 17 90 171 21 50 82 Slowdown factor 34 180 242 42 100 164

Table 3.4 shows execution time of a simple OpenFlow setup with a variable number of hosts generating TCP traffic at 1Gbps rate for a period of 1 minute.

3.9 Security Tradeoffs on Datacenter Network Micro-control

3.10 Summary and Conclusions

We presented, OFLOPS, a tool that tests the capabilities and performance of OpenFlow-enabled software and hardware switches. OFLOPS combines advanced hardware instrumentation, for accuracy and performance, and provides an extensible software framework. We use OFLOPS to evaluate five different OpenFlow switch implementations, in terms of OpenFlow protocol support as well as performance.

We identify considerable variation among the tested OpenFlow implementations. We take advantage of the ability of OFLOPS for data plane measurements to quantify accurately how fast switches process and apply OpenFlow commands. For example, we found that the barrier reply message is not correctly implemented, making it difficult to predict when flow operations will be seen by the data plane. Finally, we found that the monitoring capabilities of existing hardware switches have limitations in their ability to sustain high rates of requests. Further, at high rates, monitoring operations impact other OpenFlow commands.

We hope that the use of OFLOPS will trigger improvements in the OpenFlow protocol as well as its implementations by various vendors.

Chapter 4

Evolving Home network control

4.1 Introduction

Consumer broadband Internet access is a critical component of the digital revolution in domestic settings: for example, Finland has made broadband access a legal right for all its citizens.[1] A growing number of services are now provided over the Internet, including government, entertainment, communications, retail and health. The growth of IP enabled devices over the last decade also means many households are now exploring the use of in-home wired and wireless networking, not only to allow multiple computers to share an Internet connection but also to enable local media sharing, gaming, and other applications. Despite the growth in Internet use and the explosion of interest in home networking, the opacity of networking technologies means that they remain extraordinarily difficult for people to install, manage, and use in their homes.

In this paper we explore issues surrounding *home networks*: highly heterogeneous edge networks, typically Internet-connected via a single broadband link, where non-expert network operators provide a wide range of services to a small set of users. While we focus on home networks in this paper, we note that many environments, e.g., small offices, coffee shops, hotels, exhibit similar characteristics and thus may benefit from similar approaches. Within the Homework Project[2] we have developed a range of mechanisms that exploit the physical and social nature of the home to provide capabilities likely to be infeasible in more traditional settings, e.g., backbone and enterprise

[1] `http://www.bbc.co.uk/news/10461048`
[2] `http://www.homenetworks.ac.uk/`

networks.

In this paper we present three distinct contributions:

- We elaborate on the nature of the problems and opportunities inherent to home networks (§4.2);
- We describe our home router and how its flow-based approach enables it to help improve the user experience (§4.3); and
- We present and evaluate protocol modifications that place the homeowner in more direct control of their network (§4.4).

Finally, we present related work (§4.5) and conclude (§4.6). Note that throughout this paper we refer to the individual managing the home network as the homeowner without loss of generality; clearly any suitably permitted member of the household, owner or not, may be able to exercise control based on specifics of the local context.

4.2 The Elephant in the Room

"The technical know-how required to set up a network and run music or video across cables or wi-fi, is 'the elephant in the room that no-one wants to talk about.' " [1]

Many empirical studies in recent years have explored the clear mismatch between current networking technology and the needs of the domestic setting, in both the UK Crabtree et al. [2003]; Rodden and Crabtree [2004]; Rodden et al. [2004, 2007]; Tolmie et al. [2007] and the US Chetty et al. [2007]; Grinter and Edwards [2005]; Shehan and Edwards [2007]; Shehan-Poole et al. [2008]; Sung et al. [2007]. These studies present a weight of evidence that problems with home networking are not amenable to solution via a 'thin veneer' of user interface technology layered atop the existing architecture. Rather, they are *structural*, emerging from the mismatch between the stable 'end-to-end' nature of the Internet and the highly dynamic and evolving nature of domestic environments.

[1] http://news.bbc.co.uk/1/hi/technology/6949607.stm

4.2.1 Home Networks: Evolution?

Home networks use the same protocols, architectures, and tools developed for the Internet since the 1970s. Inherent to the Internet's 'end-to-end' architecture is the notion that the core is simple and stable, providing only a semantically neutral transport service. Its core protocols were designed for a certain context of *use* (assuming relatively trustworthy endpoints), made assumptions about *users* (skilled network and systems administrators both using connected hosts and running the network core), and tried to accomplish a set of *goals* (e.g., scalability to millions of nodes) that simply do not apply in a home network.

In fact, the home network is quite different in nature to both core and enterprise networks. Existing studies Shehan and Edwards [2007]; Shehan-Poole et al. [2008]; Tolmie et al. [2007] suggest domestic networks tend to be relatively small in size with between 5 and 20 devices connected at a time. The infrastructure is predominately cooperatively self-managed by residents who are seldom expert in networking technology and, as this is not a professional activity, rarely motivated to become expert. A wide range of devices connect to the home network, including desktop PCs, games consoles, and a variety of mobile devices ranging from smartphones to digital cameras. Not only do these devices vary in capability, they are often owned and controlled by different household members.

To illustrate the situation we are addressing, consider the following two example scenarios, drawn from situations that emerged from our fieldwork to date, reported in more detail elsewhere Brundell et al. [2011]:

Negotiating acceptable use. *William and Mary have a spare room which they let to a lodger, Roberto. They are not heavy network users and so, although they have a wireless network installed, they pay only for the lowest tier of service and they allow Roberto to make use of it. The lowest tier of service comes under an acceptable use policy that applies a monthly bandwidth cap. Since Roberto arrived from Chile they have exceeded their monthly cap on several occasions, causing them some inconvenience. They presume it is Roberto's network use causing this, but are unsure and do not want to cause offence by accusing him without evidence.*

Welcome visitors, unwelcome laptops. *Steve visits his friends Mike and Elisabeth for the weekend and brings his laptop and smartphone. Mike has installed several* *wireless access points throughout his home and has secured the network using MAC address filtering in addition to WPA2. To access the network, Steve must not only enter the WPA2 passphrase, but must also obtain the MAC addresses of his devices for Mike to enter on each wireless access point. Steve apologizes for the trouble this would cause and, rather than be a problem to his hosts, suggests he reads his email at a local cafe.*

In such ways, simple domestic activities have deep implications for infrastructures that generate prohibitive technical overheads. In the first scenario, the problem is simply that the network's behaviour is opaque and difficult for normal users to inspect; in the second, the problems arise from the need to control access to the network and the technology details exposed by current mechanisms for doing so.

Home networks enable provision of a wide range of services, e.g., file stores, printers, shared Internet access, music distribution. The broad range of supported activities, often blending work and leisure, make network use very fluid. In turn, this makes it very hard to express explicitly *a priori* policies governing access control or resource management Tolmie et al. [2007]. Indeed, fluidity of use is such that access control and policy may not even be consistent, as network management is contingent on the household's immediate needs and routines.

4.2.2 Home Networks: Revolution!

Simply creating a user interface layer for the existing network infrastructure will only reify existing problems. Rather, we need to investigate creation of new network architectures reflecting the socio-technical nature of the home by taking into account both human and technical considerations. For example, we may need to explore architectures that sacrifice scalability in favor of installability, evolvability, and maintainability.

To this end we exploit local characteristics of the home: devices are often collocated, are owned by family and friends who physically bring them into the home, and both devices and infrastructure are physically accessible. Essentially, the home's physical setting provides a significant source of heuristics we can understand, and offers a set of well understood practises that might be exploited in managing the infrastructure.

We exploit human understandings of the local network and the home to guide management of the supporting infrastructure Crabtree et al. [2003] by focusing on the home router not only as the boundary point in an edge network but as a physical device which can be exploited as a point of management for the domestic infrastructure. Within our router, we focus on flow management for three reasons:

- we do not require scalability to the same degree as the core network;
- doing so allows us to monitor traffic in a way that is more meaningful for users; and
- we can apply per-flow queueing mechanisms to control bandwidth consumption, commonly requested by users.

4.3 Reinventing the Home Router

Our home router is based on Linux 2.6 running on a micro-PC platform.[1] Wireless access point functionality is provided by the *hostapd* package. The software infrastructure on which we implement our home router, as shown in Figure 4.1, consists of the Open vSwitch OpenFlow implementation, a NOX controller exporting a web service interface to control custom modules that monitor and manage DHCP and DNS traffic, plus the Homework Database Sventek et al. [2011] providing an integrated network monitoring facility. The proposed setup is similar to the standard ISP-provided home router.

We next describe the main software components upon which our router relies. Using this infrastructure, we provide a number of novel user interfaces, one of which we describe briefly below; details of the others are available elsewhere Mortier et al. [2011]. Note that a key aspect of our approach is to avoid requiring installation of additional software on client devices: doing so is infeasible in a home context where so many different types of device remain in use over extended periods of time.

4.3.1 OpenFlow, Open vSwitch & NOX

OpenFlow is a switching standard McKeown et al. providing an open protocol for distributed control of the forwarding tables contained within Ethernet switches in a

[1]Currently an Atom 1.6GHz eeePC 1000H netbook with 2GB of RAM running Ubuntu 10.04.

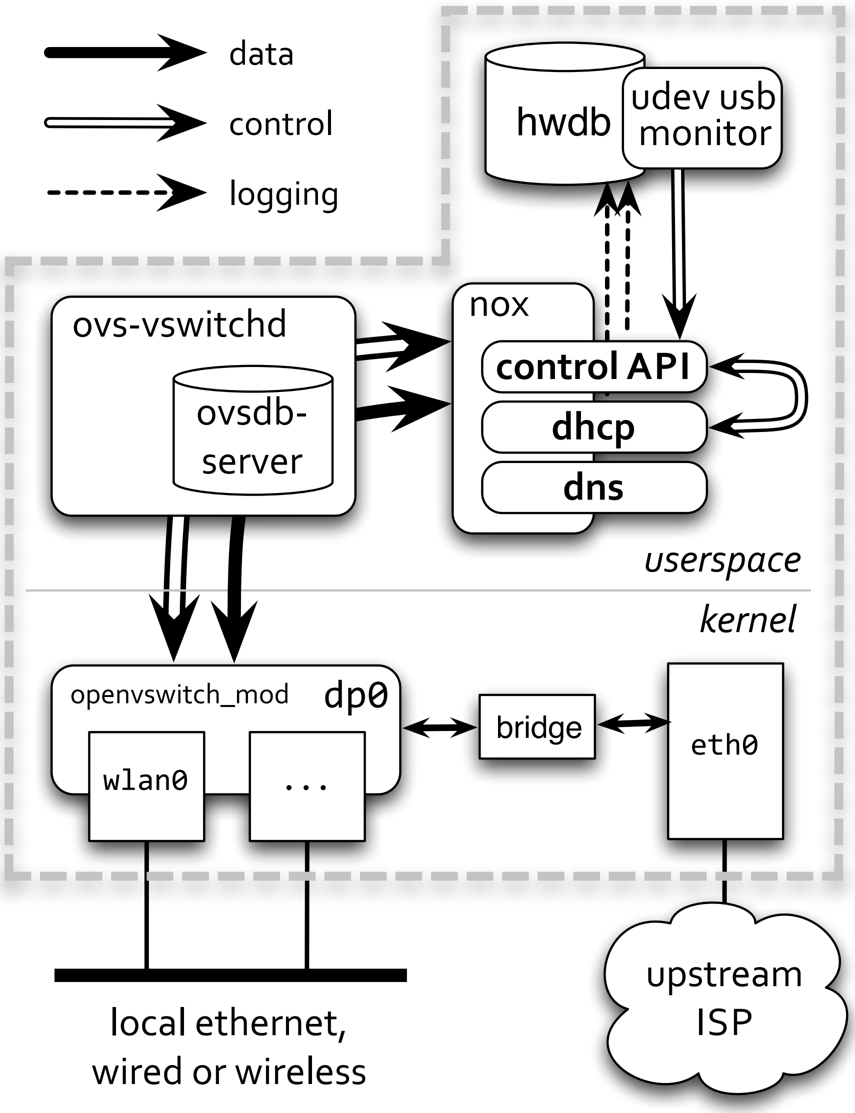


Figure 4.1: Home router architecture. Open vSwitch (*ovs**) and NOX manage the wireless interface. Three NOX modules provide a web services control API, a DHCP server with custom address allocation and lease management, and a DNS interceptor, all logging to the Homework Database (*hwdb*) (§4.4).

Method	Function
`permit/<eaddr>`	Permit access by specified client
`deny/<eaddr>`	Deny access by specified client
`status/[eaddr]`	Retrieve currently permitted clients, or status of specified client
`dhcp-status/`	Retrieve current MAC–IP mappings
`whitelist/<eaddr>`	Accept associations from client
`blacklist/<eaddr>`	Deny association to client
`blacklist-status/`	Retrieve currently blacklisted clients
`permit-dns/<e>/<d>`	Permit access to domain `d` by client `e`
`deny-dns/<e>/<d>`	Deny access to domain `d` by client `e`

Table 4.1: Web service API; prefix all methods `https://.../ws.v1/`. $<X>$ and $[X]$ denote required and optional parameters.

network. An OpenFlow *switch* has three parts: a *datapath*, a *secure channel* connecting to a controller, and the *OpenFlow protocol* the controller uses to talk to the switch.

Each datapath applies actions to flows arising on a physical interface, where *flow* is defined as a tuple of the primary packet header fields plus the physical port on which the flow is visible. Flow definition allows wildcarding of fields and specifically permits netmasks for IP addresses. Each flow can have a number of primitive actions applied; actions defined in the protocol permit full control over forwarding as well as modification of all fields of the flow tuple. The net effect is that applications can manage and control traffic according to their own definition of a network flow. Flow entries are installed by the controller when the switch notifies the controller of arrival of a packet from a new flow.

We provide OpenFlow support using Open vSwitch,[1] OpenFlow-enabled switching software that replaces the in-kernel Linux bridging functionality able to operate as a standard Ethernet switch as well as providing full support for the OpenFlow protocol. We use the NOX[2] controller as it provides a programmable platform abstracting OpenFlow interaction to events with associated callbacks, exporting APIs for C++ and Python.

Our router provides flow-level control and management of traffic via a single OpenFlow datapath managing the wireless interface of the platform.[3] We provide NOX modules that implement a custom DHCP server, control forwarding, control wireless

[1]`http://openvswitch.org/`

[2]`http://noxrepo.org/`

[3]Without loss of generality, our home route has only a single wired interface so the only home-facing interface is its wireless interface; other home-facing interfaces would also become part of the OpenFlow datapath.

association via filtering, and intercept DNS lookups. Control of these modules is provided via a simple web service (Table 4.1). Traffic destined for the upstream connection is forwarded by the datapath for local processing via the kernel bridge, with Linux's *iptables* IP Masquerading rules providing standard NAT functionality.[1]

4.3.2 The Homework Database

In addition to Open vSwitch and NOX we make use of the Homework Database, *hwdb*, an active, ephemeral stream database Sventek et al. [2011]. The ephemeral component consists of a fixed-size memory buffer into which arriving tuples (events) are stored and linked into tables. The memory buffer is treated in a circular fashion, storing the most recently received events inserted by applications measuring some aspect of the system. The primary ordering of events is time of occurrence.

The database is queried via a variant of CQL Arasu et al. [2005] able to express both temporal and relational operations on data, allowing applications such as our user interfaces to periodically query the ephemeral component for either raw events or information derived from them. Applications need not be collocated on the router as *hwdb* provides a lightweight, UDP-based RPC system that supports one-outstanding-packet semantics for each connection, fragmentation and reassembly of large buffers, optimization of ACKs for rapid request/response exchanges, and maintains liveness for long-running exchanges. Monitoring applications request events since a timestamp or during an interval defined by two timestamps. *hwdb* is active as applications may register interest in *future* behaviour patterns, triggering notification when such a pattern is detected by the database. The work described in this paper makes use of three tables: *Flows*, accounting traffic to each 5-tuple flow; *Links*, monitoring link-layer performance; and *Leases*, recording mappings assigned via DHCP.

4.3.3 The Guest Board

This interface exploits people's everyday understanding of control panels in their homes, e.g., heating or alarm panels, to provide users with a central point of awareness and control for the network. The interface runs on a dedicated touch screen in the home

[1] While NAT functionality could be implemented within NOX, it seemed neither interesting nor necessary to do so.

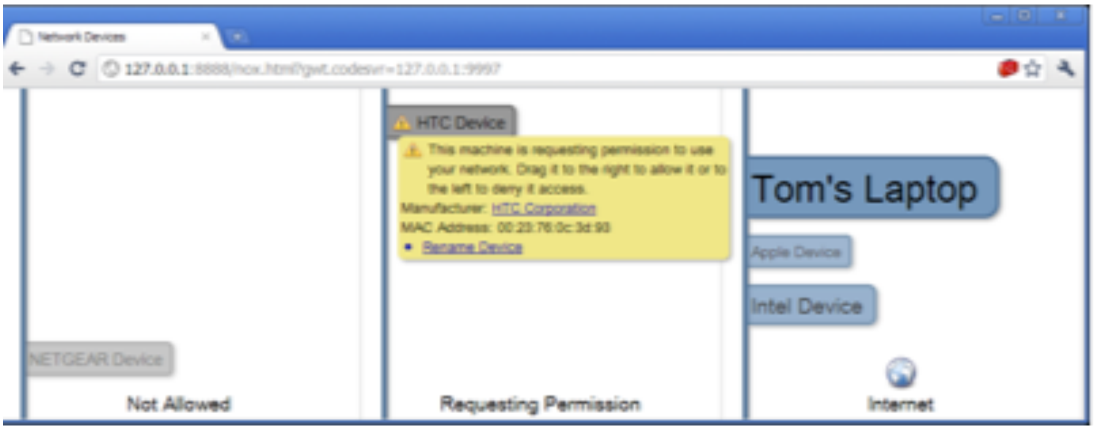


Figure 4.2: The *Guest Board* control panel, showing an HTC device requesting connectivity.

and we exploit this physical arrangement to provide a focal point for inhabitants to view current network status and to manage the network. It provides a real time display of the current status of the network (Figure 4.2), showing devices in different zones based on the state of their connectivity. The display dynamically maps key network characteristics of devices to features of their corresponding labels. Mappings in the current display are:

- Wireless signal strength is mapped to device label transparency.
- Device bandwidth use is proportional to its label size.
- Wireless Ethernet retransmissions show as red highlights on the device's label.

Devices in range appear on the screen in real-time, initially in the leftmost panel indicating they are within range of the home router but not connected. The central panel in the control displays machines actively seeking to associate to the access point: when devices unknown to the network issue DHCP requests, the router's DHCP server informs the guest board and a corresponding label appears in this portion of the display. If a user wishes to give permission for the machine to join the network they drag the label to the right panel; to deny access, they drag the label to the left panel.

The guest board provides both a central control point and, by drawing directly upon network information collected within our router, a network-centric view of the infrastructure. While this example describes a central control point in the home, the interface is implemented in HTML/CSS/Javascript allowing it to be displayed on a range of devices, currently under trial with users. The router's measurement and control APIs described above are also being used to build a wide range of other interfaces for use via smartphones, web browsers, and custom display hardware.

4.4 Putting People in the Protocol

We use our home router to enable *ad hoc* control of network policy by non-expert users via interfaces such as the Guest Board (Figure 4.2). This sort of control mechanism is a natural fit to the local negotiation over network access and use that takes place in most home contexts. While we believe that this approach may be applicable to other protocols, e.g., NFS/SMB, LPD, in this section we demonstrate this approach via our implementation of a custom DHCP server and selective filters for wireless association and DNS that enable management of device connectivity on a per-device basis.

Specifically, we describe and evaluate how our router manages IP address allocation via DHCP, two protocol-specific (EAPOL and DNS) interventions it makes to provide finer-grained control over network use, and its forwarding path. We consider three primary axes: *heterogeneity* (does it still support a sufficiently rich mix of devices); *performance* (what is the impact on forwarding latency and throughput of our design and implementation decisions); and *scalability* (how many devices and flows can our router handle). In general we find that our home router has ample capacity to support observed traffic mixes, and shows every indication of being able to scale beyond the home context to other situations, e.g., small offices, hotels.

4.4.1 Address Management

DHCP Droms [1997] is a protocol that enables automatic host network configuration. It is based on a four way broadcast handshake that allows hosts to discover and negotiate with a server their connectivity parameters. As part of our design we extend the functionality of the protocol to achieve two goals. First, we enable the homeowner to control which devices are permitted to connect to the home network by interjecting in the protocol exchange on a case-by-case basis. We achieve this by manipulating the lease expiry time, allocating only a short lease (30s) until the homeowner has permitted the device to connect via a suitable user interface. The short leases ensure that clients will keep retrying until a decision is made; once a device is permitted to connect, we allocate a standard duration lease (1 hour).

Second, we ensure that all network traffic is visible to the home router and thus can be managed through the various user interfaces built against it. We do so by allocating each device to its own /30 IP subnet, forcing inter-device traffic to be IP routed via our home router. This requirement arises because wireless Ethernet is a broadcast medium so clients will ARP for destinations on the same IP subnet enabling direct communication at the link-layer. In such situations, the router becomes a link-layer device that simply schedules the medium and manages link-layer security – some wireless interfaces do not even make switched Ethernet frames available to the operating system. Our custom DHCP server allocates /30 subnet to each host from 10.2.*.*/16 with standard address allocation within the /30 (i.e., considering the host part of the subnet, 00 maps to the network, 11 maps to subnet broadcast, 01 maps to the gateway and 10 maps to the client's interface itself). Thus, each local device needs to route traffic to any other local device thought the router, making traffic visible in the IP layer.

We measured the performance of our DHCP implementation and found that, as expected, per-request service latency scales linearly with the number of simultaneous requests. Testing in a fairly extreme scenario, simultaneous arrival of 10 people each with 10 devices, gives a median per-host service time of 0.7s.

4.4.2 Per-Protocol Intervention

Our current platform intervenes in two specific protocols providing greater control over access to the wireless network itself, and to Internet services more generally.

Our home router supports wireless Ethernet security via 802.11i with EAP-WPA2, depicted in Figure 4.3, using *hostapd*. In short, the client (*supplicant*) and our router (*authenticator*) negotiate two keys derived from the shared master key via a four-way handshake, through the EAPOL protocol. The *Pairwise Transient Key* (PTK) is used to secure and authenticate communication between the client and the router; the *Group Transient Key* (GTK) is used by the router to broadcast/multicast traffic to all associated clients, and by the clients to decrypt that traffic. All non-broadcast communication between clients must therefore pass via the router at the link-layer (for decryption

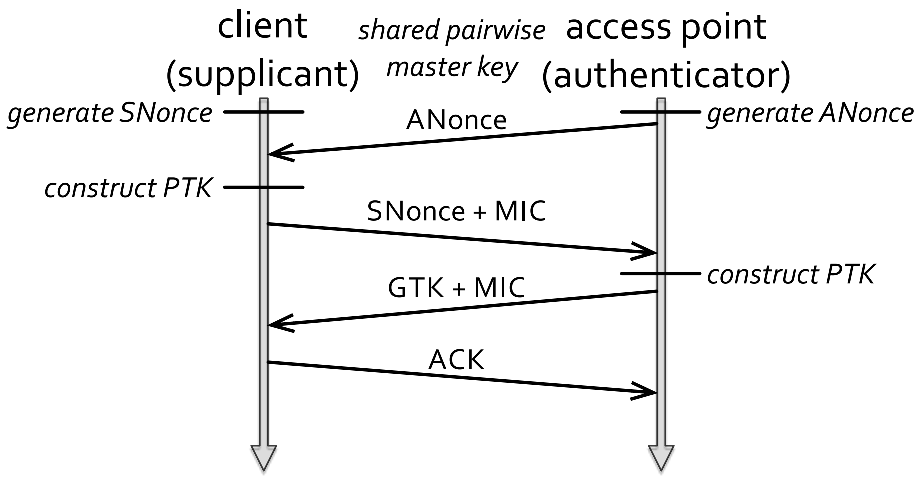


Figure 4.3: 802.11i handshake, part of the association process. Note that MIC (Message Integrity Code) is an alternate term for MAC, used in such contexts to avoid confusion with Media Access Control.

with the source's PTK and re-encryption with the destination's PTK), although the IP routing layers are oblivious to this if the two clients are on the same IP subnet.[1]

Periodically, a timeout event at the access point initiates rekeying of the PTK, visible to clients only as a momentary drop in performance rather than the interface itself going down. We use this to apply blacklisting of clients deemed malicious, such as a client that attempts to communicate directly (at the link-layer) with another, i.e., attempting to avoid their traffic being visible to our home router. We wait until the rekeying process begins and then decline to install the appropriate rule to allow it to complete for the client in question. This denies the client access even to link-layer connectivity, as they will simply revert to performing the four-way handshake required to obtain the PTK. This gives rise to a clear trade-off between security and performance: the shorter the rekeying interval, the quicker we can evict a malicious client but the greater the performance impact on compliant clients.

To quantify the impact of 802.11i rekeying, we observed throughput over several rekeying intervals. Figure 4.4 shows the impact of setting the rekeying interval to 30s:

[1]The 802.11i specification defines a general procedure whereby two clients negotiate a key for mutual communication (*Station-to-station Transient Key*, STK). However, the only use of this procedure in the specification is in *Direct Link Setup* (DLS) used in supporting 802.11e, quality-of-service. This can easily be blocked by the access point, and in fact is not implemented in the *hostapd* code we use, so we do not consider it further.

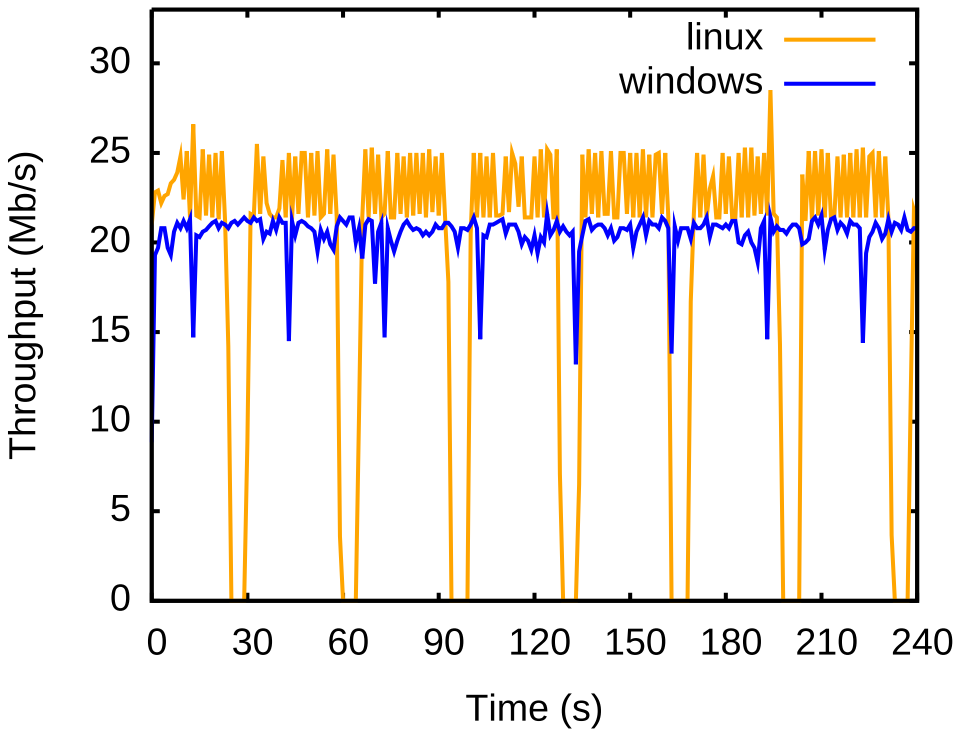
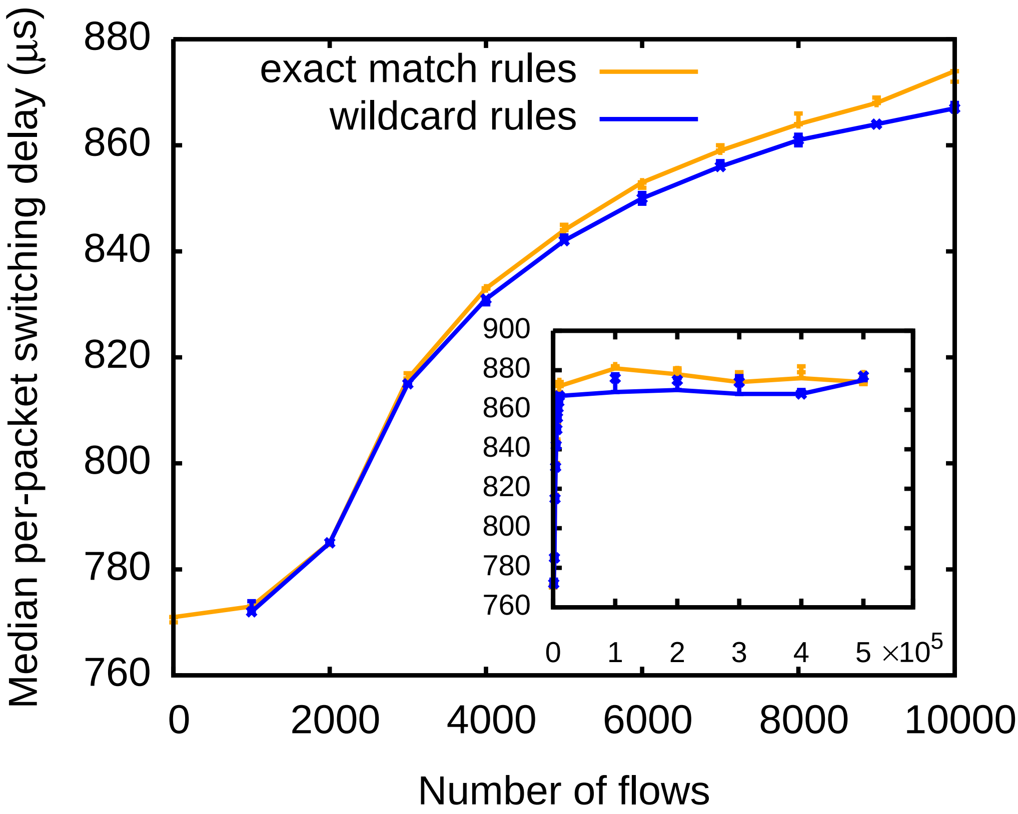


Figure 4.4: Affect on TCP throughput from rekeying every 30s for Linux 2.6.35 using a Broadcom card with the *athk9* module; and Windows 7 using a proprietary Intel driver and card.



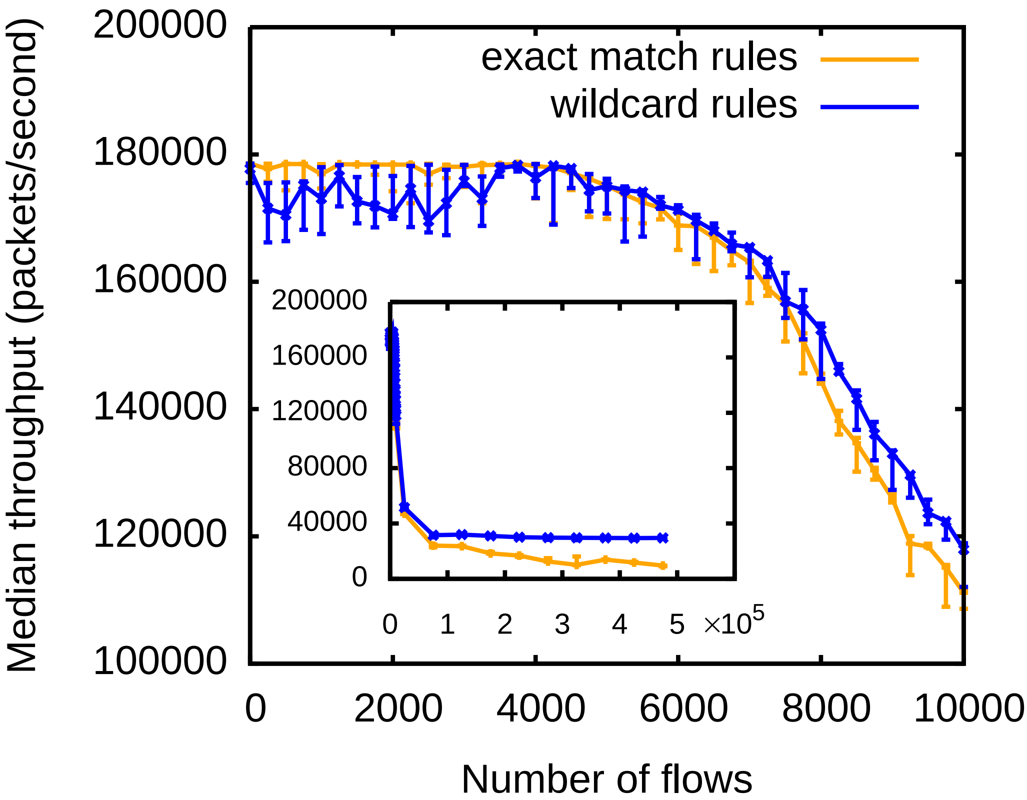


Figure 4.5: Switching performance of Open vSwitch component of our home router showing increasing per-packet latency (LHS) and decreasing packet throughput (RHS) with the number of flows. The inset graph extends the x-axis from 10,000 to 500,000.

rekeying causes a periodic dip in throughput as the wireless Ethernet transparently buffers packets during rekeying before transmitting them as if nothing had happened. This shows the trade-off between performance and responsiveness of this approach As a compromise, when a device is blacklisted, all of its traffic and subsequent rekeying exchanges are blocked. The device will be able to receive only broadcast traffic in the interim due, to the use of the GTK for such frames, until the AP initiate the negotiation of a new key.

We also intercept DNS to give fine-grained control over access to Internet services and websites. DNS requests are intercepted and dropped if the requesting device is not permitted to access that domain. Any traffic the router encounters that is not already permitted by an explicit OpenFlow flow entry has a reverse lookup performed on its destination address. If the resulting name is from a domain that the source device is not permitted to access, then a rule will be installed to drop related traffic. Performance is quite acceptable, as indicated by latency results in Figure 4.5: the extra latency overhead introduced by our router is negligible compared to the inherent latency of a lookup to a remote name server. Extending this fine-grained control requires more accurate identification of traffic to application, particularly for more complex network uses such as BitTorrent and Skype, and is a problem we are investigating in ongoing work.

4.4.3 Forwarding

Our router consists of a single Open VSwitch that manages interface *wlan0*. Open VSwitch is initialised with a set of flows that push DHCP/BOOTP and IGMP traffic to the controller for processing. Open VSwitch by default will also forward to the controller traffic not matched by any other installed flow, which is handled as follows:

Non-IP traffic. The controller acts as a proxy ARP server, responding to ARP requests from clients. Misbehaving devices are blacklisted via a rule that drops their EAPOL Aboba et al. [2004] traffic thus preventing session keys negotiation. Finally, other non-IP traffic has source and destination MAC addresses verified to ensure both are currently permitted. If so, the packet is forwarded up the stack if destined for the router, or to the destination otherwise. In either case, a suitable OpenFlow rule with a 30s idle timeout is also installed to shortcut future matching traffic.

Unicast IP traffic. First, a unicast packet is dropped if it does not pass all the following tests:

- its source MAC address is permitted;
- its source IP address is in 10.2.x.y/16; and
- its source IP address matches that allocated by DHCP. For valid traffic destined to the Internet, a flow is inserted that forwards packets upstream via the bridge and IP masquerading.

For local traffic a flow is installed to route traffic as an IP router, i.e. rewriting source and destination MAC addresses appropriately. All these rules are installed with 30s idle timeouts, ensuring that they are garbage collected if the flow goes idle for over 30s.

Broadcast and multicast IP traffic. Due to our address allocation policy, broadcast and multicast IP traffic requires special attention. Clients send such traffic with the Ethernet broadcast bit[1] set, normally causing the hardware to encrypt with the GTK rather than the PTK so all associated devices can receive and decrypt those frames directly. In our case, if the destination IP address is all-hosts broadcast, i.e., 255.255.255.255, the receiver will process the packet as normal. Similarly, if the destination IP address is an IP multicast address, i.e., drawn from 224.*.*.*/4, any host subscribed to that multicast group will receive and process the packet as normal. Finally, for local subnet broadcast the router will rebroadcast the packet, rewriting the destination IP address to 255.255.255.255. This action is required because the network stack of the hosts filters broadcast packets from different IP subnets.

To assess switching performance, we examine both latency and packet throughput as we increase the number of flows, N, from 1–500,000. Each test runs for two minutes, generating packets at line rate from a single source to N destinations each in its own 10.2.*.*/30 subnet. As these are stress tests we use large packets (500B) for the latency tests and minimal packets (70B) for the throughput tests, selecting destinations at random on a per-packet basis. Results are presented as the median of 5 independent runs with error bars giving the min and max values.

[1] I.e., the most significant bit of the destination address

Figure 4.5 shows median per-packet switching delay and per-flow packet throughput using either exact-match rules or a single wildcard rule per host. Performance is quite acceptable with a maximum switching delay of 560μs and minimum throughput of 40,000 packets/second; initial deployment data suggests a working maximum of 3000 installed flows which would give around 160,000 packets/second throughput (small packets) and 500μs switching delay (large packets). Figure 4.6 shows that the Linux networking stack is quite capable of handling the unusual address allocation pattern resulting from the allocation of each wireless-connected device to a distinct subnet which requires the router's wireless interface to support an IP address per connected device.

4.4.4 Discussion

Our evaluation shows that Open vSwitch can handle orders of magnitude more rules than required by any reasonable home deployment. Nonetheless, to protect against possible denial-of-service attacks on the flow tables, whether intentional, accidental or malicious, our home router monitors the number of per-flow rules introduced for each host. If this exceeds a high threshold then the host has its per-flow rules replaced with a single per-host rule, while the router simultaneously invokes user interfaces to inform the homeowner of the device's odd behaviour.

The final aspect to our evaluation is compatibility: given that our router exercises protocols in somewhat unorthodox ways, how compatible is it with standard devices and other protocols? We consider compatibility along three separate dimensions: range of existing client devices; deployed protocols that rely on broadcast/multicast behaviours; and support for IPv6.

Devices Although we exercise DHCP, DNS and EAPOL in unorthodox ways to control network access, behaviour follows the standards once a device is permitted access. To verify that our home router is indeed suitable for use in the home, we tested against a range of commercial wireless devices running a selection of operating systems.

Table 4.2 shows the observed behaviour of a number of common home-networked devices: in short, all devices operated as expected once permitted access. DNS interception was not explicitly tested since, as an inherently unreliable protocol, all net-

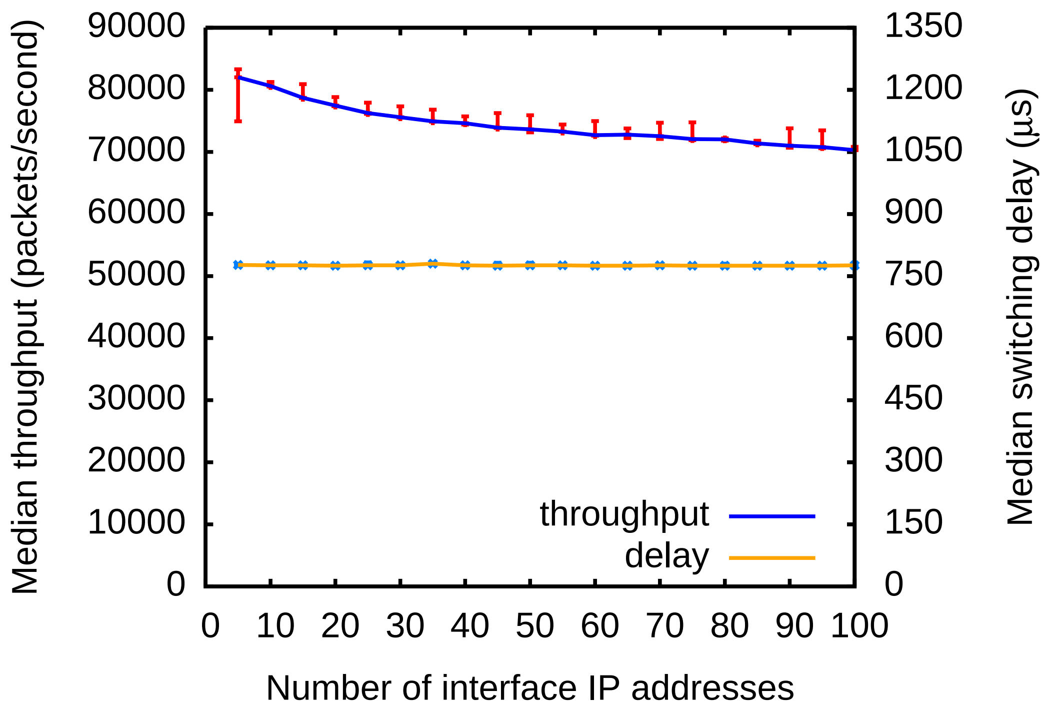


Figure 4.6: Switching performance of Linux network stack under our address allocation policy. Throughput (left axis) shows a small linear decrease while switching delay (right axis) remains approximately constant as the number of addresses allocated to the interface increases.

Device	**Denied**	**Blacklisted**
Android 2.x	Reports pages unavailable due to DNS.	Retries several times before backing off to the 3g data network.
iTouch/iPhone	Reports server not responding after delay based on configured DNS resolver timeout.	Requests new wireless password after 1–2 minutes.
OSX 10.6	Reports page not found based on configured DNS resolver timeout.	Requests new wireless password after 1–2 minutes.
Microsoft Windows XP	Silently fails due to DNS failure.	Silently disconnects from network after 4–5 minutes.
Microsoft Windows 7	Warns of partial connectivity.	Silently disconnects from network after 4–5 minutes.
Logitech Squeezebox	Reports unable to connect; allows server selection once permitted.	Flashes connection icon every minute as it attempts and fails to reconnect.
Nintendo Wii	Reports unable to reach server during “test” phase of connection.	Reports a network problem within 30s.
Nokia Symbian OS	Reports “can’t access gateway” on web access.	Reports disconnected on first web access.

Table 4.2: Observed interactions between devices and our home router when attempting to access the network.

working stacks must handle the case that a lookup fails anyway. Most devices behaved acceptably when denied access via DHCP or EAPOL, although some user interface improvements could be made if the device were aware of the registration process. The social context of the home network means no problem was serious: in practice the user requesting access would be able to interact with the homeowner, enabling social negotiation to override any user interface confusion.

Broadcast protocols A widely deployed set of protocols relying on broadcast and multicast behaviours are those for 'zero conf' functionality. The most popular are Apple's *Bonjour* protocol; *Avahi*, a Linux variant of Bonjour; Microsoft's *SSDP* protocol, now adopted by the UPnP forum; and Microsoft's *NetBIOS*.

Bonjour and Avahi both rely on periodic transmission of multicast DNS replies advertising device capabilities via TXT records. SSDP is similar, but built around multicast HTTP requests and responses. We tested Bonjour specifically by setting up a Linux server using a Bonjour-enabled daemon to share files. We observed no problems with any clients discovering and accessing the server, so we conclude that Bonjour, Avahi and SSDP would all function as expected.

NetBIOS is somewhat different, using periodic network broadcasts to disseminate hosts' capabilities. In doing so we observed a known deficiency of NetBIOS: it cannot propagate information for a given workgroup between different subnets.[1] However this was easy to overcome: simply install a WINS server on the router and advertise it via DHCP to all hosts.

In general, it may seem that our address allocation policy introduces link-layer overhead by forcing all packets to be transmitted twice in sending them via the router. However this is not the case: due to use of 802.11i, unicast IP traffic between two local hosts must *already* be sent via the access point. As the source encrypts its frames with its PTK, the access point must decrypt and re-encrypt these frames with the destination's PTK in order that the destination can receive them. Multicast and all-hosts broadcast IP traffic is sent using the GTK, so can be received directly by all local hosts. Only directed broadcast IP traffic incurs overhead which though is a small proportion of the total traffic; data from a limited initial deployment (about one month in two homes) suggests that broadcast and multicast traffic combined accounts for less that

[1] `http://technet.microsoft.com/en-gb/library/bb726989.aspx`

0.1% (packets and bytes) in both homes.

IPv6 support IPv6 support is once more receiving attention due to recent exhaustion of the IPv4 address space. Although our current implementation does not support IPv6 due to limitations in the current Open vSwitch and NOX releases,[1] we briefly discuss how IPv6 would be supported on our platform. While these limitations prevent a full working implementation in our platform, we have verified that behaviour of both DHCPv6 and the required ICMPv6 messages was as expected, so we do not believe there are any inherent problems in the approaches we describe below.

Addition of IPv6 support affects the network layer only, requiring consideration of routing, translation between network and link layers, and address allocatiocn. Deployment of IPv6 has minimal impact on routing, limited to the need to support 128 bit addresses and removal, in many cases, of the need to perform NAT. Similarly, supporting translation to lower layer addresses equates to supporting ICMPv6 Neighbour Solicitation messages which perform equivalent function to ARP.

Address allocation is slightly more complex but still straightforward. IPv6 provides two address allocation mechanisms: *stateless* and *stateful*. The first allows a host to negotiate directly with the router using ICMPv6 Router Solicitation and Advertisement packets to obtain network details, IP netmask and MAC address. Unfortunately this process requires that the router advertises a 64 bit netmask, of which current plans allocate only one per household, with the result that all hosts would end up on the same subnet. The second builds on DHCPv6 where addresses are allocated from a central entity and may have arbitrary prefix length. This would enable our router to function in much the same manner as currently, although it would need to support the ICMPv6 Router Advertisement message in order that hosts could discover it as the router.

4.5 Related Work

Many authors have argued that home networks should be treated differently to other IP-based networks. For example, Calvert *et al.*. Calvert et al. [2007] make a case against

[1] OpenFlow aims to provide support in its 1.2 release of the protocol; NOX currently has no support for IPv6; and Open vSwitch only supports IPv6 as an application specific extension.

application of the end-to-end principle in home networking. They argue that there are a number of key aspects peculiar to the home environment that the standard Internet protocols do not address. They derive a series of requirements for a home network architecture, and a design providing functions to fulfil these requirements. Many of the points they make, e.g., their "smart middle" design, resonate with our argument, and indeed, we believe our home router meets the requirements and provides the functions they describe.

Both before and after the general architectural arguments made above, a number of authors have proposed novel user interfaces to aid the homeowner in managing their network. GesturePen Swindells et al. [2002] uses line-of-sight radio interaction with purpose-built receiver tags to control network access; Network-in-a-Box Balfanz et al. [2004], where infrared port alignment provides a physical metaphor for access, plugging in to security mechanisms such as EAP-TLS and RADIUS. They also describe an interesting "phone home" service via the Windows Remote Access and IPSec policy mechanisms that enables remote clients to connect back to appear as if inside the home network.

ICEBox Yang and Edwards [2007] again concentrates on the problem of enabling the homeowner to correctly configure new devices when they are brought onto the network using a control panel approach similar to our Guest Board. They note that a future version might well subsume the home router. Eden Yang et al. [2010], by several of the same authors, follows this up by replacing the home router. Their implementation allows per-flow traffic control, but the paper lacks technical details.

All these approaches primarily address the interaction design problem, focusing on user interface solutions to the problems of managing a home network. Most rely upon specialized hardware or software installation on client devices. In contrast, our home router does not require client modification as its protocol modifications are fully backward compatible with existing stacks. It thus supports a very wide range of devices while making possible greater control of connectivity.

Several authors have proposed solutions to the specific problem of lack of visibility into what the network and connected devices are doing. In this context, HostView Joumblatt et al. [2010] uses a client daemon to log when users experience network problems. Calvert *et al.*. Calvert et al. [2010] present requirements for a general purpose "always on" local logging service, building a simple example using *tcpdump* running on a NOXBox,[1] dumping traffic into flat files. Both focus on network monitoring as a tool for troubleshooting. Finally, in presenting the Homework Database, Sventek *et al.*. Sventek et al. [2011] describe it as a component in their home network information plane. Their system uses a general-purpose policy engine to exercise control over the network by configuration of the router derived from the interaction of monitored data and policy.

We claim that, in general, these monitoring systems do not take into account the specific challenges and opportunities inherent in the home network context. Our home router goes further in exploiting the home context via specific modifications to the normal behaviour of key protocols, as well as implementing a novel network control interface.

This class of argument, that the generic Internet protocols are not appropriate in a particular environment, has previously been made in the enterprise network space. Approaches such as Anemone Cooke et al. [2006], Ethane Casado et al. [2007] and Network Exception Handlers Karagiannis et al. [2008] have all proposed systems that address the general problem of enterprise network management in different ways. They all make the argument that enterprise networks are basically different to the traditional Internet, presenting different problems and permitting different solutions. This resonates strongly with our claims that home networks should be treated differently, and in some ways with our approach of providing more intelligent centralised control. It should be noted however, that these enterprise network solutions are no more applicable to home networks than traditional Internet approaches were applicable in the enterprise!

Finally, looking back to 1984 and some of the original discussions of IP subnetting, Mogul Mogul [1984] and Postel Postel [1984] discussed using subnetting to hide site LAN interconnection from networks outside the site. They introduce techniques such as ARP-based subnetting, ARP bridging, and extension of ARP itself. ARP bridging in particular is very similar in practice to the approach we take, although we assign a subnet per-host rather than per-LAN, and we manage address allocation and connectivity using protocols unavailable at the time.

[1] http://www.noxrepo.org/manual/noxbox.html

4.6 Conclusions

This paper has drawn upon previous user studies to reflect on the distinctive nature of home networks and the implications for domestic network infrastructures. Two particular user needs that arose from these studies were for richer visibility into and greater control over the home wireless network, as part of the everyday management of the home by inhabitants. We considered how to exploit the nature of the home network to shape how it is presented and opened to user control.

Simply put, the home is different to standard networking environments, and many of the presumptions made in such networks do not hold. Specifically, home networks are smaller in size, the equipment is physically accessible and access is often shared among inhabitants, and the policies involved are flexible and often dynamically negotiated. Exploiting this understanding allows us to move away from traditional views of network infrastructure, which must be tolerant of scale, physically distributed, and impose their policies on users.

We use the Open vSwitch and NOX platforms to provide flow-based management of the home network. As part of this flow-based management, we exploit the social conventions in the home to manage introduction of devices to the network, and their subsequent access to each other and Internet hosted services. This required modification of three standard protocols, DHCP, EAPOL and DNS, albeit in their behaviour only *not* their wire formats, due to the need to retain compatibility with legacy deployed stacks.

Our exploration suggests that, just as with other edge networks, existing presumptions could usefully be re-examined to see if they still apply in this context. *Do we wish to maintain net neutrality in the home?* Inhabitants do not appear to see network traffic as equal, often desiring imbalance in performance received by different forms of traffic. *Must the end-to-end argument apply?* Householders understand and exploit the physical nature of their home and use trust boundaries to manage access; we have exploited these resources to explicitly manage the network. *Should communication infrastructures remain separate from the devices that use them?* In the home setting this separation proves problematic as people, ranging from the home tinkerer to the DIY expert, wish to interact directly with the network as they do with other parts of their homes' physical infrastructures. Our exploration suggests use of a range of displays and devices existing not as clients exploiting the infrastructure but as extensions of the infrastructure making it more available and controllable.

Inability to understand and control network infrastructure has made it difficult for people to understand and live with it in their homes. We have developed a home router that both captures information about people's use of the network and provides a point of interaction to control the network. Our initial developments have explored the extent to which residents may be involved in some of the protocols controlling the network; other protocols suitable for modification are under consideration. We are currently involved in the deployment and study of use of our home router to better understand relevant user needs and how we might more systematically exploit the data we are collecting. We are also exploring how to use this data in other areas such as security and power management.

4.7 User-Driven Resource Management at Home

4.8 Architecture

4.8.1 Helping thy neighbour: Enabling ISP - User collaboration

4.9 Personalised user traffic models

4.9.1 Bayesian Data Modeling and continuous training

4.9.2 Evaluation

4.10 Evaluation

Chapter 5

Scalable User-centric cloud networking

5.1 Introduction

Present the gap in network understanding between the clients and the ISP and present a tool that allows to bridge it.

5.2 Enabling edge user-driven connectivity

5.3 Signpost Architecture

5.4 Evaluation

5.5 Conclusions

Chapter 6

My Conclusions ...

Here I put my conclusions ...

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