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

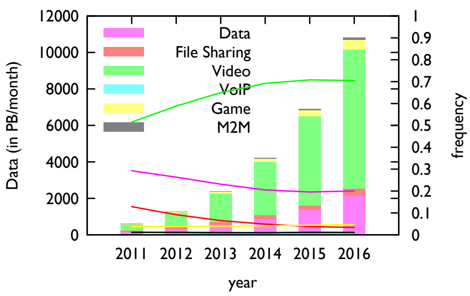
Application	rate	latency	jitter	# connections
web	0	0	0	0
video	0	0	0	0
p2p	0	0	0	0
voip	0	0	0	0
game	0	0	0	0

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

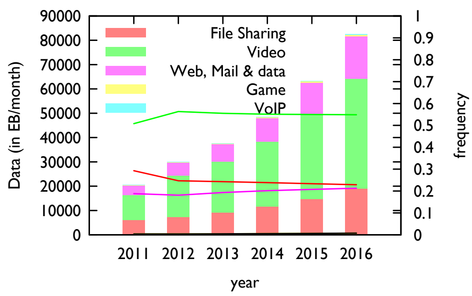
the inherent limitations of current architecture in terms of evolvability. In section 1.2, we list briefly the main contributions of this thesis and in section 1.3, we present briefly the content of each chapter of the thesis. Finally, in section 1.4 we list the publications relating to the content of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

3.1 Introduction

3.2 OpenFlow microbenchmark

OpenFlow[1], an instance of software-defined networking (SDN), gives access deep within the network forwarding plane while providing a common, simple, API for network-device control. Implementation details are left to the discretion of each vendor. This leads to an expectation of diverse strengths and weaknesses across the existing OpenFlow implementations, which motivates our work.

OpenFlow is increasingly adopted, both by hardware vendors as well as by the research community Handigol et al. [2009]; Sherwood et al. [2010]; Yu et al. [2010]. Yet, there have been few performance studies: to our knowledge, OFLOPSis the first attempt to develop a platform that is able to provide detailed measurements for the OpenFlow implementations. Bianco *et al.* Bianco et al. [2010] show the performance advantage of the Linux software OpenFlow over the Linux Ethernet switch, while Curtis *et al.* Curtis et al. [2011] discuss some design limitations of the protocol when deployed in large network environments. We consider OFLOPS, alongside Freedman et al. [2010], as one of a new generation of measurement systems that, like the intelli-

[1] http://www.openflow.org/

gent traffic and router evaluators Agilent; Ixia, go beyond simple packet-capture.

We present OFLOPS[1], a tool that enables the rapid development of use-case tests for both hardware and software OpenFlow implementations. We use OFLOPSto test publicly available OpenFlow software implementations as well as several OpenFlow-enabled commercial hardware platforms, and report our findings about their varying performance characteristics. To better understand the behavior of the tested OpenFlow implementations, OFLOPScombines measurements from the OpenFlow control channel with data-plane measurements. To ensure sub-millisecond-level accuracy of the measurements, we bundle the OFLOPSsoftware 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].

The rest of this paper is structured as follows. We first present the design of the OFLOPSframework in Section 3.3. We describe the measurement setup in Section 3.4. We describe our measurements in Section 3.5. We provide basic experiments that test the flow processing capabilities of the implementations (Section 3.5.1) as well as the performance and overhead of the OpenFlow communication channel (Section 3.5.2). We follow with specific tests, targeting the monitoring capabilities of OpenFlow (Section 3.5.3) as well as interactions between different types of OpenFlow commands (Section 3.5.4). We conclude in Section 3.10.

3.3 OFLOPSframework

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. Furthermore, measurement noise minimization can only be achieved through proper design of the measurement platform. Current controller designs, like SNA [2010]; Gude et al.

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

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

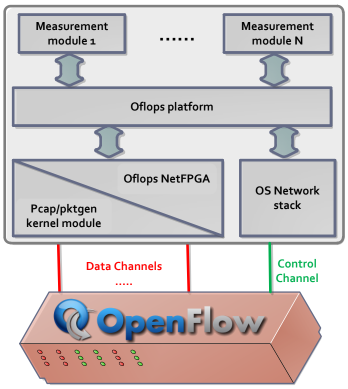


Figure 3.1: OFLOPSdesign schematic

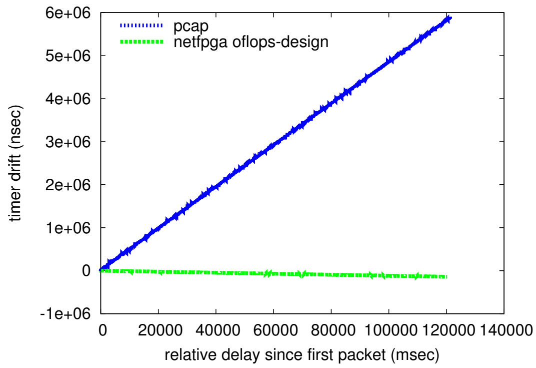


Figure 3.2: Evaluating timestamping precision using a DAG card.

[2008], target production networks and thus are optimized for throughput maximization and programmability, but incur high measurement inaccuracy. 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 OFLOPSdesign philosophy is to enable seamless interaction with an OpenFlow-enabled device over multiple data channels without introducing significant additional processing delays. 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 OFLOPSprogramming 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. OFLOPSconsists of the following five threads, each one serving specific type of events:

1. Data Packet Generation controls data plane traffic generators.

2. Data Packet Capture captures and pushes data plane traffic to modules.

3. Control Channel translates OpenFlow packets to control events.
4. SNMP Channel performs asynchronous SNMP polling.
5. Time Manager manages time events scheduled by measurement modules.

OFLOPSprovides the ability to control concurrently multiple data channels to the switch. By embedding the data channel within the platform, it is possible to understand the impact of the measurement scenario on the switching 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, OFLOPSsupports 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.

3.4 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. 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]; a full implementation of the protocol, limited though in capabilities due to hardware platform limitations.

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.

In order to conduct our measurements, we setup OFLOPSon 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 delay incurred by the NetFPGA-based hardware design to be a near-constant 900 nsec independent of the probe rate.

3.5 Evaluation

In this section we present a set of tests performed by OFLOPSto measure the behavior and performance of OpenFlow-enabled devices. These tests target (1) the OpenFlow packet processing actions, (2) the update rate of the OpenFlow flow table along with its impact on the data plane, (3) the monitoring capabilities provided by OpenFlow, and (4) the impact of interactions between different OpenFlow operations.

3.5.1 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 and flows 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. 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

Mod. type	Switch1			OpenVSwitch			Switch2			Switch3			NetFP	
	med	sd	loss%	med	sd	loss%	med	sd	loss%	med	sd	loss%	med	sd
Forward	4	0	0	35	13	0	6	0	0	5	0	0	3	0
MAC addr.	4	0	0	35	13	0	302	727	88	-	-	100	3	0
IP addr.	3	0	0	36	13	0	302	615	88	-	-	100	3	0
IP ToS	3	0	0	36	16	0	6	0	0	-	-	100	3	0
L4 port	3	0	0	35	15	0	302	611	88	-	-	100	3	0
VLAN pcp	3	0	0	36	20	0	6	0	0	5	0	0	3	0
VLAN id	4	0	0	35	17	0	301	610	88	5	0	0	3	0
VLAN rem.	4	0	0	35	15	0	335	626	88	5	0	0	3	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).

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.

3.5.2 Flow table update rate

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

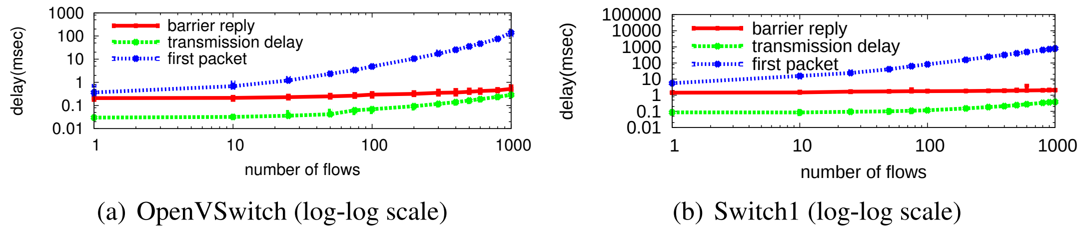


Figure 3.3: Flow entry insertion delay: as reported using the `barrier` notification and as observed at the data plane.

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 3.3 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, OFLOPSrelies 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 3.3, 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 OFLOPScontroller 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 3.3 shows the median result as well as the 10^{th} and 90^{th} percentiles (variations are small and cannot be easily viewed).

From Figure 3.3, 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 OFLOPScan 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

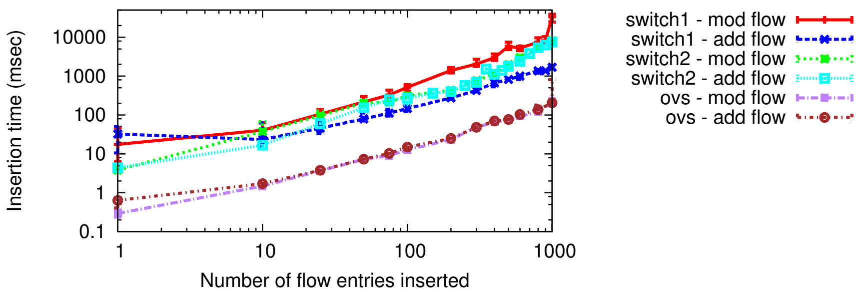


Figure 3.4: Delay of flow insertion and flow modification, as observed from the data plane (log-log scale).

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 3.4 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 3.4 are not generalizable, but rather depend on the type of insertion entry and implementation.

3.5.3 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 3.5 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 3.5 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.

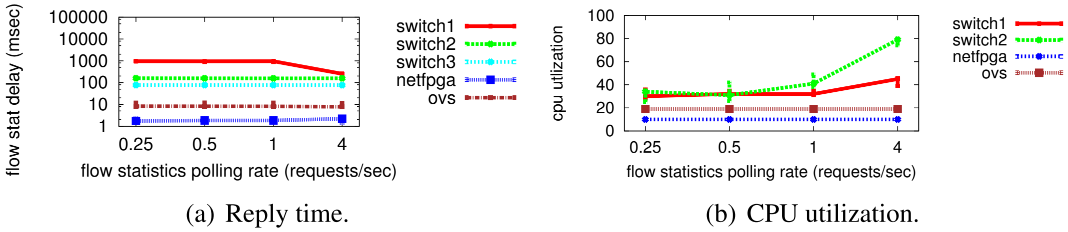


Figure 3.5: Time to receive a flow statistic (median) and corresponding CPU utilization.

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 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).

3.5.4 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

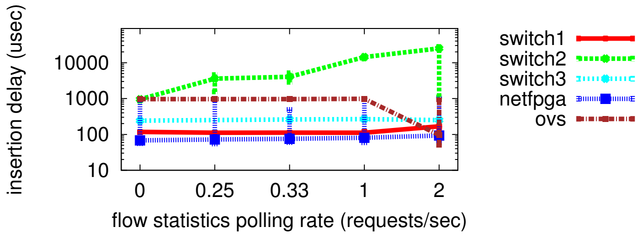


Figure 3.6: Delay when updating flow table while the controller polls for statistics.

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. [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 3.5.2 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 3.6 we can see that, for lower polling rates, implementations have a near-constant insertion delay comparable to the results of Section 3.5.2. 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 3.5(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.

3.6 OpenFlow Macrobenchmark: SDNSIM

3.7 Architecture

3.8 Evaluation

3.9 Simulating Secure and Resilient control across a datacenter

3.10 Summary and Conclusions

We presented, OFLOPS, a tool that tests the capabilities and performance of OpenFlow-enabled software and hardware switches. OFLOPScombines advanced hardware instrumentation, for accuracy and performance, and provides an extensible software framework. We use OFLOPSto 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 OFLOPSfor 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 OFLOPSwill 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.

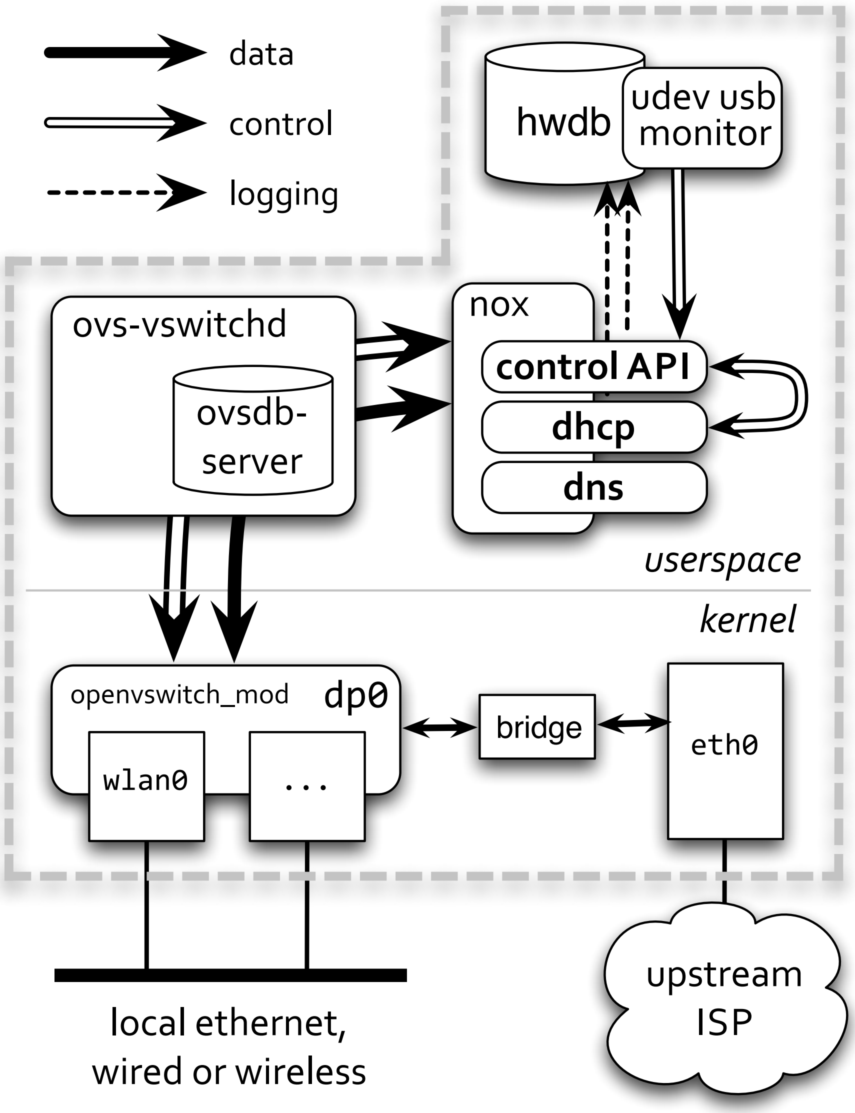


Figure 4.1: Home router architecture. Open vSwitch (*ovs**) and NOX manage the wireless interface. Three NOX modules provide a web services control API, a DHCP server with custom address allocation and lease management, and a DNS interceptor, all logging to the Homework Database (*hwdb*) (§4.4).

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.

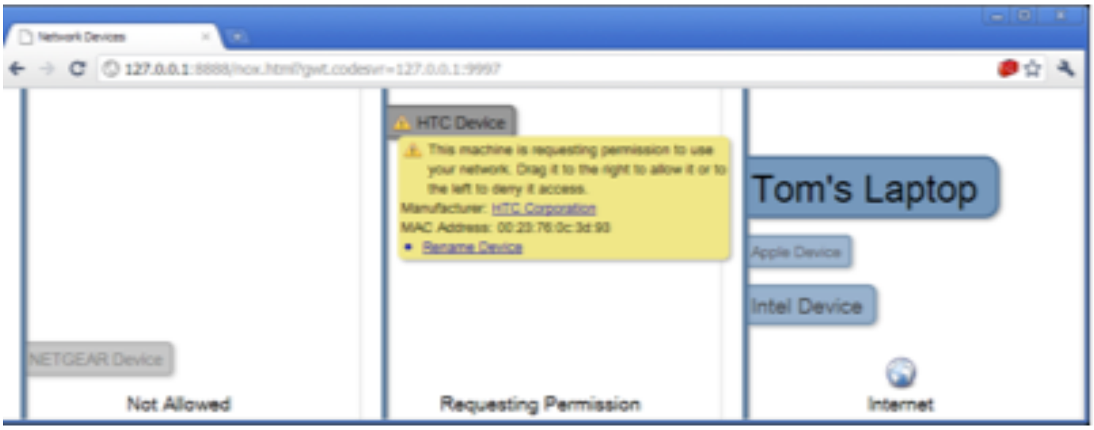


Figure 4.2: The *Guest Board* control panel, showing an HTC device requesting connectivity.

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

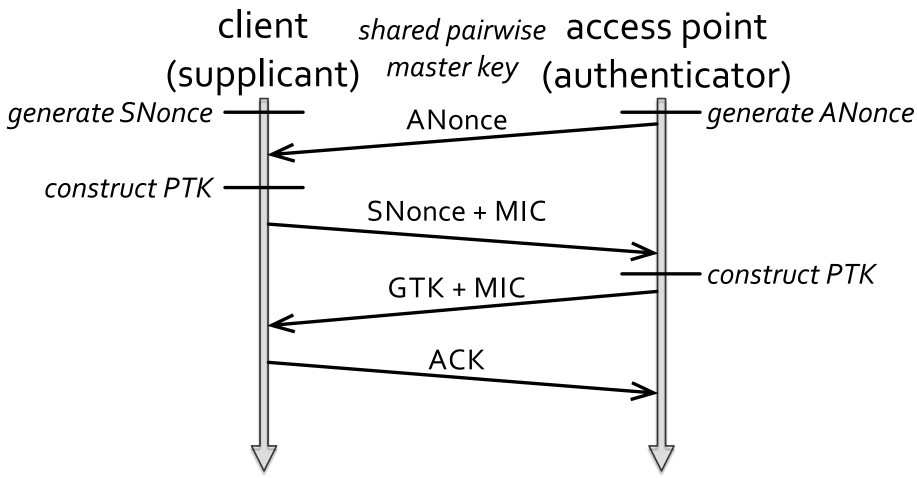


Figure 4.3: 802.11i handshake, part of the association process. Note that MIC (Message Integrity Code) is an alternate term for MAC, used in such contexts to avoid confusion with Media Access Control.

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.

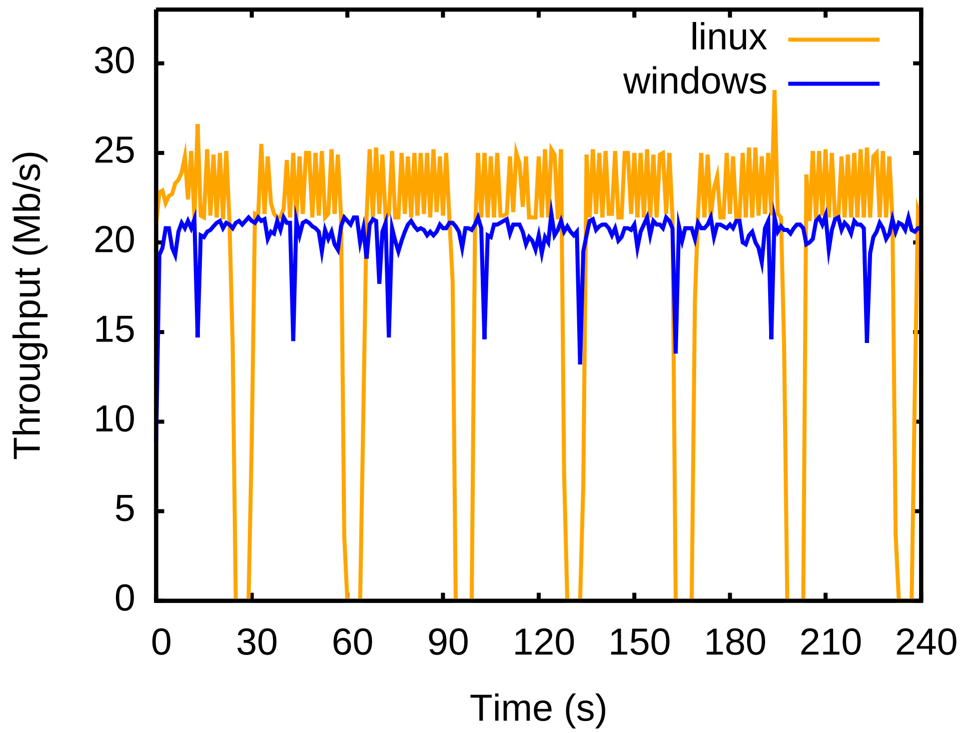
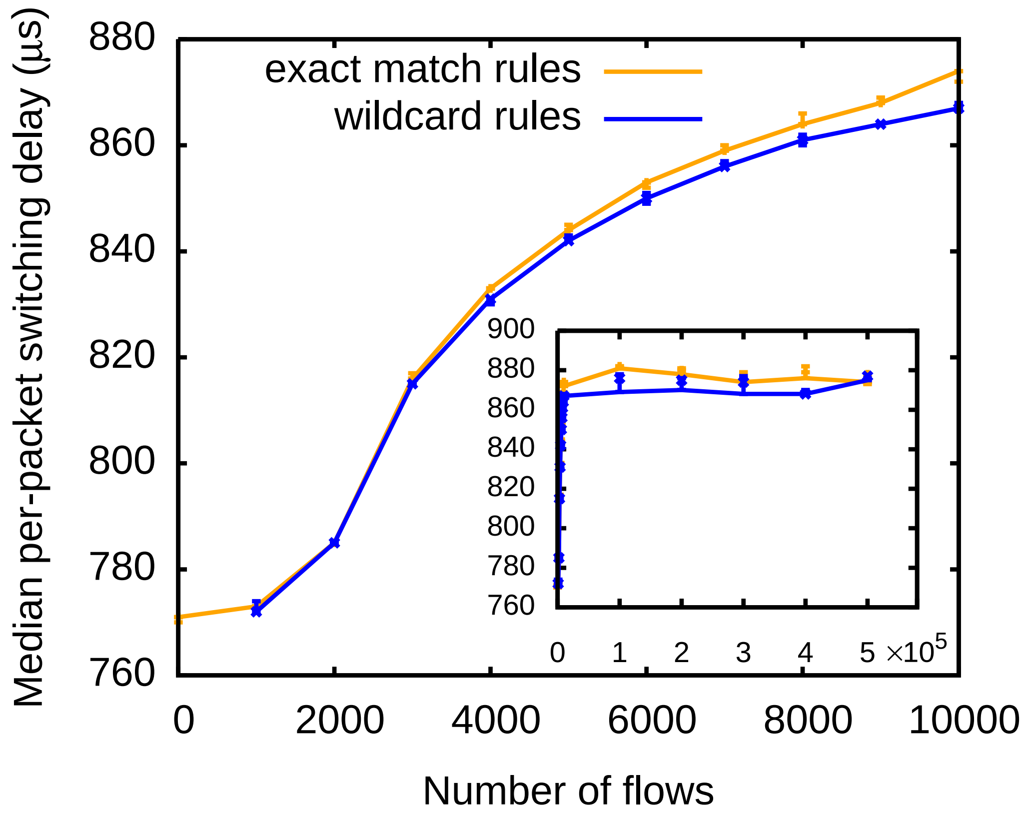


Figure 4.4: Affect on TCP throughput from rekeying every 30s for Linux 2.6.35 using a Broadcom card with the *athk9* module; and Windows 7 using a proprietary Intel driver and card.



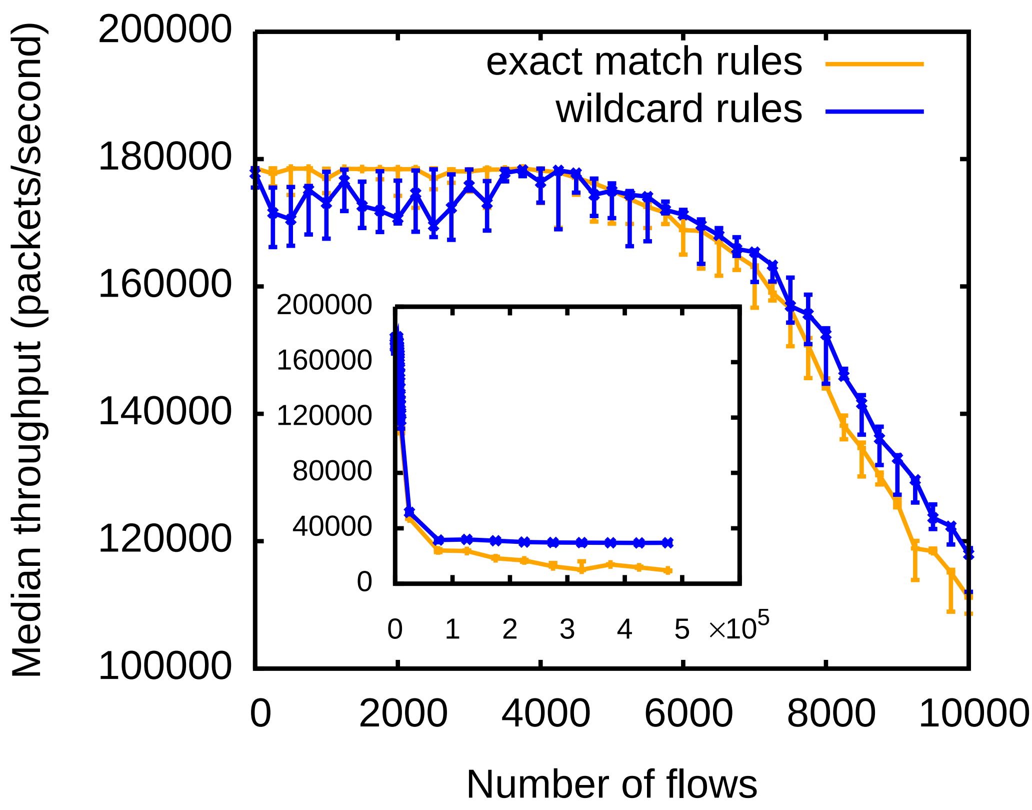


Figure 4.5: Switching performance of Open vSwitch component of our home router showing increasing per-packet latency (LHS) and decreasing packet throughput (RHS) with the number of flows. The inset graph extends the x-axis from 10,000 to 500,000.

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-

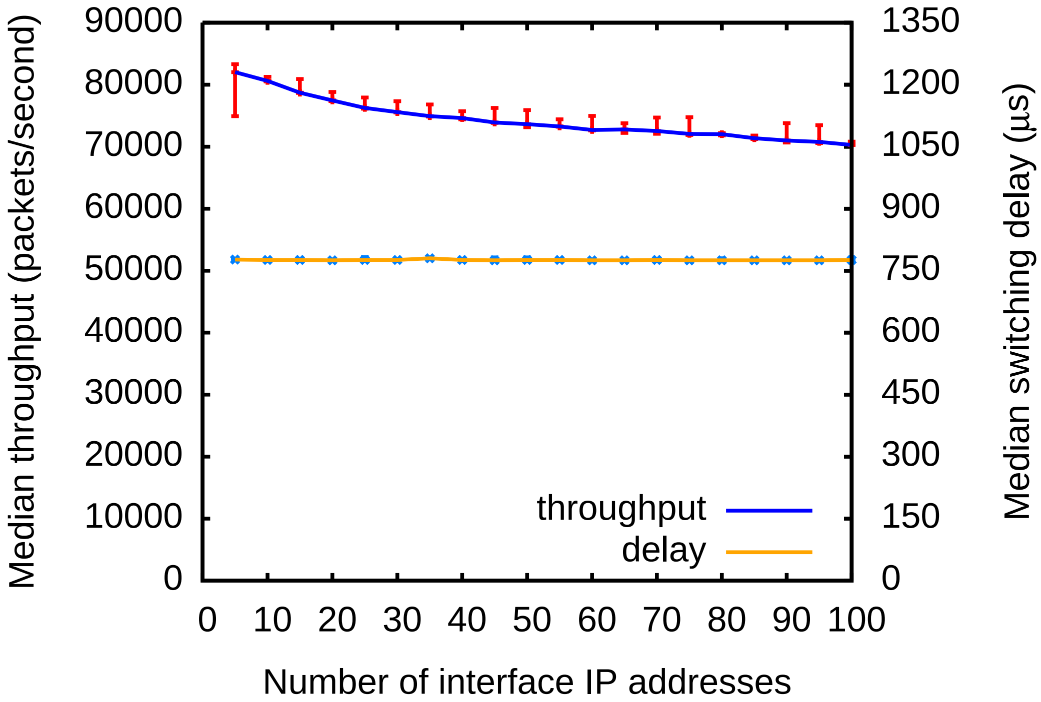


Figure 4.6: Switching performance of Linux network stack under our address allocation policy. Throughput (left axis) shows a small linear decrease while switching delay (right axis) remains approximately constant as the number of addresses allocated to the interface increases.

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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