Scalable Software Defined Networking

Charalampos Rotsos

Computer Laboratory
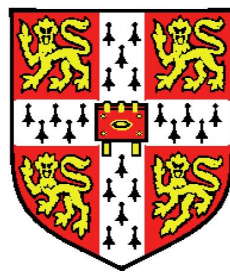University of Cambridge

A thesis submitted for the degree of
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Yet to be decided

Abstract

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Contents

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List of Publications

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

- **Charalampos Rotsos**, Jurgen Van Gael, Andrew W. Moore, and Zoubin Ghahramani. 2010. Probabilistic graphical models for semi-supervised traffic classification. In Proceedings of the 6th International Wireless Communications and Mobile Computing Conference (IWCMC '10). ACM, New York, NY, USA, 752-757.

- Mortier, R., Ben Bedwell, Glover, K., Lodge, T., Rodden, T., Rotsos, C., et al. (2011). Supporting novel home network management interfaces with openflow and NOX. Presented at the SIGCOMM '11: Proceedings of the ACM SIGCOMM 2011 conference, ACM. doi:10.1145/2018436.2018523

- Richard Mortier, Ben Bedwell, Kevin Glover, Tom Lodge, Tom Rodden, **Charalampos Rotsos**, Andrew W. Moore, Alexandros Koliousis, and Joseph Sventek. 2011. DEMO: Supporting novel home network management interfaces with openflow and NOX. SIGCOMM Comput. Commun. Rev. 41, 4 (August 2011), 464-465.

- 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., Koliousis, A., Sventek, J., "Control and understanding: Owning your home network," Communication Systems and Networks (COMSNETS), 2012 Fourth International Conference on , vol., no., pp.1,10, 3-7 Jan. 2012

- **Charalampos Rotsos**, Nadi Sarrar, Steve Uhlig, Rob Sherwood, and Andrew W. Moore. 2012. OFLOPS: an open framework for openflow switch evaluation. In Proceedings of the 13th international conference on Passive and Active Measurement (PAM'12), Nina Taft and Fabio Ricciato (Eds.). Springer-Verlag, Berlin, Heidelberg, 85-95.

- Chaudhry, A., Madhavapeddy, A., **Rotsos, C.**, Mortier, R., Aucinas, A., Crowcroft, J., et al. (2012). DEMO: Signposts: end-to-end networking in a world of middle-boxes. 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, vol., no., pp.6601,6605, 10-15 June 2012

- Anil Madhavapeddy, Richard Mortier, **Charalampos Rotsos**, David Scott, Balraj Singh, Thomas Gazagnaire, Steven Smith, Steven Hand, and Jon Crowcroft. 2013. Unikernels: library operating systems for the cloud. SIGPLAN Not. 48, 4 (March 2013), 461-472.

Chapter 1

Introduction

Computer network technologies in the recent years have become the predominant communication medium of our digital era. In 2011, a third of the global population is Internet-connected through a wide range of network technologies ITU [2011], while Internet resources, based on estimations, generate 3.4% of the global GDP du Rausas et al. [2011]. In parallel, a large fraction of our everyday social life depends on network connectivity (e.g. Social networking, e-mail, e-shopping etc.). Due to the increasing importance of network technologies, functional requirements are constantly evolving and network infrastructures *m*ust be future-proof against increasing traffic rates and performance and security policy complexity.

From an architectural point of view, network functionality is logically separated in two planes: the control and data plane. The data plane is responsible to forward rapidly packets between device ports. The control plane is responsible to orchestrate and transform network policy inputs (e.g. device configuration, routing protocol etc.) into efficient forwarding policies for the data plane. The performance of a network relies on the performance of both planes of functionality. Recent efforts in ASIC design Casado et al. [2013], for hardware-based forwarding devices, and network IO performance Dobrescu et al. [2009]; Han et al. [2010]; Rizzo [2012], for software-based switches, provide strong evidence on the scalability of the data plane functionality in supporting current network speeds. In contrast, existing control plane architectures face significant limitations to match the evolution of the data plane from a performance perspective (Section 2.2).

In contrast to the device data plane performance, which can been described through

the forwarding rate and processing latency of the device, control plane performance definition has a much higher dimensionality and is tightly coupled with the deployment environment. An example of a significant performance parameter of the control plane is the responsiveness of the control plane. Data plane routing and link layer loop avoidance algorithms use decentralised consensus algorithms to share network state and achieve resilient and distributed control. Due to the distributed nature of existing control algorithms, the convergence time during state changes is on average orders of magnitude higher in comparison to the packet processing latency of the data plane. This latency difference becomes important for high capacity links, as the number of packets forwarded over an under-optimal path, after a change in network connectivity, is increased. Similarly, a significant performance parameter for the control plane of a network is functional evolvability. Existing control plane functionality is distributed and integrated with the network device, thus requiring significant network-wide device upgrades in order to evolve the control plane. In addition, control plane performance definition involves subjective non-measurable parameters, such as user friendliness. Current network control plane architectures expose a highly complex control abstraction to the user, in order to fulfil the requirements for generic and universally applicable control, which fail to scale from a management perspective Mahajan et al. [2002].

The recent introduction of the Software Defined Network (SDN) paradigm defines a novel unified control abstraction for network devices which enables higher flexibility to redefine the control plane logic and scale performance (Section 2.3.3). The SDN paradigm supports a wide range of control mechanisms, and can be used to synthesize rapidly novel high-level control abstraction. In this dissertation we argue the thesis that:

> Current network technologies face a significant and multi-dimensional performance bottleneck on the control plane of the network. In order to improve control plane performance in a scalable manner we must redesign the control plane functionality, using the SDN control abstraction, in order to optimize specific aspects and match the deployment environment requirements.

For the remainder of this introduction chapter we justify the importance of this thesis. In Section 1.1 we discuss the evolution of existing network technologies and the

Application	rate	latency	jitter	# connections
web Butkiewicz et al. [2011]; JupiterResearch and Akamai [2006]	no requirement	< 4 sec	no requirement	> 10 (median)
video Finamore et al. [2011]	0.3 (240p) - 5 (1080p) Mbps	no requirement	-	1
peer-to-peer Pouwelse et al. [2004]; Rasti and Rejaie [2007]	maximum possible	no requirement	no requirement	maximum possible
VoIP	100 kbps (voice) - 1.5 Mbps (voice and HD video)	< 500 msec	< 100msec	1
gaming Armitage et al. [2006]	< 100 kbps	< 100 msec	< 50 msec	1

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

scalability limitations incurred by existing control plane functionality. In Section 1.2, we list our contributions and in Section 1.3, we present the content of each chapter of the thesis.

1.1 Motivation

In this section we discuss some of the motivations for our thesis. Specifically, we present the evolutionary aspect of network technologies, in terms of requirements, applications and connection technologies (Section 1.1.1) and highlight some of the limitation of the current control plane technologies (Section 1.1.2).

1.1.1 Computer Network Growth

(a) global Internet traffic trend

(b) global mobile Internet traffic trend
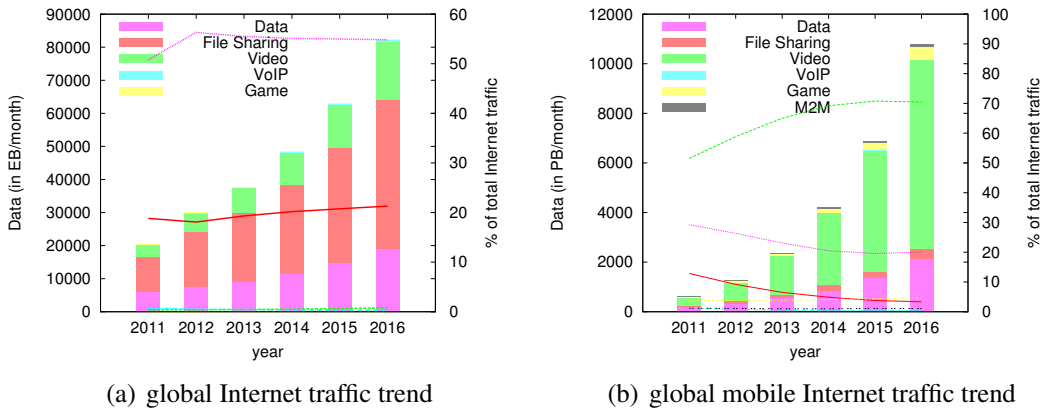
Figure 1.1: Cisco Visual Network Index reports on global network traffic per application for Internet (Figure 1.1(b)) and for Mobile Internet (Figure 1.1(a)). Application

One of the key mechanisms that formed the objective conditions for the digital revolution of our era, was the concept of computer networking. Computer networking

refs to the ability of two computers to exchange data over a communication medium. A first attempt to implement a computer network of significant size was the *ARPANET* system, a novel communication system of the times which provided higher resilience and performance in comparison to existing circuit-switched communication systems. ARPANET Beranek [1981] was adopted by a small number of US education and research institutes and allowed, for the first time in computing history, to interconnect multiple mainframes over a mess network. The initial set of standardised applications provided elementary mechanisms to exchange data: e-mail Bhushan et al. [1973], FTP Bhushan [1972] and voice Cohen [1977]. ARPANET was later replaced by the NSFNET Mills and Braun [1987] in the 80's, which finally evolved in today's Internet. As part of this transition, the research community developed also the standards for the Internet protocol suite Clark [1988].

Although the concept of computer networks was conceived in the 1960's, approximately 20 years since the implementation of a programmable computer, the adoption, as well as, the development of the technology was radical over the years. Computer networks have managed to provide a sufficient abstraction to replace a number of traditional communication systems (e.g. Telephone networks) and support the requirements for a wide spectrum of applications and deployment environments. Nonetheless, this exponential in the usage of network technologies has introduces significant requirements for networks to support large number of users and devices and performance guarantees that weren't initially consider in the design of the technologies. This growth has introduced novel scalability requirements for network and more specifically on its control plane, which is mainly responsible to support the growth. Since the ARPANET time, computer networks gained a significant position in the global social apparatus, driven by two major adopters: *personal computing users* and *businesses*.

For personal computer users, network technologies provide the medium to access rich informations sources and interconnect users and devices seamlessly. An end-user nowadays can easily use his personal computer, when connected to an Internet gateway, to connect to system abstractions like the World Wide Web (WWW) and the Cloud, and access a wealth of information and services. Currently, the WWW is the ultimate information source of our times, providing free access to a large portion of the global human knowledge, while the Web 2.0 functionality of the modern Web enables the development of highly responsive services which replace traditional information

distribution mechanisms Stempel et al. [2000]. Recent development in network applications have established novel mechanisms for fast and wide-scale social interaction. Currently, Online Social Networks (OSN) interconnect millions of users across the world, while instant messaging services, like google chat and Skype, enable real-time text, voice and video communication over the Internet. In addition, the radical reduction in cost and size of network-enabled personal computers, as modelled by Moore's Law, has increased significantly the number of devices per-user and subsequently increase the network connectivity requirements. More and more devices are shipped with network support and requires connectivity. The constantly increasing adoption of network technologies by person computer users fuels a significant portion of network innovation and motivates the development of new connection mechanisms (e.g. mobile Internet). The important role of computer networks for users can be further reflected in the government level debate to proclaim Internet connectivity as a fundamental human right Klang and Murray [2005]; Wicker and Santoso [2013], introducing significant technological challenges to scale Internet connectivity for the global population Cerf [2012].

Computer network technologies and infrastructures have become a valuable asset for the business sector as well. Business sector adopters employ computer networks primarily as a cheap, fast and multi-functional communication medium to interconnect business logic and distribute content to users. The success of network technologies to provide these functionalities motivates the business sector to invest in the technology, as well as, innovates the usage of the technologies in new domains (e.g. cloud computing abstractions in a data center and distributed content distribution). Such novel network concepts stress the capabilities of available connectivity mechanisms, highlighting interesting scalability problems (e.g. large scale data centers face significant problems to scale layer 2 connectivity). The increase in the adoption of network technologies in the business sector can be further identified in the increase of the number of Internet Autonomous Systems (AS). Since 1995 the number has exponentially increased from 2000 ASes to approximately 45000 ASes, reflecting the increase in the number of organisations using the global Internet infrastructure as a core communication mechanism for their business Huston [2005]. This increase in ASes introduced a significant scalability problems for the control plane of the largest network in the world, the Internet Labovitz et al. [1997].

The wide adoption of network technologies drives a continuous application innovation and new network use-cases emerge constantly. This innovation in network applications has a significant impact on the complexity of computer network management. The two aforementioned general classes of adopters use the same network technologies to fulfil a diverse set of requirements. In order to exemplify this problem, we present in Table 1.1 the resource requirements for a number of popular network applications, namely web traffic, video streaming, peer-to-peer applications, VoIP and gaming *tail at scale, add requirements for cloud service providers for map reduced applications* . In the table we report the requirements for each application in terms of bandwidth, latency, jitter and number of connections. From the table entries, we note that some application pairs have contradicting requirements, when using a congested link. For example, peer-to-peer applications will try to maximize used network capacity, by flooding network links, and create increase latency and jitter for delay-sensitive applications like VoIP. These contradictions are further magnified by the design abstraction of current network protocols, which hides the state of the lower layers of the network, lucks performance-related semantics and effectively reduces the short-term effectiveness of end-to-end resource control. Nowadays, the importance of the network control plane in network resource management is increased. During congestion incidents, the control plane must be able to react at flow-level timescales and dynamically allocate resources to fulfil application requirements.

Application innovation complicates also long-term network planning and introduces a flexibility requirements in the control plane. In Figure 1.1, we plot the estimated traffic volumes for six popular network application classes between the years 2011-2016 for mobile and fixed Internet, using data from the Cisco visualization index Cisco [2012e]; Mobile [2012]. From the figure, we note that network traffic is expected to increase an order of magnitude for mobile Internet, while the fixed Internet traffic is expected to increase four times. The graphs also point out the short-term application popularity churn. The video streaming class is expected to increase significantly both in traffic volume and overall traffic over the data and file sharing classes, introducing strict requirements in term of path capacity and latency. Experience in network application evolution determines that new network applications are common to gain rapid popularity, once they are introduced to the users. Network technologies must exhibit flexibility and provide a friendly network environment to fulfil the

resource requirement of the new application without infrastructural upgrades. Furthermore, once network applications establish their popularity between users, they will maintain a fixed network traffic volume for a long period of time, depending on the popularity and novelty of the application. The share of the application traffic with respect to the overall traffic volume of the network may reduce over time, especially as link speeds increase and new popular application emerge, but the network should be able to continue providing a friendly environment for the application for a long period of time. This results in a continuous enlargement of the resource allocation policies and introduces significant complexity on the network control plane.

review the data of the application trends A significant evolution in network technologies is also observed in the lower layers of the network abstraction, which encapsulate significant heterogeneity. Ethernet has been the predominant Internet link layer protocol since the 80's, mainly due to its low cost and complexity design principle. The network community has defined standards to run Ethernet over a wide range of medium types, like coper, fibber, off-licence radio frequencies, satellite links and mobile networks, while keeping the network abstraction unmodified. This approach encapsulates a number of medium properties (e.g. link layer ARQ, link rate), within the Ethernet abstraction and hides significant performance characteristics of the lower layer.

1.1.2 Control Plane Limitations

Unlike traditional distributed systems, the design of network technologies and protocols must be able to accommodate all potential future requirements. This fundamental design goals stem both because of the large number of individual components forming the network, as well as, the capability of individual components to accommodate protocol updates (e.g. ASIC silicons are optimized to implement specific network functionality at line rate, but they are unable to modify their functionality). Current control and data plane protocols, unfortunately, experience a number of design limitations primarily due to the inability of their designers to predict the radical adoption of the technology. The early adopters of the NSFNET, which defined the Internet protocol standards, were universities and research facilities and the design process aimed to provide support for asynchronous communication applications, low link speeds and

best-effort connectivity guarantees. Furthermore, in order to ease the design of network devices, the protocols followed the end-to-end design principle Saltzer et al. [1984]. The control plane on the intermediate hops of the path ensures long-term network connectivity. Current Internet protocols have managed to provide a strongly connected network, but as network size and complexity increases, the control plane becomes an important mechanism to optimize network performance.

An interesting observation on the evolution of network technologies and especially on the control plane of the network is the abstraction simplicity requirement set by the network community. The existing Internet protocols were selected through a "natural selection process" against other isomorphic protocols, developed during the early days of the NSFNET. During that period, the OSI and ITU organisations published a number of network protocol definitions ISO/IEC [1997, 2001] which provided connectivity for all layers of the network abstraction, while the ATM Forum also defined similar higher-layer protocols, on top of the ATM technology Siu and Jain [1995]. These protocol attempts provided highly detailed abstractions, as well as, highly complex protocols which, although, can address some of the current functional limitations. Nonetheless, their increased complexity introduced performance scalability problems for the computational resources of the time and the protocols became obsolete in favor of current Internet protocols.

For the rest of the section, we discuss some important network limitations of current technologies.

Security   The initial security requirements for computer network technologies were minimal. On one hand, early technology adopters, such as educational and research institutes, used networks to provide open, free and accessible services, aiming to augment technology adoption. As a result, their security requirements were minimal. On the other hand, the computing resources of the time were limited and couldn't support the computation requirements for a security-aware network design. In parallel the US Department of Defence (DoD) , in order to ensure secure transmission of classified information, designed and implemented a number of high security networks, namely MILNET, SIPRnet and NIPRnet. These networks function as partially stand-alone inter-networks owned by the DoD and provide strong security primitives in the network design. Their design supports low bandwidth connectivity (primarily HTTP

and mail services) and uses enhanced security mechanisms in the lower layers of the stack along with existing Internet protocol in the higher layers of the network of Americal Scientists Intelligence Resource Program [2000].

These initial network security requirements are currently invalidated. A McAfee report from 2009 estimates the cost for cybersecurity to approximately 600 million dollars Kanan et al. [2009]. Similarly, during the wikileaks scandal in 2011 BBC [2010], a significant number of US state documents was intercepted from the SIPRnet system, exposing the limitation in the design of the network. The threat model for network systems is wide and contains numerous attacks; from information interception to denial-of-service attacks. The research community has proposed a number of protocols to address the security requirements of today network environment, e.g. IPSEC Kent and Atkinson [1998] and loose source routing Argyraki and Cheriton [2009]. Nonetheless, although such protocol introduce enhanced security guarantees for the data plane, they also introduce significant complexity on the control plane of the network. For example, for IPsec the data plane can implement at line rate the encryption/decryption task, but an IPsec gateway must maintain protocol state for each tunnel. Network security requires security-aware control logic spanning from the lowest layers of the network abstraction and spread across the network.

Network management scalability A significant control plane scalability bottleneck can be traced back to the policy expression interface of current technologies. In Section 2.1 we provide an extensive presentation of the basic network control mechanisms and describe the exposed control abstraction. Current network control schemes rely on network administrators to manually transform the global control policy into localised policies for each network device. In addition, the layered nature of existing network devices requires individual configuration for each network layer. Furthermore, there is a luck of mechanisms to evaluate the effectiveness and validity of the resulting network configuration. Policy evaluation relies on traditional connectivity testing tools, like ping and tcpdump, and byte and packet SNMP counters from network devices. As a result, large-scale network management is a highly laborious process and requires significant experience. Ultimately, modern network management interfaces have a significant non-scalable bottleneck on the "mechanism" translating the network functional requirement into distributed device configuration, the network manager.

In Kim et al. [2011]. the authors conduct a measurement study on the evolution of the configuration of two medium-sized campus networks. Their longitude analysis highlights the constant expansion of the network policy for the two networks, as well as, the mixture in the network configuration of security and forwarding control. In addition, the network configuration process is highly subjective and depends on the device type and the deployment environment. Especially for switch and router configuration, every network policy change translates into a number of device policy updates across the network, highlighting the restricted expressiveness of the policy definition languages. Finally, device policies over time are common to contain stale rules in order to avoid potential network misconfiguration, which are pruned only when they are contradicting newer policy updates or during major policy revisions. Similarly, in Mahajan et al. [2002] the authors study global BGP protocol errors and report a significant portion of protocol misconfiguration which reduce connectivity and performance. These misconfigurations can be ascribed to the counter intuitive control abstraction of the routing protocol. The mismatch between human understanding and network abstraction is further exemplified in the domain of home networking. In Grinter and Edwards [2005], the authors contact a small scale user study and highlight the mismatch between the user-perceived network connectivity abstraction and the real network functionality. This mismatch leads to under-optimized network configuration. Ultimately, homeowners tend to sacrifice security and performance, in order to reduce the burden of network management.

The management problem is further augmented by the standalone functionality of the control plane of a set of common network devices, like performance-enhancing middleboxes, firewalls and NATs. Such devices maintain a local static network configuration, disconnected from the distributed control plane of traditional network devices. This luck of interaction may introduce unexpected network behaviours during significant network changes, e.g. subnetwork disconnections and reduced host connectivity. The network management domain requires a technological revolution, similar to the revolution of high-level programming language in the 70's. In order to scale network management performance, we require new user-friendly control abstractions which can automate the process of policy translation and unify the control domains across the network.

Resource allocation   As discussed in Section 1.1.1 dynamic and fast resource control is an important requirement for todays network technologies. Network engineers are accustomed to address this problem by network resource overprovision Teitelbaum and Shalunov [2002]. This approach though becomes insufficient as network link rates increase. Users have become accustomed to fast network functionality, which severely degrades by queueing delays and packet drops in high-speed networks. In related literature, a number of approaches has been proposed to address this problem in multiple layers of the network stack (e.g. ECN Kuzmanovic et al. [2009], DiffServ Blake et al. [1998], RSVP over MPLS-TEAwduche et al. [2001]).

Resource management in current network technologies is implemented as a feedback mechanism between two entities: the end-to-end congestion mechanism and the network forwarding mechanism. End-to-end congestion run on the end-hosts of a network flow and aims to infer the available capacity of the end-to-end path using some flow properties, e.g. packet losses, RTT variance. Network forwarding policy defines the end-to-end path between any pair of hosts over the network connection graph and, in some cases, define the prioritisation and buffer size for specific network flows. The two mechanism interact dynamically. End-to-end congestion control estimates capacity of the path and control the data rate of the flow. The aggregate flow rates are measured by the network forwarding logic to define an optimal end-to-end path which optimizes specific network-wide indexes, e.g. average link utilisation. Fundamentally, there is a strong mismatch between the time-scale of the two mechanisms which can degrade flow performance. In order to enable better resource allocation mechanism, we must evolve current control plane to react faster to the overall network performance.

Network functionality   In an effort to improve control and performance of current network technologies the network community has developed the concept of middleboxes, transparent network devices that modify the behaviour of network protocols. Devices like NATboxes, WAN optimizers and firewalls function transparently in a network and enable custom programmability in the protocol functionality without a requirement to modify the protocol specifications. Middleboxes have redefined to a great extend overall protocol functionality, as they commonly introduce new assumptions in

the protocol functionality and violate the Rubstness principle of networks [1]. In Honda et al. [2011], the authors contact a large-scale robustness measurement across the Internet and report that uncommon but protocol-legal network flow behaviours have a significant possibility to fail due to the functionality of such devices.

An important side-effect of the introduction of middlebox functionality is the re-definition of elementary network properties. A typical example of this effect is the bi-directionality property of network connectivity. The widespread deployment of NAT-boxes, which scale Internet addressing, change Internet-wide hosts connectivity. A NATed host is able to access any Internet service, but cannot receive incoming connection from any Internet host. The protocol community has developed a number of stand-alone control protocols for middleboxes, enabling end-hosts to effectively affect middlebox functionality Eggert et al. [2008]. Nonetheless, in order to enable adaptability of network technologies in new domains, without loosing the ability to evolve existing protocols, we need to integrate middlebox control with the control plane of the network.

1.2 Contributions

This dissertation contends that existing approaches to network control introduce a significant performance bottleneck in network functionality and are insufficient for the constantly evolving and diverse requirements of the new applications domains for network technologies. A more flexible approach is required to address the control requirements for modern network technologies, which unifies network control across all devices of the network and optimizes specific performance aspect in order to fulfil the functional requirements of the deployment environment. We employ the recent SDN control abstractions in order to increase the flexibility to develop new control plane architectures.

We claim the following specific contributions:

- **Control scalability**: This thesis presents two measurement platforms which en-

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[1]"In general, an implementation must be conservative in its sending behavior, and liberal in its receiving behavior. That is, it must be careful to send well-formed datagrams, but must accept any datagram that it can interpret (e.g., not object to technical errors where the meaning is still clear)." Postel [1981]

able SDN developers to understand the performance capabilities of their SDN platforms and architectures. The tool focus respectively on evaluating the control plane functionality of existing SDN switches, as well as, providing an environment to reproduce the functionality of a network and evaluate the performance of custom control plane architectures. Using these tools, we conduct a measurement analysis to evaluate the control plane performance limitations of a number of off-the-self forwarding devices and evaluate the capabilities of the various control interactions.

- **Management scalability**: We consider the problem of scalable network management in the context of the home network and design a novel control plane architectures. Motivated by recent home network users , we redesign the home router to enable homeowner to receive accurate information from their network and exercise intuitive control over the network devices.

- **Security and connectivity scalability**: As discuss in our motivations section, current Internet architecture cannot scale support for elementary connectivity properties across the Internet. User have become accustomed to employ third party services in order to enable device interconnectivity across the Internet, while sacrificing performance, security and functionality. We address this scalability problem with Signpost, a novel control plane architectures which provides scalable Internet-wide device inter-connectivity across the Internet with user-defined performance and security. Signpost provides an intelligence control plane for the end-user device which can adapt to the network capabilities of the environment and employ readily available connectivity mechanisms to enable inter-device connectivity.

1.3   Outline

The rest of this dissertation is organised as follows. Chapter 2 provides background information related to this work. It presents the architecture of current network devices and the physical limitation of network control, discusses the available control plane mechanisms and their weaknesses and discusses alternative control plane approaches and their applications.

In Chapter 3 we study the control scalability of the SDN paradigm. We present two control plane benchmarking platforms, *OFLOPS* and *SDNSIM*, designed to measure the baseline scalability of the Software Defined Networking (SDN) paradigm. Using these tools, we conduct a measurement study to characterise the performance of SDN-enabled devices, as well as, the impact of distributed control architectures in the data plane performance. In Chapter 4, we study the problem of control plane management performance, focusing on the home network setting. Using existing user studies we draw the user network management requirements and redesign the control plane architecture of the home router. Our architecture provides a simpler, user-friendly control abstraction which matches the user requirement for control and information from their network. In addition, we provide an extensive evaluation of the architecture and provide evidence on the scalability and backwards compatibility of our architecture. In Chapter 5 we investigate application of the SDN paradigm in connectivity scalability. We present Signpost, a novel user-centric control plane architecture for end-hosts, providing Internet-wide device connectivity with user controlled security. We present the architecture of the framework, the integration of the architecture with existing connectivity-enabling mechanisms and we evaluate the performance and applicability of the framework. Finally, in Chapter 6 we draw conclusions from our study and suggest further work.

Chapter 2

Background

This chapter provides an extensive discussion on network control in packet switched networks. We motivate the discussion on network control, describing the architecture of network devices and their inherent physical limitations (Section 2.1) and elaborate on existing network control mechanisms for production networks, focusing on some of their deficiencies (Section 2.2). Furthermore, we present three important network control frameworks, namely Active Networks, Devolved Control of ATM Networks (DCAN) and Software Defined Networking (SDN), proposed by the research community to address some of the limitation of current control schemes (Section 2.2). Finally, we focus on the most recent control framework, SDN, and present some of its applications in modern network problems (Section 2.4).

2.1 Forwarding Devices

Packet networks have become a *'de-facto'* approach in communication networks. Their success relies, to a great extend, on the offered high medium utilization and low-cost design principle. Packet-switched networks can function over a large set of physical layer technologies and replace tradition connection-oriented mechanisms (e.g. telephony, TV broadcast). In this section we focus on Ethernet and IP networks, the predominant protocol implementations for packet networks, and provide a design overview of a hardware *Switch*, a typical forwarding device.

Network switches are the main mechanism to multiplex Ethernet links. Their
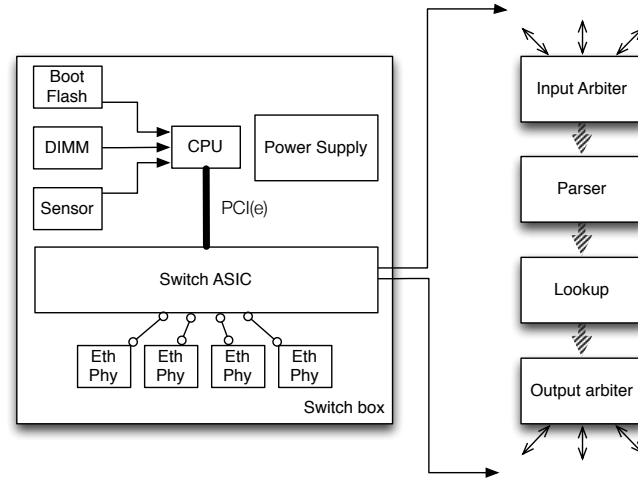
Figure 2.1: A generic architecture of a Switching device.

main functionality provides collision-free connectivity between network segments. Nonetheless, as the network complexity increases, switches augment their functional roles in a network and their hardware architecture is highly diverse. For example, unmanaged switches provide a low cost non-configurable interconnection device for small networks, supporting usually a few 1 gig ports, while distribution switches are used in large enterprise networks to interconnect aggregation switches, support multiple 10 or 40 Gig links and provide multiple mechanisms to inspect and control network traffic. In this section we will use the Top-of-Rach (ToR) switch type as an reference to elaborate on the architecture of modern switches. Such switches are used in datacenter networks to aggregate traffic between the edge and the distribution network layers. TOR switches commonly use a single Application-Specific Integrated Circuits (ASIC) silicon and can forward high-rate traffic non-blocking at line rate. As presented in Figure 2.1, a typical switch device consists of the following components:

- *management CPU*: Switch boxes contain a programmable CPU, which runs the control plane logic and provide configurability. Switch CPUs usually run a simple operating system and communicate with the switch ASICs in order to modify their functionality, based on the policy. Switch vendors usually use low-power CPUs, such as SoC PowerPC chips or even ARM and MIPS CPUs. The CPU can access runtime memory modules (Boot Flash and RAM), to store transient state, and persistent memory (e.g. SD Cards) through memory extension slots, to

store log files and configuration. In general, switch CPUs provide sufficient computation resources to run the switch control-plane functionality, but they cannot accommodate intensive processing tasks. The OS provide network services, like telnet and SSH, to provide a command line interface to network managers, while usually it also provides SNMP services to aggregate switch statistics.

- *Switch ASIC*: The switch ASIC Broadcom [2013]; HP [2012]; Intel implements in hardware the forwarding plane of the switch. The capabilities of an ASIC are variable, depending on the vendor and the cost, but define the performance limits of the device to handle data plane traffic. Implementation details of an ASIC silicon remain usually concealed, as they constitute an important asset for the producer. The design of an ASIC is an expensive process, as their design and testing period is long and requires significant human labour and material resources. As a result, switch silicon innovation has a high latency to reach the production environment. Furthermore, as in general purpose CPU design, the processing capacity of an ASIC is upper bound by the transistor density and size.

  TOR-type switches can handle line-rate non-blocking traffic for a number of ports, using a single ASIC silicon. An ASIC contains four important modules. The *input arbiter* module multiplexes and synchronizes packets from the Ethernet ports to the main processing pipeline of the silicon. The arbiter ensures non-preemptive packet processing, by bridging the rate mismatch between the silicon processing clock and the link rate. In the main processing pipeline the ASIC contains at least a *protocol parsing* module and an *memory lookup* module. The protocol parser extracts significant packet fields from network packets and the memory lookup module uses the packet fields to define the packet processing and forwarding operations. The lookup module relies on an interface with an external memory module in order to match protocol fields with forwarding policy. Memory modules have a trade-off between cost and access speed and between memory cost and memory management complexity [1]. Finally, the *output arbiter* module is responsible to apply modifications to the packet and forward it

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[1] CAM/TCAM lookup: < 10 clock cycles, SRAM: 2-3 nsec, DRAM: 20-35 nsec, http://people.ee.duke.edu/~sorin/prior-courses/ece152-spring2009/lectures/6.2.2-memory.pdf

to the appropriate output queue. Beyond the aforementioned modules, an ASIC may have additional processing modules in the main packet processing pipeline, to extend its functionality with operations like access control list (ACL) virtual network queues and flow statistics monitoring.

- *ASIC-CPU communication*: The switch CPU is connected with the ASIC over a PCI or PCI-express bus. The communication channel provides an elementary bi-directional channel: the CPU controls ASICs registers, to modify forwarding functionality, and the ASIC propagates information for exceptional states to the CPU. The channel provides sufficient bandwidth for basic control plane communication, but it is not designed to handle high rate information.

- *Memory*: Apart for the in-ASIC memory modules, modern switches also use multiple memory types to support the run-time requirements of the firmware. A switch is usually equipped with CPU Boot Flash, to boot the OS/firmware, DIMM RAM and multiple memory slots, for control plane logging and configuration persistence.

- *Ethernet ports* : The receipt and transmission of Ethernet packets is implemented as a separate hardware circuit. The module is responsible to implement the physical layer and MAC layer protocol and propagates packets to the ASICs using a Media Independent Interface (MII). The phy module usually contains small packet buffers to reduce packet losses for bursty traffic.

The physical limitation for the control plane are defined by the ability of the management CPU to communicate with the ASIC. This communication can be further characterised by the speed of the switch to read and write ASIC registers and modify the ASIC memory modules. In addition, the computational requirement of the control plane logic can impact severely the control plane performance, if the management CPU processing capacity is limited.

TOR switches are simple switch devices, supporting the traffic requirements of the edge network and provide low to medium forwarding capacity. As we move closer to the core of the network, the processing capacity requirements, as well as, device complexity are increased. Multi-chassis switches and routers cannot contain the required

functionality in a single ASIC. Packet processing is distributed between multiple silicons, complex clos interconnection crossbars are used to provide non-blocking Terabit backplane capacity Juniper [2012] and the complexity of the control plane to modify forwarding policy is increased. In addition, providing fast address lookup requires multiple distributed buffers and cache coherent protocols to ensure state consistency Cisco [2005]. For these classes of devices, the control plane abstraction has a complex and slow translation to ASIC management operations and programming flexibility is restricted.

2.2 Forwarding Control in Production Networks

Dynamic network control has been an important functionality for computer network technologies. Forwarding devices require mechanism to automate forwarding logic update when network state changes in order to ensure end-to-end connectivity. Existing standardized approaches aim for *distributed*, *autonomous* and *resilient* network control and are influenced extensively by the end-to-end principle of the Internet. A switch or a router control functionality requires only local forwarding configuration. The device at run-time uses a number of well-defined distributed protocols to discover the global network state by state exchanges with other network devices. Using the global network state, the forwarding logic determines an optimal forwarding policy which maximizes network performance. Because the state is constructed collectively, current control plane can provide guarantees only for long-term resilience. If a link is disconnected, the control logic propagates this information across the network to update the network state in other devices, while if a device is rebooted, it can automatically rebuild the global network state using only its local configuration. In this section we present existing production-level protocols that enable distributed network control. We focus on the Data-Link and Network layer protocols as these layer define the hop-by-hop forwarding policy.

2.2.1 Data-Link Layer Control

Data-Link layer control protocols provide loop-detection, and VLAN and QoS automation. Loop detection is used to avoid packet loops in networks with redundant

connectivity, since the Ethernet specification doesn't support packet timeout functionality. The spanning Tree protocol (STP) was a first attempt to address this problem, standardised by IEEE in 802.1D-1998 IEEE [1998]. The protocol implements the distributed spanning tree construction algorithm, presented in Perlman [1985]. The algorithm uses broadcast messages to discover a spanning tree over the graph of the network, with respect to a common root switch and controls a state machine per port, which disables packet forwarding when a link is not part of the spanning tree. Because the initial definition of the protocol faced significant convergence delay after a network change, IEEE introduce the Rapid Spanning Tree Protocol (RSTP), an evolve version of STP, in IEEE [2004]. In addition, a modified version of the protocol was defined to accommodate VLAN functionality, since VLAN tags can create multiple subgraphs over the network. The protocol runs individual STP algorithms for each subgraph and constructs individual spanning trees for each VLAN, thus reducing unnecessary port blocking. This functionality is provided by the IEEE Multiple Spanning Tree Protocol (MSTP) IEEE [2005], while Cisco has developed a series of proprietary protocols to address this problem Cisco [2012c,d]. Finally, IEEE has recently defined an advanced STP protocol that enables switches to discover and use in parallel redundant network links, in the IEEE 802.1aq standard IEEE [2006].

In terms of configuration automation, network vendors and standardization bodies have developed a number of protocols which disseminate device configuration to neighbouring nodes. Such protocols have high churn between vendors and each vendor so far has defined a custom standard. In this class of protocols we consider Link Layer Discovery Protocol (LLDP) IEEE [2009], supported by IEEE, Cisco Discovery Protocol (CDP) Cisco [2012a], Extreme Discovery Protocol (EDP) and Nortel Discovery Protocol (NDP). Finally Cisco has developed the VLAN Trunking Protocol (VTP), a protocol which reduces the VLAN configuration burden in inter-switch trunk links.

In the class of Data Link layer protocols we also consider the MPLS protocol Rosen et al. [2001]. MPLS is a data link or network layer protocol which enables the creation of virtual-circuit over Ethernet networks. MPLS uses simple labels ID to forward packets and the protocol is used extensively in the distribution layer of large networks, to reduce forwarding table size. In order to automate the configuration of MPLS circuits, the MPLS community defined the LDP protocol Andrerson et al. [2007] to setup automatically labels across the network. In addition, IETF defined a mechanism to

translate RSVP resource requests to MPLS tunnel configuration Awduche et al. [2001] and the autobandwidth mechanism to enforce perfromance , since MPLS doesn't provide resource control, the IETF defined the *Autobandwidth* mechanism Osborne and Simha [2002]. Autobandwidth monitors tunnel bandwidth requirements and recalculates paths when resource requirements change. A study on a deployment of this technology in the MSN network though has highlighted that the allocation policy is under-optimal for significant periods of the network functionality Pathak et al. [2011].

2.2.2 Network Layer Control

In the network layer, modern network technologies exercise control using routing protocols. Routing protocols follow a similar approach to Data Link layer protocols and provide mechanisms to disseminate local configuration to the network. Routing protocols are classified in three categories: *Link State*, *Distance Vector* and *Path Vector*. Link state protocols theory build on-top of the Djikstra algorithm Dijkstra [1959]. Routers disseminate their local forwarding configuration to the rest of the network. Using this global state exchange, each router is able to construct the global connection graph. Each router can use the graph to calculate the minimum spanning tree of the network, using Djikstra's algorithm. Currently there is a plethora of Link State protocol specification in the network community. IETF has developed the OSPF protocol Moy [1998], an Ipv4 specific routing protocol, while the Open Systems Interconnection (OSI) organisation has defined the IS-IS protocol Oran [1990], a network layer agnostic routing protocol. Link state routing protocols provide high flexibility to define the optimisation function of the routing system. Each router has view over the complete graph of the network and routers can propagate multiple link performance indexes (e.g. link load, link speed). Nonetheless, the optimization function must be homogeneous across the network, in order to avoid routing loops.

Distance Vector routing protocols employ a different approach to provide efficient global routing policies. The routing table is constructed using information from adjacent routers. Network changes are slowly propagated across the network, through point-to-point information exchanges, until all routers converge. Distance Vector protocols use the Belman-Ford algorithm Bellman [1956] to achieve routing optimality. IETF developed the RIP protocol Malkin [1998] to implement Distance Vector routing,

while Cisco has developed the proprietary IGMP protocol Rutgers [1991]. Distance Vector protocols are less extensible than Link State routing protocols, but can be implemented with smaller computational and memory requirements.

Finally, Path Vector routing protocols evolve Distance Vector protocols to support inter-domain routing. In this class of routing protocols, adjacent routers advertise the AS path towards for a specific subnet. Path Vector routing permits ASes to abstract routing policy details, but provide sufficient information for the other ASes to define their forward policy. As a result, the BGP protocol doesn't provide an explicit routing protocol, but provides a sufficient framework for information exchange. The BGP protocol Rekhter [1991] is currently the predominant Path Vector routing implementation.

Due to their distributed nature, routing protocols provide long-term routing resilience, while their mathematical foundation is provably correct. Nonetheless, the control abstraction of these protocol is not a good fit for administrator to exercise dynamic control in the network. For example, the ability of a network manager to estimate the impact of a significant forwarding policy update is reduced, as the network size get bigger. In 2008 the global Internet was severely affected by a BGP misconfiguration from the Pakistani national ISP in an effort to control traffic from YouTube service Brown [2008]. In addition, routing inconsistencies during routing changes can impact significantly network performance. In Watson et al. [2003], the author evaluate the OSPF functionality in a regional ISP and report high churn in routing even during periods without significant network events, while the latency to converge after a network change is on average on the order of seconds. Similar results have been observer in BGP. In Kushman et al. [2007] the authors highlight a strong correlation of BGP instability and VoIP performance. Nonetheless, as the network link speeds increase, the impact of such update on the data plane of the network is increased, as the number of packet that will be affected by a routing instability is equally increased. Modern high speed networks require higher flexibility in the control abstraction and faster control plane responsiveness.

2.3 Programmable Network Control

Because of the limitation of current standardized network control frameworks, the research community over the years has proposed a number of approaches to evolve

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network control. In this section we present the three most significant and complete approach to this problem, namely Active Networks, Devolved Control of ATM Networks (DCAN) and Software Defined Networking (SDN).

2.3.1 Active Networks

The problem of protocol ossification in the network layer and the requirement for network evolution, was highlighted by the network research community since mid 90's. In O'Malley and Peterson [1992], the authors argue on the generality of the 7-layer OSI network abstraction. They claimed that the networks functionality should be more dynamic and forwarding devices should be able to accommodate variable number of protocol layers. In their work they present an extensible protocol modeling framework to layer protocol processing. Motivated by these observations, DARPA funded the *Active Networks* project DARPA [1997], in an effort to develop next generation network devices that can accommodate seamlessly new protocol functionality.

Active networks modify the default packet processing mechanism and introduce the notion of *capsules*. Capsules are network packets that carry data, as well as, processing code. On each hop, the default packet processing logic is extended with the code contained in the capsule, thus redefining network functionality. This network processing approach provided user-driven protocols upgrades, without a requirement for devices upgrade. In addition, the development of novel programming languages, like Java, provided the building blocks to implement code distribution frameworks.

Research in active networks tried to define two mechanisms : the **capsule API and format** and the **switch architecture**. In terms of capsule format, the active network community defined the Active Network Encapsulation Protocol (ANEP) Alexander et al. [1997a]. ANEP, through its format specification, made a clear separation between functionality and data. An Active Node using a new protocol would inject firstly new processing logic, using code capsules, and then send the data stream, as data capsules. The format was adopted by the ANTS and Sprocket frameworks. Sprocket Schwartz et al. [2000] was an effort to develop an efficient capsule programming language by BBN technologies. The language uses a restricted set of the C language, avoiding any security vulnerable structures like pointers, while it introduced native support for SNMP browsing. Sprocket compiled source code to compact MIPS assembly. Each

switch would receive code capsules and run the code in a MIPS virtual machine. The VM could not persist any state on the switch, but it was able to modify the data section of a packet. Sprocket provided secured injected code with a public key secure hash of the code binary, but without sufficient details on the authentication logic. ANTS Wetherall et al. [1998] was an attempt by the Active Networks group in MIT to develop a sufficient capsule programming environment. ANTS uses a restricted version of the Java language to program capsules, because of the inherent object serialization functionality of Java, while the processing logic is defined through a small set of Java interfaces. ANTS permits injected code to persist flow state on a switch and modify packet content. An interesting extension of the ANTS framework was the code dissemination mechanism. An end-node deployed new protocol functionality solely to the local Internet gateway, and the code is forwarded along with the packets to each next-hop. Finally, The university of Pensylvania active networks group developed its own approach to capsule programming. PLAN Hicks et al. [1998] used a restricted version of the OCaml language to abstract capsule access to the local switch state and implement custom forwarding logic. PLAN did not follow the ANEP packet format. A PLAN capsule contains code and data and the code section replaces the network header information. In order to secure switch infrastructure, the language disallowed packet data modification or switch state persistence. Ultimately, the language provided a framework for programmable control plane.

In terms of Active Network platform architecture, the community developed a number of architectures, addressing multiple aspects of efficiency in capsule processing. University of Pensylvania proposed the SwitchWare Execution Environment (EE) Alexander et al. [1998a]. The architecture defined an OCaml module framework for capsule processing. A core focus of the SwitchWare EE was strong multi-dimension security for active networks, both on the local system, as well as, during capsule execution. SwitchWare used SANE Alexander et al. [1998b], a trustworthy operating system, to secure the functionality of the switch, and build on top of its security primitive higher level of trust. The platform addressed issues regarding secure execution and authentication, as well as, capsule code verification. PLANet Hicks et al. [1999] and Active Bridge Alexander et al. [1997b] used the SwitchWare framework to implement novel functionality in active networks.

The active networks group in University of Arizona proposed its custom approach

to high performance active network forwarding. Their approach relies on the Scout OS Montz et al. [1995], a communication-oriented OS supporting efficient layered data processing. On top of Scout, the group developed the Liquid Software API Hartman et al. [1999]. The integration of Liquid Software API and Scout, aimed to establish a tight integration between the OS and the JVM and improve capsule processing, using the JIT JAVA compiler.

The CANEs project Chae and Zegura [2002] from Georgia Tech Active Networks groups followed a different approach for the problem and designed a system which enabled multi-protocol packet processing. CANEs defined a number of abstractions, which enabled active network applications to stack multiple protocol processors on the forwarding path. CANEs project build on top of the Bowman Switch OS Merugu et al. [1999] and established a simple and efficient abstraction over the Switch resources.

Researchers from the Columbia University, presented the NetScript switch abstraction da Silva et al. [2001]. NetScript is a new programming language optimized for flexible protocol processing definition and composition. The project defines three types of protocol composition: layered composition, composition through protocol bridging and end-to-end composition. Netscript provides developers the ability to builf flexible extension in existing protocol processing.

Finally, a joint effort between the Network Laboratory of ETH and the University of St. Louis, developed a hybrid hardware and software approach for high performance capsule processing. The High Performance Active Network Node (ANN) switch architecture Decasper et al. [1999] proposes the introduction of an FPGA for each ATM interface which handles capsule execution. Using this infrastructure, the researchers where able to run the ANTS EE and develop an IPv4 and IPv6 protocol processor to run in Gigabit rates.

Active network research put forward a number of interesting insights on the controllability and evolvability problem in control plane functionality. Nonetheless, their complex and clean-slate approach, reduced their applicability in production environments. In addition, Active Network functionality was highly benefited from the relatively low rate of the network rates of the time. CPU processing capability of the time was able to accommodate the respective link rates. The rapid evolution of data rate in Ethernet interfaces to Gigabit speeds, through, makes impossible the development of programmable forwarding platforms with line rate performance in the current time.
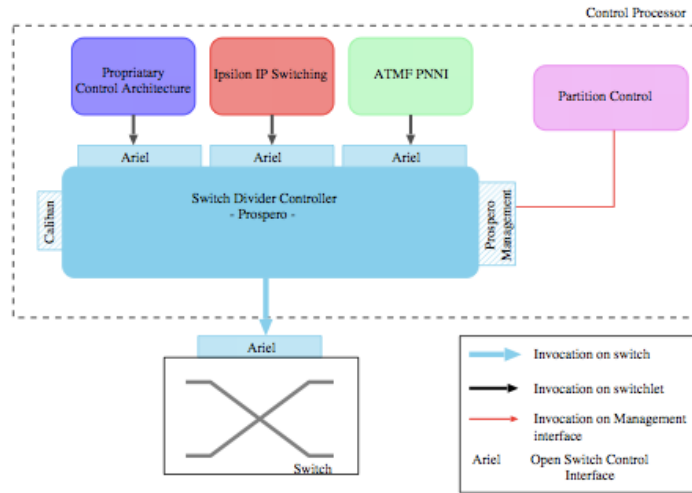
Figure 2.2: Tempest switch architecture van der Merwe [1998]

2.3.2 Devolved Control of ATM Networks

add GSMP protocol reference An effort to network programmability in ATM network was also developed by the University of Cambridge, as part of the DCAN project project [2000]. The main focus of the DCAN project was the development of a dynamic network control plane which could virtualise an ATM network. In Rooney et al. [1998], the authors present Tempest, a novel ATM switch architecture, which achieved the goals of the DCAN project. Tempest provides a clear separation between the control and forwarding plane of a network device. The control plane of network devices, is centralised in a single programmable entity, which implements intelligent and dynamic forwarding. The implementation of Tempest is logically divided between three abstractions, depicted in Figure 2.2. The Figure presents how a single switch is able to function in parallel as an IP router, an ATM switch and a Hollowman controlller Rooney [1997], a devolved ATM control framework.

Prospero Switch Divider   The *Prospero* abstraction provides a mechanism to virtualise ATM switch resources. Prospero provides a resource control interface, which can divide switch resource between multiple virtual switches, called *switchlets*. A switchlet controls a subset of the switch ports, VCI and VPI mappings, packet buffer and

bandwidth. For packet buffer and bandwidth virtualization, Prospero uses the ATM defined QoS principles. In addition, Prospero is responsible to map the control interface, exposed to controllers, with the underlying switch functionality.

Ariel Switch Independent Control Interface   Switchlets expose forwarding control through the Ariel Interface. Ariel Interface organises network control through five control objects: *Configuration*, *Port*, *Context*, *Connections Statistics* and *Alarms*. Configuration provides details for the switch configuration, Port provides primitive controllability of ports (e.g. state, loopback functionality), Context enables QoS policy control, Connections expose control of VPI/VCI mappings, Statistics exposes packet and byte counters and Alarms push state change notifications to the controller. Any Tempest switch runs an Ariel server and translates Ariel request to Prospero control requests.

Caliban Switch Management Interface   Apart from control capability support, Tempest also supported evolved network management, through the Caliban interface. The interface functionality is similar to the SNMP protocol. Caliban provides fine level SNMP-style information, but can also provide higher level aggregation operations over the switch state.

In addition to the redefinition of the network control abstraction, Tempest also proposed a relaxed network resource management scheme. Specifically, the architecture proposed a measurement-based admission control mechanism for circuit establishment Lewis et al. [1998]. The measurement scheme redefined the static resource allocation scheme in ATM network, and used effective bandwidth measurement techniques to estimate available resources. This admission control scheme provided higher utilisation of network resources, while providing QoS guaranteed.

Tempest defined a highly efficient network control abstraction. The effectiveness of the control abstraction motivates modern network control approaches, like SDN, to reimplement it over Ethernet devices. In addition, the simplicity of the control abstraction, permitted integration of the technology with existing forwarding devices and enabled line rate forwarding and efficient resource control. Nonetheless, its strong reliance on the ATM technology made the approach less relevant for the modern Ethernet-dominated networks Crosby et al. [2002].

2.3.3 SDN

A recent attempt to develop a framework for distributed and scalable control is the Software Defined Networking (SDN) paradigm. SDN Foundations [2012] enables the clean separation between the control and the forwarding plane of a network device. The control plane logic is implemented in a separate programmable device and a well defined protocol establishes the inter-connection between the two devices.

The SDN approach is inspired by relevant earlier attempts in network programmability(Active Networks and DCAN), but follows an evolutionary approach. SDN supports existing network data protocols and focuses to provide the mechanism to development custom forwarding mechanisms. The paradigm is motivated by two observations in current network technologies. Firstly, the evolution of computer networks has reduced the applicability of the multi-layer network abstraction. Production networks contain middleboxes (e.g. firewall, NAT, layer-5 switches) that operate on multiple layers of the network and engage extensively in layer violation. Such devices cannot integrate with existing control mechanisms, while they remain transparent by the end-hosts. The SDN paradigm aims to provide a new unifying cross-layer control model that can integrate control for such devices. Secondly, although network complexity has increased, network devices still use stand-alone configuration mechanisms (e.g. remote logic, CLI interfaces) and global network policies must be decomposed by network administrators in individual network device policies, to fit the existing control abstraction. In order to modify network-wide configuration, network administrators must login over telnet or use a web interface to configure each device manually. In addition, network vendors develop proprietary control protocols which reduce device interoperable. SDN enables management centralisation, while the flexibility of the control abstraction enables control innovation mechanisms that match network environment requirements.

The SDN paradigm was highly successful in the network community and within a few years since its introduction, network vendors engaged in the development of production-level implementations. In addition, the research community has developed a number of interesting SDN architectures which address several network problems. The OpenFlow protocol is currently the pre-dominant implementation of the SDN paradigm.
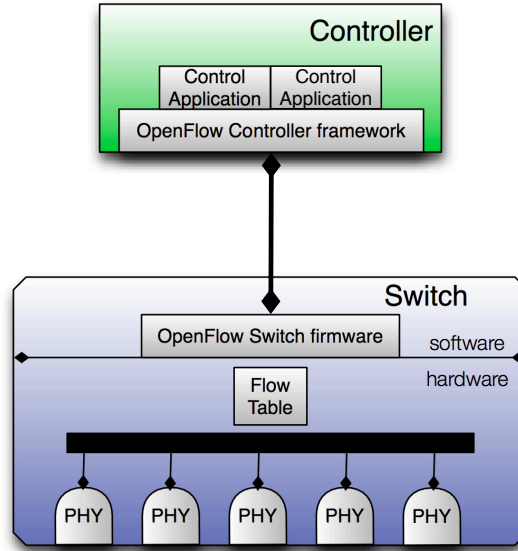
Figure 2.3: A schematic representation of a basic OpenFlow setup

OpenFlow protocol

OpenFlow is an instantiation of the SDN paradigm. The protocol was originally developed by the OpenFlow Consortium, a collaborative organisation of academic institutes, but soon its development was adopted by the ONF, a standards definition committee comprised of academic institutions and network vendors. OpenFlow has been a highly successful approach to network control. A number of vendors has introduced support of the protocol in their products while there are already OpenFlow deployments in enterprise networks Google [2013]; Kobayashi et al. [2012].

A representation of a simple OpenFlow topology is presented in Figure 2.3. A minimum OpenFlow topology consists of two entities: the *Controller* and the *Switch*. The Controller implements and disseminates the control logic of the network to the switches over a control channel. A controller can control multiple switches. In addition, the network community has developed a number of programming environments to develop OpenFlow control applications. Such programming environments provide a higher level abstraction over the OpenFlow protocol and reduce the exposure of the developer to the run-time details Berger [2012]; Gude et al. [2008b]; Switch [2013].

The switch entity is responsible to transform OpenFlow protocol operations in data

Field	OpenFlow Version
src & dst MAC addr.	1.0 [a]
input port	1.0
VLAN ID	1.0
VLAN PCP	1.0
MPLS label	1.1
MPLS class	1.1
IPv4 src/dst addr.	1.0
IPv4 proto	1.0
ARP opcode	1.0
ARP src/dst IPv4 address	1.0
ARP src/dst MAC address	1.2

Field	OpenFlow Version
IPv4 ToS	1.0
ICMPv4 Type & Code	1.0
TCP/UDP/SCTP src/dst port	1.0
metadata	1.1
IPv6 src/dst addr.	1.2
IPv6 flow label	1.2
ICMPv6 type & code	1.2
ICMPv6 Network Discovery target address	1.2
ICMPv6 Network Discovery src/dst MAC address	1.2

[a]SInce version 1.1 the protocol permits masked mac address matching

Table 2.1: OpenFlow tuple fields

path policy modifications. The OpenFlow functionality is split between the data and control layer of the switch. In the data layer, the protocol implements a simple packet processing algorithm. For each packet, the hardware extracts a number of fields and matches them against the entries of a *Flow Table*. The Flow Table is a memory abstraction which contains forwarding policy. It comprises of flow entries which conceptually consist of three parts: the flow tuple, the flow statistics and the flow action list. The flow tuple synthesizes a flow description using all the significant packet header fields. We present the list of fields in Table 2.1. The protocol associates with each flow tuple a flow mask, which permits field wildcarding in a flow definition. Flow statistics store flow packet and byte counters. The action list, contains the list of actions that should be applied on every matched packet. We present in Table 2.2 the packet processing actions defined by the OpenFlow protocol. On a packet reception, if a matching flow is found in the flow table, then the flow statistics are updated and the action list is applied on the packet. If there aren't any matching flow entries, the packet propagates as an exception to the control layer of the switch. The control plane of the switch implements the translation of the OpenFlow protocol into data path modifications. It

Field	operation	OpenFlow Version
OUTPUT	output packet to a port	1.0
SET_QUEUE	output packet to a port queue	1.0
SET_VLAN_VID	modify VLAN id	1.0
SET_VLAN_PCP	modify VLAN PCP	1.0
SET_DL_SRC SET_DL_DST	modify src/dst mac addr.	1.0
SET_NW_(SRC,DST)	modify IPv4 src/dst addr.	1.0
SET_NW_TOS	modify IPv4 ToS	1.0
SET_NW_ECN	modify IPv4 ECN bits	1.1
SET_TP_(SRC,DST)	modify TCP/UDP/SCTP src/dst port	1.0
COPY_TTL_(OUT,IN)	copy TTL value for IPv4 tunnels	1.1
SET_MPLS_LABEL	modify MPLS label	1.1
SET_MPLS_TC	modify MPLS traffic class	1.1
(SET,DEC)_MPLS_TTL	modify/decrement MPLS TTL	1.1
(PUSH,POP)_VLAN	Add/remove a VLAN header	1.1 [a]
(PUSH,POP)_MPLS	add/remove MPLS tag	1.1
(SET,DEC)_NW_TTL	modify/decrement IPv4 TTL value	1.1
(PUSH,POP)_PBB	remove/add a PBB service tag	1.3

[a]OpenFlow 1.0 defined a primitive to remove a VLAN header only

Table 2.2: OpenFlow available packet actions

provides access and modification functionality to the switch configuration and the flow table. The switch is able also to propagate autonomously information and exceptions to the controller.

The ensemble of a flow table and a set of switch ports comprises an OpenFlow *datapath* and is the core abstraction for network control. The protocol defines a number of protocol message types to manage datapath resources. OpenFlow control operations can be grouped in two categories: *Forwarding control* and *Switch configuration*. In the rest of the section we present how this functionality is addressed by OpenFlow messages and how this mechanism is evolved over the different versions of the protocol. We focus our protocol presentation over the 1.0 version of the protocol. ONF has releases three revisions of the protocol, version 1.1, 1.2 and 1.3, which change significantly the protocol specification. Nonetheless, the majority of production systems are predominantly version 1.0 compliant.

Forwarding control   OpenFlow provides fundamentally two modes of control: *reactive* and *proactive* control. In the reactive approach, the switch is configured to forward every unmatched packet to the controller, and the controller is responsible to respond with appropriate modification in the flow table. The protocol defines the `pkt_in` message type, that can propagate the header of a packet to the controller, and the `flow_mod` message type, that can manipulate flow table entries. The reactive control approach provides fine control over the traffic dynamics, but, depending on the deployment environment, can introduce significant load on the control plane. In the proactive approach, the controller is responsible to pre-install all required flows in the flow table and avoid any packet handling exceptions. Because this approach lucks data plane feedback, the OpenFlow protocol provides the `stats_req/stats_resp` and `aggr_stats_req/aggr_stats_resp` message types. These message types allow the controller to poll dynamically for flow statistics and infer network resource allocation. In order to ensure atomicity in the protocol, the protocol also define a `barrier_req/barrier_reply` message type, which provides a synch point between the controller and the switch. A `barrier_reply` is send by a switch as a response to a `barrier_req` from the controller, only if all previous operations are processed. Finally, the OpenFlow protocol provides two additional message types to increase users ability to interact with the forwarding plane: the `pkt_out` and the

`flow_removed`. The `pkt_out` message enables the controller to inject traffic in the data plane and the `flow_removed` message can notify the controller when a flow entry is removed from the flow table. The protocol defines flow timers and the switch can remove a flow with an expired timer.

Switch configuration   Apart from the control of the flow table, the OpenFlow protocol provides switch configuration capabilities. A controller can use the `switch_config_req/switc` message types, to discover switch OpenFlow operation support. In addition, the protocol provides capabilities to control port state with the `port_mod` message type. The switch is also able to notify the controller when a port changes its state (e.g. link is detected to be inactive in the physical layer) with the `port_status` message. In the recent revisions of the protocol, the steering committee has introduced the capability to control per port traffic shaping queues.

Protocol evolution   Since the specification of the version 1.0 of the protocol, the OpenFlow steering committee has produced 3 non-backward compatible revisions of the protocol. The updates in the protocol are motivated both by the osmosis between the hardware and software OpenFlow community, as well as, by the introduction of new deployment use cases.

Version 1.1 of the protocol introduces a number of modification in the main protocol pipelne in order to improve the integration of the protocol with the silicon functionality. Firstly, the default packet processing algorithm is differentiated. A switch can accommodate multiple flow tables and the lookup process searches sequentially each of the tables for flow matches. The packet must have a match in each of the tables otherwise a `pkt_in` message is generated. In addition, in order to persist partial results between tables, the protocol define a 64-bit metadata field and the action list is augmented with operations over the metadata field, as well as, over the table search process (e.g. terminate lookup, skip table). Secondly, the protocol introduces a primitive to express multipath support in the protocol. This functionality is exposed through a group table abstraction. Group table entries contain a set of buckets containing flow actions and an assigned output port. A controller in the action of a flow can forward packet to a group entry. The goup selection action can select to forward the packet either to all the buckets of the entry (ALL) or select randomly a bucket, in a manner

Language	controller
Python	NOX Gude et al. [2008b], POX Pox [2012], Pyretic Monsanto et al. [2013]
C++	NOX Gude et al. [2008b]
JAVA	Maestro Cai et al. [2011], Floodlight Switch [2013]
Haskell	Nettle Voellmy et al. [2010]
C	Mul Saikia [2013]
Javascript	Nodeflow Berger [2012]
Ruby	Trema Trema [2011]

Table 2.3: List of OpenFlow controller organised by programming language

similar to the Equal Cost Multiple Path routing (ECMP) Hopps [2000] functionality, (SELECT) or select a specific bucket (INDIRECT) or forward packet to the first group entry for which the output port can forward packet (FAST_FAILOVER). Thirdly, the protocol introduces MPLS matching support and manipulation.

Version 1.2 of the protocol extends data plane protocol support. This revision introduces support for IPv6 and Provider Bridge Network (PBB - Mac-in-Mac) traffic. In addition the protocol defines a new TLV format for flow Match definition, in order to relax the OpenFlow tuple definition. Finally, the protocol defines a model to enable multi-controller connectivity for switches. Multi-Controller schemes provides resilience to the control of the network.

In Version 1.3 the protocol definition introduces protocol support of QoS control. The protocol defines a new table abstraction, the metering table, which contains queue definitions. In addition, this protocol definition introduces the idea of multiple parallel control channels towards the same controller, in order to parallelize `pkt_in` transmission, and defines a mechanism to support message fragmentation.

Because the recent versions of the protocol has become complex, the vision of future OpenFlow deployment, is to differentiate switch abstraction and develop diverse product ranges that will provide optimized support for a subset of the protocol.

2.4 SDN applications

The introduction of the SDN paradigm proved to be extremely successful not only in the research community, but also in the network industry. Already a number of vendors provide production-level hardware support for SDN (Table 2.4, and the SDN

Vendor	Model	OpenFlow version
HP	8200zl, 6600, 6200zl, 5400zl, and 3500/3500yl	v1.0
Brocade	NetIron CES 2000 Series	v1.0
IBM	RackSwitch G8264	v1.0
NEC	PF5240, PF5820	v1.0
Pronto	3290, 3780	v1.0
Juniper	Junos MX-Series	v1.0
Pica8	P-3290, P-3295, P-3780 and P-3920	v1.2

Table 2.4: List of hardware switches with OpenFlow support

community provides OpenFlow support for most programming languages 2.3. In order to exhibit the class of problems which can be tackled by appropriate design of the control plane, in this section we present applications of the SDN paradigm in different network problems.

2.4.1 Network Virtualisation

The introduction of OS virtualization and the subsequent rise of the cloud computing paradigm has created new opportunities for computer science to reduce infrastructure costs and create new highly resilient system architectures. Although platforms like Xen provide strong guarantees on resource allocation and performance isolation on the OS level, there is still a significant gap in network virtualisation. The introduction of the SDN paradigm provides novel capabilities to the research community to develop new network abstractions and expose direct network control to tenants, while assuring the correct functionality of the network.

The first attempt to enable network virtualisation in the data center was through the FlowVisor project Sherwood et al. [2010a]. FlowVisor function as a OpenFlow proxy and sits between the OpenFlow switches and the OpenFlow controller. By appropriate message processing, a network topology discovery mechanism and a resource management policy, FlowVisor aggregate control over a set of switches and exposes a single virtual switch abstraction. The administrator can partition the OpenFlow tuple and delegate network control to different controllers, thus allowing data center tenants to control traffic for their own subnet and VM group. FlowVisor is currently adopted by BigSwitch and developed as a product. In Corin et al. [2012] the authors develop an ex-

tension for the FlowVisor platform, which enables topology virtualisation capabilities. In Drutskoy et al. [2013] the authors present FLowN, a network virtualisation mechanism which provides full control of OpenFlow tupple to all tenants and multiplexes user traffic using VLAN tags. FlowN, in addition, removes the latency incurred by control proxy by encapsulating the control transformation process in the programming library. Furthermore, state synchronisation is implemented through an SQL database, which is used by the programming library to transform OpenFlow messages. Finally, Nicira has develop Nicira Network Virtualization Platform (NVP), which claims to provide full network virtualisation and control isolation. Nonethless, the product is proprietary and implementation details remain undisclosed.

2.4.2 Security and Access Control

As we have discussed in the introduction of this thesis, network security has become a significant requirement for modern network operability. In order to improve network security, we require novel control plane architectures which are inherently secure. SDN provides a mechanism to enable fast prototyping of secure network architectures, while the high programmability of the controller allows traffic-inspecting security application integration with the control logic of the network. In an early attempt to define the SDN abstraction, researchers in Stanford developed the Ethane system Casado et al. [2007]. Ethane defines a simple policy expression language which uses as first-class object user identities and network services, and defines the interconnection ability between the two. SDN provides also the means to develop lossless, highly performant and programmable network trace collection mechanisms. In Ballard et al. [2010], the authors present OpenSAFE, a policy expression language which allows a network manager to define policies to intercept and inspect network traffic, enabling a highly flexible and dynamic network monitoring applications. Finally, in Porras et al. [2012], the authors present FortNOX, a mechanism which enables secure interaction between the control applications of a network. FortNOX enables users to assign priorities and roles to controlling applications and implements a simple resolution mechanism when two applications introduce contradicting network policies.

2.4.3 Load Balancing

The introduction of network services with global audience has created a requirement for IP indirection mechanisms, to distribute network load between servers in server farms and cloud computing infrastructures. A common approach to address this problem is through proprietary load balancing devices that function on the gateway of the server farm and distribute dynamically user request between servers. The introduction of the SDN abstraction integrates this indirection functionality in the network fabric. In Wang et al. [2011], the authors present a framework for in-network load balancing functionality. The system preinstall wildcard rules to forward new flows to a specific server. As the server load changes, the control dynamically modifies the wildcard coverage and redirects new flows to less utilised servers. In Handigol et al. [2009b, 2010], the author present a reactive approach to the problem. In the Plug-and-Serve architecture, the controller is responsible to handle each new connection and forward traffic to a specific server, based on the allocation algorithm and the current load of the system.

2.4.4 Inter-domain and Intra-domain Routing

In the context of network control, the SDN paradigm has also been proposed in order to improve the performance of existing control plane protocols. In Rothenberg et al. [2012], the authors present an integration of the Quagga Quagga routing framework with the OpenFlow protocol, in an effort to revisit the Route Reflector idea in BGP routing Bates et al. [2006]. Furthermore, In an effort to reduce the impact of routing instabilities of the BGP protocol, the authors in Kotronis et al. [2012] propose a mechanism to offload BGP routing to third party entities and use the OpenFlow abstraction to propagate resulting FIBs to the outsourced-network devices.

The programmable nature of the SDN paradigm and its ability to centralise network control has also motivated explorations on network state compression. In Sarrar et al. [2012], the authors present a library which exposes a FIB abstraction over the Open-Flow abstraction to routing applications. The library at run-time analyses the resulting FIB, as well as, the traffic pattern and calculates an minimum set of flow entries which can server a specific subset of the traffici on the fast-path of the network. In a similar effort, authors in Yu et al. [2010a] present DIFANE, a routing mechanism which uses valiant inter-routing, in an effort to compress the average FIB table size within the net-

work. The proposed mechanism uses the OpenFlow abstraction in order to partition effectively the network and disseminate forwarding state across the network devices.

2.4.5 Network Management

One of the core goals of the SDN paradigm is to provide the development environment for innovative management mechanisms which ease the network control task. One of the first application of the SDN paradigm was introduced by Koponen et al. [2010] within the context of the Onix control platform. Onix provides a centralised control abstraction to network developers, over which they can program their network control logic. The abstraction encapsulates a control state distribution mechanism which enables seamless distributed execution of code.

In a similar effort a number of novel programming languages has be proposed to formalise the control plane requirements. In Foster et al. [2011] the authors present the Frenetic programming language, a declarative language to define network control policy. The language encapsulates in the programming model significant network control programming requirements, like race conditions abstraction mechanisms. Furthermore, in Monsanto et al. [2012] the authors describe NetCore, a novel policy expression language which enables users to express their control logic. At run-time the policy adapts to the network traffic and topology in an effort to optimizes the installed state within the network. The NetCore abstraction is further enhanced with the ability to provide verifiable control policies in the network, as presented in Guha et al. [2013]. In addition, in Monsanto et al. [2013] the authors define a framework build on top of the NetCore language which enables seamless integration of the control logic between different control applications and reduces the complexity to integrate individual control applications in the network. Such control abstraction have also been discuss in the context of network control logic updates. In Reitblatt et al. [2012], the authors present a verifiable mechanism to upgrade the network control logic without any network disruption. Finally, in Voellmy et al. [2012], the authors present a novel declarative policy language which builds on top of the reactive functional programming model and provides a highly flexible architecture to develop novel control management systems.

2.4.6 Energy

In the recent years energy consumption has become an important measure of efficiency for a system architecture. Currently the network is estimated to contribute approximately 20% of the total power consumption of a data-center. Unlike CPUs which can reduce power consumption when idle, network cards exhibit a constant high power consumption, due to the constant requirement for medium sensing and physical layer frame synchronisation. As a result the most efficient mechanism to reduce network power consumption is to shutdown interfaces. In Heller et al. [2010], the authors present a power-aware control plane architecture, build on top of the OpenFlow abstraction. The application takes advantage of link redundancy and turns off interfaces when network utilisation is low.

2.4.7 Network Debugging and Measurement

The SDN paradigm, as well as, the OpenFlow abstraction provide novel mechanisms to troubleshoot a network. In Wundsam et al. [2011], the authors present a mechanism to intercept and record traffic flows from a network. Recorded flows can be replayed within the network, in order to detect policy misconfigurations which create functionality problems. In a similar effort, in Handigol et al. [2012b] the authors present ndb, a control plane debugger which enables users to register data plane breakpoint conditions and receive rich control plane run-time informationi when this conditions are met. Finally, a number of applications have been proposed to enable control plane monitoring in order to detect potential networks misconfigurations. In Khurshid et al. [2012], the author present an OpenFlow proxy service which detect flow modifications which create forwarding policy inconsistencies. In Canini et al. [2012], the authors present a model checking mechanism which uses symbolic execution to detect flow modifications which create significant inconsistencies in the data plane forwarding. Debugging applications of the OpenFlow abstraction have been also proposed in the context of home networks. In Calvert et al. [2010], the authors proposed a network controller which enables precise network logging by the home router, in order to aid ISPs to troubleshoot connectivity problems.

2.4.8 Resource Control

The high reactivity of the SDN paradigm enables fine level resource control integrated with the control plane. Already a number of control designs applicable in the datacenter environment have been proposed by the research community. In Al-Fares et al. [2010] the authors present Hedera, a novel control architecture for datacenters which improves the network utilisation in comparison to the popoular ECMP Hopps [2000] network load balancing mechanism. The system uses the flow statistics mechanism provided by the OpenFlow abstraction and at run time discovers progressively network-limited flows which are rerouted over underutilised network paths. In a similar effort, the authors in Benson et al. [2011] present a network load distribution mechanism with a higher granularity on short-lived flows. Furthermore, in Even et al. [2012] the authors propose a network embedding mechanism which is able to define job assignments in a datacenter and provide strong guarantees on network resources.

Resource control has also been proposed in the context of home network. In Yiakoumis et al. [2011] the authors propose the deployment of network virtualisation in the home network to improve resource allocation on the edges, as well as, enable core infrastructure sharing between ISPs. In Yiakoumis et al. [2012] the authors evolve this idea and introduce a simple user interface which can translate user resource requirement into ISP wide network policies.

2.4.9 Mobility

The SDN paradigm has found excellent applicability in addressing the increased control plane requirement in mobile networks. In Huang et al. [2010] the authors present PhoneNet, an application development framework which provides the ability to applications to setup multicast groups in the network through the controller. In Yap et al. [2009, 2010] the authors present OpenRoads, a network control plane for wireless network which enables seamless Access Point (AP) hand-overs for devices, as well as, network virtualisation. Finally, the authors in Li et al. [2012] discuss SDN abstraction requirements for cellular networks.

2.4.10 Network Simulation

The capability of the SDN paradigm for fast network functionality prototyping provides a novel experimentation mechanism for network researchers. Currently a number of large-scale shared infrastructures are built and maintained by research organisation. The GENI testbed Global Environment for Network Innovations (GENI) [2013] in the US funded by the NSF and the Ofelia testbed Ofelia [2013] in the EU funded by the FP7 framework provide network and computing resource to run large-scale experiments for free. Furthermore, a number of OpenFlow-based frameworks has been developed for scalable network experimentation. In Erickson et al. [2011] the authors present Virtue, a large-scale emulation framework which uses the Xen virtualization platform and the OpenFlow protocol to enable user experimentation with network topologies and VM placements in a multi-tenant data center environment. In addition, the Mininet platform Handigol et al. [2012a]; Lantz et al. [2010] has been developed by researchers in Stanford to enable scalable experimentation with the OpenFlow protocol. Mininet uses the LXC LXC [2013] linux user-space virtualisation framework to run multiple virtual machine in a single host and experiment with network functionality. Mininet has been used in the Computer Science department in Stanford to aid the introduction of students with recent research efforts in computer networks McKeown et al. [2012].

2.5 Conclusions

In this Section we have provided an in-depth analysis of network control mechanisms. We motivate our discussion in network control by presenting a generic architectural model for network devices and focus on the inherent limitations for network control. Furthermore, we present the current control plane mechanisms in production networks and, motivated by the limitations of these mechanisms, we present three control mechanisms, proposed by the research community, which aim to improve the respective limitations. Finally, we provide an extensive presentation of recent efforts to improve modern network functionality through control plane redesign. In the next chapter we present an extensive study on the scalability of the SDN paradigm.

Chapter 3

SDN Control Plane Scalability

In this thesis we develop mechanisms to scale computer network functionality, by re-designing the control plane. In our exploration we employ extensively he SDN design paradigm and the OpenFlow protocol abstraction. We chose the SDN design approach due to two core functional properties. On one hand, the clean separation of the control and the forwarding plane in a network is inherently backwards compatibility with existing network applications and interoperable with existing network devices. The evolution of the control plane of a network doesn't affect forwarding plane protocol support, while SDN supports progressive deployment in production networks without any forwarding performance penalty. Secondly, the OpenFlow control abstraction is sufficiently generic to support a diverse set of control approaches. The protocol supports reactive and proactive control schemes, while the flow definition granularity is dynamically controlled to match the application requirements. In the following chapters of this thesis we employ the OpenFlow protocol to address two diverse network scalability problems.

In this chapter we present an extensive performance analysis of the control scalability of available SDN technologies. Our exploration aims to provide an in-depth presentation of the limitations of existing implementation efforts and understand their impact in forwarding plane performance, as well as, provide a set of tools which enable SDN developers to study the performance of their network designs. The work focuses on implementations of version 1.0 of the OpenFlow protocol, the only production-level protocol instantiation of the SDN paradigm. We conduct our analysis using two measurement platforms: OFLOPS and SDNSIM. OFLOPS is a high precision

OpenFlow switch micro-benchmark platform. Using OFLOPS, we implement a set of benchmark tests to characterise the performance of elementary OpenFlow protocol interactions. SDNSIM is a macro-benchmark OpenFlow platform, which extends the Mirage framework Madhavapeddy et al. [2013] to support large scale OpenFlow-based network simulations and emulations. Using SDNSIM, developers are able to import OFLOPS switch profiles in their experiment and test the performance of their SDN design.

In this Chapter, we present the motivations (Section 3.1) and the design overview of the OFLOPS platform (Section 3.2). We select a number of off-the-self OpenFlow switches (Section 3.3) and run against them a number of measurement experiments, in order to assess the elementary protocol interaction performance (Section 3.4). Furthermore, we present the SDNSIM platform (Section 3.5) and its design approach (Section 3.7). Finally, we assess the performance of the SDNSIM implementation along with a measurement study of control scalability over the fat-tree topology (Section 3.8) and conclude (Section **??**).

3.1 Network Control Micro-Benchmark

Despite the recent introduction of the SDN paradigm, the research community has already proposed a wide range of novel control architectures Handigol et al. [2009a]; Sherwood et al. [2010b]; Yu et al. [2010b]. These architectures address significant problem of modern networking, but their deployment in production environments is not straightforward. Computer network have become a vital asset for modern enterprises, and high availability and performance are critical. Modifying established network control mechanisms must ensure these requirements and requires extensive testing and performance characterisation. An example of an early OpenFlow-based SDN deployment that faced significant problems in a production environment is reported in Weissmann and Seetharaman [2011]. The authors describe their experience in deploying the first OpenFlow production network in the Computer Science department in Stanford University. In their article, they point out that the initial deployment exhibited significant performance and reliability problems. The deployed hardware switching platform couldn't support OpenFlow message processing at high rates. For example, in the morning a significant number of users would plug simultaneously their

computers to the network, creating a large burst of new network flows. Because the reactive control approach they employed requires the generation of a `pkt_in` message for each new connection, the switch control CPU processing capacity couldn't cope with the high utilisation and either a number of flows would be dropped or the control channel would become unresponsive. In the SDN application development toolchain, there is a lack of an established and global mechanism to assess OpenFlow mplementation scalability. For traditional switch devices, the network community employs as performance metrics, the switch fabric non-blocking processing capacity and latency and MAC table size. In contrast, the control decoupling of the SDN paradigm expands the ways that the controller interacts with a switch device, while these interactions become a significant requirement for the functionality of the switch. As a result, the performance characterisation of SDN forwarding devices becomes non-trivial.

In order to fulfil the requirement for OpenFlow switch performance evaluation, we developed OFLOPS [1], a measurement framework enabling rapid development of performance tests for hardware and software OpenFlow switch implementations. To better understand the behaviour of the tested OpenFlow implementations, OFLOPS combines measurements from the OpenFlow control channel with data-plane measurements. To ensure sub-millisecond-level accuracy of the measurements, we bundle the OFLOPS software with specialized hardware in the form of the NetFPGA platform[2]. Note that if the tests do not require millisecond-level accuracy, commodity hardware can be used instead of the NetFPGA Arlos and Fiedler [2007].

3.2   OFLOPS Design

Measuring OpenFlow switch implementations is a challenging task in terms of characterization accuracy, noise suppression and precision. Performance characterization is not trivial as most OpenFlow-enabled devices provide rich functionality but do not disclose implementation details. In order to understand the performance impact of an experiment, multiple input measurement channels must be monitored concurrently, such as, data and control channels. Further, current controller frameworks, like Gude et al.

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

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

(a) NetFPGA packet   (b) Kernel-space   (c) User-space
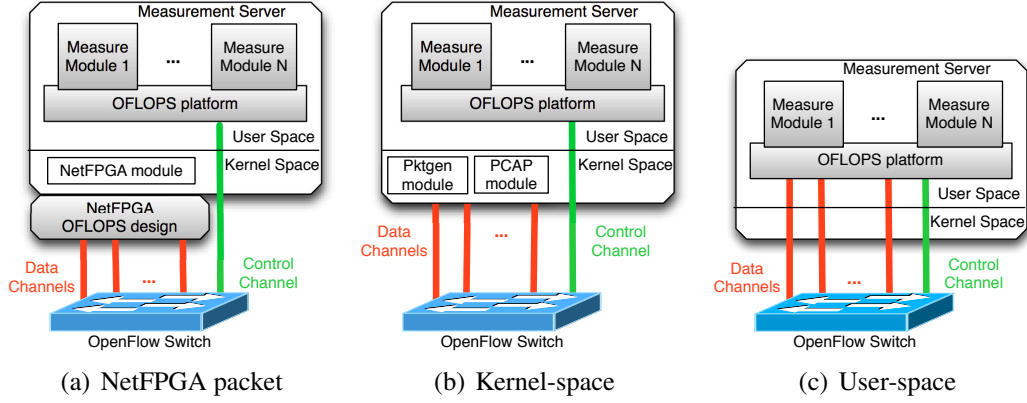
Figure 3.1: OFLOPS measurement setup. The framework provides integration with: 1) a high accuracy NetFPGA packet generator hardware design (Figure 3.1(a)), 2) kernel space pktgen traffic generation module and PCAP packet capturing module 3.1(b), 3) User space packet capture and generation threads (Figure 3.1(c)

[2008a]; Switch [2013], target production networks and incur significant measurement noise. Such controllers employ asynchronous processing libraries and multi-thread execution models, to maximize the aggregate control channel processing throughput, and provide high-level programing interfaces, that require multiple data structure allocation and modification during packet processing. The processing time of a specific OpenFlow message, especially at high rates, is subject to multiple aspects, like the thread scheduling policy and the asynchronous library execution logic Jarschel et al. [2012]. Measurement noise suppression in the control plane requires from the controller framework to minimize message processing and delegate processing control to the measurement module. Finally, sub-millisecond precision in software is subject to unobserved parameters, like OS scheduling and clock drift. The result of these challenges is that meaningful, controlled, repeatable performance tests are non-trivial in an OpenFlow environment.

The OFLOPS design philosophy aims to develop a low overhead abstraction layer that allows interaction with an OpenFlow-enabled device over multiple data channels. The platform provides a unified system that allows developers to control and receive information from multiple control sources: data and control channels as well as SNMP to provide specific switch-state information. For the development of measurement experiments over OFLOPS, the platform provides an event-driven, API that allows de-

velopers 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 3.2. Details of the OFLOPS programming model can be found in the API manual OFLOPS [2011].

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

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

2. Data Packet Capture: data plane traffic interception.

3. Control Channel: controller events dispatcher.

4. SNMP Channel: SNMP event dispatcher.

5. Time Manager: time events dispatcher.

OFLOPS provides the ability to control concurrently multiple data channels to the switch. Using a tight coupling of the data and control channels, programers can understand the impact of the measurement scenario on the forwarding plane. To enable our platform to run on multiple heterogeneous platforms, we have integrated support for multiple packet generation and capturing mechanisms. For the packet generation functionality, OFLOPS supports three mechanisms: user-space (Figure 3.1(c)), kernel-space through the pktgen kernel module module Olsson [2005b] (Figure 3.1(b)), and hardware-accelerated through an extension of the design of the NetFPGA Stanford Packet Generator Covington et al. [2009] (Figure 3.1(a)). 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.

In order to assess the accuracy of the traffic capturing mechanism, we use the topology depicted in Figure 3.2 to measure precision loss in comparison to a DAG card Endace [2012]. To calculate precision, 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
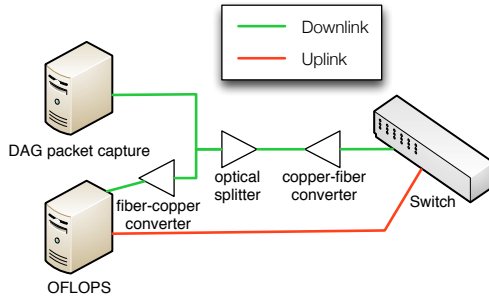
Figure 3.2: Measurement topology to evaluate capturing mechanism precision.
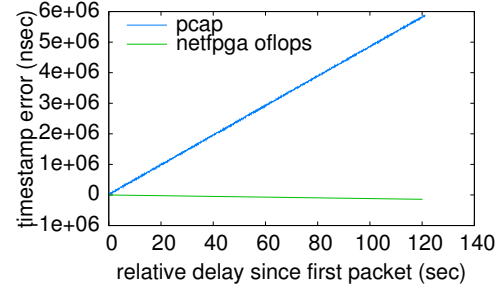
Figure 3.3: Evaluating timestamping precision using a DAG card. PCAP timestamps exhibit a significant drift in the order of microseconds, in comparison to the NetFPGA hardware design

Figure 3.3, we plot the differences of the relative timestamp between each OFLOPS timestamping mechanism and the DAG card for each packet. From the figure, we see that the PCAP timestamps drift by 6 milliseconds after 2 minutes. On the other hand, the NetFPGA timestamping mechanism has a smaller drift at the level of a few microseconds during the same period.

3.3 Measurement Setup

At the end of 2009, the OpenFlow protocol specification was released in its first stable version 1.0 OpenFlow Consortium [2009b], the first recommended version implemented by vendors for production systems. The switch performance analysis was contacted in collaboration with T-labs in Spring of 2011. During that period, the introduction of OpenFlow support in commodity switches was limited and only a small number of devices provided production-level support for the protocol. Using OFLOPS, we evaluated OpenFlow-enabled switches from three different switch vendors. Vendor 1 provided production-ready OpenFlow support, whereas vendors 2 and 3 during that period provided experimental OpenFlow support. The set of selected switches provided a representative but not exhaustive sample of available OpenFlow-enabled top-of-rack-style switching hardware, during that time. Details regarding the CPU and the size of the flow table of the switches are provided in Table 3.1. In addition the switching fabric in the vendor hardware specification reports similar non-blocking

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capacity and packet processing rates.

OpenFlow is not limited to hardware. The OpenFlow protocol reference is the software switch, Open vSwitch Pettit et al. [2010], an important implementation for production environments. Firstly, Open vSwitch provides a replacement for the poor-performing Linux bridge Bianco et al. [2010], a crucial functionality for virtualised operating systems. Currently, the Xen platform uses Open vSwitch to forward traffic between VMs in the Dum0, a configuration which is inherited by major Cloud providers, like Amazon and Rackspace. Secondly, several hardware switch vendors use Open vSwitch as the basis for the development of their own OpenFlow-enabled firmware. Open vSwitch development team has standardised a clean abstraction for the control of the packet forwarding elements (similar to linux HAL), which allows code reuse by any forwarding entity. Thus, the mature software implementation of the OpenFlow protocol is ported to commercial hardware, making certain implementation bugs less likely to (re)appear. We study Open vSwitch alongside our performance and scalability study of hardware switches. Finally, in our comparison we include the OpenFlow switch design for the NetFPGA platform Naous et al. [2008]. This implementation is based on the original OpenFlow reference implementation OpenFlow Consortium [2009a], extending it with a hardware forwarding design.

Switch	CPU	Flow table size
Switch1	PowerPC 500MHz	3072 mixed flows
Switch2	PowerPC 666MHz	1500 mixed flows
Switch3	PowerPC 828MHz	2048 mixed flows
Open vSwitch	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 OFLOPS on a dual-core 2.4GHz Xeon server equipped with a NetFPGA card. For all the experiments we utilize the NetFPGA-based packet generating and capturing mechanism. 1Gbps control and data channels are connected directly to the tested switches. We measure the processing delay incurred by the NetFPGA-based hardware design to be a near-constant 900 nsec.

3.4 Switch Evaluation

As for most networking standards, there are different ways to implement a given protocol based on a paper specification. OpenFlow is no different in this regard. The current OpenFlow reference implementation is Open vSwitch Pettit et al. [2010]. However, different software and hardware implementations may not implement all features defined in the Open vSwitch reference, or they may behave in an unexpected way. In order to understand the behaviour of switch OpenFlow implementation, we develop a suite of measurement experiments to benchmark the functionality of the elementary protocol interactions. These tests target (1) the OpenFlow packet processing actions (Section 3.4.1), (2) the packet interception and packet injection functionality of the protocol (section 3.4.2), (3) the update rate of the OpenFlow flow table along with its impact on the data plane, (Section 3.4.3) (4) the monitoring capabilities provided by OpenFlow (Section 3.4.4), and (5) the impact of interactions between different OpenFlow operations (Section 3.4.5).

3.4.1 Packet Modifications

The OpenFlow specification OpenFlow Consortium [2009b] defines 10 packet modification actions which can be applied on incoming packets. Available actions include modification of source and destination MAC and IP addresses, VLAN tag and PCP fields and TCP and UDP source and destination port numbers. The action list of a flow definition can contain any combination of them. The left column of Table 3.2 lists the packet fields that can be modified by an OpenFlow-enabled switch. These actions are used by network devices such as IP routers (e.g., rewriting of source and destination MAC addresses) and NAT (rewriting of IP addresses and ports). Existing network equipment is tailored to perform a subset of these operations, usually in hardware to sustain line rate.

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

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

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

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

processing delay is calculated as the difference between the transmission and receipt timestamps provided by the NetFPGA. We report in Table 3.2 the median processing delay for each action, along with its standard deviation, and the percent of lost packets of the measurement probe.

We observe significant differences in the performance of the hardware switches due in part to the way their firmware implements packet modifications. Switch1, with its production-grade implementation, handles all modifications in hardware; this explains its low packet processing delay between 3 and 4 microseconds. On the other hand, Switch2 and Switch3 each run experimental firmware that provided, at the time, 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 Open vSwitch software implementation lies between Switch1 and the other hardware switches. Open vSwitch fully implements all OpenFlow actions. However, hardware switches outperform Open vSwitch when the flow actions are supported in hardware.

We conducted a further series of experiments with variable numbers of packet modifications in the flow action list. 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 (e.g. Switch2 requires approximately 300 msec per packet to modify both IP source addresses and IP ToS field). Furthermore, we notice that for Switch1 and Open vSwitch there is a limit of 7 actions, which exposes limits enclosed in the implementation.

3.4.2 Traffic Interception and Injection

OpenFlow protocol permits a controller to intercept or inject traffic from the control plane. Packet interception is fundamental for reactive control applications, while packet injection enables control application interaction with network hosts. Nonetheless, the interception mechanism in OpenFlow has been characterised as a significant bottleneck for the control plane in early OpenFlow protocol deployments Kobayashi et al. [2012]. This is a direct consequence of the silicon design in current OpenFlow switches, that develop such functionality over a low-bandwidth exception-notification channel (Section 2.1). In order to characterise these functionalities, we design two simple experiments. For packet interception, we remove all entries from the switch flow table and send a measurement probe of small packets (100 bytes) on one of the data channels. We measure the delay between the time the packet was transmitted on the data channel and the time the controller received the equivalent `packet_in` message. For packet injection, we transmit `packet_out` messages over the control channel and measure the delay to receive the packet on a data channel. In Figure 3.4, we plot the median packet processing latency for `packet_in` and `packet_out` messages. We omit in this experiment Switch 3 as these functionalities incur high CPU utilisation and, after a few seconds of traffic, the control channel becomes unresponsive. For

(a) packet_in message latency

(b) packet_out message latency
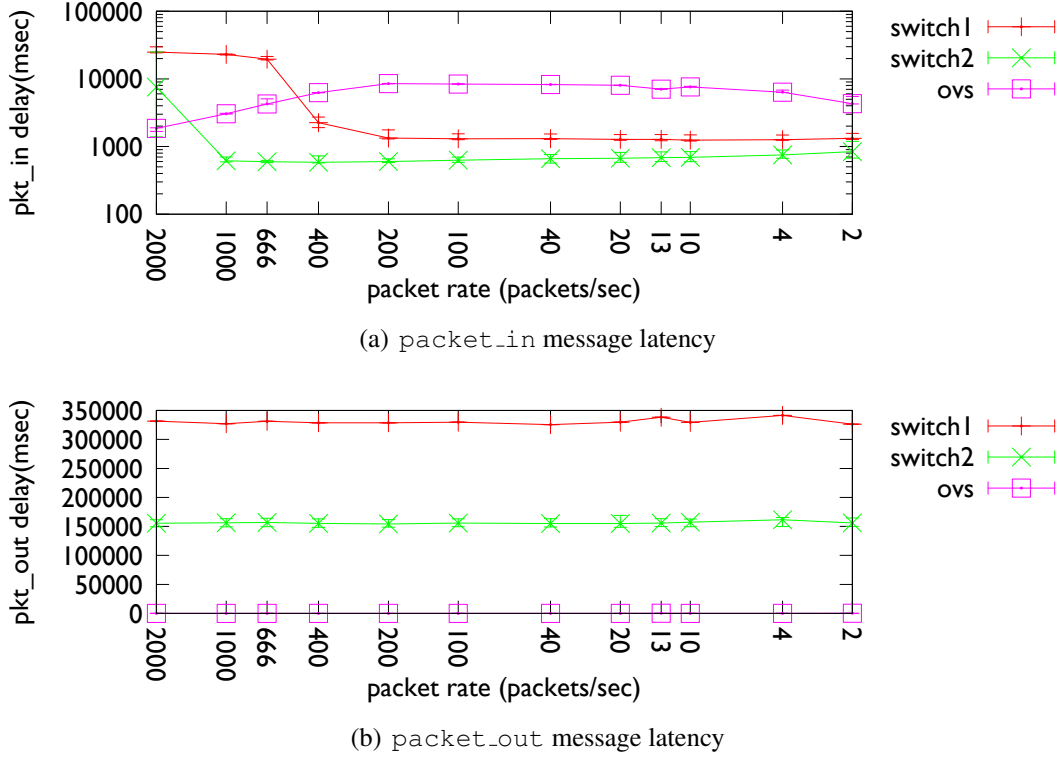
Figure 3.4: Latency to intercept and inject a packet using the OpenFlow protocol

packet_out messages, all implementations rate limit their transmission through the TCP advertised window of the control connection and as a result the latency is near constant. We observe that hardware switch exhibit high latency (150 msec for Switch2 and 350 msec for Switch1), in comparison to Open vSwitch (approximately 0.1 msec). For packet_in messages, we observe diverse behaviours between hardware switches at high packet rates. For Switch1, packet loss and latency becomes note-worthy beyond 400 packets/sec, while the switch can process up to 500 packets/sec. For Switch2 latency and packet loss are significantly lower and stable. Switch2 incurs high processing latency beyond 2000 packets/sec. Open vSwitch, has a high but stable latency for any tested data rates.

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3.4.3 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 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 OpenFlow Consortium [2009b], 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 Open-Flow 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 Open vSwitch and Switch1, Figure 3.5 shows the time to install a set of entries in the flow table. Switch2 and Switch3 are not reported as this OpenFlow message is not supported by the firmware. For this experiment, OFLOPS relies on a stream of packets of 100 bytes at a constant rate of 100 Kpackets/sec (10Mbps) that targets the newly installed flows in a round-robin manner. The probe achieves sufficiently low inter-packet periods in order to accurately measure the flow insertion time.

In Figure 3.5, we show three different times. The first, *barrier notification*, is derived by measuring the time between when the **first insertion command** is sent by the OFLOPS controller and the time the `barrier` notification is received by the PC. The second, *transmission delay*, is the time between the first and last flow insertion commands are sent out from the PC running OFLOPS. The third, *first packet*, is the time between the **first insertion command** is issued and a packet has been observed for the last of the (newly) inserted rules. For each configuration, we run the experiment 100 times and Figure 3.5 shows the median result as well as the 10th and 90th percentiles,
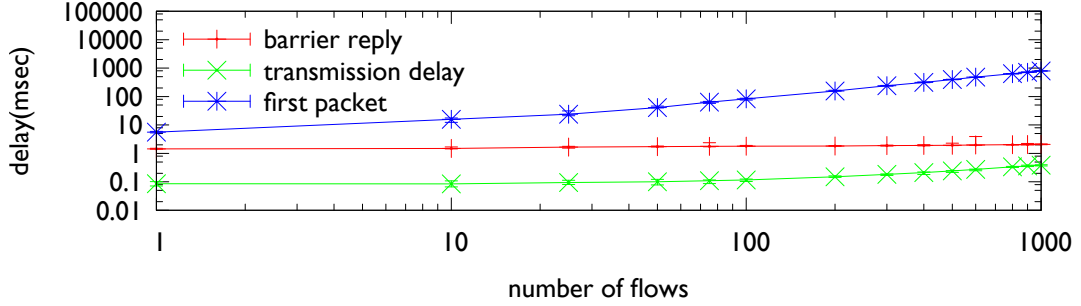
(a) Open vSwitch (log-log scale)
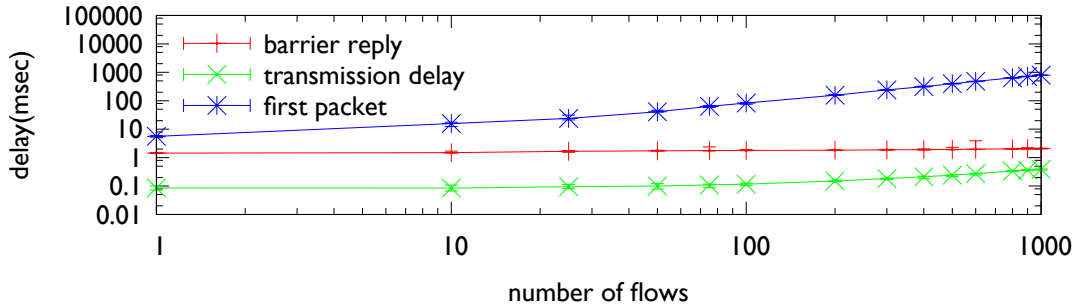
(b) Switch1 (log-log scale)

Figure 3.5: Flow entry insertion delay: as reported using the `barrier` notification and as observed at the data plane.

although the variations are small and cannot be easily viewed.

From Figure 3.5, we observe that even though the *transmission delay* for sending flow insertion commands increases with their number, this time is negligible when compared with data plane measurements (*first packet*). Notably, the *barrier notification* measurements are almost constant, increasing only as the transmission delay increases (difficult to discern on the log-log plot) and, critically, this operation returns before any *first packet* measurement. This implies that the way the *barrier notification* is implemented does not reflect the time when the hardware flow-table has been updated.

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

Flow insertion types
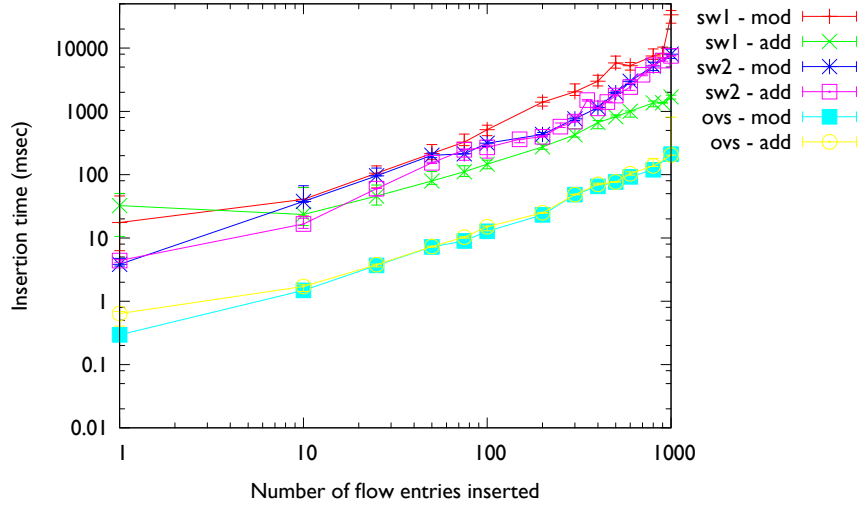
Figure 3.6: Delay of flow insertion and flow modification, as observed from the data plane (log-log scale).

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 3.6 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. In Gupta and McKeown [2001], the authors characterise the update complexity of a TCAM to be linear.

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 a TCAM. With such possible choices and range of different experiments, the flow insertion times reported in Figure 3.6 are not generalizable, but rather depend on the type of insertion entry and implementation.

3.4.4   Flow Monitoring

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

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

Figure 3.7(a) 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 is recorded for even a few queries per second being sent. Figure 3.7(b) reports the switch-CPU utilization as a function of the flow statistics inter-request time. Statistics are retrieved using SNMP. Switch3 is excluded for lack of SNMP support.

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

(a) Reply time.
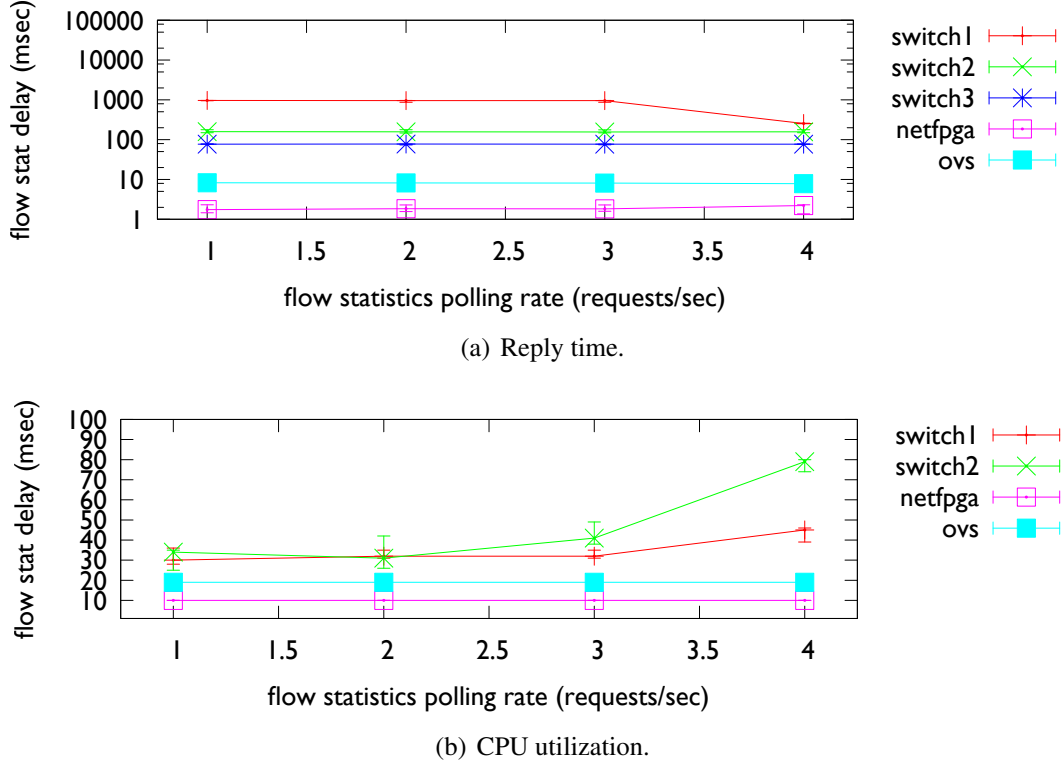
(b) CPU utilization.

Figure 3.7: Time to receive a flow statistic (median) and corresponding CPU utilization.

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).

3.4.5 OpenFlow Command Interaction

An advanced feature of the OpenFlow protocol is its ability to provide network control applications with, e.g., flow arrival notifications from the network, while simultane-
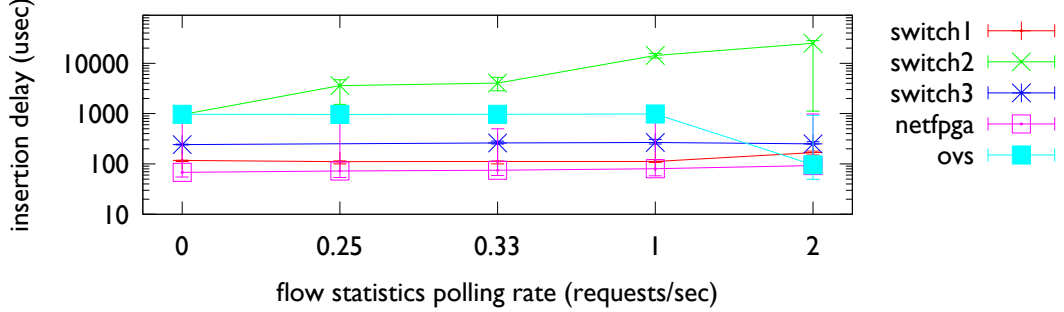
Figure 3.8: Delay when updating flow table while the controller polls for statistics.

ously providing fine-grain control of the forwarding process. This permits applications to adapt in real time to the requirements and load of the network Handigol et al. [2009a]; Yap et al. [2009]. Using OFLOPS advanced measurement instrumentation, we develop a test scenario of dynamic network control, in order to understand the behavior of the switch control and data plane. In this scenario, we emulate the simultaneous querying of traffic statistics and modification of the flow table. More specifically, we extend Section 3.4.3 by showing how the mechanisms of traffic statistics extraction and table manipulation 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 before the modified flows become active in the flow table. For each probing rate, we repeat the experiment 50 times, plotting the median, 10th and 90th percentile. In Figure 3.8 we can see that, for lower polling rates, implementations have a near-constant insertion delay comparable to the results of Section 3.4.3. For higher probing rates on the other hand, Switch1 and Switch3 do not differ much in their behavior. In contrast, Switch2 exhibits a noteworthy increase in the insertion delay. This is explained by the CPU utilization increase incurred by the flow statistics polling (Figure 3.7(b)). Finally, Open vSwitch exhibits a marginal decrease in the median insertion delay and at the same time an increase in its variance. We believe this behavior is caused by interactions with the OS scheduling mechanism:

the constant polling causes frequent interrupts for the user-space daemon of the switch, which leads to a batched handling of requests.

3.5 OpenFlow Macro-experimentation

OFLOPS, along with Cbench Cbench [2010], provides a sufficient toolchain to profile functionality of OpenFlow building blocks. Nonetheless, in order to understand the impact of scalable control in a computer network, we require mechanisms to transform OpenFlow building block performance profiles into network-wide performance measurements, under specific traffic patterns and network topology. A common practice to reason about performance and correctness of a network architecture relies on the design of experiments that reproduce specific network-wide functionalities. In the related literature on network experimentation there have been two main implementation approaches : *realistic-testbed* and *simulation*.

Realistic testbeds reproduce in full detail the properties of the deployment environment. They provide an optimal measurement environment with complete control over the parameter of the experiment and optimal time scalability. Nonetheless, realistic testbeds incur significant resource and configuration overhead, which scale sub-optimally with respect to the experiment size. For example, setting up a realistic testbed for datacenter network experimentation requires a significant number of machines and network devices, careful interconnection planning and targeted metrication and analysis of the resulting system. In an effort to improve resource scalability for realistic testbeds, the research community provides a number of shared testbeds. Shared testbeds employ techniques such as virtualization and statistical multiplexing to scale resource utilization in a multi-tenant experimentation platform Emulab [2000]; PlanetLab [2007]. However, shared testbeds are not always a good fit for network experiments. In such testing environments, there is limited resource control, while resource sharing may introduce measurement noise, which is not always detectable and removable.

In the simulation approach, researchers replace parts of the functionality of the system with simplified models Issariyakul [2012]; Varga and Hornig [2008]. Simulation reduces the complexity of large scale network experiments, and provides resource scalability. Nonetheless, the scaling property has inherent limitations. Firstly, the fidelity

Appliance	Binary size (MB)
DNS	0.184
Web Server	0.172
OpenFlow switch	0.164
OpenFlow controller	0.168

Table 3.3: Sizes of Mirage application images. Configuration and data are compiled directly into the image.

of the results depends greatly on the validity of the model assumptions. Secondly, in order to simulate network experiments, users usually need to readjust the logic of their experiments to fit with the abstraction of the underlying models. For example, POSIX socket-based applications must modify their connection abstraction to match the API of the simulation platform, while forwarding plane traffic patterns may have to transform into stochastic models.

SDNSIM[1] is a novel network experimentation framework, that bridges the two aforthmentioned approaches. The framework is written in OCaml, a high performance functional language, and extends the functionality of the Mirage [2] library OS. Developers can describe network functionality over the Mirage OS abstraction, and at compilation transform the experiment definition in a concrete experiment realisation. SDNSIM provides two experimentation options: *Simulation*, transforms the experiment definition into an ns-3 Henderson et al. [2006] simulation, and *Emulation*, translates the experiment definition in Xen-based emulation of the experiment.

3.6 Mirage Library OS

In SDNSIM we use the Mirage framework to provide an application development environment. Mirage is a a cloud-service development framework written predominantly in OCaml, where applications are single purpose appliances that are compile-time specialised into standalone kernels deployable on the Xen platform. We chose to use rhe Mirage framework due to two fundamental functional properties: low memory footprint and simplified integratability. Mirage revisits the idea of library OS; OS func-

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

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

tionality is separated into logical modules and added to an appliance only if the code expresses an explicit dependency. As a result, a Mirage application will integrate in a VM only the required OS functionality, resulting in compact OS images with minimized memory requirements. In Table 3.3, we present the compiled image size for a set of Mirage applications.

Furthermore, Mirage OS provides a simple development API for systems programming. This functionality is implemented by two core modules, named *Net* and *OS*. The OS module provides basic thread scheduling, device management and device IO functionality, while the Net module provide a network stack supporting ICMP, IP, TCP, UDP and DHCP protocols through a socket-like programming API. The interface of the core Mirage API is sufficiently generic to enable development of complex distributed services, while sufficiently simple to integrate Mirage functionality over a wide range of platforms. Specifically, a Mirage application can compile into a Xen image, a linux application and a nodeJS executable. Currently, the platform is also ported to the FreeBSD kernel space and the BareMetal OS Return Infinity [2013], a high performance assembly-code OS.

3.7 SDNSIM design

```xml
<?xml version="1.0" encoding="ISO-8859-1"?>
<topology module="Simple_tcp_test" backend="ns3-direct"
   duration="30">
 <modules>
  <library>lwt</library>
  <library>lwt.syntax</library>
  <library>cstruct</library>
  <library>cstruct.syntax</library>
  <library>mirage</library>
  <library>mirage-net</library>
  <library>pttcp</library>
 </modules>
 <node name="host1" main="host_inner">
  <param>1</param>
 </node>
 <node name="host2" main="host_inner">
```

```
  <param>2</param>
</node>
<link src="host1" dst="host2" delay="10" rate="100"
  queue_size="100" pcap="false"/>
<link_ext host="host1" dev="eth1" delay="10" rate="100"
  queue_size="100" pcap="false" ip="10.1.1.1">
</topology>
```

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

From the developer perspective, SDNSIM consists of a single executable that functions as an OCaml build system. Developers implement host functionality as Mirage applications, and use a single XML file to describe the network topology and assign functionality to network nodes. A sample XML file is presented in Listing 3.1. The configuration describes a simple client (host1) - server (host2) configuration. A minimum experiment definition must define the core code module (topology@module), the target executable (topology@backend) and the duration of the experiment (topology@duration). In order to define a host, SDNSIM uses a host XML entity. Each host entity must define a host name (node@name) and a host main function (node@main), while a number of named parameters (node/param) can be passed to the main function. The link XML entity defines a link between two hosts (link@src, link@dst) along with the device (link@queue_size, link@pcap) and propagation properties (link@rate, link@delay), using the link XML entity. Finally, links can also be used to integrate external network interfaces into the simulation, in order to allow the experiment to interact with applications outside of the experiment scope. We enable this functionality using the link_ext XML entity which is similar to the link entity, but instead of src and destination attributes, it uses the host and dev entities to define the host to which the entity will be attached. In addition, an ip attribute is used to define the address of the device.

The functionality of a node in the SDNSIM platform can be split in 3 layers. A simple representation of the architecture of an SDNSIM host is depicted in Figure 3.9. The top layer contains the application logic of the host. This layer is defined by the developer and encodes the traffic model and the network forwarding logic of the experiment. In order to allow realistic traffic patterns, SDNSIM reuses all the application

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Subsystem	Implemented Protocols
Network	Ethernet, ARP, DHCP, IPv4, ICMP, UDP, TCP, OpenFlow
Storage	Simple key-value, FAT-32, Append B-Tree, Memcache
Application	DNS, SSH, HTTP, XMPP, SMTP
Formats	JSON, XML, CSS, S-Expressions

Table 3.4: System facilities provided as Mirage libraries.

libraries supported by the Mirage platform, reported in Table 3.4. In addition, we modify the OpenFlow processing code and introduce a latency control mechanism. Using the rate control mechanism, SDNSIM can simulate and emulate switch and controller models, measured through the OFLOPS and Cbench tools. We also have implemented in OCaml the pttcp tcp test tool Pratt [2002] for model driven traffic generation.

The middle layer of the host architecture, contains the network and the OS libraries of the Mirage platform. This layer provides OS functionality to the application layer. Finally, the lower layer of the host architecture, provides integration of the Mirage OS with the execution environment of the experiment. Currently, SDNSIM supports two execution environments: the *ns-3* simulation platform and the *Xen* virtualisation platform. These two execution environments are highly heterogeneous and employ different execution models. In the rest of this section we present details on the integration of SDNSIM experiments with each execution environment. Since SDNSIM aims for high network accuracy, we focus our presentation on how integration occur on network functionality and time.

3.7.1 Xen backend

An SDNSIM emulation host uses a simple PV Boot mechanism. At startup SDNSIM initializes a VM with a single virtual CPU, loads the Xen event channel and jumps to the main function of the OS module which runs the thread scheduling loop. SDNSIM uses the OCaml Lwt language extension, an event-driven asynchronous programming library, to enable a multi-threading programming abstraction. Using the Lwt syntax, a developer can spawn new threads by annotating closures as blocking. An Lwt thread is either executing code or idles waiting for an IO event or a synchronisation primitive (e.g. a semaphore) or a timer timeout. Lwt threads are cooperative and non-

(a) ns-3   (b) Xen
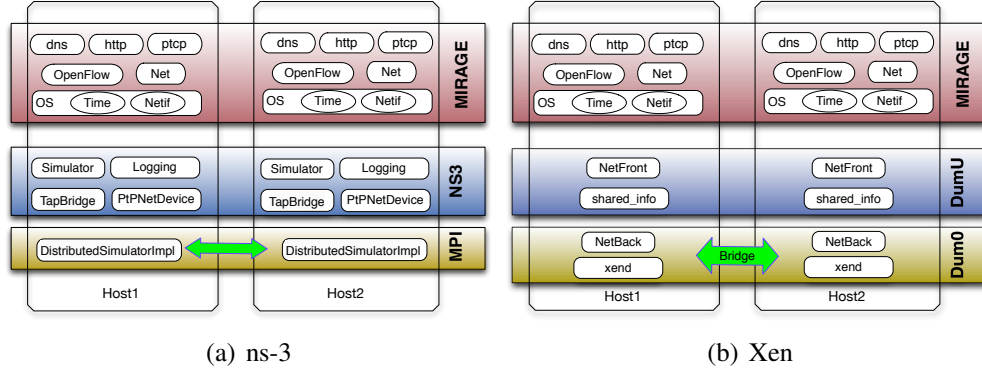
Figure 3.9: SDNSIM host internal architecture: ns-3 simulation 3.9(a) and xen real-time emulation 3.9(b).

preemptive and the main scheduling loop works as follow: Execute any resumable sleeping threads, calculate the time left until the next timer event and poll for events from the event channel until that time expires. Timing integration with the Xen platform is achieved through the Xen shared_info struct, a structure containing CPU time information which is shared between the Dum0 and the DumU VMs. Network integration is implemented using the Xen NetFront driver and the Xen event channel.

SDNSIM uses the Xen Managment API (XAPI) Xen Project to bootstrap emulations over the XEN platform. SDNSIM is able to create, start and stop VM instances and configure network topologies. Network topologies are implemented using VM Virtual Network Interface (VIF) bridging in the Dum0. A link between two hosts in an experiment definition is translate to a layer-2 bridge which contains a VIF from each VM. XAPI also expose an interface to control link rate and propagation delay for each VIF. In a Xen-based emulation of an SDNSIM experiment, the emulation setup pipeline works as follows: host definitions are compiled in VM images and equivalent VM definition are configured through XAPI, network topology description is translated into equivalent bridge setup and, once all configurations are completed, all VMs are booted.

3.7.2 ns-3 backend

ns-3 Henderson et al. [2006] is a discrete-time packet-driven network simulation framework. The core of the system consists of a discrete time simulation engine and a set

of ns-3 libraries providing network applications, routing protocols, data-link layer protocols and link emulations models. ns-3 is fundamentally an extensive refactor of the ns-2 code-base and provides a stable core of network functionality over which users can develop custom simulation scenarios.

The ns-3 backend has a significant difference from the Xen backend; the execution model is discrete and non-reentrant. ns-3 applications can only register their interest for specific time and network events, event handling is atomic and the progress of the simulation is centrally controlled by the simulation engine. In order to port the Lwt library to the ns-3 simulation engine, we transform thread blocking calls into equivalent ns-3 events. More specifically, the Mirage OS clock abstraction is bridged with the ns-3 simulation clock and all sleep calls are scheduled as ns-3 time events. A thread is resumed from a sleep call when the simulator executes the respective time event. Network blocking calls are integrated with the network device abstraction of ns-3. The packet reading thread registers a packet handler on the network device, while the packet writing thread checks the device queue occupancy and blocks while the queue is full. Finally, in order to avoid scheduling deadlocks, the OS schedules *idle* time events that resume any yielded threads. Using these transformations we are able to provide a semantically accurate Lwt integration with the ns-3 engine. Network links between hosts are simulated using the *PointToPoint* link model. This model simulates a PPP link over a lossless medium, a valid approximations for the full duplex non-shared medium of current network datacenters.

Finally, in order to increase the scalability of the SDNSIM simulation backend, we use a distributed version of the ns-3 simulation engine. The simulation engine spawns a different process for each host of the simulation and an MPI-based synchronisation algorithm establishes conservative clock synchronisation and distributed event execution Pelkey and Riley [2011].

3.8   SDNSIM evaluation

We evaluate performance and precision of the SDNSIM platform using small scale micro-benchmarks that target the performance of the OpenFlow protocol library, as well as, the scalability of the ns-3 backend. In Madhavapeddy et al. [2013], there is an exhaustive analysis of the performance of the Mirage platform, which we omit

from this section. In the rest of this section we compare the performance of our Mirage OpenFlow controller (Section 3.8.1) and Mirage OpenFlow switch (Section 3.8.2) with existing equivalent software packages and evaluate the scalability of the ns-3 backend (Section 3.8.3).

3.8.1 Mirage Controller Emulation

We benchmark our controller library's performance through a simple baseline comparison against two existing OpenFlow controllers, NOX and Maestro. NOX Gude et al. [2008b] is one of the first and most mature open-source OpenFlow controllers; in its original form it provides programmability through a set of C++ and Python modules. In our evaluation we compare against both the master branch and the *destiny-fast* branch, an optimised version that sacrifices Python integration for better performance. Maestro Cai et al. [2011] is a Java-based controller designed to provide service fairness between multiple OpenFlow control channels. We compare these controllers against our Xen-based Mirage OpenFlow controller application.

Our benchmark setup uses the *Cbench* Cbench [2010] measurement tool. Cbench emulates multiple switches which simultaneously generates `packet_in` messages. The program measures the processing throughput of each controller. It provides two modes of operation, both measured in terms of `packet_in` requests processed per second: *latency*, where only a single `packet_in` message is allowed in flight from each switch; and *throughput*, where each emulated switch maintains a full 64 kB buffer of outgoing messages. The first measures the throughput of the controller when serving connected switches fairly, while the second measures absolute throughput when servicing requests from switches.

We emulate 16 switches concurrently connected to the controller, each serving 100 distinct MAC addresses. We run our experiments on a 16-core AMD server running Debian Wheezy with 40 GB of RAM and each controller configured to use a single thread of execution. We restrict our analysis to the single-threaded case as the Mirage execution environment, at time of testing, does not support multi-threading. For each controller we run the experiment for 120 seconds and measure the per-second rate of successful interactions. Table 3.5 reports the average and standard deviation of requests serviced per second.

Controller	Throughput (kreq/sec)		Latency (kreq/sec)	
	avg	std. dev.	avg	std. dev.
NOX fast	122.6	44.8	27.4	1.4
NOX	13.6	1.2	26.9	5.6
Maestro	13.9	2.8	9.8	2.4
Mirage Xen	98.5	4.4	24.5	0.0

Table 3.5: OpenFlow controller performance.

Unsurprisingly, due to mature, highly optimised code, *N*OX fast shows the highest performance for both experiments. However, the controller exhibits extreme short-term unfairness in the throughput test. *N*OX provides greater fairness in the throughput test, at the cost of significantly reduced performance. Maestro performs as well as NOX for throughput but significantly worse for latency, probably due to the overheads of the Java VM. Finally, Mirage throughput is somewhat reduced from NOX fast but substantially better than both NOX and Maestro. In addition, the Mirage controller achieves the best product of performance and fairness among all tested controllers in the throughput test. Comparing latency, Mirage performs much better than Maestro but suffer somewhat in comparison to NOX. From the comparison results, we conclude that the Mirage controller performance is comparable to the performance of existing controlling platforms and our emulation environment can reproduce the performance of realistic OpenFlow deployment.

3.8.2 Mirage Switch

We benchmark our Mirage OpenFlow switch implementation through a baseline comparison with the Open vSwitch (OVS) Pettit et al. [2010] kernel implementation. We develop, using the OFLOPS framework, a simple forwarding test and measure the switching latency incurred by each implementation. For this experiment we use two virtual machines, one running the OFLOPS code, the other running the OpenFlow switch configured with three interfaces bridged separately in dom0. One interface provides a control channel for the switch, while the other two are used as the switch's data channels. Using OFLOPS, we generate packets on one of the data channels and receive traffic on the other, having bootstrapped appropriate the switch flow table. We run the
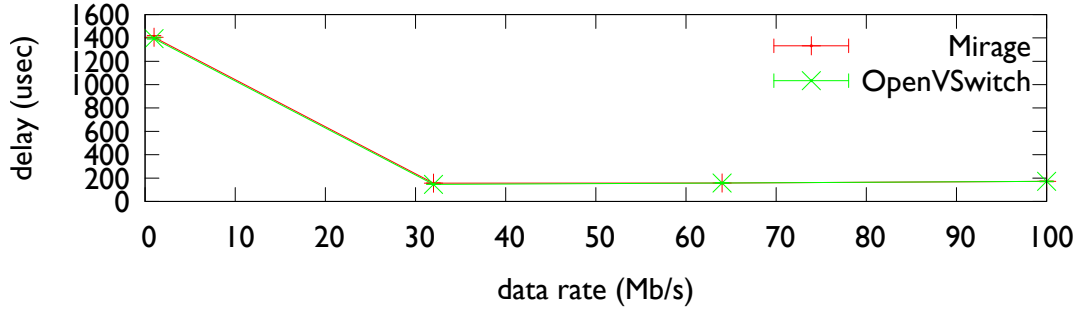
Figure 3.10: Min/max/median delay switching 100 byte packets when running the Mirage switch and Open vSwitch kernel module as domU virtual machines.

test for 30 seconds, a sufficient measurement period to detect statistically significant results. We use small packets (100 bytes)[1] and vary the data rate.

Figure 3.10 plots as error boxes the min, median and max of the median processing latency of ten test runs of the experiment. We can see that the Mirage switch's forwarding performance is very close to that of the Open vSwitch, even mirroring the high per-packet processing latency with a probe rate of 1 Mb/s; we believe this is due to a performance artefact of the underlying dom0 network stack. We omit packet loss, but can report that both implementations suffer similar levels of packet loss. From the comparison results of the Mirage OpenFlow switch, we can conclude, that our OpenFlow switch can emulate accurately software switch functionality. Nonetheless, the minimum latency of our switch emulation (approximately 100 msec) is 2 order of magnitude higher than a hardware switch (approximately 0.5-1 μsec). In order to bridge this latency gap, we propose the introduction of a slowdown factor in the emulation. A slowdown factor of ten will reduce by ten times the time reported by the clock abstraction of the Mirage platform and by ten the link rate allocated to each VIF. As a result, the slowdown factor can provide a semantically correct slowdown to the time of the experiment and use more efficiently the computational resources of the server.

(a) centralised topology   (b) distributed topology
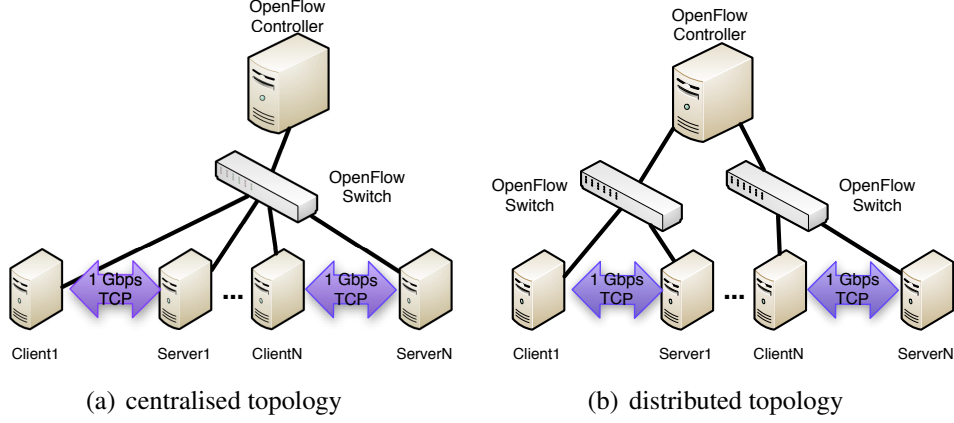
Figure 3.11: Network topology to test the scalability of ns-3-based simulation. We simulate two topologies: a centralised topology (Figure 3.11(a)) and a distributed topology (Figure 3.11(b))

	Centralised topology			Distributed topology		
Number of hosts	4	8	12	4	8	12
Wall-clock delay (in min)	13	35	75	8	25	42
Slowdown factor	26	70	150	16	50	84

Table 3.6: Wall-clock delay to run a 30 seconds simulation time of the topology presented in Figure 3.11, for variable number of network hosts. SDNSIM simulation of a network experiment using the ns-3 backend scales linearly as the traffic is localised.

3.8.3 ns-3 performance

In order to test the scalability of SDNSIM simulation we implement a simple network experiment, depicted in Figure 3.11. The topology consists of a number of switches and host pairs, connected through 1 Gbps links. Each pair of hosts generates steady state TCP traffic at line rate. We use two variations of the topology: A *centralised topology* with all the pairs of hosts connected to a single switch (Figure 3.11(a)), and a *distributed topology*, with pairs of hosts distributed between two switches and traffic remaining local to the switch (Figure 3.11(b)). Each switch is connected to an OpenFlow controller that implements a learning switch. The experiment executes 30

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[1] we use a packet size slightly larger that the minimum packet size because we append in the payload packet generation information (e.g. packet ID, packet generation timestamps).

Parameter	value
packet_in processing delay	10 msec
flow_mod insertion delay	1,2 msec
link capacity	1 Gbps
Request arrival rate	1500 retrievals/sec
link propagation delay	0.5 μsec
switch processing delay	100 μsec

Table 3.7: control hierarchy simulation parameters

seconds of simulation time on a 24-core AMD server with 128 GB of RAM.

In Table 3.6, we present the wall-clock execution time and the slowdown factor of each simulation. From the results we note that the real time to execute a simulation in SDNSIM depends on the number of network events; as we increase the number of host and, consequently, the number of packets, the execution time increases. Additional, from the comparison between the centralised and distributed topology, we note that the performance of the simulation improves when network events are localized, as the simulation can be parallelized. In the distributed topology, network events are distributed between the two switch and they execute independently, achieving near-linear scaling. These scaling properties of the SDNSIM simulation implementation provide a scalable experimentation framework for datacenter traffic models and designs Kandula et al. [2009].

3.9 hierarchical control distribution in Software-defined network

The OpenFlow abstraction provides an excellent mechanism to centralise control in a network and avoid the performance overhead of existing distributed control plane protocols. Using OpenFlow, allows to offload the control plane of all switches of a network to a single centralised network controller which has full knowledge of the network state and construct an optimal routing policy. Nonetheless, as the network size increases, the centralisation strategy will face significant problem to scale centrally the control plane requirements. Large networks require a mechanism to distribute the

control computation over multiple tightly-coupled controllers. In order to address this requirement we use SDNSIM to test a hierarchical control system. In our control architecture, we propose the introduction of a hierarchy of controllers which control a subset of the switch devices and a subspace of the OpenFlow tuple space. In order to enable control distribution, as well as, responsive control, each node of the hierarchy run a flowvisor instance to multiplex switch control channels. The flowvisor is configured to delegate control to a local controller, while also propagating control events to upper layers of the hierarchy in order to build higher level controllers which construct global view of the network and enforce higher priority control policies. In order to understand the impact of this control hierarchy, we use SDNSIM, to simulate the control architecture and evaluate the impact of multi-level control schemes on the performance of the data plane.

In our experiment we use a FatTree Al-Fares et al. [2008] network topology with 4 pods and simulate a small-scale datacenter. For data plane traffic we use a simple client-server architecture to replicate the functionality of data retrievals in Map-Reduced platforms. In the network we assign the machines hosted in the first three pods to function as data requesters and the machines hosted in the forth pod to function as data providers. Each data request consists of a small 10 bytes packet from the requester, to define the number of bytes which will be send subsequently by the data provider. The traffic size of the request is selected uniformly at random between the values 4KB, 8KB and 32KB. The request arrival rate follows a Poisson model, while the destination is choose uniformly at random between the servers of the forth pod. In addition, each client keeps a persistent long-lived background TCP connection. Using this simple model we can experiment with traffic models similar to a datacenter network. In the control of the network we simulate the control logic of the FatTree design: every 1 second the network control receives flow-level statistics from the switch and reassign network flows in order to reduce link utilisation and spread the load between redundant. In order to study the effects of our architectural approach, we variate the number of FlowVisor instances which process OpenFlow traffic before reaching the local controller of the switch and study the impact of the proximity of the controller on data plane performance, by measuring the completion time of each network flow. Further parameters of the simulation are described in Table 3.9.

3.10 Summary

This chapter discusses the scalability capabilities of the predominant SDN implementation, the OpenFlow protocol. We presented, OFLOPS, a tool that tests the capabilities and performance of OpenFlow-enabled software and hardware switches. OFLOPS combines advanced hardware instrumentation, for accuracy and performance, and provides an extensible software framework. We use OFLOPS to evaluate five different OpenFlow switch implementations, in terms of OpenFlow protocol support as well as performance. In our performance evaluation, we benchmark the packet processing, traffic interception and injection, flow table modification and traffic statistics export functionalities of the switches. We identify considerable variation among the tested OpenFlow implementations. We take advantage of the ability of OFLOPS for data plane measurements to quantify accurately how fast switches process and apply Open-Flow 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.

In addition, in this chapter we present the SDNSIM platform, an experimentation framework for large-scale high-precision experimentation with control plane architectures. SDNSIM reuses the Mirage systems abstraction layer to enable developer to program the functionality of their network. An SDNSIM experiment definition can seamlessly translate at compile into a simulation over the ns-3 simulation platform, or a high precision emulation over the Xen virtualization framework. We conduct a number of micro-benchmarks and evaluate that the software provide emulation performance comparable to software OpenFlow controller and switching platforms, while SDNSIM simulation provide good scaling properties. Furthermore, using SDNSIM we investigate the impact of hierarchical distributed control architectures on the performance of the data plane of the network. In the next chapter, we explore applications of the SDN paradigm to scale network management.

Chapter 4

Home network management scalability

In this chapter we explore the applications of SDN technologies to scale network control in home networks. Drawing conclusions from existing social and user studies, we redesign the home network control abstraction to scale management of the home network. We present a Strawman implementation of a network design which achieves simplicity and scalability of the control abstraction within the home environment. Additionally, we propose an extension of our design, which bridges the gap between the home network users performance requirements and the ISP resource allocation policy, providing a simple, scalable and user-friendly QoS mechanism.

In Section 4.1 we present a thorough review of ethnographic and social studies and elaborate on the nature of the problems and the inherent opportunities of the specific network environment. In Section 4.3, we describe our home router and how its flow-based approach enables it to help improve the user experience. In Section 4.4 we present and evaluate protocol modifications that place the homeowner in more direct control of their network. In Section 4.5 we present a simple QoS policy mechanism that provides a communication channel between the home owner and the ISP and enables a user friendly traffic scheduling mechanism for the ISP build using commodity SDN applications. Finally, in Section 4.6 we conclude the results of our exploration.

Note that throughout this Chapter we refer to the individual managing the home network as the homeowner without loss of generality; clearly any suitably authorised

member of the household, owner or not, may be able to exercise control based on specifics of the local context.

4.1 Technological and Social aspects of home networking

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. In computer network literature, a number of studies have been published that highlight the distinct properties of the home network environment. In Subsection 4.1.1 we present briefly the connectivity and traffic mix characteristics of home networks based on the outcome of relevant studies, while in Subsection 4.1.2 we discuss the relation of home networking technologies with the social context of the home, based on relevant ethnographic studies. Home networking is in parallel a social and a technical system. These two aspects interrelate dynamically and create an interesting feedback loop.

4.1.1 Home Networking as a system

Home networks are 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. Home networks use predominanrly ADSL and cable technologies for Internet connectivity, while int is not uncommon to use fiber, 3g and satellite technologies. While we focus on home networks, we note that many environments, e.g., small offices, coffee shops, hotels, exhibit similar characteristics and thus may benefit from similar approaches. Such capabilities are likely to be infeasible in more traditional settings, e.g., backbone and enterprise networks. In this section we use existing studies to present the technical characteristics of modern home network. More specifically, we present the type of devices connected to a home network, the properties of the intra-home-network traffic, as well as, the Internet traffic and the properties of local and Internet connectivity.

Recent work on home network characterisation highlights high variability and a significant number of connected devices per household. In Cioccio et al. [2011] the authors develop the Homenet measurement framework, an end-host active measurement tool accompanied by a user survey. The user survey reports that a home network connects on average 7-8 device, while active probing discovers on average only 1-2 device active during measurement. Further, the user survey reports a wide range of connected devices (e.g. smartphones, tablets, game consoles, etc.). This points out that the home network hosts a wide-range of networked devices with diverse operating systems and network stacks, and any modification in network functionality *m*ust be backwards compatible. Additionally, in Hätönen et al. [2010] the authors test a number of off-the-self home routers and unveil high variability in the semantics of the NAT and DNS functionality implemented by the router firmware. Nonetheless, since such routers are widely deployed in home networks, users network behaviour is resilient to such variability.

Home networks use predominantly wired and wireless Ethernet technologies to establish connectivity. Modern PCs provide currently support for both technologies. Wired network adapters, in their majority, support 802.3ab (1 Gbps full-duplex) standard and wireless network adapters support predominantly 802.11a/g (54 Mbps) standards with hardware-accelerated encryption, while 802.11n (600 Mbps) standard gains popularity. Modern wired home network connectivity provides lossless layer-2 transmission, but is less flexible to accommodate spatial mobility within the household. Wireless technologies are more user friendly, but their performance is susceptible to environmental parameters. The Homenet measurement Cioccio et al. [2011] study reports than on the analysed sample wireless signal strength is on average pretty good (< -80dBm). In addition, the wireless card of the measurement PC was able to receive on average 10 advertisements from nearby wireless networks, a third of which was using overlapping channel. Interestingly, these observations point out the evolution of wireless technology and contrast earlier results on Yarvis et al. [2005]. The multiple SSID receipt also highlights a significant access control problem for homeowners. A wireless network often reaches beyond the limits of a household. This problem is usually partially mitigated using WPA security encryption. Nonetheless, this policy is crude, as password knowledge provides full access to the home network and there isn't a user-friendly mechanism to revoke access.

Home network broadband connectivity has been analysed extensively by the research community. On a governmental level, official independent authorities engage in extensive ISP measurement to evaluate the service provided by broadband providers Federal Communications Commission [2012]; ofcom [2012]. In Dischinger et al. [2007a], the authors contact an active network measurement of residential broadband connections. The results of the analysis present significant performance differences between ISPs and pinpoint the performance bottleneck on the last mile of the broadband link. In Sundaresan and de Donato [2011] the authors integrate various measurement mechanisms into the home router firmware and contact a long-term performance measurement. In their analysis they unveil various differences in ISP performance and measure the impact of network throttle mechanisms, like PowerBoost DSLreports [2013]. The paper points out that broadband performance has multiple factors and cannot be measurable by a single test, while critical performance factors are distributed across the network. Finally, Netalyzer Kreibich et al. [2010], a web-based java-applet evaluating network connectivity and protocol openness, provides useful insight on broadband latency. Netalyzer, among other tests, incorporates a network buffer measurement tool, which floods a network path with packets. The analysis of the measurement results revealed that network buffer in the ISP network induce latency of up to 200 msec.

Home networks also have distinct network traffic properties in comparison to other network environments. In Reggani et al. [2012] the authors study the network traffic from a host point of view for various network environment. In a home network setting, hosts generate significant traffic volumes of filesystem and P2P applications and a large portion of the traffic remains local and is observable only from within the network. In terms of the home network Internet traffic pattern, research has highlighted both significant variability and location-dependence. In Cho et al. [2006] authors describe that during the time of their analysis in Japan there was a significant usage of P2P applications. More recent studies Maier et al. [2009] point out that users in Germany have shifted interest towards web applications and a large portion of traffic is HTTP-based. Similar results are pointed out in Erman et al. [2011], where HTTP flows from an ISP trace are mapped to application types, and online video and one-click hosting services appear as the predominant application classes.

4.1.2 Home Network as a social activity

Home networking technologies have been an interesting domain of study and application for HCI, Ubiquitous computing and sociology, since it provides an excellent environment to study the interaction between users and technology. Studies in the field usually engage in user interviews in order to understand how users perceive and interact with technology.

An important aspect in this is understanding how people perceive home network technologies. In Grinter and Edwards [2005]; Shehan-Poole et al. [2008] the authors ask from home network users to sketch their understanding of the home network. In the sketch analysis the authors highlight two important observations; user opacity to the network increases inversely proportional to their network experience – establishing the effectiveness of the deep abstraction-based design of the current network stack, and users characterize network devices within the context of the home network. Further, in Tolmie et al. [2007] the authors perform an empirical analysis of the house members with respect to technology and the home network. Interestingly, their finding detect that, on average, users are the least motivated to interact with the home network in order to optimize it as long as the perceived performance is tolerable. Additionally, network maintenance is acceptable if it can resemble in format the other household duties (well defined and simple tasks with short durations), while the interest conflict that arise due to the shared nature of some infrastructure is usually solved through negotiation between the household members. An interesting study on this field is presented in Chetty et al. [2010]. In this study, the authors develop a visualization system that inform home network users with statistics on the network bandwidth usage. Interestingly, the introduction of such a mechanism made users informed on the way the network functions and how connectivity problems can be traced to network problem or to other users. Some users, though, raised privacy concerns for such technologies.

A number of user studies have augmented the factors that shape home networking adding as an important factor the design of the building within which the network is installed. In Rodden and Benford [2003] authors describe a 7-layers model devised by the American writer Stewart Brand in Brand [1995] which describes how homes evolve architecturally after their initial establishment. Using this model authors analyse the relationships between Ubiquitous technologies and home design. This study is

further focused on the home networking technologies in Chetty et al. [2007]. Authors contact a user study in order to understand how the home design relates to the choices of users regarding their home network. The study describes how the user network decisions are affected by the design of the house, e.g., location of the network router, while at the same time how the users confuse the limits of the house with the limits of their network, e.g. users assume that encrypting their home network is not important since it is contained within the limits of the house. In Crabtree et al. [2003]; Rodden et al. [2004] the authors study a number of family homes and monitor the real time communications and the ways in which information is produced and consumer within the house. In their study they concluide that a lot of these activities have a location reference within the house, which is related to the involved member as well as the house planning, while activities can be synthesized as sequences into higher order activities. Additionally, using these observations, they propose a framework which can model such interactions.

Finally, in Shehan and Edwards [2007] authors analyze some common management and configuration problem in home networks and project them in the respective design decisions of the network systems. They 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.

add reference to Mazurek et al. [2010] for access control requirements for the house.

4.2 Motivations

4.2.1 Home Network: Use cases

Home networks use the same protocols, architectures, and tools once developed for the Internet in 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 three example scenarios, drawn from situations that emerged from fieldwork reported in more detail elsewhere Brundell et al. [2011]; Chetty et al. [2010]:

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.*

Sharing the medium socially efficient. *Richard is the teenage son of Derek and*

has a great interest in Music, downloading a lot of music from the Internet. Derek works some times in the night from home using the Terminal Services provided by his company. Tension is created between them as Derek blames Richard downloading activity for his poor performing remote desktop application.

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!

Current network functionality is spread across multiple layers that implement different abstractions, while multiple protocols are used to allow network hosts to communication over these layers. Each layer exposes a different set of control parameters and effective network management *must* exercise control on multiple layers. Ultimately, this control distribution architecture is not scalable for the average user. 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. Control of the network can be redefined, exposing only the required control and semantically appropriate abstraction, in order to scale controllability of the network.

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 phys-

ical 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 forwarding 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. This gives us a setup very similar to a standard operator-provided home router where a single box acts as wireless access point, multiplexes a wired connection for upstream connectivity to the ISP, and may provide a small number of other wired interfaces.

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

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[1]An Atom 1.6GHz eeePC 1000H netbook with 2GB of RAM running Ubuntu 10.04.
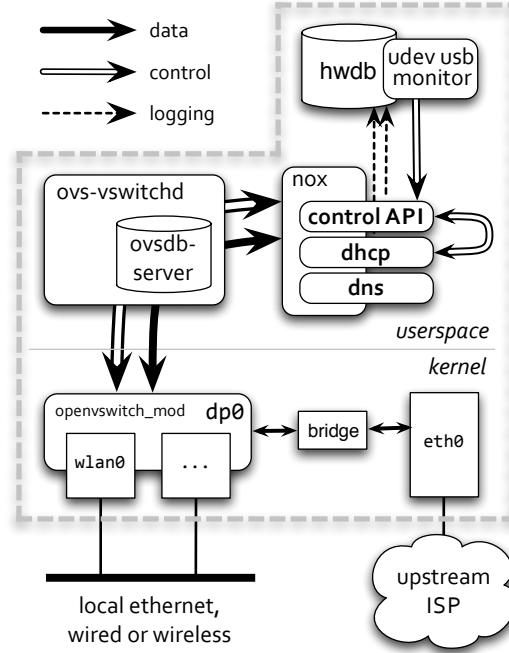
Figure 4.1: Home router architecture. Open vSwitch (*ovs**) and NOX manage the wireless interface. Three NOX modules provide a web services control API, a DHCP server with custom address allocation and lease management, and a DNS interceptor, all logging to the Homework Database (*hwdb*) (§4.4).

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

We provide OpenFlow support using Open vSwitch Pettit et al. [2010], 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 Gude et al. [2008b] controller as it provides a programmable platform abstracting OpenFlow interaction to events with associated callbacks, exporting APIs for C++ and Python.

Our network control logic, discussed in Section 4.4, is implemented over the NOX controller abstraction and split between 5 different modules. The C++ module *hwdb* synchronizes router state with the hwdb home database, presented in Section 4.3.2, the C++ module *homework_dhcp* implements our custom DHCP server, the C++ module *homework_routing* implements the forwarding logic of the design, the C++ module

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.

homework_dns implements the DNS interception functionality and the Python module *homework_rpc* exposes the control API as a Web service.

Our router provides flow-level control and management of traffic via a single Open-Flow datapath managing the wireless interface of the platform.[1] Control of the router 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.[2]

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. [2006] able to express

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[1]Without loss of generality, our home router 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.

[2]While NAT functionality could be implemented within NOX, it seemed neither interesting nor necessary to do so.
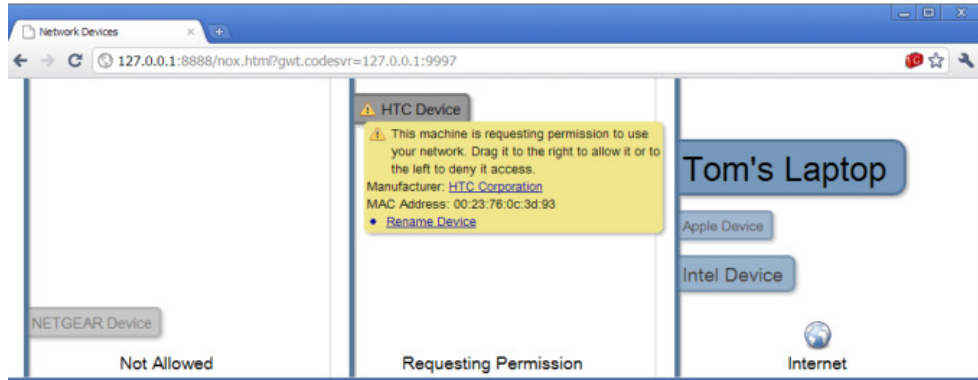
Figure 4.2: The *Guest Board* control panel, showing an HTC device requesting connectivity.

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 can execute temporal query on specific types of events. *hwdb* also provides notification functionality; applications may register interest in *future* behaviour patterns and receive notification when such patterns occur in 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. 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.

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Mappings in the current display are:

- Wireless signal strength is mapped to device label transparency, so devices supplying weak signals fade into the background.

- Device bandwidth use is proportional to its label size, e.g., Tom's Laptop in Figure 4.2 is currently the dominant bandwidth user.

- Wireless Ethernet retransmissions show as red highlights on the device's label, indicating devices currently experiencing wireless reliability problems.

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. This zone exploits the underlying strategy of placing people in the protocol discussed in Section 4.4. 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.

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. The result is that traffic between devices in the home, such as music distribution and file stores, becomes invisible to the home router. By allocating addresses from distinct subnets, all traffic between clients must be transmitted to the gateway address, ensuring all traffic remains visible to our home router. Our custom DHCP server allocates /30 subnet to each host from 10.2.*.*/16 with standard address allocation within the /30
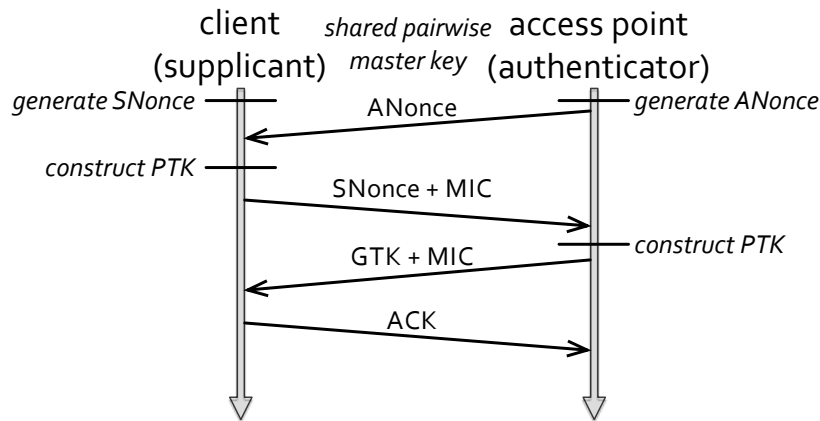
Figure 4.3: 802.11i handshake, part of the association process. Note that MIC (Message Integrity Code) is an alternate term for MAC, used in such contexts to avoid confusion with Media Access Control.

(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 EAP-WPA2 security mechanism, 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 broad-

cast/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 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 client, 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 rekeying 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: 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: to be highly responsive in detection of misbehaving clients imposes a small performance degradation. As a compromise, when a device is blacklisted, all of its traffic and subsequent rekeying exchanges are blocked. Thus the misbehaving device is prevented from sending or directly receiving any traffic before rekeying takes place, 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. This allows us to pick a relatively long rekey interval (5 minutes) while still being able to respond quickly to misbehaving devices.

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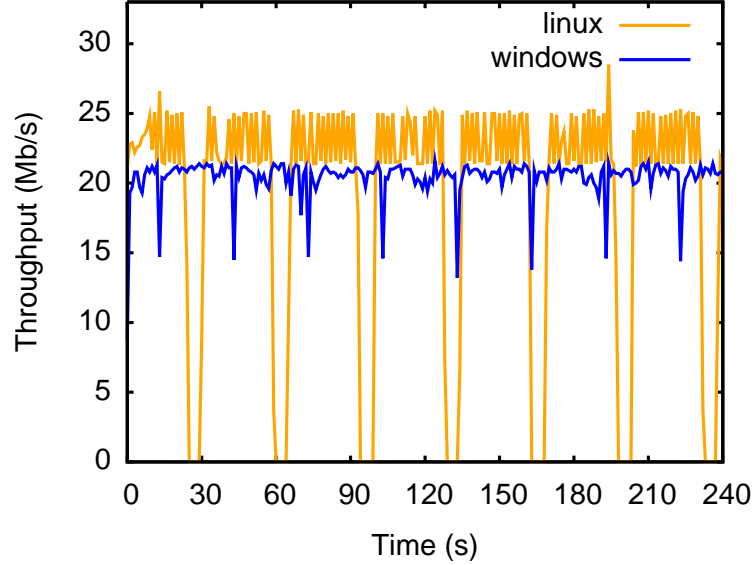
Figure 4.4: Affect on TCP throughput from rekeying every 30s for Linux 2.6.35 using a Broadcom card with the *athk9* module; and Windows 7 using a proprietary Intel driver and card.

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.

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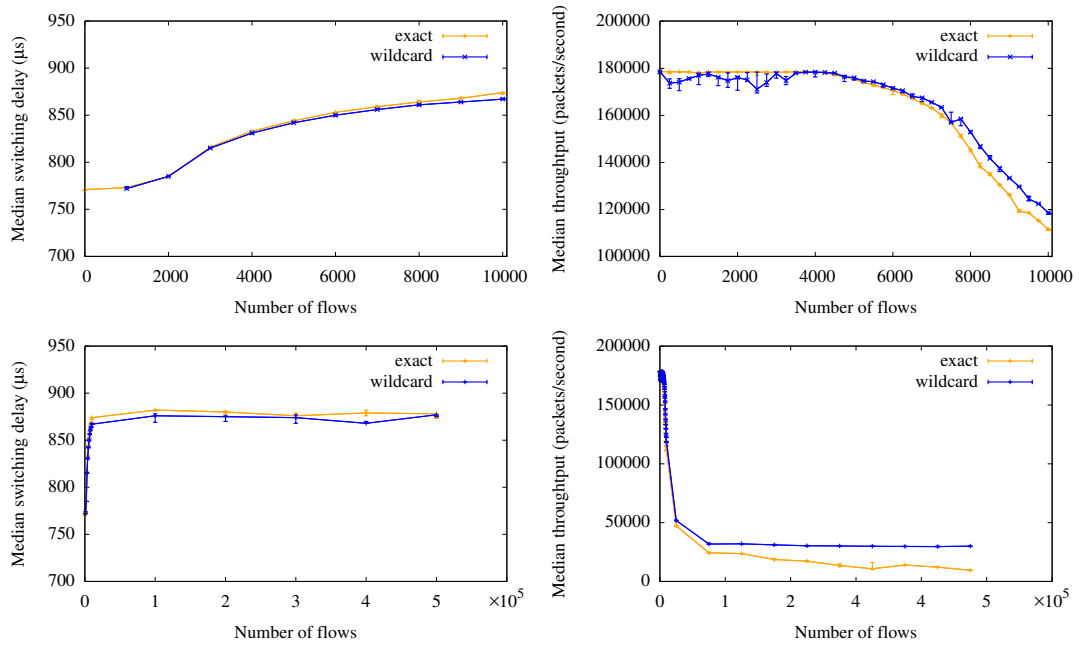
Figure 4.5: Switching performance of Open vSwitch component of our home router showing increasing per-packet latency (LHS) and decreasing packet throughput (RHS) with the number of flows. The lower set of graphs extends the x-axis from 10,000 to 500,000.

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 non-broadcast 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 Open-Flow rule with a 30 second 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.

Unicast IP traffic that passes but is destined outside the home network has a rule installed to forward it upstream via the bridge and IP masquerading. For traffic that is to remain within the home network 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

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

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 (1500B) for the latency tests and minimal packets (70B) [1] 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.

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. Increasing the number of assigned IP address has no impact on the processing latency and minimizes marginally the maximum packet processing rate. This performance behaviour can also be explained by the trie data structure that the Linux kernel uses to lookup addresses; in the house setting the lookup takes O($log_2 m$) time, where m is the number of connected devices.

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 accidental or malicious, our home router monitors the number of per-flow rules introduced for each host. If this exceeds a threshold then the host has its per-flow rules replaced with a single per-host rule, while the router simultaneously invokes user interface callback to inform the

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[1]The 30B extra overhead is due to *pktgen* Olsson [2005a], the traffic generation tool used.
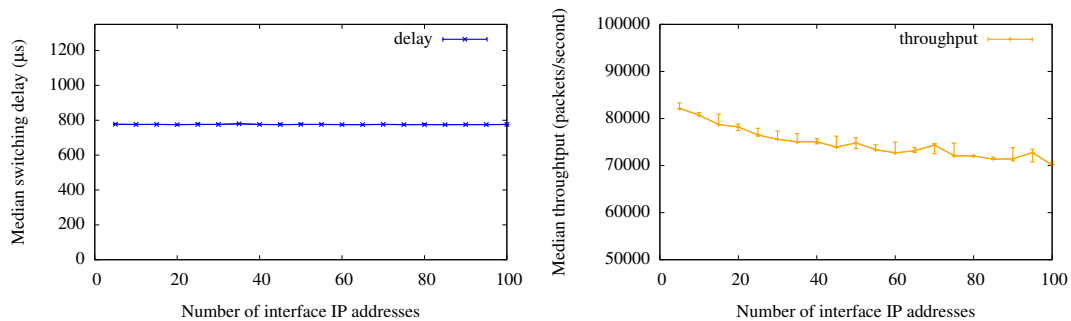
Figure 4.6: Switching performance of Linux network stack under our address allocation policy. Throughput (left figure) shows a small linear decrease while switching delay (right figure) remains approximately constant as the number of addresses allocated to the interface increases.

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 networking 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.

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.

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

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

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 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 allocation. 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. [2] 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

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[1]OpenFlow provides support in its 1.4 release of the protocol; NOX currently has no support for IPv6; and Open vSwitch only supports IPv6 as a vendor extension of the OpenFlow protocol.

[2]Some operators may still prefer to use NAT as part of a legacy of address management and operations.
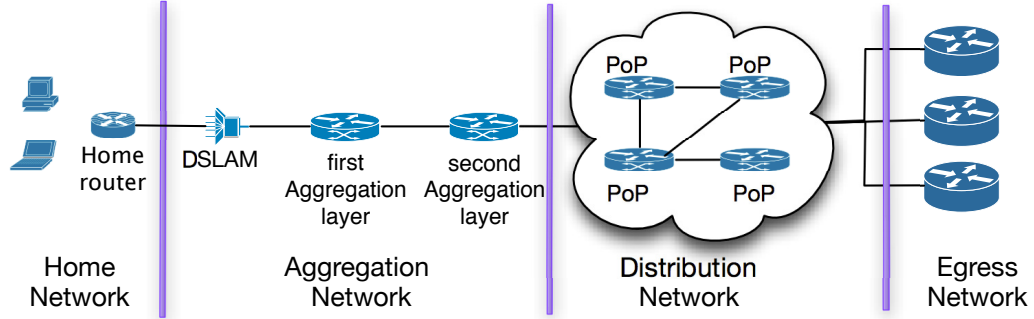
Figure 4.7: The path for each network packet of the home network to the Internet. ISP network can be split in 3 parts: The *Aggregation Network*, the *Distribution Network* and the *Egress Network*.

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 to support router discoverability by hosts.

In order to test the functionality of our approach, we set up a simple hardcoded version of our design. Specifically, we allocate a public IPv6 /64 prefix to our home router. The router uses the ISC DHCPv6 server implementation, configured to allocate addresses from a /120 subnet. Additionally on the router we run the RADVD daemon to reply appropriately to ICMPv6 messages. Using this network setup, we test MacOSX, Windows and Linux IPv6 network stacks and verified correct network configuration and Internet connectivity.

4.5 User-centric resource allocation

As we have discussed in Section 1.1.1, network application evolution has increased both the per-host resource requirements, as well as, the complexity of the resource allocation mechanism. Effectively, developing network architectures that can provide global application-specific network performance guarantees is a difficult task. The network community uses two common practices to tackle the resource allocation problem: network resource over-provision and application-aware traffic engineering. Resource over-provision increases available resources, in order to remove performance bottle-

necks. Application-aware network engineering extends the network policy to manage efficiently traffic from specific applications, e.g. in an enterprise network VoIP devices are connected to a separate high-priority VLAN. In broadband networks these approaches have limited applicability. On one hand, resource over-provision cost is non scalable on the edges of the broadband network [1], while, on the other hand, application-aware network engineering raises legal issues for Internet providers Hahn and Wallsten [2006]. In this section, we propose an architectural extension in the last-mile of the ISP, which enables homeowner to propagate per-application resource requirements. Using this mechanism, we scale the resource allocation problem in ISP management, while users can improve their network experience and gain higher understanding . In the rest of this section, we present the architecture of current broadband networks and discuss the inherent limitations in resource allocation (Section 4.5.1), we present a highly efficient network architecture for user-driven resource allocation (Section 4.5.2) and evaluate the impact of our approach on the performance of various traffic types (Section 4.5.3).

4.5.1 ISP resource allocation

In order to better introduce the reader to our system, we present in Figure 4.7 a visualisation of a broadband ISP network architecture. Although, exact network topology typically remains secret to each ISP, there is a high level design pattern. In this figure we present the network devices traversed by a packet sent from the home network to the Internet. In the Figure, we segment the network topology into four sections, the *home network*, *aggregation network*, *distribution network* and *egress network*. The aggregation network contains the Digital subscriber line access multiplexer (DSLAM), translating DSL packets to Ethernet format over the last mile, the Broadband Remote Access Server (BRAS), an authenticating and policy enforcing network device, and a number of layers of aggregation switches, multiplexing the traffic from the various BRAS onto the distribution network. Traffic from the aggregate network is routed through the distribution network towards the egress network of the ISP or another aggregation switch, if the packet is destined to an internal IP address. The distribution

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[1] optical link installation cost varies between \$50-\$200 per foot, while fibers installation in municipal areas has an annual cost of \$1.91 per foot News [2011]. Upgrading such links also has a significant network equipment upgrade cost.

network consists of a small number of large routers interconnected using high capacity links. An ISP may typically use network tunnelling technologies, like MPLS, in the distribution network, in order to reduce forwarding information on the routers. The egress network of the ISP consist of large routers, hosted in AS IXP networks and connecting the ISP with peering ASes and the rest of the Internet.

In the broadband network architecture, a number of research papers have identified a significant bottleneck in the last-mile of the network Akella et al. [2003]; Dischinger et al. [2007b]: the link between the DSLAM and the aggregation network. This bottleneck can be explained by the high oversubscription ratio of such links. The oversubscription ratio commonly varies between the values 10:1 and 50:1 Program [2013], depending on the number of users connected to the DSLAM, but it is not standardised and is strongly affected by market dynamics Leach [2013].

Through our network design, we aim to bridge a fundamental communication gap between the ISP and homeowner. Users perceive network traffic as an ensemble of flows belonging to a specific application; each application has a specific prioritisation within the house context and the user-computer interaction, e.g. Skype VoIP traffic has a higher priority than web browsing traffic and parents' teleworking traffic is more important than kids' entertainment traffic. ISPs, on the other hand, manage the traffic of a specific household as a packet aggregate with a specific source IP address and resource allocation mechanisms are implemented as monthly or daily traffic caps for the specific IP address British Telecoms [2013]; Virgin Media. Network caps rate-limit heavy-hitting households and provide long-term fairness between broadband users. Nonetheless, this approach is not sufficient for a class of Internet applications, like remote desktop and VoIP, for which performance is not tightly coupled with the available bandwidth. Through our design, we believe that there is an incentive for the ISP and homeowner entities to establish a collaborative resource control framework. Homeowner can annotate high priority flows within their traffic aggregate and thus improve user experience. ISPs can increase user-friendliness of their network policy and offload some of the complexity of their resource allocation mechanism to the end-users.

Our architecture establishes a communication channel between the household and the ISP and enables user-driven dynamically resource control on the bottleneck link towards the aggregation network. More specifically, the ISP virtualises switch resources over the last-mile and delegates control over a subset of the available resources to a

homeowner-managed OpenFlow controller. In the virtualized resources we additionally allocate minimum guaranteed bandwidth and a set of hierarchical priority queues for each household. The household controller, in real time, uses the OpenFlow protocol to forward high priority flows to the appropriate priority queue.

While the proposed solution is not able to provide a complete system to Internet-scale resource scheduling, we believe that it provides a sufficient mechanism to handle in a user-friendly manner congestion on the edge-network and scale the configuration complexity.

4.5.2 User - ISP communication

In the proposed architecture we split system functionality between three points in the network: a data-collection daemon on the end-systems of the home network, a policy enforcing daemon on the home network router and an OpenFlow controller to translate user performance requirements into ISP control policy.

End-system In order to map network flows to application, we develop a light cross-platform daemon running on home network hosts and recording connection table content. These information are collected from the connection table of the host network stack and stored in the HWDB database. The daemon accesses the connection table entries using the *netfilter-conntrack* netfilter.org project [2010] in Linux systems, the *Windows Filtering Platform* Microsoft [2012] in Windows systems and the *sysctl* for Darwin/MacOSX system. In order to match each network tuple with the respective applications, we use the `lsof` command in unix-like systems and the `netstat -p` command in Windows.

ISP infrastructure We present the network on the edge of the ISP network in Figure 4.8. In our user-centric resource allocation design the first layer of aggregation switches must expose OpenFlow control. The switch control plane is virtualised using the FlowVisor controller Sherwood et al. [2010b]. Each home router is running an OpenFlow controller which connects to the FlowVisor service and exercises control over the home Internet traffic. Specifically, the ISP virtualises the OpenFlow forward-
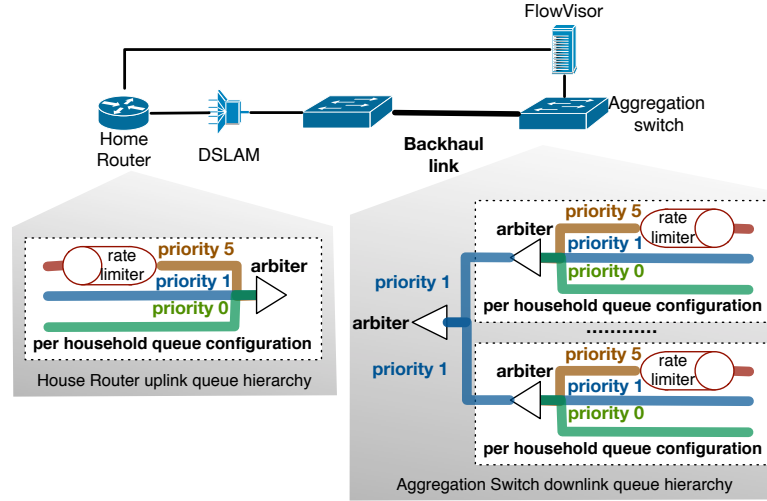
Figure 4.8: User-driven network resource allocation architecture. Switch handling the downlink from the backhaul network exposes a virtual slice to the homeowner through a FlowVisor instance. The switch allocates three queue primitives per-household: A *low latency, high priority* queue, a *medium priority* queue and a *default* queue.

ing table and exposes only a subset of the entries to each user. The FlowVisor instance propagates pkt_in messages to the home controller with a source or destination IP address equal to the home public IP address and the FlowVisor discards any *flow_mod* packet which does not contain an equivalent IP address. This FlowVisor configuration enforces a strong security mechanism; home controllers cannot control or eavesdrop traffic from other households.

At the aggregation switch and the home router we setup three priority queues for each household (The home router queues handle the upstream traffic of the household, while the aggregation switch queues handle the downstream traffic of the household): A *low latency, high priority* (LLHP) queue, a *medium priority* (MP) queue and a default queue. The LLHP queue has the highest priority between the household queues and uses a leaky bucket mechanism to rate limit traffic to the minimum guaranteed bandwidth per-household. This queue can be used by low-bandwidth low-latency applications. The HP queue doesn't enforce any rate limit, but it has a priority which is between the LLHP and the default queue. HP queue can be used by latency-tolerant high-priority applications. Finally, the default queue is used to handle all other traffic types. The queue hierarchies from each household are multiplexed towards the out-

put port with equal priorities. Large scale queue hierarchies are currently supported by service provider grade network equipment (e.g. Cisco ASR 9000 router provide 500k queues per line card Cisco [2012b]) and ISPs use this functionality to implement their capping policy. By default, all network flows are forwarded to the default queue and the home OpenFlow controller at run-time can assign flows to higher priority queues based on the user configured policy. This resource allocation mechanism is constraint per-household by the number of flows that the FlowVisor exposes to each home. This network design can be extended to evolve further the ISP broadband economical model; Users can enhance network performance by purchasing additional flow table entries and increase minimum guaranteed bandwidth on the edge.

Because our system design provides extensive forwarding control to end-users, we fortify the design with a set of mechanisms to reduce the ability of end-users to compromise network functionality. Firstly, fair allocation of flow table entries to each household, ensures fair utilisation of the forwarding resources in the aggregate switch. Secondly, the FlowVisor instance rate limits OpenFlow control channel interactions per household to mitigate DoS attacks. Finally, the Flowvisor instance discards flows that may create loops in the network, e.g. `flow_mod` messages with an Output action that forwards packet to the incoming port.

Home Router   In our design, the home router is the rendez-vous point between the policies of the two network. In order to support the state requirements of this functionality we add in the hwdb database three new tables: *Application tuple*, *Application timeseries* and *Application priorities*. Application tuple table stores mappings between applications and network tuples. This table is populated with data from the end-hosts, while the router installs a monitoring hook in order to receive new flow arrivals. Application timeserries table stores per-application network utilization information. The table is populated with data from the router using the flow stats message of the OpenFlow protocol, while the data are used by the web visualisation in order to inform users for the per-application network consumption. Finally, the Application priority table stores theapplication prioritisation policy pf the user. This table is populated with data through the interface of the system and the controller uses it to map new flows to the appropriate queue.

We expose the resource management mechanism through a user-friendly web in-
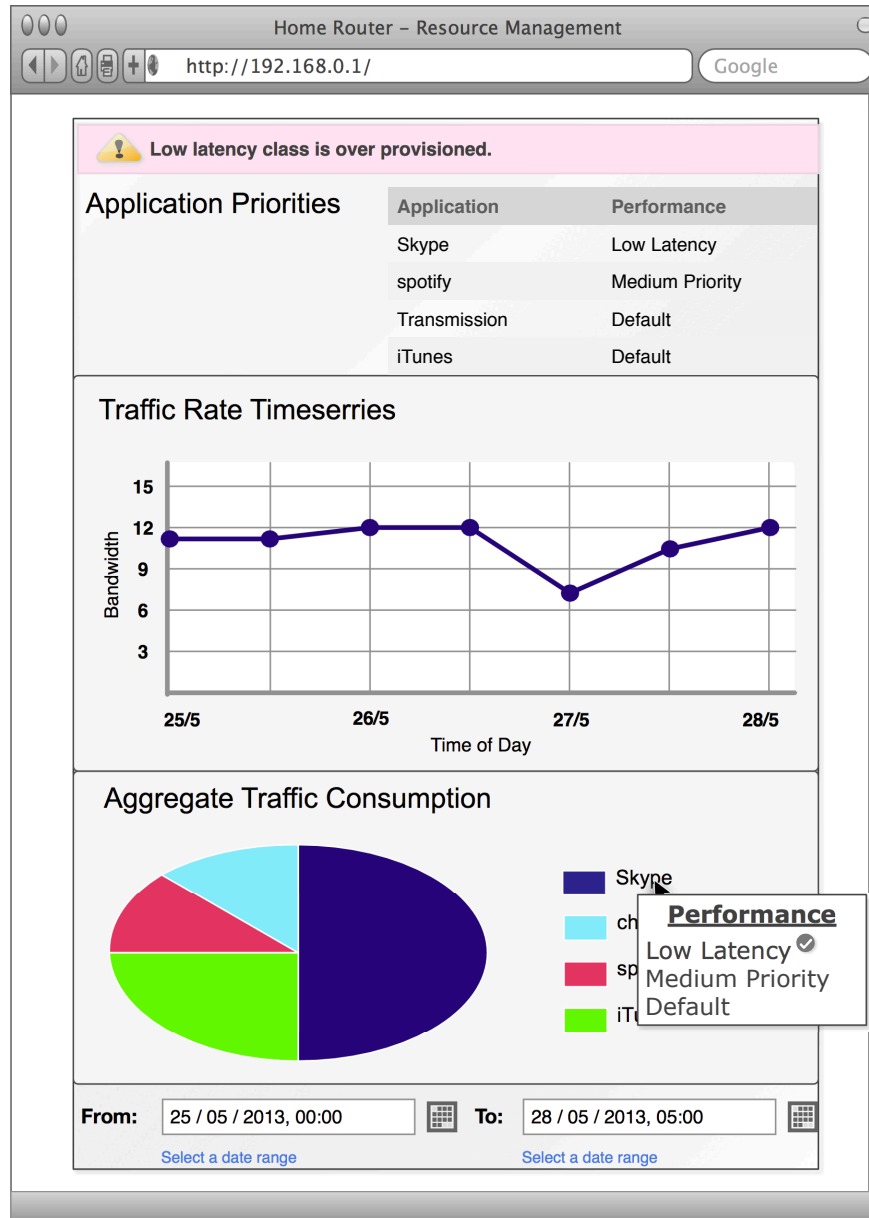
Figure 4.9: Performance mechanism user control. The user is able to view the network utilisation per application, as well as express application prioritisation.
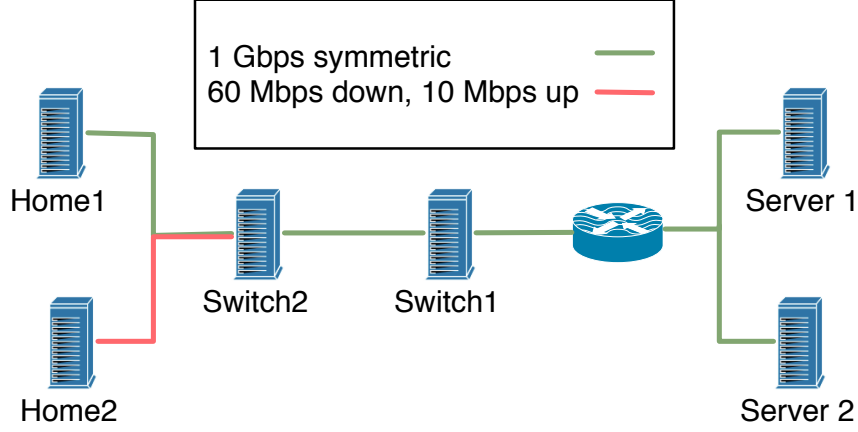
Figure 4.10: Experimental setup to evaluate the proposed resource management system.

terface depicted in Figure 4.9. Through this interface the user can view the aggregate and time serries resource consumption per application and configure application priority policy. Additionally, the interface notifies the user when the policy overutilizes the LLHP queue. Specifically, we use the packet loss counter of the OpenFlow`queue_stats` message to trigger notifications during high packet loss incidents. Through this interface we try to address the issues raised by the work in Chetty et al. [2010].

During operation, the proposed design extends the forwarding logic described earlier. Specifically, for each network flow, once the controller has verified that the flow is in accordance with the policy and destined to a non-local IP address, the controller maps the flow to an application and to a priority queue, through the HWDB database. The controller sends a `flow_mod` message with an `enqueue` action to assign the flow to the appropriate queue. In addition, if the application priority is not the default, then the controller will also send a `flow_mod` packet to the FlowVisor instance, to setup the incoming direction of the flow.

4.5.3 Evaluation

We evaluate the proposed architecture using a lab testbed, depicted in Figure 4.10. *Home1* and *Home2* emulate the networking activity of an ensemble of Home Connections. We focus the analysis on the behaviour of Home2, that emulates a single

connection in the vicinity of an ensemble of Home connections, emulated by node Home1. *Server1* and *Server2* instances run a number of listening daemon that generate traffic, based on traffic requests, from the Home instances and simulates Internet wide Services. Fnally, *Switch1* and *Switch2* emulate the switches that control the backhaul link. Steady state TCP is generated using the iperf tool Tirumala et al. [2005]. We also utilize pttcp tool, in order to simulate stochastic models of short lived TCP flows.

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.

Chapter 5

Signpost: Internet-scale secure and scalable connectivity

In this chapter we explore applications of SDN in Internet-wide inter-device connectivity scalability. The work focuses on the problem of information control and distribution between the devices of a user across the Internet; a mechanism we term a Personal Cloud. Currently Personal Clouds rely on centralised cloud providers to establish Internet-wide connectivity due to limitations in bidirectional connectivity, discussed in Section 1.1. As a result, users are subject to privacy threats and performance degredation. We argue that users require a distributed, scalable and user-friendly network control plane to enable Internet-scale user-managed Personal Clouds. We propose Signpost, an Internet-wide evolve network control plane architecture that establishes Personal Cloud functionality and provides continuous connectivity and controlled security. The architecture consists of daemons running on end-user devices, that can configure and run several off-the-self connection-establishing software packages. The proposed architecture employs a distributed negotiation protocol between end-hosts, which scales the connectivity complexity through control distribution.

In order to understand the feasibility and performance of the proposed architecture we develop a strawman implementation, that implements the core control logic of the proposed architecture. In our strawman implementation we present the integration with a number of network connection and notification services. Currently, Signpost supports SSH, OpenVPN, TOR, NAT-punch and Privoxy connection mechanisms, while it can

also propagate Multicast-DNS notifications across devices.

In this chapter, we present in Section 5.1 the motivation for this work, followed then by the key observations for our design in Section 5.2. In Section 5.3, we present the architecture of our strawman implementation and its integration with existing software. Finally, in Section 5.4 we present a number of micro-benchmark tests for our system and conclude in Section 5.5.

5.1 Personal Clouds

In the recent years, the global increase in personal computer adoption has transferred a large portion of our life in the digital domain. For example, a portion of our labour is stored in digital PDF and word processing files, while a part of our social experiences maps to digital photo collections. As a result, our physical presence has a growing digital counterpart. The main user interaction medium with his digital presence is through his personal computing devices. Nonetheless, the increase in the number of computing devices per-user introduces new challenges in digital resource management. Complimentary to their personal computer, users on average currently own and use a tablet, a smartphone and a variable number of purpose-build computing units for home entertainment and gaming. Each user device often fulfils a specific set of roles, thus requiring access only to a subset of the user digital presence, but these roles are fluid and intercept. For example, a smartphone is primarily a communication device, but end-users may use it as a media player. In the latter case, the smartphone and the home entertainment system provide similar functionality to the user and require access to the same subset of his digital presence. This transition from a single PC paradigm to a multi-device paradigm and the concurrent digital footprint augmentation creates a user requirement for new services providing global and homogeneous access and control of personal digital information and resources. We call this abstraction the user *Personal Cloud*.

In the rest of this Section, we present existing approaches providing Personal Cloud functionality (Subsection 5.1.1) and discuss their functional limitations in order to define the design goals for our Signpost system (Subsection 5.1.2).

5.1.1 Approaches

Currently, partial Personal Cloud functionality is readily available in a number of applications. Such applications provide a wide range of abstractions and each has different network resource and connectivity requirements. We group these approach in two distinct categories, based on the service architecure.

Decentralised Personal Cloud   The requirement to share information and computing resources has been a core application for computer networks since their conception. Currently the average user has access to a large number of free software packages and protocols that provide Personal Cloud functionalities, such as remote desktop access (e.g. Remote Frame Buffer protocol Richardson and Levine [2011]), file sharing (e.g. NFS Shepler et al. [2003], SAMBA file service Leach and Naik [1997]), remote login (e.g. SSH Ylonen and Lonvick [2006]), remote printing (e.g. IPP Hastings et al. [2000]) etc. between devices. Such applications follow the client-server connection paradigm and extend the computer abstraction to accommodate inter-device connectivity and resource accessibility. A user can setup and manage the equivalent services on his personal devices and enhance his user experience with Personal Cloud functionality. In addition, the network community has developed mechanisms to ease the configuration of such services. Multicast-DNS, UPnP and ZeroConf protocols allow a user to seamlessly browse and access available services upon connection to a network.

Decentralised Personal Cloud applications enable users to fully control their digital footprint in a privacy preserving manner. Data are stored on users devices and the user has full control on the propagation of his information. Nonetheless, deploying such service in the Internet raises significant scalability issues. We focus on three significant problems in Internet-scale deployments.

- *Connectivity*: Current Internet architecture cannot accommodate globally accessible network services to all connected hosts, as we have discussed in Section 1.1. As a result, the Client-server connection model of decentralised Personal Cloud applications cannot guarantee universal functionality. End-users commonly connect to the Internet through edge networks optimised for outgoing connectivity, while ubiquitous middleboxes in the Internet may disrupt connectivity. For example, NATed networks, that scale connectivity on the edges

of the network, limit incoming Internet connectivity for a significant number of devices and require manual configuration to expose services. In addition, mobile and enterprise networks employ firewalls to restrict publicly accessible services on connected hosts for security reasons.

- *Authentication*: Distributed Personal Cloud applications employ an inflexible authentication mechanism. Authentication is usually based on global or user-based pre-shared passwords and public keys. In order to grant access to a Personal Cloud service, the user must know a-priori the interest of another user to connect and enable access in the configuration of the service, while assuming availability of out-of-bands secure channels to negotiate access details.

- *Usability*: Decentralised Personal Cloud applications introduce configuration requirements which dim them inappropriate for inexperienced users. As we have already discussed in Section 4.1.2, the average end-user is highly unlike to engage in systematic service configuration, particularly if the configuration tasks are long and complex. Establishing connectivity through decentralised mechanisms is not straightforward. Functionality contains assumptions on the connectivity of the environment and users have to resolve to "trial and error" approaches to check which configuration can be effective in a specific environment.

  As an example, we describe the steps required to access files in a remote computer using the SSH service. Before the user is able to connect to a computer over SSH, he has to configure the service on his local machine, the security credentials on the server and firewall and NATbox deployed in the network. Additionally, if his public IP is expected to change over the course of a day, he needs to setup a mechanism to access the current IP configuration, like DynDNS [1]. This connectivity is subject to the ability of the user in the remote network to use the SSH protocol on a preconfigure port. In case this is not possible, the user has to resolve to a different service.

Centralised Personal Cloud   An alternative approach, which has been highly successful in the recent years, uses third party cloud services to establish Personal Cloud functionality. In this group we consider applications like the Google service suite or

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[1] http://dyn.com/dns/

Dropbox. These applications provide a simple, intuitive and ubiquitous mechanism to store and retrieve data in the cloud and define information sharing policies. Centralised Personal Cloud applications have been highly successful as they overcome the connectivity problems of the decentralised approaches, by using cloud network and computational resources. In addition, their popularity is further augmented by the social functionality supported by some of these applications. For example, Google Docs allow users to store online documents and process them in parallel with a defined subset of their contact list. Although this approach can be characterised as successful in terms of functionality, some of the properties are ambivalent and demotivate user engagement.

- *Identity*: Cloud applications provide an effective control framework to disseminate information between devices and users. Users define access policies based on online identities and the service ensures secure information delivery. User authentication mechanisms though introduce privacy concerns, since they can be used to identify and monitor users. In Krishnamurthy and Wills [2009] the authors reports cases of personal information leakage to ad services from Online Social Networks, in order to detect and characterize individuals, and Facebook has openly verified the existence of such services Juan Carlos Perez [2007].

- *Performance*: The availability of large amount of computational resources in current cloud infrastructures provide user-acceptable performance, regardless the volume of processed data. Although, this approach underutilizes the rich computational resources available in end-user devices on the edges of the Internet. Two devices connected to the same subnet will experience bloated RTT values when they communicate through a cloud service, while public cloud storage cost and performance is orders of magnitude higher than the equivalent local network file services. In Wittie et al. [2010], authors report a significant impact on the 95th quantile network performance of cloud services, due to latency and packet losses incurred by the Internet. *Add dropbox measurement study tail at scale ref*

- *cost*: Free cloud services, like iCloud and dropbox, have an interesting economical model, which provides limited free service in order to augment user-base,

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accompanied by a weak SLA's. If a part of the service is compromised and sensitive information is leaked, the service provider bears minimum obligation towards affected users Declan McCullagh [2011]. Such costs are not directly observed by the end-user, but they may impact significantly his social and work experience.

- *Availability*: Cloud services run on well connected infrastructures with a large number of network engineers ensuring security and performance. All devices can use such services over the Internet. However, the centralised architecture of such services introduce a single point of failure in inter-device communication. For example, two devices belonging to different users and connected to the same local network cannot exchange a file over Dropbox, if the firewall policy forbids connectivity with the Dropbox servers [1].

5.1.2 Design Goals

In the previous section we present the capabilities and limitations of existing Personal Cloud applications. Decentralized Personal Cloud configuration is complex for an average user, while the functionality depends on the network environment properties. On the other hand, centralised Personal Cloud applications provide better usability, but they incur privacy vulnerabilities Greenwald and MacAskill [2013] and functionality bottleneck.

We believe that an efficient and secure Personal Cloud framework, should rely on a hybrid approach to scale the problems of connectivity, security and usability. User information should be stored on end-devices, to ensure user privacy, and existing decentralized applications can provide Personal Cloud functionality. Scalable inter-device connectivity can achieved through an evolved network control plane on the end-devices. In addition, the user must maintain a globally accessible service in the cloud, which enabled an global control channel between the devices of a user. The service is used to aid end-device to bypass network restrictions, but the system can function, up to a point, without interaction with the cloud service. We set the following high-level goals for our network architecture:

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[1]Dropbox provides local network synchronization functionality between devices, but the users must have enabled their sharing policy a-priori and through the online Dropbox service

- *Connectivity*: The framework should establish a new control abstraction, focused on the inter-device communication requirements of the user. This abstraction decouples the data flow of the application from the network state, enabling the implementation to choose at run-time the most efficient network mechanism to establish a communication channel. Additionally, the implementation of the connection abstraction should be able to automatically self-heal during network disconnections.

- *Control*: Individuals should control access to their devices. Access policies should operate on the level of devices or users and rely on strong authentication and encryption mechanisms. Additionally, the control should be sufficiently dynamic to respond to environment changes, e.g. propagate trust revocation for a compromised device. In addition, the control abstraction should consider multiple security aspects and allow the user to control the trade-off between performance and security.

- *Backward Compatibility*: The framework should provide support to existing decentralised applications without any modification of their functionality.

- *Usability*: The system should expose a simple control abstraction to end-users and encapsulate all low-level interactions. Ultimately, the abstraction of the system should be compatible the existing user experience of decentralised Personal Cloud.

5.2   Finding your way with Signpost

Signpost is a Personal Cloud-enabling framework with user controlled security. The system establishes an Internet-wide overlay network between the devices of a user. The abstraction relies on a cloud-based control channel established between devices which can be used to negotiate and establish end-to-end connections, using existing decentralized frameworks. In order to ensure functionality under any circumstance, we integrate the control channel with the DNS protocol, an existing high availability and resilient service.

The system establishes a user friendly framework that automates end-to-end path configuration between devices. Signpost models existing connectivity mechanisms and encodes their configuration and assumption testing in a generic automation framework. Additionally, the system provides seamless integration with existing applications. Signpost network paths are exposed in the network layer of the OS and the control API for inter-device connection establishment is integrated with the *gethostbyname()* function. Each device is exposed to the users as a domain name and a name lookup for a device triggers the connection establishment mechanism. Inter-device traffic, destined to the DNS-provided IP, is routed through the established path. Finally, the system exposes a user-controlled security abstraction, which can provide different security properties on connections between devices. As a result, the user is able to fully control the dissemination of information between his devices, while avoiding privacy-sensitive data offload to cloud services.
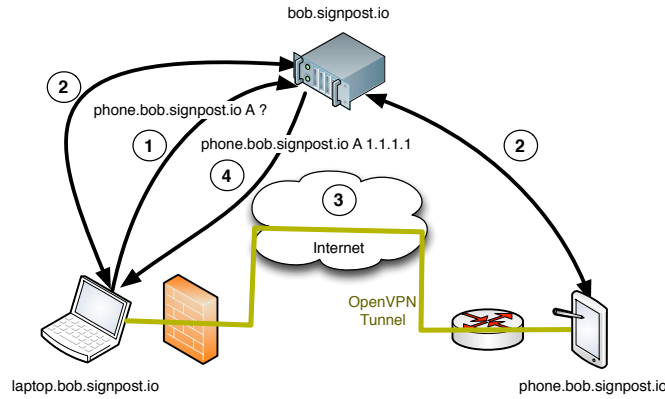
Figure 5.1: A simple example of the Signpost abstraction when the user Alice interconnects a smarthphone with the home computer over the Internet.

Add some reference to cloud controller A schematic of the abstraction that our system provides to end-users is depicted in Figure 5.1. In this scenario user Bob, who is at work and uses his smartphone, wishes to access some files on his laptop, which is behind the NATed home router. In order to express his interest to connect to his laptop, Bob must perform a name lookup for the domain name `laptop.bob.signpost.io` (step ①). The name lookup will propagate through the public DNS service to the cloud presence of his Signpost system, which we call the *Signpost con-*

troller. The Signpost controller will trigger the two devices to try multiple possible connection establishment mechanisms and setup an end-to-end path between the two devices (step ②). Once the server has ensured that a first path is available (step ③), it will reply to the initial DNS query with a local IP address which will be routed by the local network stack to the tunnel between the two devices (step ④). In parallel, the server will continue recursively to test different tactics, to discover more efficient connection mechanisms.

5.3   Signpost Architecture

Signpost is an Internet-wide secure inter-device communication system. The system reuses existing Internet protocols and connectivity mechanisms and provides an overlay local network. In Figure 5.2 we present a diagram of the Signpost architecture over different abstractions. In the lower section of Figure 5.2, we present the design of the Signpost software and its integration with existing applications. Signpost logic is contained in a single executable, and requires from the guest OS to expose an OpenFlow switch interface and redirect DNS queries to the embedded DNS resolver. The software consists of three main subsystems: A *Connection Engine* (Subsection 5.3.3) that sets up and manages *Network Tactics* (Subsection 5.3.1 in order to establish end-to-end paths, a local DNS resolver and an OpenFlow-based *Signpost router* (Subsection 5.3.2) that enhances the normal OS routing functionality with Signpost logic. In the middle layer of Figure 5.2, we present the control plane interconnection of Signpost devices. The system relies on an Internet-wide inter-device control channel, which enables capability and parameter negotiation for end-to-end connectivity. The architecture considers a *Controller Signpost* instance running on a well connected host, which bridges the device control channel across the Internet. Further, the system can establish connectivity between local devices without the mediation of the Signpost Controller. Signpost clients contain a Bonjour-based discovery mechanism, through which devices can establish ad-hoc secure and authenticated paths. In the upper layer of Figure 5.2, we present the naming organisation of the Signpost architecture. The system reuses the naming abstraction of the DNS service. Each device has a global domain name, while the domain hierarchy and name aliasing expresses the control relationship between devices and users. We extend the normal name resolution functionality of the DNS
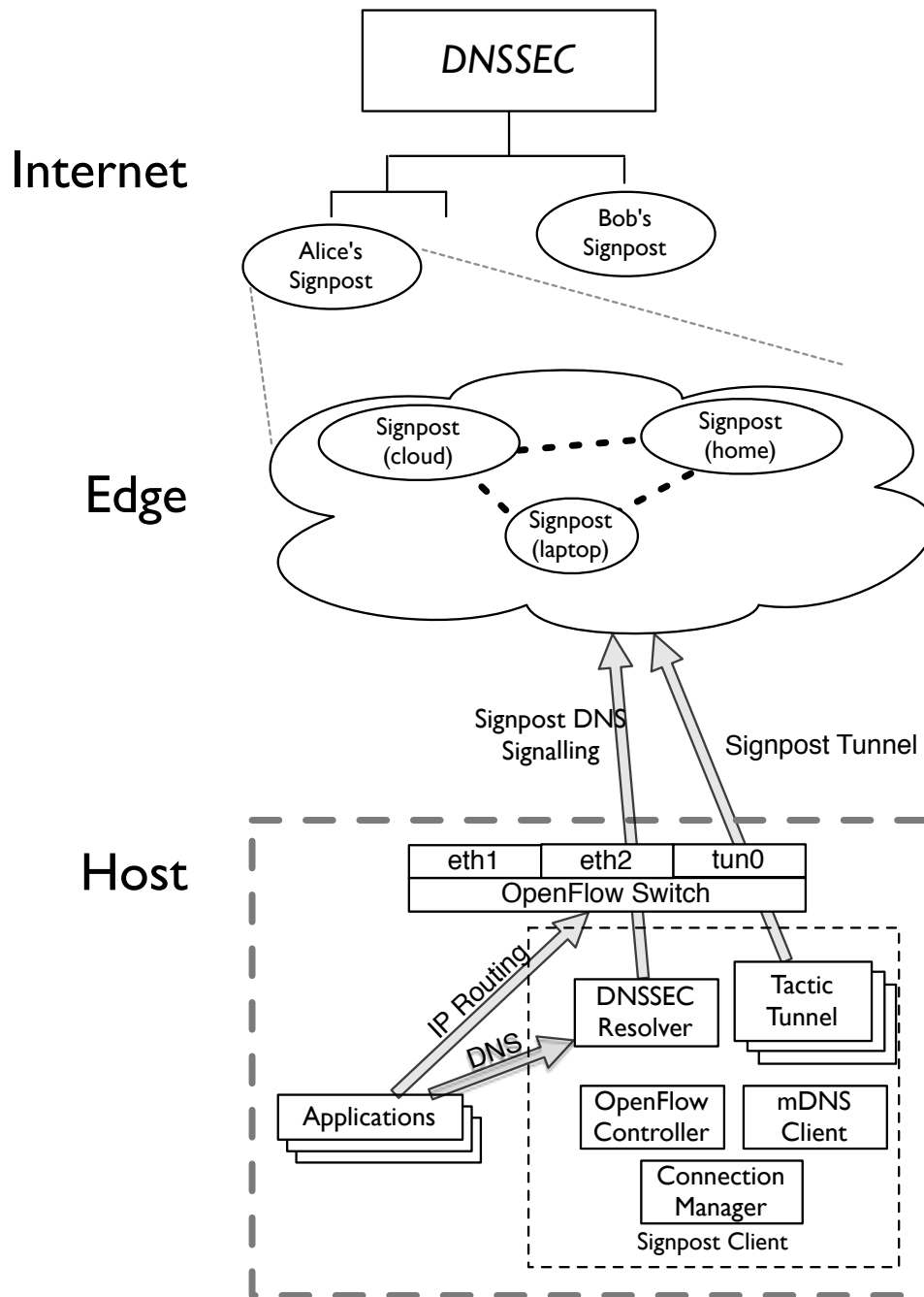
Figure 5.2: Signpost architecture

Tactic name	Purpose	Layer	Transport	Auth.	Encrypted	Anon.	Signpost Support
Avahi	Discover	7	UDP	No	No	No	Yes
Samba	Discover	7	UDP	No	No	No	No
Bonjour	Discover	7	UDP	No	No	No	Yes
Universal PnP	Discover	7	UDP	No	No	No	Yes
dns2tcp	Tunnel	7	UDP	No	No	No	No
DNScat	Tunnel	7	UDP	Yes	No	No	No
HTTP-Tunnel	Tunnel	7	TCP	No	No	No	No
iodine	Tunnel	7	UDP	Yes	No	No	Yes
NSTX	Tunnel	7	UDP	No?	No	No	No
Proxytunnel	Tunnel	7	TCP	Can be	Can be	No	No
ptunnel	Tunnel	4	ICMP	Yes	No	No	No
tuns	Tunnel	7	UDP		No	No	No
SSH	Tunnel/Encrypt	7	TCP	Yes	Yes	No	Yes
IPSec	Tunnel/Encrypt	3 (4*)	IP	Yes	Yes	No	No
OpenVPN	Tunnel/Encrypt	7	UDP/TCP	Yes	Yes	No	Yes
libjingle	Nat punch	7	UDP/TCP	Yes	?	No	No
privoxy	Anonymize	7	TCP	?	?	Yes	Yes
tor	Anonymize	7	TCP	No	Yes	Yes	Yes
stunnel	Encrypt	7	TCP	Yes	Yes	No	No
TCPCrypt	Encrypt	4	TCP	No	Yes	No	No

Table 5.1: Tactics table.

protocol and introduce the *Effectful name resolution* operation for Signpost-enabled domains; a name resolution expresses the interest of a user to establish an end-to-end path (Subsection 5.3.4). For the rest of the section we present in depth design details of the Signpost system.

5.3.1 Network Tactic

Currently the network community offers a wide selection of software to establish connectivity between network devices. In Table 5.1, we present a small survey of such mechanisms along with their network requirements and security properties. The table entries exemplify the high diversity among the available connection mechanisms. For example, a significant subset of the mechanisms utilize application layer protocol functionality in order to establish IP connectivity, thus allowing users to bypass strict network policies. An equally significant subset of the mechanisms focus on encryption and privacy enhancement of end-to-end Internet paths, while a third class of these mechanisms enable connectivity through simple service advertisement. Further, the
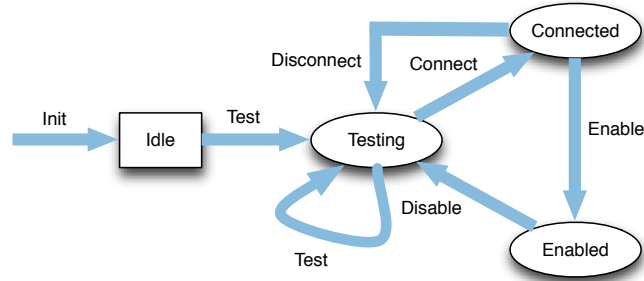
Figure 5.3: Signpost tactic lifecycle

mechanisms vary significantly on the employed network protocol and the connectivity they provide. Tunnels provide connectivity on a specific port of the transport layer, or introduce an overlay network on the network layer. The majority of the tunnelling mechanisms use UDP or TCP connectivity, while there are protocols that function user other network protocols, like ICMP. Finally, user authentication is variable. Approaches vary from user-based authentication using either passwords or certificates, to simple Pre-shared passphrases, while a subset of the protocols luck authentication support.

In the Signpost architecture we model network mechanism functionality through a simple abstraction, which we term a *Network Tactic*. A sufficiently generic specification of this abstraction is core for the establishment of an automated connectivity platform. Signpost Network Tactics are modelled as a 4 state automaton. The state space diagram is presented in Figure 5.3. A Tactic initializes in the Idle state. A test method invocation transfers the tactic to the testing state, while executing the testing logic of the tactic. The test method performs Tactic specific testing to detect network environment limitations and required connectivity configuration. If testing is successful, the Tactic can progress to the connect state which will configure an end-to-end path. Once the end-to-end path is established, the Tactic can progress to the enabled state and forward packets over the path. Finally, the Tactic automaton provides methods to backtrack from each state and clear stored state. In order to avoid packet reordering, Signpost permits the parallel existence of multiple connected tactics for a set of devices, but a single tactic can be enabled at any point. *rewrite last 2 sentences*

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Signpost defines a generic model to split functionality between the Signpost controller and client for a specific tactic in order to distribute control. The functionality of a Signpost tactic is split logically in two layers: the Southbound layer, implementing low level tactic operations, and the Northbound layer, translating the tactic abstraction into low level operations. The Northbound functionality runs on the Signpost controller, while the Southmodule functionality runs on the Signpost clients. The two layers of the tactic, communicate over the control channel using a tactic specific protocol.

As an example of this functionality split, we present the Test method of the Open-VPN tactic, an IP tunnelling system that uses certificate-based authentication and functions over TCP or UDP. In the test section of the Southbound layer, the tactic implements two methods: *i*nit an OpenVPN server with default configuration and *t*est if an OpenVPN server is accessible on a given IP and port. The Northbound layer of the tactic expose a single test method, which instructs participating devices to initiate an OpenVPN server and test client connectivity towards the other device. The first client returning a successful test result becomes the client of the OpenVPN tunnel while, if the test times-out for both devices, then the controller initialises an OpenVPN server and instructs the devices to test OpenVPN connectivity to the controller.

Discuss weight of tactics

5.3.2 Forwarding

talk in abstract ot explain specific We integrate Signpost functionality at the network layer of the host for strong backward compatibility with existing decentralized applications. A Signpost cloud is abstracted as a local subnet and persistent local IPs are allocated to devices. In addition, Signpost clients must expose a flow forwarding mechanism abstraction, like the OpenFlow protocol, of the host network control plane, to enable the Signpost agent to augment the control logic. Signpost network control forwards Personal Cloud traffic over the most efficient end-to-end path and detects connection problems.

The forwarding logic of Signpost doesn't affect network control logic for non-Signpost traffic. For Signpost flows, the control logic is Tactic-defined and can either function re-actively or pro-actively. Additionally, Tactics can inject traffic in the network, over the network control channel, and modify pro-actively flow forwarding for

Internet-wide Signpost flows. In section 5.4.1, we present in-depth how currently implemented Signpost Tactics modify network control logic. Finally, in order to reduce broadcast traffic on the Signpost local network and focus the control complexity on the network layer, we introduce a simple ARP proxy in the control application, which replies with the MAC address *fe:ff:ff:ff:ff:ff* to every ARP request for Signpost local IP addresses.

5.3.3 Connection Manager

Signpost end-to-end path management is encapsulated in the Connection Manager Subsystem. Path selection is modelled as a dynamic optimization problem with security requirements modelled as constraints and path performance modelled as the objective function. Path performance is modelled as a positive integer weight and higher weight values reflect lower performance for the path. Path weight is calculated by the weight of the Tactics establishing the end-to-end path. Tactic weight are empirically defined through a set of simple rules of thumb. Tactics that include the Controller in the forwarding path, are considered less efficient than those establishing direct connectivity, while tactics that run over connectionless protocols, like UDP, are preferred over protocol that run over connection-oriented protocols, like TCP. This simple approach appears to be sufficient at the moment, and more complex Tactic-specific mechanisms using active measurement performance estimates can be employed.

In terms of security policy, Signpost provides a simple abstraction. A Signpost Tactic can have three security properties: *encryption*, *authentication* and *anonymity*. An encrypted Tactic establishes an end-to-end path with a strong cryptographic cipher applied on both ends, an authenticated Tactic uses strong authentication to establish an end-to-end path, while an anonymized Tactic will establish an end-to-end path which obfuscates user identity. Using these security properties, the user can define a connection policy towards other Signpost devices. The policy is expressed through a configuration file and users specify security requirements on a per domain basis.

In order to enable higher flexibility, the Signpost architecture permits *Tactic synthesis* to establish end-to-end paths. For example, an anonymized and encrypted path is established through an SSH tunnel running over a TOR tunnel between two devices. The synthesis occur on the network through appropriate flow management. In case of

Tactic synthesis, the path weight is computed as the sum of the performance weight of the partial Tactics.

Signpost is able to establish multiple end-to-end paths between two devices. Unfortunately, multipath connectivity is not supported by popular transport protocols and newer protocols like SCTP and multipath TCP, supporting multipath connectivity, are not yet available in production systems. As a result, in Signpost we establish and use a single end-to-end path between any two devices. Signpost path-search uses a simple width-first search algorithm over the network tactic abstractions on the controller of the Signpost Cloud. The search is initiated by the connect method of the Manager module, with parameters the name of the devices and a list of connection properties. The Manager is then responsible to establish the end-to-end path and return once a first path is available.

The logic of the search algorithm is pretty simple. During a connection request the system spawns a thread for each Tactic to test connectivity. If the test is successful, the Tactic is instructed to connect the two end-points. If the connection is successful and either there is no other Tactic enabled or the currently enabled Tactic has a higher performance score, then the Manager will progress the Tactic state machine to the *Enabled* state. If the Tactic doesn't fulfil the security policy, the Manager recursively enables tactics over the established path, to enable Tactic synthesis. The Manager returns a successful result, when the search establishes an end-to-end path compliant with the security policy. In addition, the Manager will continue recursively to search for better path between the two devices. The recursion terminates if all remaining Tactic combinations have a higher performance weight or they are synthesized by more that three Tactics. As a result, the Manager can establish rapidly an end-to-end path between two devices and progressively optimize path performance, while the devices remain interconnected.

5.3.4 Effectful Naming

The majority of Internet-connected devices are essentially anonymous from a network perspective *IPv6* and assigned transient names (e.g., via DHCP). A fundamental requirement for the Signpost architecture is to assign stable names to each device, and provide a secure mechanism to resolve these names into concrete end-to-end paths.

Signpost naming functionality is established through the DNS protocol Mockapetris [1987] for two main reasons. On one hand, DNS is an effective solution for the problem we try to address. DNS is a widely deployed and accessible service across the Internet, which is never blocked by the local network and provides a sufficient mechanism for bi-directional authentication. In addition, the DNS service is an excellent mechanism to intercept user connectivity intentions. The internet naming service is a delay-tolerant mechanism for applications to express the interest connecting to a host. DNS domain names provide a naming representation of Internet services decoupled from the network layer technology, while the naming format is also a good match to spoken language.

Domain naming provides good scaling properties that follow a simple organisation model. Every domain name consists of a sequence of name tokens organised in a hierarchical tree structure with a single root, the empty string. Every node on the tree can be coupled with a number of DNS Resource Records (RR) which define information for the specific domain name like network addresses, naming aliases, service information and the like. In order to scale the naming service efficiently across the Internet, the protocol provides a specific RR type, the NS record, which delegates control for a domain to a specified set of DNS servers. Querying the domain tree for a specific RR requires at least the address of a DNS server. The DNS client can then follow service redirections in order to find a server responsible for the requested domain. Additionally, the explicit caching mechanism of the service reduces significantly the load on naming servers and improve the performance of the entire system.

Secure Names For All Internet Users   In the initial definition of the Internet naming service, the protocol provided very weak security guarantees. In order to enhance the security primitives the IETF standardised a number of DNS protocol extensions, describe as DNSSEC. DNSSEC defines several three RR types Arends et al. [2005] used to provide a signing chain that can authenticate DNS records. We present the authentication mechanism in Figure 5.4. In essence, a zone signs its authoritative RRsets using its private key and the RRSIG record type, and then publishes its public key via a DNSKEY RR to allow resolvers to validate the RRset signatures. In addition, the DS RR propagates trust between nameservers. Following the signing of the root zone, and certain top level domains beneath it, a chain of trust is formed back to the
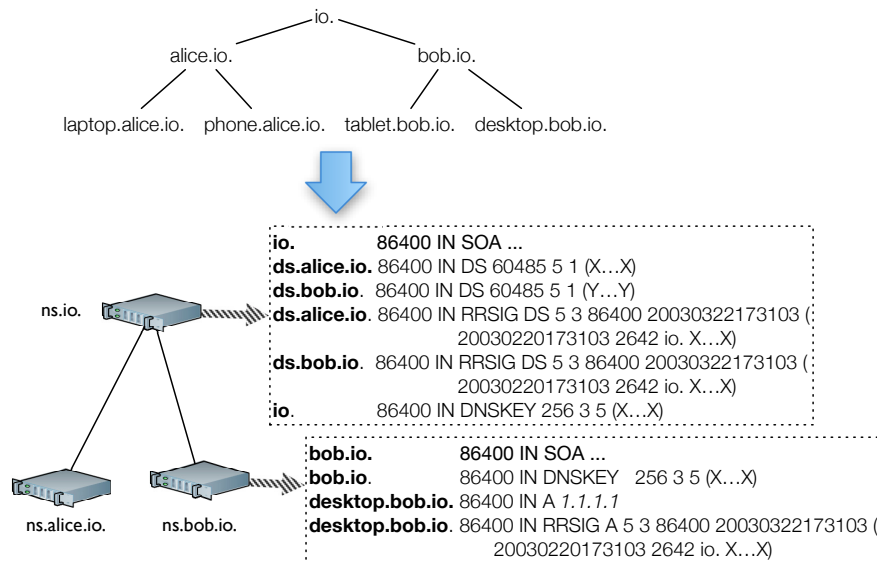
Figure 5.4: DNSSEC key configuration for the io. and bob.io. domains. The io. nameserver zone file contains a DS RR with the hash of the bob.io. DNSKEY RR and an RRSIG RR signature of the DS RR signed with the DNSKEY of the io. domain. bob.io. uses its DNSKEY to sign an A RR for desktop.bob.io.

root, whereby a given resolver can be certain that the response it has received to a query *is* the correct response from the authoritative DNS server for the name in question. The resolver requires, as in the X509 certificate architecture, only a list of authenticated anchors configured out-of-band of the protocol and injected in the authentication chain.

In terms of the Signpost system, we have been delegated control of the `.signpost.io` domain and registered a signing key with the `.io` domain. For each user of the Signpost system, we delegate and authenticate control to a subdomain and redirect DNS queries to the Signpost Controller of the user personal cloud, where the user can register its devices. As an example with reference to Figure 5.2, user Alice is granted control of the domain `alice.signpost.io` where she can register her laptop under the domain name `laptop.alice.signpost.io`. By running a Signpost server, an individual has a globally accessible authenticated public identity on the Internet via their public-private key-pair. Using this key-pair, a user can sign and authenticate messages, bootstrap public key cryptography mechanisms and run key-exchange mechanisms such as Diffie-Merkle-Hellman Rescorla [1999] and derive new shared private keys between any two devices over unsecure channels.

The base DNSSEC RR types, defined in Arends et al. [2005], provide a mechanism to authenticate responses from a nameserver to a DNS resolvers. In terms of Signpost, we are also interested enabling an authentication mechanism the requests of a resolver. This enables the server to present a different view over the resource mappings, depending on the querying entity. [1] Signpost uses the SIG(0) RR type, defined in Eastlake [2000], which functions as a signature on a request. The record was introduced in order to allow authorized clients to update RR records on an authoritative server, while it permits a client also to point to the signing entity, in order to fit the authentication within the DNSSEC key structure.

Fitting DNSSEC in Signpost   In terms of Signpost architecture, we modify DNS functionality both on the client and the controller of the architecture. On the controller we develop a programmable DNS server that functions as an authoritative server for the user domain. The server provides DNSSEC access to any host in the Internet for the SOA, DNSKEY and NS records of the domain, signed with RRSIG records on the fly. Additionally, the server can verify SIG(0) records from queries and translate signed requests from Signpost clients in Connection Manager requests. A request for an A RR for domain name `laptop.alice.signpost.io`, signed with a SIG(0) record with a key from host `desktop.alice.signpost.io`, will be translated in a connection request between Alice's laptop and desktop device to the Connection Manager. In order to enforce liveness of Signpost RR records in the Internet, we set a zero TTL value on all RR records, thus disabling any DNS caching.

In the client side of the Signpost architecture, we have developed a local Signpost-aware DNS resolver. The resolver enhances the typical resolver functionality by signing Signpost connectivity request. For normal DNS queries, the resolver will fetch recursively requested records. For RR requests under the Signpost domain, the resolver augments the query with a SIG(0) record signed with the private key of the device.

Using the DNS protocol we are also able to ensure the functionality of the system when devices are disconnected from the Signpost Controller, while connected in the same network. Signpost uses DNS-based service discovery (DNS-SD) Cheshire and Krochmal [2011b] in order to enable secure local device connectivity. DNS-SD is a

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[1] *"DNS servers can play games. As long as they appear to deliver a syntactically correct response to every query, they can fiddle the semantics."—RFC3234* Carpenter and Brim *[2002]*

specification of DNS RR organisation which enables efficient service advertisement and browsing and along with Multicast-DNS Cheshire and Krochmal [2011a] they establish an efficient local service discovery mechanism. The combination of DNS-SD and multicast-DNS is currently a widely used mechanism for service discovery in local networks and supported by most available operating systems. The Signpost system registers and advertises on the host a service record for the Signpost service with name _sp._tcp.local in the local network with a target of the domain name of the device, along with an RRSIG RR and the DNSKEY RR of the device, signed with the private key of the user. Using these records a Signpost client is able to verify a destination Signpost service and establish a control channel. The device will use the service advertisement information when a name lookup is performed. During a name lookup, the destination device will function as a Signpost Controller responsible for the specific device only and employ all the logic described previously.

5.3.5 Security and Key Management

In order to bootstrap device authentication, Signpost uses a public key cryptography mechanism integrated with the DNSSEC protocol. Signpost employs a key hierarchy, which enables the system to control and revoke trust on device keys in real time. Our key hierarchy relies and extends the key hierarchy defined by the DNSSEC protocol. For a Signpost cloud the user should construct at least two keys, A *Zone Signing Key (ZSK)* and a *Device Signing Key(DSK)*. ZSK signs the DSK and a signed hash of the ZSK is stored as a DS RR in the signpost.io name servers, in order to add the key in the global DNSSEC keychain. DSK is used by the controller to sign Device Keys. This differentiation of user keys permits a Personal cloud to have a persistent anchor in the DNSSEC key chain. The DSK can be updated in fixed weekly basis or when a key compromise is detected, without having to rely in the DNSSEC infrastructure to propagate the updates to other servers. Each device registered with the cloud must construct a private Device Key when it first joins the system and add the public key to the Controler device key cache over a trusted channel. The public key will be signed by the DSK of the Cloud and shared as a DNSKEY RR by the controller. A device of a Signpost cloud requires only an anchor in the global DNSSEC key infrastructure and it can easily verify the validate of any Signpost key.

5.4 Evaluation

In this section we analyse the performance of the Signpost system and its impact in the functionality of traditional Personal Cloud applications. We, present the implementation details of the system (Section 5.4.1), measure the performance of the Signpost tactics over the Internet (Section 5.4.2) and present a small scale study of the functionality of current application over the Signpost system.

5.4.1 Signpost implementation

Signpost is implemented predominantly in Ocaml and reuses a number of available protocol libraries. Signpost uses ocaml-dns for DNS server and client implementations, cyptokit library for cryptographic key manipulation and ocaml-openflow library for OpenFlow controller functionality. Signpost also uses a portion of C code to implement binding with the OS routing stack. Signpost provides support for a wide range of platform. We have managed to run Signpost successfully under Linux and Android, using the Open vSwitch switch implementation, and under MacOSX, using the userspace switch implementation provided by the ocaml-openflow library.

Signpost provides support for the following tactics:

- *Direct*: The tactic enables communication path between devices over the network without any tunneling mechanism. The functionality of the tactic provides a mechanism to test direct connectivity between the two devices over a number of well-known ports and if successful it will insert a single OpenFlow rule to translate Signpost IP addresses to the respective network addresses.

- *OpenVPN*: The tactic enables communication paths using the OpenVPN tunnelling mechanism. During connection, Signpost devices use the Signpost key infrastructure to generate public keys and bootstrap the OpenVPN authentication mechanism. Because of some limitation on the certificate chain evaluation of OpenSSL, during a connection the Tactic generates transient private keys, signed by the user private key, while the tactic will inject in the trusted certificate keychain a key certificate of the destination device signed by the private key of the device. The tactic configure the OpenVPN software to expose connectivity over an Ethernet TUN/TAP device Krasnyansky et al. [2002], which is added

under the control of the OpenFlow switch where OpenFlow packet forwarding rules establish full bi-directional connectivity. *Mention OpenVPN ARP cache*

- *SSH*: The tactic enables connectivity of the system using the SSH protocol. For this tactic we configure and run a separate ssh daemon on every Signpost device. The daemon runs on port 10000 and permits key-based authenticated connectivity for tunneling. User authentication is ensured by proper manipulation of authorized keys on the server configuration. Signpost clients append device public keys in the authorized_key file in an ad-hoc manner, while clients are instructed to use the private key of the device upon connection. The SSH program is configured to expose TUN/TAP Ethernet interfaces between devices, which are added under the control of the OpenFlow switch.

- *Privoxy*: This tactic enables HTTP request anonymization using the Privoxy Privoxy [2013] HTTP proxy. In order to achieve this, we have predefined a strict configuration of the privoxy software which strips all HTTP headers that may leak personal information of the user. In order to establish connectivity, the tactic handles TCP flows in a proactive manner. For each SYN packet, the tactic install bi-directional flows, forwarding data from the application to the loopback device and the listening port of the Privoxy.

- *Tor*: The tactic enables connectivity between devices over the Anonymized network of Tor Dingledine and Mathewson [2006]. Tor client software exposes a SOCKS proxy on the local machine which can provide TCP connectivity to flows over the Tor overlay network. In order to enable bidirectional connectivity over the Tor network, the tactic uses the hidden service functionality of the system. A node in Tor is able to expose listening ports. In order to achieve this, the system uses random domain names under the .onion domain to address nodes and it takes advantage of the socks protocol capability to embed name lookups in SOCK connection requests. Upon the request for connection over the Tor network, the Signpost client will negotiate with the remote device its domain name under the Tor abstraction. Upon a SYN packet transmission of the application to the remote device, the tactic will initiate a TCP connection with the local SOCKS proxy with a request to establish a path between the two devices.

In parallel, once the TCP connection is established with the local SOCKS proxy, the tactic will respond to the initial SYN request with a SYNACK and advertise a zero window in order to suppress any further data transmission from the application. Once a SOCKS response is returned by the SOCKS proxy, the tactic will either respond to the initial TCP flow with an ACK with a non-zero window and insert appropriate OpenFlow rules to permit connectivity between the two device over the SOCKS tunnel, or the client will inject a TCP RST if the SOCKS response was unsuccessful.

- *DNS-SD*: This tactic is used to advertise services provided by the Signpost devices. DNS-SD Cheshire and Krochmal [2011b] is a popular mechanism, provided by the OS, to advertise available host services in the local network. The tactic doesn't provide any path establishing functionality to applications, but it aid the advertisement of host functionality. The Tactic implementation intercepts DNS-SD service advertisement and propagate them over the control channel, to the other devices of the Cloud. Each Signpost client is responsible then to inject DNS-SD multicast packets over the local loopback device of the OS and propagates information in the local ZeroConf daemon.

- *NAT-punch*: This tactic uses simple packet injection mechanisms in order to allow devices to bypass NAT boxes. The functionality of this tactic is limited and covers only the cases of Full-cone NAT, Address-restricted NAT and Port-restricted NAT, and requires that the NAT functionality doesn't perform any stateful packet filtering. Nat punching functionality is achieve by using the Controller as an intermediate service that can infer the port mappings configuration of the NAT-box. On a TCP connection, the server will intercept the SYN request, propagate the important TCP header parameters over the control channel to the destination device and in parallel will send a SYN packet from the device to the Controller in order to infer the port mapping applied by the device. On the destination device the Signpost client will generate a SYN packet with similar values to the inital SYN packet and send the packet to the local listening service over the loopback device as well as the Controller of the Cloud. During this processing, both ends of the TCP connection hold the connection idle with a zero window. Once the exact port-mapping is inferred on the controller, the information is

Tactic name	Direct connectivity			via-cloud connectivity		
	setup (sec)	throughput (kbps)	latency (msec)	setup (sec)	throughput (kbps)	lat
Direct	10	94.1	1380	-	-	
Openvpn	21046	10	10	21466	18700	
SSH	10	10	10	10	10	
tor	10	10	10	10	10	
NAT-punch	10	10	10	-	-	

propagate to both devices, which will insert appropriate OpenFlow commands to manipulate source and destination port renumbering and notify the end-points to resume data transmission using a ACK with a non-zero window size.

5.4.2 Tunnel Evaluation

5.4.3 Application compatibility

5.5 Conclusions

- This is an elementary approach for Personal Cloud computing.

- A number of issues remain unandressed but can easily fit in the Signpost architecture

- extending the policy mechanism, we can integrate in a Personal cloud devices from other users. Need though to develop a more refined policy that will enable the user to control access from devce outside of its personal to a subset of the available services.

- Tighter DNS integration of the control protocol.

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Chapter 6

Conclusions and Future Work

Here I put my conclusions ...

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