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ORCHESTRATION OF LOGICAL RESOURCES IN SOFTWARE DEFINED INFRASTRUCTURES

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Ph.D. Thesis

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by

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ABSTRACT

ORCHESTRATION OF LOGICAL RESOURCES IN SOFTWARE DEFINED INFRASTRUCTURES

by
Elisa MAINI, Doctor of Philosophy, 2015

The diffusion of ultra-broadband (in terms of high bandwidth and low latency) connection, IT hardware advances, and growing availability of open-source software are causing a paradigm shift in the world of network architectures. In the last years, the number of devices and smart-objects connected to the network has grown exponentially and the so-called "machine intelligence" has become part of the life-cycle of industries, agriculture, smart cities, and eventually public institutions. In this context, the initiative to integrate heterogeneous networks, including wired/wireless networks and smart-objects, from both the service management and control viewpoints is considered a critical aspect of Future Networks. The effect of all these drivers is the so-called "Softwarization" of telco infrastructures, where the approach to this integration is through the deployment of a network infrastructure supporting software-driven network features that can be instantiated on-demand. These instantiations will be addressing the changing service requirements and resource constraints, yet be scalable across multiple services and multiple domains, can maintain QoS for end-users of a service, and that provide a level of isolation and security from one service to another.

Research and development activities are currently clearly focused on several concepts such as programmable networks, network virtualisation, open interfaces and platforms, and increasing the degree of intelligence inside the network. The next generation of Software Defined Infrastructures needs to move from being merely *Defined* by software to be *Driven* by software and must be capable of supporting a multitude of players that exploit an environment in which services are dynamically deployed and quickly adapt over a heterogeneous physical infrastructure, according to chaining requirements. One of the main challenges includes the design and the implementation of specific mechanisms for runtime orchestration of logical resources in wired environments. In addition to mechanisms for controlling virtual resources in Software Defined Infrastructures, another challenge includes the design and implementation of specific algorithms for the efficient mapping of virtual resources onto physical resources.

This thesis shows how network architectures based on open network features and resources abstraction offers innovative solutions addressing some of the challenges of Future Networks.

Keywords: management, orchestration, network virtualisation, software defined networking, network function virtualisation, placement algorithms, performance evaluation.

PREFACE

Some of the research described in this thesis has undergone peer review and has been published in, or at the date of this printing is being considered for publication in, academic journals, books, and conferences. This notice serves to indicate that certain parts of the material presented here have already been described by the author in the literature, and some parts are therefore subject to copyright by either publishers or the author outside this volume. Co-authors are in all instances the student's thesis advisors.

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List of Abbreviations

ATM	Asynchronuos Transfer Mode
BRAS	Broadband Remote Access Server
CAPEX	CAPital EXpenditures
CDN	Context Delivery Network
CPE	Customer Premise Equipments
DC	Data Center
DCSA	Data Collection and State Analysis
DNS	Domain Name Service
DPI	Deep Packet Inspection
EPV	Evolved Packet Core
ETSI	European Telecommunication Standards Institute
FIB	Forwarding Information Base
GRE	Generic Routing Encapsulation
GSMP	General Switch Management Protocol
ICT	Information and Communication Technology
IGRP	Interior Gateway Routing Protocol
IoT	Internet of Things
IRTF	Internet Research Task Force
IT	Information Technology
LAN	Local Area Network
MPLS	Multiprotocol Label Switching
NAT	Network Address Translation
NFV	Network Function Virtualisation
NRLD	Network Resource Description Language
NV	Network Virtualisation
NO	Network Operator
NOS	Network Operating System
ONF	Open Network Foundation
OPEX	OPerational EXpenditures
OS	Operating System
OSS	Operational Service System
OTT	Over-The-Top
OVSDB	Open vSwitch Database Management Protocol
PCEP	Path Computation Element Communication Protocol
PCRF	Policy and Charging Rules Function
QoE	Quality of Experience
QoS	Quality of Service
RO	Resource Orchestrator
SDI	Software Defined Infrastructure
SDN	Software Defined Networking
SNMP	Simple Network Management Protocol
SP	Service Provider
TCAM	Ternary Content Addressable Memory
TEM	Telecom Equipment Manufactures
VLAN	Virtual Local Area Network
VM	Virtual Machine
VMM	Virtual Machine Monitor
VNF	Virtualised Network Function
VPN	Virtual Private Network
WAN	Wide Area Network

"If we know what it was we were doing, it wouldn' t be called research".

Albert Einstein

To my husband, Andrea.

Chapter 1

Introduction

1.1 Context and motivation

The diffusion of ultra-broadband (in terms of high bandwidth and low latency) connection, IT hardware advances, and growing availability of open-source software are causing a paradigm shift in the world of network architectures [1]. In the last years, the number of devices and smart-objects connected to the network has grown exponentially and the so-called "machine intelligence" has become part of the life-cycle of industries, agriculture, smart cities, and eventually public institutions. In this context, the initiative to integrate heterogeneous networks, including wired/wireless networks and smart-objects, from both the service management and control viewpoints is considered a critical aspect of Future Networks [2].

The effect of all these drivers is the so-called "Softwarization" of telco infrastructures [3], where the approach to this integration is through the deployment of a network infrastructure supporting software-driven network features that can be instantiated on-demand. These instantiations will be addressing the changing service requirements and

resource constraints, yet be scalable across multiple services and multiple domains, can maintain Quality of Service (QoS) for end-users of a service, and that provide a level of isolation and security from one service to another.

Research and development activities are currently focused on several concepts such as programmable networks, network virtualisation, open interfaces and platforms, and increasing the degree of intelligence inside the network. The next generation of Software Defined Infrastructure (SDI) needs to move from being merely *Defined* by software to be *Driven* by software and must be capable of supporting a multitude of players that exploit an environment in which services are dynamically deployed and quickly adapt over a heterogeneous physical infrastructure, according to chaining requirements.

Programmability in network elements (routers, switches, and so forth) was introduced over a decade ago as the basis for the rapid deployment and customization of new services (i.e. the first architectural state of the Software Defined Networking, SDN conceptual view [4]). Advances in "programmable networks" have been driven by the industry adoption of OpenFlow [5] and a number of requirements that have given rise to a new business model of the same telecom business actors, and roles (e.g. the second architectural state of the SDN conceptual view: Software Defined Networks). We are moving away from the "monolithic" approach to networks where systems are vertically integrated, towards a component-based approach, where systems are made of multiple components from different manufacturers, interacting with each other through open interfaces to form a service. The result is a truly open service platform representing a marketplace wherein services and service providers compete with each other, while customers may select and customize services according to their needs (e.g. the third architectural state of the SDN conceptual view: Software-Driven/Enabled Networks) [6].

The next generation of SDIs will be engineered to facilitate the integration and delivery of Information and Communication Technology (ICT) services, computing and network clouds leading to redefine roles and relationships between the players in the value chains, whilst opening new service models and business opportunities for the digital society and economy. Moreover, SDI will enhance integration of the key enabling technologies such as programmability, network virtualisation, Network Function Virtualisation (NFV) [7], [8], and self-management.

1.2 Problem statement

The integration of the Internet, software technologies and traditional telecommunications and communication technologies, has been always a challenge for network and Service Operators (SOs), as far as service deployment and management [6], [9], [10] is concerned.

One of the main challenges includes the design and the implementation of specific mechanisms for run-time orchestration of logical resources in SDIs, considering only wired environments. A major aspect for this challenge is the development of technology-specific methods that enable the provisioning of virtual networks and storage and a processing resources over a SDN substrate infrastructure. This include the creation, configuration and tearing-down of virtual resource components, considering both networking and computational and storage resources. By using NFV, networking resources can be re-allocated according to changing network conditions or service demands. Additionally, this challenge considers the development of autonomous actions that provide virtual network stability, performance, and optimizations even with the absence of higher-level control. These include, for example, virtual resource remapping in case of resource scarcity, increased

resilience through transparent resource migration in case of hardware failure or energy saving using adaptive virtual resource consolidation.

In addition to mechanisms for controlling virtual resources in SDI, another challenge includes the design and implementation of specific algorithms for the efficient mapping of virtual resources onto physical resources in SDN [104], [12]. The mapping takes into account the top-level service and operational requirements such as QoS requirement (e.g. *minimizing network latency*). By addressing this challenge, virtual networks can be customized with "optimally" allocated capabilities such as virtual nodes (with computing and storage capabilities), virtual links and paths for specific networked services.

This thesis shows how network architectures based on open network features and resources abstraction offers innovative solutions addressing some of the challenges of Future Networks.

1.3 Contributions

The issue of the logical resource orchestration (including network functions and services) raises several research challenges. Resource orchestration should be supported by a centralised software entity (the Resource Orchestrator – RO), whose overall goal is to ensure successful hosting and delivery applications by meeting QoS of service application owners (e.g. maximise availability, maximise throughput, minimise latency, avoid overloading, etc.) and resource providers (e.g. maximise utilisation, maximise energy efficiency, maximise profit, etc.) respectively. The RO is responsible for a number of orchestration operations (including resource selection, resource deployment, resource monitoring, and resource control), which need to be programmed to control the resources at design time, as well as at the run time for ensuring the fulfilment of QoS objectives.

Based on representative use cases and application scenarios, the work in this Ph.D. develops approaches and methodologies that address the issue of resource orchestration. The contributions of this work are organized into four main Chapters, as follows.

1. **Applicability of software defined and virtualisation concepts in Future Network scenarios**: this Chapter aims to analyse the applicability of SDN, Network Virtualisation (NV) and NFV principles in evolutionary network contexts by defining innovative application scenarios. Specifically, the Chapter identifies both the main critical aspects of the current Internet – characterised by static and uneconomical resources – and the potential advantages that could be achieved by integrating new paradigms/technologies such as SDN and NFV (e.g. programmability and costs reduction) [64].

2. **Highly dynamic virtual environments description**: this Chapter aims to provide a mathematical description for highly dynamic virtual environments including virtual networks, logical networks, cloud computing networks, mobile ad-hoc networks, sensor networks and Internet of Things (IoT). Using graph and queuing theory, we have analysed logical and topological models in order to verify the expected dynamics and to get information about the network performance, efficiency, and robustness. In [81], we have developed a network model consisting of three key components: (i) a model for traffic generation, (ii) a routing algorithm for the forwarding of data packets, and (iii) a graph model to represent network topology. Using such a network model, we have analysed hypercube networks and compared them with other regular structures (e.g. regular lattice) in order to show their advantages and applicability to distributed Data Centers (DCs).

3. **Management and orchestration of logical resources in SDI**: in this Chapter the management of the "complexity" of Operators' networks is analysed by using flexible software solutions. A deep integration of software in the networks offers both the possibility to develop network functions as applications, executing either in the Clouds or in an ensemble of distributed Information Technology (IT) resources, and providing new services to the end users. In fact, SDN and NFV offer the possibility to manage and "orchestrate" both the virtual and physical networks resources according to specific requirements (e.g. latency, energy consumption) with high flexibility.

4. **Framework for the dynamic placement of virtual network functions and services**: this Chapter describes an architecture based on Resource Orchestrator. The main task of such Resource Orchestrator is to achieve a dynamic placement of virtual IT resources in the network minimising the energy consumption. Specifically, we have considered and compared different algorithms and strategies for the allocation of virtual resources on physical nodes [12], [104] and provided some experimental results by using the Very Lightweight Service Platform (VLSP) testbed[1].

To summarise, this thesis highlights the main criticality of the current Internet and investigates how new network paradigms and principles such as SDN and NFV might support Network Operators (NOs) and network administrators to make network management easier. The research approach adopted in this work may be defined as an "evolutionary approach", whose aim is to provide technical solutions and new ideas to overcome limitations of the current technologies.

[1] http://clayfour.ee.ucl.ac.uk/usr/

1.4 Thesis outline

The rest of this thesis is organized as follows. Chapter 2 provides the state-of-the art and the necessary background on driver technologies for Future Networks. It also illustrates the main open issues and research challenges highlighting the motivations and the main contribution of the thesis. Chapter 3 analyses the applicability of SDN, NV and NFV principles in evolutionary network contexts. Chapter 4 provides a mathematical description for high dynamic virtual environments. Chapter 5 analysis some aspects related to the management and orchestration of virtual networks. Chapter 6 describes an architecture based on Resource Orchestrator for the management and orchestration of network resources. In Chapter 7 some placement algorithms and strategies are considered and compared. Finally, Chapter 8 concludes with final remarks and illustrates the future direction of the work.

Chapter 2

SDN, NV and NFV: terms and definitions

The progress of IT technology is impacting the evolution of ICT and heavily the life of the modern consumers. Nowadays, ICT plays an important role in the way people interact: end users are connected anytime and anywhere by embedded devices, which include not only smartphones and tablets but a huge number of smart-objects empowered with intelligence and capabilities to interconnect with any other object (usually not considered yet as network nodes). New services demanded by end-users, are characterised by strict requirements in terms of availability, QoS, QoE, dependability, resilience and protection as well as by high dynamism (new services and applications are introduced daily/hourly). In this "complex" and pervasive environment, the network that delivers these services needs to be capable of adapting to the unpredictable shifting demands, due to the ubiquitous access, quickly, automatically and economically. As such, network management and the orchestration of network resources is becoming a key challenge both the industry and research community. Despite the evolution of technologies, most of existing management applications have been applied to the management of individual devices [14]. New approaches to address the management of Future Networks are, therefore required.

In last years SDN, NV and NFV have gained lot of attention by both industry and research community, thanks to three synergy concepts: (i) network programmability by a clear separation of data and control planes, (ii) *sharing* of network infrastructure to provide multi-tenancy, and (iii) *replacing* the functions that traditionally run on a specialized hardware, with the software-realizations that run on commodity servers.

Recently, a group of NOs, SPs, and vendors have created the ONF [15], an industrial-driven organization, to promote SDN, NV, NVF and standardize the protocols [5]. There have also been standardization efforts on SDN at the IETF [16] and IRTF [17].

2.1 Software Defined Networking

This section provides a brief survey of the state-of-art of SDN. It starts with discussing the historical prospective of "programmable" networks from the early ideas to recent developments, covering use-cases and drivers. Then, the section presents the SDN architecture models and the OpenFlow standard in particular, discussing current alternatives for implementation [18].

2.1.1 SDN precursors: road to SDN

This subsection provides overview of the early programmable networking efforts and precursors to the current SDN paradigm, which was designed to simplify network hardware while improving the flexibility of network control. While SDN has received a considerable amount of industry attention, it is worth noting that the idea of "programmable" networks and decoupled control logic has been around for many years. The Table 2.1 and Figure 2.1 provide the summary of such technologies that act as precursors to SDN (more details can be found in [18], [19], [39]).

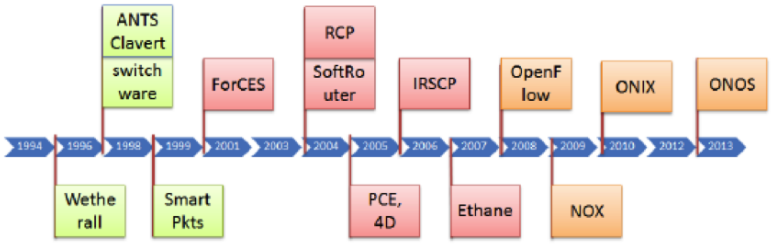


Figure 2.1: SDN precursors

Table 2.1: SDN-related technologies

Technology	**Remarks**
Open Signaling	Based on a clear separation between switching hardware and control software, the concept of open signalling creates an open programmable networking environment. Network entities can be realized as high level objects with well defined software interfaces, facilitating the creation of multiple mechanisms for connection management.
Active Networking	Refer to the addition of user=controllable computing capabilities to data networks. Network is no longer viewed a passive mover a bits, but as a general computing engine.
NETCONF [21]	Define a simple mechanism through which a network device can managed, configuration data information can be retrieved, and new configuration data can be uploaded and manipulated. Protocol allows the device to expose a full and formal APIs.
ForCES [22]	Define a framework and associated protocol(s) to standardize information exchange between the control and forwarding plane - this allows CEs and FEs to become physically separated standard components.
4D [23]	Based on three principles: network-level objectives, network-wide views, and direct control. Re-factor functionality into four components: data, discovery, dissemination, and decision planes
Ethane [24]	Network architecture for the enterprise single network-wide fine-grain policy, and then enforces it directly centralized controller that manages the admittance and routing of flows.
RCP [25]	Re-factoring the IP routing architecture to create a logically centralized control plane separated from forwarding elements. In RCP, the focus is on the BGP decision process, and the route control process needs large operators' perspective.
SANE [27]	A protection architecture for enterprise networks. Define a single protection layer that governs all connectivity within the enterprise. All routing and access control decisions are made by a logically-centralized server that grants access to services according to declarative access control policies.
SS7 [28]	Common Channel Signaling (CCS) is a signaling method which provides control and management in the telephone network. CCS uses a separate out-of-band signaling network to carry signaling messages. SS7 is a CCS system.

The Open Signaling (OPENSIG) working group began in 1995 with a series of workshops dedicated to making ATM, Internet and mobile networks more open, extensible, and programmable [29]. The core of their proposal was to provide access to the network hardware via open, programmable network interfaces; this would allow the deployment of new services through a distributed programming environment. Motivated by these ideas, an IETF working group was created, which led to the General Switch Management Protocol (GSMP) [30], a general purpose protocol to control a label switch. In the mid 1990s, the Active Networking [31], [32] initiative proposed the idea of a network infrastructure that would be programmable for customized services. However, it never achieved the significance necessary to be transferred to widespread use and industry deployment, mainly due to practical security and performance concerns [33]. The 4D project [23], [25], [34] advocated a clean slate design that emphasized separation between the routing decision logic and the protocols governing the interaction between network elements. Finally, Ethane [24] laid the foundation for what would become SDN. Ethane's identity based access control would likely be implemented as an application on top of a SDN controller such as NOX [35]. A parallel approach to SDN is under development by the IETF Forwarding and Control Element Separation (ForCES) Working Group [22].

2.1.2 SDN architecture

As shown in the Figure 2.2, a SDN architecture consists of three main tiers.

1. The *Application tier* encompasses solutions that focus on the expansion of network services. These solutions are mainly software applications that communicate with the controller.

2. The *Control Plane tier* includes a logically-centralized SDN controller, that main-

tains a global view of the network that takes requests through clearly defined APIs from application layer and perform consolidated management and monitoring of network devices via standard protocols.

3. The *Infrastructure (or Data Plane) tier* involves the physical network equipment, including Ethernet switches and routers. It provides programmable and high speed hardware and software, which is complaint with industry standards.

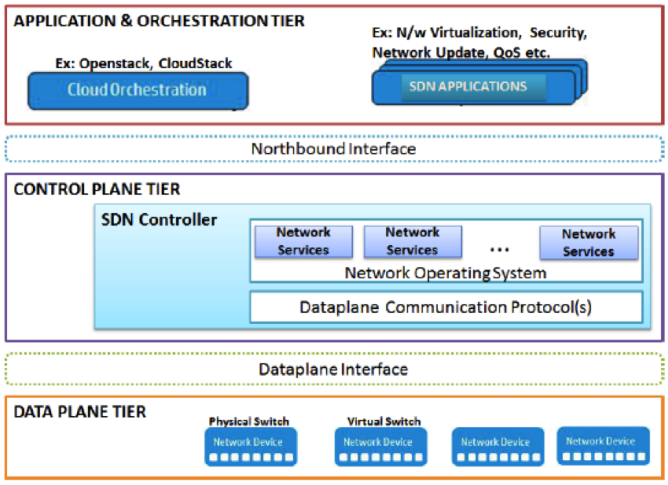


Figure 2.2: SDN architecture

At the bottom layer, the physical network consists of the hardware forwarding devices which store the Forwarding Information Base (FIB) state of the network data plane (e.g., Ternary Content Addressable Memory entries – TCAM – and configured port speeds), as well as associated meta-data including packets, flows, and port counters. The devices of the physical network may be grouped into one or more separate controller domains, where each domain has at least one physical controller. Data plane interface or standards-based protocols, typically termed as "southbound protocols", define the control communications between the controller platform and data plane devices such as physical and virtual switches and routers. There are various southbound protocols

such as OpenFlow, Path Computation Element Communication Protocol (PCEP), Simple Network Management Protocol (SNMP), Open vSwitch Database Management Protocol (OVSDB), etc.

The Control Plane tier is the core of the SDN, and is realized by the controllers of each domain, which collect the physical network state distributed across every control domain. This component is sometimes called the Network Operating System (NOS), as it enables the SDN to present an abstraction of the physical network state to an instance of the control application (running in Application Layer), in the form of a global network view.

Northbound open APIs refer to the software interfaces between the software modules of the controller and the SDN applications. These interfaces are published and open to customers, partners, and the open source community for development. The application and orchestration tools may utilize these APIs to interact with the SDN Controller. Application layer covers an array of applications to meet different customer demands such as network automation, flexibility and programmability, etc. Some of the domains of SDN applications include traffic engineering, network virtualization, network monitoring and analysis, network service discovery, access control, etc. The control logic for each application instance may be run as a separate process directly on the controller hardware within each domain.

From the above description of the architecture, we can see that the SDN controller is a key element (both in terms of southbound and northbound interactions). Ashton *et all* [26], prepared a check-list of what to look for in an SDN controller. In this list, they included the following: (i) OpenFlow support (versions and extensions); (ii) network functionality (network isolation, QoS support); (iii) programmability (APIs and policy

definitions); (iv) reliability (redundancy and availability); (v) centralized monitoring and visualization; (vi) network virtualisation support (creation and management); (vii) scalability (number of switches, hosts, flows); (viii) performance (delays, drops and throughput); (ix) security (authentications and filters); (x) vendor characteristics. This check-list provides an understanding of challenges in development of a SDN controller.

2.1.3 SDN control models

Enterprises and NOs who deploy a Software Defined Network typically use one of the two different models of SDN: centralized or distributed. Each model has different infrastructure elements and requirements to consider. A successful deployment will require choosing the right SDN architecture, then testing it in an organized way, based on the right infrastructure.

A. *Centralized controller model (or revolutionary model).* The centralized model of SDN technologies, as discussed in the SDN precursors subsection, has evolved from researchers who aimed to replace adaptive discovery, a distributed process, with central control of forwarding. In this architecture, a central software process (or centralized SDN controller) maintains the entire topology and status of the network' s devices and understands the network addressing and connectivity from the user's perspective. The central process running on the controller may support various algorithms and policies to define routes through the network for each and every flow [36], [37]. The paths are created by addressing all devices along the way to update their (forwarding) table to forward the packets along the path correctly. The OpenFlow protocol was designed to support the centralized controller to communicate forwarding table changes to network devices. This communication could

happen either proactively, based on a network map, or reactively, in response to a request from a device. The challenge in this SDN approach is the lack of a proven model for centralized control, as there is no proof that central control of networking can scale and there exists no currently accepted technology to test its capabilities. The problems of scalability and central control can be addressed in a data center, a delivery network or a Wide Area Network (WAN) core, rather than whole of the Internet or even an enterprise WAN. Deploying centralized SDN in these smaller domains can spread widely and quickly. However, recently various researchers and vendors are working to explore the best way of linking disparate SDN domains into a complete end-to-end network.

B. *Distributed SDN (or evolutionary model).* The distributed nature of networking intelligence in the Internet has been highly successful. Also, the same control protocols that are used in the Internet have also taken hold in local and private networks. Many experts and vendors, who have both witnessed and been part of this success of adaptive distributed model, believe the "purist model" (fully centralized SDN strategy), is a revolutionary one and the evolutionary approach is more prudent. To this group, which includes many IP experts and router equipment vendors, the software that should be defining network behaviour is higher-level software, perhaps even application software [36]. The distributed model "adds" mechanisms of software-based control to traditional IP and Ethernet networks. We should note that the distributed model, like the centralized model, accepts the need to gather information about network status and collect it at a central point where it can be acted on to manage the performance. However, in the distributed model, the goal of SDN is to offer more controllable behaviour. Typically, such goals are achieved by

levering on various existing protocols like Multiprotocol Label Switching (MPLS), Generic Routing Encapsulation (GRE), and policy-based protocols. For example, Policy and Charging Rules Function (PCRF) – part of the Evolved Packet Core (EPC) that supports service data flow detection, policy enforcement and flow-based charging – could be the principal means by the SDN controllers decide how to set up and manage flows [38]. The main challenge for distributed SDN is that it is yet to prove that it can offer the kind of control granularities over traffic and connectivity that centralized SDN technologies could offer. In addition, there's also the problem of what should be the accepted framework for applying distributed SDN principles - when various vendors choose different approach to integrate SDN into their existing closed systems.

2.1.4 SDN and OpenFlow

In the initial white paper [5], OpenFlow was simply referred as "*a way for researchers to run experimental protocols in the networks they use every day*". The analogy used by the authors in describing OpenFlow is to think of OpenFlow as a general language or an instruction set that lets one write a control program for the network rather than having to rewrite all of code on each individual router. In centralized SDN architecture (the model that standards group ONF support) the key element is the connecting technology that communicates central control decisions to devices. OpenFlow has become the official protocol to use in a centralized SDN model to make high-level routing decisions. As a result, the creation of central-control SDN must be based on selecting devices and control software that support the OpenFlow standard.

OpenFlow is not yet a complete standard, and is still undergoing significant changes.

Tom Nolle [42], highlighted following shortfalls of OpenFlow. Openflow doesn't have a mechanism for fully managing devices, particularly for con- trolling port/trunk interfaces and queuing. OpenFlow doesn't communicate network status fully either, so central control software will need some source of information about loads, traffic and operational state for nodes and trunks. OpenFlow also lacks a specific process for establishing the paths to take between controller and switch, so there's a question of how OpenFlow networks "boot from bare metal", meaning how they become operational from a newly installed state. Finally, majority of the existing controllers have exposed northbound APIs, by which any application or management software can gain access to the features supported by the controller. However, it is still not clear what kind of software is available to take advantage of these interfaces and how it would be integrated with the controller. All of this makes it hard to conceptualize how a current network could evolve to support a centralized SDN model. The capabilities of the control software that runs above the SDN controller itself, are the key to success for the centralized SDN model [42].

2.1.4.1 OpenFlow roadmap

Initially the OpenFlow protocol standardized a data plane model and a control plane API, mainly by relying on the technologies that legacy switches already supported [39]. For example, network elements included the support of fine-grained access control and flow monitoring. On these elements, enabling OpenFlow' s initial set of capabilities was as easy as performing a firmware upgrade (without any hardware upgrade) to make it OpenFlow-capable. It is well- known that OpenFlow' s initial target deployment scenario was campus networks, meeting the needs of a networking research community actively looking for ways to conduct experimental work on network architectures within a research – friendly

operational setting – the "Clean-Slate" program [40]. In 2008-09, the OpenFlow group at Stanford (in partnership with 7 other universities) led an effort to deploy OpenFlow test beds across many campuses and demonstrate the capabilities of the protocol both on a single campus network and over a wide-area backbone network spanning multiple campuses [24]. As real SDN use cases materialized on these campuses, OpenFlow began to take hold in other realms, such as data- center networks, where there was a distinct need to manage network traffic at large scales. This led many experts to state that SDN/Openflow "*was born in the campus, matured in the data center*" [41]. Although OpenFlow includes many of the principles from earlier work on the separation of control and data planes, the rise of OpenFlow offered several additional intellectual contributions – such as (i) generalizing network devices and functions, (ii) the vision of a network operating system, and (iii) distributed state management techniques [39].

2.1.4.2 OpenFlow pros and cons

Over the past few years, almost all of the major network device vendors have announced OpenFlow support. As there are several versions of the OpenFlow standard, vendors may not have released software for the latest version. A number of OpenFlow compatible controllers can provide central control for a community of devices, and many OpenFlow-based SDN trials and deployments have been conducted using these tools. This success can be attributed to either a planned or unplanned collaborations between equipment vendors, chip-set designers, network operators, and networking researchers.

2.2 Network Virtualisation

As mentioned by Carapinha *et all* [43], virtualisation, in general, provides an abstraction between user and physical resources, so that the user gets the illusion of direct interaction with those physical resources. NV technology is a key component that not only is an integral part of the overall design to support the evolution and coexistence of different network architectures but also acts as an abstraction layer between services and infrastructure to facilitate innovation [44].

Some researchers [39] caution that a precise definition of network virtualisation is elusive, and some disagree as to whether some of the mechanisms such as slicing represent forms of network virtualisation. Accordingly, they define the scope of network virtualisation to include any technology that facilitates hosting a virtual network on an underlying physical network infrastructure. However, there have been some well agreed definitions on what a virtualised networks should be. A virtualised network may include overlays, tunnels, virtual devices, and multi-tenancy. But, it must provide total physical, location and stateful independence. That is, a virtualised network is a faithful and accurate reproduction of the physical network that is fully isolated and provides both location independence and physical network state independence [45].

The concept of network virtualisation is not new, and the concept has been realized in the past in the form of Virtual Local Area Networks (VLANs) and Virtual Private Networks (VPNs), which have been a highly successful approach to provide separate virtual networks over a common physical infrastructure. A complete study on network virtualisation would require a separate survey [46], [47], and below we just summarize in few sentences. The detailed survey of the evolution of Network virtualisation and programmable

networks can be found in [19].

VPNs fulfil the basic goal of providing different logical networks over a shared infrastructure. However, it suffers from a few limitations, such as: (i) all virtual networks are based on the same technology and protocol stack; (ii) lack of true isolation of virtual network resources; (iii) lack of clean separation of the roles of infrastructure provider and VPN service provider; (iv) only network administrators could create these virtual networks; (v) incrementally deploying new technologies is difficult.

To overcome some of these challenges, the researchers and practitioners resorted to running overlay networks, where a small set of "enhanced" nodes use tunnels to form their own topology on top of a legacy network [19]. In an overlay network, the "enhanced" nodes run their own control-plane protocol, and direct data traffic (and control-plane messages) to each other by encapsulating packets, sending them through the legacy network, and stripping the encapsulation at the other end. NV goes a step further (of what VPNs achieve) by enabling independent programmability of virtual networks [43]. So, a virtual network is no longer necessarily be based on IP, or any other specific technology, and any kind of network architecture can in principle be built over a virtual network. Another important strength of virtualisation is the native capability to handle multi-provider scenarios and hide the specificities of the network infrastructure, including the existence of multiple administrative domains. Although some workaround solutions exist, this has traditionally been a complicated issue for VPNs. Finally, network virtualisation aims to provide true isolation (instead of just an illusory isolation, as provided by VPNs) of virtual networks – sharing the same infrastructure – by employing various approaches such as using different operating system instances.

2.2.1 SDN and Network Virtualisation

As argued by Martin Cassado of VMWare [48], Network virtualisation and SDN are two different things and somewhat incomparable. SDN is a mechanism (that is relevant to system builders) and network virtualisation is a solution. He goes on to give the software-development analogy: "*A programming language would be the SDN using which the program(s) can be built out of it. Whereas, network virtualisation, on the other hand, is a product category or solution set that customers use to change the paradigm of their network*". That is, just as server virtualisation changed the paradigm for server operations and management, network virtualisation changed the paradigm for network operations and management. So, one can use SDN in NV but it is not mandatory. The researchers, apart from Martin Cassado, have also mentioned that SDN can be applied to many problems: graphic engineering, security, policy or network virtualisation. However, SDN in NV provides the possibility of deep programmability of network infrastructures for quickly modifying network behaviour and providing more sophisticated policy controls through rich applications.

Other researchers [39] argue that although network virtualisation has gained prominence as a use case for SDN, the concept pre-dates modern-day SDN and has in fact evolved in parallel with programmable networking. The two technologies (SDN and NV) are in fact tightly coupled: Programmable networks often presumed mechanisms for sharing the infrastructure (across multiple tenants in a data center, administrative groups in a campus, or experiments in an experimental facility) and supporting logical network topologies that differ from the physical network, both of which are central tenets of network virtualisation.

Apart from SDN as an enabling technology for network virtualisation in which Cloud providers need a way to allow multiple customers (or tenants) to share the same network infrastructure, the researchers have pointed additional two ways in which SDN and NV can relate to each-other. These additional two ways are (1.) evaluating SDN control applications in a virtualised environments before deploying on operational network (ex: MiniNet) (2.) Virtualising an SDN network (ex: FlowVisor).

In this remaining part we will focus mostly on the network virtualisation in cloud environment (DCs). In this context, we will broadly classify network virtualisation into two broad approaches – hop-by-hop and distributed edge overlays [49].

2.3 Network Function Virtualisation

Proprietary appliances that are too diverse, and ever growing in numbers, make the operation of service additions and upgrades increasingly difficult. Typically, these appliances are turn-key in-line systems, that maintain real-time state of subscriber mobility, voice and media calls, security and contextual content management [50]. NFV is an initiative of the ETSI Industry Specification Group to virtualise network functions previously performed by these proprietary dedicated hardware [51], [52].

The white paper on NFV [8] defines NFV as a consolidation of network functions onto industry-standard servers, switches and storage hardware located in Data/Distribution centers – an optimized data plane under virtualisation. NFV allows administrators to replace physical network devices (traditional) with software that is running on commodity servers. This software realizes the "network functions" that were previously provided by the dedicated hardware (network devices).

NFV is about implementing network functions in software - that run today on pro-

prietary hardware – leverage (high volume) standard servers and IT virtualisation. To understand the significance of NFV, we should consider the recent trends. The trends include increased user mobility, explosion of devices and traffic, emergence and growth of cloud services, convergence of computing, storage and networks and finally new virtualisation technologies that abstract underlying hardware yielding elasticity, scalability and automation. Accordingly, challenges and issues with respect to these trends include: (i) huge capital investment; (ii) operators facing increasing disparity between costs and revenues; (iii) increasing complexity, large and increasing variety of proprietary hardware appliances in operator' s network; (iv) reduced hardware life-cycle; (v) lack of flexibility and agility; (f) launching new services is difficult and takes too long, and often requires yet another proprietary box which needs to be integrated into existing infrastructure. The major advantage of using NFV is to address the above challenges and issues. As highlighted by Yamazaki *et all* [53], NFV helps to reduce network operator CAPital EXpenditures (CAPEX) and OPerational EXpenditures (OPEX) through reduced equipment costs and reduced power consumption, and also helps to reduce complexity and make managing a network and deploying new capabilities easier and faster.

As mentioned by Manzalini [54], there are quite a lot of middle-boxes deployed in current networks: not only these nodes are contributing to the so-called "network ossification", but also they represent a significant part of the network capital and operational expenses (e.g., due to the management effort that they require). Basically, a middle-box is a stateful system supporting a narrow specialized network functions (e.g., layer 4 to 7) and it is based on purpose-built hardware (typically closed and expensive). The next significant advantage of using NFV is in removing, or even reducing, the number of middle-boxes deployed in current networks, which would realize several advantages such as cost

savings and increased flexibility.

NFV also supports multi-version and multi-tenancy of network functions, and allows use of a single physical plat- form for different applications, users and tenants [55]. As described by Yun Chao [56] NFV enables new ways to implement resilience, service assurance, test and diagnostics and security surveillance. It facilitates innovation towards new network functions and services that are only practical in a pure software network environment. We should note that NFV is applicable to any data plane and control plane functions, fixed or mobile networks, and also the automation of management and configuration of functions is very important for NFV to achieve scalability. Ultimately, NFV aims to transform the way network operators architect and operate their networks [56].

2.3.1 Functions under NFV and the use cases

The network devices that the commodity server and the software aim to replace can range from firewalls and VPN gateways to switches and routers. Researchers [51] argue that almost any network function can be virtualised. The NFV focus in the market today includes switching elements, network appliances, network services and applications. Considering the description in the white paper [8], the below list summarizes various network functions that are considered for NFV [57].

- Switching elements such as Broadband Remote Access Server (BRAS) or Broadband Network Gateway (BNG), carrier grade NAT and routers.
- Mobile network nodes such as Home Location Register/Home Subscriber Server (HLR/HSS), Serving GPRS Support NodeMobility Management Entity (SGSN-MME), Gateway GPRS support node/Packet Data Net- work Gateway (GGSN/PDN-GW), RNC, NodeB and Evolved Node B (eNodeB).

- Functions in home routers and set top boxes.
- Virtualized home environments.
- Tunneling gateway elements such as IPSec/SSL virtual private network gateways.
- Traffic analysis elements such as Deep Packet Inspection (DPI), Quality of Experience (QoE) measurement.
- Service Assurance, Service Level Agreement (SLA) monitoring, Test and Diagnostics.
- Next-Generation Networks (NGN) signaling such as Session Border Controller (SBCs), IP Multimedia Sub- system (IMS).
- Converged and network-wide functions such as AAA servers, policy control and charging platforms.
- Application-level optimization including Content delivery network (CDNs), Cache Servers, Load Balancers, Application Accelerators.
- Security functions such as Firewalls, virus scanners, intrusion detection systems, spam protection.

Considering the above listing, the use-cases of NFV can cover virtualisation of mobile Core/Edge network nodes, home environment, content delivery networks, mobile base Station, wireless LAN controllers, Customer Premise Equipments (CPE) and Operation Services Systems (OSS).

Below, we enlist three practical deployments of NFV by major Telecom vendors.

- British Telecom, in partnership with HP, Intel, wind-river and tail-f, developed as proof of concept, a combined BRAS and CDN functions on Intel Xeon Processor 5600 Series HP c7000 BladeSystem using Intel 82599 10 Gigabit Ethernet Controller sidecars [200]. BRAS is chosen as an "acid test", whereas CDN is chosen as it architecturally complements BRAS.

- Move access network functions to the Data Center: Deutsche Telecom recently launched the "Terastream" project, which simplify IP access networks with NFV and SDN [58], [59].

- Reduce OPEX by simplifying home networks: France Telecom s proposal for virtual home gateway to Broad- band Forum. This proposal aims to increase flexibility in service deployment at the edge. The project is supported by Telefonica, Portugal Telecom and China Telecom [60].

2.3.2 NFV: realization requirements

Efficient realization of virtualised network functions should consider various aspects such as flexible processing, good performance with respect to handling millions of packets, efficient isolation mechanisms, flow migration and per-flow state to support mobility and finally support for multiple domains. Hence, when planning for the network functions virtualisation, the administrator has to address the following issues.

- Network functions to virtualise, considering the return of investment.

- Approach to integrate with the existing network management infrastructure, inter-operability.

- Scalability and elasticity issues.

- Resource management approach, and APIs to expose for ease of management.
- Availability and service failover/recovery mechanisms.

With the success of NFV, next generation network functions will be implemented as pure software instances running on standard servers - unbundled virtualised components of capacity and functionality. One of the existing approaches, as explained by Barkai *et all* [50] to realize such a network functions is to divide the whole process into two-steps-as described below.

- Significant component-based unbundling: unbundling refers to breaking up the packages that once offered as a single unit, providing particular parts of them at a scale and cost unmatchable by the original package provider [61]. In this case, it is the unbundling of both capacity and functionality locked in monolithic systems. In this first step, the monolithic systems are broken to components that will be running on virtual machines.
- Dynamically assemble discrete functional components to elastic end-to-end services. In this second step, the broken down components are assembled using various techniques such as flow-mapping [50].

One should note that such "scatter-gather" rearrangement of carrier functionality needs to work on commodity hardware. In addition, realization of NFV may also pose the challenge of assembling components developed by third-parties, into whole solutions.

2.3.2.1 Requirements from the VM perspective

Researchers [61] argue that the traditional virtual machines VMs may not be able to address the challenges of NFV. Traditional VMs are Fat - with huge overheads, poor

performance, and limited to only few VMs per server. Whereas, the VMs for NFV needs to be "Small" - with minimal overhead, excellent performance, many number of VMs per server, and natively supports network functions. One of the most popular VMs designed for NFV is ClickOS [61]. ClickOS is both light-weight (just around 1.4MB) and scalable. One can run many instances (in multiple thousands) on a single commodity PC. ClickOS also boots and migrates quickly, which can be used to realize the following network functions: Broadband Remote Access Server (BRAS), residential gateway, deep packet inspection, caching solutions, and enterprise firewalls.

2.3.3 SDN and Network Function Virtualisation

NFV provides immense possibilities for the providers to take advantage of the full potential of their network infrastructures, and to offer novel commercial services to their customers. SDN is not a requirement for NFV, but the two technologies are complementary - Intel terms NFV as a complementary initiative to SDN. Administrators/engineers can implement NFV, choosing to rely on traditional networking algorithms such as spanning tree or IGRP instead of moving to an SDN architecture. Yet, SDN can improve performance and simplify operations in a network functions virtualization environment.

Jim Machi, in his report [62], discusses elaborately this relation between SDN and NFV. He begins with mentioning that both technologies are designed to increase flexibility, decrease costs, support scalability, and speed the introduction of new services. In addition, Both SDN and NFV are likely drivers for innovation in telecommunications, networking and enterprise DCs. Finally, both owe their existence to similar market forces, including (i) better processor capability – significant improvement in the processor technology, (ii) simplification in connectivity – scope for separation of planes, and (iii) virtualisation

maturity.

While SDN was originally conceived to control the operation of network hardware devices, researchers have shown that it can just as easily integrate into an NFV environment, communicating with software-based components on commodity servers. The first white paper on NFV suggests that NFV and SDN have some overlap, but neither SDN is a subset of NFV, nor the other way around. So, the important questions to address are, Where do SDN and NFV intersect? and, How will the interaction between SDN and NFV impact the evolution of both ideas? These are the interesting and challenging questions that are, and will be, addressed by various researchers and vendors, in different ways in future.

In general, as long as NFV addresses the general case of "policy-managed" forwarding, and need dynamic service orchestration. SDN can play a role in realization of the same - i.e., NFV can increase network efficiency by using SDN concepts. NFV may demand virtual network overlays - the model of tunnels and vSwitches, would segregate virtual functions to prevent accidental or malicious interaction. This use of network overlays, for virtual function segregation, in NFV will drive the need for applying SDN based solutions. The multi-tenancy requirement would also influence NFV to adopt a software-overlay network model. In addition, if NFV allows services to be composed of virtual functions hosted in different data centers, that would require virtual networks to stretch across data centers and become end-to-end. An end-to-end virtual network would be far more interesting to enterprises than one limited to the data center. SDN will play a crucial role in such an extended NFV realization. Hence, SDN when applied to NFV can help in addressing the challenges of dynamic resource management and intelli- gent service orchestration. When using SDN-based approach for NFV, there are lots of aspects that need to be looked such

as:

- To seamlessly integrate the Virtualised Network Functions (VNF) into the existing SDN and cloud architectures - importantly, from the perspective of multi-tenancy.
- To ensure that the considered SDN controller that has all the necessary features the architecture needs. For example, flow-mapping service may or may-not exist as an in-built feature of the controller.
- To ensure if the scalability aspect of the existing SDN- architecture is sufficient to support potentially hundreds of millions of subscriber flows and their "affinity-associations" [50] to virtualisation function instances.
- To extend the existing SDN control model – decoupling of not just control and forwarding, but also control and forwarding topologies [50].

Different SDN solution vendors address some or all of these challenges in different ways. A typical approach would be include necessary network services at the control-tier and provide robust, efficient northbound abstractions (APIs), apart from having an ecosystem including application developers.

2.4 Current trends and research directions

SDN is moving towards next level of standardization and various companies are bringing out their products in the market. The vendors who have their own SDN controllers are moving towards setting up an *ecosystem*. The SDN ecosystem is where all the stakeholders – asic vendors, switch vendors, controller vendors and network application services vendors - join hands to either achieve interoperability or provide complete

suite of solution. The success of the open-source controller platforms like Opendaylight, with well- defined Northbound APIs, has fuelled the trend of controlling SDN networks smoothly through applications. These applications are developed targeting various domains and network services.

Chapter 3

SDN, NV and NFV in evolutionary network scenarios

Network Carriers are experiencing an increasingly challenging environment in which they have to continuously scale their networks in order to meet rapidly growing users and traffic demands. In fact in last years, a huge number of aggregation nodes, smart devices and "things" are creating very dynamic networks especially located at the edge of the current networks, up to around users. Technological advances in terms of hardware performance, embedded communication and cost reductions are progressively moving an enormous amount of processing, storage and and communication-networking capability towards to edge. Following such trend, Edge Networks will be where more of the "intelligence" will placed.

As already introduced in the previous Chapter, SDN, NV and NFV play an important role in the design of Future Networks. In fact, network programmability offered by SDN, NV and NFV provides software solutions for a fast, flexible and dynamic deployment of new network functions and services. This means that *executable code* may

be injected into the network elements (such as router, switches and application servers) in order to create the new functionality. The use of software to dynamically program individual network devices, network systems and services are driving the evolution of the current infrastructures towards to *Future Networks and Services*. Such concept has been introduced to take into consideration these new realities in the Telecommunications industry, characterized by factors such as the explosion of digital traffic (e.g. increasing use of Internet, increasing demand for new multimedia services and for a general mobility) and the convergence of networks and services.

The key feature in Future Network architecture is a clear split between the Core Network and Edge Networks. In fact, future infrastructures will be composed by *stateless* Core Network and a *stateful* Edge Networks and DCs. Key assumption is that network functions and services will be executed in ensembles of VMs, allocated and moved across a scalable distributed platform deployed at the edge and orchestrated with DC resources as depicted in Figure 3.1. So, the collection of the information related to the state of such *Edge ICT Fabrics* [64], of their resource capabilities, related usage (i.e. states) and data flows set-up, will be crucial to support orchestration and management operations.

From the points of view of NOs and SPs, as well as from other players angle, such as OTTs, enterprise networks providers, consumer electronics providers, etc, the programmability offered by SDN and NFV plays a crucial role in more application scenarios [63] detailed in the following subsections.

3.0.1 Examples of core scenarios

Core networks scenarios typically consider SDN and virtualisation technologies as paradigms providing incremental improvements (in terms of flexibility, programmability,

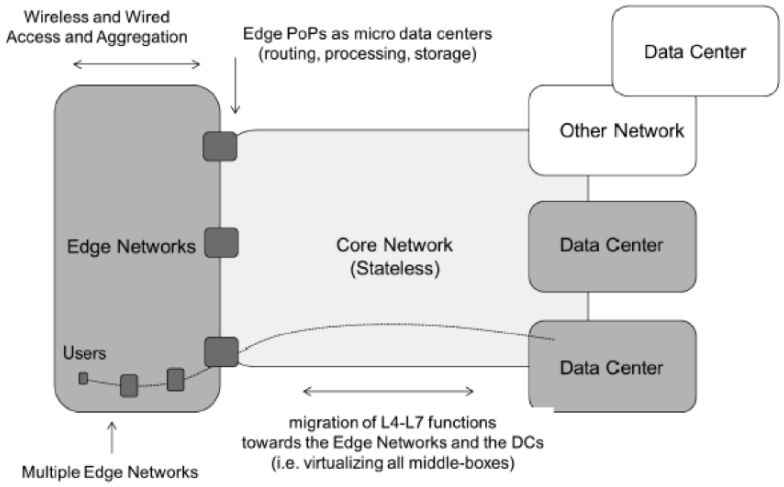


Figure 3.1: Evolutionary network scenario

etc.) of current networking concepts. Specially in SDN, it is recognized that the concept of the separation of hardware from (control) software is not really new, but the point is that the decoupling is made possible today thanks to the hardware technology advances. In the context of these core scenarios, dynamic Network Function (or Service) Chaining is one of the most mentioned classes of use cases, where IT and networks resources are integrated where network services are provided by "chaining" the execution of several service components. SDN and virtualisation techniques are often assessed as an opportunity reducing CAPEX and OPEX costs. In fact, as previously mentioned, savings may derive from centralizing and, above all, automating processes and postponing investments through optimized usage of resources (provided that carriers class performances are still achieved by the adoption of general purpose hardware). On the other hand a deeper integration of networks and IT (e.g. Cloud) domains, and the related Operations requires also a deep "change of culture" in NOs and SPs, and maybe the development of new skills for mastering "software". This might require some time to define new models of business sustainability and a seamless integration between legacy equipment and the related

management systems.

3.0.2 Examples of edge scenarios

Edge scenarios concerns the exploitation of SDN and virtualisation principles for creating very dynamic virtual networks out of a variety of aggregation nodes, devices, elements located at edge of current networks, up to around users. Some of these elements usually are not considered yet as network nodes: for example, cars, robots, drones, any smart-object with embedded communications, etc. In other words, this is about developing a "fabric" [64] made of an enormous number of nodes and elements aggregated in an application driven way, as depicted in Figure 3.2.

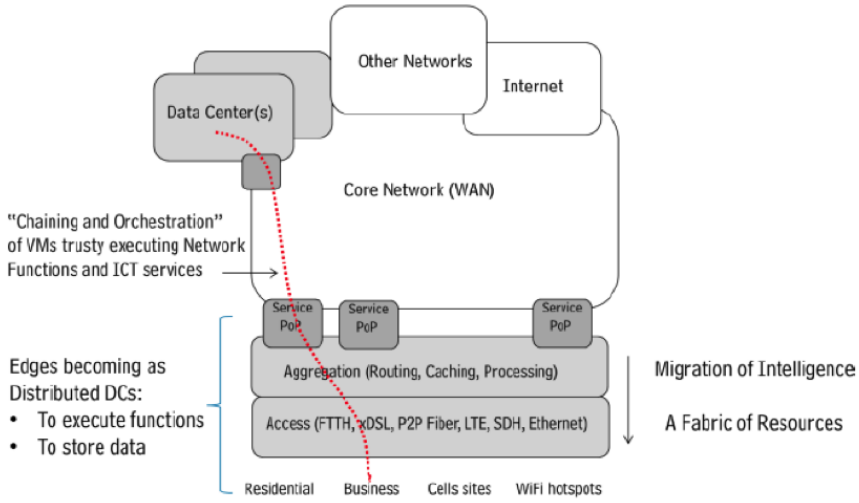


Figure 3.2: Example of scenario where the "edge" is becoming a "fabric" of resources to execute network functions and store data

In the past, the term "fabric" has been used to refer to a distributed computing system consisting of loosely-coupled storage, networking and processing capabilities interconnected by high-bandwidth links. It has also been used for describing flat, simple intra DC networks optimized for horizontal traffic flows, mainly based on a concept of "server-

to-server connectivity". Based on these previous meanings, in this context, the term fabric is extended to indicate the edge of the metro networks, becoming like as distributed DCs consisting of loosely coupled processing and storage resources interconnected by pervasive high speed wired and wireless links. Some use cases are provided in Section 3.2.

3.1 Edge ICT Fabric

In the following subsections,we provide some considerations about architectural aspects related to "Edge ICT Fabric", proposed in [64].

3.1.1 Network states

In the Edge ICT Fabric approach there is an original challenge regarding the Data Collection and State Analysis (DCSA), stemming from the fact that the network nodes are now VMs and therefore their state is also influenced by the overall POP DC conditions. The DCSA must take into account that the overall system conditions are not simply described by the state of the network elements but also by the state of the system hosting the VMs. Therefore the DCSA must have general communication capabilities, enabling cross boundaries communication between POP DCs, and general semantic capabilities to describe the state and condition of resources of very different nature and spanning different logical layers of the Edge ICT Fabric architecture.

Here we envisage an approach in line with previous works proposing approaches applicable to the management of state information spanning cross-layer in systems where the network and IT resources are strictly interacting [65], [66]. For instance, the Network Resource Description Language (NRDL) can be used to describe and cross-correlate data regarding the network and the IT resources in a unified way, enabling automated and

cognitive application service provisioning as demonstrated by the test examples reported in [67], [68], [69].

3.1.2 Scalable standard hardware nodes

Current communication networks are built on very specialized network elements with bespoke hardware and software architectures specifically developed to provide the best performance/cost ratio for the particular function they are meant to represent. This results in an exceedingly heterogeneous selection of network elements where each node can only provide the function it was originally designed for and any new service that requires new functionality typically necessitates the deployment of new specialized types of hardware.

IT processes today are embracing a very different paradigm where services are deployed as VMs running on standard hardware resources, either on site or in the cloud. This scheme allows an IT organization to respond much faster to evolving needs and to reach higher usage rates of its computing resources.

The idea of extending this flexibility to Telecommunications networks is getting a growing attention, even more when looking at a deeper integration of processing, storage and networking resources. This is still lacking today as networks are mostly based on specialized hardware nodes. Until recently, processor-based network equipment was typically designed around a heterogeneous system concept, in which the networking control plane ran on one processor architecture (e.g., x86 architecture processors) while the data plane executed on a different architecture, such as a multi-core MIPS platform, with specialized network acceleration features.

In order to benefit from the level of performance attainable with such a system, one

would accept the additional inflexibility resulting from heterogeneous software architecture as well as the complexity associated with the integration and maintenance of two different code bases. Clearly, this is not an ideal solution, and a unified system architecture, in which the control plane and data plane run on the same processor architecture while achieving the necessary cost-performance targets, is preferable for several reasons: scalable node development, development and integration is simplified; processor resource utilization is improved because the control plane and data plane can be distributed among cores with greater flexibility; and software maintenance is much easier with a common code base and a single programming environment.

Virtualisation enables operation of multiple VMs, each containing a guest Operating System (OS) and its associated applications, on the same physical board. The coexistence of multiple OSs is made possible by a software layer, known as a Virtual Machine Monitor (VMM) or hypervisor, that abstracts the underlying processor cores, memory, and peripherals, and presents each guest OS with what appears to be a dedicated hardware platform. The hypervisor also manages the execution of guest OSs in much the same way that an OS manages the execution of applications.

Virtualisation also provides a transition path for enabling innovative new designs while maintaining legacy applications. Virtualisation makes the migration easier by allowing the legacy applications to run in a shadow environment alongside new code, allowing compliance testing of the new code in real time. The ability to support legacy and new code on a single platform can also ease the regulatory compliance burden in Telecom applications. Telecom Equipment Manufacturers (TEMs) can add new features on one VM, while a legacy application runs unchanged in its own VM. Because the legacy applications run unmodified, it is significantly easier to recertify them.

TEMs can also look to virtualisation to help them take advantage of multi-core processors. Many systems require reuse of legacy code written for a single-core processor. Reworking this code for multi-core execution is often impractical. In the Telecom industry, most TEMs have significant investments in validated, single-threaded code. This code is typically irreplaceable, and in some cases only exists in binaries that cannot be modified. Virtualisation makes it possible to run multiple instances of this software on the same processor, each within its own VM, leading to significant improvements in cost, power, and size.

Recent generations of Intel®, Xeon®, Core™ and Atom™ processors provide the networking performance necessary to enable their use as a unified platform for converged networking equipment, especially when combined with high-performance packet processing software from the Intel®Data Plane Development Kit (Intel®DPDK). Each of the above processor families (specific versions) also supports accelerator technology that improves virtualization performance.

3.1.3 Global controller

The Global controller, based on the service requests and the Edge ICT Fabric states, has to compute how to direct traffic flow, routed by nodes, through these computing elements for additional processing (e.g. VMs) to execute the required services (*e.g.* L4-L7 middle-box network functions).

Efficient methods are required to create optimal said paths and Edge ICT Fabric-resource allocations under continuously changing conditions. The latter involves: i) situations in which moving users need that required data and services/network functions are moving with them, as well as ii) situations of elastic service requests where resources need

to scale up or down to meet the customer's demand.

These type of problems require efficient and dynamic reallocation mechanisms for both network and processing resources (involving path computation/traffic engineering). In addition it is necessary to design and implement scalable and dynamic discovery, control, and communication framework. This framework should enable the controller to exert its control over the edge devices, and facilitate state collection.

The discovery function is the infrastructure which the Global Controller uses to get an up to date image of the available edge assets. The discovery mechanisms will allow edge devices to join the resource pool and register their assets (i.e. resources, data and services) as candidates for utilization. Object registration and resource discovery products will be stored in a distributed data store.

The framework will implement scalable and efficient communication channels that will allow the Global Controller to manage and coordinate the edge devices. For this purpose we envision communication forms like a scalable membership service, an attribute replication service, as well as message queues, scalable publish-subscribe, and converge cast services.

An additional scope of this framework is to support the implementation of a robust controller cluster that is cloud ready, consistent, and immune to failures. The framework will be distributed and highly elastic, in order to serve the uniform growth from small scale to large scale systems. It will be based on peer-to-peer technologies that will instantiate overlay communication topologies congruent with the varied network topologies that the edge devices are embedded in.

3.1.4 Service provisioning

Service provisioning will require methods for efficient service provisioning of networking and processing resources in distributed settings. The crucial challenge of this issue is to translate higher-level constructs or primitives resulting from resource allocation/optimization mechanisms into lower-level instructions and configurations.

Provisioning logic can be split into two parts: i) primitives for individual data plane and processing elements of Edge ICT Fabrics, and ii) primitives for coordinated provisioning of several distributed Edge ICT Fabrics. This will enable programmability of forwarding functions, middle-box functionality such as fire-walling, Deep Packet Inspection (DPI), or more advanced services such as for content delivery (CDN).

For these purposes, the provisioning functionality could rely and further build on the communications framework provided by the Global controller. A provisioning program could consist of a set of higher level primitives describing network and resource configurations. This program can be executed by a run-time environment which translates them into lower-layer instructions such as OpenFlow, middle-box primitives, etc. Part of the program remains running in the run-time environment to react to events which lower-level elements such as network switches or middle-boxes are not able to handle (for example packets for which no OpenFlow entry can be found, or events which cannot be processed due to lack of resources).

The provisioning program can react on these events by, e.g., installing new rules, or reserving additional resources. The role of the run-time environment is to ensure that these high level provisioning program abstractions are correctly translated and executed into lower-level actions. Such an architecture will allow provisioning of elastic services on

top of distributed Edge ICT Fabrics, based on allocation schemes designed for the Global controller.

3.2 Use cases in Edge Networks

Some selected use cases show the key potential for using SDN and NFV to improve the quality of the applications for end users, to increase business opportunities and also to enhance the market for value-added SPs. These trends will be coupled with the economic drive given by a myriad of new players entering the telco/ICT markets. These factors are expected to impact the economic market in a way that will drive investment outside of the network infrastructure boundary and stimulate the advent of new communications paradigms [70]. The edges of the networks will be transformed into complex Micro Data Center consisting of a number of diverse and autonomous, but inter-related nodes, devices, machines: this will create a "complexity" which has to be managed and controlled [64].

The network functions and services will be exposed, as opposed to being hidden as they are currently. They will be executed in VMs running mostly in these Micro Data Center at the edge of the network, closer to the end users and customers, and partly in VMs that are in mainstream Data Center. The orchestration and management should be ensured by a system which knowing both infrastructure and network "states", will be capable of optimizing configurations on the distributed nodes.

Figure 3.3 presents an overview of a Future Network architecture that encapsulates these Micro Data Center at the edge of the network, connected by high throughput optical links and core routers to large DCs.

This Future Network architecture is being planned for the following three telco use case examples. Such use cases have as a foundation the Future Network with Micro Data

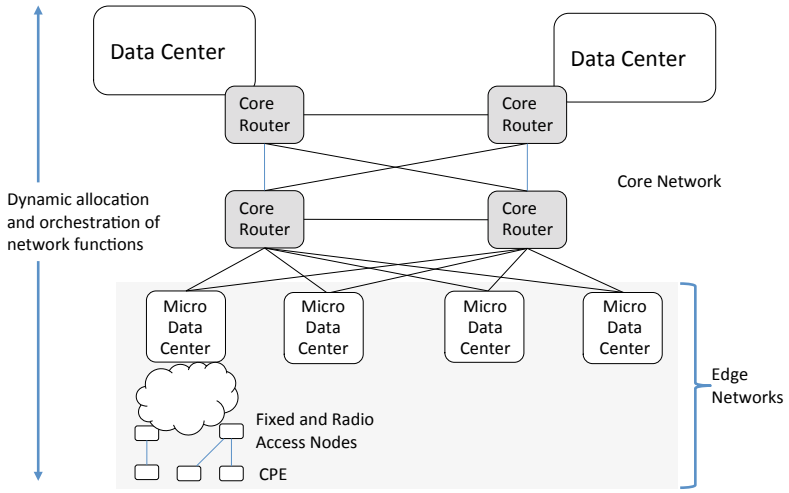


Figure 3.3: Evolutionary network scenario: Edge Networks

Centers at the edges of the network and DCs in the network, combined with virtualised Software Defined Networks. For these use cases to be deployed it is necessary that the execution of the network functions and service elements are dynamically allocated somewhere in the physical network and executed by virtual resources.

3.2.1 Provisioning of services across Edge Networks

A SP may want to provide end-to-end ICT services to end users who are attached to Edge Networks even if belonging to different NPs. This could be achieved by operating an overlay platform capable of hooking, managing and orchestrating all the virtualised resources and functions made available by the different network providers.

3.2.2 "Harnessing" storage and computing idle resources at the edge

Daily there are plenty of idle or less utilized resources in networks and services platforms. Harnessing these idle resources could allow optimizing CAPEX, whilst adopting new business models. Obviously not all services could be provided by using idle

resources: examples of provisioned services will be CDN-like services, content sharing, data collections, aggregation, transformation, optimal re-distribution of VMs across the set of networks and servers and providing stabilization of the local networks following electricity demand-response loops, etc. Also in this use-case a platform is necessary for virtual resources and functions monitoring, allocation and move.

3.2.3 Follow-me personal data and services

Data and ICT services (seen as apps executed as sets of VMs) will follow the users when they are moving from one network attachment point to another one, even across different edge networks. Management and orchestration capabilities should allow this "follow-me" service whereby these VMs will be moved seamlessly. Moreover, data and services associated to users can be even federated to build distributed virtual DCs at the edge at costs which are a small and a fraction of traditional clouds.

3.3 Socio-economic issues and business models

In the near future the edge will look like a distributed network processing architecture, deeply integrating processing, storage and networking resources. This will impact dramatically future networks evolution. Technology and business developments will be more and more strictly intertwined in the future. Obviously, a certain technology will be adopted not only if it is advantageous (reducing costs) and trusted but also if it will be able to enable desired business ecosystems (with the related foreseen business models); on the other hand, newly designed potential ecosystems will look for enabling solutions and technologies capable to bring them into reality. The introduction of this increased functionality at the edge opens up opportunities to execute network functions and ap-

plications closer to the customer increasing his quality of experience, offloading network traffic and device functionality. Additionally this will increase the reach of applications allowing an even smoother deployment of high end applications on a worldwide scale with the constraints mainly imposed by the edge ICT fabric. Of course the advent of new applications and the success of the functionality installed at the edge will be depending on the economics of the applications installed and running on this edge. Indeed, the impact of the price for using the functionality at the edge will be an important aspect here. However the ecosystem and potentially additional incentives and pricing schemes could prove at least as important. Installing the functionality at the edge involves new investments in both software and hardware and as well in the training and equipment at the developer's side. For a developer to step into this approach, he will also need to have a clear view on the costs associated to using each of the new functionalities at his disposal. Setting the price from a provider point of view will be a task involving typical investment modelling, simulation and analysis. Checking the profitability of an application developer will use this pricing in a dedicated investment analysis.

As already touched upon, the use of ICT functionality at the edge will most probably have an impact on the load of the access, metro and core network as well as on the device constraints at the customer side. It will open up a huge field of opportunities to develop and distribute applications and open the market at this point to new players. It is mandatory to tackle any economic calculation in such context in a multi-actor manner in which the full business model and ecosystem is taken into account in the calculation of one actor's business case. Adding this business model view on top of the previously mentioned detailed investment analysis for edge ICT and application providers is the key to understanding the impact of edge ICT and creating a successful business model for it.

Chapter 4

Reference model for virtual networks

Highly dynamic networks are network environments where nodes and links are regularly added or removed at short notice. Dynamic networks include virtual networks, logical networks, cloud computing networks, mobile ad-hoc networks, sensor networks and the IoTs. Such environments are within the context of Future Networks and the management/monitoring of infrastructures is today an important research field. In fact, such distributed infrastructures need to be self-organized in order to match not only the requirements of end users and network managers but also the constraints of the network infrastructures, including dynamic topologies such as networks of mobile users and virtual networks with "migratable" virtual machines.

A well-known dynamic network contexts are virtual networks. Virtual network is a collection of virtual nodes connected together by a set of virtual links to form a virtual topology. In such networks, links and nodes may be reconfigured quickly and may be, for example, powered down to save energy or the node may be redeployed to a different logical area of the network. On the other hand, virtual nodes may be brought online to deal with resources which are near their limits for bandwidth or CPU power. They are

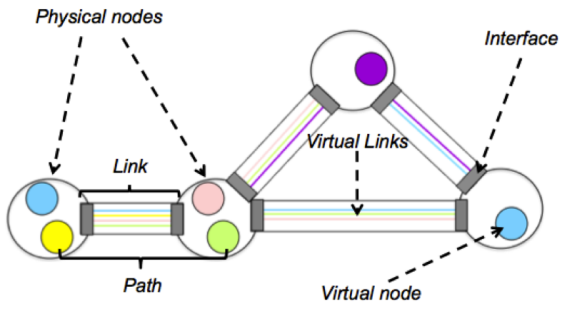


Figure 4.1: A sample model of virtual network

characterised in the literature either as a main means to test new Internet architectures or as a critical component of Future Networks. In this context, especially in virtual resource management, the virtual network description plays a key role in virtual resource discovery, selection and provisioning process.

4.1 Model definition

In virtual environments, the network resources include *node*, *link*, *interface*, and *path*. Each network element can be virtualised into multiple sub-elements. For example, (i) a physical node can be virtualised as one or more virtual nodes such as virtual routers, virtual switches or VMs running applications; (ii) a physical link may be contain multiple virtual links with different bandwidth; (iii) one or more multiple physical/virtual interfaces may connect to a physical/virtual link. An simple model of network virtualization is shown in Figure 4.1.

Generally speaking, a virtual network can be represented by a graph $\mathcal{G} = (\mathcal{V}, \mathcal{E})$, where $\mathcal{V}$ is the set of virtual nodes (vertices) and $\mathcal{E}$ is the set of virtual links. Virtual links can have a direction, but here we are only going to consider undirected links. A virtual node can transfer virtual information to another virtual node in the form of data-

packets if there is a virtual link between them. If there is no direct virtual link between virtual nodes, then a path in the network is the sequence of distinct virtual nodes visited when transferring data-packets from one virtual node to another. The degree k of a virtual node is the number of virtual links which have the virtual node as an end-point, or equivalently, the number of nearest neighbours of a virtual node. The degree of a virtual node is a local quantity, however, the virtual node degree distribution of the entire network gives important information about the global properties of a network and can be used to characterise different network topologies (in the rest of this Chapter, virtual nodes and virtual links will be denoted as nodes and links, respectively).

The binding elements between the topology and the traffic dynamics are the routing mechanisms. The path that a packet follows when travelling the network is determined by the routing algorithm. A packet travels through the network visiting different nodes. If one of the nodes is busy, the packet is stored in the queue at that node. Eventually, as the node serves its queue, the packet is forwarded toward its destination. Usually longer routes and/or congested queues mean longer delivery times. The routing algorithm tries to reduce the packet delivery time by selecting short, lightly utilised routes. In such a network, the traffic characteristics are not drastically changed as the packet transverses the network. The delivery time for a packet from its source to its destination is finite. As the load increases, the delivery time will typically increase accordingly. There is a critical load where the delivery time diverges, or at least increases dramatically. At this point the network is congested.

The statistical properties of packet traffic can be described by a model where the traffic input is *Poisson-like* where the auto-correlation decays exponentially fast. Traffic with this decay property, of which the Poisson type is a particular example, is referred to

as having *Short Range Dependence (SRD)*. From studies carried out in the early 1990's [72] it is known that Poisson-like models do not capture all the statistical properties of packet traffic. Packet traffic exhibits spurts of activity over a large number of time scales. These bursts last from milliseconds to days and they look similar independently of the time scale. This phenomenon is known as self-similar traffic. One characteristic of this *self-similar* traffic is that it has *Long Range Dependence (LRD)*, i.e. the traffic is strongly correlated at all time scales of engineering interest. This observation was a surprise as, previously, the properties of packet traffic were described as *SRD* processes. The packet delivery time is the time that elapses between the creation of a packet at its source s, to the arrival at its destination d. This time is known as the end-to-end time, packet lifetime or latency.

The following subsection describes the *LRD* statistic used to model the data traffic in virtual networks.

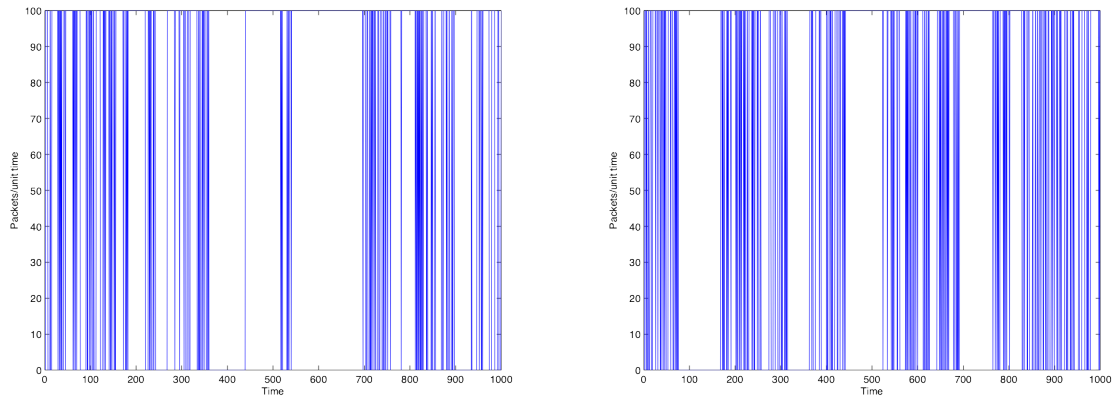
4.1.1 Long Range Dependence

The statistical nature of *LRD* traffic is formally defined in [73]. A key requirement is that the autocorrelation of packet traces $\gamma(k)$, where the lag is k, satisfies a power law decay of the form $\gamma(k) \sim Ck^{-\beta}$ where $\beta \in (0,1)$ and C is constant. Equivalently, $\gamma(k) \sim Ck^{-2-2H}$, where $H = 1 - \beta/2 \in (\frac{1}{2}, 1)$ is the *Hurst* parameter. By comparison, Poisson-like traffic has an exponential rate of decay $\gamma(k) \sim C'\alpha^{-k}$ with $\alpha > 1$ and C' a constant. The Hurst parameter distinguishes between *LRD* traffic for $H \approx 1$ and the *onset* of *SRD* traffic for $H \approx 1/2$, when the autocorrelation decay changes to exponential.

The effect of scaling is shown for Figure 4.2(a) long-range dependent and Figure 4.2(b) short-range dependent traffic for a time series of a random variable $X_n, n = 0, 1, 2, ...$ The data is averaged in batch sizes of $N = 100$.

The standard deviation in the Poisson traffic varies as the square root of the batch size, or magnification, and we see a "smoothing" of the traffic as N increases in Figure 4.2(b). Thus the mean is an increasingly effective indicator of the instantaneous load, i.e expected packet rate, in the traffic. By comparison, for *LRD* traffic, we see that the variation around the mean remains relatively high for large N in Figure 4.2(a). Even when averaged over longer time intervals by several orders of magnitude, we can still obtain packet rates which are close to 0 and 1.

One of the consequences of *LRD* traffic is that it increases queue lengths and latency dramatically. The length of a queue fed with *LRD* traffic sources decays as a power law, compared with an exponential decay if it is fed with Poisson traffic sources. The effects of *LRD* cannot be "removed" by a control mechanism and *LRD* needs to be allowed for, both in computer models of network behaviour and in the routing algorithms used to control data flow through networks.



(a) *LRD* traffic

(b) *SRD* traffic

Figure 4.2: The batch averages of packets/unit time for (a) a real *LRD* traffic trace and (b) a Poisson-based trace for the same load, for sizes $N = 100$.

4.1.1.1 Packet production model

Previous simulations of *SRD* packet traffic generation at each host have used *SRD* Poisson (or Markovian) distributions. In this case a packet is created at a host only if a random number on the unit interval, $\mathbb{I} = \{x \mid x \in (0,1)\}$, is below a discriminator value λ. Hence, for a uniform random distribution the average rate at which packets are produced at a host is λ. An alternative to this is to use chaotic maps to model the *LRD* nature of real packet traffic. We used the family of maps $f = f_(m_1 \cdot m_2 \cdot \lambda) : \mathbb{I} \longrightarrow \mathbb{I}$ defined in the unit interval $\mathbb{I}$ by $x_{n+1} = f(x_n)$ defined as [75]

$$x_{n+1} = \begin{cases} x_n + (1-\lambda)(\frac{x_n}{\lambda})^{m_1}, & \text{if } x_n \in [0, \lambda] \\ \\ x_n - \lambda(\frac{1-x_n}{1-\lambda})^{m_2}, & \text{if } x_n \in (\lambda, 1] \end{cases} \tag{4.1}$$

where $\lambda \in (0,1)$ and the parameters $m_1, m_2 \in (\frac{3}{2}, 2)$ induce intermittency.

The map produces a sequence of real numbers $x_n \in [0,1]$ which is converted into a binary Off-On sequence given by

$$y_n = \begin{cases} 1, & \text{if } x_n \in [0, \lambda] \\ \\ 0, & \text{if } x_n \in (\lambda, 1] \end{cases} \tag{4.2}$$

where λ is used to tune the "load" on the network (a new packet is generated only if $y_n = 1$). The above model, which represents the traffic as a binary sequence is also known as a *packet train* model [46] and the intermittency behaviour of the map f induces so-called *memory* in the digital output y_n giving the long range correlation effects required for the packet traffic. Furthermore, the Hurst parameter, H associated to this map is given by:

$$H = 1 - \frac{\beta}{2} = \frac{3m - 4}{2(m-1)} \tag{4.3}$$

where $\beta = \frac{2-m}{m-1} \in (0,1)$ and $m = max\{m_1, m_2\}$ with $m_1, m_2 \in (\frac{3}{2}, 2)$. Thus $m_1, m_2 = 1.5$ corresponds to Poisson-like behaviour and as m_1 and m_2 increase towards 2, the behaviour is increasingly LRD as proved in [74] (e.g. in our model $m_1 = 1.95$ and $m_2 = 1.95$).

4.2 Topology models

The way that the elements of the network are connected to each other and the nodal degree properties have an impact on its functionality. As said previously, the representation and study of the connectivity of a network is carried out using concepts from graph theory. A path that goes from source node s, to destination node d, in the smallest number of hops is called the shortest-path. The length of the shortest-path $l_{s,d}$ is the number of nodes visited when going from s to d. There can be more than one shortestpath between a pair of nodes. The characteristic path length $\bar{l}$ is defined as:

$$\bar{l} = 1 - \frac{1}{N(N-1)} \sum_{s \in \mathcal{V}} \sum_{d \neq s \in \mathcal{V}} l_{s,d} \tag{4.4}$$

where N is the total number of nodes, is the average shortest-path over all pairs of nodes. Sometimes, $\bar{l}$ is referred to as the *diameter* of the network.

In a network, there are nodes that are more prominent because they are highly used when transferring packet-data. A way to measure this "importance" is by using the concept of *betweenness centrality* of a node. We will refer to this concept here as *medial centrality*. Given a source s, and destination d, the number of different shortest-paths is $g(s,d)$. The number of shortest-paths that contain the node w is $g(w,s,d)$. The proportion

of shortest-paths, from s to d, which contain node w is defined as:

$$p_{s,d}(w) = \frac{g(w,s,d)}{g(s,d)} \tag{4.5}$$

Remark: The proportion of shortest-paths and the shortest-path length are related by

$$l_{s,d} = \sum_{w \in \mathcal{W}} p_{s,d}(w) - 1 \tag{4.6}$$

where $\mathcal{W}$ is the set that contains the nodes visited by the shortest paths from s to d. The *medial centrality* of node w is defined as

$$\mathcal{C}_B(w) = \sum_{s \in \mathcal{V}} \sum_{d \neq s \in \mathcal{V}} p_{s,d}(w) \tag{4.7}$$

where the sum is over all possible pairs of nodes with $s \neq d$. The medial centrality measures how many shortest paths pass a certain node. A node with a large $\mathcal{C}_B$ is "importance" because a large amount of packets flow through it, that is, it carries a large traffic load. If this node fails or gets congested, the consequences to the network traffic can be very drastic. The following subsections describe some interesting regular structures and no regular structures.

4.2.1 Regular symmetric networks

In a regular network all nodes have the same degree. By symmetry, the medial centrality is constant for all nodes.

4.2.1.1 Toroidal networks

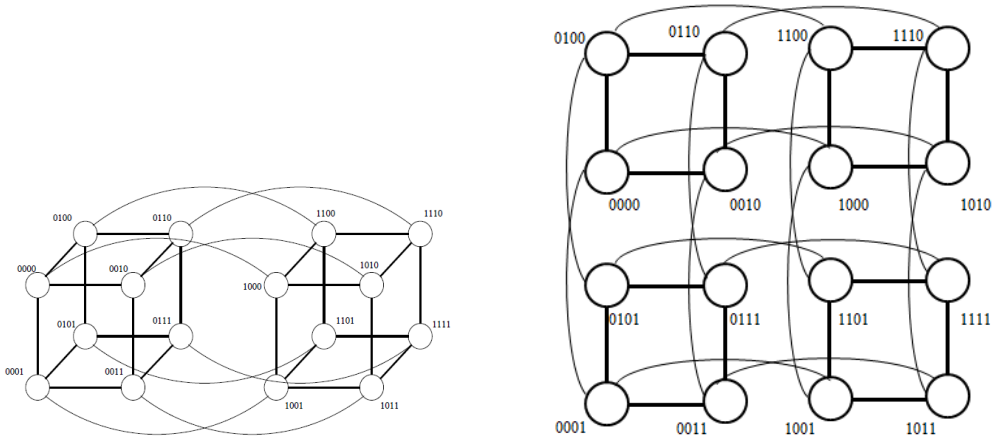
The toroidal rectangular network ($\mathcal{H}$) is based on a square lattice of nodes in which each node has four neighbours with boundary nodes appropriately identified. The finite

rectangular lattice $\mathbb{Z}$ consists of $N = L^2$ nodes. The position of each node in the lattice is given by the coordinate vector $\underline{r} = (i, j)$ where i and j are integers in the range 1 to L. The network has periodic boundary conditions throughout, and so each coordinate of (i, j) is effectively reduced $-mod(L + 1)$ to give a toroidal topology. To measure the distance between a pair of nodes the periodic "Manhattan" metric is used, which measures the sum of vertical and horizontal displacements between two nodes.

4.2.1.2 Hypercube networks

Hypercube networks play an increasingly important role in global communication operations, interconnecting networks of microcomputers in parallel and distributed environments [76], [77].

Generally speaking, an n-dimensional p-ary hypercube consists of p^n nodes. Each node has n nearest neighbours. Nodes are labelled using base-p numbers, and it is assumed that any two nodes i and j are connected via a bidirectional link if their labels differ in exactly one coordinate position, i.e. Node $(x_{n-1}, x_{n-2}, ..., x_i, ..., x_0)_{base-p}$ is connected to Node $(x_{n-1}, x_{n-2}, ..., \underline{x_i}, ..., x_0)_{base-p}$ if $(x_i \neq \underline{x_i})$, $0 \leq i < n$ [79]. Here we will focus on a binary hypercube topology where p=2. Such a structure can be associated to a graph $G(V, E)$ in which [78]: a) V has 2^n vertices; b) every vertex has degree n; c) G is connected; d) any two adjacent nodes A and B are such that the nodes adjacent to A and those adjacent to B are linked one-to-one. Note that it is possible to map the n-D hypercube topology onto a $2 - D$ mesh topology using Gray Code, modelling this kind of problem in graph-theoretical terms as that of a graph embedding [78]. In the nominal case a binary hypercube topology with $n = 4$, in Figure 4.3(a), is mapped onto the $L \times L$ mesh with $L = 4$ shown in Figure 4.3(b).



(a) 4-D hypercube

(b) 4-D hypercube into a 2-D mesh

Figure 4.3: 4-D hypercube mapped into a 2-D mesh using Gray Code

4.2.2 Random network

Random networks have been used to model communications networks. The reason is that because some of the communication networks tend to have a complex topology and the interactions defining their structure are apparently random.

From a set of nodes, a random network is built by connecting every pair of nodes with probability p. If the total number of nodes is N and if $p > 1/N$ then, with probability 1, the network is fully connected, or equivalently, there is at least one path connecting any pair of nodes. This is the only case we are going to consider here, as we are interested in connected networks. The degree distribution of a random graph is well approximated by a binomial distribution [80]:

$$P(k) = \binom{N-1}{k} p^k (1-p)^{N-1-k} \tag{4.8}$$

The degree distribution tends to be concentrated around some "typical" node degree, or average node degree k.

4.2.3 Scale-free networks

Many technological networks are not described by a random or a regular network; instead they are better described by a network where the degree distribution is described by a power law where

$$P(k) \sim Ck^{-\beta} \tag{4.9}$$

for $\beta > 1$ and C constant. The probability that a node has k edges connected to it is given by $P(k)$. In practical terms a power law distribution means that the majority of the nodes will have very few neighbours, but there is a very small set of the nodes with a very large number of neighbours. Networks with this property are known as *scale-free* because power-laws are free of a characteristic scale, that is, there is no characteristic node degree.

4.3 Virtual network model

Here we consider the model described in [81], which has been previously studied by several authors. The model consists of two types of nodes: *routers* (that store and forward packets) and *hosts* (that are also sources of traffic). Assuming the network has N nodes and a density $\rho \in [0, 1]$ of hosts then ρN is the number of total hosts and $(1 - \rho)N$ is the total number of routers. We suppose for the sake of simplicity that host nodes are randomly distributed in the network. The network model considered in this paper consists of the following key components:

1. *Traffic generation model*: a packet is generated at a host using either a uniform random distribution (Poisson-like) or a *LRD* distribution defined by a chaotic map. Each source generates its traffic independently of the other sources; the traffic load

is increased or decreased by varying the probability of packet generation at each node [74], [82]. A random destination is assigned to each newly generated packet. The destination node is selected with uniform probability among all other hosts in the network.

2. *Buffer size*: each node keeps a queue of unlimited or limited length where the newly generated packets or those waiting to be routed are stored. Any packets that is generated is put at the end of the host' s queue. If a packet arrives at a router is stacked at the end of the router's queue. Packets at the head of each queue, exceeding its maximum capability, are dropped. The packets are removed when they arrive at their destination site.

3. *Routing algorithm at every time-steps*: each node picks a packet at the head of its queue and forwards the packet to the next node. The information that each packet carries about its source and destination is used by the following routing algorithm as follow. i) A neighbour closest to the destination node is selected. ii) If more than one neighbour is at the minimum distance from the destination, the link through which the smallest number of packets has been forwarded is selected. iii) If more than one of these links shares the same minimum number of packets forwarded, then a random selection is made.

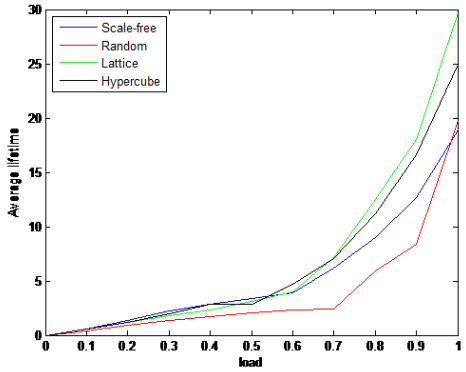
The process of packet generation, hop movement, queue updating and updating of the routing table occurs at each time step.

4.4 Topology impact on network functionality

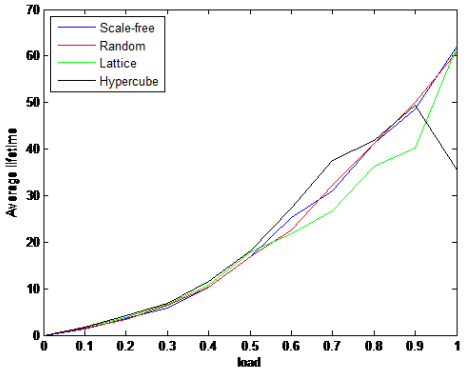
In this section we consider networks with different topologies generated using the most appropriate algorithms. For example, we use Erdős-Rényi (ER) algorithm to generate a random network and the static model introduced in [84] to generate scale-free topologies. Furthermore, square lattices with periodic boundary conditions are also considered. Using the network model and traffic generator detailed above, simulations were carried out to analyze various aspects of the end-to-end performance for each different type of network. In all cases, the network size was set to $N = 256$ nodes and the host density to $\rho = 1$.

In Figure 4.4(a) average lifetimes are plotted versus the load for the four cases with *LRD* traffic sources at each host. Here the average lifetime is simply the average time spent by packets in the network. The load is computed as the average number of packets produced by each traffic source per time step of the simulation. Figure 4.4(a) confirms that, as pointed out in [84], [74] the network topology is indeed a very important factor. In fact, a regular lattice network has longer lifetimes than a scale-free network. In Figure 4.4(b) the same measurements are made with Poisson traffic sources substituted for *LRD* sources. When the traffic sources act following a Poisson distribution we notice a less pronounced influence of the network structure, confirming the importance of selecting the traffic generation model. Note that the hypercube network presents shorter lifetimes than regular lattices and even scale-free networks. Figure 4.4(c) shows throughput plotted as a function of the traffic load. The throughput is defined as the number of packets reaching their destination per unit time per host. Results are consistent with those for the average lifetime. The scale-free network performs more efficiently for both types of algorithm. We observe that the hypercube topology presents a higher throughput than that of a square

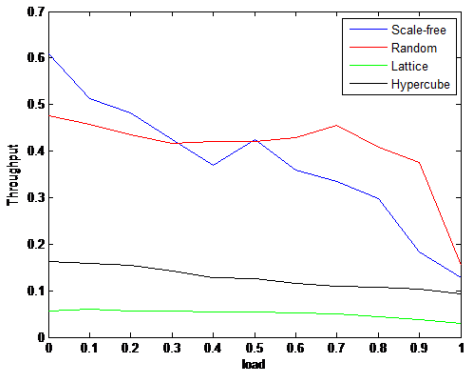
regular lattice. Similar behavior is observed for Poisson sources (Figure 4.4(d)). It is worth mentioning here that in both cases, the hypercube network structure was found to present a performance which is better than a regular square lattice but also combines



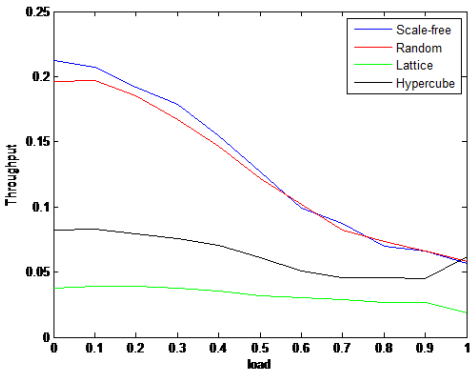
(a) *LRD* source



(b) Poisson source



(c) *LRD* source



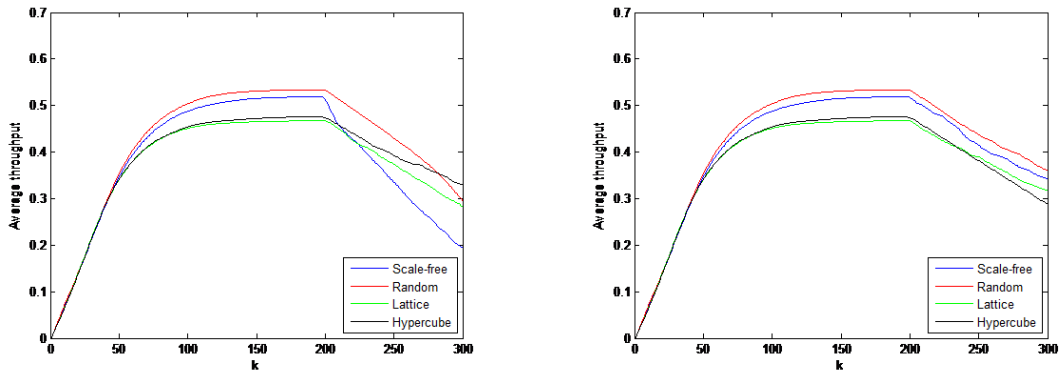
(d) Poisson source

Figure 4.4: Average lifetime and throughput versus the generation rate λ. A *LRD* traffic source is used to generate panels (a) and (c) while a Poisson traffic source for panels (b) and (c). The number of nodes is $N = 256$ and host density $\rho = 1$. Network considered are: square lattice with periodic boundary $L \times L$ with $L = 16$; Erdős-Rényi (ER) random networks with $p = 0.1$; scale-free network with $\gamma = 3$; hypercube network with $N = 2^{16} = 256$ nodes.

the beneficial effects of other topologies such as scale-free and random networks when the average lifetime is considered. This effects is even more pronounced when a more realistic *LRD* traffic generation model is considered.

In addition to the above analysis, we consider the throughput as a performance indicator measuring its change in the presence of different types of attacks. In this context, an attack is considered as a general strategy to power down nodes for different goals (for example for energy saving). In particular, two types of attacks are considered:(ii) *intentional attacks* where nodes with the highest degrees are removed from the network; (ii) *random attacks* where nodes selected at random are removed.

Figure 4.5(a) and Figure 4.5(b) show the throughput measured for different networks (such as square lattice, random, scale-free and hypercube topologies) in presence of intentional and random attacks as a function of the time k. We next look at the effects of attacks on the same networks assuming that nodes are removed intentionally or at random



(a) Intentional attacks

(b) Random attacks

Figure 4.5: Effects on throughput of intentional (a) and random (b) attacks node for different types of networks

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when $k = 200$. As expected we note that intentional attacks have a much higher effect on the overall network performance. Further, we observe that hypercube networks show much higher resilience to intentional attacks than scale free networks, again combining some of the beneficial, features of different network structures.

Chapter 5

Orchestration of logical resources in SDIs

The diffusion of ultra-broadband (in terms of high bandwidth and low latency) connection, IT hardware advances, and growing availability of open-source software are causing a paradigm shift in the world of network architectures [1]. In last years, the number of devices and smart-objects connected to the network has grown exponentially and the so-called "machine intelligence" has take part in the life-cycle of industries, agriculture, smart cities and eventually public institutions. In this context, the initiative to integrate heterogeneous networks, including wired/wireless networks and smart-objects, from both the service, management and control viewpoints is considered as a critical aspect of Future Networks [2].

The effect of all these drivers is the so-called "Softwarization" of telco infrastructures [3], where the approach to this challenge is through the deployment of a network infrastructure supporting software-driven network features that can be instantiated on-demand. These instantiations will be addressing the changing service requirements and resource constraints, yet scalable across multiple services and multiple domains, that can maintain QoS for end-users of a service, and that provide a level of isolation and security

from one service to another.

Research and development activities are clearly focused on several concepts: programmable networks, NV, open interfaces and platforms, and increasing degree of intelligence inside the network. The next generation of SDI needs to move from being merely *Defined* by software to be *Driven* by software and must be capable of supporting a multitude of players that exploit an environment in which services are dynamically deployed and quickly adapted over a heterogeneous physical infrastructure, according to changing requirements.

The integration of the Internet, software technologies and traditional telecommunications and communication technologies, has been always a challenge for network and service operators, as far as service deployment and management [6], [9], [10] is concerned. Soft-approach based on SDN and NFV should cope with heterogeneous environments providing an uniform view (virtualisation) of different technological networks and computational resources. The research challenge to asses this view with special emphasis on the wired environments are described in next sections.

5.1 Mechanism for controlling virtual resources

One of the main challenge includes the design and the implementation of specific mechanisms for run-time orchestration of logical resources in SDIs, considered for representative wired environments. A major aspect for this challenge is the development of technology-specific methods that enable the provisioning of virtual networks and storage/processing resources over SDN substrate infrastructure. This include the creation, configuration and tearing-down of virtual resource components, considering both networking and computational/storage resources. By using NFV, networking resources can

be re-allocated according to changing network conditions or service demands. Additionally, this challenge considers the development of autonomous actions that provide virtual network stability, performance and optimizations even absence of higher-level control. These include, for example, virtual resource remapping in case of resource scarcity, increased resilience through transparent resource migration in case of hardware failure or energy saving using adaptive virtual resource consolidation.

5.1.1 Resource Orchestrator

The issue of the logical resource orchestration (including network functions and services) raises several research challenges. Resource orchestration should be supported by a centralised software entity (the Resource Orchestrator – RO), whose overall goal is to ensure successful hosting and delivery applications by meeting QoS of service application owners (e.g. maximise availability, maximise throughput, minimise latency, avoid overloading, etc.) and resource providers (e.g. maximise utilisation, maximise energy efficiency, maximise profit, etc.) respectively. RO is responsible of a number of orchestration operations (including resource selection, resource deployment, resource monitoring, and resource control), which need to be programmed to control the resources at the design time as well as at the run time for ensuring the fulfilment of QoS objectives. Briefly stated, these operations are:

- **Resource selection (at the design and run time)**: an application analyses candidate software resources to determine whether they can be selected for realizing required functionality satisfying certain resource requirements and constraints (e.g. inter-operability with other software resources, compatibility with target hardware resources, cost, availability, etc.). Next, compatible hardware resources that can be

allocated to software resources are selected.

- **Resource deployment (both design and run time)**: instantiating software resources on IT infrastructure (or cloud service) and configuring them for communication and inter-operation with other software resources.

- **Resource monitoring (run time)**: monitoring of QoS of applications involves detection of event patterns (e.g. load spike) from information produced by deployed resources (e.g., usage statistics).

- **Resource control (run time)**: based on event pattern detection, a RO can react to deviation in application behaviours and initiate (policy-based) corrective actions, ideally without disrupting the run-time system. An example resource control operation could be to "move" an application by migrating it from small CPU resource configuration to extra-large CPU resource for improving throughput.

Using such operations, the RO "governs" the behaviour of the system in response to changing context and in accordance with applicable business goals and policies.

5.1.2 Resource deployment

Network function or service deployment is the general process of creating, configuring, and starting new instances of particular network function or services on a particular execution environment. Similarly, service termination is the reserve function of stopping, destroying and removing instances and/or their corresponding environment.

To efficiently manage virtual network functions and services within a virtual network, information on platform and execution environment to be necessary. In fact, for deploying new instances, the RO needs to be aware of the availability of physical (or

virtual) resources. All detailed information of the underlying resources and their current state are abstracted from the execution environment (monitoring operation).

One of the core aspects of network functions and service deployment is an efficient *resource placement*. The goal of service placement is find where/which physical resources to deploy service instances to achieve some high level objectives (such as minimizing energy consumption or load balancing). Specifically, it means find where/which physical resources to run VM instances according to a given *placement algorithm*. Generally speaking, VM placement can be *static* or *dynamic* and a particular case of dynamic placement is *live migration* described in next subsection.

5.1.3 Live migration

Programmable networks offer many advantages for the management of network functions and services that may be executed as virtual network functions in an ensemble of VMs dynamically placed into distributed platforms at edges of the network. This implies, also, the possibility to move such VMs according to requirements and constraints of the physical machines where they are hosted.

Conventional VM live migration involves the transfer of the CPU and memory state as well as the storage data. However, storage data migration in WAN is still an important challenge on which researchers are spending more efforts [85]. In the other side, the live migration inter-data centers presents the problem to allow IP change; solutions like tunnelling [86] and later-2 expansion [87] work around the problem of connection loss due to a change of the IP address. Using OpenFlow VMs are allowed keep their original IP addresses, maintaining all existing connections [88], [89]. Moreover, this protocol (i) allows the mobility between the layer-2 and layer-3, (ii) allows a programmable SDN, and

(iii) network resources can be remotely configured, controlled and monitored. Therefore, SDN-based solutions could improve management operations and performance as well as enable the VM migration in intra and inter data centers [90], [91] Recent works [92], [93] present a SDN architecture to enable the VM live migration and evaluate its performance.

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Generally speaking, the VM live migration involves several key factors such as the VM memory size, page dirty rate, the network transmission rate and the migration algorithm. The page dirty rate is the rate which the VM memory page change with. These factors and even more the migration algorithm used, can introduce relevant variations of the migration performance. There are different techniques for the live migration [94], [95], [96] that trade-off two important performance parameters: the migration time and the downtime. Migration time refers to the time required to move the VM between physical hosts while downtime is the portion of the time when the VM is not running. *stop&copy* [95] de-

signs halt the original VM and copy its entire memory to the destination. This techniques minimise the migration time but suffers from high downtime as the VM is suspended during the entire transfer. On the other side, *on-demand* [96] migration operates by stopping the VM copy only essential kernel data to the destination. The remainder of the VM address space is transferred when it is accessed at the destination. While this technique has a very short downtime, it suffers from high migration time. Among the several techniques used, the iterative pre-copy algorithm [97] minimizes the total migration time and downtime than other algorithms used, such as on demand migration and the stop&copy. Using an iterative approach, the hosted VM in the source physical machine can be kept in an active state during the migration towards the new destination. Since the VM is running, some memory pages are changed during the migration and must be re-sent. The term "iterative" means that pre-coping occurs in several rounds and the data to be transmitted during a round are the dirty pages generated in the previous round. The pre-copy phase terminates if: 1) the memory dirtying rate exceeds the memory transmitted rate; 2) the remaining dirty memory becomes smaller than a pre-defined threshold value; 3) the number of iterations exceeds a given value. After several rounds of synchronization, a very short stop-and-copy phase is performed to transmit the remaining dirty pages. Then, the VM is halted for the final state transfer and re-starts it in the new location.

5.1.4 Performance evaluation by using Stochastic Activity Networks

This section provides a formal method based on Stochastic Activity Network (SAN) which aims to analyse the live migration performance of a single VM between two different physical hosts in the network. In particular, we introduce a generic model of a Future Network infrastructure based on SDN and NFV principles. This generic model is

implemented by defining SAN sub-models and interfaces among them to share information. Specifically, it intends to proof of the advantages that could gain NOs in adopting the proposed modelling approach. In particular, our model intends to support the design phase of the network infrastructure, providing a valid tool to define its features and configuration parameters. Finally, such model could help SOs and NOs for the evaluating the impact of the new technologies on the live migration, widely used as conventional method for changing the placement of the VMs in the network.

5.1.4.1 Model description

This subsection describes our modelling approach in order to support the design of a Future Network by defining a "generic" modelling framework for performance analysis of the live migration. Our approach exploits the usage of the formal models, allowing to create the overall model of the system under analysis in a well-structured way. We adopt a component-based view of the network applying *divide-et-impera* techniques: the overall system model is decomposed recursively into sub-models until reaching an atomic sub-model. The effectiveness of this approach has been showed in [98] where a modelling framework has been defined and then implemented exploiting the flexibility of the SAN formalism.

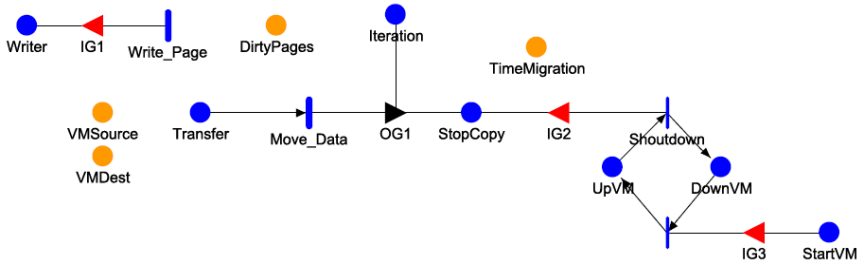


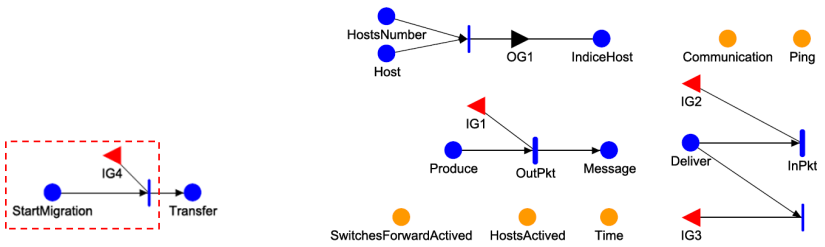
Figure 5.1: Live migration algorithm model

The analysis of the VM live migration over a SDN requires to consider the entire application field by modelling four different components: (i) the *Controller*, (ii) the *OpenFlow Switch*, (iii) the *VM* –which are the traditional components in SDN – and (iv) the *VM Live Migration Orchestrator*. This latter is a soft-component in charge of the resources management and orchestration as well as for the starting and stopping of the migration. This is argued by many efforts that the ETSI [99] is spending in this direction; however, in this work, the capability of the orchestrator is limited to the triggering the migration for a given VM. The implementation of the system has been realized using the SAN formalism [100]. The choice of this approach is due to the great flexibility and power in the modelling given by using such formal method. One of main advantages of the SAN formalism is the possibility to map each component of the designed architecture into "atomic" models. Component interfaces have been realized by sharing extended places, which contain complex data structures used by atomic models to read and write shared information.

Virtual Machine model (shown in Figure 5.3) consists of three main parts: (i) the live migration algorithm (Figure 5.1), (ii) a trigger signal (Figure 5.2(a)), and (iii) one part that represents the typical production and delivery of packets (Figure 5.2(b)). The pre-copy algorithm executes in several rounds and each iteration is modelled using the place `Iteration`. When a new iteration starts, a new token is added to this place. The extended place `VMSource` is an input parameter set as the memory size of the hosted VM into the source physical machine. `VMDest` represents the fraction of memory of such VM that is transferred to the destination machine during the migration. The memory size of the hosted VM into the source physical machine, the memory dirtying rate during the migration and the elapsed time at each round are modelled as `VMSource`, `DirtyPages`

and `TimeMigration`, respectively. In the beginning, `VMDest` is zero and one token in `Transfer` is used to start the live migration. All the memory of the hosted VM in the source physical machine is transferred to the destination. The timed transition `Move_Data` models the channel and the such transition expires when all memory of the hosted VM in the source physical machine is transferred to the destination.

When the migration starts, some memory pages (called dirty pages) change during the process and they must be re-sent to the destination. This is modelled using the place `Writer`, the gate `IG1`, the timed transition `Write_Page` and the extended place `DirtyPages`. In particular, when the migration starts, one token is in `Writer` and some memory pages change at a given rate. The timed transition is modelled as an exponential distribution with parameter equal to the page dirty rate (that is an input parameter). Pages changed during this phase are modelled by an extended place `DirtyPages`. The place `Iteration` increases one token until when one of the stop-conditions is verified. Such event is modelled using the gate `OG1`. In aprticular, when a stop condition occurs, one token is in `StopCopy` and the hosted VM in the source physical machine is halted for the final transfer round. During last iteration one token is in the place `DownVM`. When last fraction of memory has been transfered to the destination, the VM hosted on the



(a) Trigger signal (b) VM model

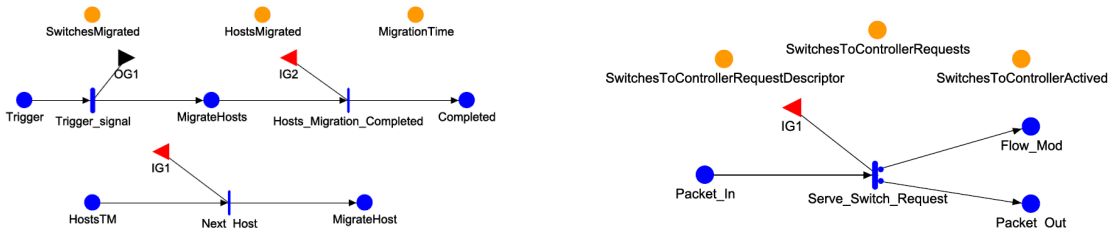
Figure 5.2: Trigger signal and Virtual Machine model

physical machine of destination is re-activated. In this case, `DownVM` is zero and one token is in `StartVM`. Morevoer, the `VirtualHost` model represents the ability to handle a trigger signal (Figure 5.2(a)) to start the migration. Figure 5.2(b) shows the `host` model representing the typical production and delivery packet operations. The timed transition `OutPkt` and `InPkt` are modelled as a deterministic distribution.

Live migration orchestrator model represents the atomic model of the entity in charge for enabling the live migration (Figure 5.3(a)). To run it, a token is in the place `Trigger`. The hosted VM in the source physical machine is selected for the migration and, after one token is in the place in `MigrateHost`. When the migration is completed, one token is added at `Completed`. The timed transition `Trigger_signal` is modelled as a deterministic distribution with a transition firing every 10 s.

The sub-model for the **Controller** is shown in Figure 5.3(b). It represents the interaction occurring between the Controller and the OpenFlow Switch. `OpenFlow_Switch` and `OpenFlow_Controller` share a common place `SwitchToControllerRequest` and the timed transition `Matching` has two cases (i.e. `Flow_mod` and `Packet_Out`).

The sub-model that represents a **OpenFlow Switch** is shown in Figure 5.4. It is argued that the behaviour of such switch is based on set of rules installed into itself.



(a) Live migration orchestrator model

(b) Controller model

Figure 5.3: Live migration orchestrator and controller model

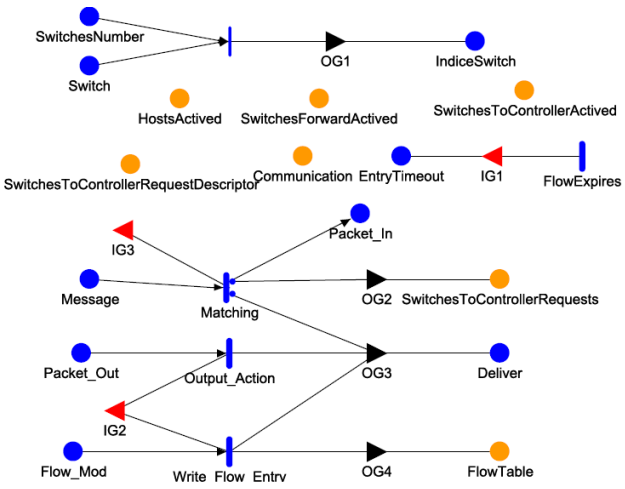


Figure 5.4: Open Switch model

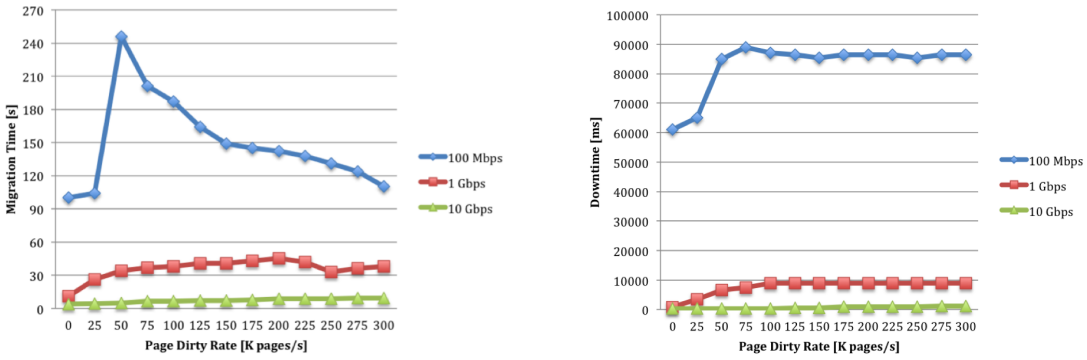
Basically, if a rule matches an incoming packet, the forwarding decision is instantaneously executed on the switch. Otherwise, if there is no matching rule, the switch asks the controller for an action to execute. We model these events by using two cases associated to the timed transition `Serve_switch_request`. For such transition a normal distribution with a mean of $4\mu s$ and standard deviation of 101.43 has been used according to the reference [101]. Moreover, `Write_Flow_Entry`, `Output_Action` and `Matching` are modelled as a uniform distribution with lower bound $4\mu s$ and upper bound $16.5\mu s$. Finally, `FlowExpires` is modelled as a normal distribution with mean 1 and standard deviation $0.2ms$.

5.1.4.2 Simulation results

This section reports some results obtained by using Möbius tool [102], a software tool for modelling the behaviour of complex systems. The modelling language is based either graphical or textual representations supporting several modelling formalisms including SAN, Markov chains and extensions as well as stochastic process algebras. Functionality

of the system can be defined as model input parameters, and then the behaviour of the system can be automatically studied across wide ranges of input parameter values. In particular, we use Möbius for the analysing and evaluating the VM live migration in SDIs.

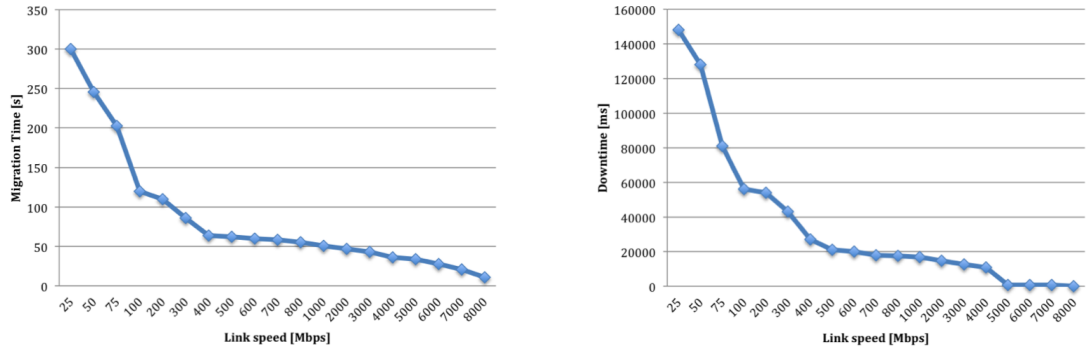
To perform useful results, we evaluate the migration time and downtime by changing the page dirty rate. Figure 5.5 shows the effect of varying the page dirty rate on migration time and downtime for three different link speed values: 100 Mbps, 1 Gbps and 10 Gbps. The memory size VM migrated experimentation is 1024 MB. This value is used for all experiments. We observe an interesting relationship between page dirty rate and migration



(a) Migration Time

(b) Downtime

Figure 5.5: Migration time and downtime versus page dirty rate



(a) Migration Time

(b) Downtime

Figure 5.6: Migration time and downtime versus link speed

performance: specifically, such relationship is not linear this occur because of the stop conditions defined in the migration algorithm. In line with some results presented in [97], if the page dirty rate is below the link capacity, all modified pages are transferred in a timely fashion resulting in a low migration time and downtime. In the other side, if the page dirty rate starts approaching towards the link capacity, the migration performance degrades significantly. Moreover, it is relevant to observe the impact of the link speed on the live migration performance. Results have been obtained considering a page dirty rate set as 300.000 pages/second. Figure 5.6 shows clearly that the migration performance are influenced by link speeds; moreover such figure highlights that relationship between the link capacity and the migration time is inversely proportional. Same consideration about the relationship between the link capacity and the downtime.

5.2 Mechanisms for mapping virtual resources onto physical resources

This challenge includes the design and implementation of specific algorithms for an efficient mapping of virtual resources onto physical resources. Specific optimization techniques are developed for efficiently mapping between virtual resources and physical network infrastructure [104], [12]. The mapping takes into account the top-level service/-operational requirements such as QoS requirement (e.g. *minimizing network latency*). By addressing this challenge virtual networks are customized with optimally allocated capabilities such as virtual nodes (with computing and storage capabilities), virtual links and path for specific networked services.

Flexibility, programmability and ultra-low latency connectivity will be some of the

key challenges to enable new service scenarios. These requirements are important also from a socio-economic perspective in order to make future Infrastructures sustainable from a business viewpoint. In particular, this thesis focuses on one of said challenging requirements which is the ultra-low latency (e.g., units of ms) connectivity. This requirement has been selected among the others (e.g., flexibility, programmability, security, dependability, etc.) as capable of creating new service models (e.g., pervasive robotics). Next subsections are focused on the problem of minimizing end-to-end latency in a so-called SDI by modelling a Network Function Chains with queuing systems. In particular, simulation results on the end-to-end allocation of resources showed that the scheme allows achieving the minimal end-to-end latency whilst minimizing at the same time the resources costs.

5.2.1 Network Function Chaining model

The reference scenario we consider in this paper is constituted by the topology depicted in Figure 5.7, which represents a generic Telecommunications infrastructure.

Such topology can be divided in different segments: (i) Cloud Computing Centralized DC (in the rest of the paper will be denoted as Cloud DC), that provide high computational and storage capabilities; (ii) Core network, composed by routers with high speed WAN connections that forward the traffic from the aggregation nodes to the Cloud

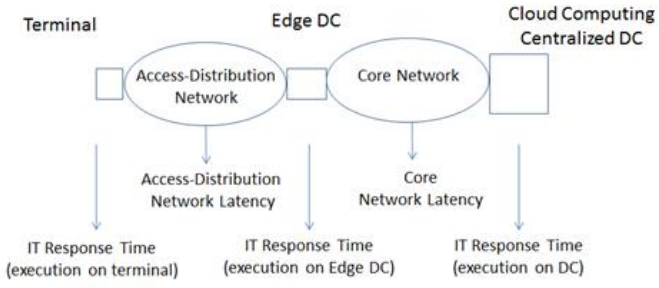


Figure 5.7: Network Function Chaining

DC and vice versa; (iii) Edge DC, which consists of small Data Centres with processing and storage resources interconnected by pervasive high speed wired and wireless links; (iv) Access-Distribution network, which is constituted by the aggregation nodes, that aggregate the traffic of thousands of Users (i.e. the Terminal). Considering the reference scenario described above, we model the network as a queuing systems. Specifically, Access-Distribution network latency and Core network latency can be modelled using M/M/1 queuing model with a single server and infinite buffer. We denote as D and H the *transmission capacity* of the Access-Distribution network and Core network, respectively. Moreover, the queue discipline follow a first come first served (FCFS) strategy. Terminal, Edge DC and Cloud DC are modelled as distributed sites, generically called *Data Centres*, and, also, we consider each of this site as computational unit, without looking into their topology. Each DC consists of a *scheduling* server, a bunch of *computing* servers and a *transmission server*. The capability of servers in each DCs depends of the number of jobs or tasks processed in each of them, as depicted in Figure 5.8.

The scheduling server receives all coming requests, and then schedules these requests to computing server. Computing server acts as the real processor, which receives tasks

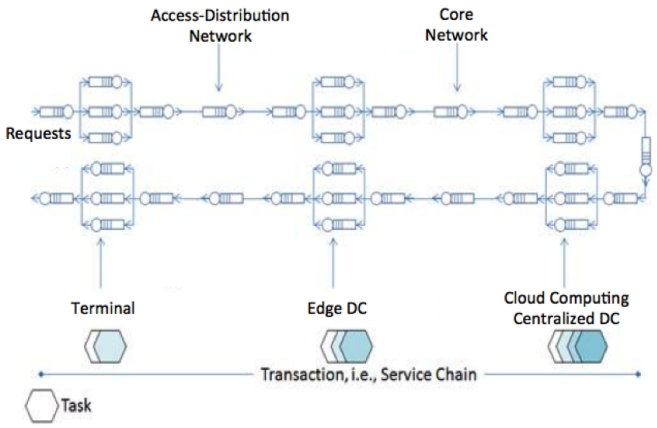


Figure 5.8: Network Function Chaining model

from the scheduling server and then processes requests using their own resources. We assume the latency of internal communications between the scheduling master and the computing server is negligible. The weight of the scheduling server represents the requests schedule rate; in particular we denote the scheduling server of the Terminal site, of the Edge DC site and Cloud DC site as A, E and I, respectively. Instead, the weight of the computing server represents tasks computation rate. We suppose there are N computing servers for the Terminal site, for the Edge DC site and Cloud DC site denoted as B_i, F_i, J_i, respectively. Also, we assume that each task is indecomposable and independent with each other. After processing, all the service results are transmitted by a transmission server, denoted as C, G and K for Terminal site, of the Edge DC site and of the Cloud DC site, respectively. Finally, we introduce an additional queue with a transmission server L.

In each DC site, two consecutive arriving requests, the inter-arrival time is a random variable, which can be modelled as an exponential random variable [106], [107], [108]. Therefore, the arrivals of the request follow a Poisson Process with arrival rate λ. In each DC, we employ possibility random generation method as scheduling scheme, which means the possibility p_i of task requests sent to computing server i is randomly generated. Thus, the arrival rate of scheduling requests to computing server i is $p_i\lambda$. According to the decomposition property of Poisson process, the arrivals of task requests at the computing server i in each DC follow a Poisson process with arrivals rate $p_i\lambda$. For each computing server, it has its own computation queue to store task requests waiting for processing. After computation phase, all results are sent to the transmission server and a transmission queue is used to store coming results. Since the whole system is a close system, the arrivals of results at the transmission queue follow the Poisson process with arrival rate λ. In each DC, the service rate of the transmission queue is determined by

the bandwidth capacity of the respective DC site.

The IT resource cost in the service Chaining Network can be charged according to the utilized resources by the time. In this paper, we employ a linear function to model the relationship between the cost and the allocated IT resources. The total cost is formulated as (5.1).

$$Cost = (\alpha A + \beta \sum_{i=1}^{N} B_i + \gamma C + \delta D + \epsilon E + \zeta \sum_{i=1}^{N} F_i + \eta G + \theta H + \iota I + \kappa \sum_{i=1}^{N} J_i + \mu K + \nu L)t \quad (5.1)$$

t is the time period with is set to 1 hour in this paper; α, β, γ, δ, ϵ, ζ, η, θ, ι, κ, μ, ν are costs of network resource servers.

5.2.2 Optimization problems formulation

This section provides a detailed formulation of the problem of allocating resources in the case in which there is only one kind of network service provided in each site of the network. As presented in the previous section, requests coming to each site of the network follow a Poisson process with arrival rate λ. In each DC site, all requests enter into the schedule queue first. The service time of the schedule queue is assumed to be exponentially distributed with mean service time A^{-1}, E^{-1} and I^{-1} for the Terminal site, for the Edge DC site and for the DC site, respectively. In particular, each service time captures the schedule capacity of the server in each site. Thus, the schedule queue is modelled as a M/M/1 queuing system and, in order to maintain the stability, the following constraints are required: $\lambda < A$, $\lambda < E$ and $\lambda < I$. Consequential, the response time of schedule queues are given by (5.2a), (5.2b) and (5.2c) for the Terminal site, for the EdgeDC site and for the DC site, respectively.

$$T_{schTerminals} = \frac{1/A}{1 - \lambda/A} \tag{5.2a}$$

$$T_{schEdgeDC} = \frac{1/E}{1 - \lambda/E} \tag{5.2b}$$

$$T_{schDC} = \frac{1/I}{1 - \lambda/I} \tag{5.2c}$$

In each site, scheduling servers distribute requests to different computing servers according to the randomly generated possibility. We suppose that in the Terminals, EdgeDC and DC sites there are N computing servers and their computational rates are represented by $B_1, B_2, ..., B_N$, $F_1, F_2, ..., F_N$ and $J_1, J_2, ..., J_N$, respectively. The service time of each computing server i is exponentially distributed with mean service time B_i^{-1}, F_i^{-1} and J_i^{-1} for the Terminal site, for the EdgeDC site and for the DC site, respectively. To maintain the stability, the following constraints are required: $p_i\lambda < B_i$, $p_i\lambda < F_i$ and $p_i\lambda < J_i$. Consequential, the response time of schedule queues are given by (5.3a), (5.3b) and (5.3c) for the Terminal site, for the EdgeDC site and for the Cloud DC site, respectively.

$$T_{compTerminals} = \sum_{i=1}^{N} \frac{\frac{p_i}{B_i}}{1 - \frac{p_i\lambda}{B_i}} \tag{5.3a}$$

$$T_{compEdgeDC} = \sum_{i=1}^{N} \frac{\frac{p_i}{F_i}}{1 - \frac{p_i\lambda}{F_i}} \tag{5.3b}$$

$$T_{compDC} = \sum_{i=1}^{N} \frac{\frac{p_i}{J_i}}{1 - \frac{p_i\lambda}{J_i}} \tag{5.3c}$$

After processing, all service results are sent to the transmission queue. In this paper, we suppose that there is no loss in the previous stages, so the arrivals of service results at the transmission queue also follow the Poisson process with arrival mean λ for each site of the network. The service time of the transmission queue is assumed to be exponentially distributed with mean service time C^{-1}, G^{-1} and K^{-1} for the Terminal site, for the

Edge DC site and for the Cloud DC site, respectively, where C, G and K capture the transmission capacity of the server in each site. The transmission queue is modelled as a M/M/1 queue and in order to maintain the stability, the following constraints are required: $\lambda < C$, $\lambda < G$ and $\lambda < K$. Consequential, the response time of schedule queues are given by (5.4a), (5.4b) and (5.4c) for the Terminal site, for the EdgeDC site and for the Cloud DC site, respectively.

$$T_{tranTerminals} = \frac{1/C}{1 - \lambda/C} \tag{5.4a}$$

$$T_{tranEdgeDC} = \frac{1/G}{1 - \lambda/G} \tag{5.4b}$$

$$T_{tranDC} = \frac{1/K}{1 - \lambda/K} \tag{5.4c}$$

As presented in Section 2, also Access-Distribution network latency and Core network latency can be modelled using M/M/1 queuing model, where D and H represent the *transmission capacity* of the Access-Distribution network and Core network, respectively. Consequential, the response time of Access-Distribution Network and Core Network are given by (5.5a) and (5.5b), respectively.

$$T_{tranAccessDistribution} = \frac{1/D}{1 - \lambda/D} \tag{5.5a}$$

$$T_{tranCore} = \frac{1/H}{1 - \lambda/H} \tag{5.5b}$$

Finally, we introduce an additional queue with a transmission server L. Its response time is given by (5.6).

$$T_{tranTrans} = \frac{1/L}{1 - \lambda/L} \tag{5.6}$$

The total response time can be formulated by (5.7)

$$
\begin{aligned}
T_{Totale} &\simeq 2\{T_{Terminal(s)site} + T_{AccessDistrivutionNet} + T_{EdgeDCsite} + T_{CoreNet} + T_{DCsite}\} \\
&+ T_{Trans} \simeq 2\{\frac{\frac{1}{A}}{1-\frac{\lambda}{A}} + \sum_{i=1}^{N} \frac{\frac{p_i}{B_i}}{1-\frac{p_i\lambda}{B_i}} + \frac{\frac{1}{C}}{1-\frac{\lambda}{C}} + \frac{\frac{1}{D}}{1-\frac{\lambda}{D}} + \frac{\frac{1}{E}}{1-\frac{\lambda}{E}} + \sum_{i=1}^{N} \frac{\frac{p_i}{F_i}}{1-\frac{p_i\lambda}{F_i}} + \\
&+ \frac{\frac{1}{G}}{1-\frac{\lambda}{G}} + \frac{\frac{1}{H}}{1-\frac{\lambda}{H}} + \frac{\frac{1}{I}}{1-\frac{\lambda}{I}} + \sum_{i=1}^{N} \frac{\frac{p_i}{J_i}}{1-\frac{p_i\lambda}{J_i}} + \frac{\frac{1}{K}}{1-\frac{\lambda}{K}}\} + \frac{\frac{1}{L}}{1-\frac{\lambda}{L}}
\end{aligned}
\tag{5.7}
$$

To simply, we consider the total response time as the double value of the one-way response time given by the summation of response time of the queues described above.

The **response time minimization problem** can be stated as: to minimize the total service response time in the network by optimizing the capacities of the master server, the computing server, and the transmission server, subject to the queuing stability constraint for each queuing system and the network resource cost constraint. Mathematically, the problem can be formulated by (5.8), where $\overline{T}$ is the upper bound of the service response time. Similarity, we employ the Lagrange multiplier method to solve the optimization problem (5.8).

We optimize the network **resource cost minimization problem** to provide network services at minimal resource cost. The resource cost minimization problem can be stated as: to minimize the total resource cost in the network by optimizing the capacities of the master server, the computing server, and the transmission server, subject to the queuing stability constraint for each queuing system and the constraint on the service response time. Mathematically, the problem can be formulated by (5.9), where $\overline{M}$ is the upper bound of the resource cost. The Lagrange multiplier method is applied to solve the optimization problem (5.9).

$$
\begin{aligned}
&\textit{minimize} && \tau && \text{(5.8a)}\\
&\textit{subject to} && \lambda < A, && \text{(5.8b)}\\
& && p_i\lambda < B_i,\ i = 1, \ldots, N, && \text{(5.8c)}\\
& && \lambda < C, && \text{(5.8d)}\\
& && \lambda < D, && \text{(5.8e)}\\
& && \lambda < E, && \text{(5.8f)}\\
& && p_i\lambda < F_i,\ i = 1, \ldots, N, && \text{(5.8g)}\\
& && \lambda < G, && \text{(5.8h)}\\
& && \lambda < H, && \text{(5.8i)}\\
& && \lambda < I, && \text{(5.8j)}\\
& && p_i\lambda < J_i,\ i = 1, \ldots, N, && \text{(5.8k)}\\
& && \lambda < K, && \text{(5.8l)}\\
& && \lambda < L && \text{(5.8m)}\\
& && Cost \leq \overline{M}. && \text{(5.8n)}
\end{aligned}
$$

$$
\begin{aligned}
&\textit{minimize} && Cost && \text{(5.9a)}\\
&\textit{subject to} && \lambda < A, && \text{(5.9b)}\\
& && p_i\lambda < B_i,\ i = 1, \ldots, N, && \text{(5.9c)}\\
& && \lambda < C, && \text{(5.9d)}\\
& && \lambda < D, && \text{(5.9e)}\\
& && \lambda < E, && \text{(5.9f)}\\
& && p_i\lambda < F_i,\ i = 1, \ldots, N, && \text{(5.9g)}\\
& && \lambda < G, && \text{(5.9h)}\\
& && \lambda < H, && \text{(5.9i)}\\
& && \lambda < I, && \text{(5.9j)}\\
& && p_i\lambda < J_i,\ i = 1, \ldots, N, && \text{(5.9k)}\\
& && \lambda < K, && \text{(5.9l)}\\
& && \lambda < L && \text{(5.9m)}\\
& && \tau \leq \overline{T}. && \text{(5.9n)}
\end{aligned}
$$

$$A = \frac{M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)\lambda}{\sqrt{\alpha}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + \lambda$$

(5.10a)

$$B_i = \frac{\sqrt{p_i}(M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)}{\sqrt{\beta}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + p_i\lambda,\ i = 1, \ldots, N$$

(5.10b)

$$C = \frac{M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)\lambda}{\sqrt{\gamma}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + \lambda$$

(5.10c)

$$D = \frac{M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)\lambda}{\sqrt{\delta}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + \lambda$$

(5.10d)

$$E = \frac{M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)\lambda}{\sqrt{\epsilon}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + \lambda$$

(5.10e)

$$F_i = \frac{\sqrt{p_i}(M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)}{\sqrt{\zeta}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + p_i\lambda,\ i = 1, \ldots, N$$

(5.10f)

$$G = \frac{M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)\lambda}{\sqrt{\eta}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + \lambda$$

(5.10g)

$$H = \frac{M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)\lambda}{\sqrt{\theta}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + \lambda$$

(5.10h)

$$I = \frac{M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)\lambda}{\sqrt{\iota}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + \lambda$$

(5.10i)

$$J_i = \frac{\sqrt{p_i}(M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)}{\sqrt{\kappa}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + p_i\lambda,\ i = 1, \ldots, N$$

(5.10j)

$$K = \frac{M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)\lambda}{\sqrt{\mu}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + \lambda$$

(5.10k)

$$L = \frac{M - (\alpha+\beta+\gamma+\delta+\epsilon+\zeta+\eta+\theta+\iota+\kappa+\mu+\nu)\lambda}{\sqrt{\nu}(\sqrt{\alpha}+\sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\gamma}+\sqrt{\delta}+\sqrt{\epsilon}+\sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\eta}+\sqrt{\theta}+\sqrt{\iota}+\sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i}+\sqrt{\mu}+\sqrt{\nu})} + \lambda$$

(5.10l)

$$A = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\sqrt{\alpha T}} + \lambda \tag{5.11a}$$

$$B_i = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\frac{\sqrt{\beta T}}{\sqrt{p_i}}} + +p_i\lambda,\ i = 1, \ldots, N \tag{5.11b}$$

$$C = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\sqrt{\gamma T}} + \lambda \tag{5.11c}$$

$$D = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\sqrt{\delta T}} + \lambda \tag{5.11d}$$

$$E = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\sqrt{\epsilon T}} + \lambda \tag{5.11e}$$

$$F_i = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\frac{\sqrt{\zeta T}}{\sqrt{p_i}}} + +p_i\lambda,\ i = 1, \ldots, N \tag{5.11f}$$

$$G = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\sqrt{\eta T}} + \lambda \tag{5.11g}$$

$$H = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\sqrt{\theta T}} + \lambda \tag{5.11h}$$

$$I = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\sqrt{\iota T}} + \lambda \tag{5.11i}$$

$$J_i = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\frac{\sqrt{\kappa T}}{\sqrt{p_i}}} + +p_i\lambda,\ i = 1, \ldots, N \tag{5.11j}$$

$$K = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\sqrt{\mu T}} + \lambda \tag{5.11k}$$

$$L = \frac{\sqrt{\alpha} + \sqrt{\beta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\gamma} + \sqrt{\delta} + \sqrt{\epsilon} + \sqrt{\zeta}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\eta} + \sqrt{\theta} + \sqrt{\iota} + \sqrt{\kappa}\sum_{i=1}^{N}\sqrt{p_i} + \sqrt{\mu} + \sqrt{\nu}}{\sqrt{\nu T}} + \lambda \tag{5.11l}$$

5.2.3 Performance evaluation

In the following section, we evaluate the performance of the resource allocation scheme proposed in the previous section by comparing it with the equal allocation scheme. Due to the computational complexity, our simulations only consider four computing servers in each DC. We assume that the schedule probabilities for such computing servers in each DC are set as $p = \{0.1, 0.2, 0.3, 0.4\}$. The mean arrival rate of requests is set in a range between $2 * 10^4$ and $6 * 10^4$ requests/s. The resource of servers [109] are charged by the value in Table 5.1.

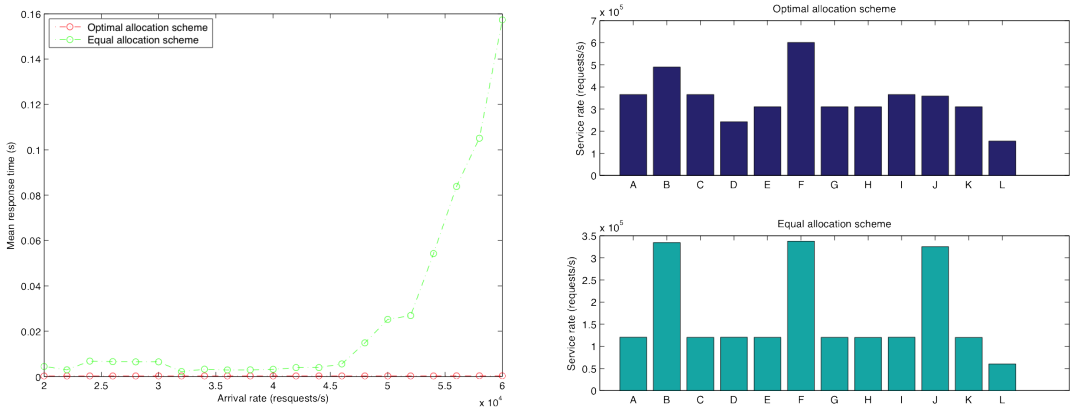
Table 5.1: Cost of servers

Resources of servers	**$/request**
α	$0.12*10^{-4}$
β	$0.48*10^{-4}$
γ	$0.20*10^{-4}$
δ	$0.20*10^{-4}$
ϵ	$0.12*10^{-4}$
ζ	$0.48*10^{-4}$
η	$0.20*10^{-4}$
θ	$0.20*10^{-4}$
ι	$0.12*10^{-4}$
κ	$0.48*10^{-4}$
μ	$0.20*10^{-4}$
ν	$0.20*10^{-4}$

5.2.3.1 Simulation results

For performance evaluation, we examine the mean response time (s) and the resource cost ($) with different values of λ (requests/s). For the purpose of comparison, we introduce the equal resource allocation scheme as a reference scheme, which is the proposed scheme without the minimization problem formulation. Specifically, in the equal allocation scheme, server's capacity A, B_i, C, D, E, F_i, G, H, I, J_i, K, L are randomly choose in order to maintain the stability constraints. Then, the resource cost and the response time are computed by using (5.1), (5.7) respectively.

Figure 5.9 shows the mean response time achieved by using both the optimal allocation scheme proposed (by solving the problem (5.8)) and equal allocation scheme. The resource cost constraint is set to 50$. From Figure 5.9(a) we can see that the proposed optimal allocation scheme achieves much lower response time compared to the equal allocation scheme under the same budget constraint. Moreover, for high values of λ, equal



(a) Comparison of the mean response time

(b) Comparison of the allocated resources

Figure 5.9: Comparison of the mean response time (panel 5.9(a)) and of the allocation resources (panels 5.9(b))

allocation scheme shows much higher response time than proposed allocation scheme, again highlighting its advantage in whole the range of arrival rate. Figure 5.9(b) shows the detailed information of the allocated resources for two schemes when λ is set to 60000 requests/s. As shown in Figure 5.9(b) the allocation of a higher portion of resources in the Terminal and Edge DC sites, leads to a smaller response time (more details are shown in Table 5.2).

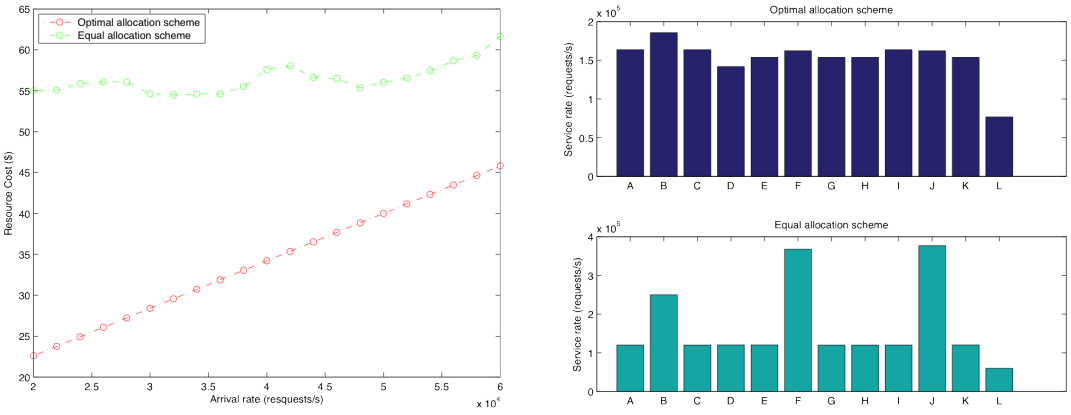
Table 5.2: Service Rate

Resources of servers	**Proposed allocation scheme**	**Equal allocation scheme**
A	$3.6534*10^5$	$1.20480*10^5$
B	$4.8936*10^5$	$3.34372*10^5$
C	$3.6534*10^5$	$1.20252*10^5$
D	$2.4267*10^5$	$1.20494*10^5$
E	$3.1004*10^5$	$1.20192*10^5$
F	$6.0076*10^5$	$3.37462*10^5$
G	$3.1004*10^5$	$1.20274*10^5$
H	$3.1004*10^5$	$1.20092*10^5$
I	$3.6534*10^5$	$1.20388*10^5$
J	$3.5842*10^5$	$3.24914*10^5$
K	$3.1004*10^5$	$1.20128*10^5$
L	$1.5502*10^5$	$0.60238*10^5$

Figure 5.9 highlights how the proposed allocation scheme can significantly improve the network performance and achieve a better performance balancing resources among

Terminal, Edge DC and DC. We can also notice that the allocation of more computation resources to the Edge DC (represented by F) and the Terminal (represented by E) improve significantly the end-to-end response time. In fact, the increase of smart nodes and devices at the edge of the network (i.e. close to the Users) globally make available enough processing-computational power, data storage capability and communication bandwidth to provide several network functions and services with local edge resources. As consequence, the allocation of the network functions at the edges of the network may improve the overall network performance as well as to provide a drastic reduction of resource costs.

In Figure 5.10 we evaluate the resource cost between the proposed optimal allocation scheme and the equal allocation scheme by using a service time constraint set as $\overline{T} = 1$ ms; this means that the mean service response time should not exceed this time requirement. As in the previous simulation, Figure 5.10(a) shows that the proposed optimal allocation scheme achieves a much lower resource cost compared to the equal allocation scheme under the same service time constraint. Moreover, we can get the reason from the allocated



(a) Comparison of the mean response time

(b) Comparison of the allocated resources

Figure 5.10: Comparison of the resource cost (panel 5.10(a)) and of the allocation resources (panel 5.10(b))

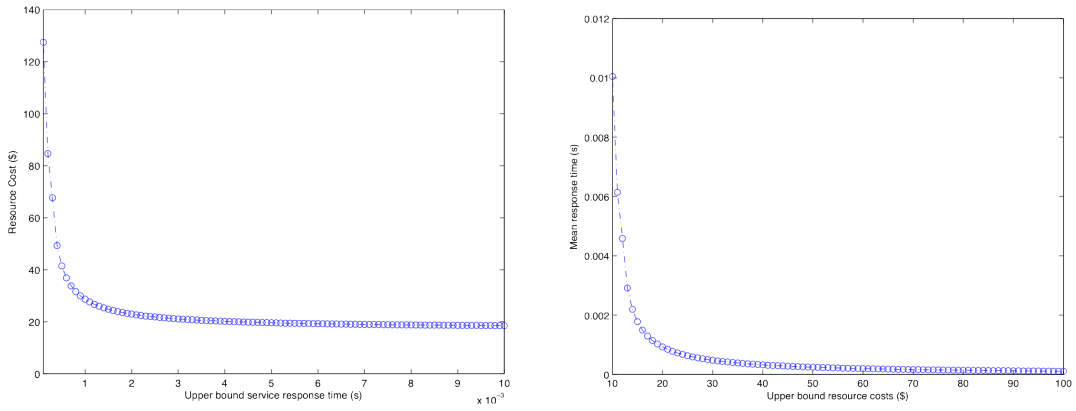
resources shown in Figure 5.10(b) when λ is set to 60000 requests/s (more details are shown in Table 5.3). Specifically, in the equal allocation scheme a smaller portion of resources are allocated to the DC sites and this degrades the performance. This is demonstrated by Figure 5.10(b), which shows how the allocation of the resources closer to the Users presents also the advantage to reduce the resource costs.

Table 5.3: Service Rate

Resources of servers	**Proposed allocation scheme**	**Equal allocation scheme**
A	$1.6348*10^5$	$1.20202*10^5$
B	$1.8546*10^5$	$2.49868*10^5$
C	$1.6348*10^5$	$1.20070*10^5$
D	$1.4174*10^5$	$1.20394*10^5$
E	$1.5368*10^5$	$1.20398*10^5$
F	$1.6225*10^5$	$3.67514*10^5$
G	$1.5368*10^5$	$1.20004*10^5$
H	$1.5368*10^5$	$1.20112*10^5$
I	$1.6348*10^5$	$1.20288*10^5$
J	$1.6225*10^5$	$3.76856*10^5$
K	$1.5368*10^5$	$1.20408*10^5$
L	$0.7684*10^5$	$0.60002*10^5$

In order to better understand the influence of upper bounds on both the resource cost and response time, additional simulations are provided in Figure 5.11(a) and Figure 5.11(b). In particular in Figure 5.11(a) we evaluate the resource cost by varying the

upper bound time constraint $\overline{T}$ between 0.1 ms and 10 ms. We can see that for $\overline{T} > 1$ ms, the resource cost performance growths drastically. Conversely, for $\overline{T} < 1$ ms, the resource cost is beyond the threshold value $\overline{M}$. In the other side, for $\overline{T} > 1$, the resource cost approaches toward a constant value. In Figure 5.11(b) we evaluate the mean response time by varying the upper bound cost resource constraint $\overline{M}$ between 10 and 100. In Figure 5.11(b) we can see that loosing the constraint the mean response time improves. Moreover, for $\overline{M} \simeq 50$, the mean response time is beyond the threshold value $\overline{T}$.



(a) Resource cost versus the upper bound mean response time constraint

(b) Mean response time versus the upper bound resource cost constraint

Figure 5.11: Influence of upper bounds on both the resource cost (panel 5.11(a)) and response time (panel 5.11(b))

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Chapter 6

Reference architecture for the dynamic placement of logical resources

6.1 Architecture description

The driving forces for both SDN and NFV have been presented together with the evolutionary scenario and use cases, which would utilize SDN and NFV within a Future Network system. This Chapter presents an overview of the management and orchestration architecture which is needed in order for such networks to operate.

From an architectural viewpoint, network functions and services can be defined as a number of software components with their accompanying context together with configuration parameters. The provisioning of a service involves the creation of a IT infrastructure, followed by the installation of all necessary software components into the infrastructure, and finally to configure and start those components. With SDN and NFV these processes can be simplified as the infrastructure provides a platform from which virtual machines can be run. SDN can be directly manifested as virtual network topologies which need to

be setup, have a managed lifecycle, and need to be shut-down – all under software control. The reference architecture, depicted in Figure 6.1, has four main layers: (i) the application layer, (ii) the orchestration layer, (iii) the abstraction layer, and (iv) the infrastructure layer.

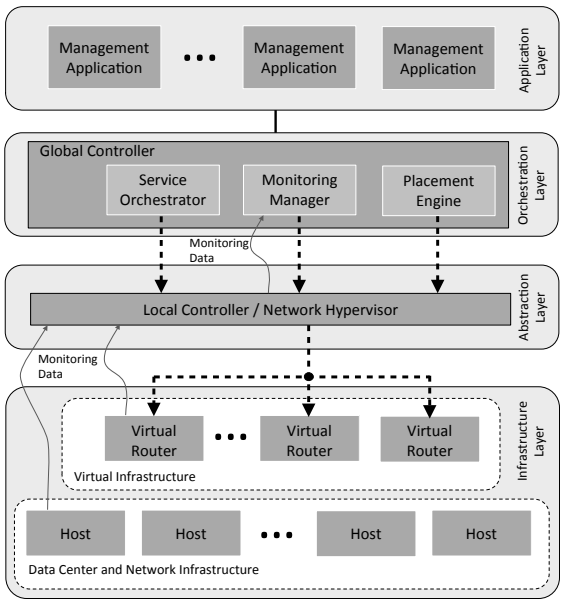


Figure 6.1: Overall system architecture and components

The **application layer** executes management applications that define the software components of a network service together with their configuration parameters. The **orchestration layer** is a software element which does most of the management and orchestration. It is in charge of managing the full lifecycle of the virtual network functions (e.g. virtual routers) in the network and the allocation of the applications running on the virtual nodes. The orchestration layer provides a *Global Controller*, which contains: (a) *Service Orchestrator*, which does the orchestration of the all elements of a service; (b) a *Monitoring Manager*, which collects and manages all of the monitoring data received from the infrastructure layer (including virtual and physical resources); (c) a *Placement Engine*,

which is involved in the placement of the virtual resources. The Global Controller is also responsible for the allocation of their applications. The **abstraction layer** contains a software element which presents an abstraction for managing virtual elements. It provides a *Local Controller* that acts as a network hypervisor, and works in a similar way to a host level hypervisor managing VMs. The **infrastructure layer** contains both the *virtual infrastructure*, which represents the virtual resources (i.e. the virtual routers) that make up the virtual networks, and the *Data Center infrastructure*, which are the physical resources that are the hosts running the VMs.

In general, the Global Controller is a distributed management infrastructure that has centralized functionality and it is responsible for the set-up, configuration, optimization, and shut-down of the network entities. As depicted in Figure 6.1, it takes input from various management applications regarding various requirements (e.g. network resources or response time) and then configures the network nodes through a set of Local Controllers.

In order to manage the challenging and dynamic infrastructures of virtual networks there needs to be a monitoring system which can collect and report on the behaviour of both the physical resources (e.g. CPU usage, memory usage) and the virtual resources (e.g. utilization level of the virtual links). These monitoring data items are sent to the Global Controller so that it can use the monitoring information in order to make decisions regarding network strategies. In particular, it may decide to add new nodes in order to fulfil the high-level policies and goals which are NOs requirements. In this way, the virtual network topology changes dynamically according to the network virtual resources usage. The following subsections describe in more detail each of the layers.

6.1.1 Application layer

As stated this layer executes management applications that define the software components and network functions of a network service together with their configuration parameters. There maybe many management applications which can interact with the orchestration layer. It is expected that some of the Management Applications will be simple, whilst others will be more complex. All of them will interact with the orchestration layer via a well-defined API.

6.1.2 Orchestration layer

The Orchestration layer is responsible for the placement of the virtual routers, the allocation of service components and functions running on the routers as applications. In particular, it is responsible for instantiating the virtual routers as it is the software element which does most of the management and orchestration and is in charge of managing the full lifecycle of the virtual routers. Mainly, the orchestration layer has the following functions:

1. it starts and stops the Local Controllers on each physical machine;
2. it acts as a control point for the platform by sending out the command;
3. it acts as a management elements for the platform by collecting monitoring data and enabling reactive behaviour.

This layer is composed of different components: namely the Service Orchestrator, the Monitoring Manager and the Placement Engine. The **Service Orchestrator** is the component in charge of performing the automatic deployment of the function/service as application running on the virtual routers.

The **Placement Engine** is the component in charge of performing the actual placement of the virtual routers according to the initial topology and the usage of the virtual network elements. This is an important feature because, when we configure a network, considering some initial information, some of these parameters may change during the course of the system's operation and a reconfiguration may be required to maintain optimized collection of information. For this reason, our approach considers a mechanism to achieve adaptation in a flexible manner. The decision on the Placement Engine is encoded in an algorithm which can be rather simple, such as counting the number of virtual routers on a host, or it can be based on a set of constraints and policies that represent the network properties. In this work we have considered i) infrastructure based measures for the placement of the virtual nodes and ii) as constraints, the usage of the virtual network entities (in this case, the usage of the virtual links) for placement. The results of using different Placement Engines will be highlighted later in this paper.

The **Monitoring Manager** is an important component of the architecture and its monitoring function is a vital part of a *full control loop* that goes from the Global Controller, through a control path, to monitoring probes which collect and send data, back to the Global Controller which makes decisions based on the data. By using various probes in many parts of the whole system, much monitoring data is sent to the Global Controller, which processes the data and can adapt the network to observed changes.

Each virtual router has a probe to monitor the usage of the network resources (e.g. the state congestion of the links). The data provided by the probes is collected by the Monitoring Manager and used by the Global Controller to create or remove the virtual routers according to the current state of the network. The monitoring software used

in this paper is called Lattice and was developed within the RESERVOIR project[1] and has been used for monitoring virtualised services in federated cloud environments [117], for monitoring virtual networks [118], and as the monitoring system for an Information Management uses Information Aggregation Points and Information Collection Points to aggregate, filter, and collect data in scalable manner within virtual networks [111]. Lattice [112] has been proven as ideal for the task of collecting monitoring data in this type of dynamic network environment.

6.1.3 Abstraction layer

This layer offers the capabilities for interacting between the Orchestrator and the Infrastructure Layers providing an abstraction. It contains the Local Controller software element, which presents a common abstraction for starting, stopping, and configuring virtual elements. A single Local Controller is started on each physical host that needs to execute virtual routers, and works in a similar way to a host level hypervisor managing virtual machines. It is a network hypervisor, which has the following functions: i) it starts and stops virtual routers; ii) it tells routers to create and remove virtual network connections, and iii) to get or set attributes on routers or links.

6.1.4 Infrastructure layer

At the bottom, the infrastructure layer consists of a number of virtual routers, which is the virtual infrastructure, instantiated in a number of physical machines (or hosts), which is the Data Center infrastructure. The virtual routers are logically independent software entities which, as a real routers, communicate with each other via network interfaces. The network traffic is made up of datagrams, which are sent to and from

[1] http://www.reservoir-fp7.eu

each router. Each virtual router can be dynamically created, dynamically destroyed in the virtual network. In fact, each router is connected to a Local Controller, which sends the instructions to start up or shut-down routers on the local machine and for routers to set-up or tear-down connections with other virtual routers.

Chapter 7

Experimental results

7.1 Very Lightweight Service Platform testbed

To validate our design and architectural work, a working implementation of the architecture explained in the Chapter 6 has been created. The experiments used the Very Lightweight Service Platform (VLSP) [110] which has been implemented by University College London for the purpose of testing and evaluating various aspects of SDN and highly dynamic virtual environments.

This platform includes run-time monitoring, adoption, and adjustment of networks like SDN, and also having a dynamic programming environment which allows the set-up of complete network topologies on-the-fly a fully SDN. The is based on a foundational framework called *User Space Routing*. This uses a set of virtual routers and virtual network connections (or virtual links) to create a network environment which can easily accommodate (i) fast set-up and tear down of a virtual router, and (ii) fast set-up and tear down of a virtual connection. As each virtual router can run programs and service elements, it becomes possible to construct an arbitrary network and compute topology.

7.1.1 Motivation

There were many motivations for designing and building the *User Space Routing* framework. These were accumulated from experience on the RESERVOIR project [114], which investigated running services in VMs, and the AutoI project [115], which investigated the virtualization of network elements, and the UniverSELF project [116], which investigated management techniques and systems for modern network architectures. It was found that the use of a hypervisor and the associated VMs did work as expected and as required, however, there were some issues that hindered various experimental situations.

Authors found that using a hypervisor and VMs added only 5% to 10% overhead to operations, compared to running the same operations in the physical machine, which is most cases was entirely acceptable. The small loss of efficiency was easily overcome by the flexibility of having VMs. In terms of experimental and research issues, some were general issues and others were specific to the domain. Moreover, they found the following general issues:

- the number of VMs that can run on a physical host is limited. This can be due to the actual resources of the physical machine that need to be shared (such as the number of cores and the amount of memory available), together with the switching capabilities of the hypervisor;

- the speed of start-up of a virtual machine can be quite slow. Although virtual machines boot up in the same order of magnitude as a physical host, there are extra layers and inefficiencies that slow them down. Also, if many VMs are started concurrently, then we observe that the physical machine and the hypervisor thrash trying to resolve resource utilization;

- the size of a VMs image is quite large. A VMs has to have a disc image which contains a full operating system and the applications needed for the relevant tasks. To start a VMs, the operating system needs to be booted and then the applications started. So every virtualised application needs the overhead of a full OS.

Moreover, authors found the following issues that were more domain specific:

- in terms of virtual networks, and virtualized routers in particular, authors observed that 98% of the router functionality they never utilized in any of the experiments that were run. Although software routers such a XORP and Quagga allow anyone to play and evaluated soft networks, the overhead of a virtual ma- chine, with a full OS, and an application where only 2% is used, seems to be an ineffective approach for many situations;

- when trying to configure the IP networking of VMs and virtual routers, there are some serious hurdles. The VMs do not talk directly to the network, but go via the hypervisor. The hypervisor has various schemes for connecting VMs to the underlying network, each of which has different behaviour. In most situations where experimentation of virtual routers is required, there needs to be a large range of IP addresses available. However, this is often hard to come by. Authors found that the limits of addressing, the IP networking configuration, and VM to VM interoperability a hindrance to network topology and network flexibility.

It was felt that to make more progress in the area of dynamic and virtual networking experimentation and research, we needed to design and build a testbed that did not have these limits, but still retain virtual machine technology. The main goals of the testbed over using a hypervisor running a standard VMs and standard OS are to have:

- better scalability;
- lower resource utilization;
- quicker start-up speed;
- reduced heaviness;
- eliminate the issue where 98% of the router functionality not needed;
- more networking flexibility.

The choice was made to write our own simple router with simple service capabilities, in Java, that could run in a Java Virtual Machine (the JVM).

7.1.2 Benefits

The benefits of a lightweight VM that includes a simple router and the basic capabilities of a service component are:

- it is possible to run many more routers on a host;
- it is easier to test scalability and stability;
- it is possible do enhanced monitoring and management evaluations;
- it provides a different way to do virtual networks: we can create arbitrary topologies using virtual routers;
- it is possible to do more evaluations of network management functions by not using complete routers and full services.

In general, it is a more effective platform for experimenting with many aspects of virtual networks.

7.1.3 The platform

The platform is designed using four main layers: (i) a *management application layer* which executes management applications that define the software components and network functions of a network service together with their configuration parameters; an *orchestration layer* which is a software element which does most of the management and orchestration and is in charge of managing the full lifecycle of the virtual routers in the network and the allocation of the applications running on the virtual nodes. It is called "Global Controller" and it does the orchestration of the all elements of a service; (iii) an *abstraction layer* which contains a software element which presents an abstraction for starting, stopping, and configuration virtual elements. It is called "Local Controller" and acts as a network hypervisor, and works in a similar way to a host level hypervisor managing VMs; (iv) an *infrastructure layer* which contains both the virtual infrastructure and represents the virtual resources (i.e. the virtual routers) that make up the virtual networks, and the which are the physical resources that are the hosts running the virtual routers. The platform uses a set of *virtual routers* and *virtual network connections* to create an environment which can easily accommodate:

- fast setup / teardown of a Virtual Router;
- fast setup / teardown of a Virtual Connection;
- each Virtual Router can run programs / service elements;

so it becomes possible to construct an arbitrary network and compute topology. The testbed has been validated in previous work we have undertaken on virtual networks and highly dynamic networks [111] [113].

7.2 Testbed

The testbed set up has three components: (i) the main component is the *Router* itself, which runs inside a JVM; (ii) a per-host controller, and (iii) a supervisor and experimental controller. The routers are complemented by a lightweight per-host controller called the *Local Controller* which has the role of sending instructions to start up or shut down routers on the local machine and to inform routers to initiate or tear down connections with other routers; and the whole testbed and experiment is supervised by a *Global Controller*. The testbed is configured with the Global Controller on one host, and the Local Controllers running on any host that is to execute virtual routers. Under control from the Global Controller, individual Local Controllers are requested to start up a new virtual router when these new routers are needed. The choice of Local Controller is decided by the Placement Engine. As described earlier, the Placement Engine uses an algorithm to determine which is the *best* host to put a router onto. The Global Controller also sends requests, via a Local Controller, to connect virtual routers together via virtual network links. To highlight how these components are distributed across the physical resources, consider a micro data center with 4 hosts. We see depicted in Figure 7.1, how these components are placed and how they interact. In the bottom left host the Global Controller is executing. It has the Service Orchestrator, the Monitoring Manager, and the Placement Engine as subcomponents. The other 3 hosts each have a Local Controller. The dashed line shows the control path from the Global Controller to all of the Local Controllers. After requests have been sent to create virtual routers and virtual links, we observe a virtual topology that spans across these 3 hosts. The solid black line represents the virtual links. An alternate view of these components, showing a layered view, sepa-

rates the control path from the virtual network. In the VLSP testbed, the virtual routers are autonomous entities and therefore the virtual network executes independently from the control elements. The control layers interact with the virtual layer. We see this view depicted in Figure 7.2.

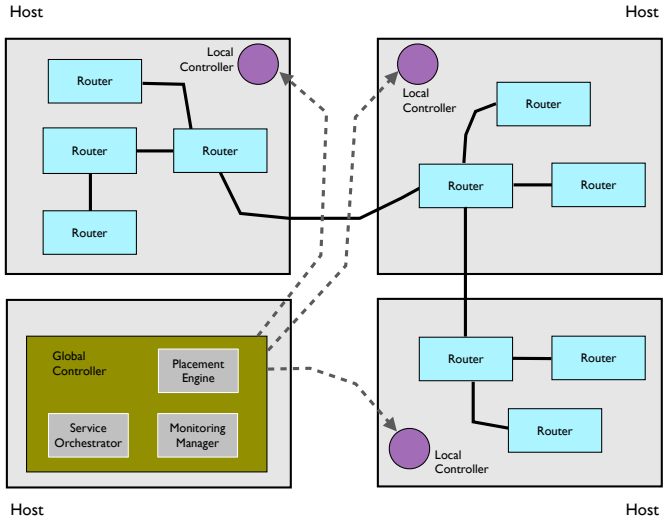


Figure 7.1: Mapping and allocation of elements to hosts

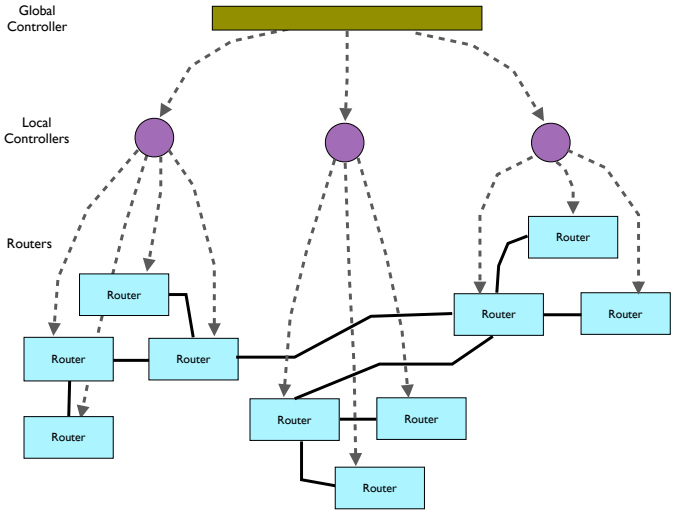


Figure 7.2: Control path to virtual routers and virtual links

7.2.1 Router Networking

The virtual router is implemented in Java and is a relatively complex software entity. The routers have virtual network connection to the other virtual routers they are connected to, and exchange routing tables to determine the short path to all other routers. Data packets are sent between routers and queued at input and output. A system of ports (like the current transport layer ports) is exposed with a *DatagramSocket* interface very similar to standard "sockets". Virtual applications can be run on the virtual routers and can listen to and send data on their associated virtual sockets. Datagrams have headers with a source address, destination address, protocol, source port, destination port, length, checksum and Time To Live (TTL). Many of the features of real IP packets are replicated in the virtual domain. As such, we can take Java software that runs on real hosts, and run it on the virtual routers, with a small effort required to make the Socket code conform the virtual DatagramSocket interface.

7.2.2 Routing and packet transmission

Routing in these virtual routers is based on *distance-vector routing*. We have incorporated the split horizon hack and poison reverse. To prevent routing storms, minimum times between table transmissions are set. In addition, because the experiment here demands a certain "churn" of virtual routers, addresses which disappear permanently must be dealt with. In distance vector routing it is well-known that dead addresses can leave routing loops. This is dealt with in the current system by implementing time to live (TTL) in packets (so that packets in a routing loop expire rather than fill the network) and also implementing a maximum routing distance beyond which a router is assumed unreachable and removed from routing tables (so that the routing loops do not persist forever).

The virtual applications can listen on virtual ports and send datagrams to any virtual address and port. Packets are queued both inbound and outbound. The outbound queue is blocking in order that transmitting applications can slow their sending rate. The inbound queue is tail-drop so that when too much traffic is sent drops will occur somewhere. TTL is decreased at each hop and, on expiry, a "TTL expired" packet is returned - this allows the virtual router system to implement trace-route as a virtual application. Virtual routers in the system send all traffic, including routing tables and other control messages, via the virtual network sockets. UDP-like, that is, delivery is not guaranteed and a failure to deliver will not be reported to the application (although if the router on which a virtual application runs has no route to the host this can be reported to the application).

7.2.3 Start-up and shut-down

The start up and shut-down of virtual routers is managed by the Global Controller and is performed by the Local Controller which resides on each host. A virtual router will be started on the same physical machine as the Local Controller. The Local Controller is also used to shut-down a virtual router or to control the connection of virtual routers with virtual links. The Local Controller behaves in the same way a hypervisor does in other virtualised environments and can also pass on Global Controller commands to Routers.

The start up and shut-down of virtual routers can be managed by the Global Controller. It is configured to create different probability distributions for router creation, router lifetimes and for new virtual link inter-arrival times.

7.2.4 Monitoring

The underlying monitoring framework used by the testbed on the routers, is known as Lattice, is described in [117] and [118]. The Lattice monitoring system has been used successfully to provide data on all of the virtual elements and the running services of a cloud computing service environment [117] as well as for virtual networks [118]. The measurements supplied have been used for service and network management. In many systems, probes are used to collect data for system management. In this regard, Lattice also relies on probes. However, to increase the power and flexibility of the monitoring we introduce the concept of a data source. A data source represents an interaction and control point within the system that encapsulates one or more probes. A probe sends a well defined set of attributes and values to a data consumer at a predefined interval.

In Lattice we have fully dynamic data sources, in which each one can have multiple probes, with each probe returning its own data. The data sources are able to turn on and turn off probes, or change their sending rate dynamically at run time. Furthermore, data sources can add new probes to a data source at run-time. By using this approach we are able to instrument virtual routers on-the-fly system without having to restart them in order to get new information. Each virtual router has at least one probe which can generate data. Monitoring data is also collected from each Local Controller. This data is send to the Monitoring Manager of the Global Controller which processes it. This is the data that is used by the Placement Engine for determining where a new virtual router is placed.

7.3 Placement Engine

This section describes work performed and presents some experimental results using the VLSP testbed. For the purpose of this paper we will will only look at collected experimental data for various Placement Engines. The evaluation of other orchestration elements, such as the Service Orchestrator, are to be covered in other papers. We show how the Placement Engine can make a decision which will enable the starting of different virtual routers on different physical hosts depending on a set of factors. A Placement Engine is a software component that encapsulates an algorithm for choosing the "best" destination to place a new virtual router. Placement Engine algorithms can be based on infrastructure metrics or on virtual network metrics. It is possible to write many different Placement Engines which rely on different metrics and algorithms. The Placement Engine is a configurable module that can be changed as needed according to different placement strategies. From the previous descriptions of the architecture and the testbed, the Placement Engine is a component of the Global Controller as shown in Listing 7.1.

The choice as to which Placement Engine to run is dependent on the high-level goals and policies that are set for the whole of the networked system. As an example, there may be a high-level goal which is "to reduce energy consumption". To satisfy such a goal, the placement engine would need to have an algorithm which placed virtual routers ensuring that the least number of physical resources were used. Conversely, a goal such as "balance the load across all physical nodes" would need a different placement engine with a different algorithm. To highlight how these placement algorithms perform we have devised an experiment whereby new routers and new links are created using a probability distribution.

Listing 7.1: Placement Engine, "PlacementEngine.java"

```
package usr.globalcontroller;
import usr.localcontroller.LocalControllerInfo;
import java.util.Set;
/**
 * A PlacementEngine is responsible for determining the placement
 * of a Router across the active resources.
 */
public interface PlacementEngine {
    /**
     * Get the relevant LocalControllerInfo for a placement of a router.
     */
    public LocalControllerInfo routerPlacement();
    /**
     * Get the relevant LocalControllerInfo for a placement of a router
         with a specific address.
     */
    public LocalControllerInfo routerPlacement(String address);
    /**
     * Get all the possible placement destinations
     */
    public Set<LocalControllerInfo> getPlacementDestinations();
}
```

The virtual routers are created using a Poisson process (with exponential distribution of inter-arrival times) as this has been shown to be a realistic distribution for a number of real traffic arrival processes on the current Internet [121, table 3]. Also, each new virtual router has a randomized "lifetime", so a virtual router can shut-down at run-time. Links are added between nodes as a random process, with every virtual router having one link plus a number of extra links, with a Poisson distribution. The routers are linked at random, so we observe that older routers tend to acquire more links. This experimental set-up provides a highly dynamic and adapting network scenario with which to test the Placement Engines. For the tests we created a testbed scenario that utilizes 4 hosts in a configuration presented in Figure 7.1 and Figure 7.2. This will give us placement data for 3 hosts. Although the number of hosts used for real virtual networks is likely to be considerably higher than 4, having 3 allows us to present our results more clearly. We have

considered three different Placement Engines for the same experimental set-up, using the randomly generated virtual topology. The algorithms embedded in each of the Placement Engines are based on monitoring data from the infrastructure or monitoring data from the virtual network. In the following more details about each placement algorithm are provided.

7.3.1 Least Used Host

Listing 7.2: Placement Engine: Least Used, "LeastUsedLoadBalancer.java"

```
/* Get the relevant LocalControllerInfo for a placement of a router.
     */
    public LocalControllerInfo routerPlacement() {
        LocalControllerInfo leastUsed = null;
        double minUse = 0.0;
        double thisUsage = 0.0;
        for (LocalControllerInfo localInfo : getPlacementDestinations()) {
            thisUsage = localInfo.getUsage(); // same as localInfo.
                getNoRouters() / localInfo.getMaxRouters()
            //Logger.getLogger("log").logln(USR.STDOUT, localInfo +" Usage
                "+thisUsage);
            if (thisUsage == 0.0) {  // found an empty host
                leastUsed = localInfo;
                break;
                }
            if (thisUsage < minUse || leastUsed == null) {
                minUse = thisUsage;
                leastUsed = localInfo;
            }
        }
        if (minUse >= 1.0) {
            return null;
        }
        return leastUsed;
    }
```

The algorithm listed in Listing 7.2 is the Least Used placement algorithm. It collects the number of virtual routers allocated to each physical host and chooses the host that has the least number of virtual routers. If more than one host is at the minimum level, then a random host is chosen. This algorithm is a kind of load balancing algorithm as it tries to get a similar number of routers on each host.

7.3.2 N at a time in a Host

Here we present the N at a time placement algorithm (Listings: 7.3, 7.4 and 7.5). It tries to allocate N routers at a time into a single host (in this run, N = 5). If the number of routers is a factor of N , then the algorithm chooses are different host. When all the hosts are packed with a factor of N, then a random host is chosen. It too collects the number of virtual routers allocated to each physical host in order to make a decision.

Listing 7.3: Placement Engine: N at a time in a Host, "NupPlacement.java"

```
/**
 * It allocates routers in blocks of N
 * It finds the LocalController which has space for another router.
 */
public class NupPlacement implements PlacementEngine {
    // The GlobalController
    GlobalController gc;
   // The no of routers to place on a host
    int count = 5;
   /**
     * Constructor
     */
    public NupPlacement(GlobalController gc) {
        this.gc = gc;
       Logger.getLogger("log").logln(USR.STDOUT, "NupPlacement:
           localcontrollers=" + getPlacementDestinations());
       }
```

Listing 7.4: Placement Engine: N at a time in a Host, “NupPlacement.java”

```
/**
  * Get the relevant LocalControllerInfo for a placement of a router
      with
  * a specified name and address.
  */
 public LocalControllerInfo routerPlacement(String name, String address)
     {
     LocalControllerInfo toUse = null;
     int minUse = Integer.MAX_VALUE;
     int thisUsage = 0;
     long elapsedTime = gc.getElapsedTime();

    // now work out placement
     for (LocalControllerInfo localInfo : getPlacementDestinations()) {
         thisUsage = localInfo.getNoRouters();
         if (localInfo.getNoRouters() >= localInfo.getMaxRouters()) {
             // cant use this one
             continue;
         }

         //Logger.getLogger("log").logln(USR.STDOUT, localInfo +" Usage
             "+thisUsage);
         if (thisUsage % count != 0) { // found a candidate with a free
             slot
             toUse = localInfo;
             break;
         }
         // now check if there is less usage
         if (thisUsage < minUse) {
             minUse = thisUsage;
             toUse = localInfo;
         }
     }
     Logger.getLogger("log").logln(1<<10, "NupPlacement:end_of_␣
         first_loop:toUse=" + toUse + "minUse=" + minUse);
```

Listing 7.5: Placement Engine: N at a time in a Host, “NupPlacement.java”

```
        // check if we didn't chose one
        if (toUse == null) {
            // chhose one with the minimum usage
            for (LocalControllerInfo localInfo : getPlacementDestinations()
                ) {
                thisUsage = localInfo.getNoRouters();
                // choose a random with min use
                if (thisUsage == minUse) {
                    toUse = localInfo;
                }
            }
        }

        // still chose nothing
        if (toUse == null) {
            //so choose a random one
            toUse = getPlacementDestinations().iterator().next();
        }
        // log current values
        Logger.getLogger("log").logln(1<<10, toTable(elapsedTime));
        Logger.getLogger("log").logln(USR.STDOUT, "NupPlacement: choose " +
             toUse + " use: " + thisUsage);
        Logger.getLogger("log").logln(1<<10, gc.elapsedToString(elapsedTime
            ) + ANSI.CYAN +  "NupPlacement:choose" + toUse + "use:" +
            thisUsage + "for" + name + "/" + address + ANSI.RESET_COLOUR);
        return toUse;
    }
```

7.3.3 Least Busy Host

Here we present the Least Busy placement algorithm. It tries to determine the host that is *least busy* in terms of virtual network traffic. It collects monitoring data from all the the virtual routers (as shown in Listing 7.6) in the virtual network and calculates how much virtual traffic has been sent on each of the hosts. The host that has the lowest amount of traffic since the last placement decision is chosen as the host for the current placement. This algorithm is useful in contexts where the QoS of the virtual network is important as it places virtual routers close to other virtual routers that are not sending much traffic.

Listing 7.6: Placement Engine: Least Busy, "LeastBusyPlacement.java"

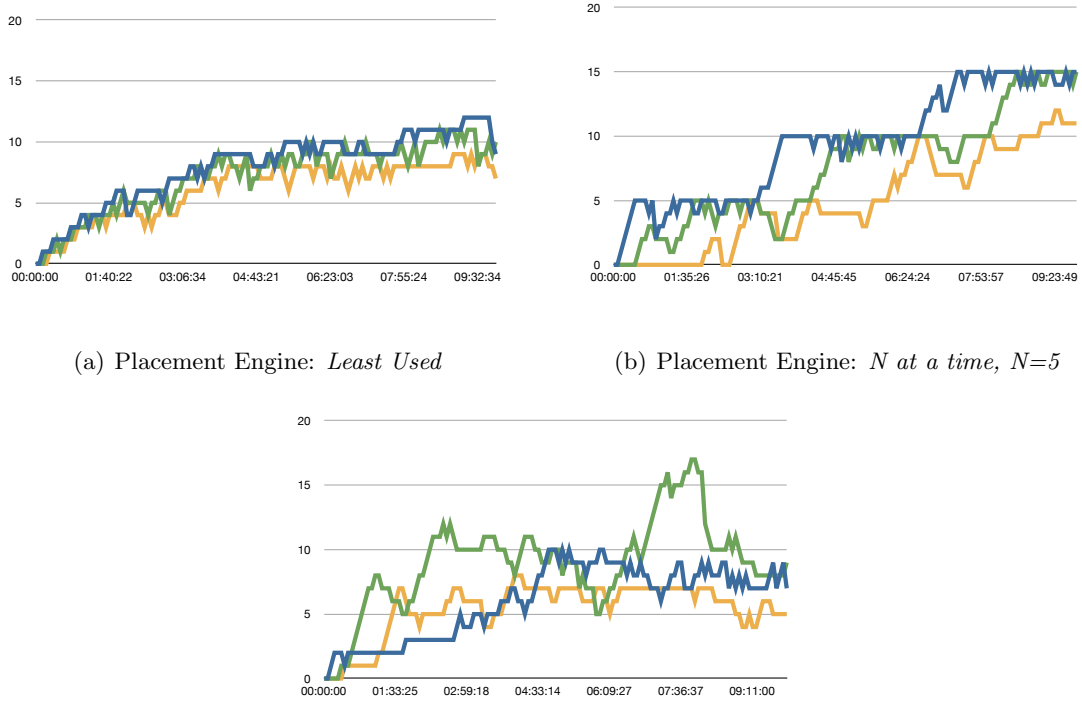
```
// at this point we know which host has what volume.
        // now we need to skip through all of them and find the host
        // with the lowest volume
        long lowestVolume = Long.MAX_VALUE;

        for (Map.Entry<LocalControllerInfo, Long> entry : lcVolumes.
            entrySet()) {
            Long volume = entry.getValue();

            if (volume < lowestVolume) {
                lowestVolume = volume;
                leastUsed = entry.getKey();
            }
        }
```

7.4 Results

Figure 7.3(a), Figure 7.3(b) and Figure 7.3(c) show the number of virtual routers allocated on each host (shown on the *y-axis*) versus the time of the experimental run (shown on the *x-axis*). The hosts: host 1, host 2 and host 3 represented by blue, green and yellow lines respectively. Due to the random creation of virtual routers, combined with a randomized router lifetime, we see that the number of routers allocated to a host can do down as well as going up.



(a) Placement Engine: *Least Used*

(b) Placement Engine: *N at a time, N=5*

(c) Placement Engine: *Least Busy*

Figure 7.3: Number of virtual routers allocated on each host (shown on the *y-axis*) versus the time of the experimental run (shown on the *x-axis*).

Both *Least Used* (Figure 7.3(a)) and *N at a time* (Figure 7.3(b)) are based on infrastructure data, and *Least Busy* (Figure 7.3(c)) relies on virtual network monitoring data.

Observation of Figure 7.3(a) shows that the allocations are very similar for each host. Observations of Figure 7.3(b) show that allocation pattern is very different from the *Least Used* algorithm. Furthermore, as routers reach the end of their lifetime we see them disappearing from the allocation count, but the algorithm still tries to pack in N routers to a host. Observations of Figure 7.3(c) show that the allocation pattern is again different from the previous two placement algorithms. This placement is not impacted by any infrastructure monitoring data, only virtual network traffic. As the traffic decreases on a host then the number of routers allocated to that host increases. These fluctuations, combined with router death, show a marked variation from Least Used and N at a time.

The results presented here demonstrate that the different embedded algorithms in each of the Placement Engines give very different placement strategies for the virtual routers. It is expected that over time the placement algorithms for virtual routers will become more complex and factor-in metrics from both infrastructure and virtual resources. These placement engines may be able to utilize or share some algorithmic elements from compute cloud placement algorithms such as [119] and [120]. By having a detailed understanding of the behaviour of these different placement algorithms, it will be possible to choose the best Placement Engine to achieve fully effective operation. The Placement Engine should be swappable at run-time in order to make placements that match changing high-level goals and policies. Such flexibility is a key aspect of a management and orchestration system.

Chapter 8

Conclusions

This thesis presented the motivations and research challenges for next generation of networks based on software-defined principles. We believe that the next generation of networks needs to move from being merely *defined* by software to *driven* and *enabled* by software and must be capable of supporting a multitude of network and service providers that exploit an environment in which network functions and services are dynamically deployed and quickly adapted over a heterogeneous physical infrastructure, according to changing requirements. Specifically, in this work we have proposed an architecture based on a resource orchestrator for run-time orchestration of logical resources in wired environments. Moreover, we have developed and implemented specific mechanisms and algorithms for an efficient mapping of virtual resources onto physical resources in Software Defined Infrastructures – considered representative of wired environments.

This work consists of three basic contributions: (i) the definition of a model representing a virtual network; (ii) the design of a network architecture based on soft-orchestration of virtual network resources; (iii) the development of placement algorithms for an efficient mapping of virtual resources onto physical resources.

Concerning the **first contribution**, a virtual network can be represented by graphs which consist of a set of virtual nodes (vertices) and a set of virtual links. A virtual node can transfer virtual information to another virtual node in the form of data-packets if there is a virtual link between them. If there is no direct virtual link between the virtual nodes, then a path in the network is the sequence of distinct virtual nodes visited when transferring data-packets from one virtual node to another. Moreover, we have introduced statistical properties of packet traffic described by a model where the traffic is both Poisson-like (or Short Range Dependence) and self-similar (or Long Range Dependence). We have considered networks with different topologies generated using the most appropriate algorithms (for example, Erdős-Rényi (ER) algorithm to generate a random network and the static model introduced in [84] to generate scale-free topologies). Using the network model and traffic generator detailed above, simulations were carried out to analyze various aspects of the end-to-end performance for each different type of network, observing that hypercube networks show much higher performance (in terms of throughput and latency) and resilience to intentional attacks than scale free networks, again combining some of the beneficial, features of different network structures.

As for the **second contribution**, from the underlying physical resources, a set of virtual networks can be created using the mechanisms of the virtualisation. These virtual networks have different properties – according to specific needs – and their creation can be programmable using SDN paradigm. An orchestrator is a software entity in charge of managing the full lifecycle of virtual resources in the network and the allocation of the applications running on the virtual elements. Our solution consists of an *orchestration layer*, which contains: (a) a *Service Orchestrator*, which does the orchestration of the all elements of a service; (b) a *Monitoring Manager*, which collects and manages all of the monitoring

data received from the infrastructure layer (including virtual and physical resources); (c) a *Placement Engine*, which is involved in the placement of the virtual resources, according to specific requirements or high-level policies (e.g. energy consumption). Specifically, it encapsulates an algorithm (based on infrastructure metrics or on virtual metrics) for choosing the "best" destination to place a new virtual resource.

Our last considerations are on placement algorithms for an efficient mapping between virtual and physical resources which are provided by the **third contribution** of this thesis. SDI would be able to create a virtual network and instantiate the requested end user' s functionalities at the required locations to provide the desired QoS, e.g. minimizing network latency. This challenge includes the design and implementation of algorithms in the Placement Engine in order to "optimise" mapping of virtual resources onto the physical resources. In this work, an optimisation technique based on the minimization problem formulation has been proposed. Simulation results show that our optimal allocation scheme achieves both much lower response time and resource costs with respect to the equal allocation scheme (used as a reference scheme) under the same budget constraint and time service constraint. Moreover, simulation results highlight how the allocation of the resources closer to the users, in order to execute network functions and services, will bring several advantages, not only in terms of flexibility but also in performance improvements and costs reductions.

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- Elisa

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