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COMPUTER SYSTEMS NETWORKING

MSc THESIS

Contributing to the pathway towards 5G experimentation with an SDN-controlled network box

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ΕΘΝΙΚΟ ΚΑΙ ΚΑΠΟΔΙΣΤΡΙΑΚΟ ΠΑΝΕΠΙΣΤΗΜΙΟ ΑΘΗΝΩΝ

ΣΧΟΛΗ ΘΕΤΙΚΩΝ ΕΠΙΣΤΗΜΩΝ
ΤΜΗΜΑ ΠΛΗΡΟΦΟΡΙΚΗΣ ΚΑΙ ΤΗΛΕΠΙΚΟΙΝΩΝΙΩΝ

ΠΡΟΓΡΑΜΜΑ ΜΕΤΑΠΤΥΧΙΑΚΩΝ ΣΠΟΥΔΩΝ
ΔΙΚΤΥΩΣΗ ΥΠΟΛΟΓΙΣΤΙΚΩΝ ΣΥΣΤΗΜΑΤΩΝ

ΔΙΠΛΩΜΑΤΙΚΗ ΕΡΓΑΣΙΑ

Συμβάλλοντας πειραματικά στην πορεία προς το 5G με έναν αυτόνομο κόμβο προσομοίωσης ενός λογισμικά ελεγχόμενου δικτύου

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ABSTRACT

As the demand in mobile broadband is tremendously increased and the heterogeneity of the services to be covered is growing rapidly, current mobile networks are close to their limits imposing the need of an evolution which is going to be introduced by the next generation technology, the ITU IMT-2020, well known as 5G.

5G brings all those capabilities required to cover the increased mobile broadband needs, support the Internet of Things and bind heterogeneous services in different industries.

This diploma thesis aims at presenting the “Network in a box”, an innovative tool we developed which is based on the key 5G principles, SDN and NFV. With Software Defined Networking (SDN) being the new approach in mobile networks, control and data plane are decoupled providing the ability to make any control related decisions centrally and transform legacy network devices to simple forwarding elements. This testbed is a portable emulated network device which is self-managed and self-optimised and can be connected between any real network devices, emulating how the 5G network will perform. This plug & play black-box testbed is also capable of providing KPI metrics of the 5G network under real circumstances when real network devices are connected to it.

The structure of this diploma thesis is decomposed in five chapters. Chapter 1 presents the challenges mobile networks will shortly face due to the growing heterogeneous demands in communications towards the year 2020 and beyond and how these can be met with the upcoming 5G technology. Chapter 2 introduces the market trend behind the new era of 5G, revealing the business context for enterprises, consumers, verticals and partnerships as well as some use cases which reflect the continuous mobile broadband evolution. Chapter 3 includes a short overview of the ongoing 5G projects, initiated under the umbrella of the European Commission, with the collaboration of communications technology vendors, telecommunications operators, service providers, small and medium-sized enterprises (SMEs) and universities. There is also a reference in 5G key enabling technologies and standardisation activities as we move towards the next generation mobile networks technology. Moving forward, chapter 4 describes in detail the technological components of 5G network architecture such as SDN, NFV, MANO and examines how these 5G key enabling technologies contribute to the overall networks’ sustainability. Finally, in chapter 5 we introduce an innovative idea developed in our university’s communications network research laboratory, an autonomous emulated portable network testbed, the “Network in a box”. We present in-depth how this portable server is deployed, operates and demonstrate the way it can be connected to real network elements emulating a real 5G end-to-end customer network. Moreover, in this last chapter we present “Network in a box” capabilities under real network circumstances when link degradations or failures take place, providing also real-time network metrics.

SUBJECT AREA: Communications Networks

KEYWORDS: 5G, Software Defined Networks, Network Functions Virtualisation, MANO, Network in a box, Openflow, Mininet, POX

ΠΕΡΙΛΗΨΗ

Καθώς η απαίτηση σε ευρυζωνικές υπηρεσίες κινητών επικοινωνιών αυξάνεται ραγδαία, τα υπάρχοντα δίκτυα κινητών επικοινωνιών πλησιάζουν τα όριά τους κάνοντας επιτακτική την ανάγκη εξέλιξής τους η οποία θα επέλθει με την τεχνολογική άφιξη της επόμενης γενιάς κινητών επικοινωνιών, ευρέως γνωστής ως 5G. Το 5G μεταφέρει όλες εκείνες τις δυνατότητες οι οποίες είναι απαραίτητες για να καλυφθούν οι συνεχώς αυξανόμενες ανάγκες σε ευρυζωνικές υπηρεσίες, να υποστηρίξουν το Internet of Things καθώς και να ενοποιήσουν ετερογενείς υπηρεσίες σε διαφορετικές βιομηχανίες.

Η παρούσα διπλωματική εργασία στοχεύει να παρουσιάσει το “Network in a box”, ένα καινοτόμο εργαλείο που αναπτύξαμε στο εργαστήριο, το οποίο βασίζεται επάνω στους θεμέλιους λίθους του 5G, το SDN και το NFV. Με το SDN να είναι η νέα προσέγγιση στα δίκτυα κινητών επικοινωνιών, ο έλεγχος διαχωρίζεται από τα δεδομένα παρέχοντας τη δυνατότητα οποιεσδήποτε αποφάσεις ελέγχου, να λαμβάνονται κεντρικά, μετατρέποντας έτσι τις κλασικές δικτυακές συσκευές σε απλά προωθητικά στοιχεία του δικτύου. Η συγκεκριμένη διάταξη μιμείται ένα πραγματικό δίκτυο, το οποίο διαθέτει δυνατότητες αυτο-οργάνωσης και αυτο-βελτίωσης, προσομοιώνοντας τη λειτουργία του 5G δικτύου. Το συγκεκριμένο εργαλείο είναι επίσης ικανό να παράσχει KPI μετρικές του 5G δικτύου κάτω από πραγματικές συνθήκες ενόσω αληθινές δικτυακές συσκευές είναι συνδεδεμένες σε αυτό.

Η δομή της παρούσας διπλωματικής εργασίας αναλύεται σε πέντε κεφάλαια. Το πρώτο κεφάλαιο παρουσιάζει τις προκλήσεις που σύντομα θα κληθούν να αντιμετωπίσουν τα δίκτυα κινητών επικοινωνιών και πώς αυτές μπορούν να καλυφθούν με την τεχνολογία του 5G. Το δεύτερο κεφάλαιο εισάγει την τάση στην αγορά των κινητών επικοινωνιών που διαφένεται πίσω από την επερχόμενη άφιξη του 5G, αποκαλύπτοντας το επιχειρηματικό πλαίσιο για επιχειρήσεις, καταναλωτές και συνεργασίες όπως επίσης και κάποιες περιπτώσεις χρήσης που αντικατοπτρίζουν την διαρκή εξέλιξη στις ευρυζωνικές υπηρεσίες κινητών επικοινωνιών. Το τρίτο κεφάλαιο εμπεριέχει μια μικρή επισκόπηση των τρέχοντων έργων πάνω στο 5G, τα οποία ξεκίνησαν υπό την αιγίδα της Ευρωπαϊκής Επιτροπής με τη συνεργασία προμηθευτών τεχνολογίας επικοινωνιών, παρόχων υπηρεσιών, μικρομεσαίων επιχειρήσεων και πανεπιστημίων. Γίνεται επίσης αναφορά στις βασικές τεχνολογίες του 5G και στις δραστηριότητες προτυποποίησής του. Προχωρώντας στο τέταρτο κεφάλαιο, περιγράφουμε σε βάθος την αρχιτεκτονική του 5G δικτύου, αναλύοντας τα SDN, NFV, MANO και εξετάζουμε πώς αυτά συνεισφέρουν στη βιωσιμότητα του δικτύου. Τέλος, στο πέμπτο κεφάλαιο εισάγουμε μια καινοτόμο ιδέα που αναπτύξαμε στο εργαστήριο δικτύων του πανεπιστημίου μας, ένα πλήρως αυτόνομο δικτυακό εργαλείο, το “Network in a box”. Παρουσιάζουμε σε βάθος πώς αυτός ο server μπορεί να εγκατασταθεί και να λειτουργήσει καθώς και τις δυνατότητές του κάτω από πραγματικές συνθήκες λειτουργίας του δικτύου, ενώ λαμβάνουν χώρα υποβάθμιση ποιότητας ή μη-διαθεσιμότητα στις δικτυακές ζεύξεις, παρέχοντας επίσης μετρικές από τη λειτουργία του δικτύου σε πραγματικό χρόνο.

ΘΕΜΑΤΙΚΗ ΠΕΡΙΟΧΗ: Δίκτυα Επικοινωνιών

ΛΕΞΕΙΣ ΚΛΕΙΔΙΑ: 5G, Προγραμματιζόμενα Δίκτυα, SDN, NFV, MANO, Network in a box, Openflow, Mininet, POX

This MSc Thesis is dedicated to my family.

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Subsequently, heartfelt thanks to the Dr. Dimitrios Tsolkas for his continuous guidance and ceaseless support all these years. He conceived the idea of implementing the self-organised “Network in a box” and maintained the vision on how this testbed device could be useful in real customer networks in the way towards 5G. Dimitris has been always standby during this long implementation period and worked with me tirelessly, remaining most of the time till late at night in the office. I cannot overlook the fact that he accepted to supervise me from the very first moment I expressed my interest, always being supportive upon the great difficulties we came across, thus making our cooperation very pleasant and constructive.

Finally, I cannot miss to thank my family and my friends, for the great support and patience they showed throughout my undergraduate and postgraduate studies, as well as all those who contributed in their own way to my effort’s successful completion.

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PREFACE

The current MSc Thesis was conducted in the Department of Informatics and Telecommunications of National and Kapodistrian University of Athens, and more specifically under the support of the Communication Networks Laboratory of Telecommunications and Signal Processing sector. The thesis started being conducted in March 2017 and ended in June 2018. Professor Lazaros Merakos and Dr. Dimitris Tsolkas were the supervisors of this MSc Thesis.

1. 5G POTENTIAL

1.1 Introduction

The future of mobile communications is likely to be very different to that which we are used to today. While demand for mobile broadband will continue to increase, largely driven by ultra high definition video, we are already seeing the growing impact of technology in our everyday life as the things around us become ever more connected. In this context, the International Telecommunication Union (ITU) set under the IMT-2020 the requirements for the next generation of mobile networks, which is now well recognized as 5G.

5G will not only be an evolution of mobile broadband networks. It will bring new unique network and service capabilities. Firstly, it will ensure user experience continuity in challenging situations such as high mobility (e.g. in trains), very dense or sparsely populated areas, and journeys covered by heterogeneous technologies. In addition, 5G will be a key enabler for the Internet of Things (IoT) by providing a platform to connect a massive number of sensors, rendering devices and actuators with stringent energy and transmission constraints. Furthermore, mission critical services requiring very high reliability, global coverage and/or very low latency, which are up to now handled by specific networks, typically public safety, will become natively supported by the 5G infrastructure.

5G will integrate networking, computing and storage resources into one programmable and unified infrastructure. This unification will allow for an optimised and more dynamic usage of all distributed resources, and the convergence of fixed, mobile and broadcast services. By leveraging on the characteristic of current cloud computing, 5G will push the single digital market further, paving the way for virtual pan European operators relying on nationwide infrastructures. This will enable multi tenancy models, where various and heterogeneous vertical industries (e.g., automotive, factories of the future, media & entertainment) can collaborate with the operators to efficiently provide their services.

5G will be designed to be a sustainable and scalable technology. Firstly, the telecom industry will compensate tremendous usage growth by drastic energy consumption reduction and energy harvesting. In addition, cost reduction through human task automation and hardware optimisation will enable sustainable business models for all ICT stakeholders.

Last but not least, 5G will create an ecosystem for technical and business innovation. Since network services will rely more and more on software, the creation and growth of startups in the sector will be encouraged.

1.2 5G benefits

5G offers enormous potential for both consumers and industry.

Two views of 5G exist today:

- *The hyper-connected vision:*

As well as the prospect of being considerably faster than existing technologies, 5G holds the promise of applications with high social and economic value, leading to a ‘hyper-connected society’ in which mobile will play an ever more important role in people’s lives.

In this view of 5G, mobile operators would create a blend of pre-existing technologies covering 2G, 3G, 4G, Wi-fi and others to allow higher coverage and availability, and higher network density in terms of cells and devices, with the key differentiator being greater connectivity as an enabler for Machine-to-Machine (M2M) services and the Internet of Things (IoT). This vision may include a new radio technology to enable low power, low throughput field devices with long duty cycles of ten years or more.

- *Next-generation radio access technology:*

This is more of the traditional 'generation-defining' view, with specific targets for data rates and latency being identified, such that new radio interfaces can be assessed against such criteria. This in turn makes for a clear demarcation between a technology that meets the criteria for 5G, and another which does not.

Both approaches are important for the progression of the industry, but there are distinct sets of requirements associated with specific new services. However, the two views described are regularly taken as a single set and hence requirements from both the hyper-connected view and the next-generation radio access technology view are grouped together. This problem is compounded when additional requirements are also included that are broader and independent of technology generation.

Every industry will be affected by 5G. Network speeds as high as 10Gbps (over-the-air) and with extremely low latency are a driving force for new applications that use massive broadband capabilities.

5G platform will provide network solutions and involve vertical markets such as automotive, energy, food and agriculture, city management, government, healthcare, manufacturing, public transportation, the IT industry and so forth.

1.3 5G (future) expectations

The 5G communications network and service environment of 2020 will be infinitely richer and more complex than today. The user experience will not only be more involving but also more immersive, supporting all aspects of social interaction, work communication, health monitoring, device and environment management, and even assisting your economic wellbeing too. The challenge now is to provide a 5G infrastructure that has the inherent capacity, capability, reliability, availability and security to provide this seamless life support in a timely and sustainable way. This new network infrastructure must be capable of connecting people, processes, computer centers, content, knowledge, information, goods and other things at high speed according to a multiplicity of application specific requirements. And while the amount of communication each person does is expected to increase dramatically, the number of connected things communicating is expected to be 10 times higher than the number of connected human users by then. 5G is not just an evolution; it is a revolution and must be designed to handle this dramatic increase in communications from the start.

5G is the next chapter of telecom networks designed to meet a more advanced and more complex set of performance requirements. 5G represents a new way of thinking. It encompasses innovative network design for deploying machine-type communication (MTC) and efficiently supports applications with widely varying operational parameters, providing greater flexibility to deploy services. As such, 5G is an important enabler of the Networked Society.

1.4 5G design objectives

5G is the next frontier of innovation for the entire mobile industry.
The three major design objectives for 5G:

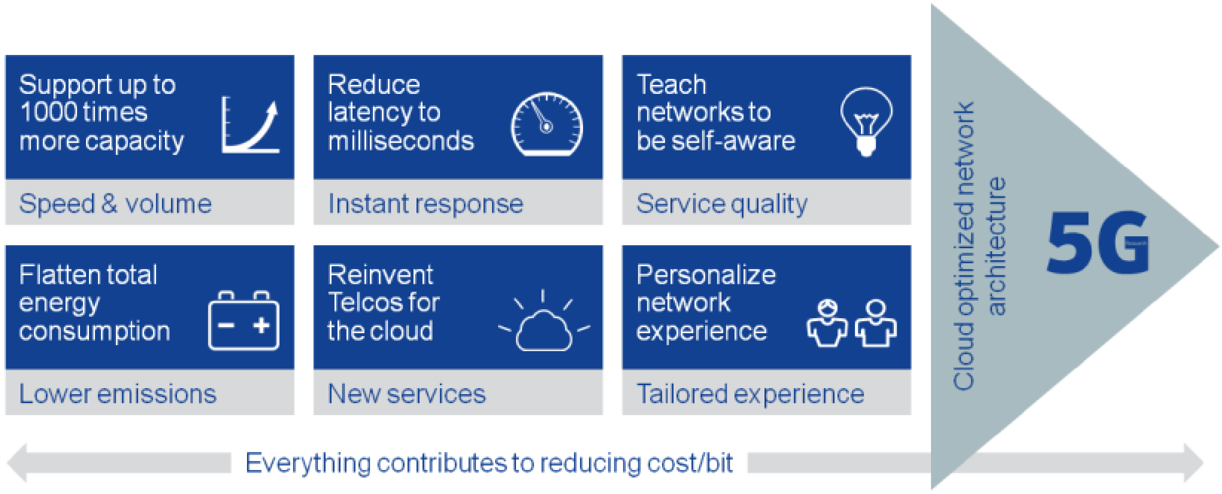
- Implementation of massive capacity and massive connectivity
- Support for an increasingly diverse set of services, applications and users; all with extremely diverging requirements

- Flexible and efficient use of all available non-contiguous spectrum for wildly different network deployment scenarios

An adaptive network solution framework will become a necessity for accommodating both LTE and air interface evolution; Cloud, SDN and NFV technologies will reshape the entire mobile ecosystem; and 5G will speed up the creation of massive-scale services and applications. The next decade promises breakthrough developments in several fundamental RAN technologies that will be required for implementing commercial-ready 5G network solutions. 5G success depends on the entire ICT ecosystem. Its growth will be built upon global LTE success. ICT ecosystem innovation will also be a major driver in creating a bigger 5G market.

The cloud paradigm will be implemented in all parts of the network to use existing resources in the best way. In a nutshell, 5G networks will be programmable, software driven and managed holistically. Essentially, communication systems beyond 2020 will need to be flexible enough to accommodate a huge range of use cases without increasing management complexity.
Thus, the main pillars of fifth generation mobile networks, as identified by Nokia, are listed below:

- Support up to 1000 times more network capacity
- Reinvent Telcos for the Cloud
- Flatten total energy consumption
- Teach networks to be self-aware
- Personalize network experience
- Reduce latency to milliseconds



*How to enable mobile broadband networks to deliver "**gigabytes** of personalized data per user per day profitably and securely" by 2020*

Figure 1: Technology vision 2020 – 6 main pillars

Source: Nokia

1.5 5G technology requirements

As a result of this blending of requirements, many of the industry initiatives that have progressed with work on 5G identify a set of requirements:

- 1-10Gbps connections to end points in the field
- sub-1 millisecond end-to-end round trip delay (latency)
- 1000x bandwidth per unit area
- 10-100x number of connected devices

- (Perception of) 99.999% availability
- (Perception of) 100% coverage
  (These are not use case drivers, nor technical issues, but economic and business case decisions; it is a business decision rather than a technical objective)
- 90% reduction in network energy usage (energy efficiency)
- Up to ten years battery life for low power, machine-type devices
- Infrastructure issues and varying service requirements and characteristics (evolution of mobile broadband, massive machine type communications [mMTC], safety critical domains, mobile cloud-based applications, video streaming)

It can be deduced that these goals are partly contradicting and, hence, an integrated system concept has to be highly flexible and scalable in order to fulfil such requirements in a cost-efficient and affordable way.

Some tangible paradigms of the various demands/challenges next generation networks will have to cope with, are:

- in terms of connectivity:

- ➢ 5b connected people
- ➢ 50-100b connected devices and sensors (massive scale)
- ➢ 50% of services without human intervention
- ➢ 1m connected devices / km^2

- in terms of capacity:

➢ Multiple GBs of data per user per day (essential need to increase network capacity by a factor of 1000)

➢ 1 zetabyte/year cumulative data traffic now → will explode to ~4 zetabytes by 2020.

- in terms of latency:

➢ current LTE networks impose latency 20-100ms; whereas future networks 10-0.5ms (vitual zero latency will enable haptic / tactile & kinesthetic feedback → remote surgical operations demanding max 1ms latency – instantaneous experience)→ URLLC (Ultra Reliable Low Latency Communications)

➢ Haptic feedback: combine feeling/touching/seeing

➢ Near zero latency will enable real time user experience

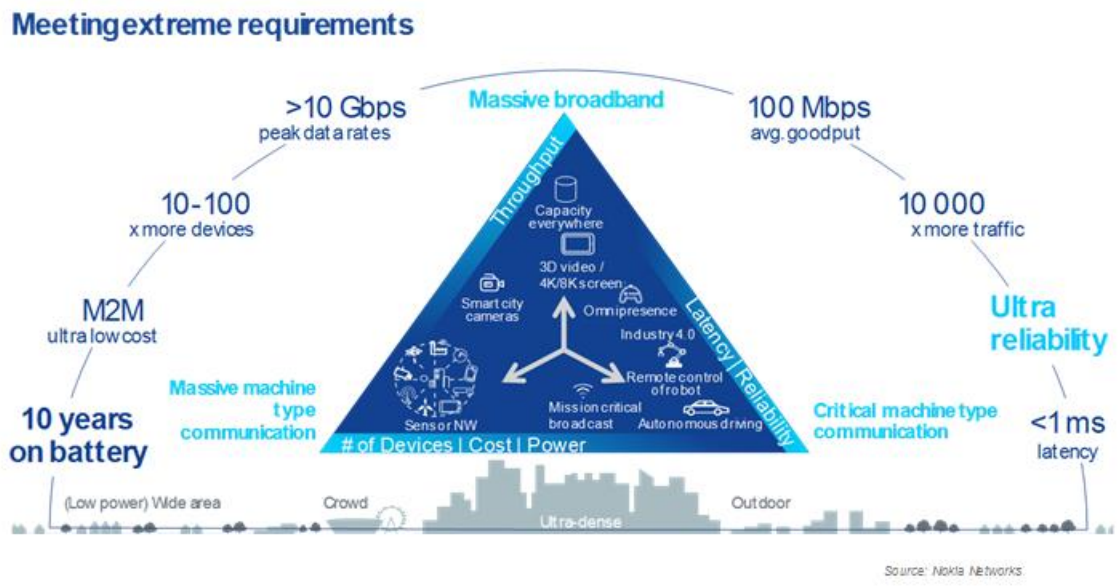


Figure 2: 5G extreme requirements

Source: Nokia

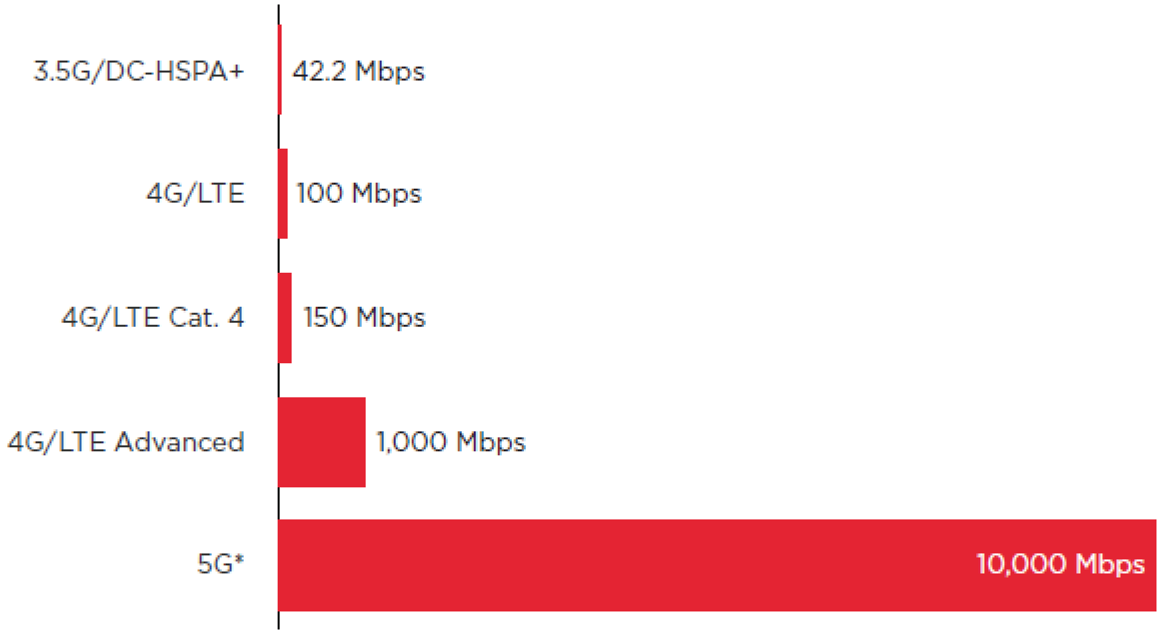


Figure 3: Maximum theoretical downlink speed by technology generation, Mbps

(*10Gbps is the minimum theoretical upper limit speed specified for 5G)

Source: GSMA

1.6 5G KEY ENABLING TECHNOLOGIES

Designing a wireless access network that simultaneously satisfies future demands for both human-centric and machine-centric services calls for technologies capable of using contiguous and wide spectrum bandwidth; flexible resource allocation and sharing schemes; flexible air interfaces; new advanced waveforms; agile access techniques; advanced multi-antenna beam-forming and beam-tracking as well as MIMO techniques; new radio resource management algorithms, are just a few to mention.

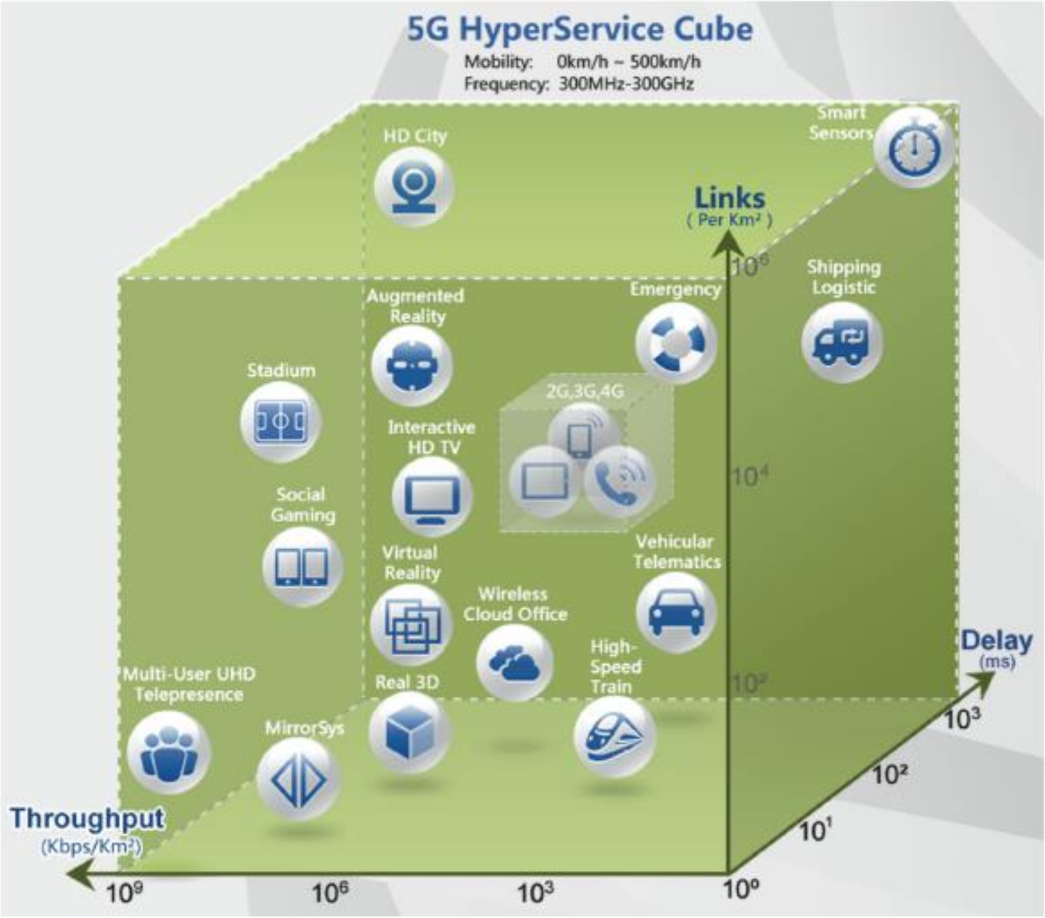


Figure 4: The Hyper Service Cube

Source: Huawei

5G technologies are expected to support:

- Architectural enhancement which includes a mixture of network tiers of different sizes, transmit powers, backhaul connections, different RATs (GSM, HSPA+, LTE, LTE-Advanced and beyond LTE-Advanced).
- BS densification: relays, picocells, femtocells.
- Low-powered radio access nodes (small cells) which can operate in licensed and/or unlicensed spectrum bands and have a transmission range of several tens to several hundreds of meters.
- Millimeter-wave communication: 30-300 GHz bands (as defined in mWT ISG).
- Advanced physical communications technology: high-order spatial multiplexing MIMO (distributed antenna systems and massive MIMO, spatial modulation).

- New system concepts to boost spectral and energy efficiency (e.g., traditional methods for radio resource and interference management [RRIM] in single and two-tier networks may not be efficient).

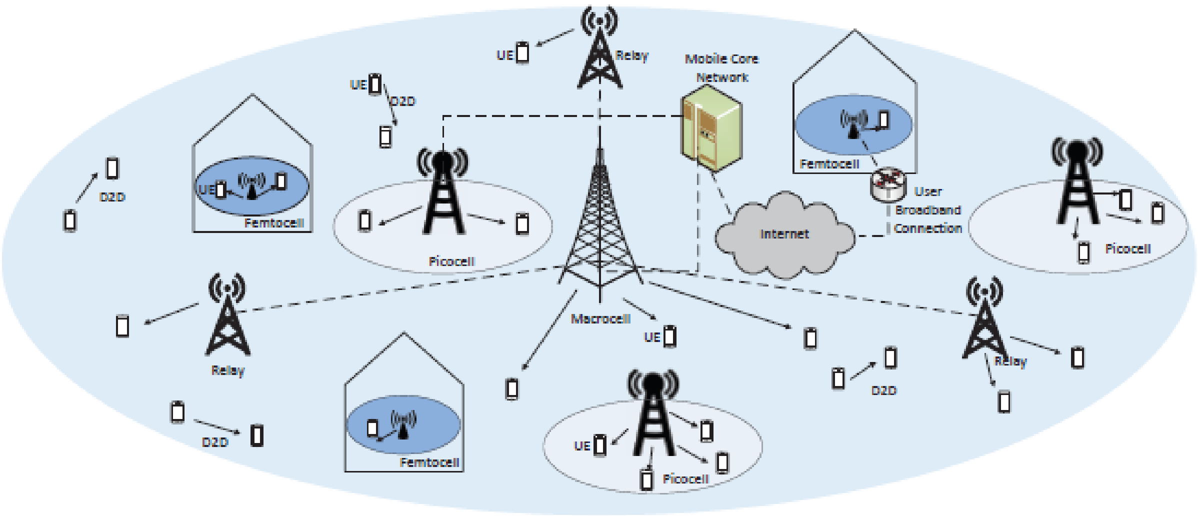


Figure 5: A multi-tier cellular network architecture

- Flexible and efficient use of all available non-contiguous spectrum for different network deployment scenarios.
- Utilisation of any spectrum and any access technology for the best delivery of services.
- On-demand customisation of mobile network technologies that better ensure QoS, increase network TVO (Total Value of Opportunity), decrease network TCO (Total Cost of Ownership), and reduce energy consumption.
- New types of network deployments, including ultra-dense radio networking with self-backhauling, device-to-device communication, dynamic spectrum refarming and radio access infrastructure sharing.

Necessary breakthroughs should be achieved towards our transition to the next generation mobile network technology:

- Multiple access/interference management and advanced waveform technologies combined with advances in coding and modulation algorithms (for massive IoT connectivity)
- Miniaturised multi-antenna technologies and significantly advanced baseband and RF architecture (e.g., for massive MIMO computations)
- Advanced RF domain processing, single-frequency full-duplex radio technologies
- Device technologies to support a vast range of capabilities
- Backhaul design for ultra dense networking
- Virtualised and cloud-based radio access infrastructure

Key enabling technologies for 5G are expected to be:

- Cognitive radio and small cells where each network element performs spectrum sensing to access the spectrum.
- Cloud-RAN (C-RAN) architecture (semi + fully centralised).

- Carrier aggregation/carrier bonding (CA/CB) in licensed, unlicensed, and opportunistic spectrum access (OSA) bands
- Millimeter-wave communication: 30-300 GHz bands
- D2D communication

2. The 5G Market

2.1 Business Context

Driven by technology developments and socio-economic transformations, the 5G business context is characterised by changes in customer, technology and operator contexts. It is expected that instant information will be just a touch away, and that everything will be connected.

2.1.1 Consumers

Significant recent technology advancement is represented by the advent of smartphones and tablets. While smartphones are expected to remain as the main personal device and further develop in terms of performance and capability, the number of personal devices will increase driven by such devices as wearables or sensors.

Supported by cloud technology, personal devices will extend their capabilities to various applications such as high quality (video) content production and sharing, payment, proof of identity, cloud gaming, mobile TV, and supporting smart life in general. They will have significant role in health, security, safety, and social life applications, as well as controlling home appliances, cars and other machines. To support such trends as multi-device and multi-access used by consumers, a comprehensive view of the future consumer’s demands is essential.

2.1.2 Enterprises

Many of the trends in the consumer segment apply to future enterprises as well. The boundaries between personal and enterprise usage of devices will blur. Enterprises will look for solutions to address security and privacy challenges associated with this hybrid type of usage.

For enterprises, mobility will be one of the main drivers for increased productivity. In the next decades enterprises will increasingly make their specific applications available on mobile devices. The proliferation of cloud-based services will enable application portability across multiple devices and domains and will offer major opportunities for enterprises. At the same time this imposes challenges to enterprises that should be managed properly (e.g., security, privacy, performance).

2.1.3 Verticals

The next wave of mobile communication is to mobilise and automate industries and industry processes. This is widely referred to as machine-type communication (MTC) and the IoT. Tens of billions of smart devices will use their embedded communication capabilities and integrated sensors to act on their local environment and use remote triggers based on intelligent logic. These devices differ in terms of requirements with respect to capabilities, power consumption and cost. IoT will also have a wide range of requirements on networking such as reliability, security, performance (latency, throughput), among others. The creation of new services for vertical industries (e.g. health, automotive, home, energy) will not be limited to connectivity but can require enablers from cloud computing, big data management, security, logistics and other network-enabled capabilities.

2.1.4 Partnerships

In many markets today, operators have already started to leverage partnerships with the so-called over-the-top (OTT) players to deliver packaged services to end users. OTT players will move to deliver more and more applications that require higher quality, lower latency, and other service enhancing capabilities (e.g., proximity, location, QoS, authentication) on demand and in a highly flexible and programmable way.

2.1.5 Infrastructure

Breakthrough technology advancements of the recent years (e.g., SDN, NFV, big data, All-IP) will change the way networks are being constructed and managed. These changes will enable the development of a highly flexible infrastructure that allows cost-efficient development of networks and associated services as well as increased pace of innovation. Operators will continue developing own services, but also expand their business reach through partnerships for both the infrastructure as well as the application development aspects.

2.1.6 Services

A global business model evolution of mobile operators’ services will include the evolution of current services as well as the emergence of new ones. Currently the most common services provided by mobile operators include point-to-point personal communication and (best effort) data services such as Web services. These services will evolve to improve both in quality as well as in capability. Personal communication will include high quality IP multimedia and rich group communication as a baseline. Data services on the other hand, will be enabled by multiple integrated access technologies, will be ubiquitous, and will be characterised by performance consistency. Data traffic volume will be dominated by video and social media.

New services will emerge for growing and new market segments such as automated industries and smart user environments, public safety and mission critical services. Many other services will be developed by leveraging capabilities such as big data, proximity, geo-community services and many others.

The new approach must be fully convergent as well as there will be no arbitrary distinction between fixed and mobile; there will be simply a seamless infrastructure satisfying everyone’s communications needs in an invisible, but totally dependable way.

2.2 Use Cases

In addition to supporting the evolution of the established prominent mobile broadband use cases, 5G will support countless emerging use cases with a high variety of applications and variability of their performance attributes: From delay-sensitive video applications to ultra-low latency, from high speed entertainment applications in a vehicle to mobility on demand for connected objects, and from best effort applications to reliable and ultra-reliable ones such as health and safety. Furthermore, use cases will be delivered across a wide range of devices (e.g., smartphone, wearable, MTC) and across a fully heterogeneous environment. The use cases and use case families serve as an input for stipulating requirements and defining the building blocks of the 5G architecture. The use cases are not meant to be exhaustive, but rather as a tool to ensure that the level of flexibility required in 5G is well captured.

5G is characterised by the diversity of use cases which will expand existing markets as well as introduce new markets. Each use case has its own set of requirements and deployment scenarios. Some representative examples of such cases as described by NGMN, are presented below.

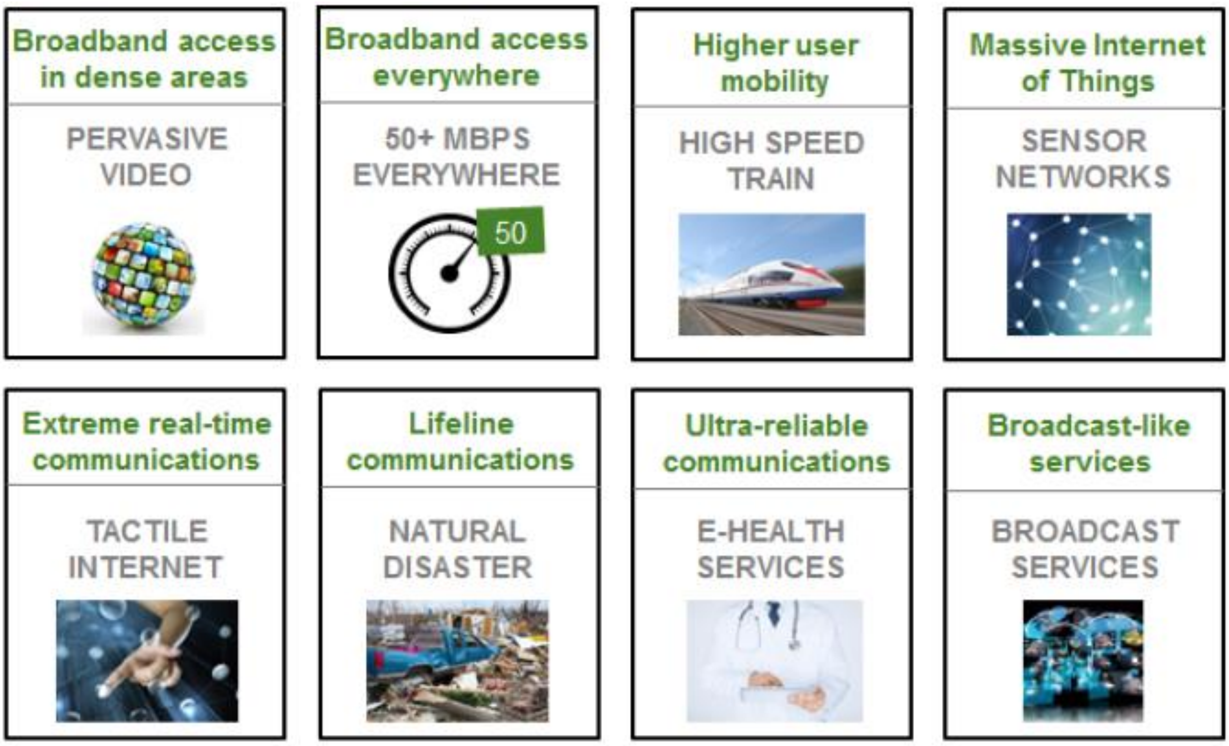


Figure 6: NGMN - 5G use case families and related examples

2.2.1 Broadband Access in Dense Areas

The broad range of growing and new use cases of the connected world is highlighted in this category with particular focus given in service availability in densely populated areas (e.g., multi-storey buildings, dense urban city centres or events), where thousands of people per square kilometre (km^2) live and/or work. Communications are expected to be pervasive and part of everyday life. Augmented reality, multi-user interaction, three-dimensional (3D) services will be among the services which play an increasingly significant role in the 2020+ timeframe. Context recognition will be an essential aspect, at the network edge (i.e. close to the user), ensuring delivery of consistent and personalised services to the customers.

Some use cases which could be located under the aforementioned category, are:

- Pervasive Video
- Smart Office
- Operator Cloud Services
- HD Video/Photo Sharing in Stadium/Open-Air Gathering

2.2.2 Broadband Access Everywhere

This category emphasises on the need to provide access to broadband service everywhere, including the more challenging situations in terms of coverage (from urban to suburban and rural areas). A consistent user experience with respect to throughput, needs a minimum data rate guaranteed everywhere. Further development of digital inclusion of people living in scarcely populated areas and in developing countries requires the infrastructure deployment cost to be a key factor in services.

This category includes the following use cases:

- 50+ Mbps Everywhere
- Ultra-low Cost Networks

2.2.3 Higher User Mobility

A growing demand for mobile services in vehicles, trains and even aircrafts is expected into the next decade. While some services are the natural evolution of the existing ones (navigation, entertainment, etc.), some others represent completely new scenarios such as broadband communication services on commercial aircrafts (e.g., by a hub on board). Vehicles will demand enhanced connectivity for in-vehicle entertainment, accessing the internet, enhanced navigation through instant and real-time information, autonomous driving, safety and vehicle diagnostics. The degree of mobility required (i.e. speed) will depend upon the specific use case.

This family includes the following use cases:

- High Speed Train
- Remote Computing
- Moving Hot Spots
- 3D (three dimensional) Connectivity: Aircrafts

2.2.4 Massive Internet of Things (IoT)

The vision of 2020 and beyond also includes a great deal of growing use cases with massive number of devices such as sensors, actuators and cameras with a wide range of characteristics and demands. This family will include both low-cost/long-range/low-power MTC as well as broadband MTC with some characteristics closer to human-type communication (HTC).

A list of IoT use cases contains among others:

- Smart Wearables (Clothes)
- Sensor Networks
- Mobile Video Surveillance

2.2.5 Extreme Real-Time Communications

Use cases with a strong demand in terms of real-time interaction, constitute this category. These demands are use-case specific and, for instance, may require one or more attributes such as extremely high throughput, mobility, critical reliability, etc. For example, the autonomous driving use case that requires ultra-reliable communication may also require immediate reaction (based on real-time interaction), to prevent road accidents. Others, such as remote computing, with stringent latency requirement, may need robust communication links with high availability.

This family includes the following use case:

- Tactile Internet

2.2.6 Lifeline Communication

Public safety and emergency services are continuously improving. In addition to new capabilities for authority-to-citizen and citizen-to-authority communication for alerting and support, these use cases will evolve to include emerging and new applications for authority-to-authority communication, emergency prediction and disaster relief. Furthermore, there will be an expectation that the mobile network acts as a lifeline, in all situations including times of a more general emergency. Therefore, the use cases require a very high level of availability in addition to the ability to support traffic surges. A paradigm of such use case is:

- Natural Disaster

5G should be able to provide robust communications in case of natural disasters such as earthquakes, tsunamis, floods, hurricanes, etc. Several types of basic communications (e.g., voice, text messages) are needed by those in the disaster area. Survivors should also be able to signal their location/presence so that they can be found quickly. Efficient network and user terminal energy consumptions are critical in emergency cases. Several days of operation should be supported.

2.2.7 Ultra-reliable Communications

The vision of 2020 and beyond suggests not only significant growth in such areas as automotive, health and assisted living applications, but a new world in which the industries from manufacturing to agriculture rely on reliable MTC. Other applications may involve significant growth in remote operation and control that will require extreme low latency as well (e.g., enterprise services or critical infrastructure services such as Smart Grid). Many of these will have zero to low mobility.

This family includes the following use cases:

- Automated Traffic Control and Driving
- Collaborative Robots: A Control Network for Robots
- eHealth: Extreme Life Critical
- Remote Object Manipulation: Remote Surgery
- 3D Connectivity: Drones
- Public Safety

2.2.8 Broadcast-like Services

While personalisation of communication will lead to a reducing demand for legacy broadcast as deployed today, e.g. linear TV, the fully mobile and connected society will nonetheless need efficient distribution of information from one source to many destinations. These services may distribute content as done today (typically only downlink), but also provide a feedback channel (uplink) for interactive services or acknowledgement information. Both, real-time or non-real time services should be possible. Furthermore, such services are well suited to accommodate vertical industries' needs. These services are characterised by having a wide distribution which can be either geo-location focused or address-space focused (many end-users).

- News and Information
- Regional Broadcast-like Services
- National Broadcast-like Services

Next figure illustrates the latency and bandwidth/data rate requirements of the various use cases which have been discussed in the context of 5G to date. These potential 5G use cases and their associated network requirements are described below.

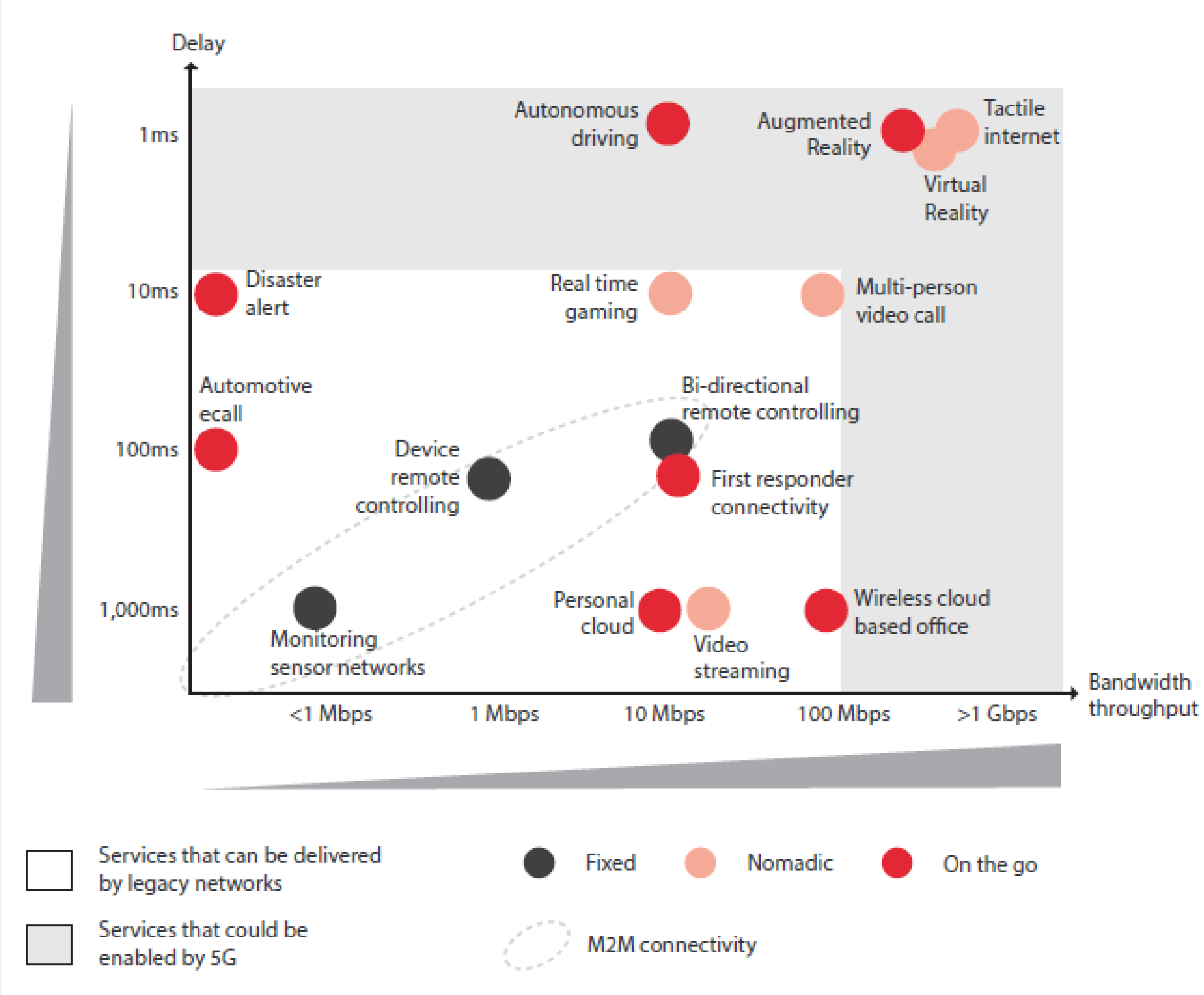


Figure 7: GSMA - Bandwidth and latency requirements of potential 5G use cases

2.2.9 5G use cases can be summarized into the following three major categories:

- **Enhanced Mobile Broadband (eMBB)**: provision of increased data rates and increased network capacity for the general subscriber. Peak data rates of 20 Gbps downlink and 10 Gbps uplink are being discussed
- **Massive Machine Type Communications (mMTC):** large volumes of low cost devices with enhanced coverage and battery life to address the Internet of Things (IoT). A battery life of 15 years is being discussed
- **Ultra-Reliable and Low Latency Communications (URLLC)**: support for highly responsive applications, e.g. vehicle to vehicle communications and virtual reality. Uplink and downlink latencies of 0.5 ms are being discussed

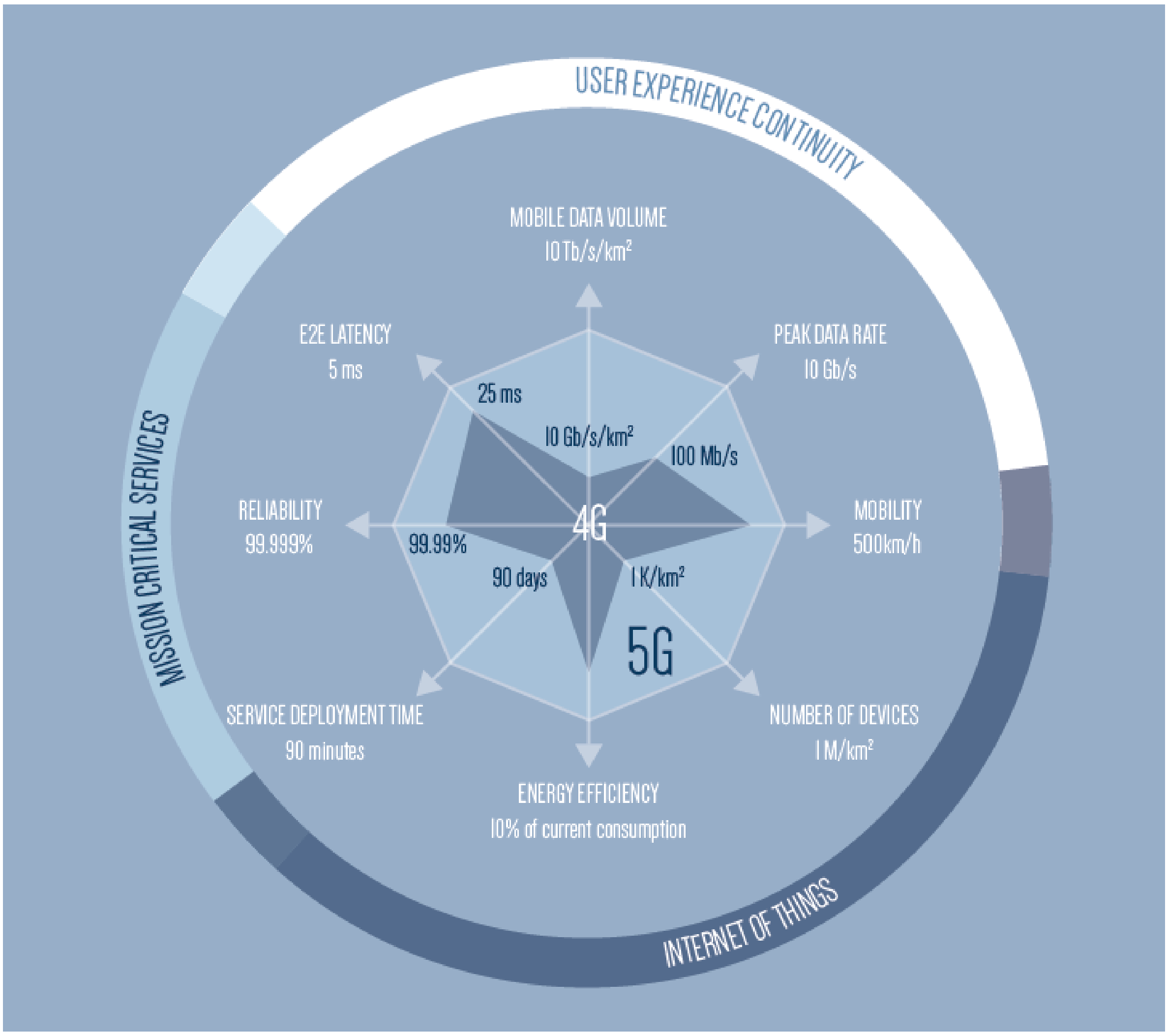


Figure 8: 5G disruptive capabilities

Source: 5G-PPP

Key ways to fulfil such demands are:

- placing content and processing to the edge of the network; as close to the user as possible using caching techniques
- new air interface using cmWave/mmWave bands, massive MIMO and beamforming techniques
- distributed cloud SDN/NFV – cloud to the edge

In this way future networks will achieve high data rate, low latency and reliability in communications.

3. 5G Projects and Standardisation

3.1 The 5G-PPP concept (Horizon 2020) and ongoing projects’ description

3.1.1 5G-PPP and its general objectives

Because of the recession and intense competition around the world, the European Union is committed to keep strengthening Europe’s role in communications. European industry has been historically strong in research, development and integration of complex systems like communication networks as well as manufacturing critical systems. Issues such as how to support 10 to 100 times more traffic per end user without increasing resource costs or energy usage, and how to provide the highest quality of service and security, need to be answered in European terms.

To achieve these goals, the European Commission, together with industry manufacturers, telecommunications operators, service providers, SMEs and researchers, initiated the 5G Infrastructure Public Private Partnership.

Founded in December 2013, the 5G-infrastructure-PPP, in short 5G-PPP, is a 1.4 billion euro (700 million euro from the European Union side and 700 million euro from private side), programme which represents a joint initiative between the European Commission and the European ICT industry to rethink the infrastructure and to create the next generation of communication networks and services.

Figure 9: 5G-PPP phase-1 projects

Source: 5G-PPP

The 5G-PPP initiative will reinforce the European industry to successfully compete on global markets and open innovation opportunities. It is expected to deliver solutions, architectures, technologies and standards for the ubiquitous next generation communication infrastructures of the coming decade.

5G-PPP is aiming at securing Europe’s leadership in the areas where Europe is strong or where there is potential for creating new markets such as smart cities, e-health, intelligent transport, education or entertainment & media.

5G-PPP is a consensus-oriented organisation aimed at fostering roadmap-driven research, which is controlled by business-related, performance and societal KPIs. The programme has a lifetime from 2014 to 2020 and is open for international cooperation and participation.
The 5G-PPP working groups are summarized below:

- Pre-Standardisation WG
- Spectrum WG
- 5G Architecture WG
- SDN/ NFV WG
- Network Management, QoS and Security WG
- Vision and Societal Challenges WG
- Security WG
- SME WG

In the 5G-PPP, the 5G Infrastructure Association (5G IA) represents the private side and the European Commission the public side.
The European 5G-Infrastructure-Association co-operates with the following global 5G institutions:

- IMT-2020 (5G) Promotion Group – China
- 5G Forum – Korea
- 5G Mobile Communications Promotion Forum – Japan
- 5G Americas – North and South America

Figure 10: Global 5G actions

3.1.2 Horizon 2020

The 5G Public-Private-Partnership (5G-PPP) is within the EU Horizon 2020 (2014 - 2020), which is is the biggest EU Research and Innovation programme ever with nearly €80 billion of funding available over 7 years (2014 to 2020) – in addition to the private investment that this funding will attract. It promises more breakthroughs, discoveries and world-firsts by taking great ideas from the lab to the market. Horizon 2020 is the financial instrument implementing the Innovation Union, a Europe 2020 flagship initiative aimed at securing Europe's global competitiveness. Seen as a means to drive economic growth and create jobs, Horizon 2020 has the political backing of Europe’s leaders and the Members of the European Parliament. They agreed that research is an investment in our future and so put it at the heart of the EU’s blueprint for smart, sustainable and inclusive growth and jobs.

By coupling research and innovation, Horizon 2020 is helping to achieve this with its emphasis on excellent science, industrial leadership and tackling societal challenges. The goal is to ensure that Europe produces world-class science, removes barriers to innovation and makes it easier for the public and private sectors to work together in delivering innovation.

3.1.3 Research & innovation collaborative projects in 5G development

It is essential that large-scale, multi-layered collaboration projects are available to achieve this transformation. The ICT sector in Europe is leading the way to drive this process, which is supported by the 5G Public-Private-Partnership (5G-PPP) in Horizon 2020 of the EU. The initiative can remove obstacles that may hamper the 5G development by achieving an early consensus among key global stakeholders, e.g. on a common 5G vision, architecture, spectrum utilisation, pre-standardisation and international collaboration between Europe and the relevant bodies in China, Japan, Korea and USA, to start from. In addition to the private continuous effort, it is of vital importance that public authorities and the private sector develop effective policies regarding spectrum, pre-standardisation and international collaboration. What we need is an evolving regulatory framework that provides a true level playing field for current and new players, thanks to the novel sustainable business models that 5G will enable.

Funding for promising projects will speed up progress. The EU plays an important role in consolidating and building on the most important research and innovation results attained in previous research programs, gathering resources for 5G tests, proof of concept and large-scale trials, and bringing the right stakeholders even beyond the ICT sector on board, notably vertical industries. The METIS project, among others – e.g., MiWeba, MiWaves, 5GNow, iJoin and CREW/EVARILOS – are very good examples of successful European initiatives. These pan-European projects aim at contributing to the foundation of 5G and have been developing and evaluating key technology component candidates for 5G systems.

Nevertheless, let us not forget that 5G is still in its early research stages. As presented above, a number of issues must be resolved before it can become a reality. Joint forces across countries, continents, industries and sectors are imperative. Europe has a key role to play in creating the right synergies, paving the way for a hyper-networked future and building a better-connected world.

3.1.3.1 Projects' domain (phases and projects' presentation)

3.1.3.1.1 FP7 (2007-2013) and projects

5G research projects have already started in the previous Framework Programme of the EU (Framework Programme 7 - FP7: 2007-2013) which was the direct predecessor of Horizon 2020.

In February of 2013, the European Commission considered several projects of FP7 like METIS, 5GNOW, iJOIN, MCN (Mobile Cloud Networking), COMBO, CROWD, MOTO and PHYLAWS as 5G or beyond 4G research projects.

These projects have already paved the way towards the vision and basic concepts of 5G. Research in the 5G-PPP has a very wide scope far beyond classical telecommunication. Europe's best research talents set the bar higher for 5G!

The 5G-PPP is organised in three phases (Phase I: 2015-2017, Phase II: 2017-2019, Phase III: 2019-2021), encompassing research stage, optimisation (2016-2017) and large scale trials (2019-2020).

It aims to deploy 5G as from 2020, which will require before 2020 to develop a series of ground-breaking technologies, global standards and to agree on relevant spectrum bands.

In some markets, like Korea and Japan, there is a huge need for high capacity mobile broadband to be deployed by 2020 for the Olympic Games. This is an ambitious timeline because the wide range of different use cases to be addressed and the new spectrum to be agreed will make standardisation complex and time-consuming. In addition, new spectrum for mobile broadband on higher frequencies (above 6 GHz) is likely to be available only after WRC 2019. These practical considerations imposed 5G development in phases.

3.1.3.1.2 Phase One

In this phase, the architecture is centred on Evolved Packet Core (EPC) and the deployment of new 5G Radio Access Technologies (RATs) using sub-6 GHz spectrum. This phase (based on 3GPP Release 15 available in September 2018) would also introduce 5G radio via dual connectivity mode with LTE as an anchor and, depending on progress in 3GPP, as a standalone option. In this scenario, the 5G radio is connected to EPC but forward compatibility to the coming 5G core needs to be assured, as well as enabling later releases to be easily backwards compatible with 5G phase one without sacrificing overall 5G performance.

Out of a total of 83 submitted proposals, 19 projects have been selected and are currently running in the Phase I (1st of July 2015 - 31st of December 2017), addressing a rich cross section of the research challenges leading to a 5G infrastructure by 2020. They are all characterised by exceptional quality and high level of innovation, reflecting the intensity of the competition between research teams in Europe and the undivided industrial support to the 5G-PPP.

Main Projects' Presentation

Phase I: Research and Innovation (R&I) projects

3.1.3.1.2.1 5G ENSURE (11.2015-10.2017)

5G Enablers for Network and System Security and Resilience

The need for a new security architecture is motivated by the fact that 5G is a platform that goes beyond telecoms and which will be far more decoupled from specific hardware and physical control of the network. This project aims to define and deliver such a security architecture, as well as some key security enablers towards the vision for a secure, resilient and viable 5G network. The key security enablers considered in 5G-ENSURE are:

- Authentication, Authorisation and Accounting
- Privacy
- Trust
- Security Monitoring
- Network Management and Virtualisation Isolation

3.1.3.1.2.2 5G-EXCHANGE (5GEx) (10.2015-03.2018)

Multi-domain Orchestration for Software Defined Infrastructures

Current market fragmentation is characterised by a multitude of telecommunication networks and cloud operators, each with a footprint focused on a specific region, while lacking inter-operator collaboration business models, services and supporting tools. This makes it infeasible to deploy and offer cost-effective infrastructure services spanning multiple countries. Existing services and inter-operator collaboration tools are very limited and cumbersome. Main challenge of 5GEx project is to invent technical and business solutions for autonomous orchestration of services across multi-domain and multi-technology environments. Such orchestration shall allow instantiating end-to-end networks and services into multi-vendor and heterogeneous technology resource environments.

Unlike traditional separation of network resources from compute and storage, 5GEx will realise composite services by seamlessly combining networking with computing and storage across domains. The project’s main purpose is an automated assignment and mapping of virtualised service elements, which represent service and network functions and components, to the underlying (physical hardware) resources which may belong to multiple operators.

5GEx will go beyond the state of the art by:
- achieving a 90-minute service setup;
- integrating monitoring instances in the multi-operator architecture;
- optimally embedding -in terms of resource utilisation and revenue- service requests into the set of virtualised resources mapped into multiple operators’ domains while matching each service SLA requirements;
- defining novel business, coordination and information models, trading mechanisms and pricing schemes.

3.1.3.1.2.35G NORMA (07.2015-12.2017)

Novel Radio Multiservice Adaptive Network Architecture for 5G networks

The technical approach followed by 5G NORMA is based on the innovative concept of adaptive (de)composition and allocation of mobile network functions, in such a way according to which, functions are placed in the most appropriate location. By doing so, access and core functions no longer (necessarily) reside in different locations, which is exploited to jointly optimise their operation whenever possible.

The adaptability of the architecture is further strengthened by the innovative software-defined mobile network control and mobile multi-tenancy concepts, and underpinned by proof-of-concept demonstrations.

The key objective of the project is to develop a conceptually novel, adaptive and future-proof 5G mobile network architecture. The architecture will enable unprecedented levels of network customisability, ensuring stringent performance, security, cost and energy requirements to be met; as well as providing an API-driven architectural openness, fueling economic growth through over-the-top innovation.

Furthermore, the 5G NORMA consortium will also demonstrate the feasibility of the key innovations developed in the project; in particular the service and context dependent adaptation of network function as well as the software defined mobile network control.

The 5G NORMA architecture will provide the necessary adaptability to efficiently handle the diverse requirements and traffic demand fluctuations resulting from heterogeneous and changing service portfolios. By overcoming the ‘one system fits all services’ paradigm of current architectures, multiple services are anticipated spanning from mobile broadband, including fixed-mobile convergence over vehicular communications, emergency services and industrial control, to massive machine type communication and sensor networks (IoT).

5G NORMA will ensure economic sustainability of network operation and open opportunities for new players, while leveraging the efficiency of the architecture to do so in a cost and energy efficient way. Additionally, 5G NORMA targets to foster pre-standardisation by building up consensus on specific aspects of the 5G mobile network architecture.

3.1.3.1.2.45G-XHAUL (07.2015-06.2018)

Dynamically Reconfigurable Optical-Wireless Backhaul/Fronthaul with Cognitive Control Plane for Small Cells and Cloud-RANs

5G-XHaul proposes a converged optical and wireless transport solution able to flexibly connect Small Cells to the core network. Exploiting user mobility, the proposed solution enables the dynamic allocation of network resources to hotspots. To support these novel concepts, the main technical and research challenges are the development of:

- Dynamically programmable, high capacity, low latency, point-to-multipoint mm-Wave transceivers, cooperating with sub-6-GHz radios.
- Time shared optical network (TSON) offering elastic bandwidth allocation, cooperating with advanced passive optical networks (PON).
- Software-defined cognitive control plane, able to forecast traffic demand in time and space, and accordingly, reconfigure network components.

Small Cells, Cloud-Radio Access Networks (C-RAN), Software Defined Networks (SDN) and Network Function Virtualisation (NVF) are key enablers to address the demand for broadband connectivity with low cost and flexible implementations.

5G-XHaul will develop wireless solutions for dynamic backhaul and fronthaul architectures alongside very high capacity optical interconnects in order to cover the stringent requirements that the aforementioned enablers pose on transport network.

Designing the transport network for dense urban scenarios, with massive deployments of Small Cells, is a key use case for 5G-XHaul. 5G-XHaul technologies will be integrated and evaluated in a citywide testbed in Bristol (UK).

A major technological impact of 5G-XHaul will be to shape the design of future promising mm-Wave systems by means of novel transceiver architectures and experimental validations. In the optical domain, novel solutions are needed to increase the flexibility of provisioning connectivity, monitoring and troubleshooting the network. The TSON technology defined in 5G-XHaul is a key stepping-stone towards the vision of Backhaul as a Service. Finally, 5G-XHaul will directly impact the adoption of SDN techniques in the wireless and optical domains.

3.1.3.1.2.5Charisma (07.2015-06.2017)

Converged Heterogeneous Advanced 5G Cloud-RAN Architecture for Intelligent and Secure Media Access

CHARISMA proposes a set of technologies targeted to accomplish the H2020 objectives. Combining radio and cabled technologies as well as exploiting network programmability and virtualisation technologies to achieve multi-tenancy, are key factors to reaching ultra high-speed broadband penetration targets and enabling rapid adoption of emerging network applications.

Providing a cloud infrastructure platform with increased spectral, energy-efficient and enhanced performance, CHARISMA targets the 5G-PPP objectives of 1000-fold increased mobile data volume, 10-100 times higher data rates, 10-100 times more connected devices and 5x reduced latency.

Low-cost Ethernet is used across the front- and back-haul, with virtualised end-user equipment (vCPE), intelligence distributed across the back-, front-hauls and perimetric data transports. Ad-hoc mobile device interconnectivities (D2D, D2I, C2C etc.), content delivery network (CDN) and mobile distributed caching (MDC) offer an energy-efficient (better than x20 improvement possible) information-centric network (ICN) architecture.

Furthermore, caching provides efficient utilisation of scarce resources by lowest common aggregation of data and/or localised execution of communications.

This ambitious project brings together 10G-wireless (via mm-wave/60-GHz & free-space optics, FSO) access and 100G fixed optical (OFDM-PON) solutions through an intelligent cloud radio-access-network (C-RAN) and intelligent radio remote head (RRH) platform with IPv6 Trust Node routing featuring very low-latency for the traffic management.

CHARISMA concept proposes an intelligent hierarchical routing and paravirtualised architecture that combines two important concepts: devolved offload with shortest path nearest to end users and end-to-end security service chain via virtualised open access physical layer security (PLS). Additionally, through its Open Access operational model, CHARISMA reinforces public-private-partnerships to promote the deployment of a single and secure Open Access NGA architecture. Offering provider/tenant isolation, it can be operated by multiple service providers via virtual slices.

CHARISMA offers the latest techno-economic tools and NFV/SDN frameworks while optimising CAPEX and fostering competition.

CHARISMA solution will provide enhanced user experience with ground-breaking low-latency services, high-bandwidth and mobile cloud resilient network security.

3.1.3.1.2.6 COGNET (07.2015-12.2017)

Cognitive networks – Building an Intelligent System of Insights and Action for 5G Network Management

One of the key requirements of 5G will be to create a network that is highly optimised to make maximum use of available radio spectrum and bandwidth for QoS.

Moreover, due to the network size and number of devices connected, it will be necessary for the network to largely manage itself and deal with organisation, configuration, security and optimisation issues.

Virtualisation will also play an important role as the network will need to provision itself dynamically to meet changing demands for resources and NFV. The virtualisation of network nodes' functions and links will be the key technology for this.

Autonomic Network Management based on Machine Learning is a key technology for self-administering and self-managing network.

CogNet project aims to research and develop a real-time network management platform with the capability to scale to address the requirements of the future 5G network.
Main objective of this project is to develop the means required in order to:

- collect and preprocess big data from the 5G network,
- develop a system for self-management of network nodes,
- apply Machine Learning algorithms to address
    a. demand prediction and provisioning, allowing the network to resize using virtualisation
    b. network resilience issues including identifying network errors, faults or conditions such as congestion or performance degradation
- identify serious security issues such as unauthorised intrusion

CogNet project deals with creation of resources 'on demand' through Network Function Virtualisation, network resilience and Quality of Service improvement and finally detection of performance degradation and respective recovery actions through resource provisioning and adjustments to network topology.

In short, CogNet is focused on self/autonomic network management. **(SON-evolution)**

3.1.3.1.2.7 COHERENT (07.2015-12.2017)

Coordinated control and spectrum management for 5G heterogeneous radio access networks

The exponential growth of mobile traffic, the drastic increase in network complexity and the strong need for inter-network coordination of wireless network resources, call for breakthroughs in control, coordination and flexible spectrum management in 5G networks. The COHERENT project deals with challenges in inter-network coordination of 5G heterogeneous radio access networks (5G HET RANs), by introducing software-defined networking design principles into radio access networks. It will develop common control interfaces and software-development kits to enable programmable control and coordination in heterogeneous mobile networks. The programmable control in 5G radio access networks will provide mobile operators a flexible and cost efficient way to implement new low layer control functions, provision wireless resources, manage different types of radio access networks (RAN sharing/RAN coordination), and thus to support open innovation in 5G mobile networks.

This project paves the way for holistic end-to-end mobile network function virtualisation solutions.

3.1.3.1.2.8 EURO-5G (07.2015-09.2017)

Supporting the European 5G Initiative mainly managing all projects, promoting, monitor and facilitate activities (workshops etc.)

As a key facilitator of the 5G-PPP governance processes, the Euro-5g project will take actions to ensure openness, fairness and transparency through all the 5G-PPP activities.

Euro-5g will manage, promote, monitor and analyse international 5G activities and will facilitate respective activities (e.g. meetings, workshops etc.) Project’s main role is to work together with the 5G-Infrastructure Association and the European Commission to have good international relations with these global initiatives with a view to ensuring global interoperability. Euro-5g will also involve highly qualified experts to produce innovation roadmaps and capture the experimental requirements for the next phases of the 5G-PPP.

The Euro-5g project will contribute directly to the 5G-PPP goal to maintain and enhance the competitiveness of the European ICT industry and to ensure that European society can enjoy the economic and societal benefits these future networks will bring.

3.1.3.1.2.9 FANTASTIC-5G (07.2015-06.2017)

Flexible Air Interface for Scalable Service Delivery within Wireless

Communication Networks of the 5th Generation

Project’s main objective is to develop a new multi-service Air Interface (AI) for below 6GHz band through a modular design, able to support all the anticipated use cases with highest efficiency and scalability without being overly complex on the network side.

The new air interface should adapt to anticipated heterogeneity (having multiple radio access technologies for multi-service support below 6GHz will be too costly).

To this direction, the project will develop technical AI components: (flexible waveform and frame design, scalable multiple access procedures, adaptive retransmission schemes, enhanced multi-antenna schemes with/without cooperation, advanced multi-user detection, interface coordination, support for ultra-dense cell layouts, multi cell radio resources management, device-to-device) and integrate them to an overall versatile AI framework.

Many key players participating to 3GPP standardisation are collaborating within the project. So, FANTASTIC-5G is well positioned to strongly facilitate the (pre-) standardisation process for 5G by comprehensively comparing technology options and starting to build up consensus.

3.1.3.1.2.10 FLEX5GWARE (07.2015-06.2017)

Flexible and efficient hardware/software platforms for 5G network elements and devices

Flex5Gware will perform research, development and prototyping on key building blocks of 5G network elements and devices both in the hardware (HW) and software (SW) domains.

The overall objective of Flex5Gware is to deliver highly reconfigurable HW platforms together with HW-agnostic SW environments, targeting both network elements and devices, and taking into account the need for increased capacity, reduced energy footprint, as well as scalability and modularity for enabling a smooth transition from 4G mobile wireless systems to the 5G era.

Through this project, design and development of analogue components to enable massive MIMO (Multiple Input Multiple Output) in mmWave (millimeter wave) spectrum bands will be carried out.

In the signal domain, important research and results will be obtained related to crucial 5G components like full duplex communications (simultaneous transmission and reception), high-speed broadband converters, etc.

The development of a sophisticated, HW-agnostic, SW platform, capable of deciding the optimal splitting of functionality between HW and SW, will yield powerful HW/SW systems, with interface abstractions, for flexible control and management, across heterogeneous wireless devices and access networks.

3.1.3.1.2.11 METIS-II (07.2015-06.2017)

Mobile and wireless communications Enablers for the Twenty-twenty Information Society-II

METIS-II orientation is the design of the overall RAN for 5G with an approach to enable efficient integration of legacy and novel radio access into a single holistic system utilising the concepts of holistic spectrum management architecture, agile resource management (RM) framework, common control and user plane framework, cross-layer and cross-air-interface as well as mobility framework

Through its strong composition and global scope (i.e. containing the leading mobile network operators and leading network vendors including non-European Partners), METIS-II will strongly support regulatory and standardisation bodies, in particular the ITU-R and 3GPP.

3.1.3.1.2.12 mmMAGIC (07.2015-06.2017)

Millimetre-Wave Based Mobile Radio Access Network for Fifth Generation Integrated Communications

mmMAGIC project will develop and design new concepts and key components for mobile radio access technology (RAT) for mm-wave band deployment.

The use of very high frequencies for mobile communications is challenging but necessary for supporting 5G extreme mobile broadband services (such as UHD TV and video streaming, virtual reality and ultra-responsive cloud-based applications) which require very high (up to 10 Gbps) data rates, and in some scenarios, also very low end-to-end latencies (less than 5 ms).

In the project, waveform, frame structure and numerology will be developed and designed as well as novel adaptive and cooperative beam-forming and tracking techniques to address the specific challenges of millimetre wave mobile communications.

It will undertake extensive radio channel measurements in the 6-100 GHz range and develop advanced channel models for rigorous validation and feasibility analysis of the proposed concepts. Seamless and flexible integration with other 5G and legacy radio interfaces will be realised through design and validation of novel internetworking functions and architecture components.

This new RAT is envisaged as a key component in the overall 5G multi-RAT ecosystem.

Self-backhauling capabilities are also foreseen, in addition to access, thereby creating a holistic, scalable and economically viable integrated 5G solution to meet future needs of operators and users.

The project also aims to accelerate standardisation of mm-wave technologies for 5G so that industry and citizens will benefit from commercialisation around 2020.

3.1.3.1.2.13 SELFNET (07.2015-06.2018)

Framework for Self-Organised Network Management in Virtualised and Software Defined Networks

Main purpose of this project is to design and implement an autonomic network management framework to achieve self-organising capabilities in managing network infrastructure (SON orchestration) by automatically detecting and mitigating a range of common network problems (currently being manually addressed by network operators), thereby significantly reducing operational costs and improving user experience.

In particular, automated network monitoring (self-monitoring) will be achieved by automatic deployment of NFV applications to facilitate system-wide awareness. HoN metrics and 5G KPIs will enable more direct and precise knowledge about real network status.

Self-optimisation actions will dynamically improve the performance of the network and the QoE of the users.

Autonomic network maintenance, also known as self-healing, contains all those corrective and preventive actions against potential network problems

Selfnet explores a smart integration of state-of-the-art technologies in SDN, NFV, SON, Cloud Computing, Artificial Intelligence (AI), Quality of Experience (QoE) and Next-generation networking. Enabling and optimising the holistic use of AI and other related technologies will facilitate novel cost-effective real-time autonomous 5G network management.

SON evolution entails remarkable benefits for network operators, service providers and users. It will enlarge 5G market share for European network operators by providing new intelligence to automatically perform SON functionalities. Moreover, it is going to strengthen the competitiveness of European service providers with optimised service and application performance, thus attracting more subscribers. OPEX will be reduced by automation and CAPEX by utilising SDN, NFV and cloud resources, as well as reduced service creation and deployment time.

Last but not least, enhanced QoE of the end users is expected along with more secured and resilient network and services.

3.1.3.1.2.14 SESAME (07.2015-12.2017)

Small cell coordination for multi-tenancy and edge services

A fundamental component of SESAME will be the virtualisation of Small Cell and their utilisation and partitioning into logically isolated ‘slices’, offered to multiple operators/tenants. The main aspect of this innovation will be the capability to accommodate multiple operators under the same infrastructure, satisfying the profile and requirements of each operator separately.

SESAME proposes the Cloud-Enabled Small Cell (CESC) concept, a new multi-operator enabled Small Cell that integrates a virtualised execution platform (Light DC) for deploying VNFs, supporting powerful Self-x management and executing novel applications and services inside the access network infrastructure.

Solutions for aggregation of data, transcoding of video content with optimised delivery in edge networks and caching at the very edge of the network, will enable a reduction in transport time and therefore, provide a crucial route to successfully reducing service-level latency.

This project targets innovations around three central elements in 5G: the placement of network intelligence and applications in the network edge through NFV and Edge Cloud Computing; the substantial evolution of the Small-Cell concept, already mainstream in 4G but expected to deliver its full potential in the challenging high dense 5G scenarios; and the consolidation of multi-tenancy in communications infrastructures, allowing several operators/service providers to engage in new sharing models of both access capacity and edge computing capabilities.

3.1.3.1.2.15 SONATA (07.2015-12.2017)

Service Programing and Orchestration for Virtualised Software Networks

Virtualisation and software networks are a major disruptive technology for communication networks, enabling services to be deployed as software functions running directly in the network on commodity hardware. However, deploying the more complex user-facing applications and services envisioned for 5G networks presents significant technological challenges for development and deployment. SONATA addresses both issues.

For service development, SONATA provides service patterns and description techniques for composed services. A customised SDK is developed to boost the efficiency of developers of network functions and composed services, by integrating catalogue access, editing, debugging, and monitoring analysis tools with service packaging for shipment to an operator.

For deployment, SONATA provides a novel service platform to manage service execution. The platform complements the SDK with functionality to validate service packages. Moreover, it improves on existing platforms by providing a flexible and extensible orchestration framework based on a plugin architecture. Thanks to SONATA’s platform service developers can provide custom algorithms to steer the orchestration of their services: for continuous placement, scaling, life-cycle management and contextualisation of services. These algorithms are overseen by executives in the service platform, ensuring trust and resolving any conflict between services.

By combining rapid development and deployment in an open and flexible manner, SONATA is realising an extended DevOps model for network stakeholders.

Key use cases focus on Virtual Content Delivery Networks (vCDN) and Mobile Edge Computing (MEC).

SONATA's open source results will have a diverse impact on an expanding telecom sector, including operators, manufacturers and third-party developers. It is expected to reduce time-to-market for networked services, optimise network management reducing OpEx and increase reliability and QoS for 5G networks and deployed services.

To widen the reach of the project's impact, SONATA will collaborate with key community initiatives, including OPNFV, OpenDaylight, OpenStack, ITU-T and ETSI's NFV ISG.

3.1.3.1.2.16 SPEED-5G (07.2015-12.2017)

Quality of Service Provision and Capacity Expansion through Extended-DSA for 5G

The main objective of SPEED-5G is to achieve a significantly better exploitation of heterogeneous wireless technologies, providing higher capacity together with the ultra-densification of cellular technology, and effectively supporting the new 5G Quality of Experience (QoE) requirements.

SPEED-5G will develop optimisation mechanisms for spectrum utilisation jointly managing UDN (ultra dense-networks), following three main dimensions:

- ultra-densification through small cells,
- additional spectrum, through spectrum micro trading in lightly-licensed bands, which are currently not utilised,
- exploitation of resources across technologies, through techniques in support of centralised / distributed smart resource management.

In SPEED-5G this three-dimensional model is referred to as extended-Dynamic Spectrum Allocation (DSA), where several spectrum bands, cells and technologies are jointly managed in order to offer improved QoE and a tremendous capacity increase in a cost-efficient manner.

SPEED-5G will provide solutions answering the request for a thousand-fold increase in mobile traffic volume over a decade and for efficiently supporting very different classes of traffic and services. Project's contribution is also expected towards the development of 5G standards and in the improvement of innovation capacity in the wider ecosystem.

3.1.3.1.2.17 SUPERFLUIDITY (07.2015-12.2017)

A Super-fluid, Cloud-native, Converged Edge System

SUPERFLUIDITY offers a converged cloud-based solution to counter the complexity emerging from three forms of heterogeneity: heterogeneous data traffic and end-points; heterogeneity in services and processing needs; heterogeneity in access technologies and their scale.

The main purpose of the project is to achieve super fluidity in the network, providing the ability to instantiate services on the fly (in milliseconds), run them anywhere in the network (core, aggregation, edge); on-demand and on third-party infrastructure, and shift them transparently to different locations using innovative fast migration and high consolidation technologies.

The main strategy which will be used to accomplish the aforementioned goals, is analysed among the following key characteristics:

- Flexibility, via an architectural decomposition of network components and network services
- Simplicity, via a cloud-based architecture.
- Agility, via virtualisation of radio and network processing tasks.
- Portability and viability, through platform-independent abstractions, permitting reuse of network functions across multiple heterogeneous hardware platforms.
- High performance, via software acceleration.

SUPERFLUIDITY aims to reduce investments and operational costs through several benefits that 5G network is expected to bring about:

- location independence: network services deployable in heterogeneous networks,
- time-independence: near instantaneous deployment and migration of services,
- scale-independence: transparent service scalability,
- hardware-independence: development and deployment of services with high performance irrespective of the underlying hardware.

3.1.3.1.2.18 VIRTUWIND (07.2015-06.2018)

Virtual and programmable industrial network prototype deployed in operational wind park

The main purpose of VirtuWind is to develop a SDN & NFV ecosystem for industrial domains, based on open, modular, and secure communication framework.

VirtuWind will adapt SDN in industrial networks by developing novel SDN-based mechanisms to implement industrial-grade QoS and to reduce CAPEX and OPEX.

The concepts developed in the project are leading to a prototype demonstration for intra/inter-domain scenarios in real wind parks as a representative use case of industrial networks, and quantify the economic benefits of the solution.

The project aims to address technical and research challenges contained in the field of programmable industrial networks via SDN and multi-tenancy support via NFV as multiple stakeholders may need different access profile.

The new concept for industrial networks will immensely benefit by transferring existing SDN concepts from other disciplines into the industrial networking domain.

3.1.3.1.2.19 5G-CROSSHAUL (07.2015-12.2017)

The 5G Integrated fronthaul/backhaul transport network

5G-Crosshaul (Xhaul) works on developing an adaptive, sharable, cost-efficient 5G transport network solution integrating the fronthaul and backhaul segments of the network.

This transport network will flexibly interconnect distributed 5G radio access and core network functions, hosted on cloud nodes, through the implementation of two novel building blocks:

- a control infrastructure using a unified, abstract network model for control plane integration (Xhaul Control Infrastructure, XCI), providing high flexibility and scalability;
- a unified data plane encompassing innovative high-capacity transmission technologies and low latency switch architectures (Xhaul Packet Forwarding

Element, XFE), capable of transporting all kinds of Xhaul traffic. This will significantly reduce the network cost leveraging the integrated network design and will improve network utilisation.

Xhaul will also facilitate network densification. New physical layer technologies and solutions (leveraging optical fiber, mmWave, free-space optics and low-cost copper infrastructure, etc.) will be explored to significantly reduce the deployment and installation cost.
It is expected to greatly simplify network operations despite the growing technological diversity and hence enable system-wide optimisation of QoS and energy usage as well.

3.1.3.1.3 Phase II projects (2017-2019)

5G-PPP Phase 2 (H2020 ICT 07 & 08, 2017)

Phase two will bring the introduction of innovative layers and architectural changes beyond those implemented in phase one to enable the full potential of 5G. In this phase, the 3GPP release 16 (available in December 2019) will fully meet the requirements of critical mMTC use cases in terms of lowest latency and highest reliability, as well as important mobile broadband enhancements by providing best quality of experience (QoE) to end users. The new 5G core will also efficiently support massive MTC.

This second phase will develop the new 5G network architecture in such a way that mobile operators will be able to make use of their existing deployments to provide higher data rates, better capacity in the near term and at the same time, introduce future-proof network architecture to support new use cases and services in the longer term.

Phase 2 pre-structuring model is defining the set of Targeted Actions (TAs) addressing their related rationale, objective, scope and expected impact. The Model version 2.0 released by the 5G Infrastructure Association members on 11.03.15 addresses:

ICT-07-2017 - *5G-PPP Research and Validation of critical technologies and systems* which is decomposed in the following strands:

- RIA Strand 1: Wireless Access and Radio Network Architectures/Technologies
- RIA Strand 2: High Capacity Elastic – Optical Networks
- RIA Strand 3: Software Networks
- CSA

ICT-08-2017 - *5G-PPP Convergent Technologies* which encompasses:

- IA Strand 1: Ubiquitous 5G Access Leveraging Optical Technologies
- IA Strand 2: Flexible Network Applications
- RIA: Cooperation in Access Convergence

- EUJ-01-2016: RIA 5G - Next Generation Communication Networks
- EUK-01-2016: RIA 5G - Next Generation Communication Networks

3.1.3.1.3.1 ICT 7 – 5G-PPP Research and Validation of critical technologies and systems

The high level objectives extracted by the ICT7 activities can be summarised among the following:

- To leverage work and results of phase 1 (WP 2014-15) and to accelerate on proof of concepts and demonstrations → 3GPP, WRC 19 milestones.
- To support a much wider array of requirements than today and with capability of flexibly adapting to different "vertical" application requirements.

- To cover a wide range of services from different use cases and application areas/verticals, for increasingly capable user terminals, and for an extremely diverse set of connected machines and things.
- To support a shift from the “Client-Server” model to “Anything” as a Service (XaaS)
- Network elements will become "computing equivalent" elements that gather programmable resources, interfaces and functions based on virtualisation technologies.
- Optimisation of cost functions (capex/opex) and of scarce resources (e.g.energy, spectrum), as well as migration towards new network architectures.

a. Research & Innovation

a.1. Strand: wireless access and radio network architecture/technologies

- Novel air interface technologies.
- Hardware architectures and network functional architectures and interfaces leading to a reference architecture for 5G in support of the forthcoming standardisation work.
- Co-operative operation of heterogeneous access networks integrating virtual radio functions into service delivery networks.
- Support of numerous devices with different capabilities, with unified connectivity management capabilities, in terms of security, mobility and routing.
- Coordination and optimisation of user access to heterogeneous radio accesses.
- Multi-tenancy for Radio Access Network (RAN) sharing, covering ultra-dense network deployments.
- Integration of Satellite Networks.

a.2. Strand: High capacity elastic - optical networks

- New, spectrally efficient, adaptive transmission, networking, control and management approaches to increase network capacity by a factor of >100.
- To provide high service granularity, guarantees for end-to-end optimisation and QoS - reducing power consumption, footprint and cost per bit.
- Integration of such new optical transport and transmission designs with novel network control and management paradigms (e.g., SDN).

a.3. Strand: Software Networks

- Software network architecture to support an access agnostic converged core network and control framework enabling next generation services.
- A unified management of connectivity, with end to end security, mobility and routing for flexible introduction of new services/solutions (e.g API's and corresponding abstractions) that allow re-location or anycast search of services and their components.
- Scalability and efficiency related to increasing deployment of software-based network equipment and functions as well as corresponding more diverse services and usages.
- Realisation of the "plug and play vision” for computing, storage and network resources through appropriate abstraction, interfaces, and layering, targeting a Network Operating System (NOS).
- Management and security for virtualised networks (across multiple virtualised domains) and services to support service deployment decisions.

b. Coordination and Support Actions of 3 M€

Activities to ensure a programmatic view of the implemented 5G Research and Innovation Actions (RIA) and Innovation Actions (IA) contain:

- programme level integration through management and orchestration of 5G-PPP project cooperation for horizontal issues of common interest in support of the commitments of the 5G-PPP contractual arrangement
- portfolio analysis, coverage, mapping and gap analysis, roadmaps
- support to the emergence of a 5G-PPP "5G vision" and key international cooperation activities
- organisation of stakeholder events
- Monitoring of the openness, fairness and transparency of the PPP process
- maintenance of the "5G web site"

Expected Impact

The expected results from R&I actions at macro level, include:

- 40% of the world communication infrastructure market for EU headquartered companies
- demonstrated progress towards core 5G-PPP KPI's
- novel business models through innovative sharing of network resources

At operational level, R&I activities contain among others:

- optimised optical backhaul architectures and technologies
- ubiquitous 5G access
- definition of 5G network architecture
- proactive contribution to the standardisation activities on 5G
- proof-of-concept and demonstrations beyond phase one/specific use cases with verticals
- novel connectivity paradigms
- network function implementation through generic IT servers
- OS like capabilities to orchestrate network resources
- trustworthy interoperability across multiple virtualised operational domains and management of multi domain virtualised networks

CSAs include exploitation and dissemination of 5G-PPP project results, stakeholder support as well as support to key international cooperation events, and definition of future R&I actions.

3.1.3.1.3.2 ICT 8 – 5G-PPP Convergent Technologies

ICT8 activities target the following high level objectives:

- To tackle scalability and usability of mixed network technological approaches that can benefit from previous research, towards validation of deployment at scale.
- For IAs: work draws on existing scientific and research results in the field and includes scalable demonstrations validated through typical usage scenario
- For RIAs: collaborative research in 5G access leveraging Taiwan testbed offers

a. Innovation Actions of 40 M€

a.1. Strand: Ubiquitous 5G access leveraging optical technologies aims to developand assess:

- new optical access network solutions based on integrated optical device prototypes,
- new optical transmission, switching and information processing techniques to support key access functionalities such as beam forming, high accuracy cm/mmWave generation and massive MIMO deployments,
- co-operative radio-optical approaches
- techniques to map 5G channels to optical transport and a co-design of the optical and wireless interfaces and protocols

a.2. Strand: Flexible network applications targets:

- the development of a multiplicity of Virtualised Network Functions (VNF) for deployment of Network Applications,
- Cloud-like 5G infrastructures, supporting network services, resource and service orchestration
- open source development framework for control functionalities and application development, open platforms to third parties

b. Research and Innovation Actions

Funding related to R&I actions has reached 5 M€ for cooperation in access convergence.

R&I activities take advantage of the supporting 5G research and demonstration facilities offered by Taiwan towards collaborative 5G research with the EU. Test beds making use of facilities offered by Taiwanese partners have been developed. Moreover, development and demonstration of an integrated convergent access across different air interface technologies and the fronthaul/backhaul/core network as well as capabilities of new spectrum access schemes, has taken place.

Innovation Actions

Some innovation activities related to the ICT8 include:

- validation of access network architecture with integrated optical technologies for the realisation of critical access and transport control function
- demonstration of technological applicability to dense access scenarios
- demonstrated scalability close to operational context and validation at scale of the VNF aggregation capability
- contribution to standards, notably 5G and optical access
- optical access interface with 10 times lower energy consumption
- open environments and open repository of network apps that may be validated and leveraged by third party developers

Research and Innovation actions at operational level, contribute to the:

- ITU-R objectives for the next generation mobile network
- 1000 fold mobile traffic increase per area
- 1ms latency objective
- results exploitation in the context of standardisation and spectrum

The presented project landscape of 5G research covers the overall mobile system including: overall architecture, RAN design, transport network design, air interface, end-to-end networking aspects, security issues and network management. As the activities are in their early phases we can expect more concrete solutions and proposals shaping the 5G reality in the near future. On the other hand, by looking closer to the presented research projects (accompanied with recent 3GPP developments, and industry elaborations), 5G trends can already be extracted to some extent.

3.2 Standardisation

Standardisation Activities

The start of commercial deployment of 5G systems is expected in years 2020+.

Industry will play the major role in the 5G Infrastructure PPP with respect to the necessary long-term investment in global standardisation and the integration of technological contributions into complex interoperable systems. Results of the 5G Infrastructure PPP projects will be suitable for global standardisation in bodies like 3GPP, IEEE, IETF and other standards and specification bodies in the IT domain, which can be contributed via established channels of 5G-PPP partner organisations to respective standards bodies. These channels will be used to exploit research results in international standardisation community.

It is clearly expected that the core of the 5G standardisation related to mobile technologies, will happen in the context of 3GPP, e.g. 3GPP RAN, CT and SA groups. However, the 5G Infrastructure PPP members will also contribute to a wide range of other standardisation bodies (IETF, ETSI, ONF, Open Daylight, OPNFV, Open Stack).

From the perspective of IMT 2020, the key constraints are given by the following two submission deadlines:

- Initial technology submission by ITU-R WP5D meeting No. 32, June 2019
- Detailed specification submission by ITU-R WP5D meeting No. 36, October 2020

ITU-R WP-5D is the ITU’s radio-communication sector engaged with developing International Mobile Telecommunication (IMT) systems.

Charged with developing future standards for 5G, the ITU-R Working Party 5D has been designated to identify and harmonise 5G spectrum in frequency bands below 6 GHz.

ITU-R Working Party 5D’s first meeting took place in Beijing, following the decision of the World Radiocommunication Conference 2015 (WRC-15) to identify and harmonise spectrum for operation of IMT systems in frequency bands below 6 GHz. WRC-15 also requested ITU-R to study potential use of additional non-harmonised national/regional spectrum above 6 GHz for IMT, and the results of those studies will be considered at the next WRC in 2019.
After that, the focus will shift to the UHF bands 30-100GHz.

ITU is continuing to work closely with administrations, network operators, equipment manufacturers, and national and regional standardisation organisations to include today’s 5G research and development activities in the IMT-2020 global standard for mobile broadband communications. A clear roadmap is shared, by 3GPP, of when the first release of 5G standards (R15) is coming out and the complete release (R16); September 2018 and December 2019 respectively.

Also, some focus will be on completing initial R&D trials in 2017 to solidify the business use cases to be proposed for 5G. Proof of concept trials will be planned in 2018 and 2019 based on R15 which is the first 5G standards release, then commercial pilot networks in early 2020, and finally full-fledge networks based on the final 5G release (R16).

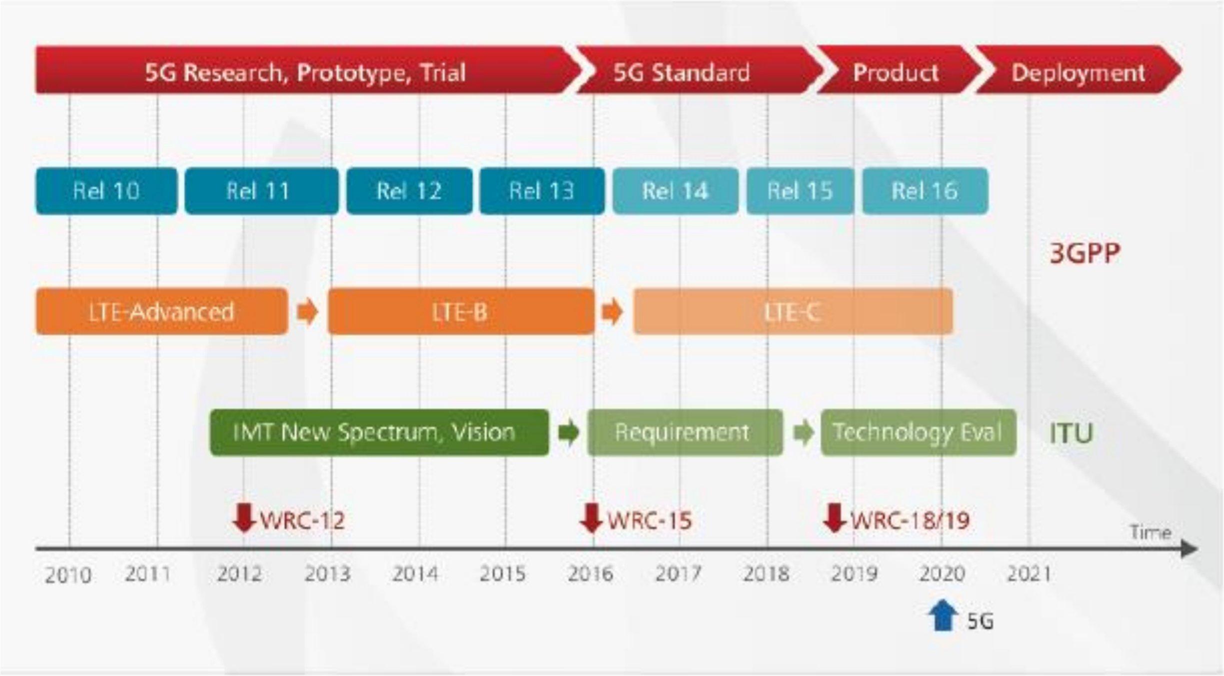
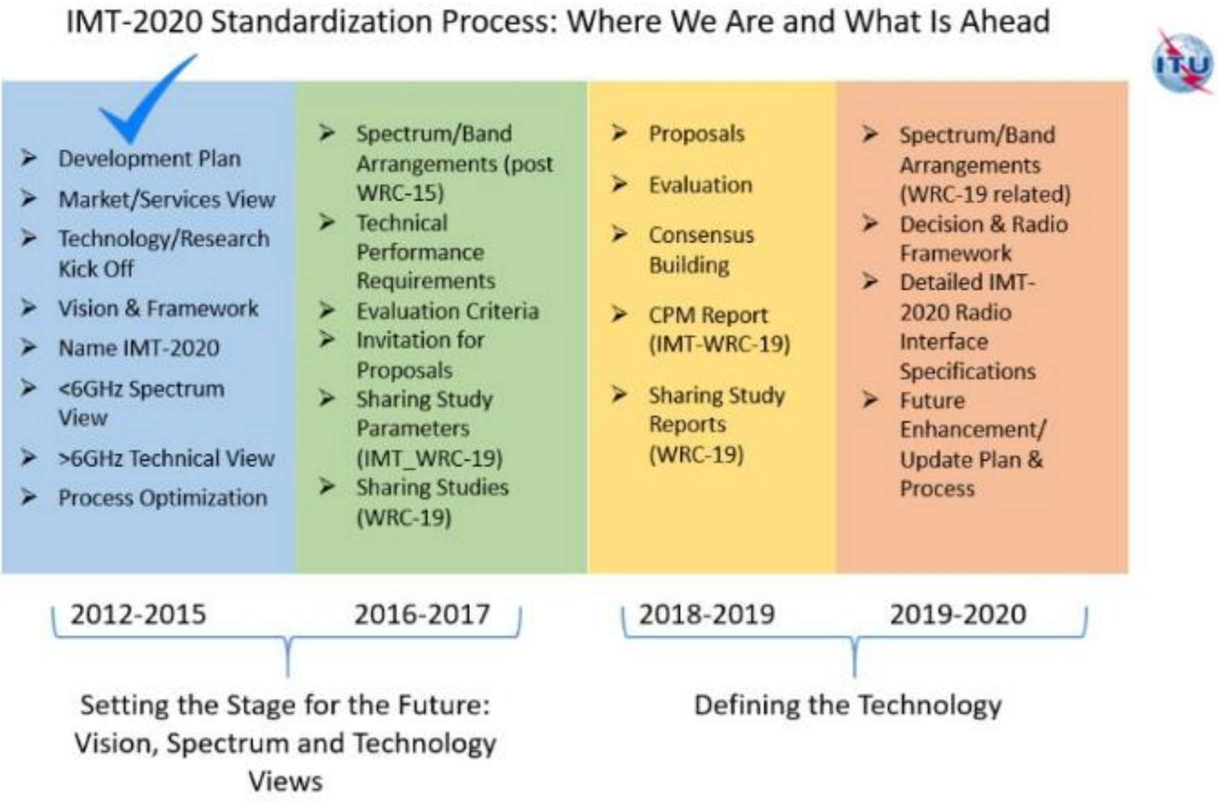


Figure 11: The 5G timeline

Source: Huawei



IMT-2020 Standardization Process: Where We Are and What Is Ahead

- Development Plan
- Market/Services View
- Technology/Research Kick Off
- Vision & Framework
- Name IMT-2020
- <6GHz Spectrum View
- >6GHz Technical View
- Process Optimization

- Spectrum/Band Arrangements (post WRC-15)
- Technical Performance Requirements
- Evaluation Criteria
- Invitation for Proposals
- Sharing Study Parameters (IMT_WRC-19)
- Sharing Studies (WRC-19)

- Proposals
- Evaluation
- Consensus Building
- CPM Report (IMT-WRC-19)
- Sharing Study Reports (WRC-19)

- Spectrum/Band Arrangements (WRC-19 related)
- Decision & Radio Framework
- Detailed IMT-2020 Radio Interface Specifications
- Future Enhancement/ Update Plan & Process

2012-2015 2016-2017

Setting the Stage for the Future: Vision, Spectrum and Technology Views

2018-2019 2019-2020

Defining the Technology

ITU

Figure 12: 5G Standardisation Process

Source: ITU

3.3 ROADMAP

The roadmap, milestones and steps to be taken towards the final deployment are essential prerequisites for the overall success of 5G. NGMN has defined a 5G roadmap that shows an ambitious timeline with a launch of first commercial systems in 2020. At the same time, it defines a reasonable period for all the industry players to carry out the required activities (such as standardisation, testing, trials) ensuring availability of mature technology solutions for the operators and attractive services for the customers at launch date. The key milestones are as follows:

- Commercial system ready in 2020
- Standards ready end of 2018
- Trials start in 2018
- Initial system design in 2017
- Detailed requirements ready end of 2015

According to 3GPP, the “Phase 1” of the 5G specifications will be ready mid-2018 as part of 3GPP Release 15. Phase 1 will concentrate on the “Extreme Mobile Broadband” (eMBB) use case. The “Massive Machine Type Communication” (mMTC) and “Critical Machine Type Communication” (cMTC) use cases will be part of “Phase 2”, which will be ready in Dec 2019 as part of 3GPP Release 16.

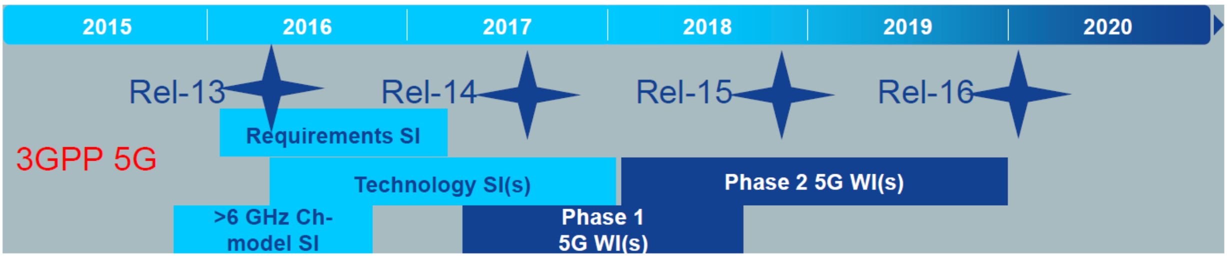


Figure 13: 5G timeline

Source: 3GPP

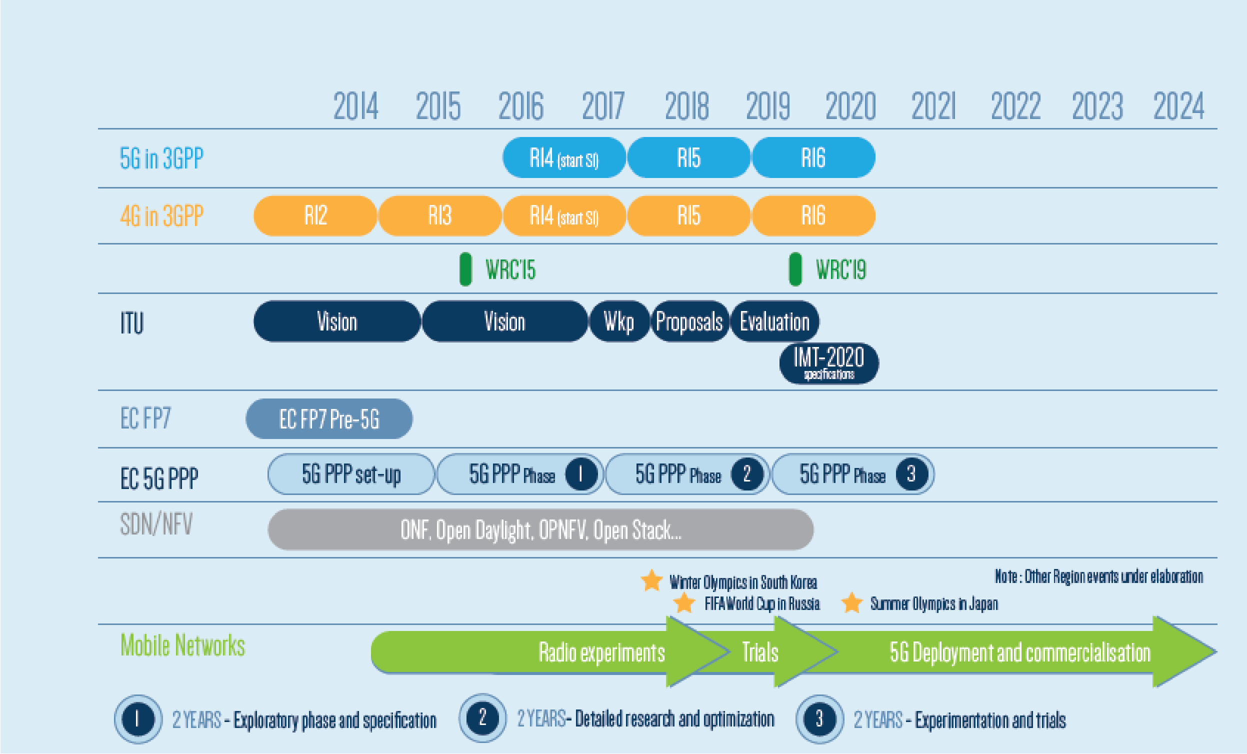


Figure 14: The 5G roadmap

Source: 5G-PPP

The launch of 5G will happen on an operator and country specific basis. Some operators might plan to launch in 2020; others will plan for a later deployment. The roadmap represents the baseline planning from an NGMN perspective and milestones might be shifted in the course of the 5G development due to external factors (e.g. standardisation process delays, etc.).

4. 5G NETWORK ARCHITECTURE

4.1 Introduction

In this second chapter, we are going to present the basic technological components 5G network architecture will be based on, such as SDN, NFV, MANO and analyse some notable effects from the penetration of these technologies into 5G network design, implementation, administration and operation (MEC, CN, SON).
We also reveal how these 5G architecture key enabling technologies enhance the overall networks' functional, architectural and commercial viability, including increased automation, operational agility, and reduced capital expenditure.

5G will be called upon to support a vast array of use cases with diverse and even contradicting performance needs. Connecting massive long-range/low-power sensors is a very different proposition to haptic feedback and remote objects' manipulation. Clearly, 5G networks will need to offer a greater range of capabilities than 4G technologies.

Designed primarily to provide mobile broadband, existing LTE and Evolved Packet Core (EPC) architecture will not be able to efficiently support the different demands, ranging from ultra-low latency services with full mobility, to extreme throughput, to the massive number of deployments that will result from the rise of the Internet of Things (IoT).
Current EPC architecture does not allow operators to evolve their radio and core networks independently. 5G architecture will break the dependency between the core and access networks, enabling convergence with Wi-Fi and fixed access and enabling functions such as QoS, session management and security to be decoupled from the underlying access technology.

While it may be possible to build a separate system for each use case, this will not be economically viable and would lead to mammoth network complexity, thus endangering sustainable business. Instead, 5G will need to be a single system that can meet all these requirements invisibly from the user's perspective. A fundamental rethinking of the mobile network is needed to realise the full potential 5G offers to support a variety of very diverse and extreme requirements for latency, throughput, capacity, and availability. This new architecture will provide key new capabilities as outlined in the following sections.

4.2 Architectural requirements

New network architecture will be essential to meet the requirements beyond 2020, to manage complex multi-layer and multi-technology networks, and to achieve built-in flexibility. 5G era networks will be programmable, software driven and managed holistically.

5G mobile networks will focus on customer experience and must be built around user needs. The value of networks will lay in their personalization and the experience of using them. Networks are expected to be cognitive and optimise themselves autonomously. Cognitive networks will use big data analytics and artificial intelligence to solve complex optimisation tasks in real time and in a predictable manner. All parts of the network will be cloud-based to use existing resources in the best way. With more intelligence placed closer to the user and the ability to process large amounts of data, network performance can be predicted and optimized. This network architecture will entail the full use of open source software technologies, industry compliance and greater cooperation with IT players. At the same time, standardization bodies and organisations such as 3GPP and ETSI will continue to help define the best standard for

5G, assuring interoperability with regard to the air interface and associated software and mobility control architecture.

5G will be driven by software. Network functions are expected to run over a unified operating system in several points of presence, especially at the edge of the network for meeting performance targets. As a result, it will heavily rely on emerging technologies such as Software Defined Networking (SDN), Network Functions Virtualisation (NFV), Mobile Edge Computing (MEC) and Fog Computing (FC) to achieve the required performance, scalability and agility.

5G will ease and optimise network management operations. The development of cognitive features as well as the advanced automation of operation through proper algorithms will allow optimising complex business objectives, such as end-to-end energy consumption. In addition, the exploitation of Data Analytics and Big Data techniques will pave the way to monitor the users' Quality of Experience through new metrics combining network and behavioural data while guaranteeing privacy.

Network functions virtualisation (NFV) and software-defined networking (SDN) provide examples for possible new design principles to allow more flexibility and tighter integration with infrastructure layers, although performance and scalability need further investigation. Both approaches stem from the IT realm: NFV leverages recent advances in server virtualisation and enterprise IT virtualisation; SDN proposes logical centralisation of control functions and relies on advances in server scale out and cloud technologies. However, none of those is essentially a networking technology, as the network is assumed to be there, before NFV or SDN can be even used. Hence, 5G will provide a unified control for multi-tenant networks and services through functional architectures deployment across many operators' frameworks, giving service providers, and ultimately prosumers, the perception of a convergence across many underlying wireless, optical, network and media technologies. 5G will make possible the fundamental shift in paradigm from the current “service provisioning through controlled ownership of infrastructures” to a “unified control framework through virtualisation and programmability of multi-tenant networks and services”.

Nearly all network functions will be software defined, cognitive technologies will automatically orchestrate the network, and content along with processing will be distributed across the network close to where they are needed.

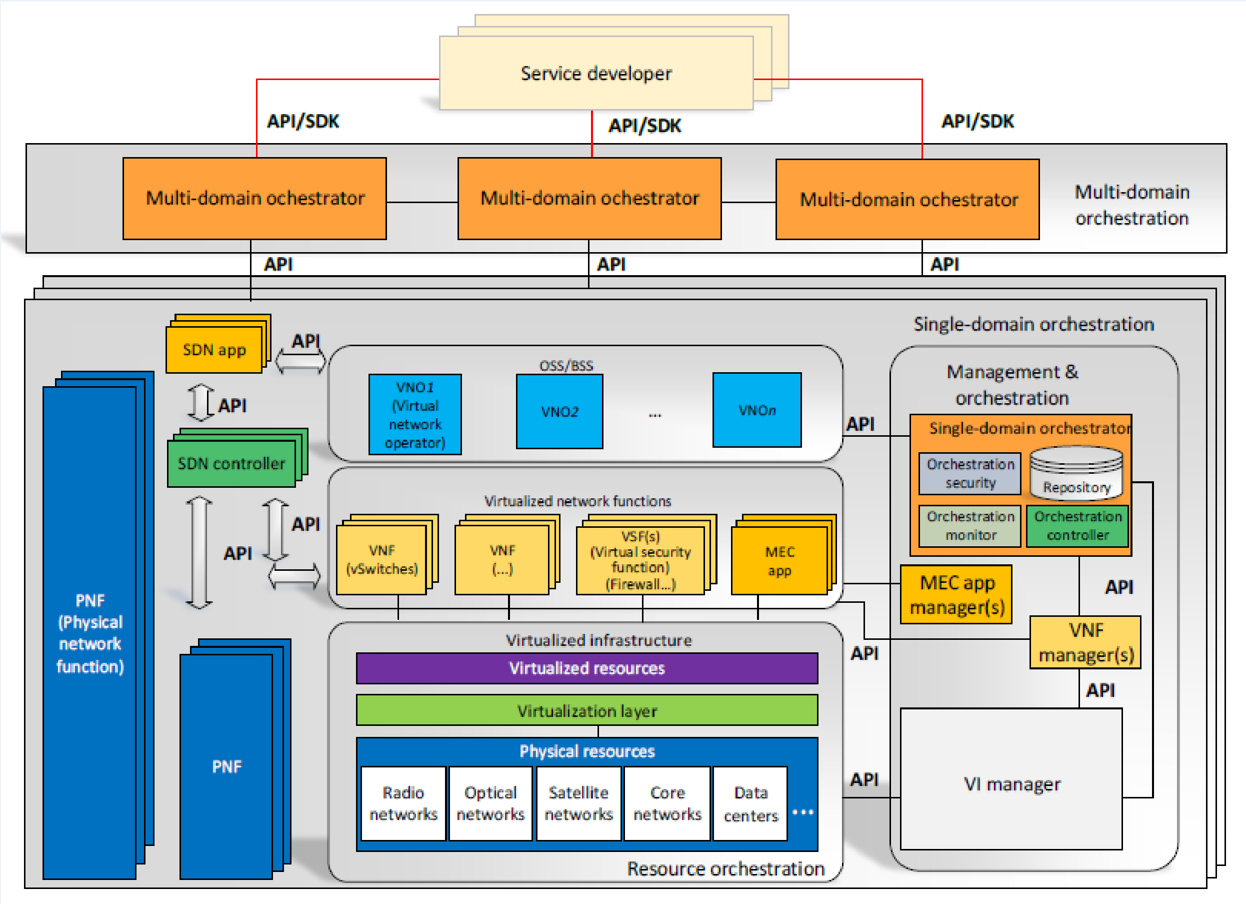


Figure 15: NFV/SDN orchestration for services

Source: 5G-PPP

4.3 Programmable networks

A flexible network will be needed to adapt to various performance requirements. Software-defined functions create a programmable infrastructure, which means that the path of packets through the network is not restricted by a fixed architecture and can be programmed and optimised for latency. Software Defined Networks (SDN) in the mobile backhaul (MBH), aggregation and backbone network enable the use of traffic optimisation, bandwidth allocation and Mobile-Edge Computing (MEC) to reduce latency. Transport SON agent(s) can collect information such as delay (per class/per interface), loss (per class/per interface), throughput (total/per PHB/per GTP), queue length, active bearers or active devices and apply this to SDN control.

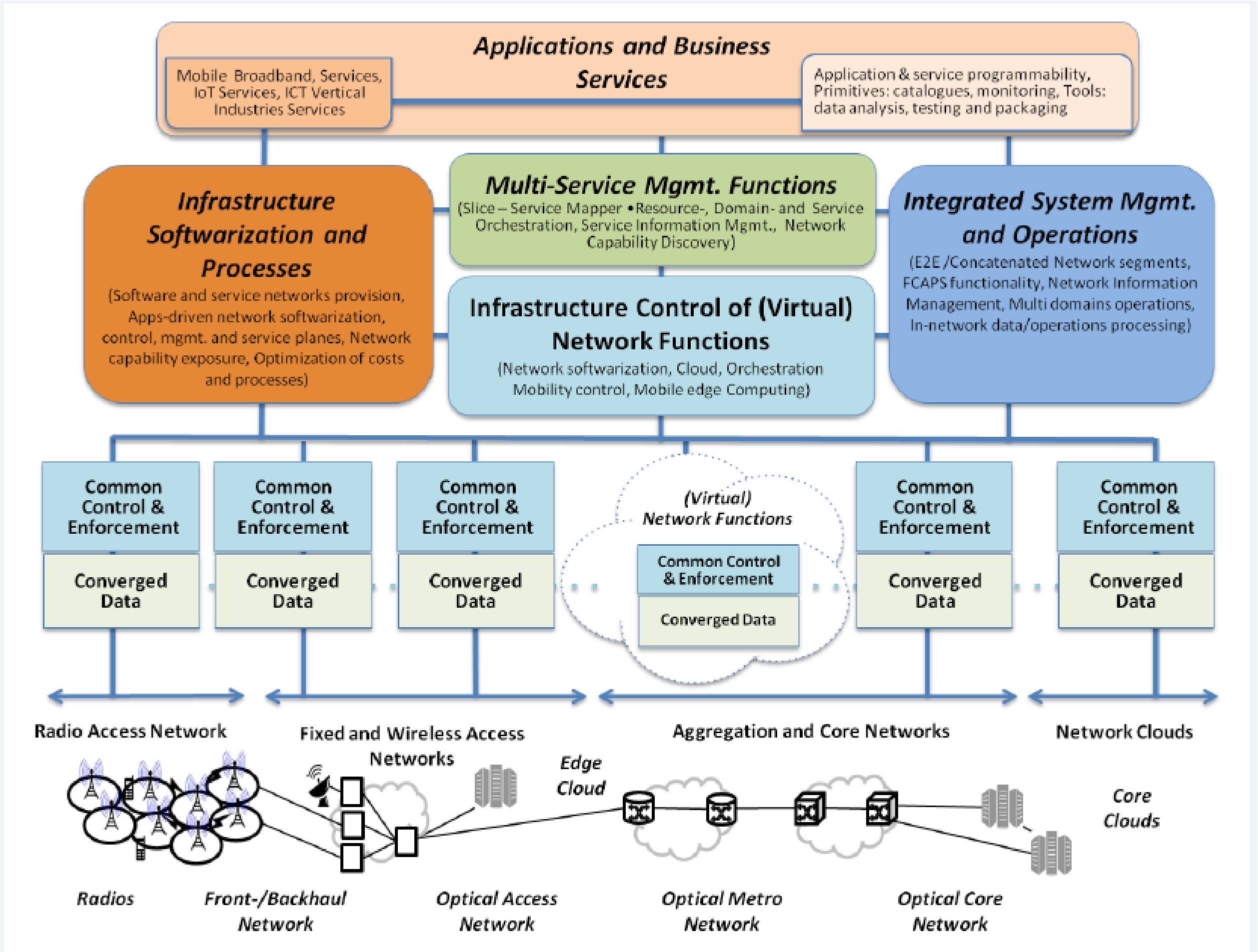


Figure 16: Overall Network Softwarization and Programmability Framework

Source: 5G-PPP

4.4 NFV (Network Functions Virtualisation)

Network Functions Virtualisation (NFV) refers to the implementation of network functions in software running on non-proprietary, commoditized hardware. This approach allows the deployment of network functions in data centres and leverages IT virtualisation technology to separate network functions from the underlying hardware. In other words, previously discrete and vertically integrated network elements can be implemented in a cloud platform to form a private Infrastructure as a Service (IaaS).

By contrast, the state-of-the-art is to implement network functions on dedicated and application-specific hardware. Hence, the main motivation for NFV is to leverage from the economy of scale of high-volume hardware platforms, to reduce time-to-market and innovation cycles within telecommunication networks through software updates rather than hardware updates, and to exploit novel data centre technology. NFV has recently attracted significant interest from the industry, which has led to the creation of a dedicated industry study group at ETSI (ETSI ISG NFV).

Implementing network functions in software on general purpose computing/storage platforms will allow for new flexibilities in operating and managing mobile networks. In mobile networks, NFV is currently discussed in the context of virtualising the core network. Furthermore, NFV and implementing mobile network functions in data centres allows more flexibility in terms of resource management, assignment, and scaling. This has also an impact on the energy efficiency of networks as only the required amount of resources may be used and overprovisioning of resources can be avoided. This resource orchestration could reuse management algorithms already developed in the IT world in order to exploit resources as efficiently as possible.

As mentioned, NFV is already applied on core networks and first trials are performed demonstrating that critical mobile network functions such as MME, PGW, or HSS can be implemented on standard IT platforms. A critical enabler of this development is, besides virtualisation technologies, the availability of highspeed IP networks and the possibility to manage them more flexibly through SDN. Interest on the latter is confirmed by the recent foundation of a working group on wireless and mobile within the Open Networking Foundation, which is the organisation that has standardised OpenFlow.

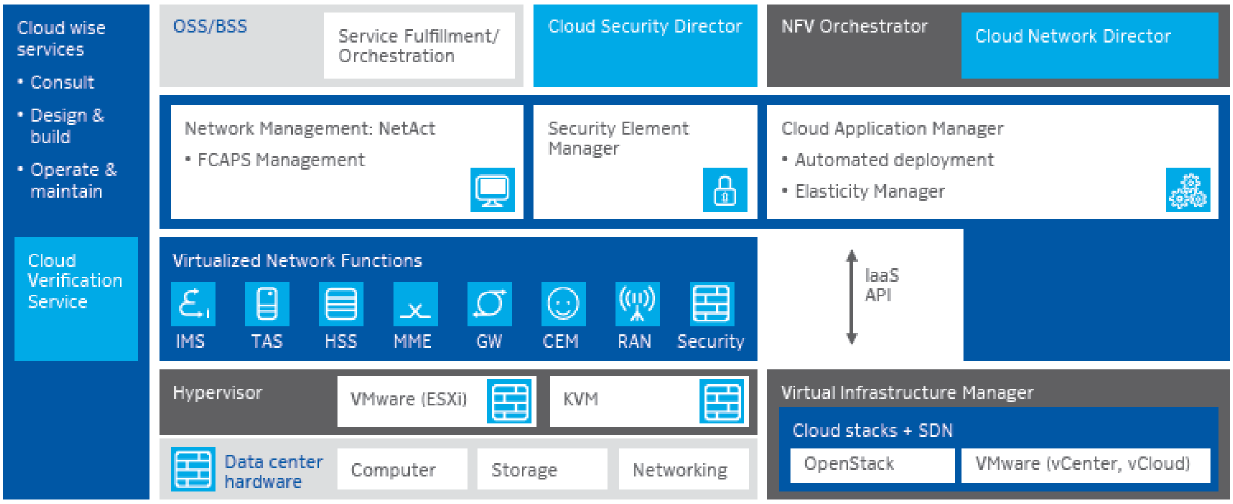


Figure 17: Separation of infrastructure, network and management layer in NFV architecture

Source: Nokia

The ETSI ISG NFV provides an excellent description of the problem area which network function virtualisation is going to provide a solution for. In addition, it provides also a comprehensive list of related challenges which are understood as areas where research is still needed.

4.4.1 Problem description

Today's networks are populated with a large and increasing variety of proprietary hardware appliances. Launching a new network service often requires yet another variety of appliance increasing the overall complexity of the network and causing numerous issues. For example, finding the space and power to accommodate these appliances is becoming increasingly difficult and costly in terms of power consumption and capital investment challenges. The rarity of skills necessary to design, integrate and operate increasingly complex hardware-based appliances poses another challenge.

Moreover, hardware-based appliances rapidly reach their end of life, requiring much of the procure-, design-, integrate- and deploy-cycle to be repeated with little or no revenue benefit. Worse, hardware lifecycles are becoming shorter as technology and services innovation accelerates, inhibiting the roll out of new revenue earning network services and constraining innovation in an increasingly network-centric connected world.

4.4.2 The objectives for solving the problem

Network Functions Virtualisation aims to address these problems by leveraging standard IT virtualisation technology to consolidate many network equipment types onto industry standard high volume servers, switches and storage, which could be located in data centres, network nodes and in the end user premises. Network Functions Virtualisation is applicable to any data plane packet processing and control plane function in fixed and mobile network infrastructures.

4.4.3 The associated research

There are a number of challenges to implement Network Functions Virtualisation which need to be addressed by the community interested in accelerating progress.

4.4.3.1 Portability/Interoperability

Network functions virtualisation requires the ability to load and execute virtual appliances in different but standardised data centre environments, provided by different vendors for different operators. The challenge is to define a unified interface which clearly decouples the software instances from the underlying hardware, as represented by virtual machines and their hypervisors [1]. Portability and interoperability is very important as it creates different ecosystems for virtual appliance vendors and data centre vendors, while both ecosystems are clearly coupled and depend on each other. Portability also allows the operator the freedom to optimise the location and required resources of the virtual appliances without constraints.

4.4.3.2 Performance Trade-Off

Network Functions Virtualisation is leading to execute network function (high level function-DPI, NAT, Firewall, etc.) on generic abstraction of the equipment (decentralised or not) which may use heterogeneous/dedicated hardware for low level function execution (cryptography, packet routing, etc.), leading to dual virtualisation layers. The generic abstraction of the equipment (virtualisation of the underlying hardware) is a challenge for computing systems to hide the heterogeneity to the Network Function Virtualisation, and is induced by the trend that efficiency and energy constraints are pushing hardware architecture towards heterogeneity and more and more use of accelerators for special functions. In fact, accelerators are orders of magnitude more energy efficient than standard processors. The challenge is how to keep the performance degradation of the two virtualisation layers as small as possible by using appropriate hypervisors[1] and modern software technologies, so that the effects on latency, throughput and processing overhead are minimised. The available performance of the underlying platform needs to be clearly indicated by service contract and dynamic management, so that virtual appliances know what they can get from the hardware.

In particular, if resource limited and frequently disconnected devices (such as desktop computers or smart phones) participate in the network Function Virtualisation, a careful design is required in order to maintain the required performance.

[1] Hypervisor is a software that can be created on top of the bare metal hardware. It implements the virtualisation layer which creates the virtualised infrastructure. VMs are created on top of the hypervisor.

4.4.3.3 Migration and co-existence of legacy & compatibility with existing platforms

Implementations of Network Functions Virtualisation must co-exist with network operators' legacy network equipment and be compatible with their existing Element Management Systems, Network Management Systems, OSS and BSS, and potentially existing IT orchestration systems if Network Functions Virtualisation orchestration and

IT orchestration are to converge. The Network Functions Virtualisation architecture must support a migration path from today's proprietary physical network appliance-based solutions to more open-standards-based virtual network appliance solutions. In other words, Network Functions Virtualisation must work in a hybrid network composed of classical physical network appliances and virtual network appliances. Virtual appliances must therefore use existing North Bound Interfaces (for management and control) and interwork with physical appliances implementing the same functions.

4.4.3.4 Automation

Network Functions Virtualisation will only scale if all of the functions can be automated. Automation of process is paramount to success.

4.5 NFV MANO (Management and Orchestration)

One of the main goals in introducing cloud computing is the harmonisation and reduction of management effort involved in operating a network. However, software-based substitutes for network elements, separating control and data plane functions, introducing new components and functions, and the need to distribute functionality across virtualised resources all call for fresh thinking in network management and operations to avoid offsetting the potential savings. Increased automation will therefore be crucial. The data and application architecture will also evolve to drive automation, not just for individual network functions or within a network domain, but also across network domains to enable network-wide management applications and service fulfilment.

According to Nokia, a new functional area, called a Global Network Orchestrator (GNO) is needed to enable the necessary automation. Such an orchestrator must contain the processes, sequences, resources, topologies and functions needed to automatically deploy and manage applications and services across the entire mobile broadband network. It must also provide network information as input for applications like SON, Customer Experience Management (CEM) and Service Fulfillment. With access to information about the status of various network functions, the management applications optimise the network end-to-end, rather than optimise individual network functions or areas. The orchestrator then ensures that changes requested and initiated by the automated operational processes and the SON and CEM functions do not interfere with each other.

For the GNO concept to work successfully across the entire network it will naturally need to integrate network functions from different suppliers. The industry therefore needs to agree the type of interfaces and standardized capabilities that a GNO will use.

The preparation for these standards has already started with ETSI NFV. The NFV work item Management and Orchestration aims to describe a framework for the management and orchestration of VNFs, including interfaces and the interworking with other operations and management systems.

The Network Functions Virtualisation Management and Orchestration (NFV-MANO) architectural framework has the role to manage the NFVI and orchestrate the allocation of resources needed by the NSs and VNFs. Such coordination is necessary now because of the decoupling of the Network Functions software from the NFVI. A consistent management and orchestration architecture is required.

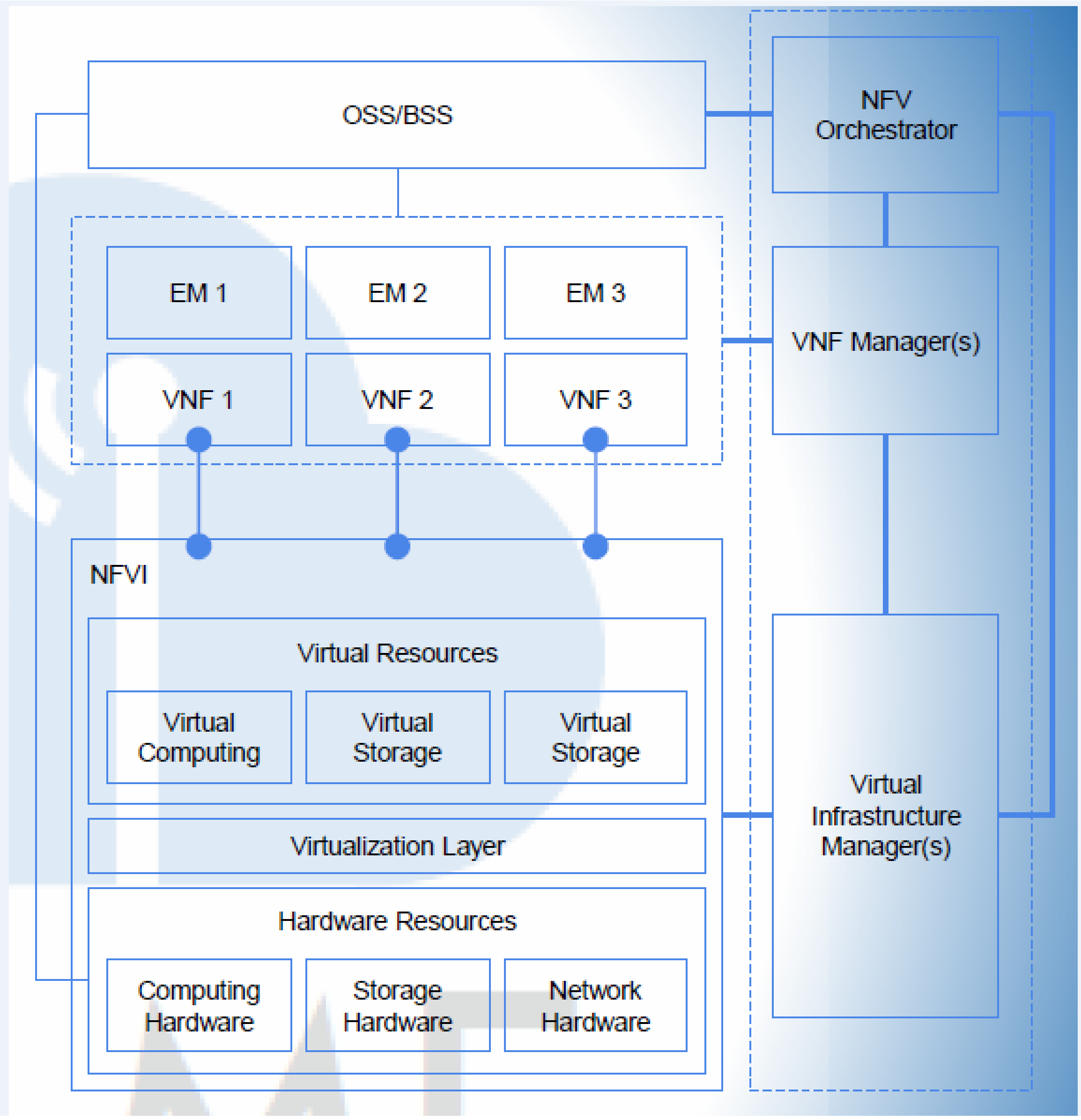


Figure 18: NFV Orchestration functions in the NFV-MANO architecture

Source: 5G-PPP

Network Functions Virtualisation presents an opportunity, through the flexibility afforded by software network appliances operating in an open and standardised infrastructure, to rapidly align management and orchestration North Bound Interfaces to well defined standards and abstract specifications. This will greatly reduce the cost and time to integrate new virtual appliances into a network operator's operating environment. Software Defined Networking (SDN) further extends this to streamlining the integration of packet and optical switches into the system e.g. a virtual appliance or Network Functions Virtualisation orchestration system may control the forwarding behaviour of physical switches using SDN.

The orchestration and federation of network resources as network functions is an important aspect of the future network ecosystem. As such, research will be relevant on the way in which resources and functions are described, protecting the know-how of the network and service providers, and at the same time opening the right interfaces so as to enable new business models to appear. Service Level Agreements automated definition and monitoring/control of network functions is also a relevant topic under the management and orchestration domain.

4.5.1 ETSI NFV MANO

The virtualisation principle stimulates a multi-vendor ecosystem where the different components of NFVI, VNF software, and NFV-MANO architectural framework entities are likely to follow different lifecycles (e.g. on procurement, upgrading, etc.). This requires interoperable standardised interfaces and proper resource abstraction among them.

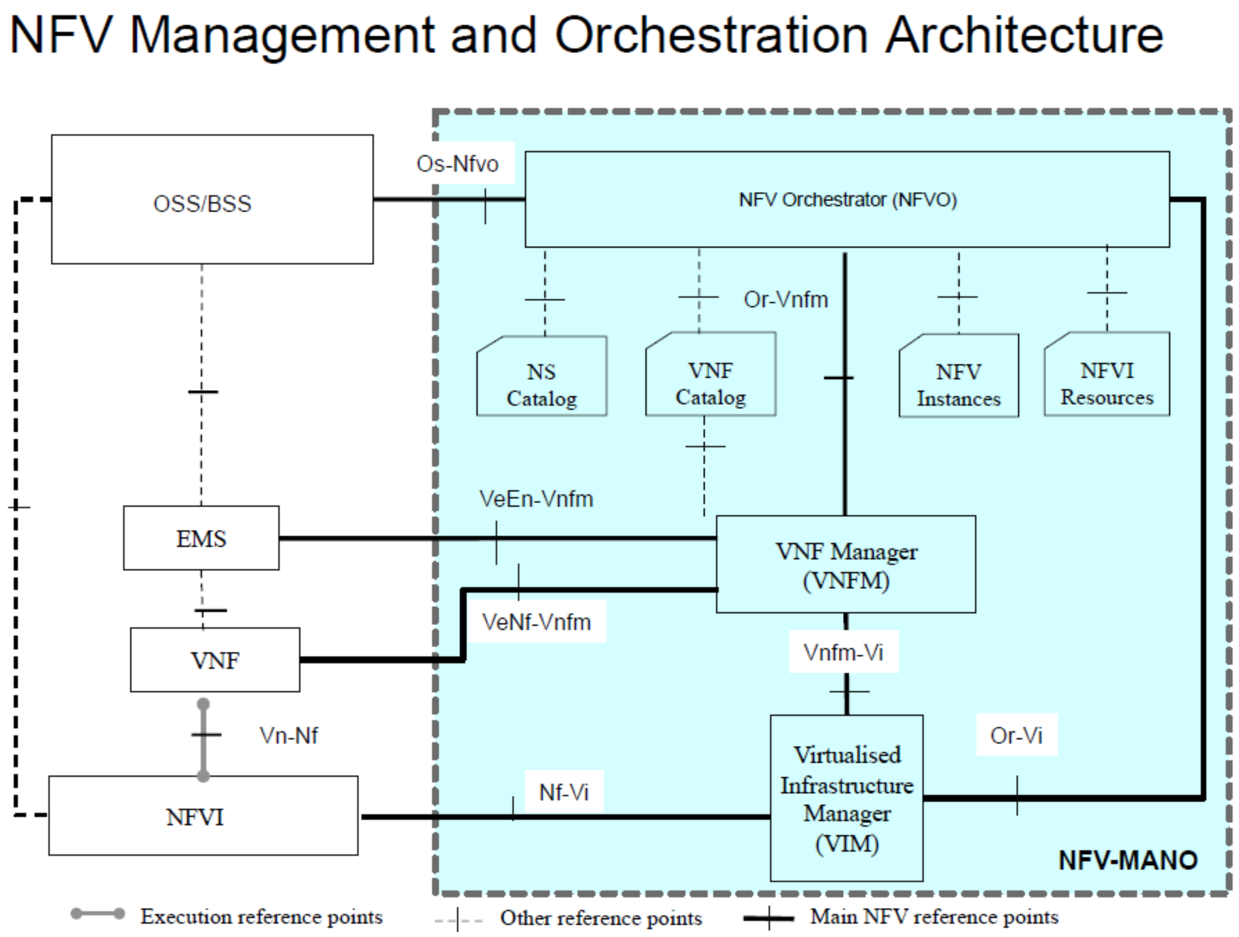


Figure 19: NFV-MANO Architecture

Source: ETSI

NFV-MANO architectural framework overview

- The NFV-MANO architectural framework identifies the following NFV-MANO functional blocks:
  - Virtualised Infrastructure Manager (VIM): deploys VNF and NS in the NFVI according to the requirements available in appropriate descriptor files.

- NFV Orchestrator (NFVO): is the entity responsible for instantiating VNFs and Network Services (NS) within the NFVI. The NFVO interacts with the VIM and VNFM through specific interfaces to create VNF.
- VNF Manager (VNFM): responsible to manage the lifecycle of VNF (creation, termination, scale up/down).

➢ NFV-MANO architectural framework identifies the following data repositories:

- NS Catalogue
- VNF Catalogue
- NFV Instances repository
- NFVI Resources repository

➢ The NFV-MANO architectural framework identifies the following functional blocks that share reference points with NFV-MANO:

- Element Management (EM)
- Virtualised Network Function (VNF): software implementation of network function that can be deployed in a virtualised infrastructure. They are represented by one or more virtual machines running different software and processes on top of industry-standard high-volume compute platforms, switches and storage, or cloud computing infrastructure.
- Operation System Support (OSS) and Business System Support functions (BSS).
- NFV Infrastructure (NFVI): Hardware and Software required to deploy, manage and execute VNFs including computation, networking and storage.

➢ The NFV-MANO architectural framework identifies the following main reference points:

- Os-Ma-nfvo, a reference point between OSS/BSS and NFVO.
- Ve-Vnfm-em, a reference point between EM and VNFM.
- Ve-Vnfm-vnf, a reference point between VNF and VNFM.
- Nf-Vi, a reference point between NFVI and VIM.
- Or-Vnfm, a reference point between NFVO and VNFM.
- Or-Vi, a reference point between NFVO and VIM.
- Vi-Vnfm, a reference point between VIM and VNFM.

4.5.2 The Open Platform for NFV (OPNFV)

The Open Platform for NFV (OPNFV) is a new open source project that aims to accelerate the evolution of NFV. OPNFV will establish a carrier-grade, integrated, open source reference platform that industry peers will build together to evolve NFV and ensure consistency, performance and interoperability among multiple open source components. Because multiple open source NFV building blocks already exist, OPNFV will work with upstream projects to coordinate continuous integration and testing while filling development gaps.

The initial scope of OPNFV will be on building NFV Infrastructure (NFVI), Virtualised Infrastructure Management (VIM), including application programmable interfaces (APIs) to other NFV elements, which together form the basic infrastructure required for VNFs and Management and Network Orchestration (MANO) components. OPNFV is expected to increase performance and power efficiency; improve reliability, availability, and serviceability; and deliver comprehensive platform instrumentation.

The pace of technology development means no vendor can provide a complete telco cloud ecosystem on its own. Partnering, open source software and open APIs are vital for extracting the greatest innovation out of an open ecosystem and for supporting multivendor deployments. There are a variety of initiatives that aim to create a telco cloud ecosystem that supports the co-existence of traditional networks and cloud environments and gives operators the option of choosing the most competitive hardware and cloud platform for their specific needs.

4.5.3 NFV BENEFITS

4.5.3.1 Sharing of resources

One of the most important benefits derived from NFV is the sharing of resources. Virtualisation abstracts the services provided by a network from the underlying physical resources that enable them. In effect, infrastructure becomes a pool of resources from which virtual networks can be instantiated.

In the literature, a lot of emphasis has been placed on the sharing benefits associated with virtualisation, and this is arguably the main motivating factor for the growth of research focusing on virtualisation in 5G networks. The sharing of resources reduces operational expenditure (OPEX) and capital expenditure (CAPEX) for Mobile Network Operators (MNO), removing the barrier of high initial investment in infrastructure associated with upgrading the network.

Infrastructure is owned by infrastructure providers (InP) and utilised by service providers (SPs) who lease virtualised resources. Further granularity can be introduced into models through the creation of specialised roles such as the mobile virtual network provider (MVNP) which leases resources from an InP and virtualises them, or a mobile virtual network operator (MVNO) which manages the virtual resources and assigns them to SPs.

NFV is also supporting multi-tenancy thereby allowing network operators to provide tailored services and connectivity for multiple users, applications or internal systems or other network operators, all co-existing on the same hardware with appropriate secure separation of administrative domains.

Today, the key players in the application and content delivery ecosystem, e.g., Cloud providers, CDNs, OCHs, data centres and content sharing websites such as Google and Facebook, often have direct peering with Internet Service Providers or are co-located within ISPs. Application and content delivery providers rely on massively distributed architectures based on data centres to deliver their content to the users. Therefore, the Internet structure is not as strongly hierarchical as it used to be. These fundamental changes in application and content delivery and Internet structure have deep implications on how the Internet will look like in the future.

What we observe today is a convergence of applications/content and network infrastructure that lead to a model of the Internet that used to separate two stakeholders: Application/content infrastructures on the one side and a dumb transport network on the other. One way to go is to enable the different stakeholders to work together, e.g., enable ISPs to collaborate with application/content providers. This can be achieved for example by exploiting the diversity in content location to ensure that ISP’s network engineering is not made obsolete by content provider decisions or the other way around. Another option is to leverage the flexibility in network virtualisation and making their infrastructure much more adaptive than today’s static provisioning.

Using NFV, each scenario can be mapped to a specific type of network which has been optimised to satisfy the corresponding requirements of the scenario. Virtualisation offers a platform to achieve this, allowing each scenario to be mapped to a virtual network which has been instantiated according to the requirements of that particular scenario.

5G, therefore, might not be considered one single type of network but rather an umbrella for a host of customised virtual networks.

4.5.3.2 OTT - Network infrastructure openness and NFV

Network infrastructure openness is still limited. It prevents the emergence of integrated OTT (cloud)-network integration with predictable end to end performance characteristics, and limits the possibility for networks to become programmable infrastructures for innovation with functionalities exposed to developers' communities. These are key issues for the competitiveness of the communication industry world-wide and are globally researched in the context of future 5G integrated, ubiquitous and ultra-high capacity networks.
NFV will allow overcoming the Over-The-Top (OTT) issue, offering application providers the capability to send traffic over the top of the Internet, across multiple networks to end users without any delivery guarantee.

4.5.4 NFV summary

Virtualisation provides the practical means to realise the flexibility required in 5G networks by allowing customised virtual networks to be created according to the requirements of different scenarios and use-cases. Virtualisation can be used to present a well-defined interface to the emerging flexible radio access technologies so that these customised virtual networks can be truly tailored according to the targeted use-cases. It can also make use of system-level techniques that provide us with the flexibility to construct customised services and virtual networks, and dynamically manage them. While the radio access technologies constitute the building blocks, system-level techniques allow us to build something useful out of them, with virtualisation forming the link between the two. Virtualisation is not a new concept in information and communications technology (ICT) and is widely used in wired networks. The advent of virtualisation in wireless networks marks the introduction of new business models and roles in ICT industry.

4.6 SDN (Software Defined Networking)

4.6.1 SDN in mobile networks

Software Defined Networking (SDN) will play a vital role in future mobile networks.

Traditionally the control plane of a network, which is responsible for managing the routing and flow of data, was implemented at a hardware level. As a result, altering the behaviour of a network required reconfiguration of a vast number of devices each containing vendor specific protocols; a costly process in terms of both time and money. SDN decouples the control plane from the data plane, allowing centralised control over the behaviour of the entire network.

The rules for handling data can now be specified in software at the controller, which communicates with the data plane (i.e., switches, routers) through an open interface. As a result, it is possible to alter the entire behaviour of the network from a single logical point without needing to physically touch the hardware. This allows for greater efficiency in the utilisation of resources as the network can be reprogrammed to meet current demands. SDN is a key component of the 5G vision of flexible networks and will have profound implications on the manner in which resources are allocated and managed.

The essence of SDN is possibly best characterised by four of its core principles:

- Decoupling of control and data planes.
  This principle is the foundation of the SDN concept. It advocates the separation of the control plane into a logically centralised software controller which is capable of managing and altering the routing of data through the network. This separation has

an implicit implication that the controller is in some way external to the physical equipment that it controls. Decoupled data and control planes co-located on the same device blurs the definition of SDN.

- Logically centralised controller:
  The extracted control plane is logically centralised into a single controller with a network wide view. This logically centralised controller may in fact consist of multiple virtual or physical controllers operating in a distributed manner, depending on the scale of the network.
- Open interfaces:
  One of the motivating factors behind SDN was to reduce the effort and cost associated with reconfiguring the vendor-specific devices in the network. An open, standardized interface between devices in the control and data planes, known as the southbound application program interface (API), is therefore a key principle of SDN.

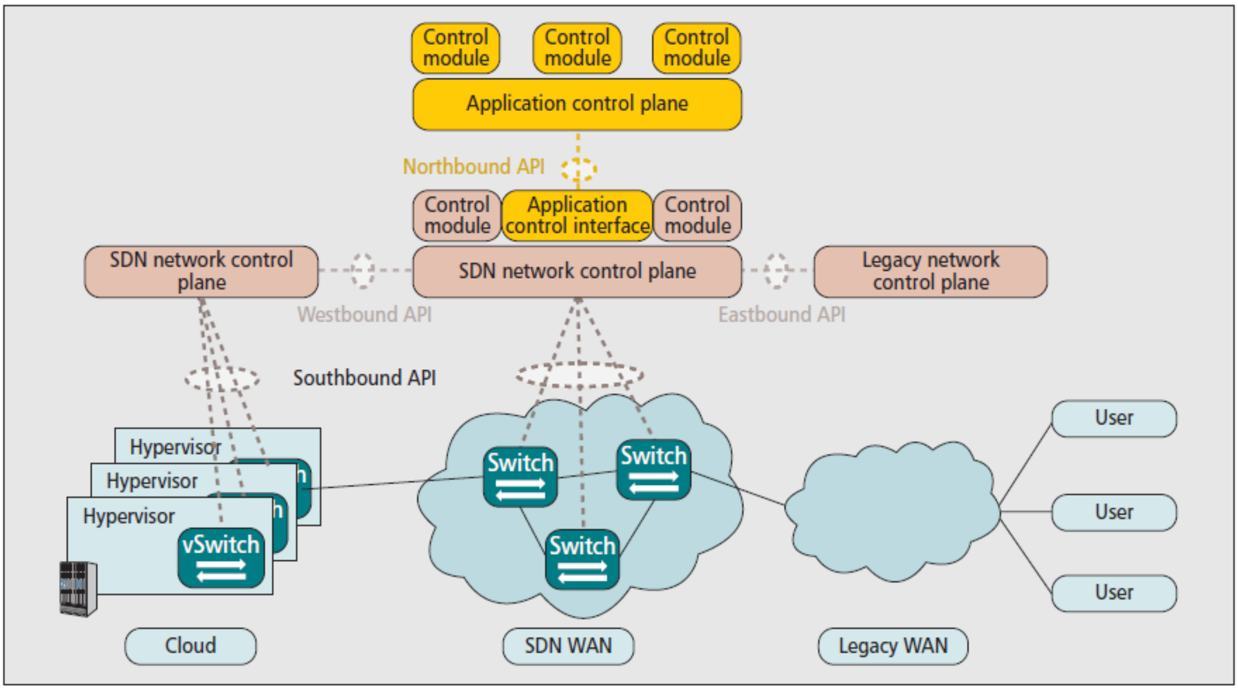


Figure 20: The two primary SDN interfaces - northbound and southbound

Source: IEEE Communications Magazine

- Programmability by external applications:
  The controller in SDN allows for programmability by external applications through the so-called northbound API. This naturally lends itself to the concept of adaptability. It allows the network operator to view the myriads of physical hardware under its control as a single programmable entity which it can configure.

A more comprehensive overview of SDN and its implications in terms of programmable networks is provided through a comparison between two of the most popular SDN architectures/standards; OpenFlow and ForCES. SDN can be used to increase the versatility of 5G networks, create and manage adaptable networks using radio access technologies as building blocks. SDN offers potential in this regard in the following ways:

- *Wireless SDN*: SDN itself is inherently adaptable, introducing greater abstractions into the network by decoupling the control and data planes. The flow of data through the network can be altered through programmable controllers. The great flexibility of SDN application in the wireless context, is derived from the extended researched in the wired domain.
- *Slicing*: Slicing refers to partitioning resources and isolating the traffic between multiple coexisting virtual networks.
- *Gathering of statistics*: SDN can be used to gather usage statistics and obtain a global view of the network. From a virtualisation point of view, it allows the virtual network operator to make informed decisions about the management of virtual resources.
- *Cloud-RAN and SDN*: SDN offers a means to flexibly connect remote radio heads (RRH) to baseband processing units (BBU).

4.6.2 SDN use cases

i. Using SDN technologies to virtualise the data center LAN enables the infrastructure management to offer the application software on-demand on a dedicated virtual tenant LAN governed by Service Level Agreements (SLAs). The tenant LAN shields the application traffic from other traffic within the data center. Without this feature it would be much more costly to build a secure telco cloud.

ii. In the case of packet gateways, the SDN inherent ability to separate the control plane from the forwarding plane, makes the network programmable via open APIs with a centralised control function. The separation of the control and forwarding functions allows each to be scaled independently, which is extremely helpful when the balance between the signaling load and the user plane traffic can vary depending on the application. Full separation of the control and the forwarding function within the gateway allows for additional service chaining. A conventional gateway does more than simply route packets. It also provides functions that include tunnel termination, deep packet inspection, network address translation and ciphering. To reduce costs and latency, virtualisation allows these functions to be applied to each data stream only as required.

iii. Traffic patterns and user behaviour in mobile networks are very dynamic. SON capabilities automatically adjust the radio access network parameters to optimise the user experience. However, it is also important to dynamically optimise the backhaul network according to actual traffic needs. Through programmability enabled by SDN, SON functions can now simultaneously optimise RAN and transport parameters for better network utilisation.

iv. IP core wide area networks are likely to be enhanced gradually with programmability introduced by SDN. There are two drivers. Firstly, end users expect on-demand delivery of VPN services for their application services. Secondly, in a distributed compute environment for virtualised network functions, the network function software will occasionally migrate to different locations for the network service to deliver a better customer experience. This flexibility needs dynamic adjustment of the wide area network connections, which can be delivered through a SDN-enhanced IP core network.

4.7 Network Slicing

4.7.1 Network Slicing Definition

Network architecture has been traditionally built around a specific use-case. For example, GSM was built primarily for voice and LTE for mobile data. In the future, this "one use case per one physical network" approach will be obsolete. The evolution of the mobile network architecture is driven by the need to provide communication services for a manifold of applications. The 5G network will be designed to be flexible enough for an operator to create an instance of an entire network virtually, that is, a customised network for each diverse use case. Different customised virtual networks will exist simultaneously and without interfering with each other. This is so-called Network Slicing.

According to network slicing concept, multiple independent and dedicated virtual sub-networks (network instances) are created within the same infrastructure to run services that have completely different requirements for latency, reliability, throughput and mobility.

A network slice, conceptually decouples a network from the underlying physical infrastructure, thereby providing individual, isolated and elastic virtual networks on demand, with unique defined characteristics.

A network slice, namely "5G slice", supports the communication service of a particular connection type with a specific way of handling the C- and U-plane for this service. To this end, a 5G slice is composed of a collection of 5G network functions and specific RAT settings that are combined for the specific use case or business model. Thus, a 5G slice can span all domains of the network: software modules running on cloud nodes, specific configurations of the transport network supporting flexible location of functions, a dedicated radio configuration or even a specific RAT, as well as configuration of the 5G device. Not all slices contain the same functions, and some functions that today seem essential for a mobile network might even be missing in some of the slices. The intention of a 5G slice is to provide only the traffic treatment that is necessary for the use case, and avoid all other unnecessary functionality.

4.7.2 Network Slicing requirements

The network slicing concept is designed to addresses all requirements. It partitions a common network infrastructure into multiple, logical, end-to-end, virtual network instances or slices with several key characteristics:

- Support a variety of business models.
  The slices support a group of services, use-cases, and business models
  with similar requirements, including industry-specific models
  and multi-tenancy. For example, an operator can run enhanced
  broadband slices to offer a variety of broadband services to its customers,
  which include web browsing, audio and video streaming.

- Provide extreme agility in the network to meet diverse service needs.
  The slices are built with only relevant network capabilities that match the
  needs of the supported service, use case or business case. For example, an
  ultra-low latency capability can be created for a slice supporting ultra-low
  latency use cases. The capabilities in the slice are not restricted to the user
  plane. The slices can also control and manage plane-relevant capabilities,
  such as a dynamic video stream control or a specific type of billing
  application relevant to the business case.

- Significantly reduce new service creation and activation times.

- Provide massive elasticity in the network to meet very dynamic traffic demands.
- Exploit analytics and context to adapt services and networks predictively and in real time.
- Enable an open services ecosystem where different parties can cooperate to introduce innovative services tailored to specific user or industry demands.
- Expose actionable network insights to application and content providers, enterprises, and industry verticals.
- Provide full programmability to enable easy integration of new network capabilities, extension of existing capabilities and easy creation of new services and business models.
- Intelligently manage and orchestrate resources and capabilities for dynamic (re)configuration of the network to meet end-to-end performance.
- Support a high level of automation powered by advances in analytics, and machine learning.
  The slices are dynamic in runtime. They include an automation framework that uses real-time analytics and monitoring for efficient use of network and cloud resources, and optimisation for the dynamic needs of services or dynamic traffic demands.

To sum up, network slices must fulfill a set of requirements such as the need for sharing and efficiently reusing resources (including radio spectrum, infrastructure, and transport network); differentiation of traffic per slice; visibility of slices; protection mechanisms among slices (a.k.a. slice isolation); and support for slice-specific management.

4.7.3 Implementing Network Slicing

To implement network slicing, technologies like software defined networking and network functions virtualisation, as well as management and orchestration processes, will have to work in harmony with a flexible radio access network that can adapt to different requirements and deployment models.

5G will not only be a ‘new RAT family’ with its radio access network but its architecture will expand to multiple systems by providing a common core to support multiple RATs (cellular, Wi-Fi and fixed), multiple services (mobile broadband, massive Machine Type Communications (MTC) and critical MTC) and multiple network and service operators. The required architecture will be enabled by Network Functions Virtualisation (NFV) and Software Defined Networking (SDN) technologies which allow systems to be built with a high level of abstraction.

Software-defined networking (SDN) and network functions virtualisation (NFV) will play an important role in the shift to network slicing. Virtualisation will enable separation of the software from the hardware and offer the possibility to instantiate many functions on a common infrastructure. With this approach, the infrastructure can be shared by different tenants and provide different services.

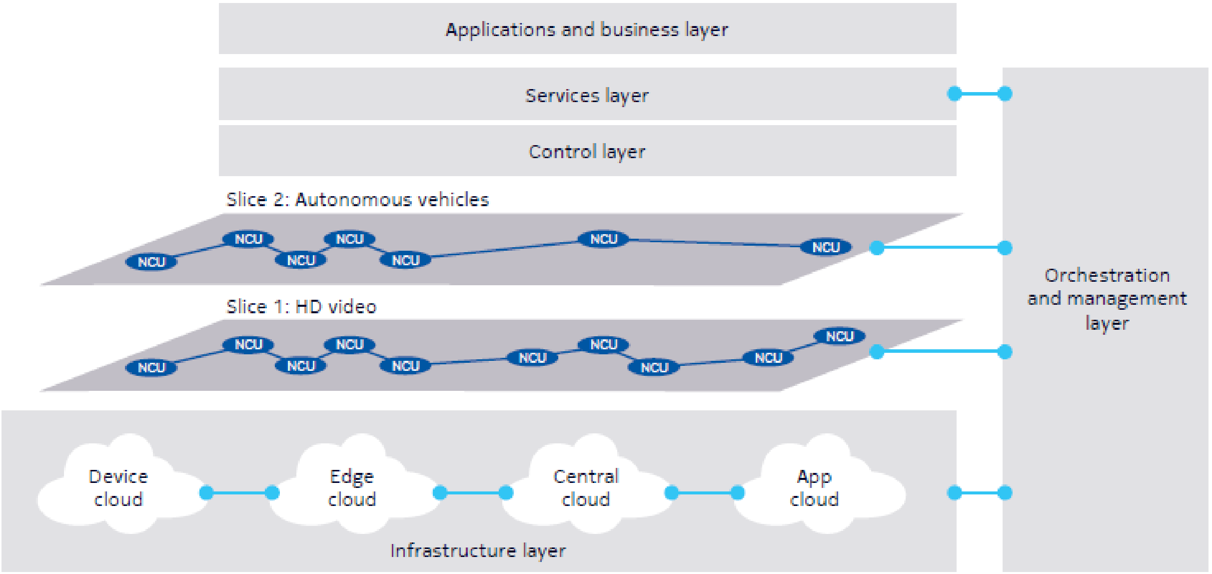


Figure 21: Conceptual architecture for dynamic network slicing in 5G

Source: Nokia

In this architecture, the *services layer* acts as the logical interface between network and business applications. It provides abstraction of the network towards applications and interfaces for easy service creation and optimisation.

The *control layer* hosts the logical end-to-end control for the network. It provides abstraction of the network towards the services layer. In deployments, the control layer may consist of multiple controllers coordinated or federated appropriately to provide end-to-end control and programmability.

The *orchestration and management layer* supports design, creation, and activation of individual slices on the common infrastructure. Management and orchestration is enhanced using analytics and machine learning. In addition, analytics are exploited to optimise the infrastructure resources within a slice, as well as across different slices sharing the same infrastructure.

Finally, the *infrastructure layer* hosts the physical and virtual resources needed to create end-to-end network slices. These include both virtualization software and hardware comprised of memory, compute, storage, and networking resources.

The slices are created and deployed over a distributed cloud infrastructure, each with unique capabilities dedicated to a supported service group, use case, or business model.

To enable this approach, network slicing leverages key technology advancements in:

- Distributed cloud infrastructure and cloud native applications
- NFV
- End-to-end orchestration
- SDN and programmable networking
- Network big data, analytics, and machine learning
- Services oriented architectures
- Intent based network programming

4.7.4 Network Slicing benefits

4.7.4.1 Flexibility

The network slicing provides the flexibility to run multiple network instances (slices) on the same physical network infrastructure.
It also allows operators and vendors to enable new business models by offering NaaS. This can be extended from the core network down to radio access. The flexibility behind the slice concept is a key enabler to both expand existing businesses and create new revenue sources. Third-party entities can be given permission to control certain aspects of slicing via a suitable API, in order to provide tailored services according to the needs of any industry whether automotive, healthcare, logistics, retail or utilities. In that context, network slicing is expected to be the key enabler for service-determined connectivity and fast traffic forwarding.

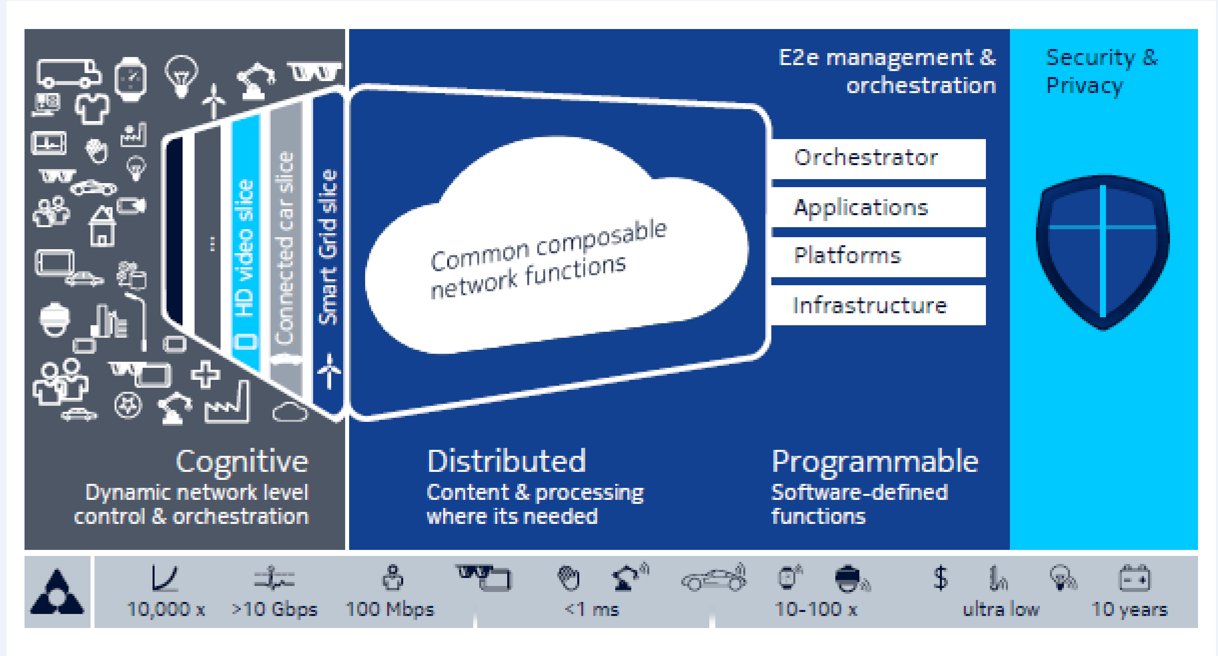


Figure 22: Network Slicing enabling Network-as-a-Service

Source: Nokia

4.7.4.2 Dynamic programmability and control

The 5G network slices support dynamic programmability and control by leveraging SDN principles. And the dynamic programming of network slices can be accomplished either by custom programs or within an automation framework driven by analytics and machine learning.

4.7.4.3 Automation of the network operation and optimisation

Creating more network slices inherently adds complexity to network operations and ongoing optimisation efforts. Therefore, the dynamic network slices are designed from the ground up to enable maximum possible automation of operations and optimisations. Automation is enabled by analytics, machine learning, network big data, and network programmability.

4.7.5 Network Slicing heterogeneous use cases

A variety of services will depend on the network providing low latency access under full mobility conditions. For example, V2X applications will require seamless service continuity as the vehicle moves between the serving areas of local gateways.

Another example is to provide simultaneous access to Internet services through a central gateway and access to a local Content Delivery Network (CDN) site through a local gateway. Supporting such re-locatable low latency and high reliability (multi-connectivity) services will require the 5G access point, or an aggregator cloud, to route traffic either to the centralised IP anchor, local IP anchor or directly to the Mobile Edge Computing (MEC) application. This is achieved by introducing service-aware forwarding at the radio.

Moreover, a customised virtual network for ultra-low latency autonomous vehicle control can co-exist with a customised virtual network for 3D video /4K screen viewing, which requires extremely high throughput.

4.7.6 Network Slicing summary

5G network slicing can be used to ensure that end-to-end performance meets customer expectations, as well as service and application requirements.
It offers an effective way to enable this shift and partition a single common 5G infrastructure into multiple logical end-to-end networks. It also provides the service agility needed to address diverse:

- Users (people and machines)
- Use cases
- Requirements for latency, throughput, and availability

To leverage network slicing properly, the individual segments (radio access network (RAN), transport, metro, core, edge cloud, central cloud), which were formerly treated separately, must be examined as a whole. And, performance optimisation must be adapted and coordinated, across the entire network.

Network slicing will provide operators with the capability to establish different deployments, architectural flavors and performance levels for each use case or service group. What is more important, is that they can run all network implementations simultaneously in parallel.

The introduction of 5G will allow operators to become more flexible and efficient by moving from a rigid network to an agile one that can meet many diverse needs with new as-a-service business models using network slicing.

4.8 Mobile Edge Computing (MEC)

4.8.1 MEC definition

The days of differentiating on coverage and capacity are long gone. Operators are looking to deploy differentiating, cutting-edge services with the best-possible consumer experience as rapidly as possible.

A full cloud stack can provide a solution that effectively introduces a distributed cloud platform very close to the end user. The use of virtualised resources and a virtual resource manager can support several concurrent applications and makes it easy to deploy or withdraw applications and content to meet the changing needs of the market.

Moving the gateway and application server closer to the radio can significantly reduce latency even further. Services are no longer tied to a single point-to-point IP connection, enabling the connectivity path to be freely chosen according to actual service demand. This any-to-any connectivity model, in which devices communicate directly through local switching at the RAN level avoids unnecessary data forwarding to centralised mobility anchors (gateways). This offers the shortest and best path for routing traffic that needs low latency while at the same time ensuring continuity and seamless mobility.

To address ultra-reliability and low latency we will need to build a resilient system dynamically managed that offers high-availability and brings content close to users, on demand and instantly. The key network architecture evolution comes from the following concepts.

MEC is a network architecture that enables cloud computing capabilities and an IT service environment at the edge of the cellular network and a key emerging technology of 5G together with Network Functions Virtualisation and Software-Defined networking.

4.8.2 Addressing 5G requirements using MEC

The prime goals of MEC are listed below:

- Optimisation of mobile resources by hosting compute intensive application, such as image processing, m-gaming, at the edge network.
- Optimisation of the large data before sending to the cloud
- Enabling cloud services within the proximity of mobile subscribers.
- Providing context-aware services with the help of RAN information

The possible application scenarios include many aspects, such as dynamic content optimisation, computational offloading in IoT, mobile big data analytics and smart transportation.

Mobile Edge Computing architecture has three basic components:

- Edge devices include all type of devices (both mobile phones and IoT devices) connected to the network.
- Edge cloud is the less resourceful cloud deployed in each of the mobile base stations. Edge Cloud has the responsibility of traditional network traffic control (both forwarding and filtering) and hosting various mobile edge applications (edge health care, smart tracking etc.)
- Public cloud is the cloud infrastructure hosted in the Internet.
  The key element of Mobile Edge Computing is the MEC IT application server which is integrated at the RAN element. The MEC server provides computing resources, storage capacity, connectivity and access to user traffic and radio as well as network information.

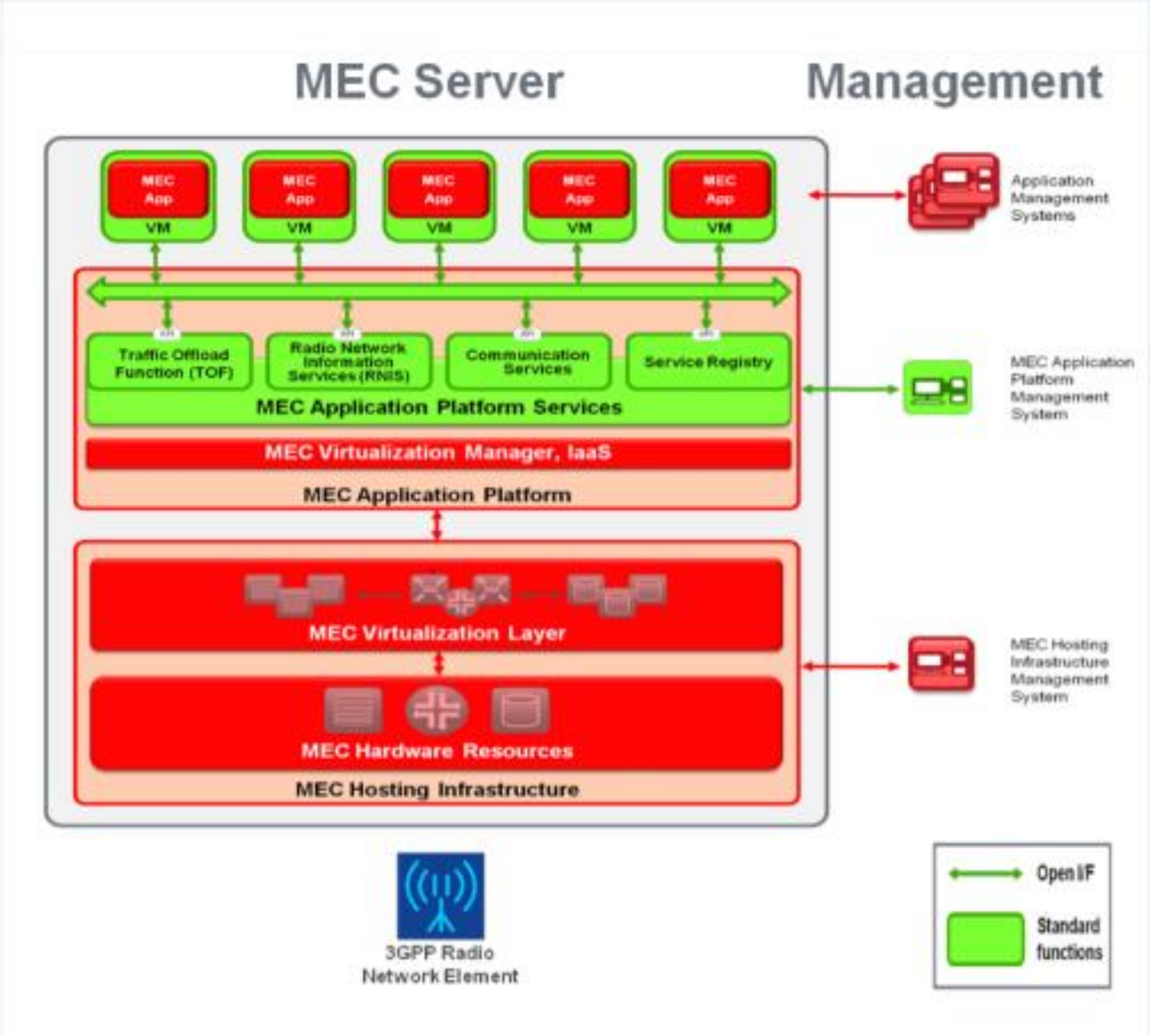


Figure 23: MEC server platform overview

Figure 23 shows an overview of MEC server platform, which consists of a hosting infrastructure and an application platform.

The MEC hosting infrastructure consists of hardware resources and a virtualisation layer. The details of the actual implementation of the MEC hosting infrastructure (including the actual hardware components) are abstracted from the applications being hosted on the platform. The MEC application platform provides the capabilities for hosting applications and consists of the applications virtualisation manager and application platform services.

- The virtualisation manager supports a flexible and efficient, multi-tenancy, run-time and hosting environment for applications by providing Infrastructure as a Service (IaaS) facilities.
- The MEC application-platform services provide a set of middleware application services and infrastructure services to the applications hosted on the MEC platform.

4.8.3 MEC business and technical benefits

Mobile-edge Computing provides a new ecosystem and value chain as well as the opportunity for all players within it to collaborate and develop new business models they can each benefit from.

The major advantages of mobile edge computing include its low latency (1ms), proximity, high bandwidth (100Mb/s to 1Gb/s), and real-time insight into radio network information and location awareness. Meanwhile, MEC allows cellular operators to open their radio access network (RAN) to authorised third-party, such as developers and content providers, which can create great business benefits.

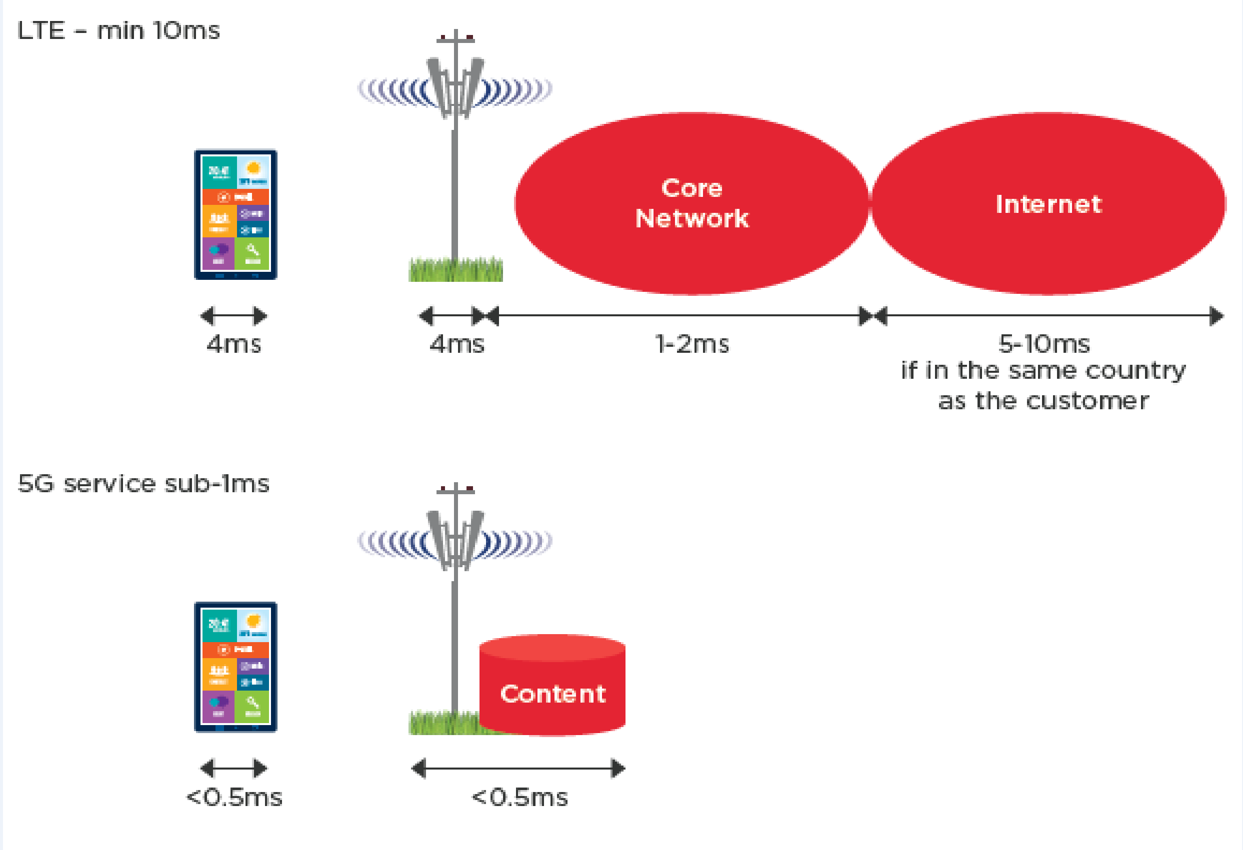


Figure 24: Latency performance for LTE compared to latency requirement for 5G

Source: GSMA

Mobile Network Operators (MNOs) can rapidly deploy new services for consumer and enterprise business segments which can help them differentiate their service portfolio. Adding new revenue streams from innovative services delivered from closer to the user can improve the MNOs bottom line whilst improving end user QoE. New applications which are aware of the local context in which they operate (RAN conditions, locality, etc.) can open up entire new service categories and enrich the offering to end users.

Placing relevant applications on or near the base station not only offers advantages to consumer and enterprise end users. It also reduces the volume of signaling offloaded to the core network and could also reduce OPEX for the MNOs, compared to hosting in the core. The MNOs could increase their revenue by charging based on the resource usage (storage, NW bandwidth, CPU, etc.) of each content provider, if such resource usage could be obtained via specific APIs in MEC server.

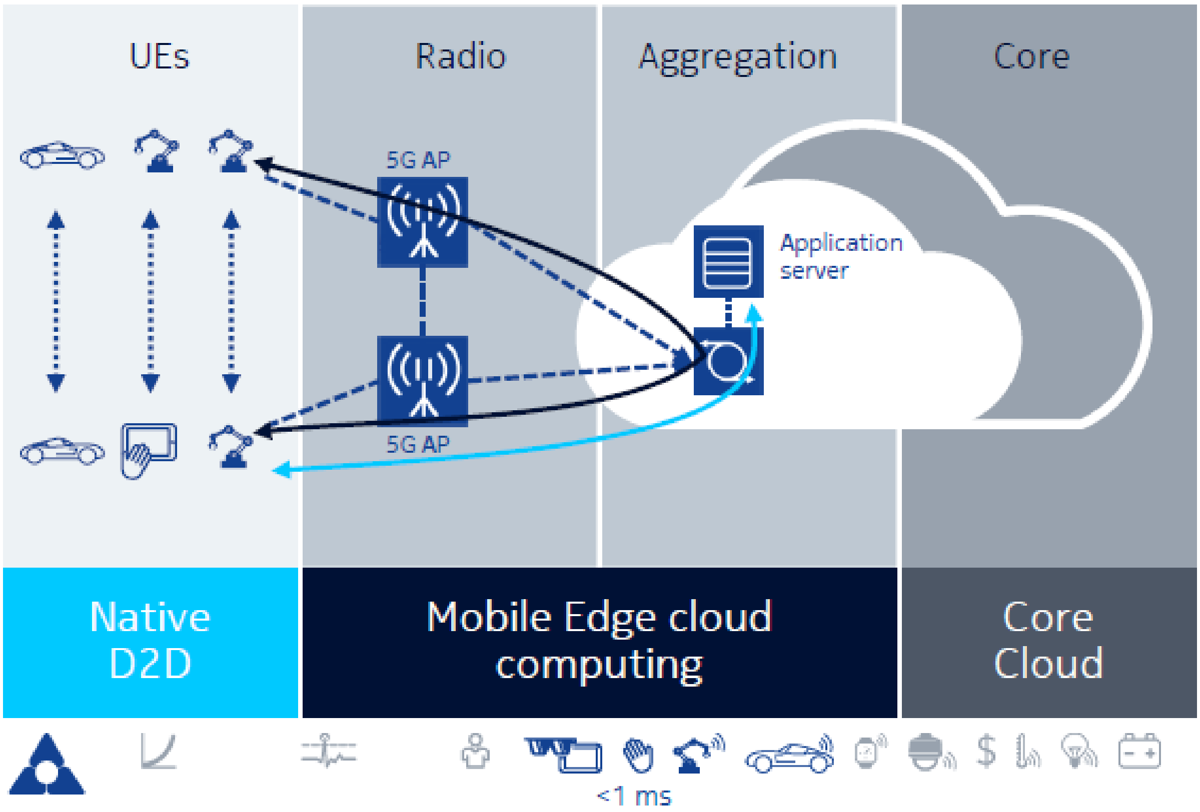


Figure 25: Mobile Edge Computing

Source: Nokia

Software and application providers can serve the new ecosystem by developing and bringing to the market innovative and ground breaking services and applications that can take advantage of the information on radio network capabilities and conditions available at the base station. The application space is open to anyone: software and application providers, infrastructure vendors and MNOs.

The use of open standards and Application Programming Interfaces (APIs), as well as the use of familiar programming models, relevant tools chain and software development kits are key pillars to encourage and expedite the development of new disruptive applications or the adaptation of existing services and applications to the new Mobile-edge Computing environment.

4.9 Cognitive Networks

A cognitive network is a network with a cognitive process that can perceive current network conditions, and then plan, decide, and act on those conditions. The network can learn from these adaptations and use them to make future decisions, all while taking into account end-to-end goals. We explicitly distinguish the cognitive network concept from that of a cognitive radio. A cognitive network possesses end-to-end goals, giving it a network-wide scope. In contrast, a cognitive radio possesses user-centric goals giving it local scope. The two concepts share common traits, however. Both concepts share similar models of cognition, learning from past experiences which influence decisions made in the future.

In effect, all elements in the network involved in data flow are part of the cognitive process, capable of providing information about the network and offering adaptability. The network should not be reactive, but should instead be able to make decisions based on predictive models constructed using past observations. In summary, the cognitive network inputs observations of network performance, uses these observations in a decision-making process, and implements actions based on these decisions through adjustable network elements.

In order to be effective, the cognitive network requires extensive knowledge of network state for the decision-making process. Focusing on obtaining network state information, the cognitive process must have access to state across the entire network. Knowing the state of the entire network is somewhat unrealistic and, as a result, the cognitive process should be able to deal with incomplete information. Often the process will only require a subset of state information, obtaining the relevant pieces through filtering. The layered nature of networks provides a blockage in terms of the flow of state information in the network. Often a layer may be able to provide information that could potentially influence an adaptation at a different layer. Hence, cognitive networks must operate cross-layer.

As previously mentioned, cognitive network requires adjustable network elements that allow it to implement a set of actions based on the decisions it makes. In this regard, a cognitive network is limited by the flexibility of the network itself. If the cognitive process is unable to adjust the network based on the decisions it makes and in accordance with its end-to-end goals, then the application of the cognitive network is fruitless. Instead, a SAN is needed which presents tunable or modifiable components, allowing the cognitive process to adjust one or more layers in the network stack belonging to various network elements.

Cognitive networks offer great and obvious potential in the context of adjustable 5G networks. They also remove the need for an operator to tune the network which is instead capable of autonomously adapting itself to the various service requirements.

The concept of a cognitive network is a broad topic with many different techniques fitting the description, yet the realization of a truly cognitive network remains unseen. The need for an adaptable network designed using artificial intelligence and cognitive techniques has been identified since 2003. Thirteen years later, our networks are arguably more adaptive, but this adaptivity is confined to certain parts of the network and arises from the use of algorithmic techniques applied in these areas, rather than an inherent intelligence permeating the entire network. The lack of a true SAN has restricted the development of the cognitive network concept; however, it may be on the cusp of experiencing its coming of age moment. Similar to the way in which advances in SDR preceded and enabled a plethora of research in the area of cognitive radio, the current movement towards a software defined RAN, coupled with software defined networking techniques, may herald a renewed interest into extending the cognitive radio concept to the entire network.

4.10 Self-Organising Networks

5G is going far beyond radio. To achieve built-in flexibility current networks will transform from comprising vertically integrated discrete network elements, to being cognitive, cloud optimised and seamless in operation.

Networks will become cognitive to be able to optimise themselves autonomously. Cognitive networks using big data analytics and artificial intelligence will solve optimisation tasks too complex for humans.

Self-organised capabilities enable the network to efficiently predict demand and to provide resources, so that it can heal, protect, configure and optimise accordingly. The platforms will do this by generating the minimum cost on network equipment (CAPEX) and operations cost (OPEX), whilst keeping QoS tailored to user demand with adequate resources. The operational cost includes network resource allocation, service provision and monitoring, as well as energy efficiency. Moreover, the management platforms will offer network resilience mechanisms, such as the identification of network errors, faults or conditions like congestion or performance degradation. Also, they will identify serious security issues such as unauthorised intrusion or compromised network components, and liaise with autonomic network management to formulate and take appropriate action.

The overall objective is to create a cognitive and autonomic management system developed through the application of policies that can self-adapt to the changing conditions of the network and to the external environment in which the network operates, via a well-defined set of self-organising functions. These platforms also need to support multi-tenancy environments.

Autonomic self-protection capabilities in the 5G network that might defend users against infrastructure attacks (such as a distributed denial-of-service attack), as well as providing self-healing capabilities to the 5G network, are a key aspect of the network intelligence expected in the novel 5G technologies.

Software network technologies are introduced as fundamental enablers to realise the requirements of programmability, flexibility (e.g., re-configurability, reusability and infrastructure sharing), adaptability (e.g., self-configuration, self-protection, self-healing and self-optimisation) and capabilities (e.g., mobile edge computing, network slicing, autonomic network management) expected to be inherent in 5G networks.

4.10.1 Automated Network Management

Automated management is necessary to handle the complexity in the 5G resource orchestration platform. Automated management in multi-administration environments involves defining novel business, coordination and information models, trading mechanisms and pricing schemes. Autonomic management of SDN and NFV components can be implemented in an environment that uses monitoring data collected from the various components and functions in the network, and applies machine learning (ML) techniques and algorithms to develop a model which in turn informs the network management decisions. ML techniques could address the challenge brought by accurate service demand prediction and provisioning in virtualised environments. This should allow the network to resize and provision itself to serve predicted demand according to parameters such as location, time and specific service demand from specific users or user groups. To realise these ML techniques, approaches from Big Data handling are likely to become necessary.

4.10.2 The OAM challenge

The Operation and Management (OAM) of the wireless mobile network infrastructure (including WIFI) plays an important role in addressing future network challenges in terms of constant performance optimisation, fast failure recovery and fast adaptations to changes in network loads, architecture, infrastructure and technology. Self Organising Networks (SON) are the first step towards the automation of networks' OAM tasks, introducing closed control loop functions dedicated to self-configuration, self-optimisation, and self-healing. The tendency introduced with SON is to enable system OAM at local level as much as possible. The OAM systems are getting more and more decentralised. The long-lasting dilemma has thus been on finding a right balance between centralised control versus distributed SON. However, first generation SON functions need to be individually configured and supervised by a human operator. This manual configuration and tuning is getting less and less practical, due to the increasing complexity of the SON system, since multiple SON functions being operated in parallel may have interdependencies and lead to network performance degradations due to inconsistent or conflicting configuration.

These topics are also covered by research activities in the area of Cognitive Networking (CN). CN was investigated as an extension of Software Defined Radio (SDR) to get a full set of functions required to deploy an overall cognitive radio system. There are a lot of research results available with focus on Spectrum-Sensing Cognitive Radio.

4.10.3 Objectives to overcome the challenge

CN describe a radio network that employs a cognitive process (i.e., involving thinking, reasoning and remembering) and learning capabilities in order to achieve end-to-end goals. This applies to both the horizontal network (i.e., including all the protocol stack of wireless networks, both radio access and backhaul/transport) and the vertical management views (i.e., abstracting network elements and their configuration towards a holistic high-level view). Control loops need to work not only for single independent functions, but also to be extended for the complete environment to be managed, which may involve several layers of control loops. The control loop diagnosis and decision making processes need to be adapted automatically by learning, e.g. based on the results of previous actions, in order to improve their effectiveness and efficiency, leading to cognitive processes driven and controlled through high-level operator goals.

4.10.4 SON architecture proof of concept

Nokia demonstrates the capabilities of the programmable 5G multi-service architecture through several proofs of concept, including:

- A fully self-aware software-defined transport network that automatically adapts itself to changing service requirements and the needs of different network slices and customer experiences. This is achieved by a Self-Organizing Networks (SON) solution for transport in combination with a multivendor Software-Define Networking (SDN) fabric control that acts across SDN domains.
- Programmable APIs are also introduced to virtual core network elements in order to adapt core network behaviour in run time, unlike today’s elements that require hours or even days to be re-configured. As a result, the core network can adapt to dynamically changing needs such as the creation of new network slices or mobility profiles either immediately or on demand.

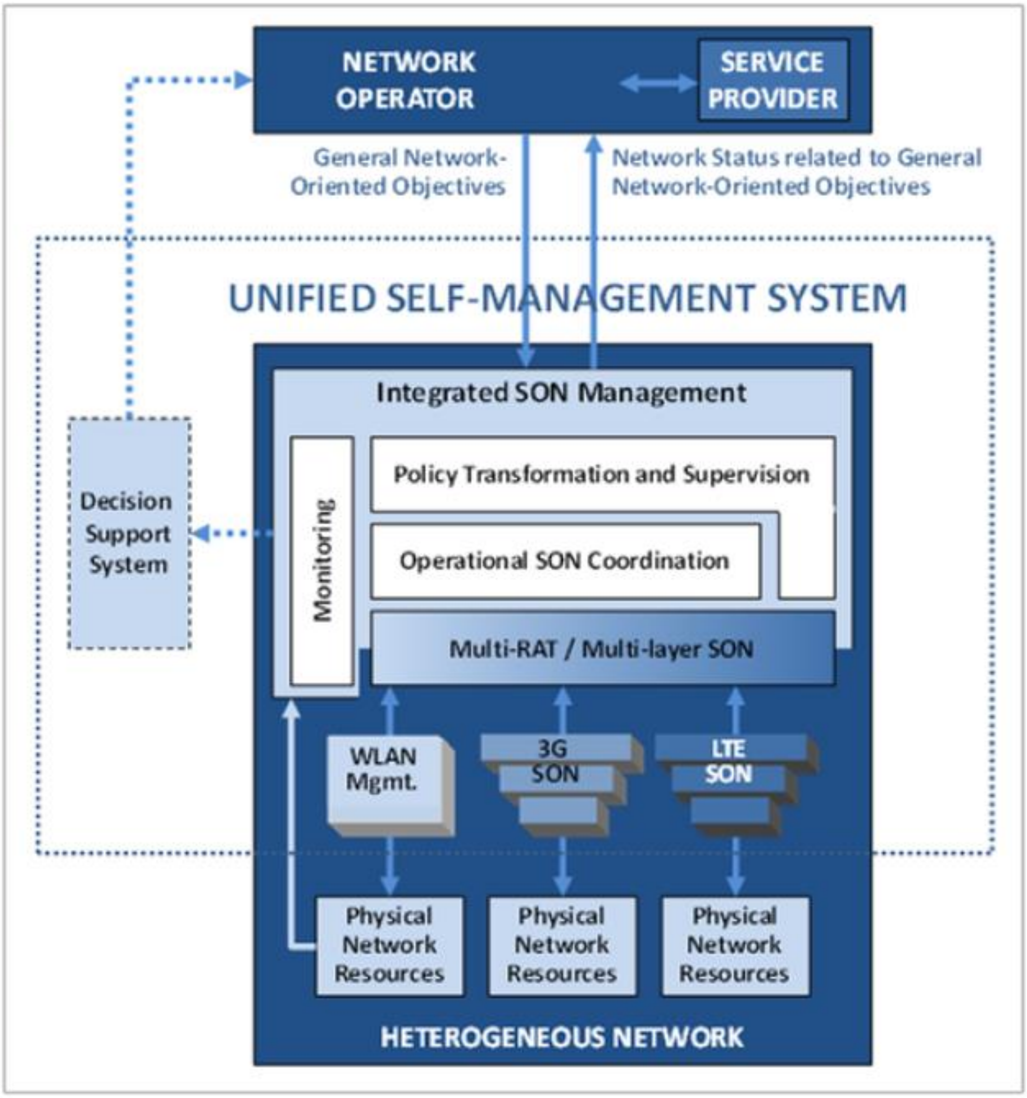


Figure 26: Integrated SON management

Source: RAS

4.11 What we covered in this 4th chapter

In this chapter, we presented the 5G architecture pillars; SDN, NFV-MANO, MEC. Extensive analysis has been also performed in regards of future network characteristics; Cognitive and Self-Organised.

5G is expected to reduce service creation time and facilitate the integration of various players delivering parts of a service. 5G systems will be built on more efficient hardware. The ultra-efficient 5G hardware will be energy aware, very flexible and interworking in very heterogeneous environments. The increased efficiency of the 5G infrastructure will allow costs to be dramatically reduced, as it will consume a fraction of the energy that existing 4G mobile networks consume for delivering the same amount of transmitted data.

To address the challenge of managing and operating complex heterogeneous infrastructure efficiently, a high degree of flexibility, agility and adaptivity is required in the functions that a network can perform. Therefore, concepts such as network softwarisation provide a promising way forward. In view of this, the 5G vision involves the adoption and integration of specific technical approaches supporting this paradigm, such as SDN and NFV.

In SDN, the control plane is decoupled from the data plane and is managed by a logically centralised controller that has a holistic view of the network. Besides placing HWA functions physically in the network, NFV enables the execution of software-based network functions on commodity hardware (general-purpose servers) by leveraging software virtualisation techniques. Through joint SDN and NFV developments, supporting a set of management and control plane functionalities, significant benefits can be achieved. These benefits are associated with flexible, dynamic and efficient use of the infrastructure resources; simplification of the infrastructure and its management; increased scalability and sustainability; and provisioning of orchestrated end-to-end services. Using these technology solutions, operational and business models such as multi-tenancy can be supported through network slicing and virtualisation.

To support new business models, 5G network architecture will enable functions to be offered as a service, that is Network-as–a-Service. If all network elements from access, core, OSS to security and analytics are virtualised and sliced out as one integrated service, it should be possible for an operator to create an instance of an entire network virtually, relying on whatever underlying infrastructure is available for the defined geography. Using the power of programmability, the operator can customise such a ‘network instance’ for any industry enterprise, whether automotive, healthcare, logistics, retail or utilities.

5. SDN – NETWORK BOX

5.1 Introduction

As it was thoroughly analysed in the previous chapters, 5G demands in terms of latency, capacity, coverage and heterogeneity are extreme. The technology advances in network architecture design which are necessary in order to meet all those strict requirements imposed by 5G, are now available through the benefits originated from the NFV and SDN penetration.

With NFV being the key enabler to develop software-based network functions on commodity hardware by leveraging virtualisation techniques and SDN bringing the ability to decouple the control from the data plane through the usage of a logically centralised controller, 5G Architecture needs can become reality.

Tremendous benefits are anticipated from this joint operation of SDN and NFV, ranging from dynamic and efficient use of the infrastructure resources and their management to increased network scalability and sustainability.

To this direction, we developed an experimental testbed in order to emulate the 5G network capabilities using state-of-the-art techniques so as to deploy and retrieve KPI metrics from what is expected to be the norm in next generation mobile networks.

Our testbed is comprised of a portable server which emulates 5G network by deploying a custom topology of OVS's, as complex as the user decides to be and can be used as plug & play machine in real customer environments where it demonstrates how customer network will behave under real conditions such as continuously heavy or burst traffic, link degradations or failures and even more.

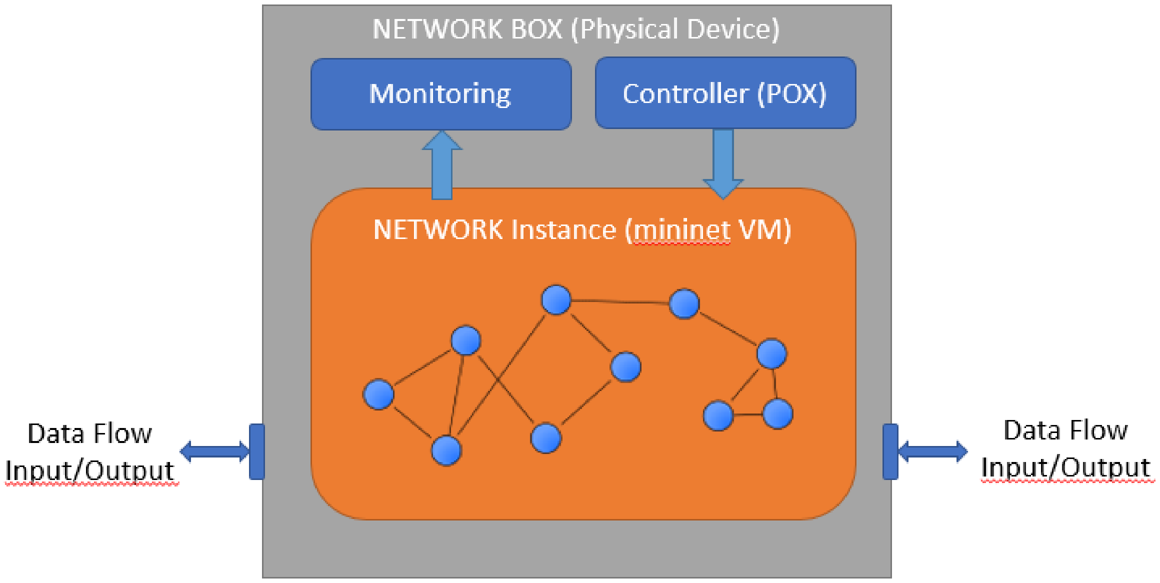


Image 1: The SDN-based Network BOX

Leveraging from the existing Mininet emulator capabilities and the python-based POX controller our portable testbed is qualified to go beyond and reveal the real 5G network demands and capabilities either if it is anticipated to be used in order to emulate the 5G Access, Transport or Core Network.

As it is already well-known, Mininet emulator can be used to create a custom network topology of switches and internal hosts, where hosts can establish communication and are able to exchange data in a way that emulates end-to-end network topology. This approach is great but not as realistic as it happens to be in real networks.
In a real scenario, the network topology will be somehow complex with possibly hundreds of switches being interconnected and multiple links between them, and hosts are always real elements, i.e. standalone real servers or virtual machines which may not necessarily be part of the network topology as Mininet currently requires them to be.
Mininet emulator provides the ability to configure the network topology (number of switches and links between them), in a custom way but also requires hosts' configuration and connection to switches in order to have a functional emulated network.

But what if the hosts are not part of the topology as it always happens to be when we are talking about real networks and particularly 5G?
Here comes our innovative solution which goes beyond the existing mininet capabilities and by leveraging 5G main pillars, SDN & NFV state-of-the-art techniques, provides an implementation where two real hosts, for example two separate Linux-based VMs, are interconnected and exchange data through our portable testbed.
In this way we succeed in having a real black-box network which can be interleaved anywhere into customer network infrastructure, providing the ability to connect multiple hosts to our testbed's external interfaces, administered by different NICs, and establish communication.

This last chapter presents in detail our innovative implemented idea, the so-called **"Network in a box"**. Our approach provides the ability to create a custom network topology, as complex as we decide it to be, based on Mininet VM image which is connected and managed by POX controller (remote controller running on Mininet VM), in a portable server configured in a custom way, where we could connect two hosts and check how they communicate with each other through a network which always adapts to possible changes such as link failures/delays, QoS type etc., exploiting SDN capabilities.

5.2 Technical details

We will now present the technical aspects of the presented idea which led to our innovative proposal.
In our solution we use a single server (Host) with the following characteristics:

- Ubuntu 16.04 LTS
- Memory: 16GB
- Processor: Intel Core i5-6500 CPU @ 3.20GHz x 4
- Graphics: Intel HD Graphics 530 (Skylake GT2)
- OS type: 64-bit
- Disk: 250 GB SSD

For hardware abstraction purposes, the virtualisation application we use is Virtual Box released by Oracle
(Version 5.0.40_Ubuntu r115130)

Our solution includes 3 different VMs:

- 2 Ubuntu 16.04 64-bit VMs with 2048 MB of RAM, 30GB disk and 1vCPU and
- the Mininet VM: 3GB RAM, 8GB disk

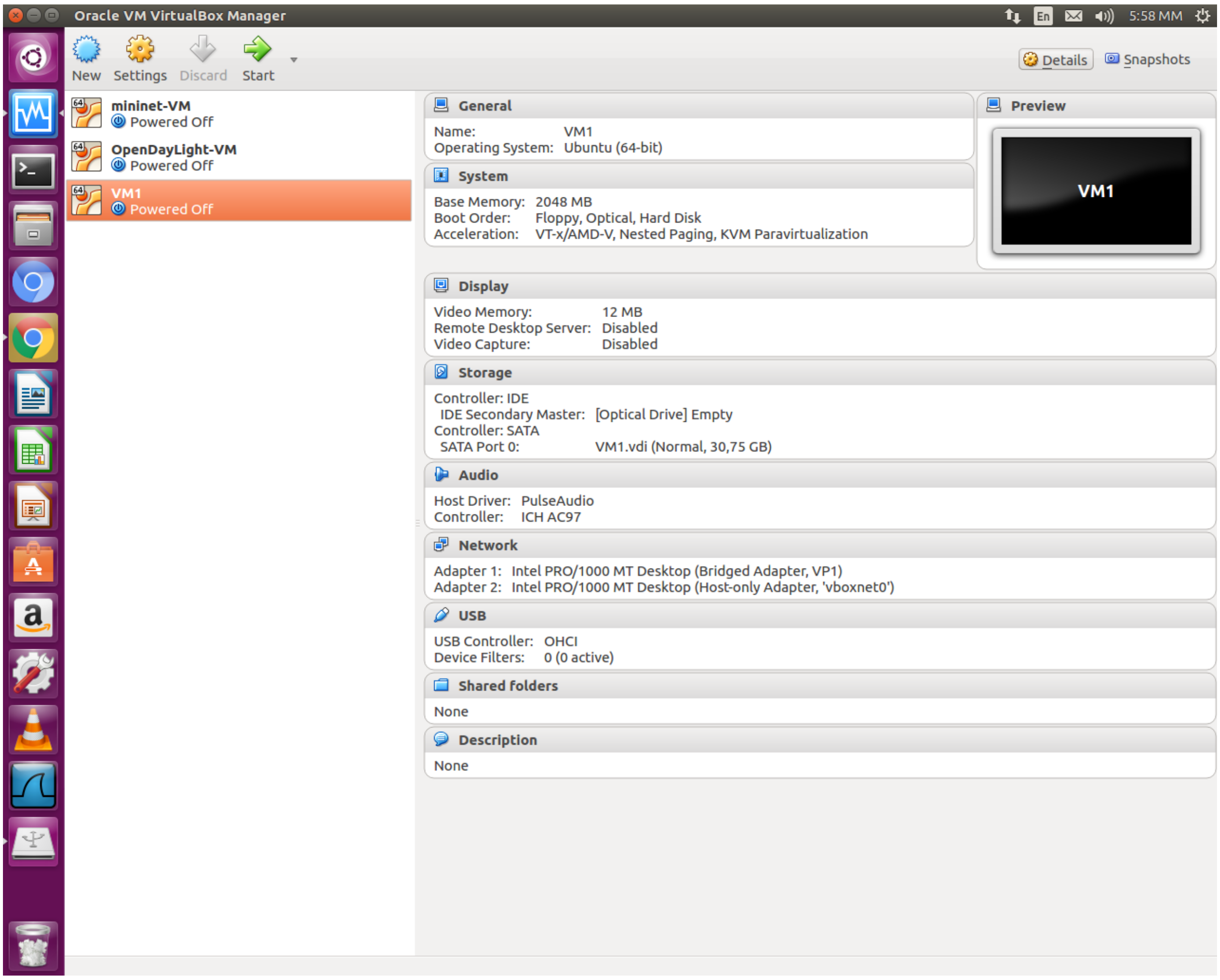
Network Configuration

In all 3 VMs we have configured two Network Adapters in the following way:

1st Network Adapter in bridged mode attached to external physical host’s interface

2nd Network Adapter configured as Host-only used for internal communication between VMs in VBox and for communication of guest VMs with the host (Ubuntu server which is our testbed).

As far as the testbed is concerned, we have explicitly configured it with the aforementioned Mininet VM details with regards to Memory and Disk size. A view of the guest VMs’ configuration regarding Memory, Disk size allocation, vCPU and Networking is presented in below screenshots:



mininet-VM
Powered Off

OpenDayLight-VM
Powered Off

VM1
Powered Off

General

Name: VM1
Operating System: Ubuntu (64-bit)

System

Base Memory: 2048 MB
Boot Order: Floppy, Optical, Hard Disk
Acceleration: VT-x/AMD-V, Nested Paging, KVM Paravirtualization

Display

Video Memory: 12 MB
Remote Desktop Server: Disabled
Video Capture: Disabled

Storage

Controller: IDE
IDE Secondary Master: [Optical Drive] Empty
Controller: SATA
SATA Port 0: VM1.vdi (Normal, 30,75 GB)

Audio

Host Driver: PulseAudio
Controller: ICH AC97

Network

Adapter 1: Intel PRO/1000 MT Desktop (Bridged Adapter, VP1)
Adapter 2: Intel PRO/1000 MT Desktop (Host-only Adapter, 'vboxnet0')

USB

USB Controller: OHCI
Device Filters: 0 (0 active)

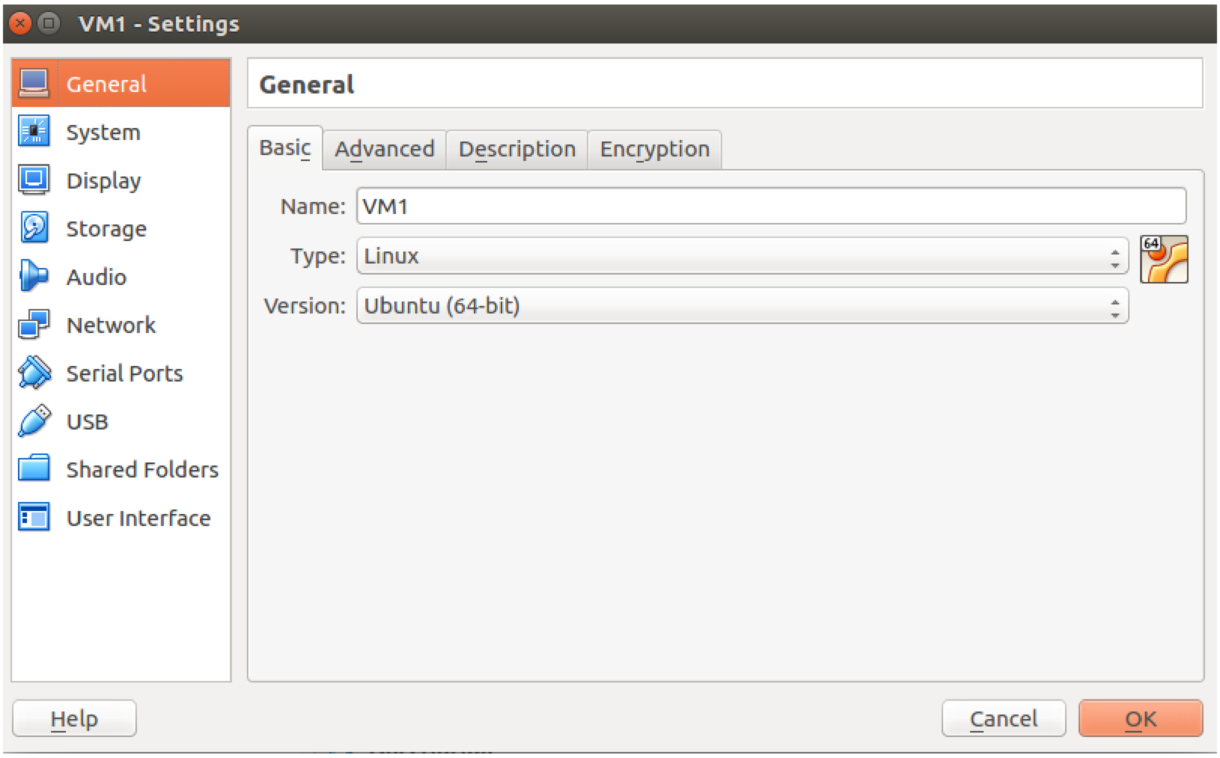
Shared folders

None

Description

None

Image 2: Generic view of guest VMs in VBox

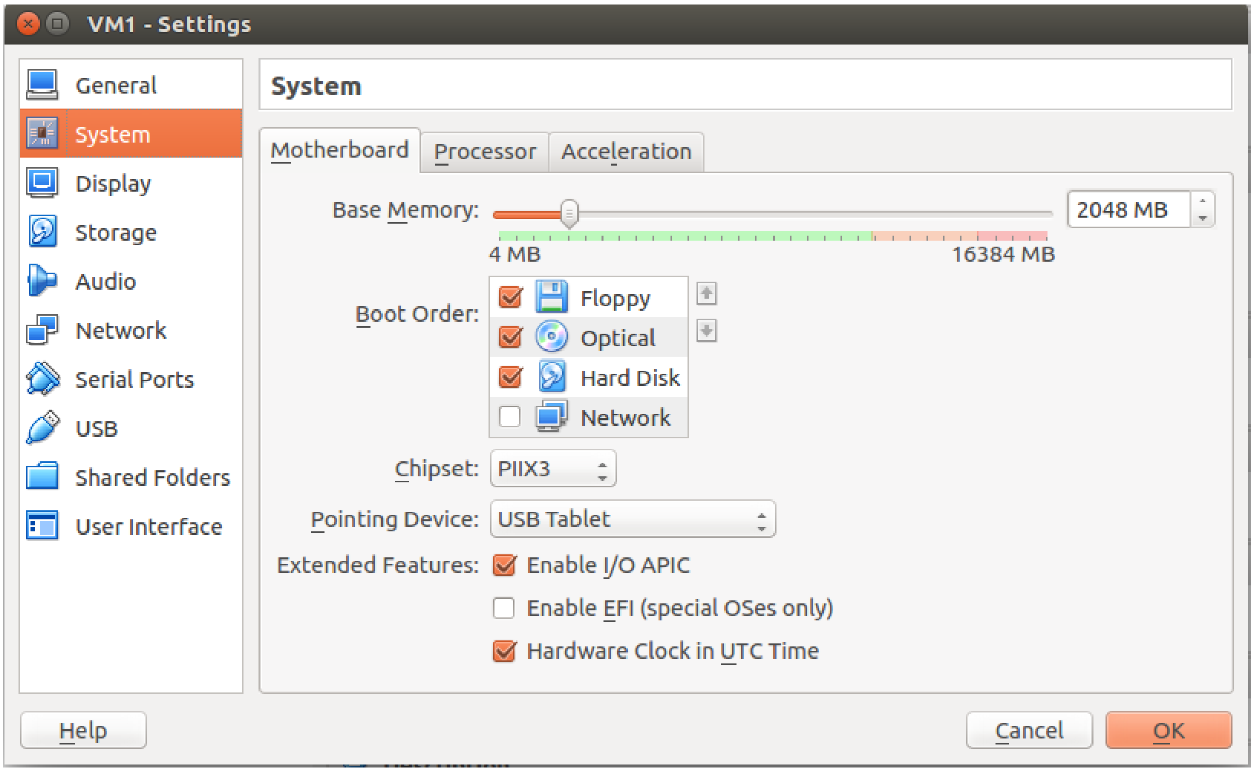


Name: VM1

Type: Linux

Version: Ubuntu (64-bit)

Image 3: Guest VMs' OS details



Base Memory: 2048 MB

4 MB

16384 MB

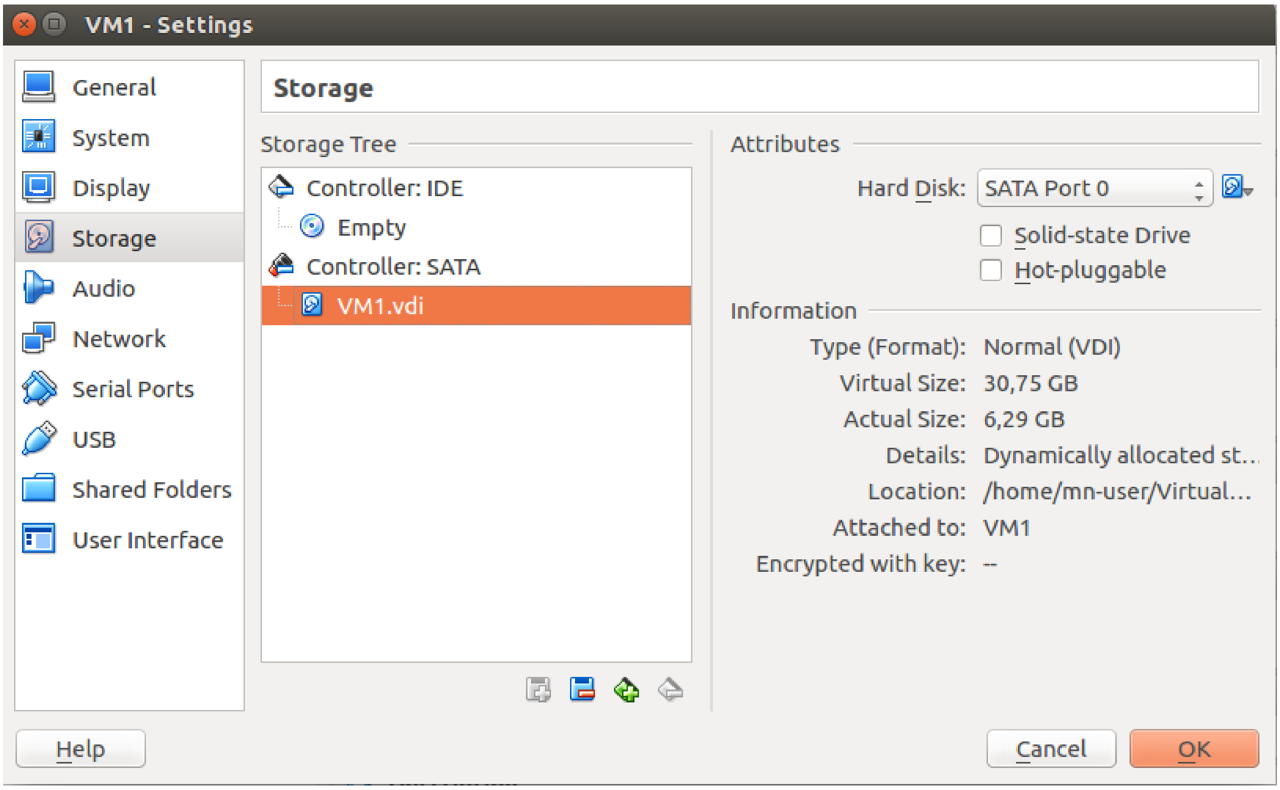
Boot Order:
☑ Floppy
☑ Optical
☑ Hard Disk
☐ Network

Chipset: PIIX3

Pointing Device: USB Tablet

Extended Features:
☑ Enable I/O APIC
☐ Enable EFI (special OSes only)
☑ Hardware Clock in UTC Time

Image 4: Guest VM Memory allocation



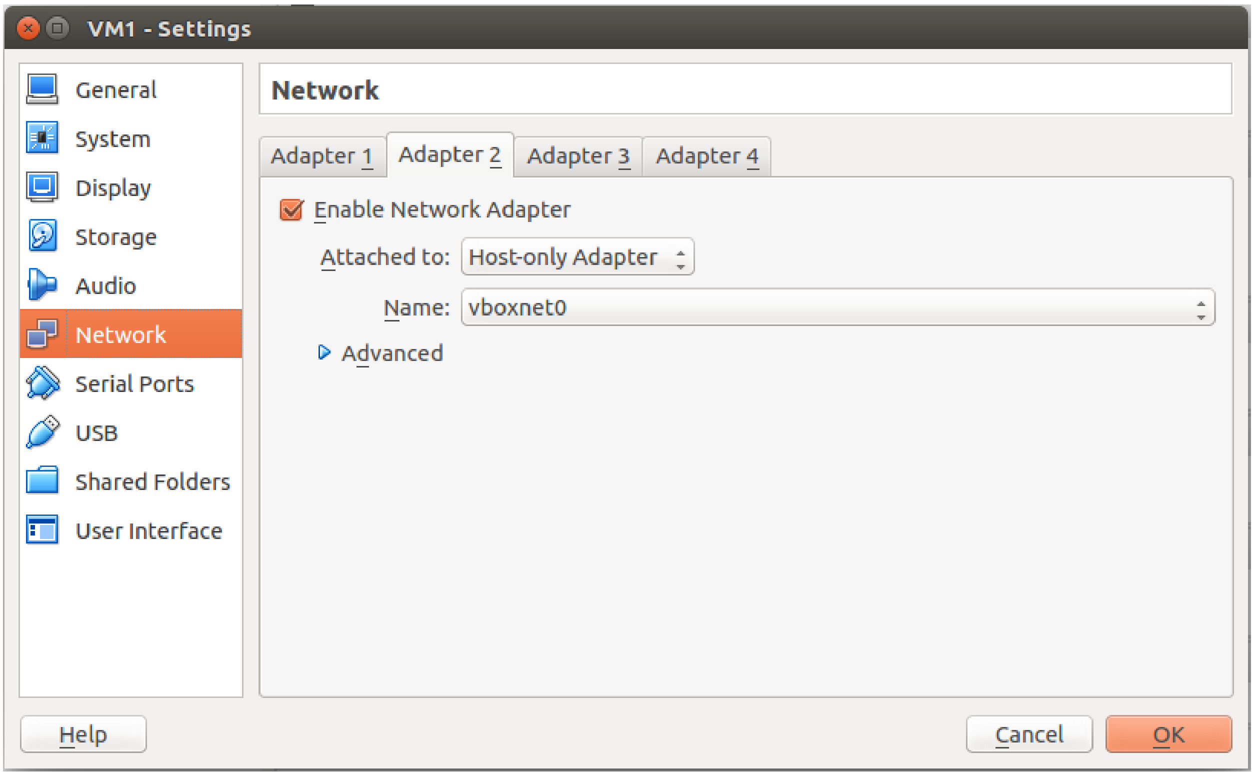
Storage

Storage Tree
Controller: IDE
Empty
Controller: SATA
VM1.vdi

Attributes
Hard Disk: SATA Port 0
☐ Solid-state Drive
☐ Hot-pluggable

Information
Type (Format): Normal (VDI)
Virtual Size: 30,75 GB
Actual Size: 6,29 GB
Details: Dynamically allocated st…
Location: /home/mn-user/Virtual…
Attached to: VM1
Encrypted with key: --

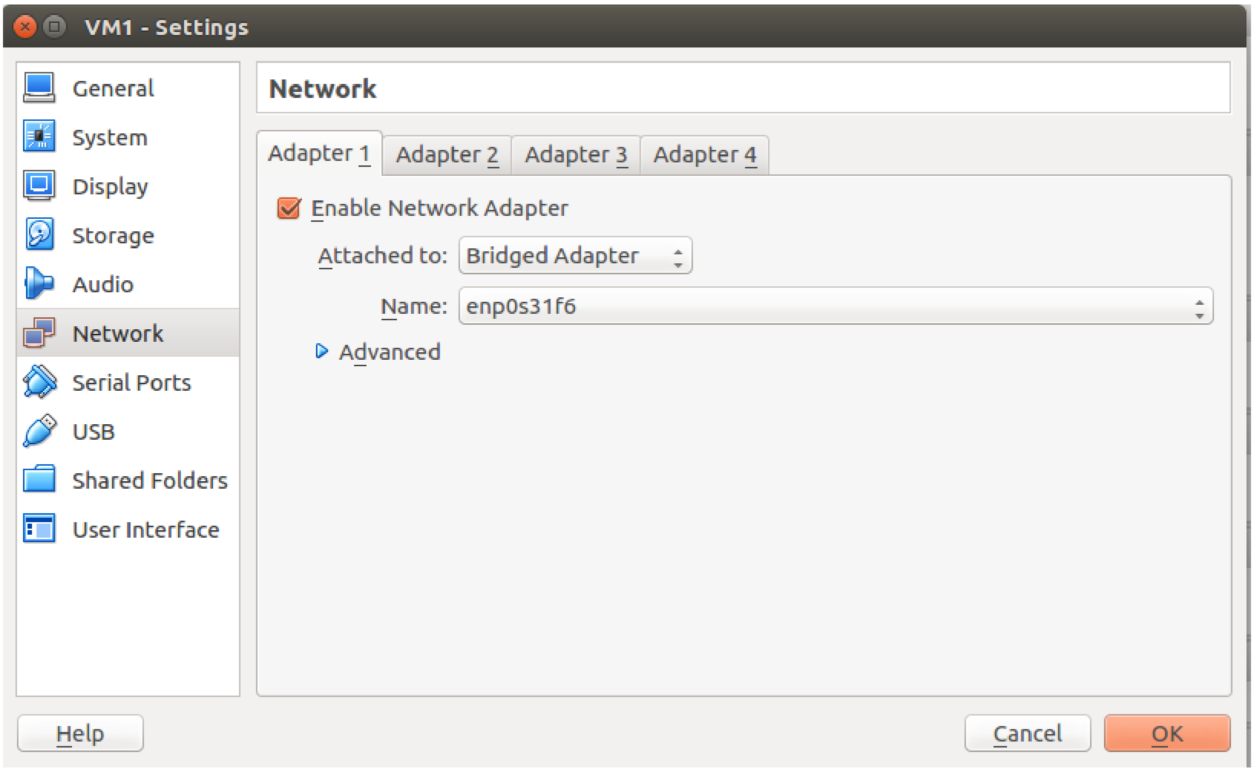
Image 5: Guest VM Disk allocation



Network

☑ Enable Network Adapter
Attached to: Host-only Adapter
Name: vboxnet0
Advanced

Image 6: Guest VM Networking – Host-only Adapter



Network

☑ Enable Network Adapter

Attached to: Bridged Adapter

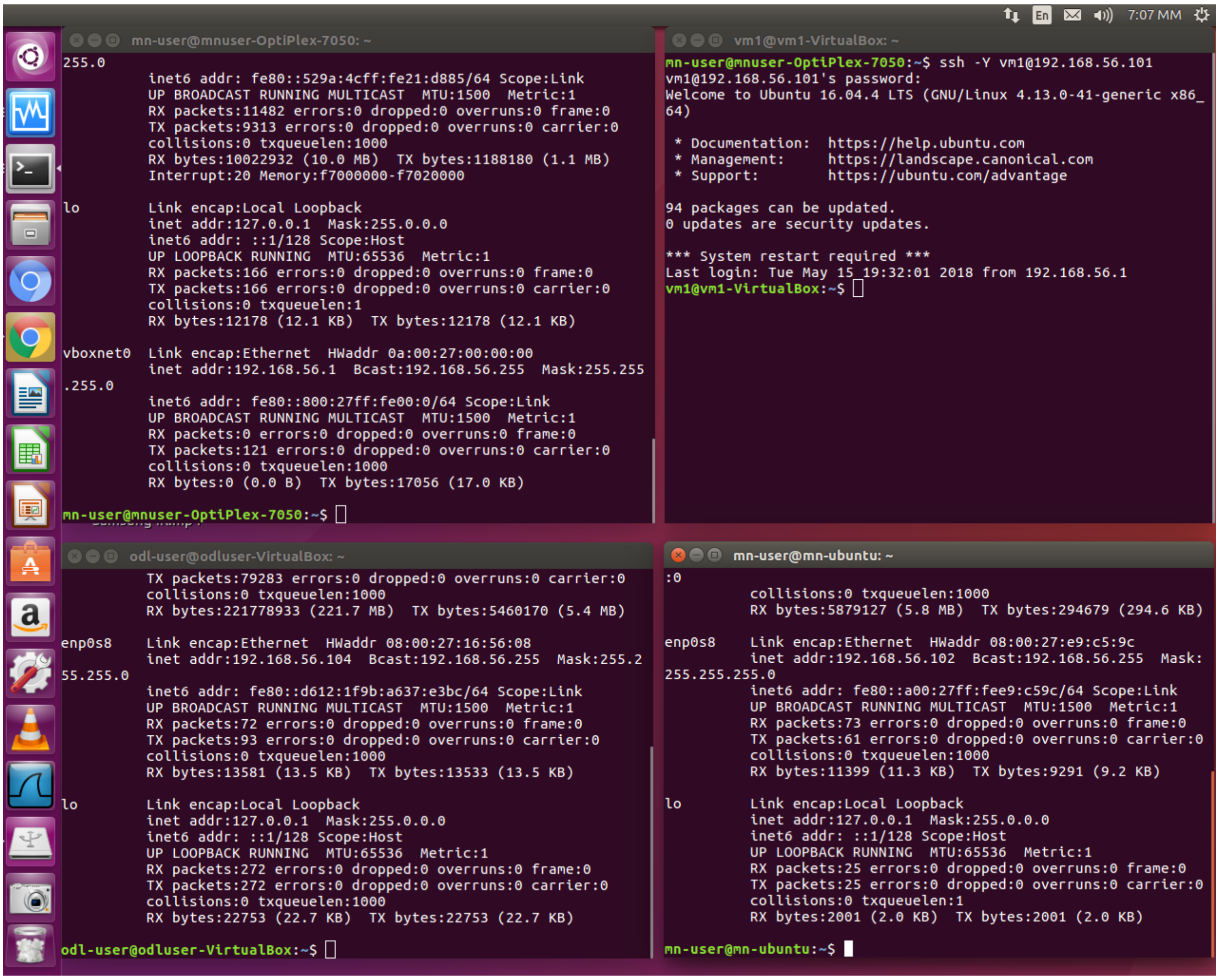
Name: enp0s31f6

Image 7: Guest VM Networking – Bridged Adapter

As shown in the VBox images above, we use two guest VMs (VM1 and VM2) which are real external hosts in our experiment and the mininet-based testbed being interleaved between them, so traffic generated between the hosts will be directed through the testbed network.

We start all three VMs from VBox: VM1, VM2 and testbed server with the configuration provided in the screenshots above.
When each VM boots up, we check the VBox internal interface IP address and connect to that VM from our Ubuntu Host (server machine), in the following way:

```
$ ssh -Y <VM-username>@<VM-VBox-IP>
```



```
255.0
          inet6 addr: fe80::529a:4cff:fe21:d885/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:11482 errors:0 dropped:0 overruns:0 frame:0
          TX packets:9313 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:10022932 (10.0 MB)  TX bytes:1188180 (1.1 MB)
          Interrupt:20 Memory:f7000000-f7020000

lo        Link encap:Local Loopback
          inet addr:127.0.0.1  Mask:255.0.0.0
          inet6 addr: ::1/128 Scope:Host
          UP LOOPBACK RUNNING  MTU:65536  Metric:1
          RX packets:166 errors:0 dropped:0 overruns:0 frame:0
          TX packets:166 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1
          RX bytes:12178 (12.1 KB)  TX bytes:12178 (12.1 KB)

vboxnet0  Link encap:Ethernet  HWaddr 0a:00:27:00:00:00
          inet addr:192.168.56.1  Bcast:192.168.56.255  Mask:255.255
.255.0
          inet6 addr: fe80::800:27ff:fe00:0/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:0 errors:0 dropped:0 overruns:0 frame:0
          TX packets:121 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:0 (0.0 B)  TX bytes:17056 (17.0 KB)

mn-user@mnuser-OptiPlex-7050:~$ 
```

```
mn-user@mnuser-OptiPlex-7050:~$ ssh -Y vm1@192.168.56.101
vm1@192.168.56.101's password:
Welcome to Ubuntu 16.04.4 LTS (GNU/Linux 4.13.0-41-generic x86_
64)

 * Documentation:  https://help.ubuntu.com
 * Management:     https://landscape.canonical.com
 * Support:        https://ubuntu.com/advantage

94 packages can be updated.
0 updates are security updates.

*** System restart required ***
Last login: Tue May 15 19:32:01 2018 from 192.168.56.1
vm1@vm1-VirtualBox:~$ 
```

```
          TX packets:79283 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:221778933 (221.7 MB)  TX bytes:5460170 (5.4 MB)

enp0s8    Link encap:Ethernet  HWaddr 08:00:27:16:56:08
          inet addr:192.168.56.104  Bcast:192.168.56.255  Mask:255.2
55.255.0
          inet6 addr: fe80::d612:1f9b:a637:e3bc/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:72 errors:0 dropped:0 overruns:0 frame:0
          TX packets:93 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:13581 (13.5 KB)  TX bytes:13533 (13.5 KB)

lo        Link encap:Local Loopback
          inet addr:127.0.0.1  Mask:255.0.0.0
          inet6 addr: ::1/128 Scope:Host
          UP LOOPBACK RUNNING  MTU:65536  Metric:1
          RX packets:272 errors:0 dropped:0 overruns:0 frame:0
          TX packets:272 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:22753 (22.7 KB)  TX bytes:22753 (22.7 KB)

odl-user@odluser-VirtualBox:~$ 
```

```
:0
          collisions:0 txqueuelen:1000
          RX bytes:5879127 (5.8 MB)  TX bytes:294679 (294.6 KB)

enp0s8    Link encap:Ethernet  HWaddr 08:00:27:e9:c5:9c
          inet addr:192.168.56.102  Bcast:192.168.56.255  Mask:
255.255.255.0
          inet6 addr: fe80::a00:27ff:fee9:c59c/64 Scope:Link
          UP BROADCAST RUNNING MULTICAST  MTU:1500  Metric:1
          RX packets:73 errors:0 dropped:0 overruns:0 frame:0
          TX packets:61 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1000
          RX bytes:11399 (11.3 KB)  TX bytes:9291 (9.2 KB)

lo        Link encap:Local Loopback
          inet addr:127.0.0.1  Mask:255.0.0.0
          inet6 addr: ::1/128 Scope:Host
          UP LOOPBACK RUNNING  MTU:65536  Metric:1
          RX packets:25 errors:0 dropped:0 overruns:0 frame:0
          TX packets:25 errors:0 dropped:0 overruns:0 carrier:0
          collisions:0 txqueuelen:1
          RX bytes:2001 (2.0 KB)  TX bytes:2001 (2.0 KB)

mn-user@mn-ubuntu:~$ 
```

Image 8: Terminals depicting connections to testbed VM, guest VMs and host machine

The final solution we followed in order to achieve the expected behaviour was to bing up mininet topology with 6 switches and 2 internal mininet hosts (optional for our real case scenario) in the following way:

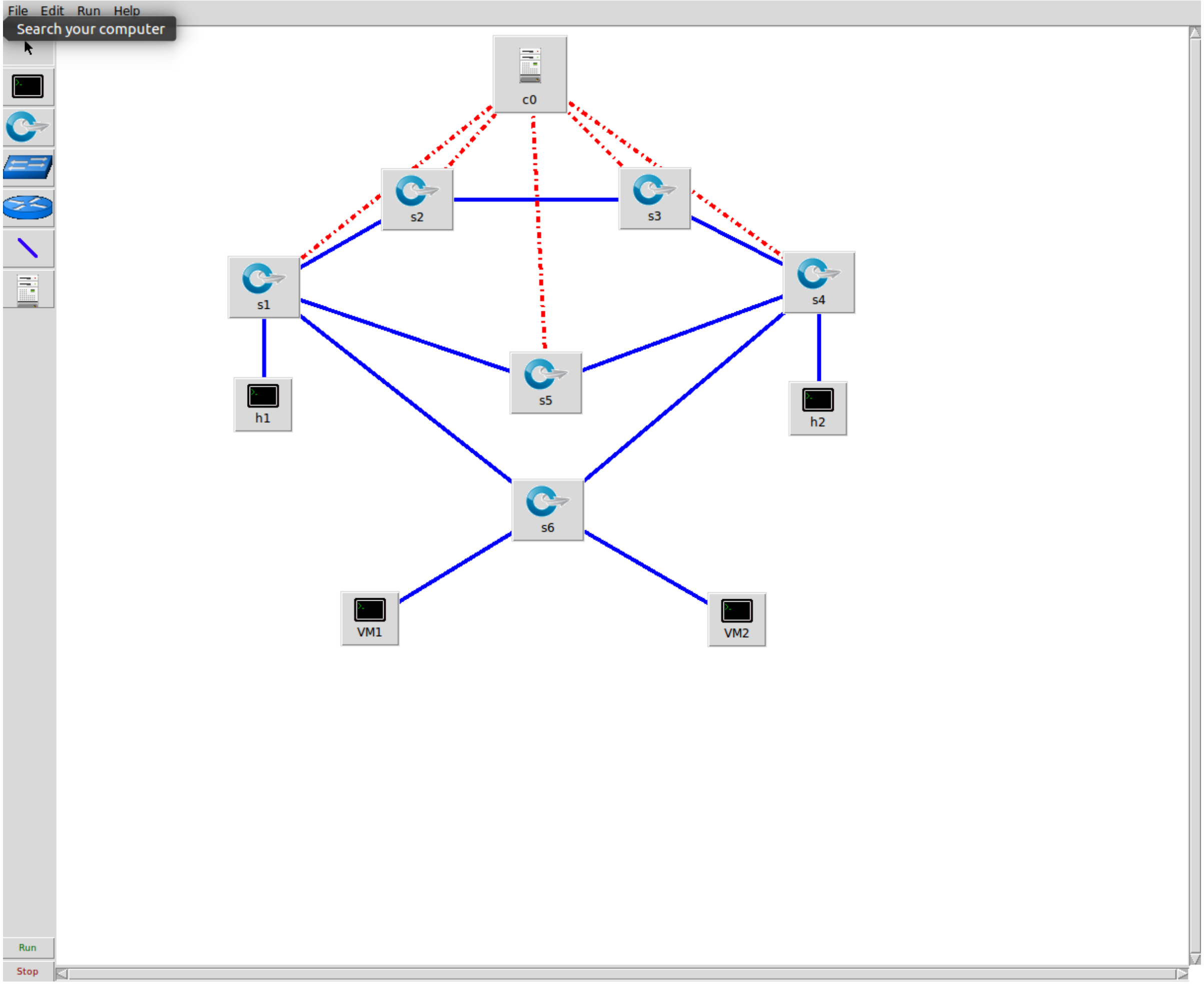


Image 9: ***Network in a box*** **proposed topology**

For our testbed VM we will open 3 terminal windows in total (one for mininet cli, one for POX remote controller and one for flow entries' configuration of OVS's)

POX installation instructions

In our testbed VM running mininet image, the command which needs to be executed in order to install Pox controller is:

```
$ git clone http://github.com/noxrepo/pox
$ cd pox
```

We start POX remote controller issuing the following command in one of the mininet-VM terminals:

```
$ sudo ~/pox/pox.py forwarding.l2_pairs info.packet_dump samples.pretty_log log.level
--DEBUG --address=127.0.0.1 --port=6633 openflow.of_01
```

The final solution we have to follow in order to achieve the expected behaviour, is to bring up a mininet topology with 6 switches and 2 internal mininet hosts using our

custom python script named *custom_heavy5_br.py* which has been created under mininet/examples directory in mininet-vm.
Python script code for mininet topology bring-up is attached in AnnexA ?

In the portable testbed VM, Switch s6 acts as bridge where the two Host VMs (VM1 and VM2) will be connected to. At this point we would like to mention that internal mininet hosts h1 and h2 are deployed for mininet topology bring-up purposes and will not be used at all throughout our experiment.

Once mininet topology is brought up, we are going to see Openflow messages being exchanged between mininet OVS's and POX remote controller. Connection of controller and mininet switches has been properly established.

Going forward, we will now apply ovs flow entries for each OVS, so as to achieve two data paths; one main path through s1→s2→s3→s4 and a failover path which is going to be used in case of a link failure or degradation below a threshold, s1→s5→s4.
In this way, assuming that VM1 sends some traffic to VM2, the data path to be followed will be:

VM1→s6→s1→s2→s3→s4→s6→VM2, (if main path is going to be used),

or

VM1→s6→s1→s5→s4→s6→VM2, (in case failover path is going to be followed)

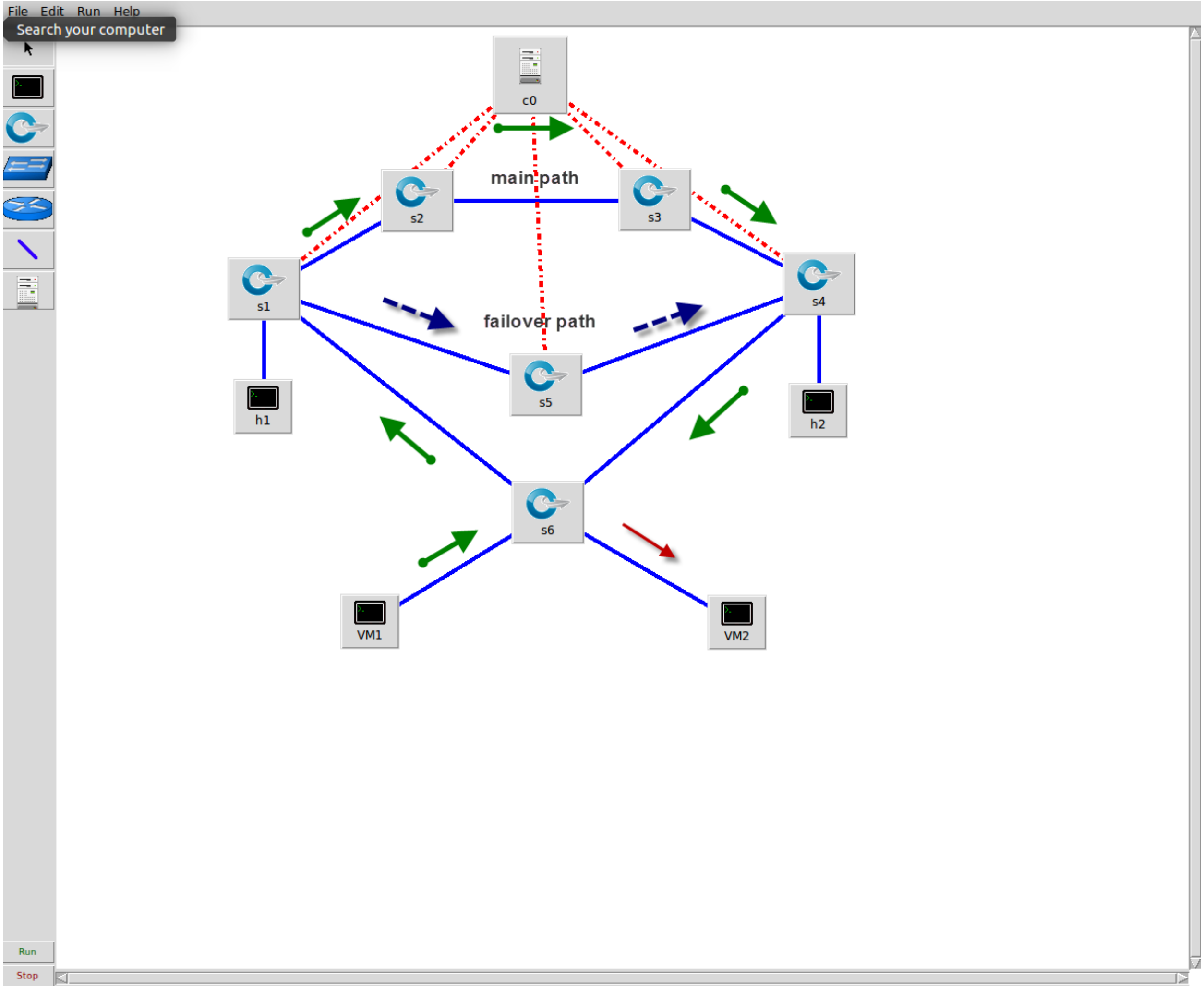


Image 10: OVS Topology and possible routes from VM1 to VM2

On the other hand, when VM2 sends a packet to VM1, the paths to be followed are:

VM2→s6→s1→s2→s3→s4→s6→VM1, (if main path is going to be used),

or

VM2→s6→s1→s5→s4→s6→VM1, (in case failover path is going to be followed)

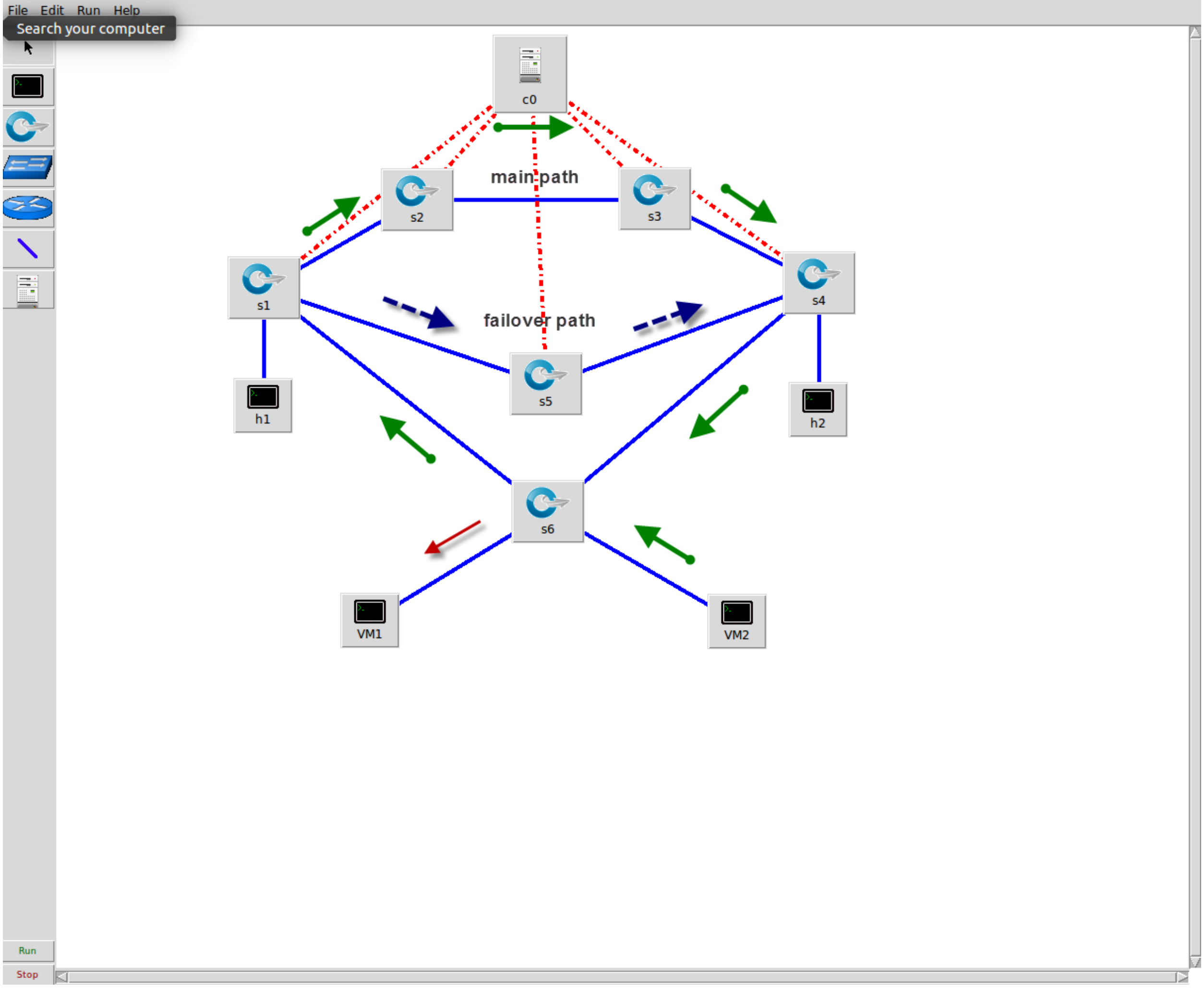


Image 11: OVS Topology and possible routes from VM2 to VM1

Experiments

In our first experiment, VM1 is the server and VM2 acts as client.
We use iperf command in both VMs to establish and verify connectivity of the VMs while traffic is passing by mininet OVS's.

We open a terminal, connect to mininet-VM (i.e. `$ ssh -Y mn-user@192.168.56.102`) and start pox controller

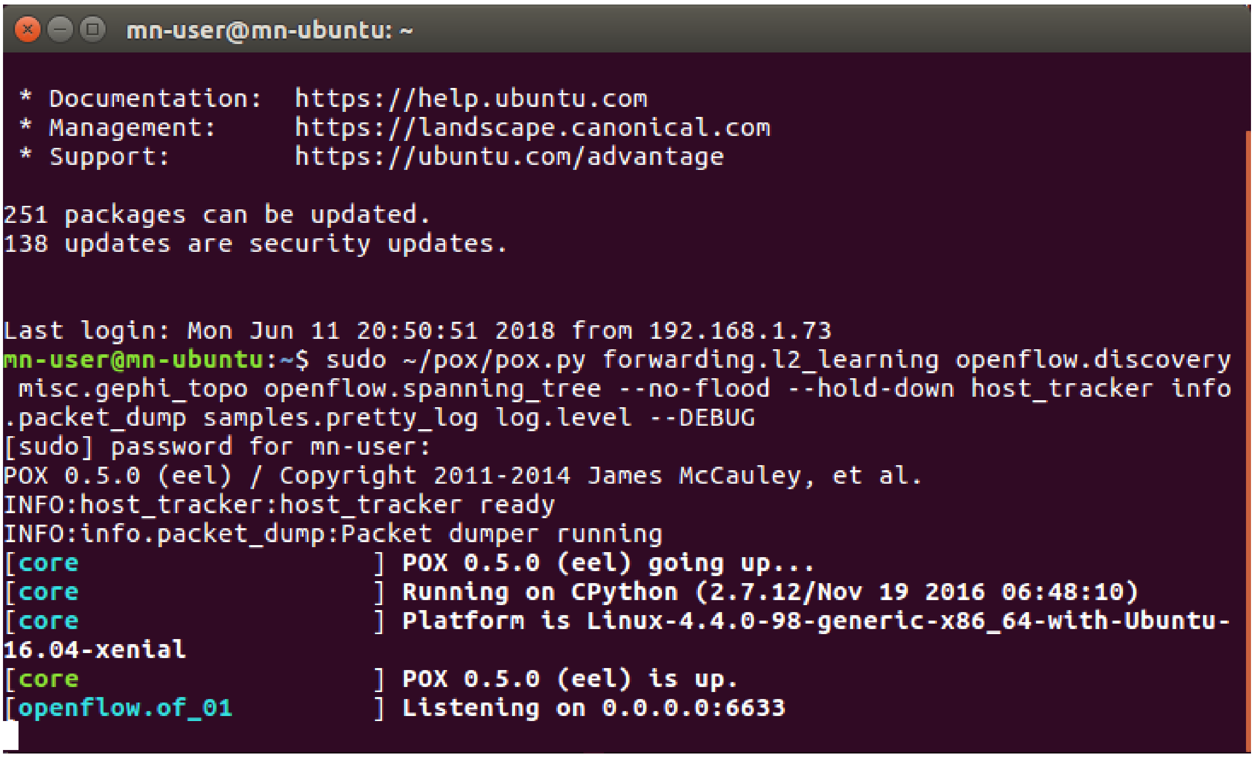
Then in mininet VM, we start mininet topology using the *custom_heavy5_br.py* python script in the following way:

```
$ sudo ~/pox/pox.py forwarding.l2_learning openflow.discovery misc.gephi_topo
openflow.spanning_tree --no-flood --hold-down host_tracker info.packet_dump
samples.pretty_log log.level –DEBUG
```

or simply:

```
$ sudo ~/pox/pox.py forwarding.l2_pairs info.packet_dump samples.pretty_log log.level
--DEBUG --address=127.0.0.1 --port=6633 openflow.of_01
```

POX controller will be successfully started and listening to port 6633.



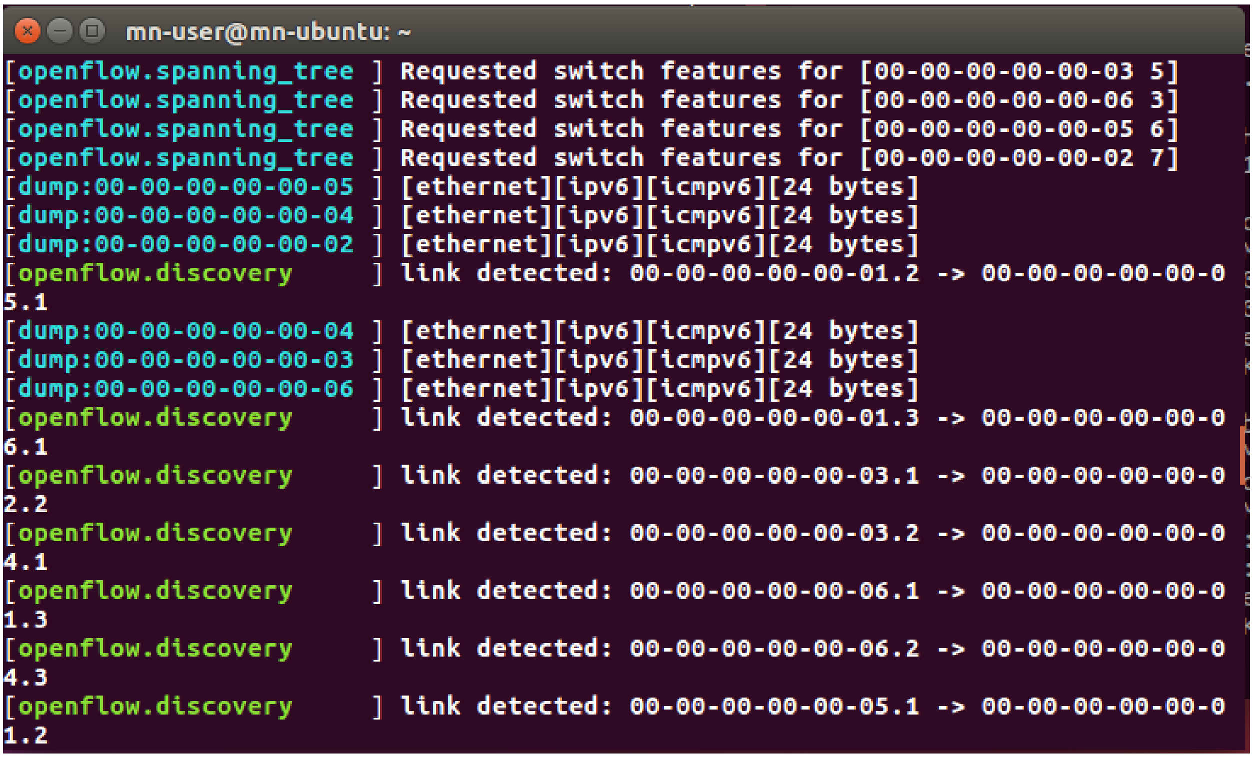
```
 * Documentation:  https://help.ubuntu.com
 * Management:     https://landscape.canonical.com
 * Support:        https://ubuntu.com/advantage

251 packages can be updated.
138 updates are security updates.


Last login: Mon Jun 11 20:50:51 2018 from 192.168.1.73
mn-user@mn-ubuntu:~$ sudo ~/pox/pox.py forwarding.l2_learning openflow.discovery
 misc.gephi_topo openflow.spanning_tree --no-flood --hold-down host_tracker info
.packet_dump samples.pretty_log log.level --DEBUG
[sudo] password for mn-user:
POX 0.5.0 (eel) / Copyright 2011-2014 James McCauley, et al.
INFO:host_tracker:host_tracker ready
INFO:info.packet_dump:Packet dumper running
[core                    ] POX 0.5.0 (eel) going up...
[core                    ] Running on CPython (2.7.12/Nov 19 2016 06:48:10)
[core                    ] Platform is Linux-4.4.0-98-generic-x86_64-with-Ubuntu-
16.04-xenial
[core                    ] POX 0.5.0 (eel) is up.
[openflow.of_01          ] Listening on 0.0.0.0:6633
```

Image 12: POX controller startup

Then we start custom mininet topology in our testbed and connect it to pox controller which is also running on the same VM (testbed VM):

```
$ sudo mn --custom mininet/examples/custom_heavy5_br.py --topo mytopo --
controller=remote,ip=127.0.0.1,port=6633 --switch ovs,protocols=OpenFlow10
```

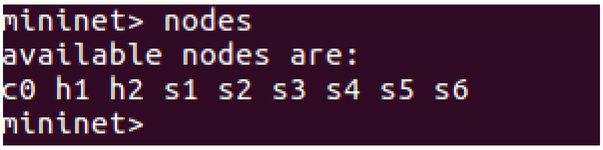
Mininet topology is brought up and at the same time POX controller starts displaying Openflow messages between controller and virtual switches (OVS’s)



```
[openflow.spanning_tree ] Requested switch features for [00-00-00-00-00-03 5]
[openflow.spanning_tree ] Requested switch features for [00-00-00-00-00-06 3]
[openflow.spanning_tree ] Requested switch features for [00-00-00-00-00-05 6]
[openflow.spanning_tree ] Requested switch features for [00-00-00-00-00-02 7]
[dump:00-00-00-00-00-05 ] [ethernet][ipv6][icmpv6][24 bytes]
[dump:00-00-00-00-00-04 ] [ethernet][ipv6][icmpv6][24 bytes]
[dump:00-00-00-00-00-02 ] [ethernet][ipv6][icmpv6][24 bytes]
[openflow.discovery     ] link detected: 00-00-00-00-00-01.2 -> 00-00-00-00-00-0
5.1
[dump:00-00-00-00-00-04 ] [ethernet][ipv6][icmpv6][24 bytes]
[dump:00-00-00-00-00-03 ] [ethernet][ipv6][icmpv6][24 bytes]
[dump:00-00-00-00-00-06 ] [ethernet][ipv6][icmpv6][24 bytes]
[openflow.discovery     ] link detected: 00-00-00-00-00-01.3 -> 00-00-00-00-00-0
6.1
[openflow.discovery     ] link detected: 00-00-00-00-00-03.1 -> 00-00-00-00-00-0
2.2
[openflow.discovery     ] link detected: 00-00-00-00-00-03.2 -> 00-00-00-00-00-0
4.1
[openflow.discovery     ] link detected: 00-00-00-00-00-06.1 -> 00-00-00-00-00-0
1.3
[openflow.discovery     ] link detected: 00-00-00-00-00-06.2 -> 00-00-00-00-00-0
4.3
[openflow.discovery     ] link detected: 00-00-00-00-00-05.1 -> 00-00-00-00-00-0
1.2
```

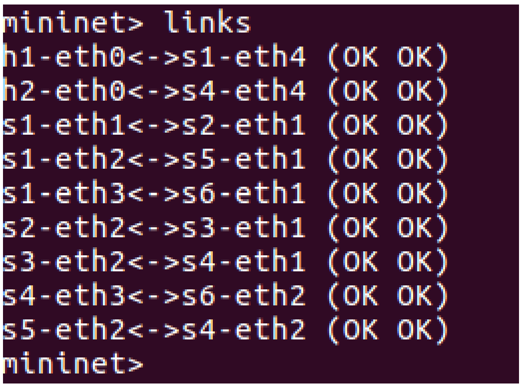
Image 13: POX flow messages and link discovery

Mininet topology contains 6 OVS, where s6 acts as main bridge.
We can now check mininet topology using the following commands in mininet prompt: *nodes*, *links*, *dump*



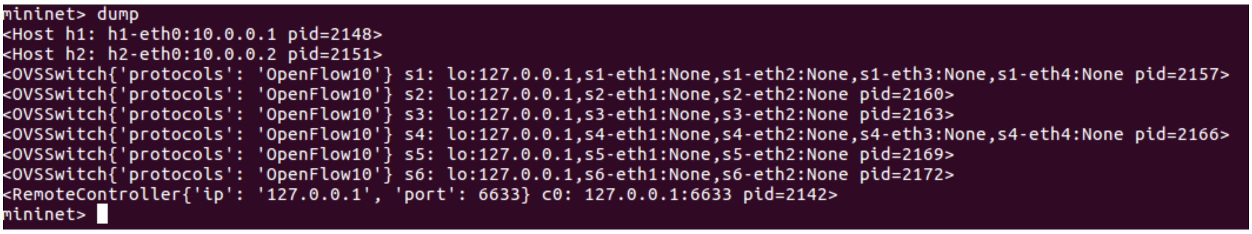
```
mininet> nodes
available nodes are:
c0 h1 h2 s1 s2 s3 s4 s5 s6
mininet>
```

Image 14: Mininet nodes



```
mininet> links
h1-eth0<->s1-eth4 (OK OK)
h2-eth0<->s4-eth4 (OK OK)
s1-eth1<->s2-eth1 (OK OK)
s1-eth2<->s5-eth1 (OK OK)
s1-eth3<->s6-eth1 (OK OK)
s2-eth2<->s3-eth1 (OK OK)
s3-eth2<->s4-eth1 (OK OK)
s4-eth3<->s6-eth2 (OK OK)
s5-eth2<->s4-eth2 (OK OK)
mininet>
```

Image 15: Mininet links



```
mininet> dump
<Host h1: h1-eth0:10.0.0.1 pid=2148>
<Host h2: h2-eth0:10.0.0.2 pid=2151>
<OVSSwitch{'protocols': 'OpenFlow10'} s1: lo:127.0.0.1,s1-eth1:None,s1-eth2:None,s1-eth3:None,s1-eth4:None pid=2157>
<OVSSwitch{'protocols': 'OpenFlow10'} s2: lo:127.0.0.1,s2-eth1:None,s2-eth2:None pid=2160>
<OVSSwitch{'protocols': 'OpenFlow10'} s3: lo:127.0.0.1,s3-eth1:None,s3-eth2:None pid=2163>
<OVSSwitch{'protocols': 'OpenFlow10'} s4: lo:127.0.0.1,s4-eth1:None,s4-eth2:None,s4-eth3:None,s4-eth4:None pid=2166>
<OVSSwitch{'protocols': 'OpenFlow10'} s5: lo:127.0.0.1,s5-eth1:None,s5-eth2:None pid=2169>
<OVSSwitch{'protocols': 'OpenFlow10'} s6: lo:127.0.0.1,s6-eth1:None,s6-eth2:None pid=2172>
<RemoteController{'ip': '127.0.0.1', 'port': 6633} c0: 127.0.0.1:6633 pid=2142>
mininet>
```

Image 16: Mininet dump

Open s6 with xterm and execute: ./connect.sh (script details in ANEX I)
Script is used to bind s6 switch to external physical interface enp0s3, acting as bridge.

```
mininet> xterm s6
```

A new window will come up where we execute the connect.sh script.

```
$ ./connect.sh
```

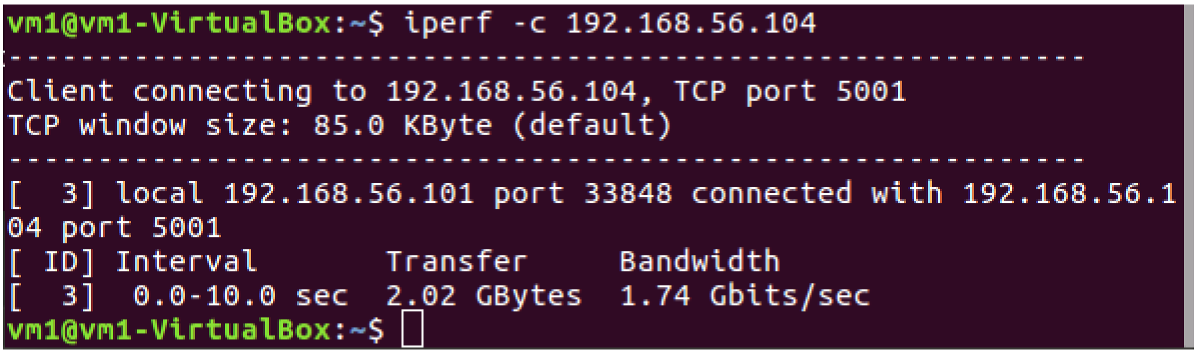
The script should be customized accordingly based on the Host’s external interface allocated IP address and the gateway IP.

Then, flow entries’ configuration follows which enables traffic routing through the main or failover path with higher priority selected on the main path.

Detailed OVS flow table/entry configuration based on Openflow protocol specifications, is provided in ANEX II.

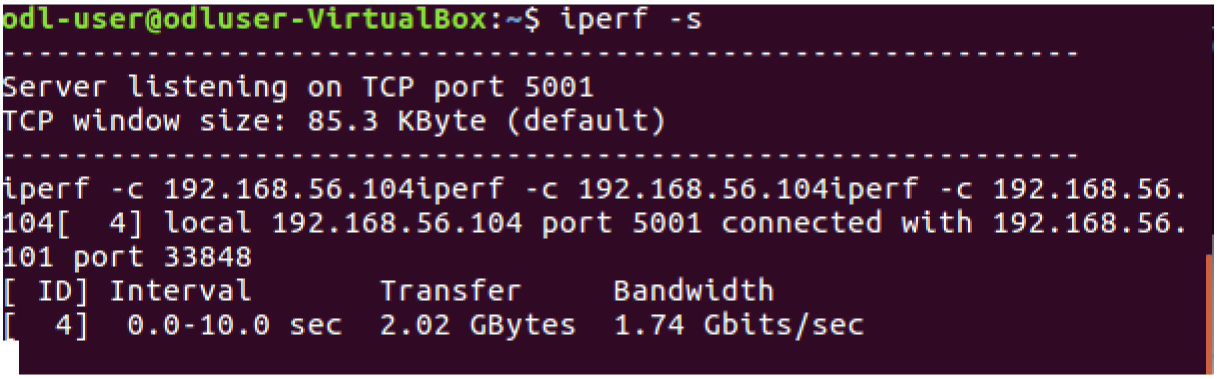
Once flow entries are configured in all OVS’s, we are ready to start the test.

As mentioned earlier, VM1 acts as the iperf client and VM2 acts as the iperf server.



```
vm1@vm1-VirtualBox:~$ iperf -c 192.168.56.104
------------------------------------------------------------
Client connecting to 192.168.56.104, TCP port 5001
TCP window size: 85.0 KByte (default)
------------------------------------------------------------
[  3] local 192.168.56.101 port 33848 connected with 192.168.56.1
04 port 5001
[ ID] Interval       Transfer     Bandwidth
[  3]  0.0-10.0 sec  2.02 GBytes  1.74 Gbits/sec
vm1@vm1-VirtualBox:~$
```

Image 17: VM1 - iperf client



```
odl-user@odluser-VirtualBox:~$ iperf -s
------------------------------------------------------------
Server listening on TCP port 5001
TCP window size: 85.3 KByte (default)
------------------------------------------------------------
iperf -c 192.168.56.104iperf -c 192.168.56.104iperf -c 192.168.56.
104[  4] local 192.168.56.104 port 5001 connected with 192.168.56.
101 port 33848
[ ID] Interval       Transfer     Bandwidth
[  4]  0.0-10.0 sec  2.02 GBytes  1.74 Gbits/sec
```

Image 18: VM2 - iperf server

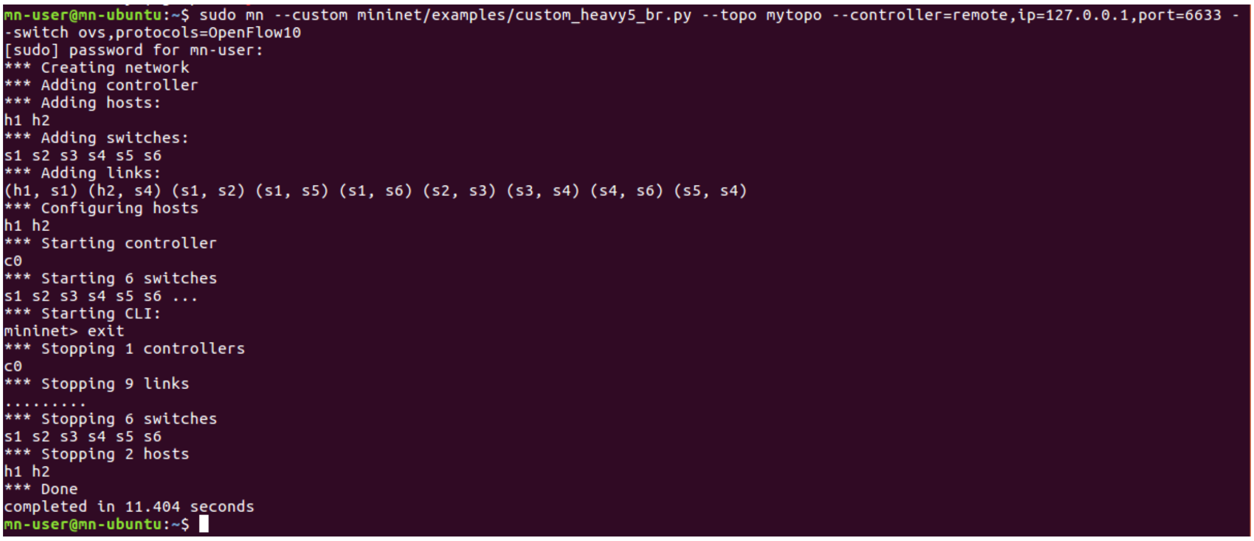
Open s6 with xterm and execute: ./disconnect.sh (script details in ANEX I)
Script is used to detach OVS s6 from external physical interface enp0s3.

```
mininet> xterm s6
```

A new window will come up where we execute the connect.sh script.

```
$ ./disconnect.sh
```

Stop mininet topology by exiting mininet prompt and killing mininet topology of switches and hosts. POX controller is notified that mininet network has been terminated and connection is closed.

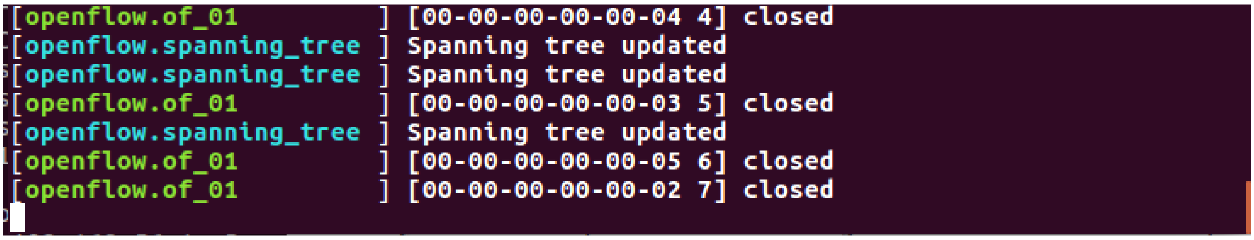


```
mn-user@mn-ubuntu:~$ sudo mn --custom mininet/examples/custom_heavy5_br.py --topo mytopo --controller=remote,ip=127.0.0.1,port=6633 -
-switch ovs,protocols=OpenFlow10
[sudo] password for mn-user:
*** Creating network
*** Adding controller
*** Adding hosts:
h1 h2
*** Adding switches:
s1 s2 s3 s4 s5 s6
*** Adding links:
(h1, s1) (h2, s4) (s1, s2) (s1, s5) (s1, s6) (s2, s3) (s3, s4) (s4, s6) (s5, s4)
*** Configuring hosts
h1 h2
*** Starting controller
c0
*** Starting 6 switches
s1 s2 s3 s4 s5 s6 ...
*** Starting CLI:
mininet> exit
*** Stopping 1 controllers
c0
*** Stopping 9 links
.........
*** Stopping 6 switches
s1 s2 s3 s4 s5 s6
*** Stopping 2 hosts
h1 h2
*** Done
completed in 11.404 seconds
mn-user@mn-ubuntu:~$
```

Image 19: Exiting Mininet prompt

```
mn-user@mn-ubuntu:~$ sudo mn -c
*** Removing excess controllers/ofprotocols/ofdatapaths/pings/noxes
killall controller ofprotocol ofdatapath ping nox_corelt-nox_core ovs-openflowd ovs-controllerovs-testcontroller udpbwtest mnexec ivs
 ryu-manager 2> /dev/null
killall -9 controller ofprotocol ofdatapath ping nox_corelt-nox_core ovs-openflowd ovs-controllerovs-testcontroller udpbwtest mnexec
ivs ryu-manager 2> /dev/null
pkill -9 -f "sudo mnexec"
*** Removing junk from /tmp
rm -f /tmp/vconn* /tmp/vlogs* /tmp/*.out /tmp/*.log
*** Removing old X11 tunnels
*** Removing excess kernel datapaths
ps ax | egrep -o 'dp[0-9]+' | sed 's/dp/nl:/'
***  Removing OVS datapaths
ovs-vsctl --timeout=1 list-br
ovs-vsctl --timeout=1 list-br
*** Removing all links of the pattern foo-ethX
ip link show | egrep -o '([-_.[:alnum:]]+-eth[[:digit:]]+)'
ip link show
*** Killing stale mininet node processes
pkill -9 -f mininet:
*** Shutting down stale tunnels
pkill -9 -f Tunnel=Ethernet
pkill -9 -f .ssh/mn
rm -f ~/.ssh/mn/*
*** Cleanup complete.
mn-user@mn-ubuntu:~$
```

Image 20: Mininet cleanup



```
[openflow.of_01          ] [00-00-00-00-00-04 4] closed
[openflow.spanning_tree ] Spanning tree updated
[openflow.spanning_tree ] Spanning tree updated
[openflow.of_01          ] [00-00-00-00-00-03 5] closed
[openflow.spanning_tree ] Spanning tree updated
[openflow.of_01          ] [00-00-00-00-00-05 6] closed
[openflow.of_01          ] [00-00-00-00-00-02 7] closed
```

Image 21: POX controller closes connection upon Mininet topology termination

6. CONCLUSION AND FUTURE WORK

This MSc thesis presents the current state in mobile networks as well as the foreseen extraordinary demands which are expected to explode during the coming decade. It demonstrates how 5G can meet the rising needs as well as its key enabling technologies. It also presents the ongoing projects' status in the area of 5G and emphasizes on the 5G network architecture design and its advantages, compared to nowadays' conventional networks which are characterised by a static architecture not able to deal with the dynamic and always changing needs. The current networks' limitations raise the need for an alternative approach to effectively face these challenges.

This alternative approach is SDN, which decouples the control from the data plane and transforms the network elements to simple forwarding devices, routing the traffic according to rules set to them by the control plane. SDN has been described in terms of architecture, controller, dominant protocol, use cases and advantages.

As in any technology, a very important factor in the evaluation of SDN is the customer perception of the 5G networking technology which is based on the capabilities exposed and KPI metrics collected under specific use cases, which in turn provide the ability to quantify user perception of the network capabilities through QoS and QoE.

To this end, as part of this thesis we have developed a SDN based **Network in a box**, which is a portable plug & play testbed device capable to be interconnected to any legacy network component and emulate how 5G network performs under real circumstances, providing also the ability to extract KPI metrics from the examined topology. It presents how the 5G network behaves upon link degradation or link failures while traffic keeps being managed by the self-organised network capabilities without interruption. The implemented testbed device has been presented and evaluated and its contribution goes far beyond an abstract framework introduction, as it provides a practical implementation of real-time SDN based 5G network which apart from its already notable capabilities, can be used as a proof of concept for application related experiments in the testbed's northbound interface and provide application related metrics under various scenarios which can take place in the emulated network. It also describes in detail the implementation steps, which can be replicated by any researcher.

Some interesting issues that have been identified as future work points are the following:

- The extension of **Network in a box** testbed with a more complex network topology to provide more than one backup paths, in case that link degradation/failures are detected again (first) backup path
- The experimentation with different kinds of network problems, not related to link failure (i.e. heavy congestion)
- Extended performance evaluation of the testbed
- The integration of different application types to the testbed, such TCP-based video streaming, web browsing or IPTV and QoS/QoE extracted metrics.

Technologies such as NFV/SDN and HetNets are already being deployed by operators and will continue to enable the move towards the hyper-connected society alongside developments in 5G. Considerable potential also remains for increasing 4G adoption in many countries, and we expect 4G network infrastructure to account for much of the $1.7 trillion the world's mobile operators will invest between now and 2020. Operators will continue to focus on generating a return on investment from their 4G (and 3G) networks by developing new services and tariffing models that make most efficient use of them. Current telecom infrastructure is expected to work with the 5G core network as it is backward compatible. But to deliver on 5G promises, current 2G/3G/4G networks will have to be upgraded, or probably replaced. New 5G RAN (Radio Access Network) architecture with new high frequency power amplifiers and new filters will be developed to handle the mmWave traffic processing which is needed to boost data throughput to maximum 20Gbps. This is needed in order to implement massive Machine Type Communications (mMTC) or M2M, and provide connection density of one million devices per km², which are some of the promises of 5G. Similarly, current devices can still work with pre-5G networks (3G or 4G), but new devices will have to be designed and developed to access and utilise the power of 5G. Even smart applications need to be updated, to cope with the updated smart device hardware, to handle the high speed flow of data within 5G. Neither devices nor smart applications' vendors would accept to be the bottleneck in the 5G journey.

ABBREVIATIONS - ACRONYMS

1G	First Generation
2G	Second Generation
3D	Three-dimensional
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
5G IA	5G Infrastructure Association
5G-PPP	5G Infrastructure Public Private Partnership
AI	Air Interface
API	Application Programming Interface
BBU	Baseband Processing Units
BSS	Business System Support
CA	Carrier Aggregation
CB	Carrier Bonding
CAPEX	Capital Expenditure
CDN	Content Delivery Network
CEM	Customer Experience Management
CESC	Cloud-Enabled Small Cell
CLI	Command Line Interface
C-RAN	Cloud-RAN
CSA	Coordination and Support Actions
C2C	Customer to Customer
D2D	Device to Device
D2I	Device to Infrastructure
DevOps	Development and Operations
DSA	Dynamic Spectrum Allocation
EM	Element Management
eMBB	Enhanced Mobile Broadband
EPC	Evolved Packet Core
ETSI	European Telecommunications Standards Institute
EU	European Union
FP7	Framework Programme 7
FSO	Free-Space Optics
GSM	Groupe Spécial Mobile
GSMA	GSM Association
GTP	GPRS Tunneling Protocol
HD	High Definition
HET RANs	Heterogeneous Radio Access Networks
HoN	Health of Network
HSPA	High-Speed Packet Access
HTC	Human-Type Communication
HW	Hardware
IaaS	Infrastructure as a Service
ICN	Information-centric Network

ICT	Information and Communication Technology
IEEE	Institute of Electrical and Electronics Engineers
IETF	Internet Engineering Task Force
IMT	International Mobile Telecommunication
InP	Infrastructure Providers
IoT	Internet of Things
IP	Internet Protocol
IPTV	Internet Protocol Television
IPv4 / v6	Internet Protocol version 4 / version 6
ISG	Industry Specification Group
ISP	Internet Service Provider
ITU	International Telecommunications Unit
ITU-R	International Telecommunications Unit - Radiocommunication Sector
ITU-T	International Telecommunications Unit – Telecommunications Standardization Sector
KPI	Key Performance Indicator
LSPS	Labeled Service Parameter Set
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
M2M	Machine - to - Machine
MCN	Mobile Cloud Networking
MDC	Mobile Distributed Caching
MEC	Mobile Edge Computing
MIMO	Multiple Input Multiple Output
ML	Machine Learning
mmWave	Millimeter Wave
MNO	Mobile Network Operators
MTC	Machine Type Communications
MVNO	Mobile Virtual Network Operator
MVNP	Mobile Virtual Network Provider
NaaS	Network as a Service
NAT	Network Address Translation
NBI	Northbound Interface
NE	Network Element
NFV	Network Functions Virtualization
NFVI	NFV Infrastructure
NFV-MANO	NFV Management and Orchestration
NFVO	NFV Orchestrator
NGA	Next-generation Access
NGMN	Next Generation Mobile Networks
NOS	Network Operating System
NS	Network Service
OCHs	Optical Channels
OF	OpenFlow
OFDM	Orthogonal Frequency Division Multiplexing

ONF	Open Networking Foundation
OS	Operating System
OSS	Operation System Support
OPEX	Operational Expenditure
OPNFV	Open Platform for NFV
OSA	Opportunistic Spectrum Access
OTT	Over the Top
OVS	Open vSwitch
PHB	Per-Hop-Behaviour
PLS	Physical Layer Security
PON	Passive Optical Network
QoE	Quality of Experience
QoS	Quality of Service
R&I	Research and Innovation
RAN	Radio Access Network
RAS	Radio Access Spectrum
RAT	Radio Access Technology
RF	Radio Frequency
RIA	Research and Innovation Actions
RM	Resource Management
RRH	Remote Radio Heads
RRIM	Radio Resource and Interference Management
SAN	Software Adjustable Network
SDK	Software Development Kit
SDN	Software Defined Networking / Software Defined Network
SDR	Software-defined Radio
SLA	Service Level Agreement
SME	Small and Medium-sized Enterprises
SON	Self-Organizing Networks
SP	Service Provider
SW	Software
TA	Targeted Action
TCO	Total Cost of Ownership
TCP	Transmission Control Protocol
TSON	Time Shared Optical Network
TVO	Total Value of Opportunity
UDN	Ultra-dense Networks
UHD	Ultra High Definition
URLLC	Ultra-Reliable and Low Latency Communications
V2X	Vehicle to anything
vCPE	Virtualised End-User Equipment
VIM	Virtualised Infrastructure Manager
VM	Virtual Machine
VNF	Virtualised Network Function
VNFM	VNF Manager
WRC	World Radiocommunication Conference
XaaS	Anything as a Service

XCI	Xhaul Control Infrastructure
XFE	Xhaul Packet Forwarding Element

ANNEX I

The **Network in a box** implementation, as well as instructions to prepare and verify it, are available in a public Github repository at the following URL:
https://github.com/ddimopou/SONEX

ANNEX II

“Network in a box” setup instructions are also depicted in detail below:

custom_heavy5.py

```
from mininet.topo import Topo
import time, re, sys, subprocess, os
from mininet.cli import CLI
from mininet.net import Mininet
from mininet.link import TCLink

class MyTopo( Topo ):
    "Simple topology example."

    def __init__( self ):
       "Create custom topo."

       # Initialize topology
       Topo.__init__( self )

       # Add hosts and switches
       host1 = self.addHost('h1', mac = '00:00:00:00:00:01')
       host2 = self.addHost('h2', mac = '00:00:00:00:00:02')
       switch1 = self.addSwitch('s1')
       switch2 = self.addSwitch('s2')
       switch3 = self.addSwitch('s3')
       switch4 = self.addSwitch('s4')
       switch5 = self.addSwitch('s5')
       switch6 = self.addSwitch('s6')

       # Add links
       self.addLink(switch1, switch2)
       self.addLink(switch2, switch3)
       self.addLink(switch3, switch4)
       self.addLink(switch1, switch5)
       self.addLink(switch5, switch4)
       self.addLink(switch1, switch6)
       self.addLink(switch4, switch6)
       self.addLink(host1, switch1)
       self.addLink(host2, switch4)

topos = { 'mytopo': MyTopo  }
```

connect.sh

```
#!/bin/bash

# connect.sh
# this will attach Mininet switch s6 to the Internet


sudo ovs-vsctl add-port s6 enp0s3
sudo ifconfig enp0s3 0
sudo ifconfig s6 192.168.1.72
sudo ip route add 192.168.1.0/24 dev s6  proto kernel  scope link  src 192.168.1.72
sudo ip route add default via 192.168.1.254 dev s6
sudo ip route show
ping -c 3 google.com
```

disconnect.sh

```
#!/bin/bash

# connect.sh
# this will detach Mininet switch s6 to the Internet

sudo ovs-vsctl del-port s6 enp0s3
sudo ifconfig s6 0
sudo ip route del 192.168.1.0/24 dev s6  proto kernel  scope link  src 192.168.1.72
sudo ip route del default via 192.168.1.254 dev s6
sudo ifconfig enp0s3 192.168.1.72

sudo ip route show
ping -c 3 google.com
```

dns.txt

```
$ sudo vim /etc/network/interfaces

# interfaces(5) file used by ifup(8) and ifdown(8)
auto lo
iface lo inet loopback
auto enp0s31f6
iface enp0s31f6 inet dhcp
#dns-nameservers 8.8.8.8 8.8.4.4

$ sudo service networking restart
```

OVS_commands.txt

```
*****************************
**  Generic commands   **
*****************************

To enable multiple openflow versions in my bridge:
ovs-vsctl set bridge br0 protocols=OpenFlow10,OpenFlow11,OpenFlow12,OpenFlow13

By default OpenFlow 1.0 enabled. Use -O to add more:
vs-ofctl -O OpenFlow13 dump-flows br0

//////\\\\\\
sudo ~/mininet/examples/miniedit.py   --> start miniedit

ovs-vswitchd --version
sudo ovs-ofctl dump-flows s1

**START POX**  --> pox supports OF v1.0
sudo ~/pox/pox.py forwarding.l2_learning openflow.discovery misc.gephi_topo openflow.spanning_tree --no-flood --hold-down host_tracker info.packet_dump samples.pretty_log log.level --DEBUG

sudo ~/pox/pox.py forwarding.l2_pairs info.packet_dump samples.pretty_log log.level --DEBUG --address=127.0.0.1 --port=6633 openflow.of_01

4-5 sec for POX to update failed link status

##Configuring OVS bridges
ovs-vsctl add-br mybridge
ovs-vsctl show
ifconfig mybridge up
#ovs-vsctl del-br mybridge
ovs-vsctl add-port mybridge eth0
ovs-vsctl show
ifconfig eth0 0
dhclient mybridge
ifconfig
route -n
ip tuntap add mode tap vport1
ip tuntap add mode tap vport2
ifconfig vport1 up
ifconfig vport2 up
ovs-vsctl add-port mybridge vport1 -- add-port mybridge vport2
ovs-vsctl show
ovs-appctl fdb/show br1
ovs-ofctl show mybridge

ovs-ofctl dump-flows mybridge
ovs-vsctl list Bridge  -->records of different tables in OVS db
ovs-vsctl list Port | more   --> Port details on Ports table
ovs-vsctl list Interface | more  --> configuration details on Interface table
```

```
mininet> dump
ip link ls dev eth0
```

****
** ovs-ofctl commands   **
****

```
ovs-ofctl show <bridge>
ovs-ofctl snoop <bridge>
ovs-ofctl dump-flows <bridge> <flow>
ovs-ofctl dump-flows <bridge>
ovs-ofctl dump-ports-desc <bridge>  --> port statistics
ovs-ofctl dump-tables-desc <bridge>

ovs-ofctl add-flow <bridge> <flow>
ovs-ofctl del-flows <bridge> <flow>
```

****
** Mininet topology start command   **
****

```
sudo mn --custom mininet/examples/custom_heavy5.py --topo mytopo --controller=remote,ip=127.0.0.1,port=6633 --switch ovs,protocols=OpenFlow10
```

** POX installation instructions **

In mininet VM:

```
git clone http://github.com/noxrepo/pox
cd pox
```

** Start POX command **

```
sudo ~/pox/pox.py forwarding.l2_pairs info.packet_dump samples.pretty_log log.level --DEBUG --address=127.0.0.1 --port=6633 openflow.of_01
```

****
** Testbed setup + Flows' configuration **
****

Once VMs boot up, check connectivity between them (Host-Only adapter) and connectivity to internet.

--> Open a terminal, connect to mininet-VM (i.e. ssh -Y mn-user@192.168.56.102) and start pox controller:

```
sudo ~/pox/pox.py forwarding.l2_learning openflow.discovery misc.gephi_topo openflow.spanning_tree --no-flood --hold-down host_tracker info.packet_dump samples.pretty_log log.level --DEBUG
```

--> Start mininet with custom_heavy5.py and connect it to pox controller running on the same VM (mininet-VM):

```
sudo mn --custom mininet/examples/custom_heavy5.py --topo mytopo --controller=remote,ip=127.0.0.1,port=6633 --switch ovs,protocols=OpenFlow10
```

(6 OVS -- s6 acts as main bridge)
--> When mininet starts, check: nodes, links, dump
--> Open s6 with xterm and execute: ./connect.sh
(script to bind to external physical interface enp0s3)

** s1 **

```
sudo ovs-ofctl del-flows s1

mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s1-eth1 ofport
1
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s1-eth2 ofport
2
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s1-eth3 ofport
3

sudo ovs-ofctl add-flow s1 priority=100,in_port=3,actions=output:1
sudo ovs-ofctl add-flow s1 priority=50,in_port=3,actions=output:2
sudo ovs-ofctl dump-flows s1
```

** s2 **

```
sudo ovs-ofctl del-flows s2

mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s2-eth1  ofport
1
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s2-eth2  ofport
2

sudo ovs-ofctl add-flow s2 priority=100,in_port=1,actions=output:2
sudo ovs-ofctl dump-flows s2
```

** s3 **

```
sudo ovs-ofctl del-flows s3

mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s3-eth1  ofport
1
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s3-eth2  ofport
2

sudo ovs-ofctl add-flow s3 priority=100,in_port=1,actions=output:2
sudo ovs-ofctl dump-flows s3
```

** s4 **

```
sudo ovs-ofctl del-flows s4
```

```
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s4-eth1  ofport
1
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s4-eth2  ofport
2
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s4-eth3  ofport
3
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s4-eth4  ofport
4

sudo ovs-ofctl add-flow s4 priority=100,in_port=1,actions=output:3
sudo ovs-ofctl add-flow s4 priority=100,in_port=2,actions=output:3
sudo ovs-ofctl dump-flows s4
```

** s5 **

```
sudo ovs-ofctl del-flows s5

mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s5-eth1  ofport
1
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s5-eth2  ofport
2

sudo ovs-ofctl add-flow s5 priority=100,in_port=1,actions=output:2
sudo ovs-ofctl dump-flows s5
```

** s6 **

```
sudo ovs-ofctl del-flows s6
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s6-eth1 ofport
1
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface s6-eth2 ofport
2
mn-user@mn-ubuntu:~$ sudo ovs-vsctl get Interface enp0s3 ofport
3

sudo ovs-ofctl add-flow s6 priority=100,in_port=3,actions=output:1
sudo ovs-ofctl add-flow s6 priority=100,in_port=2,actions=output:3
sudo ovs-ofctl dump-flows s6
```

** Testbed Teardown **
in mininet vm execute: xterm s6
in s6 switch execute: ./disconnect.sh --> this will remove s6 bridge from mininet external physical interface
exit mininet-VM and execute: sudo mn -c

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