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Hybrid 5G optical-wireless SDN-based networks, challenges and open issues

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Abstract: The fifth-generation (5G) mobile networks are expected to bring higher capacity, higher density of mobile devices, lower battery consumption and improved coverage. 5G entails the convergence of wireless and wired communications in a unified and efficient architecture. Mobile nodes, as defined in fourth-generation era, are transformed in heterogeneous networks to make the front-haul wireless domains flexible and intelligent. This work highlights a set of critical challenges in advancing 5G networks, fuelled by the utilisation of the network function virtualisation, the software defined radio and the software defined networks techniques. Furthermore, a novel conceptual model is presented in terms of control and management planes, where the inner architectural components are introduced in detail.

1 Introduction

The fifth-generation (5G) telecommunication networks have emerged as a promising vehicle towards the enhancement of the technical capacity of current networking. 5G is expected to enable a major leap forward supporting a wide range of applications such as services based on machine-type-communications (MTC) and causing revolutionary changes in radio interfaces and spectrum usage. 5G networks will be always accessible, fast, highly reliable and efficient in handling a very large number of devices, including 'smart' objects in the Internet of Things (IoT). In the era of 5G, wireless communications face a challenging task: the shift from the conventional client–server model to the anything as a service (XaaS) paradigm.

Modern network infrastructures involve thousands of heterogeneous nodes with diverse features and capabilities and various networking technologies with different characteristics and interfaces. Specialised technological needs have to be identified and mapped for preparing the 5G designs, e.g. architectures, technologies and standards. 5G promotes the integration of the mobile and wireless with the wired and optical communications, given licenced and unlicenced spectrum features, while supporting the ubiquitous communication access to machine-to-machine (M2M) and IoT infrastructures under common, flexible, and virtualised network architecture.

The realisation of these new types of services requires a dynamic information technology (IT) infrastructure which will be flexible and easily programmable, enabling cost- and resource-efficient agile service composition. To this end, the concept of intelligent heterogeneous networks (HetNets) has emerged as a hierarchical and flexible solution to provide cognitive front-haul wireless architectures of multiple technologies. HetNets in nature enclose three powerful technologies: (i) the network function virtualisation (NFV), (ii) the software defined radio (SDR), and (iii) the software defined networks (SDNs) [1].

The purpose of this study is to provide an overview of the main technologies supporting HetNets, to discuss challenges brought by the realisation of HetNets and to provide a prototype architectural model for managing networks and their services. The contributions of this paper are summarised as follows:

a. It provides an overview of NFV, SDR and SDN technologies and how their full potentials can be exploited in the context of 5G HetNets.
b. It highlights challenges brought by the delivery of HetNets concerning physical, functional and security aspects.
c. It presents an architectural model, based on the challenges addressed, that will foster opportunities for new ways to design, deploy, operate, and manage networks and their services.

The rest of the paper is organised as follows: Section 2 presents the main technological characteristics of 5G HetNets. Section 3 provides the motivation of this work while Section 4 presents related studies. Section 5 discusses the challenges that upcoming 5G HetNets face, Section 6 presents the concept of the proposed hybrid architecture and Section 7 concludes the paper and discusses future work.

2 Intelligent HetNets

This section presents the main characteristics of the key technologies that enable the deployment and operation of HetNets, namely NFV, SDR and SDN. 5G network elements could be converted to 'computing equivalent' elements with the aim of the aforementioned three key technologies. Key features of HetNets enabled by NFV, SDR and SDN are:

- separation of control and data plane;
- virtualisation of network functions;
- advancing programmable networks;
- control of computational resources using orchestration;
- standard-based configuration protocols;
- mechanisms for hardware resource management and allocation;
- automation of control, deployment and business processes; and
- automated resource orchestration in response to application/function needs.

2.1 Network function virtualisation

NFV is a promising technology with the potential to fulfil the flexibility and programmability requirements of 5G. NFV

decouples network functions from hardware appliances allowing the realisation of network functions on general-purpose processors (i.e. decoupling network services from platforms). NFV employs standard IT virtualisation technology to consolidate multiple network equipment types onto industry standard high-volume servers, switches, and storage devices [1]. As a result, flexible network architectures that are capable of adapting different 'vertical' adaptation requirements are feasible by industry players and operators [2].

2.2 Software defined radio

SDR, on the other hand, constitutes a compelling technology that allows effective reconfiguration of radio by using software components and libraries. Hence, a single device can be used for multiple purposes in a cost-effective way, e.g. operating as wireless fidelity, global system for mobile communications, worldwide interoperability for microwave access and long-term evolution (LTE), by simply reprogramming channel characteristics such as modulation, power and coding.

2.3 Software defined networking

SDN fulfils a dream of many past wireless generations. It decouples the control from the underlying infrastructure, transforming the existing network resources to programmable abstracts. The network is treated as a logical and virtual domain [3], allowing the function of intelligent and cognitive procedures onto the underlying network elements and devices. Programmable SDN controllers receive user-friendly commands through application programming interfaces (APIs) and they govern the forwarding plane of the network without needs of physical processing or specification understanding. SDN separates the network control from the data plane and introduces abstractions and means for network programmability.

SDN and NFV are complementary approaches which combined have the potential to foster opportunities for new ways to design, deploy, operate and manage networks and their services.

3 Motivation

Wireless traffic has experienced explosive growth over the past decade, driven by the evolution of the next generation services and the vast applications of mobile devices. A broad community, including both academia and industry, expects that current fourth-generation (4G) mobile networks will not be able to meet the advancing and pressing demands that access networks will face by 2020. Concurrently, limitations and lack of flexibility of current network infrastructures hinder the development of very high capacity networks that could be able to address modern, vertical services. On the other hand, traffic originated from the 4G/5G front-haul domains are carried by optical transport access, metro and core networks. Current traditional fixed-grid wavelength division multiplexing (WDM) networks seem inefficient to cope with the exponential growth of traffic, e.g. multimedia streams, coming from heterogeneous wireless interfaces. Even though (i) advanced modulation schemes pave the way for 100 Gb/s and beyond rates and (ii) efficient and cost-effective access technologies are continuously developed between the end users and the central office (CO), a challenging bottleneck is emerged where the 10-year-old division of the optical spectrum into a fixed 'wavelength grid' is not able to support rates of 400 Gb/s and above.

This work is motivated by the growing importance of the technologies that emerge to address the shortcomings of the currently deployed core/metro networks such as NFV, SDR and SDN. The potential and the advantages of these key technologies open a set of currently open questions concerning (i) the exploitation of SDN and NFV technologies in 5G HetNets, (ii) the convergence of heterogeneous wired and wireless networks in a seamless and flexible way, (iii) the design and support of advanced and secure virtualisation orchestration, (iv) the enhancement with real-time communication between the control and management levels and the underlying network components and (v) the

capability of supporting network 'slices' in the whole network. By considering the SDN concept from a slightly different angle than other works in the literature, we discuss the potential of implementing an SDN-based hybrid optical wireless network that is able to support (i) flexibility, (ii) virtualisation, (iii) elasticity, (iv) MTC traffic support, (v) highly agile distribution and management of network resources slices and (vi) secured management interfaces.

4 Related studies

In this section, we provide related studies on the areas of 5G-enabled heterogeneous wired and wireless networks, SDN and NFV concepts and virtualisation. The concept of programmable networks has been comprehensively studied in [3]. The idea behind the SDN notion was discussed as well as the way the SDN enables innovation through network flexibility and adaptability. The authors presented the SDN architecture and the OpenFlow standard. SDN-based protocols, services and schemes were also provided and potential SDN usages and directions were pointed out. Thyagaturu *et al.* [4] examined the SDN paradigm in optical networks. They focused on the infrastructure layer, the control layer and the application layer, where they studied the concepts of network virtualisation, orchestration and multilayer networking. In addition, open challenges and future directions were highlighted towards SDN-based optical access networks. Kreutz *et al.* [5] presented the motivation of the SDN approach and how it differs from traditional networking. Also, the building blocks of the SDN notion were presented, giving emphasis to the hardware infrastructure, the APIs, the SDN controllers and the SDN programming languages. The survey is also focused on debugging and troubleshooting issues while it provides new opportunities and applications towards SDN development. Similarly, in [6] the latest developments in the area of SDN were explored, including features, potential benefits of SDN and existing research efforts towards SDN-based networking. Recently, the development of SDN concept in wireless networks was presented in [7]. Four classes of popular wireless networks were discussed, namely cellular, sensor, mesh and home networks. The work also provides unexplored opportunities for using SDN in wireless networks towards network optimisation. The work in [8] introduced several SDN-based extensions to controller platforms, switches and base stations in cellular networks. The authors investigate how subscriber mobility, fine-grained measurement and control and real-time adaptation are addressed using SDN functions. In [9] the network virtualisation was discussed subject to cloud computing. The rationale behind the proliferation of virtualisation was examined while applications of SDN approach to cloud computing were compiled. The expansion of SDN technology in IoT is also a challenging accomplishment. The work in [10] demonstrated how an IoT SDN controller originally is able to incorporate and support scheduling functions over task level, multi-hop, and heterogeneous ad-hoc paths. The authors presented the application of an SDN prototype in electric vehicles, electric charging sites and smart grid infrastructures. Big data is also a popular research topic. Cui *et al.* introduced how big data meets the SDN concept in [11]. They deal with big data applications, including big data processing in cloud data centres, data delivery, joint optimisation, scientific big data architectures and scheduling issues. They also showed several SDN applications where the big data can benefit such as traffic engineering, cross-layer design and security. Traffic engineering was also examined in [12] subject to SDN applications. The paper presented the state of the art in traffic engineering for SDN, including discussion in flow management, fault tolerance, topology update and traffic analysis.

Our study differs from the aforementioned works by focusing on the integration of heterogeneous wired and wireless networks using SDN, NFV and SDR technologies. In this survey, we intend to highlight the challenges towards the optimisation of modern HetNets using cutting-edge concepts that are not fully utilised yet.

5 Challenges

This section presents the challenges that modern HetNets based on SDN and NFV technologies are currently facing. The overall network structure is a complex structure that shall be treated as a single HetNet consisting of multiple different resource types and thus managed as a single entity instead of treating layers separately and individually.

5.1 Challenge 1: to specify, define, and implement an SDN-based, flexible, and virtualised high-capacity, hybrid optical-wireless architecture

The need for defining and adopting innovative architecture to address the current limitations of network infrastructures is appointed. This will be achieved by converging modern, broadband wireless solutions with the optical technology in the access and the metro/core domains. Optical networks in the access and metro domains provide high bandwidth and reliable service support; however, they require mass deployment of fibre optic infrastructure to connect multiple subscribers at homes or business premises (e.g. the fibre to the home paradigm) [13]. Thus, the introduction of the optical technology, in general, increases the necessitated investments and the respective capital expenditure. On the other hand, wireless access technologies require less infrastructure deployment, while they are able to provide flexible and ubiquitous connectivity. However, due to their limited capacity, autonomous wireless access solution is 'problematic' with respect to bandwidth demanding applications support. The leverage of the complementary advantages of both technologies could provide a flexible and viable access solution, deploying a hybrid wireless-optical access network. The converged architecture will be empowered by SDN technology in controlling the underlying network components and entities [4].

5.2 Challenge 2: to promote and advance the seamless integration of heterogeneous wired and wireless networks to programmable and dynamic network elements

Apart from the specification of a converged hybrid optical-wireless architecture, which is necessary to uniformly manage all resources, it is necessary to promote the underlying network components into programmable, flexible and dynamic 'computing equivalent'. From the early beginning, during the lifecycle of HetNets deployment, hardware abstractions and models should be employed to enable a programmable interface for hardware state configuration including hardware presentation layers (HPLs) and hardware interface layers (HILs). Optical and wireless components will be advanced to cognitive programmable devices, where their features and configuration will be optimised in terms of resource allocation, interface presentation and functionality [14]. The physical characteristics of both optical and wireless network devices will be available for optimisation depending on network dynamics (users, traffic, spectrum availability, energy consumption and user specifications). To this end, the effective use of switches, routers, base stations, and M2M devices will enable the realisation of new generation 5G-enabled, high-capacity networks in real-world scenarios [15].

5.3 Challenge 3: to instil intelligence and advanced control in the hybrid 5G architecture

The essential capabilities of the SDN technology should be utilised in the context of HetNets by designing and implementing advanced SDN models and controllers for the innovative architectures [16]. The controllers will address two core 5G software network challenges: (i) efficient and on-the-fly flow control of heterogeneous resources and services and (ii) unified cloud-hosted control and management, including the need for efficiently handling failures and recoveries in SDN across the 5G architecture [17]. The separation of the control and data planes will enable the smooth operation of hybrid optical-wireless devices. Intelligent gateways with both optical and wireless interfaces will be deployed and effectively utilised for handling and processing the 5G traffic

streams from the mobile users to the optical back-haul. In addition, restoration mechanisms will be applied in terms of reusable components, which will allow fast and efficient restoration of the existing failures. Definition of metrics and queries for capturing and handling time-varying events will take place [18]. In addition, the hybrid architecture should demonstrate the potential of the SDN paradigm to make 5G suitable for all kind of data traffic including M2M and human-to-machine (H2M) traffic streams. In detail, it should be clarified how a cellular radio access network (RAN) system and an MTC data collection network can be dynamically integrated in an SDN-based 5G RAN with MTC and human-type communications (HTC).

5.4 Challenge 4: to design and develop SDN-specific reusable programming solutions and components including APIs, libraries, and virtualised components

It is necessary to develop and establish a methodology for designing, implementing and maintaining software components, libraries and APIs for effectively managing SDN controllers. The designed libraries will handle the interconnection between 5G and the optical layers by supporting the co-existence of multiple network domains. They will also support cognitive traffic engineering in M2C network components. The software modules will support the dynamic update of network/service architectures and the optimisation of costs and processes allowing application driven network 'softwarisation'. They will also provide a transparent layer of programming tools that will support the definition of high-level abstractions and the development of single-tier programming modules, enabling a uniform control orchestration protocol for any network background (e.g. same management routine will be applied in wireless and optical networks from the perspective of administrators/deployers).

5.5 Challenge 5: to design and support advanced and secure virtualisation orchestration

This challenge involves the inclusion of unified management adopting modern allocation slicing schemes and abstractions for delivering virtual resources, services, functions and hardware, with specific focus and interest on control and orchestration, in particular in federated domains (e.g. multiple operators, customer networks and data centres). Interoperability issues will be addressed through coordinating multiple SDN control domains, with focus on novel standardised orchestrators [19]. Integration of network capabilities across heterogeneous environments, real-time monitoring of physical and virtual network resources and automated high-scale provisioning of security are some key traits of advanced virtualisation orchestration. Proactive and reactive decision-making schemes need to be developed in the control plane. Advanced virtualisation techniques will be designed and implemented in order to make viable for multiple tenants the usage of the network resources. An open and secured platform will be available for tenants, end-users, providers, and stakeholders for functioning and realising network slices in real time, fulfilling thus the 'zero latency' concept in establishing new network services or applications.

5.6 Challenge 6: to support dynamic real-time adaptive processing

There is a crucial requirement to develop adaptive processing mechanisms and traffic engineering strategies for supporting high-capacity, low-latency and spectrum-optimised management in the underlying network architecture. Real-time monitoring mechanisms will be designed and distributed across the hybrid architecture. These mechanisms will monitor all traffic streams, services, applications and quality of service (QoS) guarantees from the 5G connection interfaces (mini base stations, LTE compliant SDR, and evolved node B – eNodeB) [20]. Novel bandwidth allocation schemes and algorithms will be devised for alleviating the bandwidth distribution in the 5G access architecture, giving emphasis on fair and efficient bandwidth distribution over the virtualised network. In the metro/core domain, it is necessary to

focus on utilising elasticity features by offering narrower wavelength defining. Load balancing and traffic forwarding techniques will be developed at the routing level by effectively controlling the physical characteristics of the optical transmission devices. Adaptive spectrum management mechanisms will be developed for allowing the complete reconfiguration of the spectrum access characteristics in the underlying base stations. Advanced physical and medium access control (MAC) strategies should be examined for supporting direct and indirect access to H2C and M2C gateways or/and base stations in order to ensure a high-level spectrum provisioning in M2M communications.

5.7 Challenge 7: to design and implement SDN-based energy management schemes

The energy-efficient management will be controlled by cognitive energy-aware SDN libraries that will allow the total manipulation of the optical and wireless network entities based on traffic conditions [21]. The respective libraries will support optimised code generation offering energy-efficient alternatives to avoid wastes. Mechanisms for measuring and estimating energy consumption, techniques for modelling energy behaviour of hybrid 5G network systems and models for detecting bad energy 'smells' are among the objectives of the advanced energy schemes. Doze and cycle-sleep mechanisms will be applied for all node entities in order to save energy when the existing traffic is low or even absent. The hybrid 5G architecture will advance effective energy-efficient mechanisms to the converged 5G optical terminals, allowing doze and sleep modes when the traffic originated from the 5G edges is low or completely absent. Analytical power minimisation models need to be devised for supporting low power consumption in optical and wireless domains.

5.8 Challenge 8: to design, integrate, and implement SDN-controlled network prototypes

In the context of the developed architecture, it is important to design, integrate, and implement innovative prototypes and platforms to meet the high-demanded requirements of the 5G challenges. In order to provide a high-capacity hybrid optical-wireless access network, the introduction of a 5G hybrid optical-wireless optical network unit (ONU) prototype is demanded. Traditional ONU devices are promoted to SDN-based hybrid optical-wireless gateways, capable of handling 5G traffic streams and optical signals at the same time in a smooth and efficient way [4]. This prototype will leverage the network performance in the access network by increasing the capacity of the network, the flexibility of the high-layer functionalities, and the capabilities of the front-haul optical-wireless device/gateway. Furthermore, it is important to establish an elastic optical programmable configuration platform for addressing the static wavelength modulation in current optical transport networks [22]. Current optical routing networks are not able to dynamically manipulate their physical characteristics, e.g. the modulation or the baud rate. The hybrid 5G architecture will cover this gap by integrating a novel programmable platform in the optical layer towards control and management, using powerful software libraries and APIs, transmission options, physical and MAC features and switching capabilities of the underlying transponders, routers, and wavelength add/drop and selection devices. Lastly, an innovative radio access infrastructure needs to be introduced; the MTC-enabled cloud-based RAN (C-RAN). By efficiently interconnecting the MTC domains with cellular networks, the MTC-enabled C-RAN will utilise dynamic, cloud-based SDN controllers for managing the radio interface of the most cutting-edge 3GPP technologies (LTE and LTE-A) so as to adequately handle traffic streams stemming from M2M or/and H2M data centres and data domains.

5.9 Constraints and difficulties

The application of the aforementioned challenges and directions is not a straightforward way. Network and service providers have been relying on the promise of SDN, NFV and intelligent HetNets

to leverage the deployment of new services and applications by establishing high-network automation, programmability, and overall reduced costs. However, modern HetNets must overcome specific constrains and difficulties in creating agile intelligent network infrastructures. We distinguished the most critical contains towards this goal:

- Lack of standardisation. Many integrated heterogeneous wired–wireless networks still remain without standardisation. This limitation hinders the development of new devices, services and equipment.
- Controller coordination. SDN presents brand-new challenges. An efficient management policy is needed to address open questions such as how many controllers are needed or where should the controllers be placed to avoid conflicting instructions.
- Rigorous management. In order for HetNets to scale, there is a need to meet management needs such as monitoring, patches and upgrades. These needs are separate from SDN and NFV but of equal importance.
- Complexity. The cost of growing network operations usually come along with a growing cost, particularly due to increased complexity and growing number of system interdependencies. SDN-based HetNets induce some complexity as they advance the traditional network infrastructure to intelligent and dynamic programmable networks.
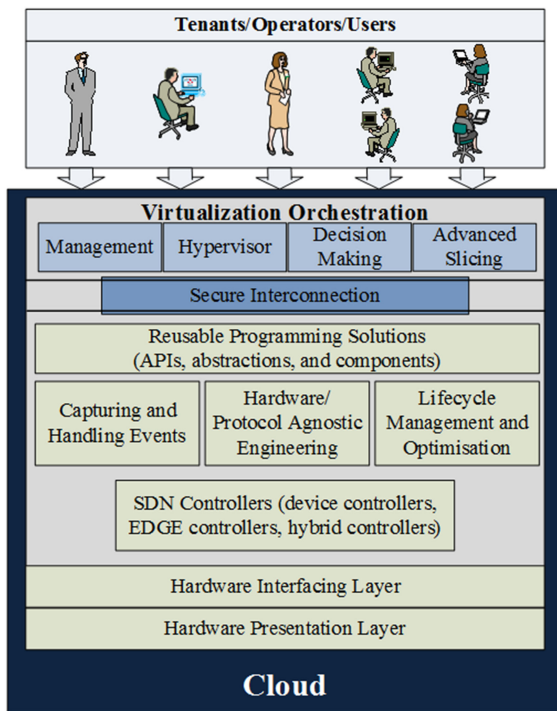
6 Proposed hybrid 5G architectural model

6.1 Overall concept

The overall concept of the proposed architecture lies upon the idea that the only way to take full advantage of the tremendous technological advancements in telecommunications is to build a unified, clear and simple to use system that is easily adaptable to users' needs. The 5G front-haul components in combination with high-capacity backbone optical network segments constitute a highly heterogeneous system of diversified technologies [23]. For that reason, it is really not only challenging but also crucial for telecommunication providers to adopt and deploy such systems in cost-efficient and energy-conserving ways.

The key cutting-edge schemes that are employed and enhanced by the proposed architecture to enable the intended hybrid architecture are NFV, SDR and SDN. NFV allows the realisation of network functions without requiring the installation of extra service-specific equipment. This approach leads to lower CAPital EXpenses and OPerational EXpenses. Furthermore, it provides advanced migration capabilities among different hardware platforms. SDR offers extensive flexibility and adaptability to radio interfaces based on dynamic conditions. In that manner, various wireless access technologies can be rapidly deployed on demand (under the 5G umbrella). SDN gives the ability to the administrators of telecommunication systems to manage resources through programmable software components. On these grounds, intelligence shifts from the network devices to the core software controller, allowing hardware/protocol-agnostic solutions. The considered overall model involves the integration of NFV, SDR, and SDN in an effort to efficiently virtualise the hybrid optical-wireless infrastructure.

Sun et al. [1] argue that this type of integration is possible and is expected to lead to significant reduction to equipment cost and energy consumption, while increasing openness and multi-tenancy. Cho et al. [24] support that the best solution for an efficient 5G cross-layer architecture is the combination of SDR and SDN. The corresponding approach seems to be the most promising solution for modern network applications, such as M2M, vehicle-to-X, and IoT communications; a claim which is also supported by Trivisonno et al. [15]. In addition, it has now become evident and common belief to the academia and industry that the most viable technique to allow efficient sharing of network infrastructure and radio spectrum resource is the abstraction via network virtualisation, as also explained by Liang and You [25]. One of the most prominent characteristics of the unification, virtualisation, and abstraction of HetNets is the interdisciplinary nature of this

Fig. 1 *Proposed conceptual model in terms of control and management planes*

approach. First of all, such a hybrid architecture covers both the fields of wireless networks and optical communications [26]. Furthermore, the proposed system will be the result of a holistic approach which involves all related areas, from the physical layer (wireless and optical links) up to the application layer and the end-users. Moreover, it is evident that the specific concept expands from the networks/telecommunications disciple to the software engineering discipline (which involves the development of APIs and related software libraries). Finally, there is a clear financial aspect related to the business perspectives of such an approach and of course the expected cost savings in terms of lower capital and operational expenses [27].

6.2 Positioning of the proposed architecture

The proposed hybrid 5G architecture aims at integrating individual existing technologies for 5G networking and developing virtualisation models and software components for efficient system management. Initial, it is necessary to analyse user, network, and service requirements, define an exploitation plan, conduct techno-economical study and evaluate the designed scenarios. Next, the HPL and HIL abstractions models have to be developed to enable a hardware/protocol-agnostic reuse process. New cloud-hosted SDN controllers should be implemented along with metrics and policy management library. Programming libraries need to be developed to allow uniform network control, with the adoption of well-defined software engineering techniques. New virtualisation orchestration techniques and slicing algorithms should be designed, considering NFV approaches (such as OpenNaaS and Accelerated Open vSwitch). Software libraries for supporting flexnode/flexgrid have to be developed to enable flexible routing [28].

6.3 Conceptual model

A critical component for virtualising 5G networks is the hypervisor that abstracts the underlying physical SDN network into multiple logically isolated virtual networks providing an effective slicing allocation scheme in both optical and wireless domains. In essence, the hypervisor governs dynamically the management plane depending on the constantly evolving tenant needs and requirements. The control plane stands below the management layer. It encloses all the required software libraries, models, definitions and abstractions which are necessary to efficiently

utilise the underlying network infrastructure. A secure interconnection sub-layer between the management and the control layers addresses the new, security challenges of the involvement of intelligence in the management and control planes. It ensures adequate authentication and privacy mechanisms on reacting to cyber and malware attacks. A repository of reusable programming artefacts (user-friendly APIs and components) is established in the upper level for providing a high-level programming environment. The proposed conceptual model is depicted in Fig. 1. Multiple tenants (users, third telecommunication companies, operators, and stakeholders) are able to use the architecture, modules, components, services, applications, and capabilities in a secured and virtualised manner. The model comprises of two main levels, the management level and the control level. The multi-level approach of the proposed concept aims at providing high capacity, adaptive and virtualised network services to multiple tenants by effectively using a HetNet infrastructure. The management level includes: (i) a unified management component, (ii) a decision-making component and (iii) an advanced slicing component for virtualised multi-tenant network. The unified management component allows information to flow between the management level and other levels. To this end, it includes management interfaces which allow settings to be enforced in network devices and information to be retrieved back into the management level, for example, to be reported to the network administrator [29]. Furthermore, two other important interfaces exist, namely the interface between the data and the control levels, which is also known as southbound interface, and the interface between the control and the management levels, which is also known as northbound interface. The interaction between the data and the control planes is carried out via the OpenFlow protocol. The decision-making component governs the SDN network devices to make specific actions, e.g. load balancing, routing path determination and failure/recovery policies. In essence, the decision-making component operates as an information tank between the management and the control levels supporting both proactive and reactive management of the network. The advanced slicing component, also known as network virtualisation component, abstracts the underlying physical network infrastructure so that one or multiple virtual networks can operate on the physical network [30]. NFV is the main function behind the slicing component which is capable of adapting different 'vertical' adaptation requirements. The function is realised by the hypervisor that creates multiple isolated slices or virtual networks from a given physical network infrastructure. FlowVisor, AdVisor and CellVisor are examples of hypervisors that are used for optical and wireless networks [31]. An advanced virtualisation technique is triggered allowing the flexible sharing of physical networking resources when a new slice is issued for a tenant. Convergence core network architecture prototypes, procedures and protocols for heterogeneous access integrations will be available in the repository that will offer components addressing the various needs of the 5G network lifecycle from requirements acquisition, design and implementation to deployment, monitoring, remote network re-configuration and maintenance.

To this end, traditional software architecture techniques like reference architectures, tactics, patterns, architecture description languages (ADLs) etc. will be used. APIs are directly connected with hardware abstractions that offer a complete device modelling. The goal of the hardware abstraction is to hide the technological details and specification of the underlying HetNet resources. On the other hand, the HIL utilises the raw interfaces provided by the presentation layer and transforms the device capabilities to user-friendly abstractions. The control plane also includes the hardware/protocol-agnostic reuse process. This process is capable of reusing existing libraries and software classes to describe new optical, wireless, radio, hybrid, M2M, and MTC interfaces. It is also able to reconfigure existing hardware that operates in different modes. In addition, modules of the code base can be characterised as hardware/protocol-specific (when they are manipulating a specific hardware/protocol through its API) or hardware/protocol-agnostic (e.g. algorithms that are serving a cause not related to a specific hardware/protocol). Modules that are hardware/protocol-agnostic
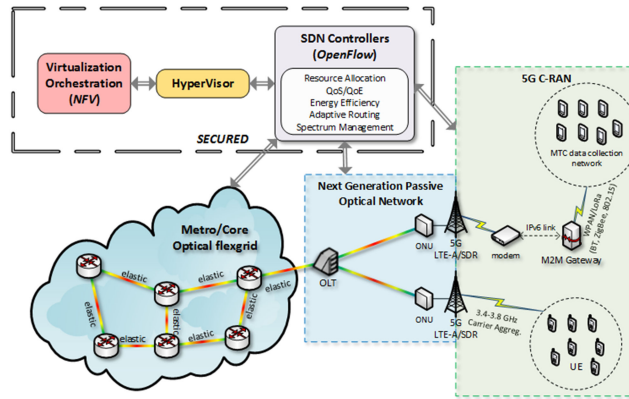
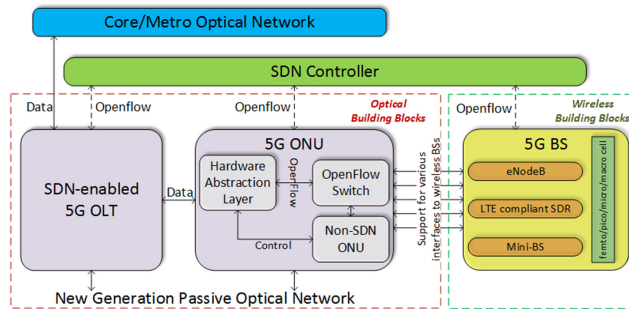**Fig. 2** *Overview of the proposed architecture*

Fig. 3 *5G hybrid optical-wireless ONU*

can be directly added to the reuse repository, whereas hardware/protocol-specific modules can be refactored to their two components (when possible), and the obtained hardware-agnostic part be treated as a reusable artefact.

The SDN controllers exploit the capabilities of the hardware/protocol abstractions. The proposed architecture advances the provided controllers to the cloud for stimulating the validity of the control plane. Each SDN controller governs a device or a set of common devices in the underlying hybrid network. An efficient mechanism called capturing and handling time-varying events is utilised to recognise and validate changes, modifications and other events that take place in the underlying network devices. For instance, an SDN controller may trigger an event when a user moves from one 5G base station to another. One more innovative feature is the policy/learning mechanism. This mechanism comprises of software libraries that are focused on learning patterns for acquiring tenants' behaviour related with the network usage to provide adaptive and self-learning methods to better manage network resources and demands.

6.4 Components of the proposed architecture

The proposed architecture envisages to leverage the migration of the traditional 'client–server', static networks to XaaS, flexible, and dynamic network slices, without needs of owning hardware, software or the cognitive objects themselves [32]. It promotes the advancement of the conventional 'plan and operation' model of serving network services to a secured and virtualised model of offering customable network services on demand in a 'zero latency' process in the access, the metro/core, and the radio access domains. By observing Fig. 2, the major components of the proposed hybrid 5G architecture are depicted. The main network domains are highlighted, namely the optical core network, the optical access network, and the C-RAN. All parts of the system are controlled in a unified manner by SDN controllers, which allow the abstraction of network resources that can be orchestrated through virtualisation. The hypervisor is responsible of abstracting the underlying physical SDN network into multiple logically isolated virtual SDN networks, each with its own controller [31]. Using the OpenFlow protocol, the hypervisor establishes multiple SDN networks which correspond to a 'slice' of the underlying optical

wireless infrastructure. Each tenant can operate its own virtual SDN network by defining its own operating system, configuration parameters and operation options independent of the other tenants.

6.5 Innovative elements of the proposed architecture

The introduced hybrid 5G architecture incorporates innovative elements, which notably progress the state of the art, as described in the following four subsections.

6.5.1 5G hybrid optical-wireless ONU prototype: Fig. 3 presents the innovations introduced by the proposed architecture in the integration of the optical-wireless domain. It unifies the management of optical components (realised via NG-PON2) with wireless 5G components [33]. The latter may involve a variety of cutting-edge wireless points of access, such as eNodeB, LTE compliant SDR, and mini-BS, forming cells of various sizes. The physical joint between the optical and wireless domain is the 5G-capable ONU device which is attached to the corresponding base station. The architecture will offer common control of the HetNet components by implementing central SDN control through OpenFlow, including even non-SDN entities which are accordingly abstracted. The underlying wavelength selective switches (WSSs) will be integrated with the corresponding SDN controllers. The COs will be interconnected with the WSSs using point-to-point optical fibres. Each SDN-controlled WSS will be also enhanced with optical transponders and amplifiers that will also be integrated with the corresponding SDN controllers [13].

Fig. 4 presents the novel features that will be added by the proposed architecture at the optical metro/core network, in regard to elastic routing and adaptive wavelength switching. As illustrated in the figure, the hierarchical routing is extended and enhanced with advanced elasticity provided by high-level SDN control. Furthermore, the optical switching at the core network is optimised in terms of flexibility and performance via the use of WSS–ADM (add/drop multiplexer), which will be configurable through OpenFlow by the SDN controller [34]. The extensive programmability of the core network will enable the provision of superior energy efficiency, QoS/QoE, and resources slicing orchestrated via NFV network virtualisation.
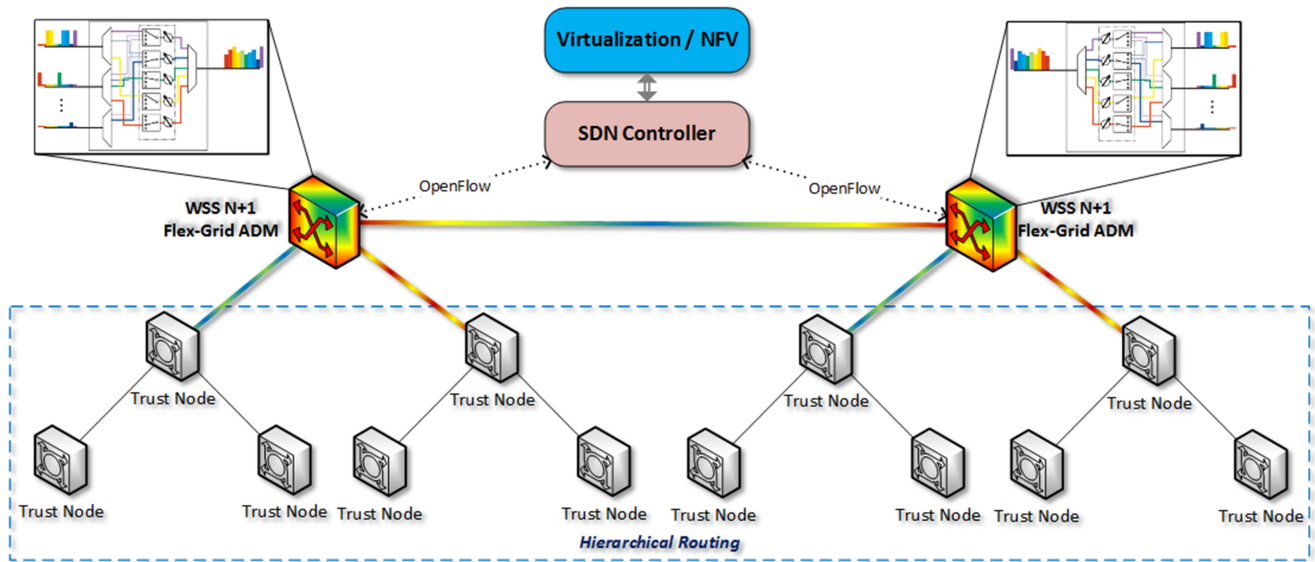
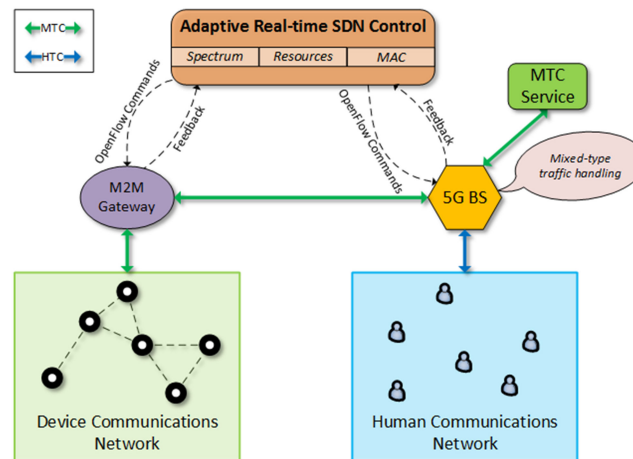**Fig. 4** *SDN-controlled WSS and Hierarchical routing in optical network*

Fig. 5 *5G C-RAN with mixed MTC–HTC traffic*

6.5.3 Mixed-type (MTC–HTC) capable 5G C-RAN: Fig. 5 presents the innovative elements introduced by the proposed architecture in the efficient handling of heterogeneous types of communications at the wireless domain. In particular, with the growth of IoT applications, effectively serving device-to-device traffic along with traditional user traffic has become quite challenging. Meeting the special requirements of device-to-device (or M2M) traffic, while maintaining high degree of user perceived QoE, especially in the wireless domain, necessitates advanced network control schemes. The proposed architecture will provide such schemes through SDN control (OpenFlow). As shown in the respective figure, the developed techniques will allow real-time management of the spectrum, the available resources, and the applied MAC at the M2M gateway as well as the 5G BS, according to the received network feedback.

6.5.4 Virtualisation open platform: The new advances that the proposed hybrid 5G architecture introduces in the field of network virtualised orchestration and hypervision are illustrated in Fig. 6. A virtualisation open platform allows highly agile distribution and management of network resources slices, while ensuring advanced security features. The main entities of the respective platform are the virtualisation orchestrator and the hypervisor. The former incorporates the management and control planes, as well as the unified security framework. It provides high level network slicing capabilities, which allow tenants to fulfil their exact requirements for resources in a dynamic real-time manner. The orchestrator first abstracts the underlying physical network and then creates separate virtual networks (slices) through specific abstraction and isolation

functional blocks [31]. For example, multiple optical channels are created, following the WDM technique, as 'slices' at the photonic layer of the underlying optical domain. The 5G mobility management offers a lot of advantages including no need to deploy any mobility-related component at the access domain and per-flow mobility support [35]. Inter-Internet service provider (ISP) handoff provides flexibility to tenants that move from one ISP to another [36]. The orchestrator is also able of enforcing centralised decisions regarding issues such as energy consumption policy [37]. Thus, efficient energy management can be applied to the hybrid optical wireless networks by simply activating an SDN-controlled energy-efficient policy. The developed security framework will realise the overall security policy and the applied intrusion detection system; it will also regulate inter-provider access and tenant privacy over the network architecture. The virtualisation orchestrator will enable the aforementioned features though NFV techniques. The appropriate network abstractions will be provided by the hypervisor, which allows virtual networking via virtual switching of dynamically configured VMs. Ultimately, the output of the virtualisation platform will be applied on the physical hybrid infrastructure over SDN control.

7 Conclusions

This article discusses the potential of advancing the concept of 5G mobile networks by using NFV, SDR and SDN techniques. A new conceptual model has been introduced, where the innovative elements that compose the proposed architecture have been presented in detail. We have integrated wireless and wired components to create flexible and efficient 5G-based frameworks.
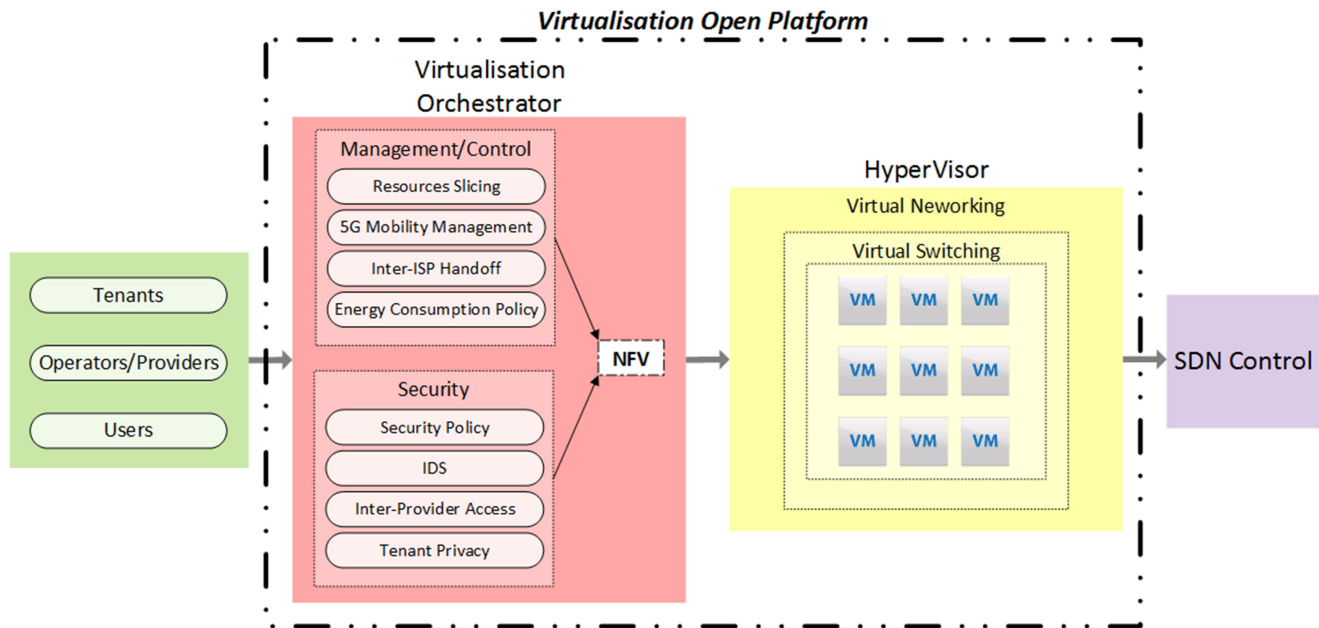
Fig. 6 *Hybrid 5G virtualisation open platform*

An open platform has been also introduced, able to highly agile distribution and management of network resources slices, while ensuring advanced security features.

8   References

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