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Review

End-to-end programmable, cloud-based virtualized HetNet: Advances made & challenges to address

M. Moshiur Rahman[a,*], Charles Despins[a], Sofiène Affes[b]

[a] ETS, University of Quebec, Montreal, Canada
[b] INRS-EMT, University of Quebec, Montreal, Canada

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ABSTRACT

Future networks (5G and beyond) will demand provisioning of novel services with a varied range of service requirements, and an order of magnitude increase of wireless data traffic, while at the same time decreasing the network operation cost. To address these issues, wireless network virtualization is seen as a key enabling technology for future networks. Virtualization offers cost-effective and efficient resource utilization by sharing the resources among multiple operators. Also, in contrast to traditional service specific inflexible network implementations, adoption of innovative network technologies demand certain level of flexibility and control over the networking fabric. In this respect, we argue that, for realizing a programmable and flexible heterogeneous virtual network infrastructure, software defined networking (SDN) & cloud computing technologies are the key tools to leverage on. This will ensure efficient resource utilization through sharing, enable programming of the underlying heterogeneous network infrastructure as a system and provide on-demand, elastic resource provisioning. In this paper, we lay out the key requirements and architectural components of end-to-end programmable heterogeneous virtual wireless networks (HVWNs). To report on the advances made in the pertinent technologies in realizing a HVWN architecture, we also present a brief survey of research on wireless network that leverage SDN, programmable radio plane and cloud computing technologies. We also investigate various actors and their roles in such HVWN environment and address various research issues and challenges in realizing such an architecture.

1. Introduction

The Information and communication technologies (ICT) industry is going through a revolutionary change in the last decade. These changes are manifesting themselves in the form of various new services, smart and slick personal computing devices and even in the architectural changes in the mode of computing itself. In a more *connected and communicative* information society, wireless networks are playing the role of major connection medium due to its ubiquitous presence in the information eco-system [1]. For its increasing importance as a communication channel, the stress on wireless networks for carrying significantly more traffic with varied quality of service (QoS) requirements is stronger than ever before. But it is a well known fact that with scarce radio spectrum [2] and limited control over the networking gear, operators are struggling to cater for such needs. With vendor locked-in devices, it is not possible to provision new network services that require novel protocols or processing algorithms for optimal service provisioning. The way forward is to rethink the way traditional networks work and re-architect them, so that, they offer more flexibility [3] and fine-grained control over the network resources that will enable the operators to provide novel differentiated services, while at the same time ensuring efficient resource utilization.

Wireless network ecosystem consists of different types of networks that differ from the services they provide, their key performance indicator (KPI) requirements (e.g., throughput, delay, bandwidth need, etc.), also the type of network nodes used and their power requirements. For example, wireless sensor networks (WSNs) are application specific, they use low power nodes that communicates sporadically with bursty traffic. Power efficient operation of the WSNs is the main concern due to their limited battery capacity. WiFi networks operate in the unlicensed spectrum band and normally the applications (e.g., web browsing, file transfer, etc.) used in these networks are not very delay sensitive but might result in high amount of data traffic. On the other hand, cellular networks operate on licensed spectrum and they provide

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* Corresponding author.

E-mail addresses: mohammad-moshiur.rahman.1@ens.etsmtl.ca (M. Moshiur Rahman), charles.despins@etsmtl.ca (C. Despins), affes@emt.inrs.ca (S. Affes).

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guaranteed service for various delay-sensitive applications (e.g., voice, live video, etc.). Hence they have stringent requirements on network delay and throughput. One of the problems with current network implementation is that the networks are service specific, hence, network nodes are tailored to serve a specific type of service.

This service specific network deployment has both higher capital and operational expenditures (CAPEX & OPEX). The astounding cost of network operation also impedes new business players to enter the market. The vision of future networks (e.g., 5G and beyond) demands the presence of various network operators that would provide differentiated services to users in heterogeneous wireless network environments. In this respect, it is necessary to have a service agnostic deployment of physical resources that can be used economically and flexibly in an on-demand basis for provisioning various wireless services. We argue that to materialize such a network architecture, a virtualized network infrastructure is required that is composed of programmable and flexible network resources which will be shared by different virtual network operators (VNOs). The physical resources (including the licensed wireless spectrum) will be provided by one or more infrastructure providers (InPs) who will deploy, manage and lease the physical and virtual resources to the VNOs. Also, to alleviate the problem of vendor specific inflexible nodes that are not amenable for adopting new wireless networking technologies, software defined networking (SDN) technologies should be incorporated in implementing the network infrastructure. And on-demand, elastic resource provisioning should be ensured following a cloud-based network deployment model.

Virtualizing the wireless network infrastructure enables sharing of the physical resources by multiple operators at the same time. This will ensure efficient resource utilization which is critical for the success of any successful business operation. Virtualization is the process of abstracting physical resources, so that, multiple network entities (VNOs), can have shared access to these resources to deploy their own customized network. Virtualization for the wired networks is a well studied and well understood topic [4] and this technique has been employed in computer systems for a long time, for abstracting memory [5], storage [6], or virtual system [7]. In comparison, virtualization of wireless networks, is a fairly recent trend [8–11]. Virtualization of wireless networks has immense benefits. Besides providing a platform for shared access of network hardware resources, it can also enable shared access of wireless spectrum [12], which can mitigate the long standing spectrum ossification problem [13]. By shared usage of wireless resources (both equipment and radio spectrum), wireless virtualization can reduce a network's CAPEX and OPEX [14,15]. Wireless network virtualization (WNV) can be achieved in different ways. But we deem SDN as a significant enabler for successful realization of WNV.

SDN [16,17] is able to abstract physical resources for its ability to separate the network control plane from the data plane. Thus it can provide absolute control over the network substrate in the form of programming it. The flexibility provided by SDN is instrumental in providing novel services that require to change device functionalities to provide differential services [18]. In addition to provide flexibility in managing the network infrastructure, SDN can also reduce network cost (both CAPEX and OPEX) by replacing expensive network nodes with off-the-shelf (OTS) cheaper programmable data plane equipment and centralizing controller in IT servers.

To further reduce the network cost, expensive special purpose network nodes that performs specific tasks, e.g., mobility management, gateway functionalities, billing, etc., can be implemented as software instances that run on IT servers. This can be achieved by separating network device hardware from the software that runs on it. This separation of network devices and software is knows as network function virtualization (NFV) that is being actively sought after by major telecom operators and vendors around the globe [19]. In NFV model, the virtual network functions (VNFs) are put in centralized locations, i.e., data centers where the physical resources (e.g., processing, storage, networking, etc.) are pooled together. In a distributed pooled resources model, these data centers are basically distributed clouds of resources managed by infrastructure owners (InPs), who can provide on-demand, elastic resources to the operators (VNOs). Network nodes (e.g., base stations (BSs), access points (APs)) can also be implemented as software instances in these data centers. To handle the high processing requirements of baseband signals, besides the software instances, special purpose FPGA-based processing boards can also be installed in he data centers.

Hence, we argue that for realizing a programmable & flexible heterogeneous virtual network infrastructure, SDN & cloud computing technologies are the key tools to leverage on. In such a network infrastructure, VNOs will be able to offer their differentiated services in their target networks (e.g., WSN, cellular or WiFi) leasing virtual resources from one or more InPs. In this paper, we identify the key requirements of such a heterogeneous virtual wireless network (HVWN) infrastructure, then we discuss different components for an end-to-end solution for a programmable, elastic HVWN following a top-down approach. To report on the advances made on pertinent technologies for realizing the HVWN, we survey the proposals on programmable and cloud-based wireless network architectures and analyze their added value and limitations from the perspective of an end-to-end solution for HVWN. We also point out the open problems and challenges in realizing a programmable, elastic HVWN.

A survey on wireless network virtualization appears in [20] where various projects on wireless network virtualization have been presented. Some performance metrics for virtual wireless networks is also discussed in this paper. This paper presents a generic survey of wireless network virtualizaion, whereas in our paper, we approach virtualization of wireless networks from end-to-end programmability point of view. We also consider the heterogeneous wireless network environment consisting of cellular, WiFi and sensor networks. Quadir et al. have presented an overview of different architectural proposals on programmable wireless networks in [21]. The paper has focused on three trends on wireless network architectures namely, software defined wireless networks, cognitive radio networks and virtualizable networks. In its approach, virtualization was not considered as an integral part of the wireless architectures rather as a separate trend. But in our paper, the target is virtualization of heterogeneous wireless networks while providing end-to-end programmability and on-demand elastic resources provisioning.

The rest of the paper is organized as follows: in Section 2, key requirements of HVWN is identified. Survey of proposals on wireless networks using SDN, programmable radio and cloud computing is given in Sections 3, 4 and 5, respectively. Section 6 describes different layers for the end-to-end programmable HVWN solution. Different actors and their roles in a HVWN environment are discussed in Section 7 and in Section 8, potential research issues and challenges have been identified. Finally, we conclude the paper in Section 9.

2. Requirements of programmable virtual wireless networks

A virtualized wireless network must satisfy certain requirements, some of these critical requirements are discussed in this section.

2.1. Virtual network (VN) isolation

The VNs sharing a common physical infrastructure should be perfectly isolated from each other, so that, to a VNO, it will appear that it has the sole-ownership of the (virtual) network. Operation of a VN should in no way affect the other VNs sharing the same physical resource, e.g., for two VNs sharing a common physical node, if load increases in one VN, traffic belonging to the other VN should not suffer from additional delay in processing, queuing or reduction in throughput. Service level agreements (SLAs) between the VNOs and the InPs should be always fulfilled. SLA is basically a subset of key performance indicators (KPIs) which might comprise of minimum guaranteed processing power, memory space, bandwidth/throughput, maximum downtime of system, etc.

2.2. End-to-end programmability

VNOs should have complete flexibility over the virtual/physical resources they lease from one or more InPs. This flexibility is demonstrated through their ability to modify (program) the underlying resources in a way that best supports their intended service requirements. For example, in a virtual LTE network implementation, a VNO should be able to program the core network switching fabric to route its core network packets through the optimum routing graph consisting of mobility management entity (MME), switching gateway (S-GW), packet data network gateway (P-GW), policy and charging rules function (PCRF), etc., nodes. Similarly, for the radio access plane, a VNO might require customized radio processing chain to process its baseband signal. Hence, provisions should be made so that, it can assemble various processing blocks (e.g., for frequency transformation, modulation, coding, etc.) in a programmatic manner [22]. Also, a VNO should be able to implement its custom protocol stack to optimize its intended service performance, hence, programmatic control over the protocol layers is also necessary.

2.3. On demand resource provisioning

In the VNO-InP business model, a VNO would request for its required resources (virtual/physical) to the InP. Upon availability of the resources, the InP would assign the requested resources to the VNO, forming a service level agreement (SLA) between the InP and the VNO. During its operation, if the VNO need additional resources (e.g., computing, storage, radio spectrum, etc.) it would request the InP for the lease of these additional resources. InPs should be able to cater for such on demand elastic resource provisioning. This is where the cloud computing model comes into play in a virtual wireless network ecosystem. In this model, an InP can be seen a as cloud service provider that composes of geographically distributed *cloud* of resources. A VNO receives the lease of its requested resources from the InP without the necessity of being aware of the physical location of the resources.

2.4. Network function virtualization (NFV)

One of the major motivation behind network virtualization is to reduce the CAPEX and OPEX of network provisioning, so that, the operators can cope up with the increasing network cost and also, new players can get affordable entry to the market. To address this issue, major telecom operators and vendors are opting for network function virtualization (NFV) [19]. The main idea behind NFV is to separate network hardware from the software that runs on it, this will pave the way to implement different network functionalities as software instances in a general IT platform. This paradigm shift in network architecture will replace the traditional special-built network nodes which are not only expensive but also very power hungry.

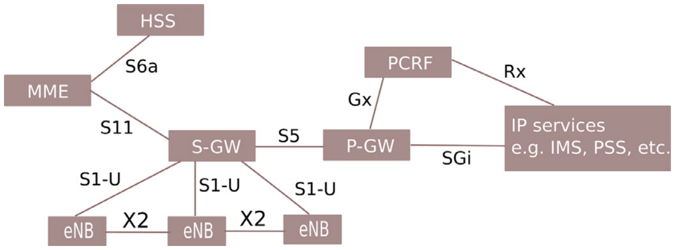

Fig. 1. A block representation of EPS.

2.5. Dynamic spectrum sharing

Scarcity of the licensed spectrum is the *Achilles' heel* for the next generation wireless networks. Despite all the advances made in network architectures, baseband processing, error correction channel coding, etc., limited licensed spectrum remains the major bottle neck for telecommunication networks. To alleviate this problem, efficient utilization of the radio spectrum in time (time division multiple access (TDMA)), frequency (frequency division multiple access (FDMA)), space (space division multiple access (SDMA)) is necessary [23]. Especially in the virtual wireless networks environment, dynamically sharing the spectrum among the incumbent VNs while respecting the SLA is of utmost importance. Opportunistic sharing of the licensed spectrum in combination with utilizing the unlicensed spectrum band wherever possible might mitigate the spectrum scarcity problem to a great extent. Also, the use of millimetre (mm) wave for future 5G network is gaining momentum as many researchers from industry and academia are strongly advocating on its favor [24,25]. Due to its ability to provide higher throughput for lower transmission distance mm wave is an ideal transmission candidate for small cells [26].

2.6. High capacity front-haul

Next generation user applications will have very high data rate requirements, for this reason, the volume of traffic to and from the user equipments (UEs) is huge. For a centralized baseband processing architecture as in C-RAN [27], traffic is carried from the baseband pool in data centers to remote radio heads (RRHs). The connection between the data center and the RRHs constitutes the front-haul of the C-RAN. Due to the high volume of transmitted data, traffic per RRH will be in tens of Gbps range. To design this high capacity front-haul is particularly challenging. To accommodate such high capacity traffic, fiber optic based front-haul becomes the ultimate design choice. But due to geographical constraints it might not always be possible to connect RRHs to the data center by fiber optic cable, hence, high capacity microwave links should be considered for those areas. Advanced pre-coding and compression techniques can greatly benefit improving the C-RAN front-haul capacity [28,29].

3. SDN for wireless network virtualization

Traditional networks are designed to have distributed control for scalability reasons. In this structure, network intelligence is distributed throughout the network, where each network node have both control and data forwarding logic. For example, in the simplified presentation of an evolved packet system (EPS) in Fig. 1, the evolved node Bs (eNBs) are the last mile radio access points. Each eNB has decision making and forwarding functionalities. It makes the local radio resource management decision for allocating radio resources to individual users. It also communicates with the neighbouring eNBs via X2 interfaces to cooperate resource provisioning. Functionalities like mobility management, policy implementation, charging, access control and even access to internet are managed by decision nodes resided in the core network. The problem with this kind of network architecture is manifold, firstly, the network architecture is very inflexible, it operates with a fixed set of network protocols and it is not possible to implement a novel network protocol that will have optimal performance for a new service. Secondly, because of vendor locked-in network nodes, an operator have less freedom to purchase network equipment from different vendor companies because the proprietary equipment sold by vendors generally do not interoperate well enough with one another. Thirdly, the formidable cost of the network equipments discourages network operators to provision new services as it will require to add new equipments to the network, sometimes replacing previously purchased well-functioning equipment. The high cost of network roll-out also acts as an entry barrier for new entrants to the heterogeneous wireless networks' business eco-system. Finally, the special purpose hardware based networks also have higher operational cost due to higher power consumption and requirement of a significant number of highly skilled man power for operation and management of the network. Software defined networking can resolve these issues to a great extent by flexible creation and management of networks using inexpensive programmable switches and off the shelf general purpose servers.

Software defined networking [30,31] is a relatively new paradigm in network architecture designing that has created a lot of interest in both industry and academia alike. SDN is a complete makeover of the norm with which network intelligence and forwarding cooperate with each other. SDN enables *programming the underlying network as a system* by separating the control plane from the data plane. It provides high level abstraction of the network hardware, using which a centralized controller can program the network. As defined in the Open Networking Foundation (ONF) white paper [32], in a SDN architecture, network control and data planes are decoupled from each other and the intelligence and state of the network is logically centralized in the controller platform. SDN facilitates traffic engineering [33], it has also been used in large scale wide area network (WAN) [34]. SDN can also function as an enabler for network function virtualization (NFV) [19, 35] which is a major sought after technology by telecom operators around the globe. Though the immense interest on SDN is pretty recent, the core idea of programmable networks is the accumulation of research advances on different aspects in this area [36,37]. To summarize, the main components of SDN architecture are:

- Separation of network data plane from the control plane
- Logically centralized control and global view of the underlying network infrastructure
- Programmability and modularity of the control plane
- High-level abstraction of the hardware layer
- Open application programming interfaces (APIs) for data plane [38] and control pane [39–43], so that, both planes can grow independently of each other.

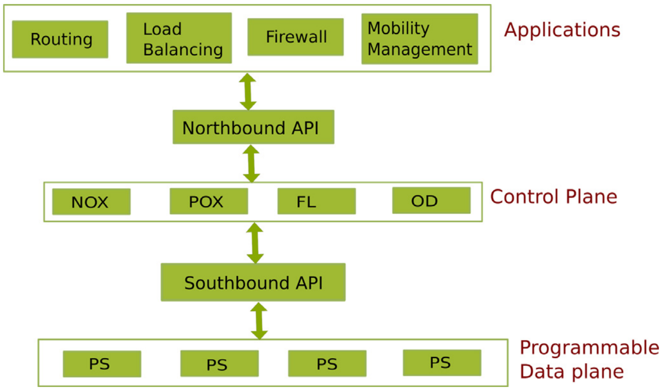

Fig. 2. Simplified representation of a SDN architecture.

A simplified schematic for a SDN architecture is shown in Fig. 2. The top tier is the application layer where the network applications reside that define the operational behavior of the network. Different applications, for example, routing, mobility management, access control via firewall, load balancer can be part of this layer. VNOs can have one or more applications *packed* together for a particular service provisioning. For easier management of different applications in the application layer, the northbound API [44,45] is used that ensures the synchronous operations of different applications. The controller layer consists of network operating systems (NOSs) [39,40,42], that interfaces the application layer with the forwarding layer. This layer is responsible for dynamically setting up (and tearing down) of network path according to the application layer instructions by modifying the underlying programmable switching fabric. For this purpose, the controllers use well defined southbound API (e.g., OpenFlow [38], NetConf [46], ForCES [47], etc.) to program the underlying switching fabric. SDN is gaining increased interest from both wireless industry and academia working on wireless network research to facilitate service differentiation, easier network management, network innovation and convergence of heterogeneous wireless networks. We classify the proposals on wireless networks leveraging SDN according to their target wireless domain, i.e., WiFi, sensor and cellular networks. We compare the proposals from their capability of providing an end-to-end programmable virtualized solution for the target wireless network domain.

3.1. SDN for wifi networks

SDN has been used for WiFi networks for implementing applications based service provisioning. Also, SDN is leveraged as a tool for implementing virtualization of WiFi access points (APs). Odin [48] is a software-defined wireless network prototype for enterprise WLANs. It implements flow-based virtualization technique to enable network operators to implement different WLAN services as network applications. In this architecture, a Odin master is the central controller entity that uses OpenFlow [38] to program switches and APs that it controls. Each AP is packed with a Odin agent that communicates with Odin master by using Odin's custom protocol. The applications on top of the Odin master uses Odin's primitives to implement different enterprise services. Odin is a single operator solution to implement virtual AP abstraction and does not consider the case when multiple VNOs operate on a common infrastructure. Also, it does not consider abstraction and sharing of radio resources.

EmPOWER [49] is an experimental testbed for SDN and NFV experimentation. The testbed's data plane consists of OpenVSwitch [50] and Click Modular Router [51], while Floodlight [43] has been used as the controller platform. It also utilizes a power management component called Arduino. This AP-based test-bed has provisions for implementing different network applications as slices. But the feasibility of implementing a resource allocation based multi-VNO platform is not discussed in the paper. Also virtualization of radio resources has also not been discussed.

3.2. SDN for wireless sensor networks (WSNs)

To resolve the management problem of WSNs, SDN has been used for smart management of the sensor networks. For example, software-defined wireless sensor network (SD-WSN) [52] proposes a flexible, generalized architecture for WSN. To overcome the resource underutilization and network management problems of traditional application specific WSNs, the authors proposes a programmable sensor network by following the control and data plane separation paradigm of SDN. To handle the *data-centric* characteristics of WSN, as opposed to the *address-centric* model of OpenFlow [38], a modification of the OpenFlow protocol, named Sensor OpenFlow (SOF) has been proposed in this paper. SOF uses two different addressing schemes, *Class-1: compact network-unique addresses* and *Class-2: concatenated attribute-value pairs (CAV)* that suits the data-centric operation mode of WSNs. Managing the control channel overhead and additional latency (due to data exchange between the control and the data planes) to ensure the desired performance SD-WSN would be a challenging task.

Gante et al. proposes a WSN framework to facilitate management of a WSN [53]. The authors proposes distributed control mechanism by incorporating a software-defined controller in each sensor BS. Application layer above the controller dictates the flow-table format of the sensor nodes. As dictated by the application (e.g., temperature, humidity sensing), the controller collects information from the sensor nodes and defines flow tables. For calculating the optimal routes among the sensor nodes, the controllers forms an adjacency matrix that consists of the connection information (e.g., distance, signal strength, energy level, etc.) between the adjacent nodes. In this model, each node forms its own neighbor table which is sent to the BS to enable the controller to build a network interconnection map. The energy-aware routing mechanism proposed in this paper is very efficient for low-powered sensor network environment but as sensor networks are power limited, periodical update of the neighbor tables from sensor nodes might create significant overhead burden.

3.3. SDN for cellular networks

Software-defined network paradigm has been proposed for cellular networks for both core and access network parts. These proposals leverage on network programmability to foster rapid innovation, easier network management and also lower network CAPEX and OPEX. Some of such notable proposals are discussed in this section. SoftRAN [54] proposes a software-defined centralized control plane for radio access network. It abstracts all the base stations (BSs) in a geographical area as one virtual big base station, composing of a programmable central controller and individual base station function as radio elements. All cross radio element resource planning is made by the controller, i.e., if decisions of one BS impact the decisions of another neighbouring BS, those decision should be made by the controller. As the controller has a network-wide view, this scheme will help in reducing interference, smooth the handover process and also can facilitate data offloading. On the other hand, decisions that are based on frequently varying radio parameters should be taken locally by the individual radio elements. SoftRAN basically targets to ease the management of a RAN by providing better control on network management issues like: load balancing and interference management.

SDMN [55] is a SDN based implementation of cellular core networks. It introduces a new MobileFlow stratum that decouples network control from the user plane. A MobileFlow controller controls the underlying MobileFlow forwarding engines (MFFEs) which are interconnected by IP/Ethernet network. MFFEs incorporates standard mobile network tunnelling process, such as GTP-U, GRE encapsulation/decapsulation etc., that facilitates MobileFlow controllers to interoperate with legacy evolved packet core (EPC) nodes (e.g. MME, PGW, SGW, etc.). SDMN enables to create multiple virtual core networks over the same hardware resources. This work basically focuses on the core network part of cellular networks, while virtualization of radio access network has not been addressed. Also slice management issue on a shared infrastructure has also no been discussed.

CellSDN [56] has been proposed as a way of simplifying design and management of cellular network using SDN. This architecture suggests to allow network control applications to express control policies based on subscriber attributes rather than the traditional trend of using network addresses and locations. Local agents are used in switches to enable fine-grained control of real time applications. Switch functionalities haven been enhanced for deep packet inspection (DPI). It proposes slicing mechanism called CellVisor that is an extended version of FlowVisor [57] capable of slicing cellular network resources. This work focuses on cellular network virtualization from user attribute point of view. Issues like radio spectrum virtualization (sharing among different VNOs), SLA enforcement have not been discussed in this position paper.

A scalable architecture for cellular core network is presented in SoftCell [58], which offers control of high level network policies for mobile users. The central controller in this architecture implements network policies by directing traffic through a sequence of commodity middle boxes and forwarding devices. Structure of BSs and middle boxes remain unchanged but each BS is paired with an additional switch that performs packet classification of the traffic from the user equipments (UEs). In this way part of the traffic management is offloaded toward the edge of the network and the network controller installs high level service policies to the underlying network nodes. While SoftCell architecture brings flexibility in maintaining cellular core networks, multi-tenant virtual network implementation was not studied in this work. Moreover, the work focuses on the core network part of cellular infrastructure, efficacy of such fine grained control over radio resources was not investigated.

SoftAir [59] is a software-defined network architecture for 5G wireless networks. In this architecture, core network functionalities are implemented in data centers that consists of controllers in servers and programmable switches. RAN functionality is distributed between the data center and the RRHs. Modulation and demodulation functionalities are performed at the RRH while more demanding PHY and MAC layer functionalities are pooled in the data center. To realize such network model, it is imperative to have high capacity front-haul between the data center and the RRHs. In certain geographical region, where it is not possible to have fiber optic cable or high capacity microwave links between the RRH and the data center, realizing such network model will be very difficult.

A software-defined control plane architecture for 5G networks is presented in [60]. In this architecture, a hierarchical network controller model is presented that enables service differentiation by allowing varied level of performance for different core network functionalities. A connectivity management as a service (CMaaS) paradigm is also presented which is a unified approach in managing user connectivity and simplifies user mobility, handoff and traffic routing. This work proponents for a all-SDN programmable future network. While it acknowledges that SDN can be instrumental for implementing NFV, it does not discuss a multi-slice solution for virtualizing wireless networks. SoftMoW [61] presents a programmable, recursive and reconfigurable cellular WAN architecture. The hierarchical construction of the architecture enables seamless inter-connection among core networks, programmable control plane and global optimization. It presents a novel label swapping mechanism for end-to-end path setup that enables each controller to operate only on its logical topology. Scalable optimization achieved in SoftMoW architecture facilitates different network-wide optimization, for example optimal routing, handover minimization in a certain area. SoftMoW aims at resource management in cellular WAN, specifically at the network core. But efficient resource utilization through shared resource usage in a virtualized platform is no discussed in the paper.

Table 1
Proposals for software defined wireless networks.

Network type	Proposals	Virtualization method	Layers affected	Slice management	Studied wireless parameters	Summary
WiFi	Odin [48]	Flow-based	Application, Control Data planes	NA	Throughput, Handoff	Implements WLAN services as network applications.
WiFi	EmPOWER [49]	Flow-based	WiFi APs	NA	NA	An experimental testbed consisting of APs for SDN & NFV research.
WSN	SD-WSN [52]	NA	Sensor nodes	NA	NA	Uses SOF protocol to communicate between the control and data planes.
WSN	[53]	NA	Sensor node and BS	NA	NA	Controller installed at each BS to facilitate network management.
Cellular Access	SoftRAN [54]	Big virtual BS abstraction	RAN functionalities	NA	NA	Addresses RAN management issues by abstracting RAN in a certain geographical area.
Cellular Core	SDMN [55]	Flow-based	EPC	NA	Basic 3GPP attachment and bearer establishment	Uses novel MobileFlow stratum.
Cellular Core + RAN	CellSDN [56]	Flow-based	Core and RAN nodes	CellVisor	NA	Enforces control policies based on subscriber attributes.
Cellular Core	SoftCell [58]	NA	Core network	NA	NA	Controller routes traffic based on UE policies.
Core	[60]	NA	Core network	NA	RTT delay, throughput	Proposes an all-SDN programmable core network.
Core	[61]	NA	Core network	NA	Handover	Hierarchical control plane leveraging level swapping mechanism.
Heterogeneous networks	OpenRoads [65]	Flow-based	RAN	FlowVisor	Latency, throughput	Creates overlay virtual networks on top of WiFi/WiMAX substrate.

OpenRAN [62] is a software-defined virtualized RAN architecture for heterogeneous networks. It consists of three parts: wireless spectrum resource pool (WSRP) which is responsible for virtualizing radio spectrum, cloud computing resource pool (CCRP) that consists of physical processing pool and SDN controller which controls the underling network by abstracting control functions of the access nodes. This model proposes virtualization in four levels: application, cloud, spectrum and cooperation levels, respectively. Though this model outlines a general model of the software-defined HetNet is does not give any detail on the implementation technologies that might be used to realize such an architecture. Also the authors do not discuss issues like slice management, virtualization technology used, i.e., flow-level virtualization or hard-slicing (i.e., physical segregation of resources), etc.

3.4. SDN for heterogeneous networks

OpenRoads [63] is a seminal work on using SDN paradigm for wireless networks. This platform uses SDN to build a programmable virtualized wireless data plane. OpenRoads consists of basically three layers: a *flow layer* where the flow-tables of different data plane nodes are modified using OpenFlow [38] protocol. Different wireless configuration parameters, like: SSID, wireless channel assignments, transmission power level are controlled and monitored by SNMP protocol. To enable resource sharing among multiple clients, a *slicing layer* is used to slice the network using the FlowVisor [57]. The *controller layer* which is built on NOX [39], has a global view of the whole network and it allows the network applications (by different network users) to add/modify flow-table entries in the underlying data plane. OpenRoads is a heterogeneous platform that supports both WiFi and WiMAX networks. It has been shown that the platform supports seamless vertical handover between the disparate wireless technologies [64]. But the work does not discuss virtualization of radio resources (e.g., antenna, wireless spectrum, etc.). Also the effect of elastic capacity provisioning in a flow-based virtualization as this, has not been studied in this work, which is a critical issue for an end-to-end virtual wireless network provisioning. The proposals on software-defined wireless networks are summarized in Table 1. In the table, flow-based virtualization refers to the fact that traffic flows belonging to a single VN is grouped together and isolated from the traffic flow of other VNs that share the same physical infrastructure. Whereas big virtual BS abstraction method, abstracts the BSs in a certain geographical area as a single, large BS which facilitates management of all the physical BSs.

3.5. Virtualization without SDN

There have been works on wireless network virtualization that necessarily do not use the SDN concept of separating network control from the data plane. Network Virtualization Substrate (NVS) [66] is a WiMAX virtualization platform for creating virtual wireless networks on a common physical substrate. It is basically a MAC layer virtualization technique that allows bandwidth-based and resource-based slicing through a slice scheduler. Moreover, it also incorporates customized flow scheduling for each slice in a BS.

A virtual base station architecture for WiMAX network is presented in [67]. In this model, virtual base stations are implemented in an external substrate that uses layer-2 switched data path and a control path to the BS. Radio resources of a BS is virtualized to create isolated slices that can implement different flow types with customized flow scheduling algorithms. SplitAP [68] is a WLAN virtualization architecture, focused on fair sharing of uplink airtime across a group of users. A physical AP can be shared by different slices that can run different algorithms to control the UL airtime among different user groups. In Ref. [12], the virtualization of the air interface of the LTE network has been studied. Here, a hypervisor was used for virtualizing the wireless spectrum.

Different experimental test-beds (using SDN or not) have been developed to do research on clean-slate networking technologies leveraging virtualization. GENI [69], Planetlab [70], AKARI [71], SAVI [72], OFELIA [73], 4ward [23] to name a few.

From the discussion presented in this section, it is obvious that the focus of different research initiatives is very monolithic. While some address SDN-based WiFi networks, others are interested with implication of SDN in WSN or cellular networks. SDN has been used for facilitating network management and provisioning of new network protocols and services for a particular wireless network technology. Hence, a roadmap for provisioning an end-to-end programmable heterogeneous virtual network is absent in the aforementioned literature. Also, the majority of the proposals focus on programmability of the underlying switching fabric while programmability of wireless spectrum has not received the due attention.

4. Programmable radio plane

Radio plane consists of radio front-ends and radio spectrum. This last-mile access network part constitutes a very important part of the end-to-end virtual wireless network framework. For a true virtual network implementation virtualization of the radio plane is of utmost importance. This section discusses the proposals on virtualization of radio transmission chain and wireless spectrum. We classify the state-of-the art into two categories: programmable front-end and programmable nodes & spectrum sharing.

4.1. Programmable front-end

Radio front-end consists of the radio transmission chain of the transceiver systems. Programmability of the front-end gives greater control over the PHY layer processing and it also paves the way for implementing novel PHY layer processing schemes. Sora [74] is a programmable radio platform where the PHY and MAC layer functionalities are implemented in general-purpose processor (GPP) platform. Sora hardware platform consists of a radio front-end for wireless transmission and reception, a radio control board (RCB) for interfacing radio front-end with the processing engine in the server, and GPP servers. Tan et al. [74] also demonstrate SoftWiFi, a software-defined wireless system that can seamlessly interoperate with IEEE 802.11 a/b/g network interface cards. Success of such implementation is very interesting for cloud-based virtualization of wireless access networks using general purpose IT-grade servers, as it shows the feasibility of such network architecture.

OpenRadio [22] is a design for programmable wireless data plane. It provides a modular and declarative programming interface for PHY later processing of the wireless protocol stack. The architecture is divided into processing and decision planes, where the processing plane includes directed graphs of different algorithmic actions (e.g., different modulation, coding schemes) and the decision plane contains the logic as to which processing plane graphs should be used for a particular wireless stack implementation. Various wireless protocols, like WiFi, LTE can be implemented using the off-the-shelf DSP chips using this model. The hardware processing abstraction enabled by OpenRadio [22] can be leveraged for virtualization of radio front-end.

MPAP [75] is a SDR architecture based on Sora [74] platform that virtualizes the radio front end to support different radio standards on the same transmission hardware. It uses a SDR service layer which is basically a virtualization layer. To minimize interference among virtual nodes sharing a common physical node, a scheduler is used. Spectrum is shared among different virtual nodes in an opportunistic manner. Use of GPP hardware to run software implementation of different radio functionality adds significant CAPEX and OPEX gain to such architecture.

4.2. Programmable nodes and spectrum sharing

Shared access of radio nodes as well as wireless spectrum is critically important for virtualization of wireless networks. Virtual radio [76] is a virtualization framework that proposes to virtualize wireless nodes as well as the radio spectrum. In this model, the virtualization manager which is an InP-side component, takes virtual node instantiation requests from the prospective VNOs and upon the availability of resources creates new virtual nodes on a shared physical node. The paper however does not give any insight on how isolation would be managed among the incumbent VNOs that share a common physical node. Also the authors proposes to use various multiple access schemes (e.g., CDMA, TDMA, FDMA) for spectrum virtualization. But how to handle the added degree of complexity due to the viralization of radio spectrum is not discussed.

The spectrum virtualization layer (SVL) presented in [77] is a sub-PHY layer that provides transparent abstraction for spectrum allocation. It allows dynamic spectrum allocation (DSA) to be implemented in a technology agnostic spectrum manager. SVL enables abstraction of radio front-end which is very important for sharing (i.e., virtualizing) of the physical front-end by multiple players. One of the major advantages of SVL architecture is that it is fully implemented in software using Sora [74] platform.

Picasso [78] is a full-duplex (FD) transceiver system that can simultaneously transmit and receive signals using the same frequency band. The is a significant breakthrough in the traditional half-duplex transceiver systems that we use today. The major problem of designing a FD system is the leakage transmit power received at the receiver chain, which is order of magnitude higher than the received signal. This phenomenon knows as self-interference (SI) makes realizing a FD difficult. Picasso resolves the SI problem by reducing SI using both analogue and digital cancellation techniques. Moreover it enables spectrum slicing using special purpose FPGA-based digital filters.

The architectures on programmable radio plane are summarized in Table 2. The proposals discussed in this section provides techniques for modular PHY layer processing using both general purpose processors and special purpose hardware. Techniques for virtualizing radio spectrum have also been discussed as part of some of the proposals. But programming abstraction for upper layer network resources e.g., switching fabric, server pool which are critical components of and end-to-end programmable virtualized platform are not discussed in these solutions. To alleviate the spectrum scarcity problem, full duplex (FD) radio system can be used [79] that enables to use radio spectrum for both uplink and downlink at the same time. The ability to virtualize the FD system will add an additional degree of freedom in spectrum sharing among multiple VNOs.

5. Cloud computing for wireless networks

Cloud computing is a relatively new paradigm for large scale distributed computing. The major benefit of cloud-based infrastructure is its ability to provide on-demand computing resources in convenient pricing schemes, e.g., pay-as-you-go, paying for the leased resources that can be elastically scaled up or down depending on cloud clients' demand at a specific point of time. Cloud resources basically composes of storage, computing and networking elements.

There are three mainly three types of abstraction for cloud-based service provisioning, namely, infrastructure-as-a-service (IaaS), platform-as-a-service (PaaS) and software-as-a-service (SaaS). In IaaS model, processing, storage, networking and other computing resources are provided as a standardized services by cloud providers to their clients. The IaaS clients can deploy and run their own operating systems (OSes) on the leased resources from the cloud provider. For example, Amazon web services (AWS) [80], Microsoft Azure [81], Google Compute Engine (GCE) [82] are some popular IaaS platforms. In case of PaaS model, a higher level of abstraction of network resources are used and the cloud clients are provided with run time systems using which they can build

Table 2
Representative summary of work on programmable radio plane.

Programmability	Architecture	Programmable domain	Hardware platform	Layers affected	Virtualization	Summary
Front-end	Sora [74]	Protocol	GPP, FPGA	PHY, MAC	No	Programmable SDR platform using GPP servers.
Front-end	OpenRadio [22]	Protocol	FPGA	PHY	No	A programmable wireless data plane.
Front-end	MPAP [75]	Protocol, radio front end	GPP, FPGA	PHY	Yes	It is a SDR application based on Sora [74] platform,supports multiple radio standards.
Front-end & Spectrum	Virtual Radio [76]	Radio nodes, spectrum	Special purpose	PHY, MAC	Yes	A virtualization framework for radio spectrum and wireless nodes.
Front-end & Spectrum	SVL [77]	Radio spectrum	GPP, FPGA	sub-PHY Front-end & Spectrum	Yes	A sub-PHY layer providing transparent abstraction for DSA.
Front-end & Spectrum	Picasso [78]	Radio spectrum, front end	FPGA	PHY	Yes	A RF front-end architecture with full-duplex transmission capability.

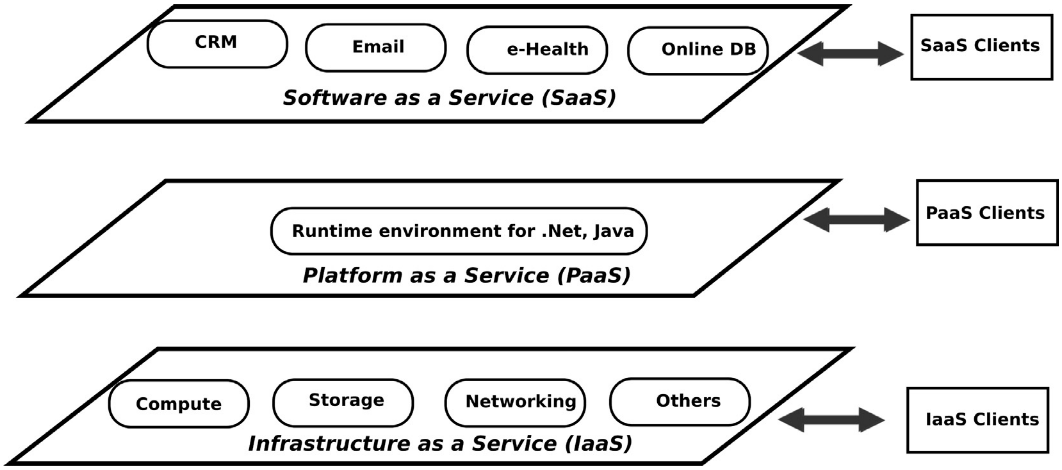

Fig. 3. Different models of cloud computing.

(program) their own customized applications and run on the PaaS platform. Apprenda [83] is a PaaS platform for developing .Net and Java based applications. On the other hand, SaaS model is the highest level of abstraction provided by the cloud providers where different applications are provided as services to the clients. Example of SaaS are: email services, various customer service management application, e-health software services, etc. Fig. 3 shows a schematic representation of different cloud models.

When cloud computing technology is extended to the virtual wireless network domain, besides the traditional cloud resources (e.g., compute, storage, network, etc.), a cloud provider should also provide access to various wireless access nodes (e.g., APs, BSs, Repeaters, sensor nodes, etc.), core network elements (e.g., EPC for LTE core network) as well as access to wireless radio spectrum. VNOs will build their customized networks with the above mentioned leased resources.

In this section, we shall discuss various cloud-based proposals for wireless networks. We have classified the state-of-the-art for cloud-based wireless networks according to the network types, i.e., cloud solutions for cellular, WiFi and heterogeneous networks. We also point out the added value of the proposals and the missing elements for and end-to-end virtualized wireless network provisioning.

5.1. Cloud solution for cellular networks

Cloud-based solutions for cellular networks have been proposed for elastic, on-demand resource provisioning, reduction of network cost and easier management of the network infrastructure. We discuss some of the notable proposals of such cloud-based solutions from both industry and academia in this section. In the position paper [84], Virtual Telco, a cloud based architecture for telecommunications network is presented. It proposes to replace several expensive centralized telecommunication control plane functionalities as distributed applications. This applications should be available on-demand and would be implemented over a pool of computing and networking resources. Operators will manage pooled hardware resources and thus basically serve as a infrastructure-as-a-service (IaaS) providers. As a use case of virtual telco, a distributed mobility management entity (dMME) for LTE core network has been also studied in this paper. Virtual Telco solution is basically a distributed cloud-based solution for several key cellular core network functionalities. The impact of such form of virtualization on the RAN below has not been investigated. Also, the virtualization techniques to be used for such virtualization has not been discussed in the paper.

China Mobile Research Institute (CMRI) [27] proposed a Cloud RAN (C-RAN) architecture, where data processing functionalities (layer 1 to layer 3) of BSs are pooled for centralized processing and radio access is provisioned via fiber-fed RRHs. Two modalities of C-RAN architecture is discussed: one is full-centralization, where layer 1 to layer 3 functionalities are implemented centrally and the other is partial-centralization that implements baseband (layer 1) processing as part of the RRH and all other functions in centralized pool. C-RAN is a virtual cloud-based implementation for cellular access networks where various PHY and MAC layer processing functionalities are implemented as software instances. This model does not discuss about the VNF based implementation of core network functionalities, also, spectrum sharing techniques among different VNOs are also not been explained.

Wireless network cloud (WNC) [85] was proposed by IBM research group. The structure composed of radio front-end device that consists of RRH, antenna and A/D, D/A converters and IT-grade server platform where all the PHY and MAC layer processing take place. Besides the IT-grade servers, to satisfy the computational demand of PHY layer processing, FPGA-based implementation of the channel decoders has been proposed in WNC architecture. 10 GbE or InfiniBand technology has been recommended to carry CPRI protocol over the optical front-haul from the baseband pool to RRHs. Timing synchronization in a TDD-based implementation has been proposed to be implemented using IEEE 1558 precision timing protocol (PTP). A TDD WiMAX based adoption of the architecture was implemented in [86]. The testbed studies the virtualization performance of a very limited number of implemented VBSs, scalability of such a platform for large-scale VBS pool deployment has not been discussed in the paper.

CloudIQ [87] framework implements the baseband processing of BSs in a general purpose hardware platform. The authors in the paper show that at least 22% savings can be achieved in computing resources by exploiting the variation in processing load among different BSs, when the baseband processing of a geographically grouped BSs is centralized in a common IT platform. OpenAir [88], an open source implementation of LTE standard, was used to implement the CloudIQ framework. This paper mainly focuses on the computing resource management and savings in the processing load when BSs in a certain area are grouped to be processed in a common IT platform to achieve a certain statistical guarantee. End-to-end virtual cellular network implementation was not studied in this work.

Kempf et al. [89] proposes to move the control plane of evolved packet core (EPC) of 4G network to the cloud using SDN. Two extensions to the OpenFlow [38] version 1.2 is used to centralize the control plane of the EPC in a data center. The extensions used are: defining virtual ports that allow packet encapsulation and decapsulation and the other is to allow flow routing using GPRS tunnelling protocol (GTP) Tunnel Endpoint Identifier (TEID). As a result, the GTP control plane can be decoupled from the serving gateway (S-GW) and packet data network gateway (P-GW) and moved to a virtual machine (VM) situated in a data center. This proposal shows the strength of SDN technology in implementing cloud-based virtual system. However, this paper addresses issue of cloud-based implementation of a specific cellular protocol, it does not give solution to cloudify the heterogeneous networks as a whole.

Huawei’s SoftCOM [90] is a vendor perspective towards a fully cloud network architecture. It envisions the cloud-based network architecture in four dimensions: Equipment-Level Cloud-Lization (decoupling hardware from the software), Network-Level Cloud-Lization (decoupling the forwarding plane from the control plane), IT system Cloud-Lization (using IT infrastructure for telecommunication purpose) and Internetized Operation (to transform telecommunications systems to internet-oriented systems). It is a throughout virtualized cloud-based approach targeting at reducing CAPEX and OPEX of the network operators. Important issues e.g., virtualization of the radio spectrum (both licensed and unlicensed bands), slice management for operational management of VNOs in an InP platform need to be analyzed for successful realization of such a platform.

EASE [91] is an on-demand cloud-based model for elastic mobile core networks. The article discusses the feasibility of on-demand creation of elastic cloud-based service for EPC with their life cycle management. The authors also presents several implementation variants of EPC-as-a-service model focusing on full and partial virtualization approaches.

5.2. Cloud solution for heterogeneous networks

Some cloud-based solution for wireless networks targets at adhoc networks, a mix of WLAN and cellular networks, for flexible resource provisioning and easier network management. A SDN-based cloud architecture for mobile adhoc networks is presented in [92]. An extension of the OpenFlow [38] protocol is used to implement wireless adhoc scenarios. Here, the nodes can operate in multiple radio access technologies (RATs), each node has a local controller that operates on behest of a central controller. In case, the connection to the central controller is unavailable the local controller falls back to operate using traditional ad-hoc protocols. The authors have simulated SDN routing as a cloud application to showcase the feasibility of such an implementation. It it to be noted, while this proposal shows the feasibility of SDN-based cloud implementation of mobile ad-hoc networks, this is a very specific case of wireless network implementation and is no suitable for an infrastructure based wireless network.

Carmen [93] is a cloud-centric network architecture for providing seamless mobility in a mobile personal grid (MPG) which is a collection of networked devices own by a user. In this architecture, the meta-states of a MPG is maintained in the cloud and a connectivity maintenance entity called *Avatar* ensures the situation-aware mobility of the user in the MPG. Carmen is a user-centric cloud approach for managing a user’s mobility in different wireless environment and various user devices belonging to the same user. This is a conceptually different approach than the end-to-end virtual wireless network deployment. Rather than virtualizing the communication network, it virtualizes the user space that consists of the wireless environment a user moves in and different devices it uses.

Concert [94] is a cloud-based architecture for cellular network edge. It uses SDN to decouple the control and the data planes to facilitate management of network applications. It distributes computing resources at different location to facilitate latency-dependent applications which is more like partial-centralized processing discussed in [27]. It uses a control plane entity called *conductor* that takes care of virtualization and orchestration of data plane resources. This architecture is very interesting for its ability to virtualize edge network and also for tackling the resource placement issue to meet the delay requirement of delay-sensitive applications. But virtualization of the core network and efficient slice management in an end-to-end programmable virtual network are the missing pieces in such a solution.

FluidNet [95] is a framework for dynamically reconfiguring the backhaul in a cloud-based radio access network for small cells. It implements logically re-configurable front-haul to apply appropriate transmission strategies that matches user profile and dynamic traffic load pattern. It serves the dual purpose of maximizing traffic demand satisfaction in the access network while optimizing compute resource utilization at the BBU pool. The authors have shown that FluidNet [95] achieves 50% improvement in traffic load satisfaction while minimizing BBU resource usage by 50%. Hence, this architecture further improves the efficiency of the C-RAN model.iJOIN [96] project proposes a RAN-as-a-service (RANaaS) architecture where the radio access network is implemented using virtualization in a cloud infrastructure. Rather than full centralization, it provides flexible centralization of the RAN functionalities and offers it as a service. This provides a compromise between achievable flexibility and depth of virtualization that VNO can choose during its negotiation phase with the InP.

Follow Me Cloud (FMC) [97] is a framework for smooth migration of all or only a required portion of an ongoing IP service between a UE and the serving data center (DC). In this approach, to ensure the best quality of experience (QoE), mobile cloud services follow the respective users by migrating all or part of the services

Table 3
Representative summary of cloud-based wireless networks.

Network type	Proposals	Virtualization	Layers	BB HW	Key attributes
Cellular	Virtual Telco [84]	Yes	Core	Traditional equipment	Distributed implementation of some core network functionalities.
Cellular	C-RAN [27]	Access	GPP servers	Partial & full centralization of BBU pools	
Cellular	WNC [85]	Yes	Access	GPP servers	VBS implementation in GPP servers.
Cellular	CloudIQ [87]	Yes	BB processing	GPP servers	Saves processing load for BB implementation in GPP servers.
Cellular	[89]	Yes	Core (EPC)	Traditional equipment	Uses extension to OpenFlow [38] to virtualize EPC.
Cellular	SoftCom [90]	Yes	Core, Access	GPP servers	Provides cloud abstraction for node, network and system.
Cellular	EASE [91]	Yes	Core	GPP servers	Implements EPC-as-a-Service for cloud-based EPC.
Heterogeneous	[92]	Yes	Adhoc	Both GPP servers and special purpose HW	Uses controller redundancy for SDN-based cloud architecture for Adhoc networks.
Heterogeneous	Carmen [93]	Yes	Access	Special purpose	User-centric mobility management for MPG.
Heterogeneous	Concert [94]	Yes	Core, Access	GPP servers & special purpose	Distributed computing resources for managing delay-sensitive traffic.
Heterogeneous	Fluidnet [95]	Yes	Access	GPP Servers	Dynamically reconfigurable back-haul for C-RAN.
Heterogeneous	iJOIN [96]	Yes	Access	GPP Servers	RANaaS architecture for virtual RAN provisioning.
Heterogeneous	FMC [97]	Yes	Core	GPP servers	A framework for migration of ongoing IP service between a UE and the service data center.

to an optimal DC. The feasibility of the FMC concept has been proven via an OpenFlow [38] based implementation in [98]. This proposal gives a solution for QoE management is a cloud-based virtual network implementation.

A summary of the cloud based wireless network architecture in given in Table 3. Significant advances have been made in cloud computing technology for wired network domain. Investigation on implication of cloud technology for wireless domain in a fairly recent trend. Because of strict QoS requirement (e.g., network delay, throughput, etc.) in wireless services, design of cloud infrastructure need careful consideration. Placement of VNFs for wireless services, distance between the wireless data center and the radio access network [99] is critically important. In a cloud-based infrastructure provisioning of compute, memory and network resources among multiple VNOs is well understood but more research effort is required for programmatic abstraction of wireless resources and their subsequent sharing among multiple VNOs.

6. End-to-end programmable, elastic HVWN

In heterogeneous wireless networks ecosystem, we observe different kinds of network deployments targeted for specific purposes. For example, wireless sensor networks (WSNs), adhoc networks, WiFi networks, cellular networks, etc. These networks have a varied range of performance requirements which translates to varied levels of spectrum (licensed or unlicensed) requirement, signal processing demand, wireless transport mechanism, security provisioning, billing mechanism, etc. In a virtual wireless network environment, VNOs will provide different kinds of services targeting various commercial applications that will require them to deploy one or more of the above mentioned network types. For this reason, it is imperative to have an end-to-end solution for provisioning programmable, elastic, heterogeneous virtual wireless networks, so that, VNOs can build their own customized network leasing the required resources from one or more InPs. Fig. 4 shows a typical scenario of heterogeneous virtual wireless networks. Here, the physical infrastructure deployed by InPs consists of wireless data centers (WDC) that are interconnected via metropolitan optical network (MON), geographically distributed virtualized base stations (BSs), WSN, WiFi hotspots, home networks, etc. The WDC houses storage and computing resources (e.g., blade servers) as well as programmable networking fabric (e.g., software-defined switches) for implementing network functions as software instances for different network types. Some of the servers contains network controller for flow-based virtualization [57] implementation. The controllers dynamically program the underlying programmable switching fabric (we use the generic term switch to refer to programmable switches, routers and other middle boxes) as dictated by a specific VNO. A mobile virtual network operator (MVNO) providing LTE service can implement its core network components, e.g., MME, PGW, SGW, PCRF, etc., as software instances in WDC. For baseband signal processing, the MVNO can process signals in software instances of BSs implemented in the WDC and transport the processed signals from the WDC to remote radio heads (RRHs) via optical fiber front haul. But the additional delay incurred in centralized processing in WDCs might not meet the QoS requirements of certain delay-sensitive applications (e.g., voice, video conferencing, etc.). In such case, processing of such traffic should be done in distributed virtualized BSs that are distributed in the coverage area of the MVNO [100].

A WiFi VNO implements the applications (e.g., authentication, authorization, accounting, mobility and interference management) necessary to run its end-to-end operation in WDC and programs the programmable WiFi nodes leased from the InP via its controller platform which translates the applications requirements to instructions recognized by the nodes. The nodes can be connected to the WDC either via optical fiber or microwave links depending on the available logistics. Also a MVNO can share all or part of the WiFi nodes' slices to increment its coverage in the area and also for offloading traffic. The virtualizer in the WDC is responsible for managing the isolation between the VNOs sharing the same physical nodes.

For virtual sensor networks, instead of deploying application specific sensor nodes, an InP deploys programmable generic sensor nodes that is capable of sensing various environmental aspects (e.g., temperature, humidity, wind speed, etc.). VNOs providing sensor network services lease slices of the sensor nodes to collect their intended environment data. This data can be forwarded to a WDC through a slice of a BS (cf. Fig. 4) deployed in the sensor network vicinity. Virtualizer in the WDC forwards the data to the appropriate VNOs (applications) where the data is processed to extract the desired information.

Over the top (OTT) service providers, for example, IPTV, online gaming provider, can lease processing and storage resources form the InPs and implement various processing blocks (optimized to for the intended services) as software instances in WDC and provide their services to the end users. Shared access of physical nodes (in WDC and customer peripheral equipments (CPEs)) and

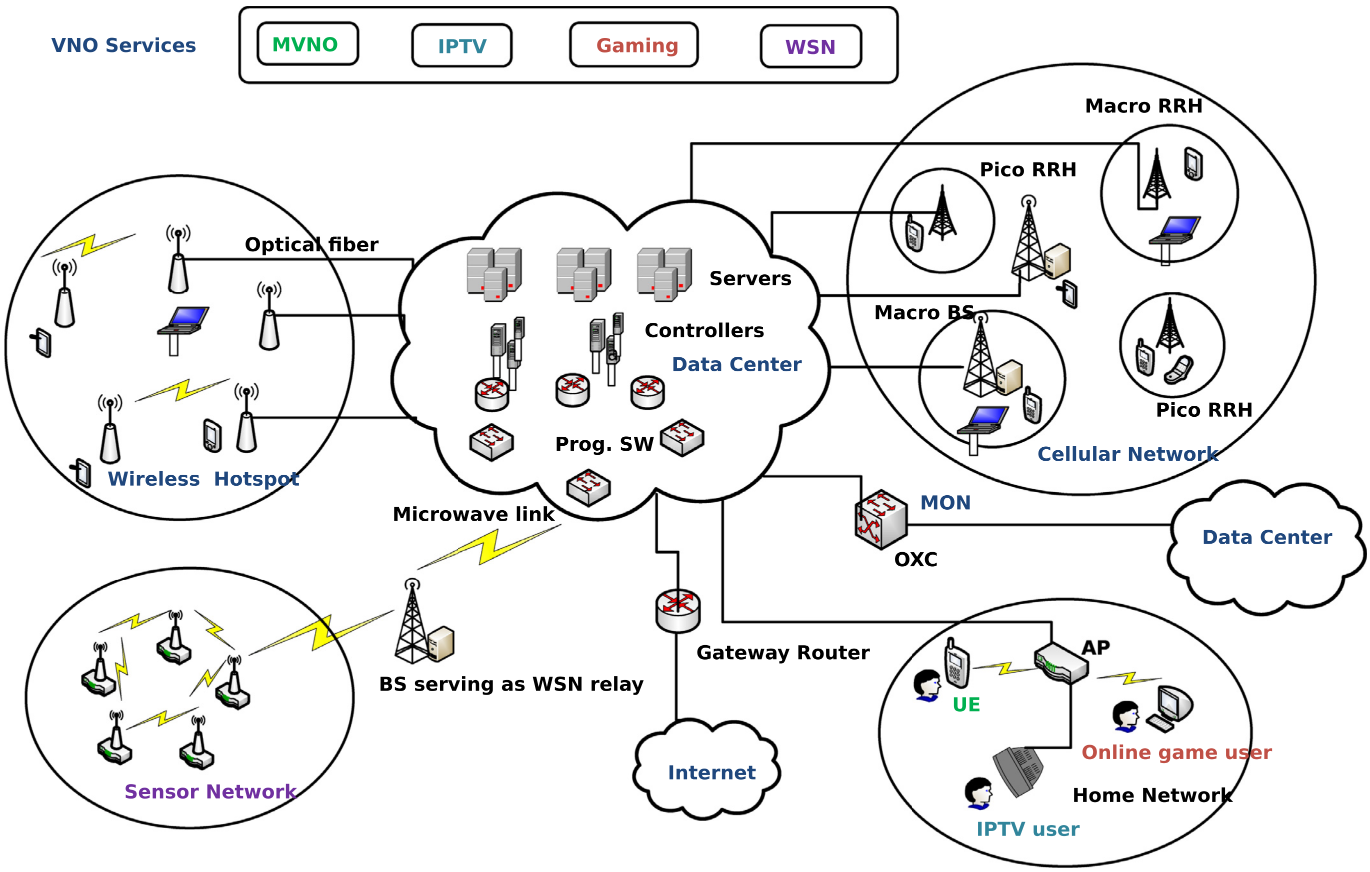

Fig. 4. Heterogeneous virtual wireless networks scenario.

wireless spectrum can be administered by incorporating local controllers in the CPEs in addition to the global controller at the WDC.

A layered representation of HVWN is given in Fig. 5. In this section, we briefly discuss the various layer of the HVWN model.

6.1. Management and orchestration layer

The management and orchestraion layer manages the resources and VNFs of the virtualized platform. It consists of physical and virtual resource managers that controls the physical and virtual resource provisioning, admission control of new VNOs, etc. The VNF manager is responsible for the instantiation, management and life cycle management of the VNFs. The spectrum manager is responsible for shared (virtualized) access of the radio spectrum among different VNOs. It can provide either static or dynamic spectrum sharing among the incumbent VNOs. The global orchestrator orchestrates the overall operation of an InP's platform. Fig. 6 gives a flow representation of different steps followed by the management and orchestration layer during a VNO request for setting up a virtual network.

For a programmable virtualized network, orchestration of computing resources (i.e., processing, memory and storage) [101] as well as the transport network [102] is important. In a cloud-based virtualized platform, for realizing sophisticated cloud services, orchestration of the infrastructure is important that include provisioning of resources, their usage monitoring, elastic scaling up and down of resources and eventual termination of the resources. Commercial IaaS services, e.g., Amazon EC2 [103], Microsoft Azure [81], Google Cloud Platform [82] offers cloud resources in granularity of virtual machines (VMs). These providers have their proprietary cloud orchestration solutions. In addition to the basic VM-based cloud services more sophisticated cloud service abstraction are being investigated, e.g., virtual private cloud instances [104] that combine cloud services with virtual private network (VPN), rapid cloning of VMs [105,106] to deal with overload conditions, etc. A data centric orchestration of cloud services is proposed in [107] that uses structured data models, a declarative query language and transactional ACID (atomicity, consistency, isolation and durability) semantics.

6.2. Service layer

Services provided by VNOs can be very different from each other. For example, a VNO can be either a mobile virtual network operator (MVNO), an IP TV provider, an online game provider, etc. The servie layer mainly expresses the services of different VNOs as forwarding graph of different virtual network functions (VNFs). A particular VNF can be shared by multiple VNOs. (cf. Fig. 5 where VNF3 is shared by MVNO, Online game and IPTV).

Virtualization enables convergence between network and cloud infrastructure. This allows combined management and optimization of networking and cloud resources. A virtualized probrammable infrastructure provides the service providers the opportunity to implement customized network solutions for their services that leverage cloud-based resources. Service oriented architecture (SOA) is a core element of cloud computing technology. The analysis of the complementary nature of the SOA and network virtualization is a very active are of research [108–110].

For providing network as a service (NaaS) model, it is imperative to determine the service requirements through network service description. For example, let us consider a service use case that performs big data analytic. The service has a specific requirement on processing, memory, storage as well as the underlying network. Network operators who offers resources to the service

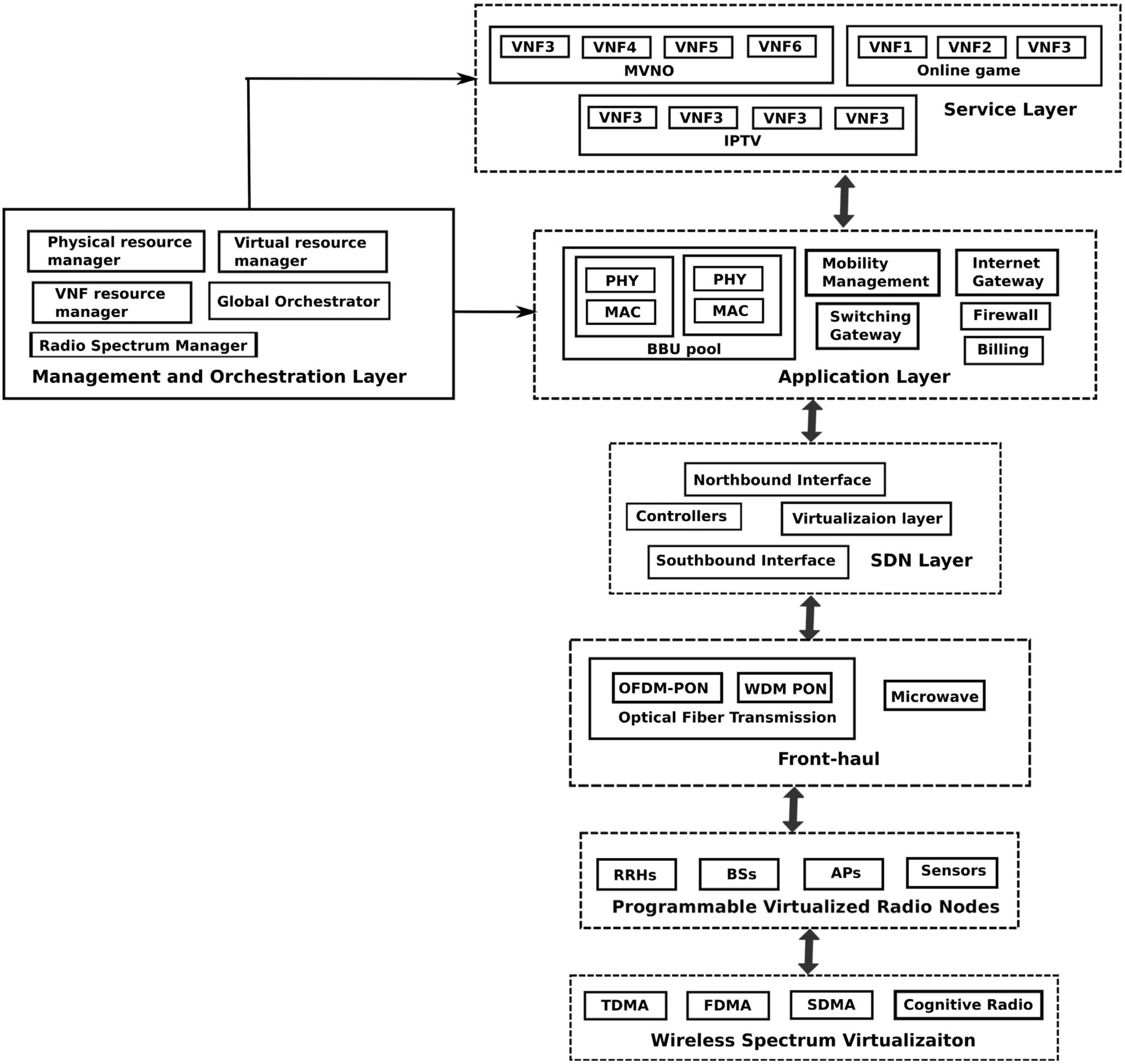

Fig. 5. Functional blocks of end-to-end programmable heterogeneous virtualized wireless networks.

providers should publish description of their offerings, e.g., available compute and storage resources, network nodes that can be reached via their networks, available bandwidth, latency performance of their networks, firewall or access policies, etc. The service providers then can select a particular network operator from their network service description who matches their service requirements. In telecommunications, there are two standards namely, Open Service Access (OSA) Parlay X [111] and Open Mobile Alliance (OMA) Service Environment (OSE) [112] that provides service layer abstraction for offering telecom infrastructure to upper layer applications. An architecture for dynamic composition of web based telecom services was proposed in [113].

For creating and end-to-end service oriented network, service composition is critical for coordinating computing and networking resources. Though significant study has been done on web service composition, a number of open issues need to be resolved for network service composition for successful realization of NaaS. Integration of traditional telecom network and cloud computing infrastructure for future 5G networks results in a large scale integrated network. Hence, scalability is an important requirement for such large scale integration.

In a HVWN environment, it is imperative to facilitate the implementation of different services with varying QoS requirement. But provisioning of QoS-aware services is particularly challenging when resources (both computing and networking) are distributed across a heterogeneous network segments. Ensuring inter domain QoS becomes particularly difficult in a converged network that consists of both traditional and cloud-based resources.

6.3. Application layer

This layer consists of different network applications that performs various network operations. For example, routing of traffic in the (virtual) network, managing the mobility of the users, blocking

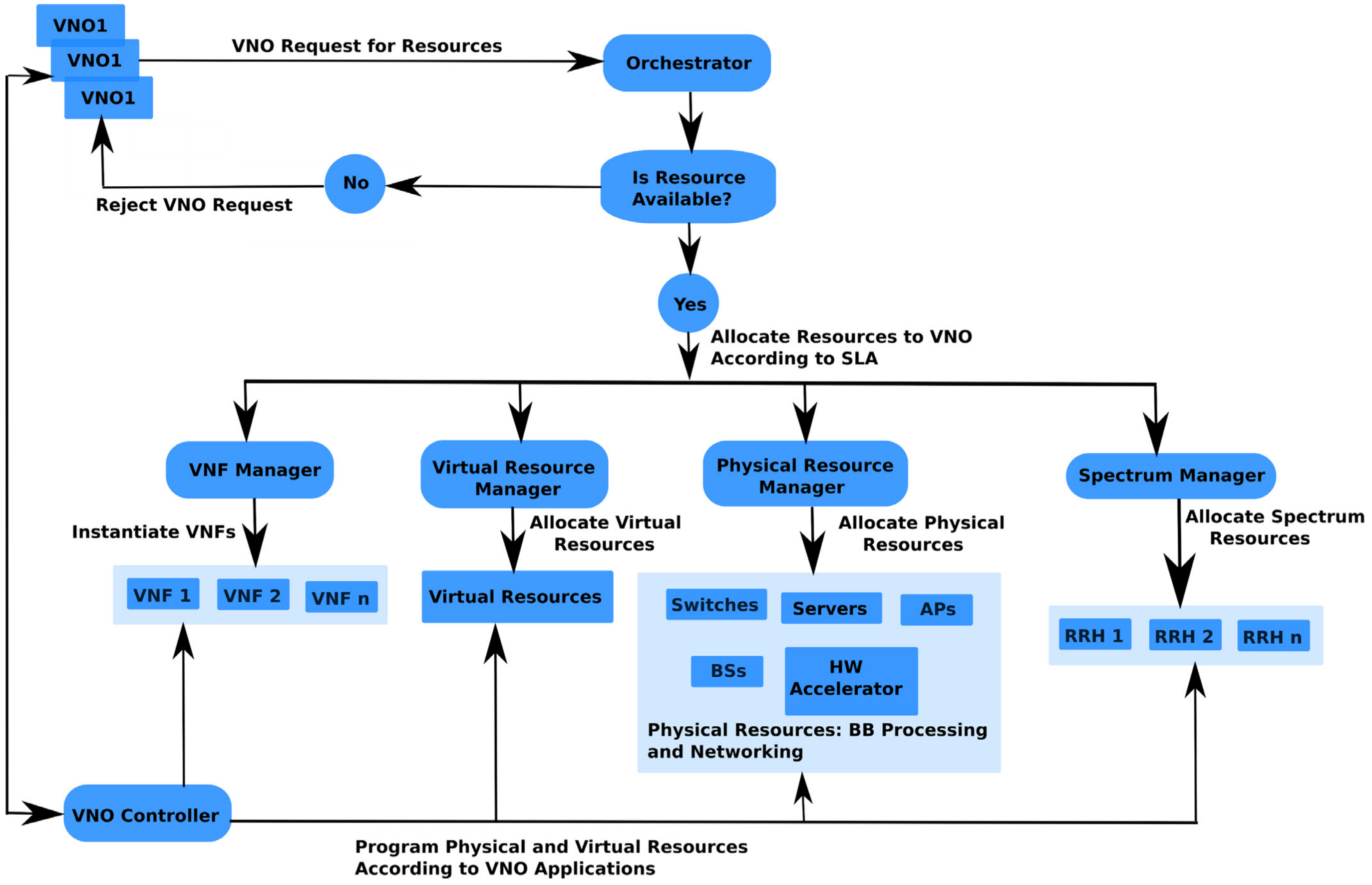

Fig. 6. Flow diagram of operational steps of the management and orchestrator layer.

malicious traffic, etc. These applications are in fact, the virtual network functions (VNFs) that performs different network functions. These applications instruct the controller layer, which in turn programs the underlying switching fabric to implement the application functionalities. For VNs that requires performing baseband operation in the WDCs, software instances of the network nodes (e.g., BSs, APs, etc.), baseband unit (BBU) pools are also implemented in this layer.

Placement of VNFs in virtual environment as well as mapping of virtual resources for VNFs are of critical importance. A formal model for resource allocation for VNF in a virtualized environment has been presented in [114]. The issue of managing dynamic network services and resources has been discussed in [115]. In this paper an orchestrator-based architecture has been presented that ensures automatic placement of virtual nodes and allocation of network services for the nodes. A model for formalizing the chaining of VNFs using a context-free language is proposed in [116]. In this model, the mapping of VNF graphs to resources are described as a Mixed Integer Quadratically Constrained Program (MIQCP) for finding the placement of the network functions and chaining them together. Greedy algorithm and tabu search-based heuristic was proposed in [117] for mapping and scheduling of VNFs.

6.4. SDN layer

To enable network programmability, separation of control and data planes is necessary. In a SDN paradigm, network intelligence is centralized in network controllers that programmatically modify the forwarding behavior of the underlying data plane devices. The main components of the SDN layer are the virtualization and the controller sub-layers.

Virtualization layer. A virtualization layer creates an abstraction of the underlying physical infrastructure. It also enforces isolation among the VNs that share common physical resources, such that, to the VNOs it appears that they own the data plane of their individual networks. The isolation or separation enforced by a virtualization entity, i.e., a hypervisor can be either physical or logical. In physical isolation, which is also known as *hard slicing*, dedicated physical resources are provided to the VNOs [14,66]. Whereas in logical isolation, known as *soft slicing*, instead of dedicated physical resources, a VNO is provided access to resources that are shared with other VNOs [57,64] while respecting the SLA (satisfying agreed upon KPIs) between the InP and the VNOs. While hard slicing provide dedicated resource guarantee, it also can result in inefficient resource utilization. On the other hand, with soft slicing, efficient resource utilization can be ensured with minimum guarantee on resource availability for each VNO. One of the most popular mode of achieving soft slicing is flow-based virtualization approach [57], which is basically bundling the flows from individual VNOs and isolating the bundles from each other.

Controller platform. A controller is a centralized control plane intelligence for a VNO. It has the global view of the virtual network and it operates on the behest of the applications residing at the upper layer. The controllers at the early stage of SDN, e.g. NOX [39], POX [40], Ryu [41] are more suitable for academic research for validating various SDN protocols and algorithms. Increased interest on SDN from all the major operators and vendors around the globe has prompted collaborative open source project like Opendaylight [42] which is a production-grade SDN controller. Different companies have their proprietary SDN controller platform that are capable of controlling packet-based and/or optical transport networks. Some of the examples of production-based SDN controllers are: Floodlight [43] from Big Switch Networks, Nuage [118] from Nokia, Virtuora from Fujitsu, Open SDN Controller [119] from Cisco Systems, Contrail from Juniper Networks Inc, etc.

While SDN facilitates network management by abstracting the underlying physical infrastructure, it is not convenient to write complex network application using the *match-action*-based programming paradigm of OpenFlow [38]. There are instances when two different applications attempt to modify a single flow-table entry that gives rise to programming conflicts. To alleviate the issue, a northbound API [44,45] can facilitate the synchronous operation of multiple applications at the upper layer by arbitrating conflicting operation of multiple applications, that tries to implement rules that might conflict with each other trying to modify a certain data plane device at the same time.

A southbound interface/API [38,46] is a control channel protocol that communicates the instruction from the controller to the underlying switching fabric. Most widely used southbound API is OpenFlow [38] where a controller modifies the forwarding behavior of the underlying switches by populating the forwarding tables of the switches with match-action based rules to dictate the forwarding of the packets traversing the switches. But the basic match-action based programming model of the OpenFlow [38] give rise to scalability issue. Extensive research and development effort is going on in the industry for a more efficient option for southbound API. One very promising open source initiative is Fast data input/output (FD.io) [120] that supports flexible, programmable and composable services on a generic physical platform. The key component of the FD.io is virtual packet processing (VPP) [121] platform which is a based on a packet processing graph. The modular construction of the VPP allows to plug-in a new packet processing module (i.e. node in the packet processing graph) without any change in the underlying code base.

6.5. Baseband signal processing

Two different varieties of baseband signal processing is possible. One is *in-situ processing* which is similar to the processing mechanism of traditional BSs [66], i.e., signal is processed in the physical BSs that have been virtualized (sliced) into multiple virtual base stations (VBSs). The other is to push the baseband signal processing to a centralized location that contains baseband unit (BBU) pools [85], this is in fact, pushing the baseband processing to the cloud. The two different models have their relative pros and cons. The *in-situ processing* will provide faster signal processing and transmission latency will be very low but as the VBSs run on special purpose hardware, the VNOs will have less flexibility in curtailing the processing characteristics of the VBSs to better fit their service requirements. Moreover, this type of implementation will be more expensive for their use of special purpose (e.g., FPGA-based) hardware. On the other hand, in cloud-based baseband processing in BBU pools, the VNOs will enjoy more flexibility and control over the baseband processing chain. In this model, BSs are implemented as software instances in IT servers, hence modifications to the processing chain is merely including software patches. Scaling (up/down) of resources is very convenient in this model because if any VNO need additional VBS instances, it can request the InP to allocate more VBS instances and in an IT-based platform, it is very convenient to elastically scale the resources. But the downside of this implementation is, the software VBSs have to full-fill the real time processing need of wireless networks which is quite significant. Moreover, carrying the processed signal from the BBU pools to the radio end introduces additional latency which might deteriorate performance of delay-sensitive applications like voice, live video, etc. Hence, a VNO has to lease resources according to the requirements of its intended service provisioning.

6.6. High capacity front-haul

Data traffic in wireless networks is increasing in an exponential manner due to video traffic domination. For this reason, in a cloud-based network implementation, a high capacity front-haul is necessary to carry traffic from the data-center to the RRHs. Being a high capacity traffic conduit, fiber optic cables are capable of carrying very high amount of traffic with very low latency, thus making them an obvious solution for high capacity front-haul. Different passive optical network (PON) solution for fiber optic communication is available in the market, for example, wavelength division multiple access PON (WDM-PON), orthogonal frequency division multiple access PON (OFDM-PON), etc. But due to geographical and logistic limitation, it might not be possible to use fiber optic front-hauls in some places. For those locations, high capacity microwave links should be used to carry traffic to and from the data-centers to the RRHs.

Statistical multiplexing gain can be achieved by pushing the Inphase and Quadrature (IQ) data to a centralized baseband pool [122]. It also enables energy efficient resources usage and saves CAPEX and OPEX. Limitation on fronthaul capacity can adversely affect spectrum efficiency, energy efficiency and quality of experience (QoE) by the users [123].

6.7. Programmable virtualized radio nodes

Depending on the deployment modalities radio access can be provided either by remote radio heads (RRHs) that compose of simple radio transceiver and antennas (for the C-RAN model [27,85]) or as part of virtualized base stations [66,67], programmable WiFi APs and sensor nodes. For the RRH deployment, sharing of the nodes by different VNOs can be facilitated by making the RRHs full-duplex (FD) capable [78], so that, different VNOs can share the antenna at the same time either in uplink (UL) or downlink (DL) direction by scheduling them in time domain. Furthermore, fine-grained control over the PHY layer processing blocks can be achieved by using programmable radio [22] based front-end. But implementing distributed RRHs for radio access demands high capacity front-haul links. Optical fiber is the obvious choice for such front-haul links due to their very high capacity and ultra low transmission delay. But deploying fiber-based front-haul might not be possible in every geographical scenario. In such cases, network coverage should be provided by in-situ physical BSs that have been sliced (virtualized) to be share among multiple VNOs (cf. Fig. 4). These BSs will be connected to the WDC via high capacity microwave links.

6.8. Wireless spectrum virtualization

Radio spectrum is the bottle neck for wireless networks, especially those operating in licensed spectrum band. Hence, licensed spectrum should be virtualized, so that, different VNOs can synchronously share them in time (TDMA), frequency (FDMA) and space (SDMA). Spectrum manager in the management and orchestration layer is responsible for managing the sharing of the licensed spectrum among the incumbent VNOs. To mitigate the spectrum scarcity problem, unlicensed spectrum should also be used in opportunistic manner wherever possible. Leveraging cognitive radio (CR) [124] technologies, VNOs can opportunistically share the free frequency band that is not currently being utilized by the primary users. Discussion of CR technology is out of the scope of this paper, interested readers can read the above mentioned paper and the references within. Opportunistic spectrum use can be administered by the Local controllers in the transmission nodes which have access to spectrum availability information in the area where the node is operating.

A spectrum virtualization layer (SVL) is introduced in Ref. [125] that supports flexible spectrum programmability below traditional wireless physical layer. Yang et al. [126] proposes an opportunistic spectrum sharing based resource allocation scheme for virtual wireless networks. The authors formulate the wireless resource allocation problem as NP-hard integer problem and propose dynamic programming and heuristic algorithms to solve the problem. In Ref. [12] wireless spectrum virtualization was achieved by scheduling spectrum resources to various virtual operators according to spectrum availability and demand from the operators.

7. Actors and their roles in a HVWN environment

The virtual wireless network paradigm in a HVWN can bring drastic changes in the business eco-system of heterogeneous wireless networks. A flatter and simplified data-plane with centralized programmable control plane architecture has the potential to introduce novel business dynamics in this area. There will be significant role change among equipment manufacturers (i.e., vendor companies), network operators and third party software providers. In this section, the roles of different players in a HVWN environment is briefly discussed.

7.1. Equipment manufacturers

The manufacturers of network nodes will produce simplified data plane devices which can be programmed through high-level abstraction. Unlike present day, complicated hardware, new data plane devices will have open APIs through which high level programs will be able to modify their forwarding behaviors. The devices can range from simple match-action based forwarding gear to more sophisticated APs, routers and middle boxes, capable of doing deep packet inspection (DPI). Standardized southbound API (e.g., OpenFlow [38]) support should be provided by all vendors. This will get rid of the closed, ossified construction of present day network equipments and operators will be able to easily integrate components from different vendor companies.

7.2. Infrastructure providers (InPs)

Physical infrastructure of the network is established and maintained by the InPs. The physical infrastructure includes the computing, storage and networking resources, as well as the radio access nodes and backhaul links. They are also responsible for creating virtual network resources by *slicing* the physical resources. These virtual resources in turn are leased by the VNOs to roll-out their own (virtual) network. From cloud computing perspective, the InPs can be seen as infrastructure as a service (IaaS) providers. An InP can also own licensed spectrum which it will share among the VNOs it is hosting. In addition, an InP can also function as a VNO to provision any specific service. To enable the cloud tenants (i.e., the VNOs) to implement their customized network applications, InPs should support standardized northbound APIs [44] that will open-up a flexible, high-level programming abstraction of the underlying virtual resources, so that, the network programmers can write sophisticated applications without having to be aware of the physical resources. Currently, there is no standardized northbound API but efforts [127] are being put forth in this direction.

7.3. Mobile virtual network operators (MVNOs)/service providers (SPs)

MVNOs/SPs lease virtual network resources from the InPs and build their own customized networks. Using the flexible abstraction of the physical resources, the VNOs (MVNOs/SPs) can implement their network with customized network protocols tuned for optimal performance of their intended services. VNOs can offer a variety of services using the IaaS platform of the InPs. For example, MVNOs can implement their services using customized mobility management, policy enforcement and charging policies. Their virtual existence is transparent to the general users as there is no change required on the UEs and service offering model is similar to that of a physical network operator today.

Over the top (OTT) service providers like YouTube, Netflix, online game providers etc., can lease resources (e.g., wireless spectrum) from InPs to ensure a minimum QoS (rather than Internet's best effort services) of their services, so that user satisfaction can be ensured which is very critical for their continued business success. As service differentiation is one of the major benefits of software-defined HVWN, it is technically very convenient for the InPs to ensure QoS for such OTT SPs. By having their own virtual network, SPs can implement their customized processing (e.g., transcoding for HD video, accelerated streaming protocols, etc.) functions to enhance the quality of their services.

7.4. Third-party software companies

Different network services are implemented as software packages in HVWN. Third party software companies, specialized on network applications can produce different applications as per requirement of the InPs and VNOs. In this model, software packages can be provisioned as *managed services* by the software companies. This will relieve the network operators of having a dedicated software department for implementing new services and making patches for the existing services. The advantage of such a business model is two fold: on one hand, the VNOs can save operational expenditure by not maintaining a software team and on the other hand, new software companies can flourish that are specialized in developing network applications.

7.5. Inter ISP-VNO traffic offloading

As mentioned earlier, mobile users' traffic is dominated by high volume video applications. It has been observed that, users tend to be static [128] while using high data rate applications like: HD movie, online gaming, etc. Most often the users are under the coverage of a WiFi hotspot, typically run by a internet service provider (ISP). To reduce the strain on the licensed spectrum of a VNO, the high data rate traffic of static users can be offloaded to the ISP's WiFi. The ISP can charge the VNO according to their service level agreement (SLA). Depending on the SLA, an ISP can have various access and charging policies for different VNOs.

8. Potential research issues & challenges

HVWN is a very promising network architecture that make possible building end-to-end programmable, on-demand virtual networks for a range of wireless network environments. But a number of challenges need to be addressed for a successful realization of HVWN. Some of these challenges are briefly discussed in this section.

8.1. Standardization of APIs

For a successful, well accepted design solution, it is important to ensure the interoperability of applications and equipments developed by different players i.e., equipment vendors, operators and third party software companies. To materialize this, standardization of different interfaces (i.e., northbound, southbound, east-westbound) is of utmost importance. OpenFlow [38] is already a well accepted standardized southbound API (maintained by ONF [129]) for interfacing the network nodes with the controller layer. Many commercial products by different vendor companies are available in the market that use OpenFlow as a southbound API. Standardization of northbound API [44], [45] is also necessary, so that, network programmers can build modular, reusable applications [130] without worrying about the underlying physical hardware and control platform. ONF has already started a working group [127] to standardize the northbound API. Similarly, for control platform interoperability, a standard east-westbound API is also needed which should be agreed upon by all the parties (e.g., vendors, operators) involved.

8.2. Balance between flexibility and complexity

Different levels of abstraction is possible for building a software-defined virtual wireless networks. A FlowVisor [57] abstracts the physical network in flow-level granularity, so it is convenient to build flow-based virtual wireless networks using this hypervisor model. But this hypervisor model does not give any control over the processing modality of the devices, hence, it is not possible to modify the PHY, MAC layer processing chains of devices using this model. On the other hand, OpenRadio [22] provides a rich platform to compose novel wireless protocol stack by separating the protocol from the hardware. It supports different wireless protocols (e.g., WiFi, 4G) on a common hardware platform and enables a programmer to select processing blocks at the PHY layer. But the platform does not provision for upper layer management, for example, building complex, modular network applications is not possible through this architecture. Hence, during network build-up, a compromise has to be made between the level of flexibility and the depth of control that the platform will provide for building sophisticated, efficient programmable virtual wireless networks on top of a common physical substrate.

8.3. Security threats minimization

While SDN allows to build network applications to provide a secured wireless network, it has its fair share of security pitfalls. Interestingly, the unique characteristics of a SDN paradigm, i.e., the separation of control & data planes and network programmability opens up doors for various security threats. Kreutz et al. [131] identified couple of threat vectors for software defined networks, e.g., faked traffic flows, switch vulnerability, compromise of controller and control plane communications, etc. Interestingly, these are all specific to the software defined networking paradigm. To alleviate the above mentioned security threats, some precautionary measures are also proposed in [131], for example, replication of network controller and applications, so that, a back up node can take charge in case the acting one fails. There should be diversity among the controllers and they should be provisioned for auto-healing mechanism to recover from a security attack. Security measures to protect the network should be an integral part of the network design process from the very early phase.

8.4. Virtualization of wireless spectrum

Due to stochastic nature of radio propagation environment, abstraction of wireless spectrum is very challenging. Virtualization of wireless spectrum can be achieved by static or dynamic allocation of spectrum among the incumbent VNOs. While static allocation provides guaranteed spectrum allocation, it might result in inefficient spectrum utilization. On the other hand, dynamic spectrum allocation that ensures fairness requires efficient scheduling algorithms. Opportunistic spectrum sharing in non-contiguous frequency band along with the use of non licensed band can be beneficial for the VNOs.

8.5. Definition of isolation

Virtualization bring about the contradictory concept of maintaining isolation among VNOs while they share common resources. Hence the definition of slicing need to be agreed upon among the concerned parties (e.g., vendors, operators, third parties, etc.). This brings forth the discussion on *hard slicing* vs *soft slicing*. Hard slicing refers to dedicated resources allocated to a VNO and soft slicing means that there will not be any dedicated resource allocation per say but the VNOs will have guarantee for minimum KPIs through the agreed upon SLA. While hard slicing will ensure perfect isolation and higher customer satisfaction by providing higher QoE, it will result inefficient resource utilization. On the other hand, soft slicing will increase resource utilization but it might also impact the performance (in the form of achieved QoE) of the VNOs.

8.6. Integration of cognitive radio (CR)

Spectrum scarcity is a pressing problem in wireless networks especially for cellular operators. Cognitive Radio (CR) technology [124] can go a long way to minimize the spectrum scarcity problem by enabling the use of idle spectrum by other users. The main idea behind CR is, to allow secondary users to utilize unused (idle) radio spectrum belonging to primary users. A CR senses its surrounding environment and adaptively tunes its transmission parameters to transmit data while maintaining required QoS. For its ability to *virtually* expand the radio spectrum, it has been proposed [132,133] to be used in existing networks.

8.7. Backward compatibility

Using SDN and Cloud computing for wireless networks is a fairly recent trend in wireless research. The ultimate goal is to replace the distributed traditional networks with logically centralized control platform. But for its gradual inclusion to the existing network infrastructure, it is very important to ensure its smooth interoperation with the existing wireless network infrastructures. Various *buffer devices/applications* can be placed at the interface of the two modes of networks that will complete the necessary translation of control and data plane information. Keeping the processing delay in such buffer devices/applications to a bare minimum will be a challenging issue.

8.8. Additional delay in virtual networks

Delay is a critical parameter for ensuring QoS of the applications in a network. Virtualization requires additional layers of abstraction that introduces additional processing delays in the network. Moreover, for centralized processing of signals there is an additional delay for transmitting the signal the RRHs and the centralized BBU pools. For this reason, careful planning of the BBU pool (i.e. data center) dimension and spanning length of the optical fiber is needed, so that, a balance between network cost and QoS is achieved [99]. To fulfil the QoS requirement of delay-sensitive traffic, special purpose hardware should be used in data centers in addition to general purpose IT grade platform.

SDN is predominantly used in reactive mode, i.e., each time a switch gets a new packet it sends the packet to the controller to decide on the forwarding rule for that particular packet flow. This model is not scalable for a production network that involves thousands of switches where each switch handles hundreds of million of new flows. To resolve the issue, proactive active switch programming should be used where the controller installs forwarding rules to switches for known traffic destinations.

9. Conclusion

In future heterogeneous wireless network scenario, different types of service providers will provide services in various target network environments. And a cost-effective network solution to the services providers can be provided through a virtualized infrastructure. In this paper, we bring forth the convergence of virtualized heterogeneous wireless network infrastructure that facilitates abstraction of physical resources, hence paving the way for their efficient utilization.

The two key requirements that the future service providers will need are programmability and elasticity of their networks which will provide them enough flexibility & control over the network substrate and make them able to scale up/down their network resources to meet customer demands. In this respect, we have presented an end-to-end programmable, cloud-based solution for heterogeneous wireless networks named HVWN. It provides programmability in both network core and access by employing SDN and programmable radio technologies. To meet the service requirements of different kinds of networks, HVWN uses cloud-based resource pools in distributed WDC as well as virtualized APs that use general purpose hardware and in-situ signal processing. VNOs can lease appropriate resources form the InPs to deploy their customized virtual networks. Different layers of the HVWN have been discussed in detail. To showcase the advances made in pertinent technology to materialize the HVWN concept, a survey of software-defined wireless networks, programmable radio plane and the use of cloud computing for wireless networks has also been presented in this paper. Business cases for virtual wireless networks have also been discussed. Finally, we explored the critical research issues and challenges to resolve in implementing programmable virtualized heterogeneous networks.

To sum up, virtualization of heterogeneous wireless networks is very significant in combating different logistic problems of current network deployments as well as to cater for future network demand. But a broad range of research issues and challenges are need to be tackled. In this paper, we have presented the current technologies that are instrumental in realizing a HVWN platform, we have also explored the missing pieces of the puzzle that are needed for successful materialization of HVWN.

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