Configuration Cost vs. QoS Trade-off Analysis and Optimization of SDR Access Virtualization Schemes

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***Abstract*—Virtualization is seen as a killer application of software defined networking (SDN). Virtual radio access network (RAN) is an emerging concept for 5G and beyond 5G networks and it is gaining increased attention from both academia and industry alike. Moreover, due to the current telecommunication trend of increasing network traffic and decreasing revenue, telecom operators all over the world are looking for network function virtualization (NFV) to reduce network deployment and running cost by maximizing resource sharing. In this paper, we classify virtual RAN into three possible PHY-MAC models that leverage SDN for virtualizing the underlying RAN substrate. A novel multi-criteria utility function is also proposed to evaluate the trade-offs between network cost and achievable QoS from PHY-MAC layers perspectives of these virtual RAN models. Analytical results show that a hybrid virtualization model attains the optimal balance between network cost and QoS and hence is the best virtual RAN model.**

***Index Terms*—Radio access networks, Platform virtualization, SDN, Quality of service, PHY, MAC.**

I. INTRODUCTION

Data traffic is growing in an exponential manner in cellular network. Different user applications in smart-phones and tablets are generating a plenitude of data which is mostly dominated by video traffic. Different service providers (SPs) are offering services that have varied requirements of network protocols and data processing for optimal service provisioning. Today's cellular networks, characterized by vendor specific network nodes with complex control plane functionality is struggling to satisfy such requirements and is incapable to meet the need of future network dynamics. Moreover the high capacity requiring user applications are creating a serious strain on the limited licensed spectrum. Telecom network operators are struggling to keep up with this increasing traffic demand while the revenue is not increasing in a similar pace. For this reason, it is a pressing need to re-architect the current network infrastructure that will facilitate innovation by enabling network programmability and ensure efficient resource utilization while reducing the overall network cost.

We argue that virtualizing the network infrastructure can resolve the challenges faced by the future to a great extent. And we deem software defined networking (SDN) as an enabler for wireless access virtualization, as it adds an extra degree of freedom by enabling programmability of the underlying physical infrastructure due to its unique ability to separate the network control from the data plane. SDN can provide a programmable networking fabric where multiple isolated virtual networks can operate on a shared pool of physical resources. It can also enable new business dynamics by separating the role of infrastructure providers (InPs) and SPs and / virtual network operators (VNOs), where the InPs are responsible for deployment and management of the physical resources and SPs & VNOs lease the virtual resources from the InPs to roll-out their own customized networks. Using IT-grade network equipment for baseband processing, the overall network deployment cost can be reduced, moreover the use of general purpose hardware platform will further reduce energy consumption which in turn will reduce carbon foot-print of the telecom industry.

Different aspects of wireless virtualization has been studied in different research initiatives, for example, spectrum virtualization [1],[2], virtualization for different wireless technologies (a.e., WLAN, WiMAX, LTE) [3],[4],[5],[6]. Major telecommunications vendors and operators are teaming up for research in network function virtualization (NFV) [7]. European commission's co-funded project, FP7-iJOIN [8] is investigating the use of cloud computing for a RAN as a Service (RANaaS) paradigm. Due to its added flexibility in network designing, software defined networking (SDN) is being seen as a crucial driver to virtualize wireless access [9],[10],[11] and core [12]. To enable a shared, elastic, virtual wireless network infrastructure, cloud computing is also being envisioned as a crucial component [13],[14],[15].

The aforementioned works focus on particular aspects (e.g. radio spectrum, base band processing nodes, various wireless technologies, access and core networks, etc.) of wireless virtualization but no unified solution to wireless access virtualizaton is present in the open literature. In this regard, we classify radio access network (RAN) virtualization into three models that use SDN for virtualizing the underlying radio access network. We have proposed a network utility method that considers network cost (both deployment and running costs) and achievable data rate to evaluate the pros and cons of the virtualization models and give a guidance to a network designer to choose a certain framework/model that satisfies the budget constraint and quality of service (QoS) requirement of the intended service to be provisioned. In this article, Section

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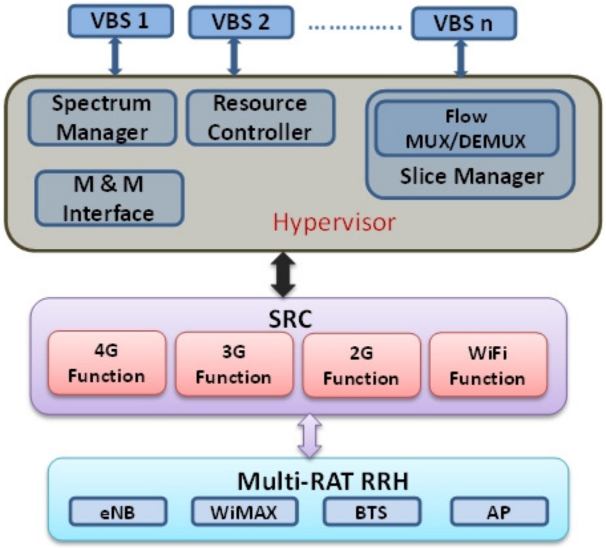

Fig. 1: Bolck diagram of a multi-RAT SBS.

II details the RAN virtualization models, while in Section III, we present the utility model and analysis results, finally, conclusion is drawn in Section IV.

II. VIRTUALIZED SDRAN CLASSIFICATION

We classify virtualized SDRAN models into three frameworks: locally virtualized network (LVN), clustered/remote virtualized network (CVN/RVN) and hybrid virtualized network (HVN), respectively. This section gives detail description of the virtualized SDRAN models.

A. *Locally Virtualized Network (LVN)*

LVN architecture

A novel BS architecture, referred to as super base station (SBS), which is an enhanced version of the multi-RAT BSs [16] with hardware augmentation (by including a hypervisor module) has been proposed for the LVN framework. The hypervisor consists of four components: resource controller, spectrum manager, slice manager and management and monitor (M&M) interface (Figure 1). The resource controller is in-charge of physical resources (compute, storage, etc.) provisioning among the incumbent virtual base stations (VBSs). The spectrum manager does the air interface virtualization, it is basically a spectrum allocation entity that provides radio resources to the VBSs according to their need and service level agreement (SLA). Specialized software libraries (SLs) are used to handle the resource allocation for each RAT. For example, the SL for OFDMA-based networks (LTE, WiMAX) assigns physical resources at the granularity of physical resource blocks (PRBs) of the OFDMA frame structure. Similarly, for other incumbent RATs, the corresponding SLs will partition resources depending on the underlying PHY and MAC layer technologies.

The slice manger is the virtualizing entity (software defined) that implements flow-based virtualization [17]. It ensures the isolation between different virtual base stations. It has a flow multiplexing/demultiplexing unit that manages flows to different slices (VBSs). For proper management of the wireless access, a VNO needs to monitor the state of its nodes and act if any change is necessary. This functionality is provided by the M&M API of the hypervisor.

The hypervisor interacts with the single radio controller (SRC) [16], which is a unified network controller for multi-standard radio resource management. As we can see from Figure 1, the SRC has 4G, 3G, 2G and WiFi function modules which manage the corresponding transceiver units at the multi-RAT remoter radio heads (RRHs).

The models in [3], [4] and [5] modify the existing network nodes and use a separate IT-based overlay network to implement virtual networks. But the LVN model proposed in this paper uses a single network substrate composed of SBSs to implement VBSs. We propose to use OpenFlow [24] for flow-level virtualization inside the SBS; also the nodes in LVN are multi-RAT capable.

For n_{op} operators operating in an area A, if the number of slices per SBS is n_{sl},the required number of SBSs in that area is (modifying equation in [18])

$$N_{SBS} = \frac{n_{op}}{n_{sl}} \times max\left(\frac{A}{\pi \times d_{sbs}^2}, \frac{N_{ue} \times R_{ue}}{R_{SBS}}\right) \qquad (1)$$

where, d_{sbs} is the coverage radius of a SBS, N_{ue} is number of active users, R_{SBS} and R_{ue} are SBS data rate capacity and the average user data rate requirement, respectively. In the analysis, macro-SBSs are rolled out for coverage limited case, whereas smaller (micro and pico) cells are deployed for capacity-limited case according to traffic demand of specific regions.

A SBS being basically an augmentation of a traditional BS, we use the cost of a traditional BS as a basis for calculating the SBS cost. We suppose that the cost of every SBS increases by γ (= 0.2) (this is just a simplified assumption, as SBS facilitates resource sharing, there will be economies of scale) with the number of slices it houses. So, the cost of the SBS radio equipment is

$$C_{eq_i}^s = C_{eq_i} \times [1 + \gamma \times (n_{sl} - 1)] \qquad (2)$$

where, C_{eq_i} is the cost of a traditional BS at tier i, n_{sl} is the number of slices in a SBS. We use the method for *cumulated discounted cash flow (CDF)* to calculate the total cost per tier i in present time. We are skipping detail analysis of network dimensioning and cost modeling for the virtual SDRAN models due to space limitation.

B. *Clustered/Remote Virtualized network (CVN/RVN)*

SDN and cloud computing are at the core of the proposed CVN/RVN model. By separating the control and data planes, SDN enables network programmability, innovative service provisioning in otherwise closed telecommunication networks.

Resource sharing, elastic and on-demand resource provisioning is possible via a cloud computing paradigm. In this model, BS functionalities are implemented in software in IT-grade servers having GPP, while radio access is provided via fiber-connected, distributed, multi-RAT RRHs. This model consists of three parts: the Network Orchestrator (NO), the Radio Access Network (RAN) and the Core Network (CN).

Network orchestrator (NO)

The NO controls the underlying physical and virtual resources. It contains controllers for both the RAN and the CN. Each controller has a network (sub-)controller that controls the underlying SDN-based network fabric. The compute & storage (sub-)controller controls the computing and storage resources. The design of NO is motivated by the SDI resource management system in [10], which is used to controls and manage the underlying networking & computing resources in a wired network environment. The NO proposed in our paper, controls and manages the underlined network fabric and the corresponding compute & storage resources for a multi-RAT virtual wireless access network. For virtual networks configuration & monitoring, it provides an interface to the VNOs and SPs.

Radio access network (RAN)

The RAN is composed of network fabric and compute & storage parts. A detailed network diagram is shown in Figure 2. The underlying constituent parts are described below.

Network fabric: SDN separates network control plane from the forwarding plane which greatly facilitates implementation of virtual networks. A VNO or SP can build its own customized network by leasing virtual nodes from the InPs. The SDN applications (by VNO, HD video provider, Sports channel provider, Gaming companies, etc.) can be built by using high level network programming API (a.e. Pyretic [19]). Domain specific programming languages like Pyretic [19] are programmer-friendly and provide high level network abstraction and facilitates programmers to write modular network applications. Different controller platforms (a.e. POX [20], NOX [21], Ryu [22], FloodLight [23], etc.) translates these SDN applications for the underlying southbound APIs. A FlowVisor [17], which is basically a transparent proxy implements virtualization. It ensures isolation among the VNOs/SPs (SDN applications).

The high level network policies specified in SDN application are installed in the underlying SDN-enabled switches via a southbound API, a.e. OpenFlow [24]. A multi-RAT interface layer (ADC/DAC) translates the information to the appropriate RAT by the optical (/microwave) front-haul.

Compute & storage unit: The compute & storage controller takes the high-level requirements from the third parties (a.e. VNOs and SPs) and allocates computing, storage and radio resources according to the service level agreements (SLAs). Heterogeneous multi-RAT technologies use different PHY, MAC layer functionalities and radio resource management (RRM) techniques. To facilitate development of customized RAT technologies, different PHY, MAC and RRM techniques are deployed as individual software modules in GPP servers (c.f. bottom-left part in Figure 2). As such, any VNO or SP can combine different modules to efficiently deploy its intended service & application. As different PHY layer functionalities have high processing requirements, special purpose hardware and hardware accelerators are used for this purpose. We refer to the RAN part of the CVN/RVN architecture a central processing center (CPC). From the economic and service-quality points of view (more will be discussed in Section III-B), the size of CPCs can vary. When a single *large*-CPC is used to cover a certain geographical area A, we refer to this network as a remote virtualized network (RVN). When a number of *smaller*-CPCs are distributed to cover the area A, the network is called a clustered virtualized network (CVN).

Core Network (CN)

The core network (CN) functionalities (MME, PCRF, etc.) are implemented as software instances and the network is virtualized through flow-based slicing. As the main focus of this paper is the radio access network and due to space limitation, we are not giving implementation details of the CN, we will detail it in our future publication.

C. Hybrid Virtualized Network (HVN)

The CVN/RVN model has advantage from network cost perspective but due to the use of optical fiber for carrying baseband signals from CPC to RRHs (and vice versa) and added delay compromises the achievable data rate, hence network QoS. On the other hand, though the LVN model can guarantee better QoS than the CVN/RVN model, it is entitled to overall higher network deployment cost. To alleviate this problem, a HVN can be used, which is basically a combination of the LVN and the RVN. A HVN uses wireless data-centers (CPCs) with SBSs distributed in the coverage area to meet the service requirement of delay sensitive traffic. For an example, suppose a data-center (either type RVN or CVN) covers a certain metropolitan area that has many offices in the down-town which produces significant amount of voice and live video traffic during the office hours. A data-center with distributed RRHs might not be able to cope with this highly delay-sensitive traffic demand. To alleviate this problem, a number of SBSs can be distributed through out the down-town area, in order to handle the delay-sensitive traffic (voice, live video, etc.) and off-load the more delay-tolerant (text, file transfer, web browsing, video streaming, etc.) traffic to the data-center. A network designer has to take into consideration the demography and expected traffic patterns of a certain area and design a HVN that covers the whole region and is able to handle the traffic QoS demand in most efficient way. A HVN can be expressed as

$$HVN = p_c \times RVN + (1 - p_c) \times LVN \tag{3}$$

where, p_c is the portion of the HVN network that uses a data-center (i.e., the CVN/RVN part) and $(1 - p_c)$ is the portion of the network of the HVN that uses SBSs (i.e., the LVN part).

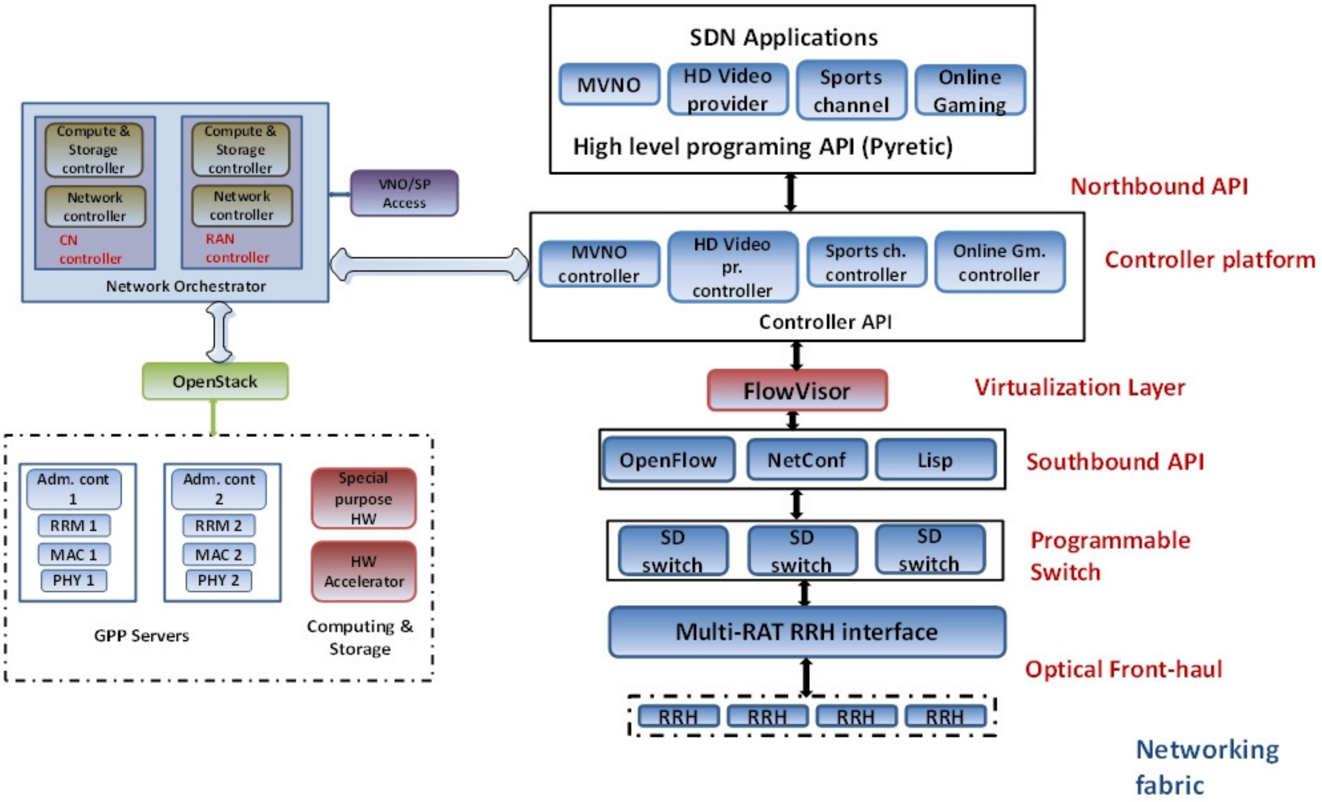

Fig. 2: Functional block representation of a CVN/RVN RAN with a network orchestrator.

III. ANALYSIS OF THE VIRTUAL SDRAN MODELS

The virtualization frameworks have their relative pros and cons from network cost, energy efficiency [25] and QoS point of views. Using IT-grade network equipment in a CVN/RVN architecture is more cost-efficient than deploying SBSs in a LVN framework. But using radio over fiber (RoF) for carrying signals from CPC to the RRHs (and vice-versa) introduces transmission delay, power dissipation and other RoF anomalies which contribute to the achievable network QoS. To investigate the trade-offs between a network operator's budget and the service quality requirements of the intended service, we have developed an analytical model for the proposed virtualization frameworks. This model considers both network cost and the QoS (achievable data rate) as well as the operator's preference for cost effectiveness and service quality of the network. Network cost modeling is inspired by [18] on cost analysis of 3G cellular systems. In our own analysis, we have considered only single-RAT multi-tier networks for the sake of simplicity and conciseness. The most general multi-RAT multi-tier HetNet case is under investigation and the subject of a future publication. We have considered long term evolution time division duplex (LTE-TDD) downlink transmission, as a test case for evaluating the achievable QoS in different virtual wireless models. The granularity of the physical resources considered is the physical resource block (PRB) of the OFDMA frame structure. In this section, we briefly discuss LTE-TDD system and network utility model construction followed by analytical results.

TABLE I: Special subframe configuration for normal cyclic prefix.

Special subframe configuration	CP in OFDM symbols DwPTS	GP	UpPTS
0	3	8	1
1	8	3	1
2	9	2	1
3	10	1	1
4	3	7	2
5	8	2	2
6	9	1	2

A. *LTE-TDD configuration*

LTE operates in two different modes: Time Division Duplex (TDD) and Frequency Division Duplex (FDD). In our analysis, we have considered the TDD mode of operation due to its wide acceptance among mobile operators around the world. One other key motivation is that TDD, in contrast to FDD, could operate in full-duplex mode.

However, using TDD requires tight coordination and synchronization among network equipment in the same coverage area. The special sub-frame (in the OFDM frame structure) mainly takes care of the DL-UL synchronization. This subframe constitutes of three parts: the Downlink Pilot Time Slot

(DwPTS), the guard period (GP) and the Uplink Pilot Time Slot (UpPTS). The GP mainly compensate for the switching time (i.e. toggling between Tx/Rx modes) of the network nodes and the propagation delay between the evolved node Bs (eNBs) and the UEs. Table-I [26] shows the sub-frame configuration for the LTE-TDD using normal cyclic prefix.

B. Data rate and Utility function construction

Achievable data rate in an OFDM transmission system that incorporate optical fiber as an intermediary transmission medium can be deduced modifying the data rate equation of [27] as follows

$$R_{LTE} = \frac{N_{sub} \times N_{mod} \times N_{cod} \times (T_{sf} - t_{enb} - d_{cpc} \times d_l)}{[1/(n \times \frac{BW}{N_{FFT}})](1+G) \times T_{sf}} \times FER' \quad (4)$$

where, N_{sub} is the number of data sub-carriers, N_{mod} is the number of modulated bits per symbol, N_{cod} is the coding rate, *BW, n and G* are the operating bandwidth, sampling factor and the cyclic prefix length, respectively. T_{sf} is the length of the special sub-frame, t_{enb} is the switching time of the base station (eNB in a LTE network) and d_{cpc} is the radius of the CPC, l is the RoF transmission latency per km. And FER' models the severity of the transmission channel by encompassing different PHY layer parameter (a.e., SNR, channel condition, etc.).
Now, we define the multi-criteria network utility function that is composed of network cost and achievable data rate. A network operator should be able to express their preference in terms of level of importance to network cost (both CAPEX and OPEX) and QoS (data rate). The preference indicates how important one criteria is (over the other) in the framework selection process. Since, network cost and QoS are not compensatory in the selection of a particular framework, the nullity and unity of the utility function is important [28]. For this reason, we compose the network utility as the geometric sum of normalized network cost and QoS gains:

$$\begin{aligned} U_{opt}(args1) &= max_{args2}[U(args)] \\ &= \left(\frac{C_{max} - C}{C_{max}}\right)^{w_c} \times \left(\frac{R_{LTE}}{R_{LTE}^{max}}\right)^{(1-w_c)} \end{aligned} \quad (5)$$

where, w_c and $(1 - w_c)$ are the cost and data rate weights respectively and args2 = coverage radius of a macro BS (MBS) (d_{MBS}), CPC coverage radius (d_{cpc}), user density (ϕ), HetNet configuration (ν), system bandwidth (BW), GP , args1 = other PHY and MAC layer (modelled by α) and $args = args1 \cup args2$. Also maximum cost of a network, $C_{max} = max_{(d_m,\phi,\nu)}C$ and $R_{LTE}^{max} = max_{(BW,GP,d_{cpc})}R_{LTE}$.

C. Results

The optimal size of a CPC depends on different network parameters such as BW, d_{MBS}, ϕ, ν, etc. One of the most critical parameters affecting the CPC radius is the GP value of an OFDMA subframe. Figure 3 shows how the CPC size varies for different GP values. It is observed that, when the primary concern is the QoS (i.e. less emphasis is given on the cost), CPCs with lower size are suggested but when the operational budget is constrained, a network designer should go for bigger CPCs having larger coverage area. A CPC size of 1 to 3 km (in a 20 km coverage area) is preferred for a wide range of w_c values. Interestingly, in the extreme case, if there is no budget restriction (w_c = 1), the optimal CPC size is 10 km, which means RVN is never the optimal design choice.

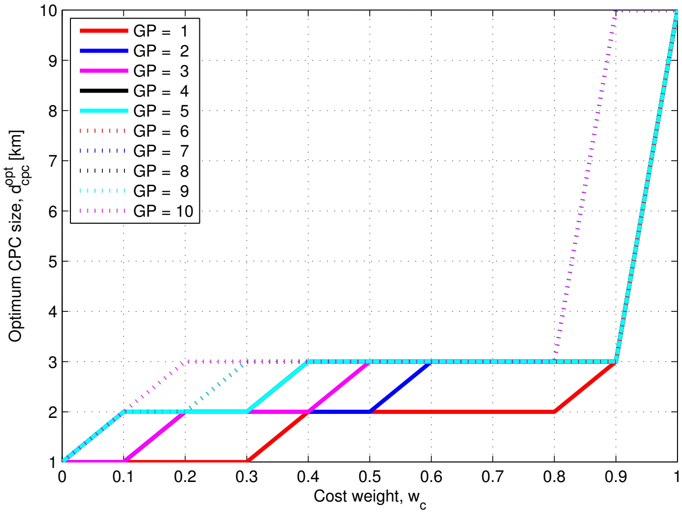

Fig. 3: Optimum CPC size, d_{cpc}^{opt} vs. cost weight, w_c for different GP values [BW = 20 MHz, ϕ = 1000, d_{MBS} = 0.7 km, ν = [20,30,50]%, α = 1.4]

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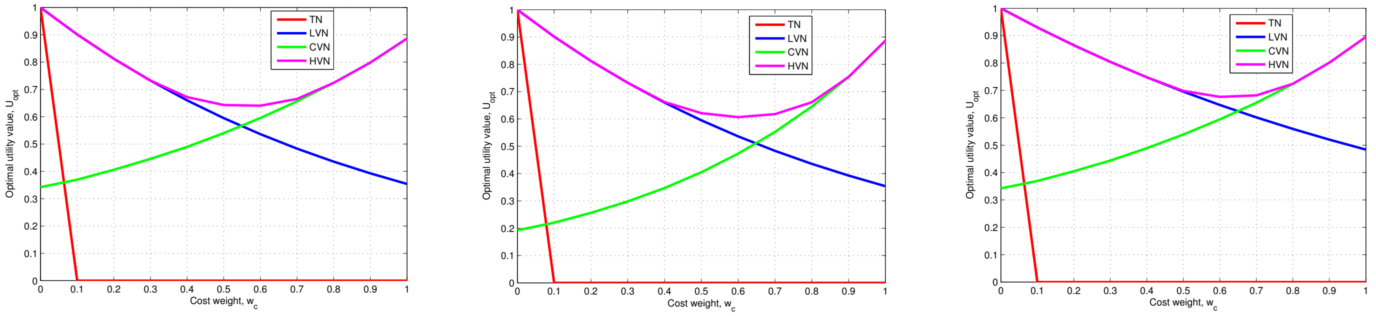
Figure 4 shows the network utility behaviour for different frameworks (including a LTE network denoted as TN) for the optimal GP values (GP_{opt} = 4, when α = 1.4. It is seen that, for different network parameter settings, HVN has the best utility behaviour. For the mid range of w_c values (a.e. when $w_c = 0.4 - 0.8$, HVN clearly has the best utility performance. For lower w_c values, the HVN utility is the same as the LVN, whereas for higher w_c it coincides with that of the CVN. Acknowledging the fact that, HVN has lower cost than LVN for lower w_c values and higher QoS than CVN for higher w_c, it is the best network design choice. The value of w_c is a subjective design choice, which will depend on a VNO's/SP's investment constraint and intended service.

IV. CONCLUSION

Three different variants of wireless access virtualization models have been explored in this paper. The virtual wireless access models have been analyzed from a cost-QoS perspective and have also been evaluated from the respective technical challenges of PHY-MAC layer efficiencies. It has been found out that, for optical fiber based front-haul, MAC layer parameters such as the GP in a OFDM frame structure can be optimized from a network's cost-QoS trade-off analysis. Selection of an appropriate virtualization model for a certain scenario is a critical challenge; the composite utility model presented in this article provides guidance to network designers to choose the network model that fulfil a VNO's investment target as well as service requirement constraints.
While the CVN/RVN model has a cost advantage, the LVN



(a)

(b) BW = 10 MHz

(c) ν = (100,0,0)%

Fig. 4: Optimal network utility; U_{opt} vs cost weight, w_c for different frameworks [BW = 20MHz, ϕ = 1000, d_{MBS} = 0.7 km, ν = [20,30,50]%, α = 1.4].

model provides a better QoS guarantee. In designing a network, both network cost and QoS are important criteria and an apt network design should optimally balance the both. From the analytical results presented in this paper, it can be concluded that, HVN can in fact, attain a better balance between network cost & QoS according to a VNO's/SP's investment constraint and service provisioning goal.

For successful deployment of virtual wireless access, certain critical challenges need to be overcome. Because wireless channels are inherently broadcast in nature, radio resource abstraction and isolation are not easy. Due to varying nature of wireless channels, it is much difficult to provision static or dynamic resource allocation. For the fiber-fed RRHs, besides round trip delay, other radio over fiber issues (a.e. dispersion, attenuation, loss, etc.) should also be considered carefully for CPC dimensioning. In our future work, we will consider advanced PHY-MAC layer techniques like coordinated multi point (CoMP), joint resource scheduling and processing among neighboring BSs, etc. in our analysis.

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