2014 3rd International Conference on Eco-friendly Computing and Communication Systems

Green Wireless Access Virtualization Implementation: Cost vs. QoS Trade-Offs

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***Abstract*—Wireless access virtualization is considered to be a major enabling concept of future 5G networks. It fosters network innovation, rapid time to market for emerging networking concepts and enables cohabitation of different virtual networks with customized network protocols on the same physical infrastructure. It can also alleviate the ossification problem of radio spectrum that has been a major concern for telecommunication operators. Virtualization is also a key enabler for green communications as it not only reduces energy consumption by ensuring efficient use of hardware resources through resource sharing but also facilitates use of renewable energy sources for the communications infrastructure. This paper presents two different types of frameworks to classify wireless network virtualization design alternatives. The benefits of virtual wireless networks are very often expected from a cost perspective. Yet provisioning of stringent quality of service (QoS) requirements calls for a thorough analysis especially from PHY & MAC layers perspectives. A method for selecting the most efficient network architecture has been proposed that takes into account both network operators' (and/or service providers') cost and QoS constraints. The analytical model considers both the capital expenditure (CAPEX) and operational expenditure (OPEX) for cost analysis, while the achievable data rate in different virtual frameworks has been considered for QoS modelling.**

***Index Terms*—Wireless access, virtualization, Cost benefit analysis, QoS, PHY, MAC.**

I. Introduction

In recent years, there has been a surge of new mobile computing devices in the form of smart phones, tablets, etc. These wireless devices run a plethora of different applications that have high bandwidth requirements. This change in usage behaviour has transformed the traditional voice-centric telecommunication network to a more data-centric network. Capacity craving user applications are now posing a serious strain on the cellular network architecture which is constrained by the limited licensed spectrum. Future 5G wireless networks are expected to be more demanding from both the wireless capacity and the underlying network functionality perspectives. Moreover, present-day cellular networks using complex control-plane protocols and vendor-specific configurations are not fully amenable to network agility and innovation to overcome these challenges. For this reason, it is imperative to re-architect the network structure in such a way to make most efficient use of network resources and provide flexibility to incorporate new network technologies.

Virtualizing the functionalities of wireless access networks solves the aforementioned problems to a great extent. Virtualization ensures efficient resource utilization by sharing the same physical resources (provided by infrastructure providers(InPs)) among a group of service providers (SPs). Recognizing the instrumental role of virtualization, major telecom operators and vendors are planning to resort to network virtualization [1].

Wireless access virtualization can also act as a key enabler for energy efficient communications. The information and communications technologies (ICT) industry account for 2% to 3% [2] of the world's total carbon emission which is doubling every four years. From telecommunications network perspective, wireless access networks is responsible for up to 60% - 80% [3] of the total network energy consumption. Reducing carbon emission by enhancing green communication technologies is an active area of research and standardization [4]. A virtual access network can improve energy efficiency by pooling baseband resources and using low-power commodity hardware. Moreover, virtualization can as well be leveraged to maximize the use of available renewable energy powering the network infrastructure, thus even further lowering its carbon footprint [4].

Virtualization of computer networks is a well investigated area [5] but in comparison wireless virtualization has received little attention until recently. Virtualization research is being conducted in several test beds [6], [7], [8], [9]. Wireless virtualization is beneficial from a network operator's economic perspective as it reduces both the CAPEX and OPEX by advocating resource sharing among multiple parties. However, in such a virtual network environment, provisioning of QoS for the user applications poses a significant challenge.

To this end, we propose two wireless access virtualization frameworks that differ in terms of the approach to virtualization and also in terms of the underlying physical equipment. We also provide an analytical model that takes into account the network cost (both CAPEX and OPEX) and achievable data rate (as QoS) to form a utility model that will help a network designer to choose the most suitable network architecture satisfying a operator's investment and service level objectives. The rest of the paper evolves as follows: Section II discusses related work on wireless virtualization. Our proposed

978-1-4799-7002-5/14 $31.00 © 2014 IEEE
DOI 10.1109/Eco-friendly.2014.91

frameworks are described in Section III. We analyze the cost and QoS trade-offs for the proposed frameworks in Section IV, challenges associated in wireless access virtualization are discussed in Section V and finally conclusions are drawn in Section VI.

II. Related Work

LTE network virtualization was studied in [10] mainly from spectrum virtualization point of view. The virtalization framework proposed in [11] uses VBS substrate outside the modified WiMAX BS. It uses two separate networks: one is the modified 4G WiMAX network and the other is the IT-based virtualization substrate.The NVS in [12] is a flow-level virtualization implementation which works on frame-level granularity. Though the NVS framework provides better isolation and scheduling mechanisms, there is no proper management interface for virtual network operators (VNOs) to control and have a network-wide view of their nodes. OpenFlow wireless [13] separates control and data planes by using OpenFlow [14]. This architecture can be divided into two parts: the datapath network segment, which consists of OpenFlow enabled wireless nodes (APs and WiMAX BSs) and the control network segment, that consists of controllers, FlowVisor in IT servers.

A wireless network cloud (WNC) prototype was implemented by Z. Zhu et al. [15]. It implements TDD-based WiMAX VBS pools in IT platforms using servers with general purpose processors (GPP). But issues like slice isolation and novel protocol experimentation are not explored which are critical for virtual networks. A virtualized radio access network, C-RAN has been proposed and implemented in [16]. Two implementation variants are discussed in the C-RAN architecture, one is the full centralization and the other is partial centralization. But no details are given on the particular virtualization techniques used. Software defined networking (SDN) for cellular networks was advocated in [17]; the required extensions to the controller platform and network equipment such as base stations and switches were proposed in this article.

A survey on wireless virtualization appears in [18]. Possible wireless virtualization frameworks based on cooperation among underlying physical infrastructure owners is presented. A multi-dimensional virtualization framework for wireless access networks is presented in [19]; it consists of two separate components, the control and management layer and the virtualization layer. ETSI-NFV [1] and FP7-MCN [20] projects are aiming at using SDN, cloud computing technologies for realizing mobile network virtualization.

The frameworks described in this paper provide virtualization in a multi-tier heterogeneous network (HetNet) scenario consisting of multiple radio access technologies (multi-RAT) base stations which has not been examined in the aforementioned previous work. We investigate the impact of radio over fiber (RoF) communication delays on the QoS performance of the proposed virtual wireless network models. To facilitate the design of a virtual wireless network, we analyse and compare the cost versus QoS trade-offs of the proposed frameworks. To the best of the authors' knowledge, this is the first initiative to analyse and report on the cost-QoS trade-off of virtual wireless networks.

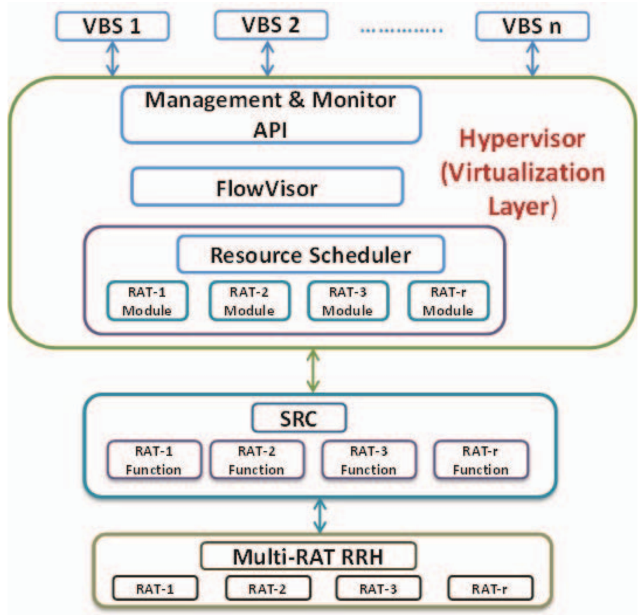

Fig. 1: LVN virtualization flow diagram.

III. Wireless Access Network Virtualization Frameworks

Different radio access technologies with varied capabilities are pervasive in the wireless ecosystem. Efficient utilization of radio resources in such a multi-tier, multi-mode radio environment is critical. As such multi-RAT enabled BSs are increasingly common and are considered in our proposed wireless virtual network frameworks.

We propose two different types of frameworks to classify wireless network virtualization design alternatives: one is the locally virtualized network (LVN) that is implemented by changing the existing network nodes with the addition of a supervising entity that is responsible for the virtual node management in the physical node. The other, the clustered/ remote virtualized network (CVN/RVN) is an approach to wireless networks that uses software defined networking (SDN), OpenFlow controllers, fiber-based distributed multi-RAT RRHs, etc. Pooling baseband functionalities is not a new concept, but for fiber-connected distributed radio heads, the allowed maximum length of the fiber cable is an important design consideration. In this context, the CVN/RVN framework implementation discussed in section III-B leverages virtualization principles to a greater extent than approaches previously described in the open literature. We describe the frameworks in detail in the following subsections.

A. Locally Virtualized Network (LVN)

For the LVN framework, we propose a BS architecture that is an enhanced version of the multi-RAT BSs [21] with hardware augmentation to make them virtualization-capable. We refer to these newly created base stations as super base stations (SBSs). A hypervisor is used to slice (virtualize) the physical SBS. The hypervisor consists of three components: a resource scheduler, a FlowVisor and a Management & Monitoring (M&M) application programming interface (API) (Figure 1). The resource scheduler assigns physical resources to the incumbent virtual base stations (slices). It ensures the isolation between different virtual base stations. There are specialized software libraries (SLs) 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 FlowVisor [22] is based on OpenFlow [14] technology that enables VNOs to administer different flows with customized flow dimensions, i.e., the VNOs can implement their customized network protocols, policy management functionalities, traffic shaping algorithms, etc. This ensures customizability and innovation on part of the VNOs. For proper management of the network, a VNO needs to monitor the state of its nodes and act if any change is needed. This functionality is provided by the M&M API of the hypervisor.

The hypervisor interacts with the single radio controller (SRC) [21], which is a unified network controller for multi-standard radio resource management. As we can see from Figure-1, the SRC has different RAT function modules which manage the corresponding transceiver units at the multi-RAT SBS. In a multi-tier heterogeneous network (HetNet) scenario, there will be macro-SBSs, micro-SBSs and corporate-pico SBSs. But being a customer deployed equipment we do not consider the SBS version for femto-cells.

Please note that the previous models in [11], [12] and [13] require modifications to the existing network nodes as well use a separate IT-based network for implementing virtualization functionalities. In contrast, the LVN model proposed here uses a single network substrate composed of SBSs that use an OpenFlow-enabled FlowVisor inside to implement the VBSs. Furthermore, the nodes of the proposed LVN are multi-RAT capable.

B. Clustered/Remote Virtualized Network (CVN/RVN)

The concept described in this paper for the CVN/RVN framework involves performing the BS functionalities in software in IT-grade servers having GPP and providing radio access via fiber-connected, distributed, multi-RAT RRHs. This framework consists of three parts: a central processing center (CPC) which is basically a data-center where radio signal processing, virtualization of the wireless platform, virtual operator management, etc. take place; an optical fiber network connecting the CPCs in a certain geographical area and distributed RRHs.

From the economic and service-quality points of view (more will be discussed in section IV), the use of CPCs can

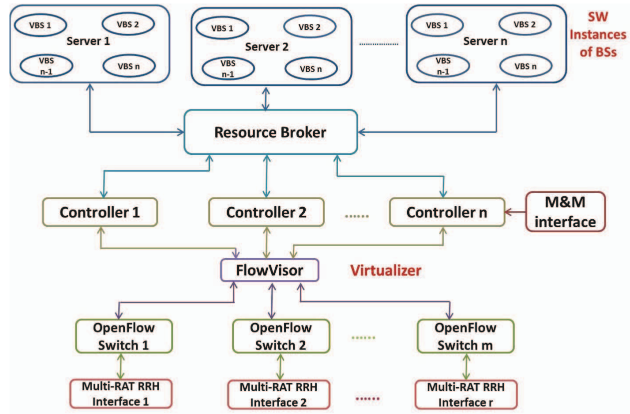

Fig. 2: CVN/RVN virtualization flow diagram.

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).

Software defined networking (SDN) and OpenFlow [14] are at the center of the construction of the CPC. BSs are implemented as software instances in high performance GPP servers which are connected to an OpenFlow-enabled switching fabric (cf. Figure 2). A network-wide FlowVisor [22] is in charge of *slicing* the network, i.e., it allocates computing resources considering the VNOs' service-level agreement, load condition, QoS requirements, etc. It is also in charge of the radio resources allotment among the VNOs according to the underlying radio access technology each VNO is using. The operation and management (O&M) interface provides the operation and management capabilities to the VNOs. And the RRH interface-layer controls the fiber-connected RRHs. For a given multi-RAT scenario, a mechanism similar to that introduced in section (III-A) for LVN can be used. In a multi-tier HetNet case, the macro, micro and corporate-pico BSs will have different amount of hardware resources (e.g. processing cores) depending on their expected processing capabilities. As the femto BSs are randomly distributed as per the user demand, they are not implemented as part of the CPCs.

The CVN/RVN model proposed here uses software instances of BSs implemented in servers with distributed fiber-connected RRHs and OpenFlow [14] for rendering virtualization. Also the proposed CVN/RVN provisions for multi-RAT RRHs. In [15], VBS pooling in two servers is considered, but it does not analyze the case when the scale of pooling VBSs becomes large as that of a data-center. Also critical virtualization issues like slice isolation and customized network stack implementation capabilities for VNOs are not addressed in [15]. Unlike the proposed CVN/RVN model, the C-RAN architecture [16] does not use OpenFlow [14]. Our proposed OpenFlow based [14] CVN/RVN architecture accounts for these aforementioned criteria. RoF becomes a critical issue for a large data-center implementation. The CVN/RVN model takes into consideration the RoF issue and provides a guideline for data-center dimensioning. From a broader perspective, we envision the distributed CPCs as a 'cloud of wireless data-centers'.

The added delay in the CVN/RVN architecture might compromise the requirements of latency-sensitive applications. To alleviate this problem, baseband processing functions can be distributed among the CPCs and the *enhanced* radio heads that have the capability of *in situ*-data processing. We refer to this model as the *Hybrid Virtualization Framework (HVF)* that will be the subject of future publication on its ongoing analysis.

IV. Cost and QoS trade-off Analysis for Virtual Network Frameworks

TABLE I: Evaluation scenarios.

Scenario	BW [MHz]	ϕ [$/km^2$]	d_{MBS} [km]	HetNet [%, %, %]	α
1	20	1000	0.7	[20,30,50]	1.4
2	10	1000	0.7	[20,30,50]	1.4
3	20	1000	0.5	[20,30,50]	1.4
4	20	1000	0.7	[100,0,0]	1.4
5	20	100	0.7	[20,30,50]	1.4
6	20	1000	0.7	[20,30,50]	3.0

The virtualization frameworks presented in section III are quite different from the underlying network structure and hardware choices. Hence, they have their relative pros and cons as far as the network cost, energy efficiency [23] and QoS are concerned. For an example, using IT-grade network equipment in a CVN/RVN architecture is more cost-efficient than using SBSs in a LVN framework. But using radio over fiber for carrying signals from CPC to the RRHs (and vice-versa) has its own challenges and limitations from a network QoS point of view. In this section, we present analytical results on the impact of GP values and different network parameters on the CPC size. We also report on the optimal network utility behavior for different design choice and show how to select a certain virtualization framework for a particular service provisioning.

To investigate the trade-offs between a network operator's budget and the service quality requirement of the intended service, we have developed an analytical model for the proposed virtualization frameworks. This model considers both the 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 [24] on cost analysis of 3G cellular systems. In our own analysis, we have considered only single-RAT multi-tier networks due to lack of space and for the sake of simplicity and conciseness. The most general multi-RAT multi-tier HetNet case is under investigation and the subject of future publication. We have considered long term evolution time division duplex (LTE-TDD) downlink transmission. The granularity of the physical resources considered is the physical resource block (PRB) of the OFDMA frame structure.

In a TDD system, maintaining time synchronization between downlink and uplink (DL-UL) transmissions is critical. The lack of synchronization can disrupt proper decoding of the transmitted information. In the CVN/RVN framework, this is more critical as the radio propagation path involves a span of optical fiber between the RRHs and the CPC. OFDMA subframes handles the synchronization between the transmitter and the receiver. The time slot that is responsible for this time synchronization is called the guard period, GP. The data transmission rate for an OFDMA system employing RoF can be expressed as (modifying the equation in [25])

$$R_{lte} = \frac{N_{sub} \times N_{mod} \times N_{cod} \times (T_{sf} - t_{enb} - R_{cpc} \times d_l)}{[1/(n \times BW/N_{FFT})(1+G) \times T_{sf}]} \times (1 - exp(-\alpha\sqrt(\delta))) \tag{1}$$

where, N_{sub} is the number of data subcarriers, 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 $\delta = \frac{14-GP}{14}$ is the ratio of the pilot-bearing symbols to the total number of symbols in a sub-frame, and α is a parameter that models the severity of the channel by the degradation rate at which identification and synchronization errors increase and hence the throughput decreases through the negative impact of a lower pilot to sub-frame ratio δ. This parameter should depend on most of physical-layer parameters such as channel BW, SNR, modulation, coding, etc.

For a CVN/RVN model, the GP size in a OFDM frame structure plays a critical role in determining the optimal CPC size, d_{cpc}^{opt}. In a TDD system, the GP should be significantly long to accommodate round-trip-delay (RTD) to the fiber-fed RRH and DL-UL switching of the base stations. For this reason, when the GP value is small lower CPC size is desirable in a CVN/RVN model. This is evident in Figure 3, that shows lower GP values permits smaller d_{cpc} size, especially when cost weight, w_c is small. When design target is to build more QoS efficient network (i.e. lower w_c), the d_{cpc} should be small so that RTD is minimized. But using longer GP size, larger d_{cpc} can be rolled out (hence lower cost) because longer RTD can be accommodated in larger GP. Figure 4 shows the variation of d_{cpc} on various network configuration parameters (c.f. Table I). It should be noted that longer GP values can also decrease network *good put*, so it is important to determine the optimal GP value that provides better QoS. For this reason, we form a multi-criteria utility model that comprehends network cost and QoS compromises. The optimal network utility, U_{opt} is composed as

$$U_{opt}(args1) = min_{args2}[U(args)] \\ = w_c \times \frac{C}{C_{max}} + (1 - w_c) \times \frac{R_{lte}^{max} - R_{lte}}{R_{lte}^{max}} \quad (2)$$

where, args2 = $d_m, \phi, \nu, BW, GP, d_{cpc}$, i.e., MBS coverage radius, user density, HetNet configuration, transmission bandwidth, GP in OFDM sub-frame and CPC size, respectively; args1 = other PHY and MAC layer parameters and $args = args1 \cup args2$. Also, $C_{max} = max_{(d_m,\phi,\nu)}C$ and $R_{lte}^{max} = max_{(BW,GP,d_{cpc})}R_{lte}$.
MAC layer parameter like GP size can be optimized from cost-QoS trade-off. Figure 5 shows the optimal network utility for different frameworks using optimal GP value. It is observed that up until the value of $w_c = 0.24$, LVN is the best design choice. Because at this range, QoS is the main design concern (a.e. for applications like, voice, live video, etc.), hence more expensive LVN is the preferred network choice. Beyond that threshold, CVN is the best framework of choice. This design range is suitable for services that have less strict QoS requirement (a.e. file transfer, non-real time applications, etc.) and can be provisioned by less expensive CVN/RVN model. At lower cost weight values, it is interesting to note that , a *large CPC* in the RVN case is not an optimal design choice as larger fiber length to RRHs in a big CPC decreases effective network throughput. Again, a change in a physical-layer parameter such as BW has a significant impact on the network utility behavior. When BW is 10 MHz (scenario 2), the normalized QoS part in equation (2) becomes larger, which eventually increases the total network utility value. It is worth noting that in this case, the w_c threshold beyond which CVN starts to dominate LVN shifts to 0.58. The effects of MBS coverage radius, network homogeneity, and user density are illustrated through the plots labelled as scenarios-3, 4, and 5, respectively.

V. CHALLENGES

Successful deployment of virtual wireless requires addressing certain critical challenges. Some of these challenges are briefly discussed in this section.
Isolation of VNOs/SPs: Isolation in virtual wireless access is challenging because radio resource abstraction and isolation are not easy as wireless channel is inherently of broadcast nature. Moreover, unlike wired networks, the transmission channel is fluctuating in time, space and frequency domains. Co-layer and cross-layer interferences in a HeNet environment also make VNO isolation difficult.

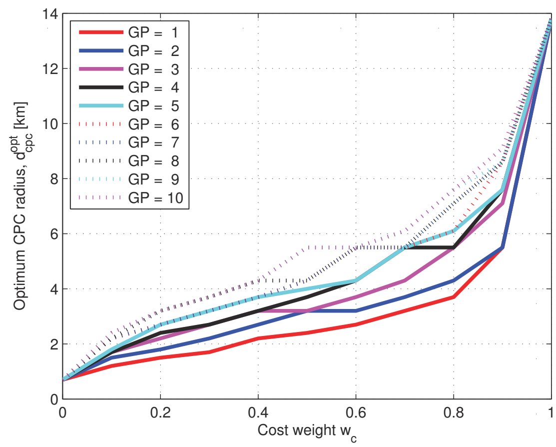

Fig. 3: Optimum CPC radius, d_{cpc} vs. cost weight, w_c for different GP values in reference scenario-1 (Table-I)

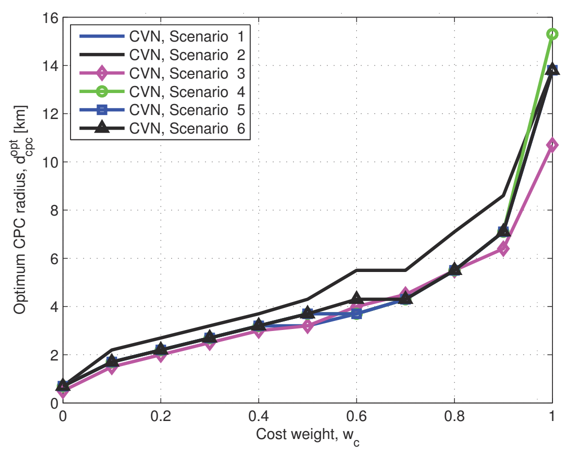

Fig. 4: Optimum CPC readius, d_{cpc} vs. cost weight, w_c for different scenarios (table-I)

Resource allocation: Resource allocation refers to static or dynamic provisioning of virtual nodes and links on the respective physical node and links respectively. It is much difficult in wireless environment due to variability of radio channels, user mobility, interference, frequency reuse, power control, etc. Also the DL-UL asymmetry should also be considered during resource allocation.
Mobility management: A mobile user might update its location with different MVNOs which make tracking the user difficult in a virtual wireless a access environment. To alleviate this problem, a centralized location management can be used, but it can introduce delay as well as raise the single point of failure problem.
Network security: For an efficient virtual wireless access, network nodes will be increasingly intelligent with self-healing and context awareness capabilities. This increases the network

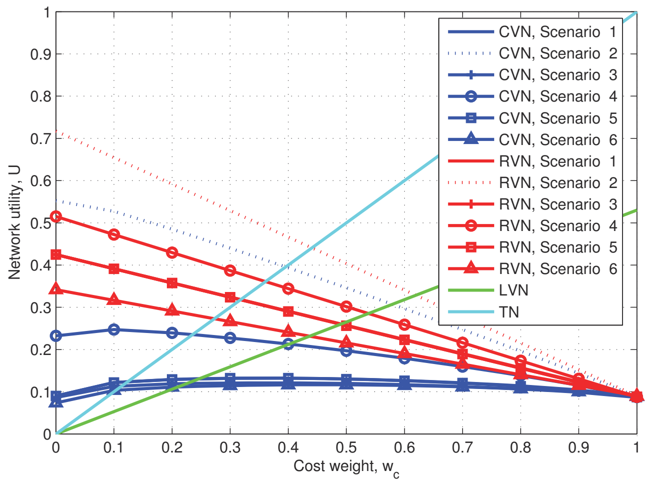

Fig. 5: Optimal network utility using optimal GP value, GP_{opt} vs. cost weight for different scenarios (Table-I)

vulnerability when a compromised party behaves in a malicious manner taking advantage of the virtualization mechanism. Multi-level protection approach can enhance network security to a great extent.

Radio over fiber (RoF) considerations: For the optical network part, the length of the fiber to the RRHs, hence the coverage dimension of the CPC should consider the round-trip delay of the packets as it might set a limit on the quality of the intended services. Issues with radio transmission over fiber (dispersion, attenuation, loss, etc.) are also important design considerations.

VI. Conclusion

In this paper, detailed implementation architectures of the proposed virtual access frameworks have been provided. For the CVN/RVN model, we have analysed the impact of GP value of the OFDMA frame structure on the wireless data-center (CPC) radius. MAC layer parameter like GP size can be optimized from cost-QoS optimization for the frameworks. The effect of different network parameters on the optimal CPC radius has also been evaluated for optimal GP value. As a network design guideline, a compound network utility model has also been provided that takes into account the network CAPEX and OPEX and the achievable data rate to compare different virtualized frameworks. This should help a network architect to select the most suitable virtual network framework that supports both the operator's budget constraint and service quality requirement.

It is observed that, for applications (voice, live video, etc.) having tight QoS requirements LVN is the preferred framework. But if the intended service is more delay-tolerant (a.e. file transfer, video streaming, etc.) CVN/RVN is a better choice. As RoF issues penalize the QoS in a RVN, CVN is the better design choice. In practice, a network consisting of both LVN and CVN parts will be an ideal design option to balance network cost & QoS requirements. This type of network, called hybrid virtual access network (HVN) is the subject of our ongoing research. We are analyzing different PHY & MAC layer issues of a HVN.

For analysis, a rather simplified radio propagation condition has been assumed. Future extensions of this work will focus on incorporating more advanced techniques like, coordinated multi-point (CoMP), joint resource scheduling, etc. Algorithms for handling interference and hand-off in a heterogeneous multi-RAT virtual network will also be analyzed.

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