4G RAN Infrastructure Sharing by 5G Virtualized Mobile Network Operators: A Tutorial

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Abstract—**Active radio access network (RAN) infrastructure sharing has emerged as a promising solution for efficient spectrum utilization, capital and operational cost savings, improved MVNO penetration rates and lower broadband retail prices in both emerging and developed markets. This paper presents a tutorial on the testbed implementation of an active RAN sharing architecture, leveraging multi-vendor virtualized 5G and 4G core networks running on commodity hardware and proprietary 4G RAN equipment (eNodeB). Troubleshooting techniques used for different implementation challenges encountered are also presented in this contribution. The performance of the proposed architecture was validated using end-user quality of experience (QoE) as the key performance indicator. The results show no performance degradation when RAN sharing is being utilized.**

Index Terms—**RAN sharing, software defined networking (SDN), network function virtualization (NFV), cloud computing, virtual local area network (VLAN).**

I. INTRODUCTION

The conventional and still prevalent business model in carrier networks is based on mobile network operators' full ownership of the physical network elements. The vertically integrated business model means that operators are responsible for network architecture planning/design, acquisition of civil engineering resources, network implementation supervision, network operation and management, marketing and service delivery to end users, and customer relationship management. This business model requires large capital investments (CAPEX) and operational expenditures (OPEX) which is a privilege only established mobile network operators can afford. This has created an infrastructural entry barrier for new entrant operators to participate in the telecommunication market resulting in a monopolistic telecommunication market. For this reason, entrant operators have concentrated their broadband infrastructure rollout in urban areas because of the attractive profit margins they present while established operators are able to extend broadband access to certain rural areas (those that promise better investment incentives).

Another challenge facing operators is the high spectrum prices [1]. Spectrum is generally allocated by regulators and the government via auctions. The spectrum price is determined by a range of factors including market penetration, average revenue per user (ARPU) and national policy decisions. In emerging markets, most governments are in financial distress and may inflate spectrum prices to help cover some of their debt. According to the GSMA's latest spectrum pricing report, mobile network operators do not consider spectrum cost as sunk [2]. This means that the capital investment towards spectrum acquisition weighs heavily on consumer pricing decisions, which usually ramps up final consumer prices. The high spectrum costs correlate with poor quality broadband services delivered to end users [3].

There has been snail progress on service-layer innovation. In other words, most operators have been merely focused on providing connectivity and very little attention has been paid to growing and diversifying service offering. The steep cost associated with rolling out and running mobile networks has been cited as the primary inhibitor of innovation [3]. By observation, another culprit behind the slow innovation on the service layer is the lack of competition. Competition is one of the key drivers of business change. When organizations see others in their market implementing new technology, they tend to mimic them for future competition. Unfortunately, the monopolization of the telecommunication industry by established operators stifles competition and discourages innovation.

The mobile wireless technology is evolving at a rapid pace with 5G being the hottest topic. Unfortunately, the hype is building faster than the infrastructure. In South Africa, 5G footprint is still geographically concentrated (mainly available in metropolitan areas). Moreover, very few operators namely, MTN [4], Vodacom [5] and Rain [6] have deployed 5G mobile networks using temporary 5G spectrum (i.e.700 MHz, 800 MHz, 2.6 GHz, and 3.5 GHz bands) allocated by the Independent Communications Authority of South Africa (ICASA). These operators plan to increase their 5G footprint as soon as permanent 5G spectrum is released. On the other hand, entrant operators are finding it difficult to penetrate the 5G market due to the infrastructure bottlenecks which exacerbate the already wide digital divide.

In order to fuel digital inclusion, broadband affordability and service-level differentiation, a shift from sole infrastructure ownership to infrastructure sharing is a potential solution. Infrastructure sharing can improve broadband

affordability through numerous channels, including CAPEX and OPEX savings and increased competition (by breaking the infrastructure barrier faced by entrant operators). Infrastructure sharing is the new normal in most developed countries with reported benefits such as substantial decline in retail prices and high quality of service stemming from increased service-layer innovation. The South African government released the Electronic Communications Amendment (ECA) Bill [7] which stipulated government's intentions to build a wholesale open access network (WOAN) in an attempt to deliver nationwide and affordable mobile broadband access. WOAN is envisaged to stimulate service-level competition through infrastructure sharing. Unfortunately, existing WOAN rollouts are either abandoned or not performing well due to poor Internet speeds and general disinterest by mobile virtual network operators (MVNOs). Infrastructure sharing using WOAN might not be the best way forward, but voluntary infrastructure sharing is a feasible solution to combat digital inequality and lack of competition in emerging markets.

As the radio access network (RAN) infrastructure usually constitutes the largest portion of infrastructure cost, it will be prudent for operators to consider ways to share these costs. Operators should consider sharing of passive network elements (such as civil works, site, mast, power supply) and sharing of active radio network elements (such as antennas, transceivers, spectrum) to cost-effectively achieve the performance of sites, 5G capability and acceptable retail prices. In this type of sharing agreement, each operator operates its own core network and connect to a common RAN with its sharing partners. RAN infrastructure sharing is defined in 3GPP Release 14-15 standard specification and formally known as multi-operator core networks (MOCN). Implementing RAN sharing is not a trivial task as it involves integrating multi-vendor core networks to a single RAN. This paper provides a tutorial on how to build a full-fledged mobile network with RAN infrastructure sharing capabilities, leveraging LTE base stations and 5G and 4G core networks.

The paper is organized as follows: Section II provides a state-of-the art review and highlights our contributions, Section III presents the overall architecture of the testbed, key components descriptions, configuration steps, troubleshooting techniques, system integration and lessons learned during testbed commissioning, Section V provides a comprehensive discussion of the results from implementation. Lastly Section VI concludes the paper and provides future direction.

II. RELATED WORK

3GPP has defined and ratified different kinds of architectures with varying degrees of sharing : multi-operator RAN (MORAN): where only passive elements of the RAN infrastructure are shared, multi-operator core network (MOCN): where both spectrum and base stations are shared; and gateway core network (GWCN), in which both the RAN equipment and some elements of the core network are shared.

To date, there has been numerous research studies directed towards RAN sharing. Most of these efforts (such as [8] [9]

[10] [11] [12] [13] [14] [15]) have been focused on 4G/5G RAN sharing in virtual environments where RAN elements are logically and physically split into two architectural components namely, the remote radio heads (RRHs) and baseband unit (BBU). The BBU component is then deployed as a local network entity on commodity hardware to create what is commonly known as cloud-RAN (C-RAN). This deployment is enabled by network function virtualization (NFV) [16] and cloud computing [17].

Alaez et al.[8] proposed an open-source testbed design to demonstrate MOCN LTE sharing executed on a virtualized infrastructure following the C-RAN architecture. Kernel-based Virtual Machine (KVM)[18] was used for the deployment of the core network and emulated radio components. The authors emulated the BBU component using an extended version of Network Simulator3 (NS-3)[19]. The testbed implementation supports sharing of the BBU by two telcos with each telco owning their own dedicated RRH and core networks. To validate the feasibility of MOCN LTE sharing in virtualized environments, the authors analyzed performance metrics such as scalability and network overhead.

Similar to Alaez et al.[8], Calero et al. [9] proposed and validated an open-source architecture for MOCN using a tool called LENA [20], the LTE-extension of NS-3, for mobile network emulation. Their work conducted an empirical study of the techno-economic and performance implications of sharing the RAN infrastructure between multiple network operators. The authors found that there was a negligible difference in the the number of connections and associated number of operators.

Markendahl et al. [10] proposed different business model options and implications of MOCN and MORAN sharing solutions for indoor deployments using femtocells [21] and distributed antenna systems (DAS) [22]. The authors highlight the benefits deploying "small cell as a service" in local area networks and the benefits of outsourcing the operation and management of such deployments to 3rd party actors.

Turk et al. [11] conducted a city-wide experimental study of RAN sharing (MOCN specifically) on live LTE networks between two network operators. The authors tested the effect of RAN sharing by observing (over a period of 20 days) the average uplink and downlink user throughput before and after RAN sharing.

Lin et al. [12] proposed a transparent RAN sharing technique following an independent box approach, where a network node called a "RAN Proxy" is inserted between the core network and base stations. The RAN Proxy connects multiple network operators to a shared base station via secure and isolated tunnels configured on the proxy node. Two network architectures were evaluated: the one-level proxy architecture where a single RAN Proxy was inserted in level-1 backhaul (which interconnects a small cell and a macrocell) and the two-level proxy architecture where two RAN Proxies are inserted in level-1 backhaul and level-2 backhaul (which interconnects a macrocell and the core networks). The authors analyzed the impact of adding this new node on network

performance by measuring latency and throughput in a one-level proxy network deployment.

Ksentini et al. [14] proposed a fully programmable RAN slicing architecture based on the 3GPP dedicated core network (DCN) (similar to MOCN where traffic is routed to the appropriated core network) principle and programmable RAN. Additionally, the authors also proposed a two-level MAC scheduling mechanism to abstract and share networking and computing resources among slices. The proposed RAN slicing architecture was implemented on top of a 3GPP-compliant emulator called OpenAirInterface (OAI) [23] to derive key performance results, particularly throughput and latency performance. Authors argued that using a strict admission control mechanism is paramount for proper regulation of the number of admitted slices to avoid violation of service level agreement of each slice.

Kokku et al. [15] proposed a remote RAN sharing solution called Cell-Slice which achieves slicing without out modification of base stations' schedulers for easy integration to existing mobile network deployments. The proposed solution makes use of a gateway which is inserted between the RAN and core network and is equipped with algorithms to override uplink and downlink scheduling decisions taken by the base station. Cell-Slice focuses on deployments which prioritize spectrum sharing to achieve high wireless resource utilization. The authors built and evaluated their Cell-Slice prototype on a Picochip WiMAX testbed and carried out performance evaluation by streaming videos over the network. The key performance metric measured was throughput.

The publication coverage on RAN sharing is relatively high. However, most studies relied on emulation and simulation tools for their testbed implementation. This includes simulated LTE stacks such as base stations and air interfaces which does not fully represent a real service provider environment. All the reviewed studies (except Kokku et al. [15]) do not explicitly mention whether or not their implementations were based on spectrum resource sharing. Last but not least, the reviewed papers were not verbose on implementation details such as testbed design and deployment, implementation challenges, troubleshooting and lessons learned which makes it challenging to reproduce these testbed implementations.

III. Design and Implementation

A. Contribution

This paper presents an implementation of an LTE testbed with active RAN sharing capabilities (including spectrum resource sharing) consisting of multi-vendor proprietary and open-source components. The main contribution of this paper is three fold:

- A step-by-step guide on how to successfully deploy a fully-fledge carrier grade network with RAN infrastructure sharing capabilities will provided. We believe this guideline will help practitioners in the telecommunication field to save time implementing their testbed designs.

- The key challenges encountered alongside troubleshooting techniques used and lessons learned during the deployment and integration of heterogeneous components of the RAN sharing solution will be highlighted.
- Performance benchmarking between the shared network and the monopolized network infrastructure will be conducted based on quality of experience (QoE) assessments.

Figure 1 depicts the proposed mobile network infrastructure with RAN resource sharing capabilities we implemented. As shown in the figure, the testbed implemented constitutes two different network operators (operator A and operator B). Each operator has their own distinct virtualized core network which connects to a shared LTE base station (i.e. eNB). Subscribers connect to their home core networks via strongly isolated network slices created using virtual LANs (VLANs). The core networks are deployed on a common computing environment using OpenStack cloud platform. In this section, we provide deployment guidelines for each component constituting the proposed testbed architecture. This guidelines are based on our experience with implementing the RAN sharing architecture.

IV. Design Principles

A. Core Network Deployment

For our testbed, two flavors of virtualized core networks were deployed, one from Cumucore (i.e. 5G core) and the other from Fraunhofer (i.e. 4G core). The use of different core networks was to demonstrate sharing in a multi-vendor environment. The Cumucore core network is 3GPP compliant and support both non-standalone (NSA) and standalone (SA) functionality for compatibility with 5G and previous generations of mobile networks. These core networks are cloud-native solutions designed using microservices for each function. The core networks can be deployed in a single (centralized) or multiple (distributed) bare metal or virtualized platforms such as OpenStack, Kubernetes, KVM and VMWare. Both these core network solutions promise benefits such as flexibility, cost reduction and efficiency leveraging the advantages of NFV. Using virtualized cores makes it easier to migrate the testbed into different environments and also makes it possible to scale the network up/down on demand with minimal reconfigurations. This section presents key implementation details for the virtualized core networks deployed on OpenStack, Stein release (supporting self-service networking).

1) Hardware Requirements: For our testbed implementation, we opted for the centralized core network deployment on OpenStack virtual machine (VM) instances. Each instance was assigned 2 virtual CPUs, 2GB RAM, 60 GB Hard Drive and 2 virtual NICs.

The core networks were deployed on Debian-based Linux (i.e. Ubuntu 16.04) operating systems (OS). The resource assignment was based on the minimum hardware requirements of both cores.
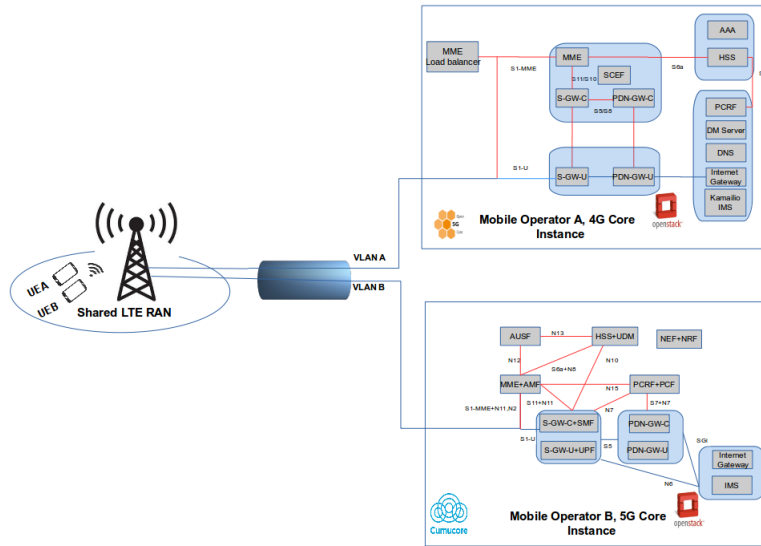
Fig. 1. Overview of the MOCN Architecture

2) Software Dependencies: In order to successfully deploy the core networks, the following software dependencies need to be pre-installed for both cores:

- MySQL client and server libraries: Needed for running the HSS function which is emulated with SQL database.
- GTP module: Required for tunneling in the user plane.
- OpenSSL library: For security and encryption functions.
- SCTP: To provide guaranteed message delivery between the MME and base station on the S1-MME interface.

3) Network Configuration: Each OpenStack instance was configured with two virtual network interfaces (see Figure 1). The first interface is used to connect the core network to the shared base station. The second interface connects the core network to the Internet. Optionally, a third interface can be configured for management purposes (e.g. SSH connectivity). The interface connecting to the Internet was configured as the default route with DHCP and NAT enabled. The microservices (i.e. core network functions) communicate with each other over localhost (Network 127.0.0.0/24)

4) Installation: The core networks can be installed from source-code or software binaries. For the core networks' installation, we used pre-installed Ubuntu and the software binaries of each core, all bundled in an ISO image. The instances were instantiated with said ISO images following the guideline in [24].

5) Microservice Configuration: For the core networks to work, certain parameters must be configured by modifying or creating configuration files for each microservice namely, the mobility management entity (MME), serving and packet gateway (SGW/PGW). Table I highlights mandatory parameter configurations on each core.

B. Base Station Commissioning

The overall functionality of a mobile network depends on proper configuration of the base station. In order to configure the base station via a user interface, an element manager (i.e. BTS Manager) is required. The element manager is also used for monitoring the base station connection status. For our testbed, we used a Flexi Zone Indoor LTE Pico cell from Nokia operating in the 1800Hz (indoor R&D license) frequency band. The cell used supports a maximum of 840 active users with a coverage of 200 meters. Table II highlights the mandatory fields that are configured during base station commissioning.

C. SIM provisioning

This section describes the parameters in the SIM card required for the authentication which needs to be provisioned in the home subscriber server (HSS). Before provisioning the SIM cards on the HSS, we programmed two SysmoUSIM-SJS1 SIM cards [25] with operator specific parameters as recorded in Table III. The following tools were used to program the SIM cards:

- A smart card reader supported by pcsc-lite software stack on Linux
- A credit card size sysmoUSIM-SJS1 card to rewrite
- The ADM1 key for the card. This is the admin password used when writing USIMs
- The sysmo-usim [26] program

A detailed guideline on how to use the sysmo-usim program is provided in [27]. After SIM programming, the SIM cards were provisioned in the databases of their home core networks. A total of four mandatory tables were populated with the SIM card identity and authentication values. Bash scripts were used to streamline the programming and provisioning process.

D. System Integration

In order to build a full-fledge mobile network, all network components had to be integrated. The major components integrated were the base station and the two core networks. An important requirement in integrating these two components

TABLE I

CONFIGURATION OF CORE NETWORK MICROSERVICES

Parameter	Microservice configured	Description
S1 address	MME, SGW/PGW	IP address where the MME is listening for incoming control connections via SCTP, and the UPGW is listening for incoming user traffic via GTP from the base station. The IP address of the S1 interface has to be in the same subnet as the base station.
Mobile country code (MCC)	MME	Mobile code consisting of three digits used to uniquely identify the country of each network operator.
Mobile network code (MNC)	MME	Two digit code used to uniquely identify each network operator.
Tracking area code (TAC)	MME	A code in the range of 0 to 65536 used to track the UE's (user equipment) position.
S10 address	MME	IP address of the control interface between multiple MMEs.
UE address	SGW/PGW	Starting IP address of an IP pool used to assign IP addresses to UEs during attach process.
DNS address	SGW/PGW	The IP address sent to the UE during the attach process used by the UE for sending DNS queries. Google's DNS service (8.8.8.8) is recommended.
Maximum number of users	SGW/PGW	Number of users supported by the core network. This parameter is dependent on the capacity of the base station.

TABLE II

BASE STATION CONFIGURATIONS

Parameter	Description
MME address	The primary IP address of the MME of each core network.
PLMN codes	The PLMN consists of the MCC and MNC associated with each MME.
VLANs	IP address and subnet mask of the tagged transport interface. QoS for the VLAN must be enabled when creating VLANs.
Transport Ethernet Interface	IP address and subnet mask of the un-tagged transport interface.
Tracking area code (TAC)	Used by the MME to track the UE's position.
Application Addresses	This defines the user-plane, control-plane and management-plane addresses for traffic on each VLAN.
IPV4 Routing	Defines the control-plane source IP address (i.e. base station backhaul interface IP) and the gateway (i.e. the IP address of the server running the core network instances).
NTP server	Specifies the time server used by the base station for network time synchronization.

TABLE III

PROVISION AND PROGRAMMED SIM PARAMETERS

Parameter	Description
PLMN codes	MCC and MNC configured on the base station and on MMEs
Mobile station international subscriber directory number (MSISDN)	A 15 digits mobile phone number used to uniquely identify a subscriber internationally.
k	A 32 hexadecimal digits key used for authenticating subscribers of the mobile network
OP	A 32 hexadecimal digits operator code used for user authentication. This value is the same to all subscribers belonging to the same network operator.
Sequence number (SQN)	Security parameter used during subscriber authentication.
International mobile subscriber identity (IMSI)	Used to to identify subscribers of the mobile network. The format of the IMSI is MCC + MNC + MSIN (Mobile Subscription Identification Number) and it consists of a maximum of 16 digits.
Access point name (APN)	The name of the Packet Data Network (PDN) to which the UE requests connectivity. The default value is "internet".
Authentication Management Field (AMF)	Added to the authentication token in the user authentication request message. For LTE, a safe value to use is 0x8000.
Name	Name of network operator.
Integrated circuit card identifier (ICCID)	A 20 digits number used to identify SIM hardware. It consists of a 2 digits ISO 7812 Major Industry Identifier, country code, issuer identifier and a 12 digits SIM number. The first 6 digits of the ICCID is allocated by ITU but can be randomly generated since ICCID is not transmitted anywhere.

was to ensure strong isolation on the backhaul to avoid interference between the two mobile network operators. This required integration of a switching mechanism to the base station.

In order to integrate the two core networks to the shared base station, two VLAN interfaces were created (following [29]) on the server running core network instances, specifically on the ethernet interface connecting to the base station (i.e. S1 interface).The 8021q module was loaded into the kernel before creation of the VLAN interfaces. Each VLAN interface was assigned a private ip address within distinct subnets. VLAN interfaces were also configured in the base station with QoS enabled. Each VLAN configured in the base station was assigned an IP address within the VLAN subnet of the core network it serves. A private network was also configured between the transport ethernet interface of the base station and the s1 interface of the core network instances. To separate the user and control traffic for each operator, a second set of user plane and control plane addresses was added on the base station using the configured VLANs. The management plane was configured to use the transport network.

A mapping of the base station VLANs and MMEs was implemented using a combination of distinct MCC and MNC (commonly known as PLMN) and the S1 VLAN addresses of the core networks. UEs connection to the base station was through inspection of PLMN information inside connection requests from the UE. UEs intergration to the core networks was implemented using authentication of subscriber identity and security information provisioned on the HSS databases. The integration of the core network to the packet data network (i.e. public internet in our case) was through proper configuration of OpenStack's provider network and configuration of the PGW config file.

E. Troubleshooting

When setting up a testbed with RAN sharing capabilities, several challenges related to installation and configuration were encountered. This section gives an overview of the major challenges experienced when deploying the architectural components in Figure 1. The corresponding troubleshooting techniques implemented are also highlighted in Table IV.

TABLE IV
IMPLEMENTATION CHALLENGES AND TROUBLESHOOTING TECHNIQUES

Challenge	Troubleshooting Technique
SIM writing	Make sure to specify the right ADM keys for each SIM card. Install all software dependencies of SysmoUSIM program Check if SIM is not physically damaged. Make sure SIM is properly inserted using pcsc_scan command
PLMN broadcasting	Check core network status to see if all services are running. Check if base station is in active state and GPS module is connected. Make sure the UE is within transmission range of the base station.
Integrating base station to core networks	Set OpenStack Neutron security groups to allow SCTP traffic. Make sure all core network services are active. Verify S1 interface configuration by pinging both the VLAN and transport interface of the core network from the base station, tcpdump and Wireshark come in handy here). Make sure there are no typographical errors on the PLMN and MME configuration of the base station. Make sure TAC codes configured are within the range supported by the core networks and they match the values set in the base station.
UE attachment and registration	Verify user existence on HSS database. Make sure provisioned user data on HSS matches SIM data and APN. SysmoUSIM software providers a SIM reading script for this purpose. Make sure SIM is not damaged
Connecting to internet from UE	Make sure core network can connect to the Internet using ping tests. Make sure DNS is set up correctly inside PGW config an also resolv.conf files. Make sure that you have masqueraded the Internet interface. Make sure you have set your default gateway interface in the core network.
OpenStack deployment	See [28] for a detailed troubleshooting guide.

F. Admission Control Procedure

This section describes the admission control procedure followed on our testbed implementation. The base station periodically advertises all available networks (PLMNs) in its domain. The UEs start in a deregistered state, meaning they are not attached to the mobile network. The UE can be set to auto scan available PLMNs or the user can do a manual scan. In our case, we enabled auto scanning. Once the UE picks its home PLMN, it sends an initial attach message using the RRC protocol [30], which contains the IMSI and other UE identity and security information. Once the base station has processed the attach message, it sends a connection setup message (via the applicable VLAN) to the MME of the UE's home network using the S1-AP protocol [31]. Upon receiving the message, the MME establishes diameter communication with the HSS using the S6a protocol [32]. The HSS checks if the UE is provisioned in its database. If the UE exists, then connection is accepted and a bearer between the UE and the core network is created, in this case, the UE is successfully registered. Otherwise, if the UE does not match any entries in the HSS database, then the connection request is rejected. After successfully attaching to the network, the UE's profile is locked to the PLMN for all ensuing communication.

V. PERFORMANCE EVALUATION AND LIMITATIONS

In order to evaluate the end-user quality of experience (QoE) on the proposed RAN sharing solution, we performed video streaming tests on the shared testbed and compared it with the QoE delivered by Vodacom and MTN commercial networks. The test results indicated no visible performance differences. However, it is noteworthy that the testbed was deployment in a semi-sterile indoor environment with direct line of communication, with negligible interferences in the air interface. Moreover, the UEs were kept stationery (i.e. within the coverage area of the base station), and the UEs' mobility was therefore not considered. The testbed was implemented indoors because of lack of outdoor spectrum license.

VI. CONCLUSION

Spectrum remains the scarce and costly lifeblood of telecommunication networks. The current business model of monopolizing an entire spectrum allocation has resulted in underutilization of this limited radio resource. We believe active RAN infrastructure sharing can ensure more-efficient usage of spectrum while driving down CAPEX in telecommunication industry. This paper presented a tutorial on how such a sharing solution can be implemented on a testbed, by introducing a VLAN-based sharing mechanism for proper handling of the user-plane and data-planes of sharing partners. This paper also presented a high-level architecture and the implementation and troubleshooting details of each architectural component.

The key beneficiaries of this research effort are practitioners in the telecommunication industry who can use this work as a basis for their RAN sharing testbed design and implementation. Small operators and incumbent operators can also use this work as evidence of the feasibility of infrastructure sharing to unlock cost savings and to improve broadband penetration rates.

The VLAN-based sharing mechanism is still highly vendor-dependent and lacks transparency. For instance, the network operator is not fully aware of QoS slicing on the RAN since

it is closed and proprietary. Therefore, a more vendor-neutral (i.e. independent of the base station) sharing solution which adheres to standards is required. In future we will extend our testbed to integrate a 3GPP-compliant cloud RAN running on generic hardware to build a full-fledged multi-RAN virtualized solution.

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