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3 authors:

Liljana Gavrilovska
Ss. Cyril and Methodius University

Valentin Rakovic
Ss. Cyril and Methodius University

Daniel Denkovski
Ss. Cyril and Methodius University

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**Liljana Gavrilovska · Valentin Rakovic ·
Daniel Denkovski**

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Abstract This paper presents the generic definitions, basic functionalities and current research trends in Cloud Radio Access Networks and its derivatives, Virtual Radio Access Networks and Open Radio Access Networks. Moreover, the paper provides practical results, insights, and lessons learned regarding the limitations and unforeseen issues of Radio Access Networks virtualization. The paper also discusses the potential developments and possibilities for commercial roll out of novel Radio Access Networks approaches.

Keywords Cloud RAN · Virtual RAN · Open RAN · 5G

1 Introduction

Cloud Radio Access Network (C-RAN) and its derivatives has been identified as one of the potential technologies that can meet the underlying 5G technical requirements in radio access. The C-RAN [1] fosters efficient network and resource sharing as well as real-time and flexible scheduling in a centralized fashion.The general RAN architecture consists of local base stations (BSs), baseband units (BBUs) and possibly remote radio heads (RRHs). By exploiting Software Defined Everything (SDx) and virtualization, the C-RAN concept can evolve towards the Virtual RAN (V-RAN).

V-RAN increases the wireless system scalability and flexibility and overcomes several challenges in current legacy wireless systems, such as interference problems and power consumption [2]. V-RAN also enables networks to

Liljana Gavrilovska · Valentin Rakovic · Daniel Denkovski
Faculty of Electrical Engineering and Information Technologies, Ss Cyril and Methodius University in Skopje Karpos 2 bb, 1000 Skopje, N. Macedonia
Tel.: +389 2 3099 114
Fax: +389 2 3064 262
E-mail: (liljana,valentin,danield)@feit.ukim.edu.mk

become programmable, adaptable, centrally managed and cost effective. The V-RAN approach provides the possibility for a very large number of RRHs to be connected to a single BBU through high speed fronthaul (usually fiber optics). The V-RAN separates the remote radio head (RRH) from the baseband unit (BBU). Compared to a traditional base station (BS) (where the RRH and BBU are coupled together) it improves the network resource sharing. Moreover, it enables for easier migration to newer generation of wireless technologies while supporting the legacy technologies through software and component isolation [3, 4].

Recently the V-RAN has started to evolve from the concept of C-RAN, towards the concept of Open-RAN (O-RAN) [5]. O-RAN is fostering more open and smarter radio access networks by relying on openness and Intelligence [6]. To address the complexity issues, operators and vendors cannot rely on conventional human intensive means of deploying, optimizing and operating the mobile networks. Instead, the mobile networks must be able to facilitate new intelligence-based technologie (i.e. ML/AI), hence facilitating automated operational network functions that will reduce the operational costs.

This paper presents the definition, function, current research challenges and evolution of the C-RAN concept into its latest derivatives such as V-RAN and O-RAN. The paper also provides some real-world practical results and discusses the lessons learned. Moreover, it presents notions and vision of how C-RAN will evolve in the future. The paper is organized as follows. Section 2 presents the generic concepts, main advantages and features related to C-RAN. Section 3 elaborates the V-RAN approach focusing on current trends and state of the art research. Section 4 presents the evolution from V-RAN to O-RAN and the latest academia and industry trends. Section 5 provides practical insights, findings and results regarding the real-world deployment of V-RAN. Section 6 discusses the industry trends, standards and possible future development directions of the C-RAN concept. Section 7 concludes the paper.

2 Cloud RAN

C-RAN refers to a cellular network architecture where the baseband signal processing and network functions of radio access network are performed in a cloud. The C-RAN architecture consists of three building blocks, i.e. BBUs (located in the cloud), RRHs (acting as remote antenna elemets) and fronthaul links that interconnect the BBUs and the RRHs, Figure 1.

In C-RAN, traditional Based Stations (BSs) are decoupled into two parts - distributed RRHs and BBUs clustered into a pool. The pool is placed at a centralized site (i.e., cloud) having a set of BBUs. This enables the radio resources of different BBUs to be shared and meet the dynamic user demands. The cloud controls the RRHs and is also reconfigurable, i.e., the number of BBUs can be

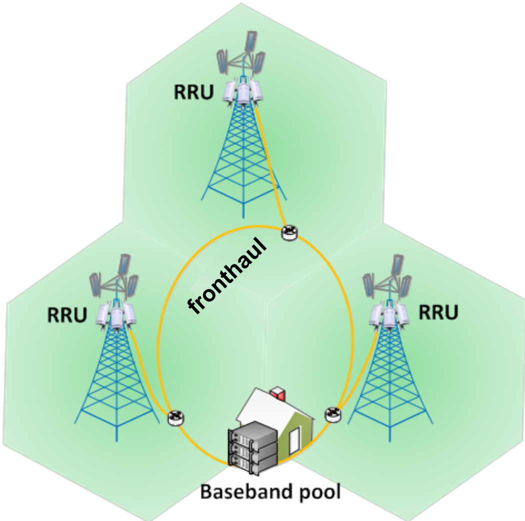


Fig. 1 Generic C-RAN architecture

changed with time. The cloud leverages the baseband processing by exploiting general purpose processors. Signal processing resources in the cloud are dynamically allocated on demand basis. Various functions including modulation, coding, fast fourier transform, and selection of suitable frequency or channel are performed in the cloud. Conversely, the RRHs represent the antennas that transmit radio signals from the BBU cloud to the users in the downlink and forward the baseband signals from users to the cloud for processing in the uplink. The main functions of the RRHs are the radio frequency (RF) amplification, up/down conversion, filtering, digital processing, analog-to-digital conversion, digital-to-analog conversion and interface adaptation. As most of the signal processing functions are performed in the cloud, RRHs can have simple design and can be distributed in a large scale scenario in a cost efficient manner. The fronthaul provides the communication links between the BBUs and the RRHs. Various technologies, such as optical fiber communication, standard wireless communication, or microwave/millimeter wave communication can be used for implementing this fronthaul links [7]. Optical fiber communication fronthaul has the capability to support high transmission capacity at the expense of high cost and inflexible deployment. Whereas, wireless fronthaul is cheaper and more flexible at the cost of reduced capacity and lower reliability.

The C-RAN architecture facilitates several benefits, compared to the legacy wireless systems, such as [8]:

– *CAPEX and OPEX reduction:* The deployment and maintenance cost of per cell site can be reduced significantly, because the BBUs are centralized and only the RRUs are distributed at different cell sites.

– *Wireless technology coexistence:* C-RAN and its centralized BBU design can support multiple wireless standards, which can be effectively deployed, managed and utilized based on the user demands, leveraging a fully heterogeneous wireless system.
– *Energy efficiency and green deployment:* C-RAN can improve the energy efficiency by reducing the number of active cell sites when required, and thereby decreasing the overall power consumption of the operator. Moreover, during low traffic periods, underutilized BBUs can be turned off and their traffic can be redistributed to the active BBUs.
– *Spectral efficiency improvement and reduction in inter-channel interferences:* The centralized BBU can share the resources dynamically and cooperatively among the multiple cells (i.e. RRUs). Thus, the resources can be utilized effectively as per service demand. The inter-channel interference can be alleviated as a result of the joint scheduling and processing.
– *Throughput improvement:* C-RAN can facilitate dense RRU deployment schemes in areas that require high throughput services.
– *Business Model Transformation:* The C-RAN concept will generate more business models, such as the BBU pool resource rental system, cellular system as a service, as well as more freemium services.

C-RAN is expected to bring and foster many improvements in wireless systems. However it has several limitations that can inhibit its practical implementation. Serious problems in C-RAN are *security and trust* . Common security threats of conventional wireless networks, such as primary user emulation attack and spectrum sensing data falsification attack, are notable examples of C-RAN related security threats and trust problems [9]. Since in the C-RAN the BBUs are collocated together in the cloud, it has a high risk of *single-point failure*, resulting in entire network outage. The C-RAN also introduces a huge *fronthaul overhead* in the links between the RRHs and the cloud that can be more than an order of magnitude higher compared to the backhaul requirements [10]. In addition, fronthaul latency/jitter is also a significant limitation for future C-RAN based wireless systems. In specific cases the centralized signal processing can increase the latency in the system, resulting in suboptimal C-RAN's performance. As a result, the C-RAN has started to shift its focus to advance computing technologies such as virtualization and edge computing. The following section focuses on the V-RAN specifics and current trends.

3 Virtual RAN: The evolution of C-RAN

Virtualization facilitates the creation of logically isolated instances over abstracted physical hardware, which can be shared in a dynamic, efficient and flexible manner. Virtualization has been utilized for many years in the area of data storage and cloud computing. Network virtualization represents a novel evolution of virtualization that plays a crucial role for the practical deployments of C-RAN concept. Unlike C-RAN the V-RAN architecture promotes flexible control, low cost, efficient resource usage, and diversified applications, and can address many of the underlying issues related to cloud deployment of RANs.

The approach, referred as Virtual RAN, i.e. V-RAN, fosters the decoupling of software and hardware functionalities. Due to the V-RAN's HW/SW decoupling, flexibility, scalability and its inherent centralized nature, it can facilitate a wide plethora of future services, such as massive machine access, mission criticality, tactile internet, etc. V-RAN leverages the wireless/radio and BBU resources to be shared by many RRHs, based on the underlying traffic conditions. This minimizes the operational and investment costs while running the wireless system and promotes improved energy efficiency [11–13]. It also encourages innovations and fosters the new business players to enter into the markets at lower costs [14].

Virtualization and cloud infrastructure for IT applications have been already well studied and developed. However, the V-RAN concept poses completely different requirements on the cloud infrastructure. For example, *hypervisor-based* and *container-based* virtualization represent two fundamental virtualization technologies that can be applied in V-RAN [15, 16]. Both technologies incorporate different means of virtualization, orchestration and resource scaling. They are exemplified in many different virtualization frameworks, such as VMware, OpenStack, Kubernetes, Docker, Hyper-V, etc. The majority of the existing ICT deployments exploit, either the OpenStack (hypervisor-based virtualization) or Docker (container-based virtualization) frameworks. Recently, several activities have strived to develop and incorporate multi-functional orchestration engines, such as OMF [17], OSM [18], etc, in the V-RAN ecosystem. However, their current applicability is very limited and far from comercial deployments due to instability, resource consumption or limited scope of features.

The hypervisor-based virtualization, i.e. Virtual Machine (VM) runs a complete guest operating systems (OSs). This leads to a computationally resource intensive operation, which ultimately results in lengthy VM deployments and slow booting of the guest OS. OpenStack represents the most advanced and scalable hypervisor-based virtualization framework. It is utilized in many ICT related scenarios that require efficient management of computational, storage and networking resources. OpenStack has modular architecture, consisted of a plethora of services that have versatile functions and support dynamic deployment and deletion. The implementation of OpenStack cloud platform makes it easier to manage the whole infrastructure, through a highly-configurable integration engine, with a set of core projects [19, 20].

The container-based virtualization, represents a technology that leverages fast and secure development, running and deployment of software applications. Container-based virtualization fosters the execution of specific software application in isolated system environments called containers. Every container is a running instance of an OS image, representing a read-only lightweight template that delineates and manages the container's system processes. Docker framework is an open source container-based virtualization technology that fosters lightweight yet scalable deployment of multiple independent software instances. Docker containers run in isolated fashion with respect to the host OS. The access to the hardware resources (i.e. the communication interfaces and processing/memory units) are virtualized within each container. Compared to OpenStack, Docker does not require the deployment of a full OS, as it runs inside the host's OS kernel. This makes Docker significantly lighter and swifter compared to OpenStack. However, it lacks the cloud management infrastructure that is available with the OpenStack [21, 22].

Recent results show that the containerized V-RAN solution are the most appropriate for RAN virtualization, due to the strict delay sensitive and resource scaling requirements [23]. Moreover, containerized V-RANs impose lower resource overhead and do not have to rely on bulky orchestration and management frameworks, such as OMF and OSM. Table 1 provides a summary for both virtualization technologies and their applicability.

Table 1 Virtualization technology comparison

Virtualization technology	**Deployment time**	**System outage due to reconfiguration**	**Applicable scenarios**
Hypervisor-based	High	Very High	Core network and service layer deployment
Container-based	Negligible to Perceptible	Negligible to Perceptible	RAN deployments

Although the V-RAN has attracted significant attention both from academia and industry, it poses significant limitations regarding the scalability and latency. This issues can be addressed by decentralizing the V-RAN down to the edge and fog computing [24], a concept known as Mobile Edge Computing or Multi-Access Edge Computing (MEC). In MEC, the computing capabilities are pushed closer to the radio access (and, in turn, closer to the subscribers), fostering low-latency and high-bandwidth access to any content, applications and services. The distributed nature of MEC architecture also makes it ideal for supporting high volumes of connected devices, which is one of the main focuses in future wireless systems, such as 5G, [25].

While, V-RAN represents an extension of the conventional virtualization paradigm, it has distinct properties stemmed from the wireless channel, making the virtualization and orchestration more complicated [26]. Thus, it requires novel methods, algorithms and mechanisms for management and orchestration. Specifically, wireless and computational resources have to be shared and distributed to different RRHs in a fair and efficient manner. Moreover, wireless virtualization requires "smart" algorithms that can optimally allocate the underlying resource while taking into consideration the wireless phenomena such as channel capacity, reliability, etc. In V-RAN, the radio resource abstraction and isolation is not a straightforward process due to the inherent broadcast and stochastic features of the wireless communication channels [27]. Many technical and management research challenges have to be addressed, before the V-RAN's commercial deployment. The following section elaborates how the addressing of current V-RAN open issues leads to novel concepts such as Open RAN.

4 Towards O-RAN

By striving to address the most impending issues, the V-RAN is evolving from the concept of C-RAN, towards the concept of Open-RAN (O-RAN) and focuses on two fundamental pillars: Openness and Intelligence. Open interfaces are vital to support smaller vendors and operators to swiftly introduce novel services, and enable operators to tailor the network based on their own requirements. Openness also enables multivendor V-RAN deployments, resulting in a more competitive and richer ecosystem. Moreover, open source software and hardware designs can facilitate faster, and more efficient innovation and commercial deployment, while preserving the backward compatibility with legacy systems. Future wireless systems such as 5G and beyond 5G will also become significantly more complex, due to network densification and richer and more demanding applications. Hence, the operators and the vendors of the mobile networks should be self-organizing. They should be able to leverage new technologies, such as Machine Learning (ML) and Artificial Intelligence (AI), in order to automate operational network functions and reduce operational costs. The telco industry has identified the efforts for providing an open virtualized RAN as the first notable evolutionary step towards the 5G. Figure 2 depicts the relation and evolution of the C-RAN concept and its derivatives V-RAN and O-RAN.

The number of research and development activities that focus on the O-RAN concept is constantly increasing under the umbrella of the O-RAN alliance that provides the necessary framework for O-RAN commercial development and deployment [5]. The O-RAN initiative stems from three key principles:

- Lead the industry towards open, interoperable interfaces, RAN virtualization, and big data enabled RAN intelligence;
- Specify APIs and interfaces, driving standards to adopt them as appropriate, and exploring open source where appropriate;
- Maximize the use of common-off-the-shelf hardware and merchant silicon and minimizing proprietary hardware.

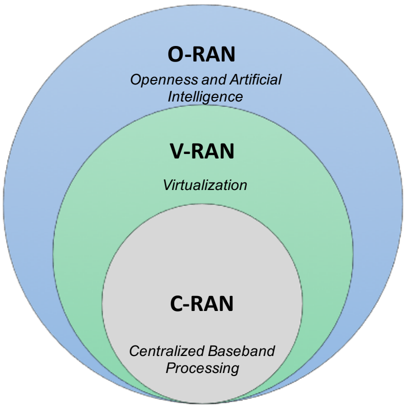


Fig. 2 C-RAN evolution towards O-RAN

Based on these key principles the O-RAN initiative extensively exploits advanced technologies such as: Software Defined, AI enabled RAN Intelligent Controller, RAN Virtualization, Open Interfaces, White box hardware, Open Source software. Their major characteristics are:

Software Defined, AI enabled RAN Intelligent Controller. The O-RAN architecture aims to extend the SDN concept of decoupling the control plane (CP) from the user-plane (UP) in the RAN's, by fostering embedded intelligence. This approach, extending the CP/UP split, further enhances the traditional RRM functions with embedded intelligence by introducing a RAN Intelligent Controller (RIC).

The main benefit from the decoupling is the possibility of the UP to be more standardized. This allows easy-scaling and cost-effective solutions for the UP. The second benefit is to allow more advanced control functionality, which delivers increased efficiency and better radio resource management. These control functionalities will then leverage analytics and data-driven approaches including advanced ML/AI tools.

O-RAN strives to lead the industry for the development of AI-enabled RICs. The O-RAN initiative develops specifications, software reference designs, drives operator proof-of-concepts and supports operator field trials. Even the most complex networks supporting the O-RAN AI-enabled RIC are envisioned to have inherent ability to offer efficient, optimized device and radio resource management through closed-loop control.

RAN Virtualization. RAN virtualization is one of the fundamental tenets of the O-RAN architecture. O-RAN focuses on delivering Network Function Virtualization Infrastructure/Virtualized Infrastructure Manager (NFVI/VIM) requirements to enhance virtualization platforms in support of various splits over the protocol stack (i.e. network slicing). For example, high layer split between PDCP and RLC, low layer split within PHY, etc. The O-RAN initiative also focuses on analyzing the benefits and performance of relevant open source virtualization communities (such as OPNFV, ONAP, Akraino, M-Cord, OpenStack, etc.) to design key solutions such as programmable hardware accelerators, real time processing, light weight virtualization technologies.

Open Interfaces. The O-RAN reference architecture is built on a set of key interfaces between multiple decoupled RAN components. These include enhanced 3GPP interfaces for efficient multi-vendor interoperability. Additionally, O-RAN envisions an open fronthaul interface between the BBUs and RRHs, as well as an open interface between the RIC and the V-RAN.

White box hardware. To take full advantage of the economies of scale offered by an open computing platform approach, O-RAN's reference designs specify high performance, spectral and energy efficient white-box base station hardware. The given O-RAN reference platforms, support a decoupled approach and offer detailed scheems for hardware and software architecture that facilitate efficient design and deployment of the BBUs and RRHs.

Open Source software. Most of the O-RAN architecture components (e.g. RIC, protocol stack, virtualization plaftorm etc.) are and will be delivered as open source solutions, through existing open source communities, like Linux Foundation, OMF, etc. The O-RAN open-source software framework implements the standardized 3GPP interfaces, and also expects to offer the reference design for next generation RIC-based RRM.

Figure 3 depicts the O-RAN reference architecture. It is designed to enable the next generation RAN infrastructures. Empowered by principles of intelligence and openness, the O-RAN architecture is the foundation for fostering the V- RAN concepts on open hardware, with embedded AI-powered radio control. The architecture is based on well-defined, standardized interfaces that enable open, interoperable ecosystem, which will complement standards promoted by 3GPP and other industry standardisation bodies. The main features and functional modules of the O-RAN reference architecture include the: RIC non-Real Time (non-RT) layer, RIC non-Real Time (near-RT) layer, Multi-RAT Centralized Unit (CU) protocol stack and platform, Distributed Unit (DU) and RRH Function definition.

The O-RAN initiative is still in its early stages. Most of the envisioned goals are work in progress that is expected to evolve, during the different development stages, as a result of the increasing practical work with C-RAN, V-RAN and O-RAN. Hence, it is very important that future research activities specifically focus on practical and real-world trials with respect to the virtualized RAN concepts. Some specific findings from practical experimentation with V-RAN are presented in the following section.

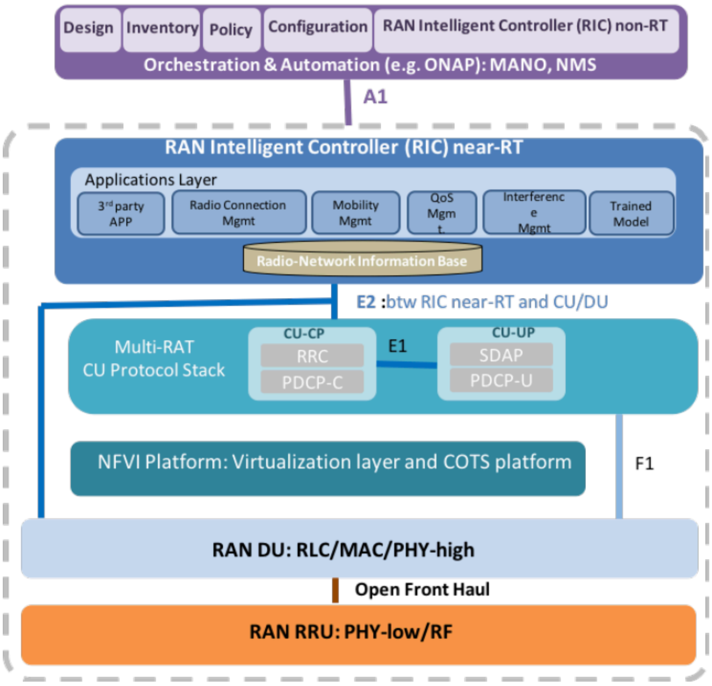


Fig. 3 O-RAN Reference Architecture

5 Practical results and lessons learned

V-RAN (i.e. O-RAN) deployments will heavily rely on self-organization and intelligence-based technologies. Fostering efficient operation requires large knowledge base and understanding of the V- RAN performance behavior. This section presents some specific experimental results regarding the V-RAN performance behavior and discusses the lessons learned related to real-world operation and practical deployment of such systems. They could be used as the primary step in understanding commercial V-RAN deployments. Moreover, the generated knowledge base could be used as input in advanced intelligence-based algorithms for optimal system orchestration and management.

The platform in the experiment consists of a virtualized LTE system that can be used for practical experimentations related to V-RAN deployment and orchestration. It comprises of two core logical entities, Remote Radio Heads (RRHs) and Multi-access Edge Computing (MEC) segment, both implemented on commercial-grade hardware components, Figure 4. The RRHs are implemented on a Software Defined Radios (SDR) platform utilizing the Universal Software Radio Peripheral (USRP) devices, developed by National Instruments. The RAN-specific baseband processing is performed in a softwarized virtual environment of BBUs, provided in the MEC segment. The

MEC platform incorporates a container-based virtualization that utilizes the docker framework. The specific experiment platform uses a commercial LTE BBU software, Amarisoft . The Amarisoft implements a commercial-grade full stack LTE Rel. 14 The Amarisoft can be executed on General-Purpose Processors (GPP) and deals with buffers of samples in system memory, making it compatible with any RF front-end, such as the USRP devices.

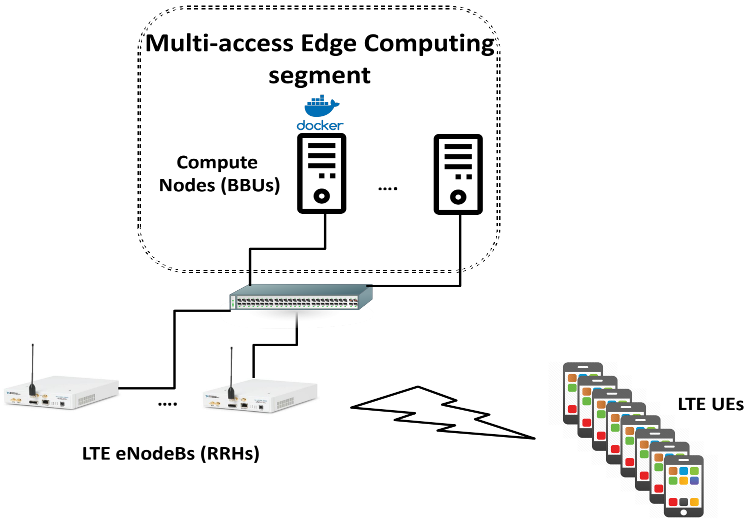


Fig. 4 V-RAN platform generic architecture

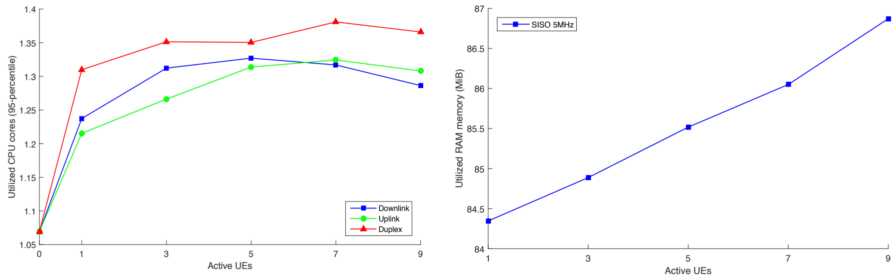
The LTE mobile stations i.e. UEs also ran over the USRP devices and use the srsLTE software. The srsLTE toolkit fosters the operation of a full-stack LTE Rel. 9. The MEC segment runs over a set of dedicated compute nodes. The nodes represent the available MEC pool of resources such as, CPU and RAM that are allocated to the virtual LTE instances. The nodes run on a server-grade machines with Intel Xeon processors over an Ubuntu 16.04 LTS using a low latency kernel. The fronthaul link between the RRHs and the BBUs is enabled by 10GbE links, routed over a 10GbE switch. Table 2 presents the relevant experiment's parameters.

The presented result focus on specific V-RAN related Key Performance Indicators (KPIs) such as, *CPU utilization*, *RAM utilization*, *Resource limitation* and *fronhaul impact*.

Figure 5 presents the CPU and RAM utilization, of the virtualized LTE system, in dependence of the number of active UEs. The active users stream TCP applications that consume the full system capacity. It is evident that the CPU utilization does not increase for higher number of active users, i.e. there is

Table 2 Experiment parameters

Experiment parameters	Parameter value
Channel bandwidth [MHz]	5, 10, 15
No. of eNB	1 - 2
No. of UE mobile devices	1 - 11
Antenna mode	SISO, 2x2-MIMO
LTE earfcn	1575, 3350
Modulation	Adaptive based on channel conditions
UE type	USRP X310/B210 with srsLTE



(a) CPU Utilization (b) RAM Utilization

Fig. 5 Resource utilization vs number of active UEs

no evident scalability effect, Figure 5a. This represents a very valuable finding with respect to understanding the overall virtualized system behaviour. It is highly dependent on the LTE's PHY layer that has to decode the full OFDMA sequence of subcarriers irrespective of the number of active users. Moreover, the CPU utilization attains highest values for the duplex mode of operation, because it must encode/decode both UL and DL signals at the same time. It is also evident that the uplink requires higher computational power than the downlink for larger number of devices. This effect is a result of the most distant UEs from the eNodeB that have the worst channel condition. Hence, the communication heavily depends on the systems turbo channel coding, requiring higher computational power at the eNodeB for the decoding process. The Figure 5b also shows the RAM utilization in dependence of the number of active devices. It is obvious that the RAM increases for higher number of devices. However, the amount of memory required for the eNodeB is very small and several orders of magnitude less, compared to the available resources of a MEC server. Hence, the memory usage is not a critical issue for any V-RAN solution.

Figure 6 depicts the attained throughput under limited CPU resources. Specifically, in the given scenario the applications are run over an 5MHz or a 10MHz LTE configuration. For the 5MHz configuration the system is not upper limited on the available CPU resources, whereas for the 10MHz case the

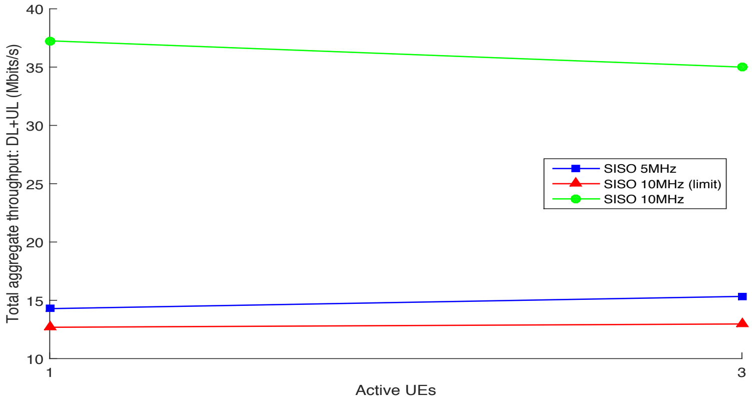
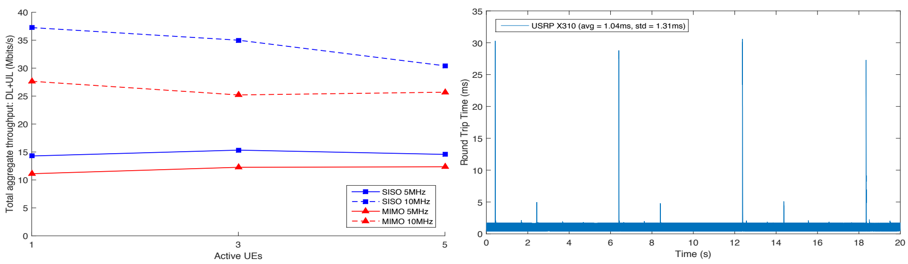


Fig. 6 Throughput degradation due to CPU limitation

system is upper limited to the maximum CPU resources that are consumed by a 5MHz LTE eNodeB. The comparison of both scenarios provides insights on how efficient and reasonable is to use high throughput configurations but with less than optimal virtual resources. As seen from the figure, the throughput experience significant degradation when the CPU resources are limited. Hence, it is more efficient to operate the virtual LTE system in lower system configurations (lower bandwidth and/or SISO mode of operation) without posing limitation on the virtual resources, than in higher (higher bandwidth and/or MIMO mode of operation) system configurations and limiting the virtual resources. This finding is very important for RAN virtualization as it shows a fundamental concept i.e. that there is *no need for virtual resource scaling*. In essence, it is more efficient to reconfigure the system based on the free virtual resources, than to rescale the virtual instances (containers), while operating the system in higher system configurations.



(a) Achieved aggregate LTE throughput (b) RAM Utilization

Fig. 7 Fronthaul design impact

Figure 7 depicts the importance and requirement of a low-latency highly efficient fronthaul design in case of RAN virtualization. Figure 7a delineates the achieved throughput when operating the virtualized LTE system for SISO and MIMO configuration. Opposed to the expectations, the MIMO configuration achieves worse performances than the SISO configuration. This behavior is a result of the particular protocol and driver design used in the USRP's fronthaul. The specific driver/protocol design has high end-to-end latencies, on average 1ms, and in specific cases up to 30ms, as presented in Figure 7b. Although the given fronthaul latency is adequate for reliable and robust LTE SISO operation, for the MIMO deployment it achieves very poor performances. The coherence time of the MIMO channel in this case is in order of a millisecond. Hence, the fronthaul must provide latencies that are approximately an order of magnitude lower than the channel coherence time in attempt to facilitate efficient and reliable MIMO operation. This is one specific illustration that demonstrates the requirement for a low latency, highly efficient fronthaul. The Ultra-Reliable and Low Latency Communications (URLLC) represents another focal scenario that requires a very low latency fronthaul.

5.1 Lessons learned

The remainder of the section summarizes the conclusions from the presented results and the lessons learned from running some practical V-RAN deployment scenarios, mainly focusing on the virtual resource usage and some infrastructure limitations:

Virtual resource usage. One of the focal conclusions from the presented results is that there is no need for resource scaling of the virtual resources, i.e. CPU and RAM, as a result of several aspects:

- **Scalability.** As shown in the results a virtualized LTE has very small digital resource footprint regarding the RAM. The system also does not increase its CPU consumption for higher number of users, due to OFDMA. Because OFDMA is the pillar of the PHY layer in 5G, it can be expected that even for virtualized 5G, the scalability will not have significant impact.
- **Virtual resource limitation.** MAGNUM demonstrated that limiting the virtual resources would have detrimental effects on the attained user performance and experience. When lacking the required virtual resources, it is more efficient to reconfigure the system in a lower mode of operation (lower bandwidth and/or SISO mode of operation) instead of limiting the virtual resources.
- **Multi-tenancy.** In RAN virtualization the main resource bottleneck is in the fronthaul link capacity. Conventional servers can easily house tens or even hundreds of virtual eNodeBs (regarding processing and memory capabilities). However, the same number of eNodeBs will require enormous fronthaul data rates. For example, a 20 MHz LTE requires approximately

1Gbps fronthaul capacity. Higher system bandwidths will require proportionally higher fronthaul capacities. Housing several tens of virtual base stations will necessitate a fronthaul capacity that spans in order of hundreds of Gbps, for future systems even in the order of Tbps. Hence, the number of eNodeBs housed in a given server will be significantly less than the server's upper limit, with respect to its computational resources.

Infrastructure limitations. Fronthaul design plays a crucial role in the overall system performance of a virtualized wireless network. Main issues for further research are:

- **Low-latency design.** The results demonstrated that having a low-latency fronthaul is of outmost importance for proper operation of the system. As a rule of thumb, the end-to-end latency between the RRH and the BBUs should be approximately an order of magnitude lower than the latency requirement of any system algorithm or service. As a result, conventional wireless systems can only be virtualized and deployed in the network edges. Cloud deployments are practically unfeasible. Moreover, communication protocols used for the data exchange between the RRHs and the BBUs must be very swift, light weight and scalable.
- **Link capacity.** The data rate between the RRHs and BBUs is extremely high. Future research should pay considerable attention on methods that can easily scale the required link capacity, or utilize methods that can decrease the data rate on the fronthaul (e.g. compression algorithms). This issue is especially important for high bandwidth systems such as LTE Carrier Aggregation, and 5G.

This section presents a set of achieved real-world V-RAN experimental results that provide valuable insights regarding the operation of current V-RAN and future O-RAN systems. They clearly show that there is still a requirement for more extensive practical research regarding the O-RAN systems. The following section elaborates on the current status and possible future directions for development of C-RAN systems and its derivatives (V-RAN and O-RAN).

6 A way forward

Many research and development activities exist in the area of C/V/O-RAN. Both academic and industrial communities have already intensively started to focus their attention on how to efficiently deploy virtualized RAN solutions. As already discussed, the initiatives such as Linux Foundation, ONAP, O-RAN Alliance, etc. pave the way forward for the commercial roll out of the virtualized RAN technology based on open-source software. The technology is still in its early stages and requires substantial practical research. Most recent research findings (such as ones presented in Section 5) demonstrate that RAN virtualization is feasible but has to be separated from the **scope** and **benefits** related to conventional virtualization (i.e. cloud computing).

Scope. RAN virtualization has different focus and scope compared to conventional cloud computing (service virtualization). As such, it is erroneous to apply the same technological concepts and assume the same benefits as in-service virtualization, such as efficient computation resource usage in multi-tenancy deployments. Table 3 provides a more detailed comparison between both.

Table 3 Technology comparison

	C/V/O-RAN	**Cloud computing**
Client/BS data rate	Gbps range, constant stream	Mbps range, bursty
Latency and jitter	Range of us to very few ms	Range of ms
Data lifetime	Extremely short (baseband signaling)	Long (content data)
Allowed recovery time	Range of ms (avoid outage)	Range of seconds - minutes
Number of clients per centralized location	Hundreds	Thousands, even millions

Benefits. The main benefits of RAN virtualization are its ability for fast deployments and system reconfiguration. These features can be important in scenarios with high dynamicity and unpredictability. Moreover, RAN virtualization can foster fast and cost-effective development and rollout of novel and next generation wireless technologies. It will also leverage concepts such as Multifunction RF, where a single radio can reconfigure between different wireless technologies based on the underlying scenario and conditions.

Apart from the academia and industry related RAN virtualization efforts, there are several standardization initiatives that focus either on: *i)* standardization of virtualization aspect or *ii)* standardization of transport network aspects. The relevant standardization activities are presented in Table 4.

The standardization activities mostly focus on the cloud virtualization aspects and orchestration and on the transport layer mechanisms that facilitate advanced fronthaul operation such as per stream/user QoS, enhanced scheduling and ultra-fast synchronization. Although there are several different standardization activities that target the RAN virtualization, the ecosystem is still very fragmented and lacks overall cohesion and clear vision. It can be expected that future activities will be more aligned between each other and will provide a better synergy between the specific RAN virtualization standards and the wireless technology standards (i.e. 3GPP, IEEE). The initiatives such as the O-RAN will play a crucial role in the future development of the technology and pave the road for more coherent standardization and deployment process.

Table 4 Standardization activities

Standardization category	**Standardization activity**
Virtualization	ETSI NFV Industry Specification Group (ISG) [28] Open Networking Foundation (ONF) [29] Metro Ethernet Forum [30] Open Platform for NFV [31] 3GPP 5G NRM [32]
Transport network	IEEE 1914 - Next Generation Fronthaul Interface(NGFI) [33] IEEE 1904.3 [34] IEEE 802.1Qbv, 802.1Qbu [35] IEEE 802.1CM [36] IEEE 1588 [37]

7 Conclusions

Cloud-RAN represents an auspicious technology, which proposes centralization of the baseband processing resources in a cloud environment. Plethora of ongoing academic and industry activities related to the C-RAN technology exist and attempt to facilitate significant cost savings, improved system performance and enable new business models and opportunities. However, introducing the novel concepts such as virutalization (i.e. V-RAN) and openness and intelligence (O-RAN) in the system, can resolve the C-RAN specific limitations and features.

This paper provides an overview of the generic concepts, main limitations and evolution of the C-RAN approach. The presented practical results and lessons learned, pinpoint the current status and future research activities that are imminent for C-RAN and its derivatives (V-RAN and O- RAN). The paper also discusses the potential development directions, and possibilities for commercial roll out, by analyzing the current industry and standardization activities.

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