IEEE Access
Multidisciplinary | Rapid Review | Open Access Journal

Received 10 February 2024, accepted 6 March 2024, date of publication 11 March 2024, date of current version 15 March 2024.
Digital Object Identifier 10.1109/ACCESS.2024.3375749

SURVEY

RAN Virtualization: How Hard Is It to Fully Achieve?

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ABSTRACT Radio Access Network (RAN) virtualization stands as a pivotal concept in the realm of 5G networks and beyond. It emerges as a viable solution not only to address energy cost concerns but also to optimize material and radio resource management. Despite numerous deployment trials worldwide, a comprehensive realization of Virtual RAN (V-RAN) remains elusive. Current platforms tackle various aspects of V-RAN but encounter numerous limitations. In this paper, we conduct a survey on the progress of RAN virtualization to date and discuss the persisting barriers to its full realization in future mobile radio networks. Initially, we revisit the fundamentals of virtualization and its evolution over recent decades, elucidating the distinctions between Cloud RAN (C-RAN), V-RAN, and Open RAN concepts. Subsequently, we offer an in-depth tutorial on the implementation procedures of V-RAN as per different vendors. Lastly, we shed light on persisting issues within vendor platforms and demonstrate, via simulations, the constraints on their performance concerning supported Base Band Units (BBUs) and devices, as well as coordination among various entities.

INDEX TERMS RAN virtualization, B5G, C-RAN, V-RAN, OpenAirInterface, srsRAN.

I. INTRODUCTION

The roots of virtualization trace back to the 1960s, originating from collaborations between IBM's Cambridge Science Center and MIT (Massachusetts Institute of Technology) [1]. Initially, technologies like hypervisors were devised to enable multiple users to access computers concurrently, primarily for batch processing tasks. However, alternative solutions emerged over time, notably the time-sharing technique, which partitioned users within operating systems [2]. This approach gained prominence, leading to the development of operating systems like UNIX and Linux. Despite these advancements, virtualization remained underutilized until the 1990s. At this juncture, companies began crafting proprietary physical servers, limiting the compatibility of applications across different hardware vendors [3]. Virtualization emerged as a natural solution to this challenge, becoming increasingly popular in the 2000s [4]. Companies like VMware spearheaded the development of software virtualization systems for x86-based architectures, while free software options such as Xen, KVM, and VirtualBox gained traction, democratizing virtualization across various domains, including servers, storage, data, applications, and networks. The principles of hardware abstraction and resource sharing inherent in virtualization proved instrumental in reducing equipment energy consumption, as well as capital and operational expenditures [4].

Since 2012, ETSI (European Telecommunications Standards Institute) has been actively working to standardize Network Function Virtualization (NFV), a novel virtualization approach aimed at future mobile radio networks. With the advent of 5G, NFV has been integrated into the core network and is now poised to extend into the Radio Access Network (RAN) and beyond.

The abstraction of baseband unit functionalities initially surfaced with the Cloud-RAN (C-RAN) concept, which centralized baseband processing resources into a unified Baseband Unit (BBU) pool to dynamically manage radio resources [5]. Subsequently, the V-RAN concept emerged, emphasizing the decoupling of radio resources management introduced by C-RAN, while the Open RAN concept seeks to promote openness, interoperability, and intelligence. However, operationalizing V-RAN remains a challenge. While various vendors have developed platforms for RAN virtualization, they grapple with numerous limitations.

The associate editor coordinating the review of this manuscript and approving it for publication was Jjun Cheng.

A. RELATED WORK

In this section, we present a comprehensive overview of survey papers that serve as a background for our study. The existing surveys predominantly focus on the Cloud-RAN (C-RAN) concept, its deployment, and associated opportunities. The earliest surveys on C-RAN, published in 2014, provided insights into the concept, centralization, virtualization, and key technologies such as uplink Coordinated Multiple Point (CoMP) and General Purpose Platform (GPP) based C-RAN testbed [5], [6]. Another survey in the same year reviewed fronthaul compression techniques for C-RAN, emphasizing advanced signal processing solutions based on network information theoretic concepts [7].

Subsequent surveys in 2015 delved into comprehensive overviews of C-RAN technology architecture, transport network techniques, fronthaul constraints, Spectral Efficiency (SE), Energy Efficiency (EE), and resources allocation in Heterogeneous-Cloud Radio Access Networks (H-CRANs) [8], [9], [10], [11]. The focus shifted to C-RAN system architectures and key techniques like fronthaul compression, large-scale collaborative processing, channel estimation, and radio resource allocation in 2016 [12], [13], [14].

In 2017, surveys began addressing the concept of virtualization in C-RANs alongside the progress of C-RAN works [11], [15], [16], [17], [18]. The following year, attention turned to the utilization of SDN (Software Defined Network) and NFV (Network Function Virtualization) technologies in C-RAN, as well as challenges preceding the 5G rollout [19], [20], [21], [22]. Topics such as Fiber-Wireless (Fi-Wi) paradigm, fronthaul link technologies, clustering algorithms, and RRH (Remote Radio Head) and BBU (Baseband Unit) entities were also explored.

Since 2019, C-RAN surveys have continued to investigate functional splits, throughput enhancement, interference management, energy efficiency, security, and system cost reduction [23], [24], [25], [26], [27], [28], [29], albeit without addressing the main concern of RAN virtualization concretization.

Similarly, numerous survey papers ([30], [31], [32], [33], [34], [35], [36], [37], [38]) on Open RAN have been published, mainly outlining the basic concepts of C-RAN and highlighting the advantages and commercial opportunities of Open RAN. RAN virtualization was briefly discussed, with only one survey in 2013 providing an overview of 3GPP RAN Sharing Enhancements and mobile carrier network virtualization [40]. This survey presented a spectrum sharing-based solution called the Network Virtualization Substrate (NVS) and demonstrated its feasibility in meeting the needs of future virtualized mobile carrier networks. Since then, no other comprehensive survey on RAN virtualization has been identified in the literature.

B. MOTIVATIONS OF THE ARTICLE, SCIENTIFIC CONTRIBUTIONS AND STRUCTURE OF THE PAPER

To the best of our knowledge, there exists only one survey on RAN virtualization, as mentioned earlier. Dated back to 2013, that survey is now outdated considering the recent advancements, methodologies, and platforms developed for V-RAN. In this paper, we propose a new survey that showcases the recent progress in V-RAN implementation and summarizes the challenges hindering its complete realization.

The primary contributions of this survey are as follows:

- Firstly, we elucidate the distinctions between the concepts of C-RAN, V-RAN, and Open RAN, and analyze the significant research endeavors undertaken for each.
- Secondly, we outline the steps toward achieving complete RAN virtualization, along with the necessary technological tools.
- Lastly, we delve into the persisting issues that impede the full realization of RAN virtualization.

The remainder of the paper is structured as follows: Section II elucidates the concepts of C-RAN, V-RAN, and Open RAN, tracing their evolution from the virtualization concept and highlighting ongoing research in RAN virtualization. Section III provides further insights into the RAN virtualization process as documented in the literature. Section IV discusses the challenges that continue to hinder the practical implementation of V-RAN. Finally, Section V concludes the survey.

II. RAN VIRTUALIZATION: BASIC CONCEPTS AND RESEARCH ADVANCES

Around 2014, researchers began to explore various implementations of C-RAN, which offered numerous advantages over traditional RAN setups. More recently, two additional RAN concepts, V-RAN and Open RAN, have emerged. In the following sections, we revisit the fundamentals of virtualization and its gradual integration into mobile radio networks. Subsequently, we delineate the distinctions between the concepts of C-RAN, V-RAN, and Open RAN, while also surveying the most pertinent research efforts associated with each concept.

A. THE VIRTUALIZATION CONCEPT

1) PRINCIPLE AND ADVANTAGES

Virtualization involves running multiple operating systems on a single physical hardware, creating virtual versions of them at a higher abstraction level. It offers flexibility by allowing multiple OS instances on one computer and easy migration to other machines. Virtualized instances ensure uninterrupted service during shutdowns or maintenance, and scalability by simplifying node addition or removal. It increases hardware utilization by hosting multiple OS simultaneously, adapts to workload changes by reallocating resources among virtual machines. Financially, it reduces acquisition costs and lowers maintenance and electricity expenses. Administratively, it transforms physical machines into easily transferable files, simplifying migration.

2) THE DIFFERENT TYPES OF VIRTUALIZATIONS

The hypervisor, as highlighted in [42], serves as the linchpin of virtualization, forming the core component that enables the deployment of virtualization platforms. These platforms facilitate the concurrent operation of multiple operating systems on the same hardware. Various types of virtualization have been developed within the realm of computer science:

- ***Full Virtualization:*** In this paradigm, the hypervisor emulates a complete hardware environment for each virtual machine, endowing each with its own set of virtual hardware resources provided by the hypervisor. This setup allows virtual machines to execute applications independently. Full virtualization offers benefits such as user isolation and shared utilization of a single computer system among multiple users, as outlined in [43] and [44]. However, it may impact system performance and application speed due to the hypervisor's data processing demands, which consume a portion of the physical server's computing power and resources. Additionally, the hypervisor requires suitable interfaces, known as device drivers, to access the machine's resources. The absence of drivers for specific hardware resources can hinder full virtualization's operation on a given machine, posing challenges for organizations adopting new hardware advancements.
- ***Para-Virtualization:*** In contrast to full virtualization, para-virtualization employs a different approach. Here, the hypervisor offers a programming interface (API) that allows guest operating systems direct access to the physical hardware of the host system. This method, described in [43] and [44], delivers performance advantages over full virtualization. Para-virtualization also streamlines backup processes, facilitates rapid migrations, enhances system utilization, promotes server consolidation, and contributes to power conservation, among other benefits. The performance gains of para-virtualization are contingent on the workload, with the degree of benefit closely tied to the volume of hypercalls, which are communications between the operating system and the hypervisor. The efficacy of these hypercalls in reducing compute time for specific workloads determines the actual performance enhancement. Workloads generating numerous hypercalls may experience substantial performance improvements compared to running the same application in full virtualization.

Another classification of virtualization, based on its application in system communications, encompasses "Application virtualization," "OS virtualization," and "Network virtualization":

- ***Application Virtualization:*** Application virtualization, as outlined in [43], involves decoupling the execution of applications from the local environment. This process entails configuring remote applications on a server and delivering them to end users' computers. Users perceive virtualized applications as identical to locally installed apps on physical machines. The primary benefits of this approach include facilitating remote work, ensuring portability, enhancing flexibility, and centralizing application management.
- ***OS Virtualization:*** OS virtualization, also known as Operating System-level virtualization, is a technology enabling the operation of multiple isolated user spaces, termed containers, on a single operating system (OS) kernel [43]. Rather than allocating dedicated hardware for each OS, multiple containers or virtual machines can share the same physical resources. This fosters efficient resource utilization and minimizes wastage.
- ***Network Virtualization:*** Network virtualization abstracts and decouples network resources from the underlying physical hardware, enabling the creation of independent virtual networks. In this approach, described in [43], the aim is to establish a flexible, scalable, and programmable virtual network layer that operates autonomously from the physical infrastructure. Network virtualization empowers organizations to manage and configure virtual networks independently of the underlying physical components.

3) NETWORK VIRTUALIZATION IN WIRELESS AND CELLULAR NETWORKS

Since the inception of the virtualization concept, research on network virtualization has proliferated, giving rise to new areas of study such as virtualization in wireless networks. The objective has been to introduce virtualization and control mechanisms using NFV and SDN technologies in wireless networks [24], [45], [46], [47]. This endeavor has led to the proposal of new wireless network models, including:

- Virtual WiFi, which facilitates the virtualization of wireless network functions [48].
- SoftRAN (Software Defined centralized control plane for Radio Access Network), as described in [49], enhances a virtual wireless network with features like load balancing and interference management.
- MobileFlow, introduced in [50], focuses on routing control within virtual wireless networks.
- CROWD (Connectivity management for eneRgy Optimized Wireless Dense networks), as detailed in [51], employs SDN as a solution for MAC layer reconfiguration and connectivity management in wireless virtual networks.

Subsequently, RAN virtualization emerged as an evolution of C-RAN in 5G cellular networks [24].

B. FIRST STEP TOWARD RAN VIRTUALIZATION: THE C-RAN

1) PRESENTATION

The C-RAN, also known as Centralized RAN or Cloud RAN [8], represents a significant evolution in radio access network (RAN) architecture, particularly from the decentralized structure prevalent in 4G networks. In traditional RAN architectures, the baseband processing resources were distributed, with baseband unit (BBU) and remote radio head (RRH) units co-located at each cell site [8].

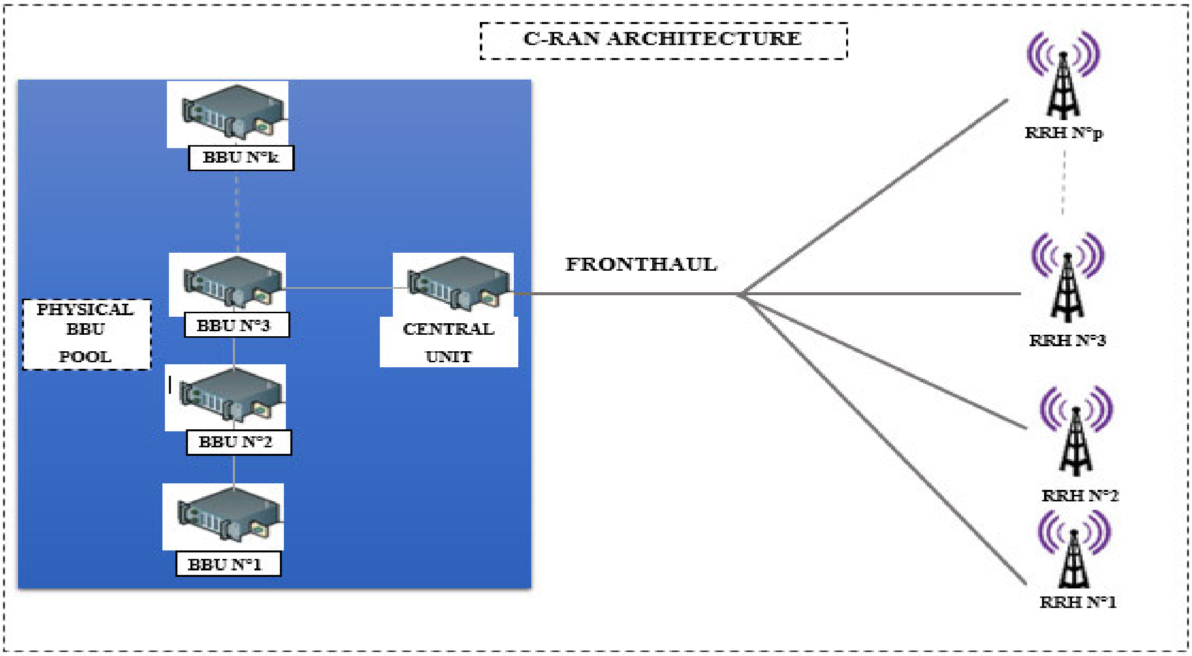

FIGURE 1. C-RAN architecture.

With the advent of the C-RAN concept, a new architecture emerged, characterized by the centralization of baseband processing resources to create a unified resource pool [5], [8]. This centralized pool allows for dynamic resource sharing between base stations, enabling resources to be allocated on-demand (see Fig. 1) [5], [8]. The consolidation of BBUs into a central BBU pool is the defining feature of Centralized RAN.

In the C-RAN architecture, both baseband processing and higher-layer functions are executed within the BBU Pool [23]. The primary objective is to leverage joint processing and scheduling of radio resources to enhance traffic capacity and mitigate interference in cellular systems [11]. This approach, akin to cloud computing principles, has led to the moniker "Cloud RAN."

The C-RAN architecture comprises three key entities [8], [23]:

- ***The BBU Pool [7], [8]:*** The BBU Pool, located at a centralized site, comprises a collection of baseband units (BBUs) that are separated from the remote radio heads (RRHs) by a fronthaul network. These resources within the BBU Pool are dynamically allocated to different BBUs to effectively address user demands and optimize network performance.
- ***RRHs [8]:*** RRHs play a crucial role in providing network coverage and facilitating the transmission of baseband signals between user equipment (UEs) and the BBU pool. Typical functions performed by RRHs include RF amplification, filtering, as well as analog-to-digital and digital-to-analog conversion.
- ***The Fronthaul [8]***: The fronthaul serves as the communication link between the BBU and RRH, facilitating the exchange of data and control signals. Common protocols used in the fronthaul include CPRI (Common Public Radio Interface) [52] or OBSAI (Open Base Station Architecture Initiative). Various transport technologies, such as fiber optics or wireless communication utilizing standard or millimeter radio waves, can be employed for fronthaul connectivity.

The distribution of functions among these RAN entities is contingent upon the chosen functional split option by network operators [25]. The term "functional split" refers to the delineation of network functions across different network elements. It dictates how processing tasks are allocated between the RAN and core network components, determining which tasks are centralized and which are distributed across remote sites in a mobile network deployment.

2) ADVANTAGES, LIMITATIONS, AND RESEARCH EFFORTS

The advantages and limitations of C-RAN are outlined in Table 1.

The motivation behind the C-RAN architecture in 5G and beyond lies in reducing CAPEX and OPEX, which has led to intensive research on energy efficiency over the past decade. For instance, various power control mechanisms, frameworks, and virtualization techniques have been proposed to enhance energy gains, as documented in [53], [54], [55], [56], [57], and [58]. Additionally, a correlation between the computation complexity of C-RAN cooperative transmission and energy consumption has been identified in [59], offering another avenue for reducing energy usage. Concurrently, numerous contributions have focused on refining C-RAN architecture. New architectures like Heterogeneous C-RAN (H-CRAN) have been introduced in [10], [60], and [61], while service-oriented C-RAN architectures [11], [62],

TABLE 1. C-ran advantages and limits.

	Advantages	References
C-RAN	Reduction of CAPEX and OPEX Minimization of the energy consumed Spectral Efficiency(SE) Better interferences handling Ease of maintenance and expansion Better adaptability to non-uniform traffic	[6], [9], [12], [13], [58], [142]
	Limits	References
	Fronthaul Latency Security problems	[11], [13]

lightweight C-RAN architectures [63], and split C-RAN architectures [8], [64] have emerged to address fronthaul burdens, boost processing capabilities, leverage energy benefits, and ensure ubiquitous network coverage. Moreover, the integration of new technologies such as beamforming, multi-user MIMO, massive MIMO, NOMA, and mmWave communications, along with clustering in the C-RAN architecture, has been explored in [65], [66], [67], and [68].

Further contributions (e.g., [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83]) have focused on developing new topology reconfigurations, resource allocation algorithms, and transmission strategies to enhance C-RAN throughput. As fronthaul delay remains a significant drawback of C-RAN, research efforts have also concentrated on minimizing end-to-end delay in C-RAN. Works such as [84], [85], [86], [87], [88], [89], [90], [91], and [92] have proposed solutions based on novel architectural approaches and delay-aware resource allocation algorithms. Lastly, research endeavors documented in [93], [94], [95], [96], [97], [98], and [99] aim to further reduce inherent C-RAN costs using various techniques.

C. THE EVOLUTION TOWARD V-RAN

1) DEFINITION AND ARCHITECTURE

The Virtual RAN (V-RAN) concept represents an evolution of the C-RAN, as noted in [24]. The pioneering research paper on "RAN Virtualization" is documented in [100] in 2014. This paper introduced a novel virtual network architecture for Cloud-RAN base stations, aimed at presenting the core network with an abstracted view of the physical one. By logically grouping macro and small cells into virtual cells and introducing virtual components into the C-RAN BBU Pool, the authors proposed virtualization as a means to simplify C-RAN deployment and address the growing signaling load and latency requirements (Fig.2.). Consequently, the V-RAN architecture inherits from the C-RAN architecture and consists of three main entities: RRHs, the fronthaul, and the virtual BBU Pool. The virtual BBU Pool serves as the core component of V-RAN, leveraging SDN and NFV technologies to decouple proprietary hardware from software functions and create new virtual BBUs containing these functions. This approach enables V-RAN to support various services of the 5G scenarios, including Enhanced Mobile Broadband (eMBB), Machine Type Communication (MTC), and Ultra-Reliable Low Latency Communication (URLLC).

2) MAIN RESEARCH ADVANCES ON V-RAN SO FAR

The research endeavors concerning RAN Virtualization initiated in 2016 can be bifurcated into two primary classifications: architectural propositions and resource management propositions for V-RAN.

a: ARCHITECTURE AND FRAMEWORKS PROPOSALS FOR V-RAN

Various frameworks ([101], [102], [103], [104]) have been presented in the literature to underscore the benefits of virtualization and demonstrate how virtual machines can supplant physical radio access network entities. In [101], a comprehensive Virtualized-CRAN (V-CRAN) architecture was proposed, leveraging concepts of Virtualized Passive Optical Network (VPON) and Virtualized Base Stations (V-BSs). V-CRAN comprises two principal components: VPON, a virtual communication channel facilitating communication between multiple Remote Units (RUs) and a Distributed Unit (DU); and V-BS, a fusion of baseband processing resources in the DU-cloud, VPON in fronthaul, and a cluster of RUs at cell sites. Simulation results illustrated that V-CRAN achieves higher throughput and is more energy-efficient than traditional CRAN and distributed RAN. Reference [102] delineated the design of an end-to-end 5G platform founded on C-RAN architecture, integrating a virtualized RAN, optical/wireless Fronthaul, and cloud-based backend. The wireless and optical domains are managed by a hierarchy of Software Defined Networking (SDN) controllers, responsible for end-to-end optimization, including the Fronthaul and 5G air interfaces. The architecture adopts a modular eNodeB (eNB) design, wherein virtualized BBU and RRH entities are implemented using Commercial Off-The-Shelf (COTS) components. Reference [103] presented a virtualization solution for managing network slices in C-RAN architecture to facilitate the deployment of 5G prototypes. This solution, based on OpenStack's built-in SDN Controller, configures network resources. C-RAN aims to modularize and amalgamate core network services through SDN, transforming into a service-oriented core or a software-defined node, offering a customizable RAN service environment. Another framework proposed in [104] addresses functionalities that facilitate hypervisors as enablers for RAN as a Service (RANaaS). This framework, called eXtensible Virtualization Layer (XVL), is a software layer implementing such functionality and can be added atop existing radio hypervisors. It utilizes cross-platform communication libraries to facilitate

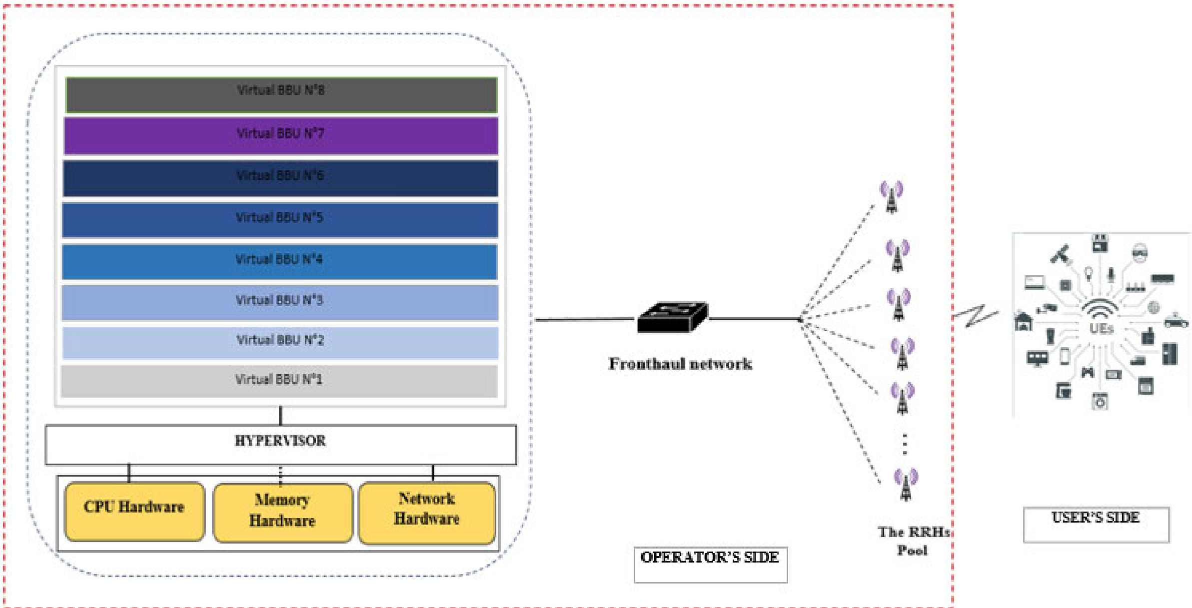

FIGURE 2. V-RAN architecture.

easier integration of different programming languages and Software-defined Radio (SDR) platforms.

- ***Radio resource management operations in V-RAN***, akin to C-RAN, have attracted significant scientific attention, primarily focusing on radio resource allocation, energy efficiency, latency, and security concerns. Various approaches have been proposed to enhance system performance.

b: RADIO RESOURCES ALLOCATION

In [105], the authors introduced the Resources nEgotiation for NEtwork Virtualization (RENEV) algorithm, facilitating dynamic virtualization of radio resources. RENEV abstracts resources by customizing them in isolation among different Requesting Base Stations (BSs), enabling slicing and on-demand delivery of resources. Reference [106] provided novel reconfigurable solutions grounded in C-RAN, particularly an elastic resource utilization framework where Virtual Base Station (VBS) size, Remote Radio Head (RRH) density, and transmit power can dynamically adjust to fluctuations in per-user capacity demand. This framework offers higher energy efficiency and data rates. Reference [107] proposed a dynamic allocation approach for processing resources in a C-RAN BBU Pool, supported by Network Function Virtualization (NFV) concepts. This approach, experimented in the Iris testbed with high-definition video streaming, dynamically allocates resources through BBU processing virtualization.

c: ENERGY SAVING

Reference [108] presented an energy-saving scheme for C-RAN based on the formation of Virtual Base Stations (VBS). Virtualized network resources and functional entities of baseband processing were virtualized to enhance energy efficiency. Addressing energy efficiency maximization in virtualized C-RAN, [109] proposed estimating the number of Virtual Machines (VMs) a server can support without compromising operating efficiency. A power model of virtualized servers was introduced to optimize VMs and maximize energy efficiency. Reference [110] introduced a virtualization framework for Fog Radio Access Network (F-RAN) to enhance energy efficiency in 5G networks. Using Mixed Integer Linear Programming (MILP) models, the energy efficiency of F-RAN was evaluated and compared to conventional C-RAN architecture, revealing a 30% power saving.

d: LATENCY ISSUES

In [111], researchers conducted experimental evaluations within the 5G segment of the Advanced Research on NetwOrking testbed (ARNO-5G) to assess the fronthaul latency requirements specified by Standard Developing Organizations (SDO). They also examined the impact of virtualization on the fronthaul latency budget for Option 7-1 of the functional split. The findings revealed that, under the considered Option 7-1 functional split, the fronthaul latency requirements were 250 μs. In [112], the authors demonstrated that in V-RAN, factors such as virtualization technologies, the functional split option, and the number of elements deployed in the same computational resource influenced the available latency budget in the mid-haul. The paper also established the mid-haul allowable latency as a function of these parameters.

e: SECURITY CONCERNS

In [113], researchers explored a BBU hoteling scheme based on the concept of Access Cloud Network (ACN), where an

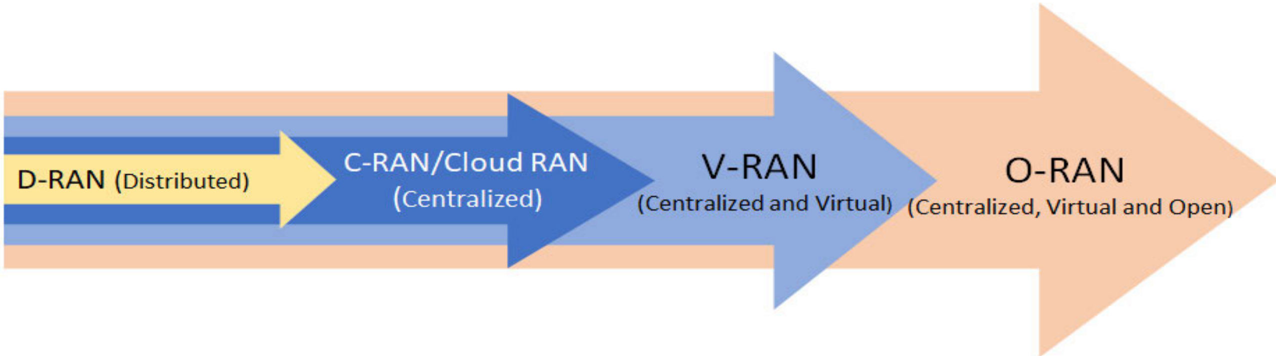

FIGURE 3. The RAN Evolution from C-RAN to Open RAN.

ACN comprises virtual BBUs (vBBUs) situated in metro data centers (metro DCs). However, processing failures within the ACN posed obstacles to C-RAN realization. To address this, the study proposed three protection approaches: 1+1 ACN protection, 1+1 ACN and vBBU protection, and partial ACN protection. Simulation results indicated that both 1+1 ACN and 1+1 ACN and vBBU protection necessitated significant backup capacity to ensure 100% survivability in the event of single link and single-DC failures. Consequently, the authors suggested a partial ACN protection approach, which offered degraded services with only an 8% increase in network resources.

D. OPEN RAN: A NEW CONCEPT TO COME

The Open Radio Access Network, abbreviated as Open RAN or ORAN, signifies an ongoing evolution in mobile network architectures, extending the principles of Virtual RAN by incorporating elements of openness and intelligence (Fig.3) ([30], [31], [32], [33], [34], [35], [36], [37], [38]). Spearheaded by the O-RAN Alliance (Open-Radio Access Network Alliance), a dynamic global consortium comprising mobile network operators, manufacturers, suppliers, and research and academic entities engaged in collaborative efforts within the telecommunications sector worldwide [24], [36], [114].

There are nuances of terminology in the Open RAN context that need to be clarified:

- Open RAN or ORAN terminologies are used to refer to the network architecture.
- O-RAN is used to designates the Alliance group.

Open RAN is engineered to foster interoperability and standardization within the Radio Access Network (RAN), while also amalgamating software components from diverse vendors [24]. This openness facilitates the deployment of multi-vendor Virtual RAN (V-RAN) setups, fostering a more competitive and robust ecosystem ([24], [30], [31], [33], [34], [35], [36], [37]). Furthermore, leveraging open-source software and hardware designs can accelerate innovation and commercialization, all while maintaining backward compatibility with legacy systems. As wireless systems, particularly 5G and beyond (B5G), grow in complexity due to densification and the demand for richer applications, mobile network operators and vendors are compelled to adopt self-organizing strategies [24].

Incorporating technologies such as Machine Learning (ML) and Artificial Intelligence (AI) into Open RAN can automate operational network functions and drive down operational costs. The telecommunications industry recognizes the establishment of an open virtualized RAN as a pivotal step toward realizing the potential of 5G ([24], [30], [31], [33], [34], [35], [36], [37]). Consequently, the reference architecture for Open RAN primarily comprises:

- ***A Non-real-time intelligent controller (non RT RIC):*** Responsible for rule management, RAN analysis, and AI-based feature management [24], [31].
- ***A Near-real-time RIC controller:*** Tasked with radio resource management (RRM) and additional functions like quality of service (QoS) management and handover control [24], [31].
- ***A Multi-RAT protocol stack:*** Supporting various protocol stacks for multiple radio access technologies, including 4G and 5G, with built-in virtualization capabilities [24], [31].
- ***The Open DU (O-DU) and Open RAN Radio Unit (O-RU):*** Comprising Layer 2 functions and baseband/radio signal processing functionalities [24], [31].

Given the organizational and coordination challenges posed by Open RAN's multi-vendor nature, recent research has predominantly focused on surveys ([24], [30], [31], [33], [34], [35], [36], [37]), elucidating generic definitions, reference architectures, and implementation challenges.

III. IMPLEMENTATION STEPS OF A VRAN

The RAN virtualization process unfolds in two distinct phases [Ref]. Initially, the first phase involves abstracting each physical resource within the RAN, including BBU storage and BBU Central Processing Unit (CPU). Subsequently, the second phase entails virtualizing various mechanisms within the radio access network.

A. THE ABSTRACTION PROCESS OF THE RAN PHYSICAL RESOURCES

The abstraction of RAN physical resources is a procedure that enables the creation of one or more virtual replicas of these resources, encompassing all their components such as Operating System (OS), storage, CPU, network functions, etc. Each generated virtual replica is termed a Virtual Machine (VM) or domain. The abstraction of RAN physical resources can be executed using servers, personal computers, or any electronic devices. The pivotal tool responsible for realizing the hardware abstraction is the Hypervisor.

1) HYPERVISOR: THE FUNDAMENTAL TOOL FOR RAN ABSTRACTION PROCESS

The Hypervisor [115] emulates all the necessary hardware components for running software. In the market, there exist two categories of Hypervisors [115]: Type 1 Hypervisors and Type 2 Hypervisors.

- ***Type 1 Hypervisors***, also known as native or "bare metal" hypervisors, are installed directly on the hardware without any intermediary OS This positioning grants Type 1 Hypervisors complete and privileged control over the hardware resources. These resources are then abstracted and allocated to the Virtual Machines (VMs). Below are some recent Type 1 Hypervisors suitable for RAN virtualization projects:

a: VMWARE ESXI

VMware ESXi (formerly ESX) is a Type 1 Hypervisor developed by VMware. It was initially released in 2001, followed by a second version in 2010. Its kernel, called VMkernel, manages the created virtual environment and controls access to the underlying physical hardware. VMkernel also provides conditions to ensure smooth execution of all system processes within the virtual domain specific conditions. Key processes running atop the VMkernel include:

- Direct Console User Interface (DCUI): This interface, utilized through the server console, facilitates VMkernel management and low-level configuration.
- Virtual Machine Monitor (VMM): Also known as VMX, this process generates the virtual environment.
- Other Agents: Additional agents within the VMkernel provide high-level VMware Infrastructure remote control and the General Information Model (GIM) system.

ESXi, a Type 1 Hypervisor deployed for virtualization [116], [117], introduced a system storage layout enabling flexible partition creation and management.

b: XEN

Xen, a Type 1 Hypervisor originally developed in 2003 by the University of Cambridge computer laboratory, comprises several components that collaborate to deliver one or multiple abstracted environments known as "domains." These components include the Xen Hypervisor, Domain 0 Guest (referred to as Dom0), and Domain U Guest (referred to as DomU). Xen utilizes the Borrowed Virtual Time (BVT) scheduling algorithm to ensure low-latency dispatch of a domain when an event occurs [118]. Initial memory allocation for each domain is established at its creation [118], with memory zoned between domains to provide secure isolation. This type of Type 1 Hypervisor was deployed in [119] and [120].

c: KVM HYPERVISOR

Introduced in 2006 and later incorporated by Qumranet, the KVM hypervisor [42] is an open-source virtualization technology that converts a Linux system into a hypervisor. This transformation occurs through a minimally intrusive method that integrates KVM as a kernel module, providing abstraction capability. KVM is integrated into the Linux kernel as a loadable module, treating each virtual machine (VM) as a Linux process managed by the standard Linux kernel. The Linux kernel utilizes the Completely Fair Scheduler (CFS) [42], a sophisticated process scheduler, for advanced process planning. Modifications to the CFS scheduler include the inclusion of a Cgroups (Control groups) resource manager, enabling process resource sharing. KVM utilizes Linux memory management services, maintaining VM memory akin to other Linux processes and enabling memory page sharing via the Kernel Same-page Merging (KSM) feature [121]. This type of Type 1 Hypervisor was deployed in [107] and [122].

d: MICROSOFT HYPER-V

Released in 2008 by Microsoft, Hyper-V [123], [124] simplifies communication between hardware, the operating system, and virtual machines (VMs). Hyper-V offers features such as live migrations, hosted OS isolation, security, reliability, and performance improvements [123], [124]. Each VM machine in Hyper-V allows manual CPU settings adjustments by administrators to align with business or IT operator requirements, enabling reservation of a portion of the server's total processing resources for a VM. Administrators can also limit the consumption of processing resources by a single VM on a host. Hyper-V employs two memory management and optimization techniques, including Dynamic Memory (DM). In this technique, the Dynamic Memory Virtual Service Consumer (DM VSC) monitors guest OS memory usage.

Another technique utilized is Smart Paging, which leverages temporary storage for memory caching to ensure adequate RAM allocation for virtual machines (VMs) [63], [125].

This type of Type 1 Hypervisor deployment was observed in [63] and [125]. All types of Type 1 Hypervisors discussed are intended for implementation within large-scale network virtualization environments, such as those managed by IT operators [115]. A comparative analysis of these hypervisors is provided in the Appendix.

- ***Type 2 Hypervisors:***

Unlike Type 1 Hypervisors directly installed on hardware, Type 2 Hypervisors are software that operates within an operating system (OS). Installation of Type 2 Hypervisors is similar to any software application, making them easier

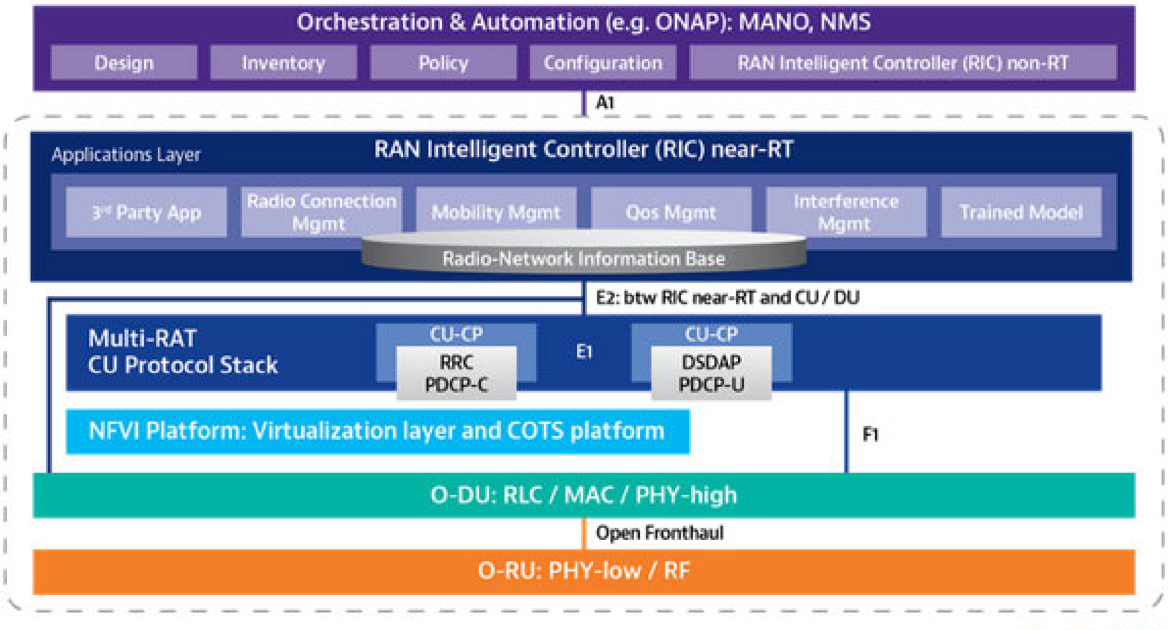

FIGURE 4. Reference architecture of the Open RAN.

to set up but lacking control or priority over hardware resources. Consequently, their performance may be limited, and they may encounter unstable virtual environments. Type 2 Hypervisors are typically used for small-scale testing or in research and are popular in academia due to their flexibility and ease of use. The two most widely used Type 2 Hypervisors are:

e: VMWARE WORKSTATION

VMware Workstation Pro and Player are Type 2 hypervisors developed by VMware, compatible with x64 versions of Windows and Linux OSs. They allow the creation and simultaneous operation of VMs on a single physical machine, each capable of running its own OS, including various versions of Windows, Linux, BSD, and MS-DOS. VMware Workstation Player is free, while VMware Workstation Pro requires a license. These hypervisors are utilized in [64] and [126].

f: VIRTUALBOX

VirtualBox, developed by Oracle in 2010, is a powerful x86 and AMD64/Intel64 virtualization product suitable for business and individual testing purposes. It is available as open-source software under the GNU General Public License (GPL) version [64]. VirtualBox runs on hosts including Windows, Linux, Macintosh, and Solaris, supporting a wide range of guest operating systems, such as various Windows and Linux versions. This hypervisor is employed in [128].

2) SETTING UP THE VIRTUAL ENTITY CONTAINER

The creation of a Virtual Machine (VM) by the Hypervisor serves as a virtual entity container, each with its unique setup algorithm. This section delineates the VM setup process using VMware Workstation Pro, renowned for its user-friendly interface and availability as a free hypervisor. The algorithm outlined in Table 2 is universally applicable across electronic devices, facilitating the creation of VMs tailored to access hardware features like CPU, memory storage, and Hard Disk. However, additional steps are necessary to virtualize the mechanisms and protocols inherent to the Baseband Units (BBUs) within the newly created VMs, ensuring comprehensive control over the BBU operating system.

B. IMPLEMENTING A RAN ENTITY VIRTUAL MECHANISMS

The present operation is achievable in two steps: 1) installation of a platform supporting a 3GPP 4G or 5G RAN protocol stack standards-compliant on the created VM, 2) building and running the BBU's mechanisms on this VM.

1) INSTALLATION OF THE 3GPP 4G OR 5G RAN PROTOCOL STACK PLATFORM

In the literature, we distinguish four open source 3GPP 4G or 5G RAN stack platforms: OpenAirInterface [129], srsLTE [130], free5GRAN [131] and UERANSIM [132].

- ***OpenAirInterface:*** *OpenAirInterface (OAI)* OpenAirInterface (OAI) serves as a pivotal platform tailored for 4G and 5G mobile telecommunications systems. Originating from its development at Eurecom, OAI's software stands as an open-source solution delivering a standards-compliant implementation of a 3GPP 4G LTE stack. This stack seamlessly operates on a commodity x86 CPU and a USRP radio device. Notably, OAI's stewardship has transitioned to the OpenAirInterface

TABLE 2. General setting up algorithm of a virtual entity container using VMware workstation pro.

Algorithm: SETTING UP A NEW VIRTUAL ENTITY CONTAINER
Input: Intel Hardware Core (TM) i7, 500 Go Hard Disk(HD), 16Go RAM Memory
1: Initialization
2: Download package *VMware WORSTATION*
3: Set up *VMware WORSTATION*
4: **If (Erreur Hyper-V = TRUE)**
5: Set automatic *WHP* *// WHP :*
6: **Else**
7: Define Installation Folder *Path*
8: Execute *VMware WORSTATION*
9: Create Home / new *VM* *// VM: Virtual Machine*
10: **If (Disk Image ISO = TRUE)**
11: Set Install *ISO*
12: **Else**
13: Set Install blank HD *VM*
14: /* Some new variables {*OS : Operating System, DC: Disk Capacity, CPU: Central Processing Unit , NA: Network Adapter*} */
15: Set variables { *OS, DC, CPU, Memory, NA*}
16: *OS = Ubuntu 18.04 (Linux)*
17: DC = 10 GB
18: CPU= 2 Cores
19: Memory= 2GB
20: NA= NAT
21: Power ON the *VM*
Output: VM { *OS = Ubuntu 18.04, DC = 10 GB, CPU= 2 Cores, Memory= 2GB, NA= NAT }*

Software Alliance (OSA), a French non-profit organization dedicated to fostering open-source software and tools for 4G and 5G wireless research. Comprehensive in its scope, the OAI software encompasses the entirety of the protocol stack outlined in the 3GPP LTE standards, including Releases 8 and 9, and partially 10 and 11. It also has implementations of the e-UTRAN UTRAN (both eNB[1] and UE[2]) and the EPC (MME,[3] SGW,[4] PDN[5] and HSS[6]).

- ***srsLTE:*** srsLTE, developed by Software Radio Systems (SRS) in Ireland, is an open-source LTE SDR platform. It encompasses a complete protocol stack UE (srsUE) along with a physical layer downlink transceiver link. Additionally, it offers a full protocol stack eNB known as srseNB and an srsEPC that contains core network functions. A third-party eNB and EPC can be integrated to establish an LTE SDR system [133].
- **Free5GRAN**, an open-source 5G RAN stack, is equipped with a receiver capable of decoding MIB and SIB data. It functions as a cell scanner and operates in SA mode [134].
- **UERANSIM**, developed by free5GC, is an open-source project focused on 5th generation (5G) mobile core networks. It includes both a UE and a 5G RAN (gNodeB) implementation, serving as a 5G mobile phone and a base station for testing and studying the 5G core network and system [135].

[1]Evolved Node B (eNB).
[2]User Equipment (UE).
[3]Mobility Management Entity (MME).
[4]Serving Gateway (SGW).
[5]Public Data Network (PDN).
[6]Home Subscriber Server (HSS).

The choice of platform determines the installation process. Table 3 outlines the installation algorithm for the OpenAirInterface platform developed by Eurecom [136].

TABLE 3. Installation algorithm of the OpenAirInterface platform.

Algorithm: THE OPENAIRINTERFACE PLATFORM INSTALLATION
Input: VM { OS = Ubuntu 18.04, DC = 10 GB, CPU= 2 Cores, Memory= 2GB, NA= NAT }
1: Initialization
2: Launch *VM{OS, DC, CPU, Memory, NA}*
3: Get linux-low-latency-hwe-1804 *//Low latency kernel*
4: Set Ens1{ *IP*= 192.168.40.1, *netmask*= 255.255.0.0, *mtu*= 9000}
5: Set Ens2{*IP*= 192.168.40.2, *netmask*= 255.255.255.0, *mtu*=9000 }
6: Set Ens3{IP= 192.168.0.3, netmask= 255.255.255.0, *mtu*= 9000 }
5: *UHD*_Tab_modules=[tree, htop, ethtool, smartmontools, hardinfo, gnome-disk-utility, libboost-all-dev, wireshark, cpufrequtils, python-scipy, automake, qt4-dev-tools, python-pip, python-zmq, libqwt-dev, python-setuptools, OAI_UE, OAI_EPC, OAI_RRH, RAN Protocol stack]
6: **for (i=1 to length(*UHD*_Tab_modules[]))**
7: Import *UHD_Tab_modules*[i]
8: Install *UHD_Tab_modules*[i]
9: Run *UHD_Tab_modules*[i]
10: **end for**
11: Clone *EttusResearch/uhd*
12: Cmake ../ & Make test
13: export PATH_LIBRAIRY=/usr/lib
14: Clone E*urecom/openairinterface5g.git*
15: Change Directory openairinterface5g
16: Define oaienv *//defines environment variables*
Output: : VM { *OS = Ubuntu 18.04, DC = 10 GB, CPU= 2 Cores, Memory= 2GB, NA= NAT }*+ OpenAirInterface Platform

2) BUILDING AND RUNNING THE MECHANISMS OF THE BBU

The mechanisms of BBU (Baseband Unit) are largely consistent across the platforms mentioned earlier, with the exception of those still in conceptual stages. These mechanisms are organized into layers, each supported by various protocols. The specific mechanisms of OpenAirInterface BBUs are detailed below. In the OpenAirInterface platform, the BBU mechanisms are split in five layers [129]: the Physical layer, The MAC (Medium Access Control) layer, the Packet Data Convergence Protocol (PDCP) layer, the RLC (Radio Link Control) layer and the RRC (Radio Resource Control) layer.

The installation process for the BBU mechanisms from the OpenAirInterface platform onto the created VM is outlined in Table 4. Eurecom may refine this procedure over time.

IV. VRAN: THE REMAINING PROBLEMS TO MAKE IT REAL

In this section, we present the remaining problems to achieve a completed V-RAN. In fact, through the study of recent works, we examine to what extend these works have met the RAN virtualization defined by ETSI in [133]. We will

TABLE 4. BBU protocols and mechanisms implementation algorithm in openairinterface.

```
Algorithm: BBU MECHANISMS IMPLEMENTATION
Input: VM { OS = Ubuntu 18.04, DC = 10 GB, CPU= 2 Cores,
Memory= 2GB, NA= NAT }+ OpenAirInterface Platform
Initialization
Run OPENAIR/Cmake_T ./build_oai -h //build OAI software
BBU_Tab_dependencies=[BBU_Packages]
for ( i=1 to length(BBU_ Tab_dependencies[]))
    Import BBU_ Tab_dependencies[i]
    Install BBU_ Tab_dependencies[i]
    Run BBU_ Tab_dependencies[i]
end for
OAI_BBU Configurations {
    IP = 192.168.40.4 ;
    RF = local
    N_Tx =1
    N_Rx =1
    Band = 7
    Max_gain=116 }
Set configs
Run OAI_BBU.conf
Output: VM { OS = Ubuntu 18.04, DC = 10 GB, CPU= 2 Cores,
Memory= 2GB, NA= NAT }+ OpenAirInterface + BBU Running
```

also highlight the problems obstructing large-scale V-RAN realization up today for the IT operators.

A. ATTEMPTS OF REAL V-RAN IMPLEMENTATION BY IT VENDORS

Various telecommunications groups and vendors have introduced proposals for RAN virtualization solutions or tools in recent years.

In 2021, Ericsson, a leading 5G equipment manufacturer in Europe, inaugurated a new laboratory in Ottawa to develop their virtualized Distributed Unit (vDU) and Central Unit (vCU) [134]. NEC Corporation, a major Japanese multinational corporation, unveiled open virtualized RAN software tailored for the global market on September 28th, 2022 [135]. On the other hand, Huawei has opted not to adopt any V-RAN solution due to political reasons [136]. Around 2022, Intel introduced a vRAN Reference Implementation, featuring 4th Gen Intel Xeon Scalable processors with Intel vRAN Boost, in collaboration with Dell PowerEdge XR servers and Wind River Studio, providing significant performance and scalability benefits in network environments. To the best of our knowledge, only one vendor's V-RAN solution has been deployed on a large scale to date, namely Samsung's V-RAN solution [137]. Comprising a vCU and a vDU, Samsung's 5G vRAN kit enables processing for the upper layer of the RAN and real-time processing functions, respectively. Although this solution was anticipated to offer cost-effective deployment and operation meeting various requirements, it was deployed by Verizon in the United States in January 2021, and there is no available feedback on this deployment [138].

Apart from these comprehensive V-RAN prototypes, industries have also proposed hardware and software tools to enhance performance and scalability. For instance, ASOCS enterprise introduced a virtual Base Station (vBS) around 2017 [151], while Dell launched the PowerEdge XR5610 server, a ruggedized, single-socket server optimized for Edge and Telecom workloads [152]. Wind River Studio offers a production-grade Kubernetes cloud platform for managing edge cloud infrastructure, deployed using FlexRANTM Reference Software [152]. In 2021, Lenovo proposed the Lenovo ThinkEdge SE450 server to integrate the Intel Select Solution for V-RAN [153]. This integration allows customers to deploy various 5G vRAN and MEC solutions more securely and easily than ever before. Around 2023, Nokia introduced the Nokia AirScale radio access solution [154], delivering effective coverage and capacity across 2G, 3G, 4G, and 5G mobile networks. Leveraging Nokia's innovative ReefShark System on Chip (SoC) technology, AirScale products enhance radio and baseband performance and capacity within compact designs, prioritizing energy efficiency.

B. ATTEMPTS OF REAL VRAN IMPLEMENTATION IN ACADEMIA AND RESEARCH

The different attempts to implement a VRAN and encountered in literature are mainly conducted by research laboratories. In [139], the V-RAN carried 2 vBBUs, and 2 RRHs deployed on 3 physical 7th generation Intel(R) Core(TM) i5 processor and 8 GB of RAM machines. The first physical machine supported the vBBU pool and the EPC, whereas the two other machines were worker nodes containing the RRH entities. The LTE stack platform used was OpenAirInterface. The authors presented through simulation results the CPU and memory consumption of the vBBUs and RRHs entities. Another V-RAN was proposed in [140]. This V-RAN embraced 2 physical machines, interconnected one virtual BBU, one RRH and one commercial User Equipment (UE). The LTE stack platform used was OpenAirInterface in Docker containers. A simulation of a communication between the BBU and the UE in the case of access to videos on YouTube by the UE shows that the fronthaul rate varies according to the UE rate. In [141], the authors also proposed the realization of a V-RAN with the OAI platform. This V-RAN architecture included one virtual RCC or BBU, two RRS or RRHs and two UEs. Four personal computers are installed with Ubuntu Linux 14.04 and OAI software to function as OAI EPC, RCC and two RRS, respectively. The Universal Soft Radio Peripheral (USRP) B210 was adopted as the radio frequency front end. The two UEs were smartphones with Rohde and Schwarz SwissQual QualiPoc softwares. The simulation results of this V-RAN showed that the fronthaul bandwidth occupation is fixed in the current implementation of OAI C-RAN. Making it dynamically adjustable to user traffic would be a critical issue. The authors in [122] presents a demo of V-RAN with the OpenAirInterface platform. This V-RAN was composed of one RCC or BBU, one RRH and one commercial UE. The RCC was deployed on a commodity Intel x86 PC connected to the RRH deployed on a commodity Intel x86 PCs through a Gigabit Ethernet (GbE) switch. No simulation was provided by the authors. The article [107] proposed a dynamic allocation method of the processing resources in a Virtualized BBU Pool. This V-RAN solution was composed of 2 vBBUs, 2 RRHs and 2 virtual UEs. The V-RAN was deployed on Iris testbed, the reconfigurable radio testbed of Trinity College Dublin and used srsLTE as a LTE stack platform. The simulation results revealed a significant improvement in the quality of the video transmission with the proposed dynamic allocation approach. In paper [147], the authors introduced a prototype of a mobile edge cache system with a primary emphasis on aligning with established Long-Term Evolution deployment and content-location solutions. The prototype was specifically crafted for conducting assessment tests and evaluations of caching solutions. Subsequently, the findings demonstrated enhancements in Quality of Experience (QoE) for mobile users achieved by caching content at the Base Stations (BSs). Their LTE network comprised two primary sections known as EPC (Evolved Packet Core) and Evolved-Universal Terrestrial Radio Access Network (E-UTRAN). This E-UTRAN was composed of a UE and an eNodeB interconnected by a LTE-Uu interface.

The analysis of the V-RAN architectures in the aforementioned research works shows the gap with the ETSI virtualization model and helps us extract the obstructing problems. Indeed, the ETSI NFV reference model, based on an SDN-NFV architecture, consists of Element Management Systems (EMS), Virtual Network Functions (VNFs), and a Network Function Virtualization Infrastructure (NFVI). The different EMS entities regroup and control multiple VNFs at once according to the provided service. The whole architecture is administrated by an NFV Management and Orchestration (MANO) block.

In our study, we have also developed a V-RAN utilizing the OAI platform. This setup consists of 2 virtual Base Band Units (vBBUs), 2 Remote Radio Heads (RRHs), and 2 virtual User Equipments (UEs). The virtual BBU Pool is hosted on an Intel Core (TM) i7 machine equipped with 16GB of RAM memory. We choose the VMware Workstation Pro as hypervisor.

The choice of VMware Workstation, was informed by several performance studies. Initially, references [143] and [148] emphasize that Type 1 Hypervisors are well-suited for large-scale IT operator infrastructures, while Type 2 Hypervisors are recommended for small tests or research purposes. Being in a testing and research context, we opted for a Type 2 hypervisor. The paper [149] conducted a performance analysis between VirtualBox and VMWare Workstation 15 Player, focusing on the efficiency of the applied file system. Using the Filebench tool and workload tests such as fileserver.f, webserver.f, varmail.f, and randomfileaccess.f, the results indicated that VirtualBox and VMWare exhibit nearly identical performances, with a slight advantage favoring VirtualBox in numerous instances.

Another paper, [150], evaluated VMware Player and Oracle VM VirtualBox to assess virtualized operating system performance and resource utilization. Three benchmark tests: PiTest, Prime Benchmark, and Geekbench 2 were employed to measure CPU performance, prime computation, and overall system performance. The results presented represent the mean values obtained after four measurements for each test. These findings indicate that both virtualization software options yielded comparable results, with VMware Player achieving slightly better outcomes in all three tests.

These tests showed a performance equivalence between VMware and VirtualBox. However, what led us to choose VMware is the information provided in the paper [64], stating that VirtualBox, as a newer product, is reportedly more prone to bugs than VMware. Additionally, the ease of setting up bridged, host, or NAT networking in VMware was a contributing factor.

Each vBBU was installed on a virtual machine. We used Eurecom's OAI LTE stack platform to virtualize the entities functions. This simulation enabled us to conduct our own real implementation experience of a V-RAN to better assess the challenges that hinder its large-scale deployment.

The resource utilization of the vBBU, when not yet connected to a UE, involves initiating various threads for protocols like PRACH and scheduling. It then initializes processes for different layers, such as Physical, MAC, PDCP, RLC, and RRC, before setting parameters, creating threads, and entering a listening mode to locate a UE. When connected to a UE, resource utilization increases due to signaling between the OAI-UE and eNB, involving security mode commands exchange, ULSCH transmissions, RRC exchanges for UE capability requests, and data exchanges. This traffic averages 30Mbps.

Fig.5 illustrates the CPU and memory usage of the various virtual Base Band Units (vBBUs) proposed by [139] and [141], as well as those obtained through our simulations using the OAI platform. To facilitate comparison, we standardized our environment to the same scale as the other approaches in terms of CPU and memory allocation. The figure reveals that the CPU and memory consumption for a single vBBU is nearly equivalent across all three studies.

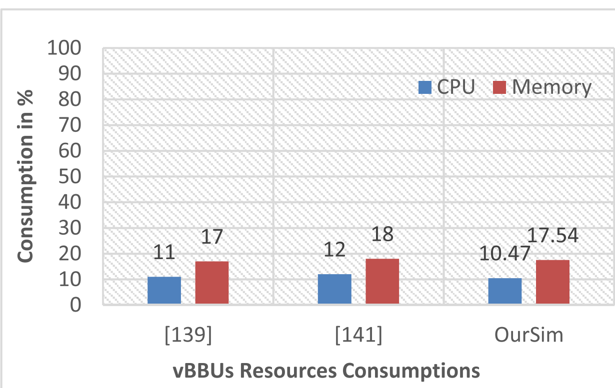

FIGURE 5. Comparison of the CPU and Memory consumptions of different vBBUs.

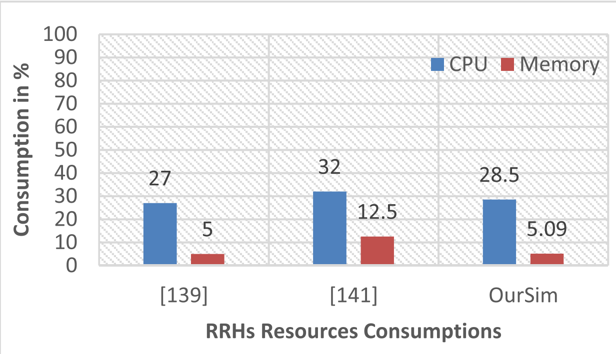

FIGURE 6. Comparison of the CPU and Memory consumptions of different RRHs.

In Fig.6, we present the CPU and memory usage of the Remote Radio Heads (RRHs) implemented in [139] and [141], and our V-RAN. It is evident from the figure that the CPU and memory consumption in [139] and our V-RAN are similar. However, the CPU and memory usage of the RRHs in [141] are comparatively higher.

C. OBSTRUCTING PROBLEM 1: LACK OF FLEXIBILITY IN NETWORK FUNCTIONS VIRTUALIZATION

The Network Function Virtualization (NFV) principle outlined by ETSI in its reference architecture, as detailed in [133], introduces a virtualization layer where Virtualized Network Functions (VNFs) operate independently and offer flexibility. These VNFs can be organized into Element Management Systems (EMS) to deliver various services such as network slicing.

Network slicing facilitates the creation of multiple virtual networks within a single physical networking infrastructure. Each network slice represents a distinct virtualized instance comprised of a dedicated subset of resources. Specifically, it includes an isolated portion of available virtual resources (such as computation and storage) along with a set of traffic management rules.

However, existing LTE or 5G stack platforms are not designed with this level of flexibility. The Base Band Units (BBUs) are typically integrated stacks of functions, lacking modularity. Future efforts should address this limitation by either enabling access to modular functions within BBUs or developing new platforms where Virtual Network Functions (VNFs) operate independently.

TABLE 5. Comparison of the number of vBBUs per pool.

PAPERS	NUMBER OF vBBUSs PER POOL
[139]	2
[140]	1
[141]	1
[122]	1
[107]	2

TABLE 6. Comparison of the number of UEs per vBBU Pool.

PAPERS	NUMBER OF UEs PER vBBU POOL
[139]	NA
[140]	1
[141]	2
[122]	1
[107]	2

D. OBSTRUCTING PROBLEM 2: NEEDS OF ORCHESTRATION BETWEEN THE VBBUS

The main objective of C-RAN and V-RAN was the centralization of the BBUs control. This centralized control should be reproduced in virtualized RANs and performed by an orchestrator. This orchestrator must ensure:

- The control of the BBUs activity
- Material resources provisioning and control
- Scheduling
- Real-time and dynamic allocation of network resources
- Management of the Pool of BBUs: fault management, performance, capacity planning and optimization

This principle is not applied in all the aforementioned V-RAN solutions. Yet, in [139], the authors proposed an orchestrator named kubernetes but it still presents several practical problems in terms of CPU consumption.

E. OBSTRUCTING PROBLEM 3: LIMITATION OF THE NUMBER OF VBBUS IN THE POOL

A persistent challenge in achieving full RAN virtualization is the restricted accessibility of virtual Base Band Units (BBUs) within the pool. As outlined in [14], a BBU pool serves as a centralized entity in C-RAN, typically situated in a cloud or datacenter environment. It comprises multiple BBU nodes equipped with robust computation and storage capabilities, responsible for resource processing and dynamic allocation to RRHs based on current network demands.

However, previous investigations, as depicted in Table 5, have unveiled a scarcity of virtual BBUs within the pool. The maximum count of BBUs in the pool, reaching only 2, significantly diverges from the actual requirements of a radio access network BBU Pool. This limitation stems from the intricate nature of LTE or 5G Radio Access Network stack platforms, which exhibit inflexibility and operational challenges in supporting a single BBU, let alone multiple virtual instances. We addressed this constraint in [144] and [145] by enhancing the OpenAirInterface (OAI) platform to facilitate the support of an unlimited number of virtual BBUs and RRHs. Furthermore, in [146], we demonstrated that CPU and memory consumption could be further optimized through a novel approach leveraging machine learning techniques.

TABLE 7. Comparison table of type 1 hypervisors.

Hypervisors	ESXi	Hyper-V	KVM	Xen
Commercial Solutions	vSphere	Hyper-V	• Proxmox VE • RedHat Virtualization (RHV)	• OracleVM • Citrix XenServer
Main clients	Large companies	Medium and large companies	Public cloud companies	Public cloud companies
Selling arguments	Market leader, reliability, innovation	• Scalability • Flexibility • Powerful with Windows VMs • In strong progress	• Very flexible • open-source • In strong progress	• open-source • Leader of cloud players
Example of customers	Private companies excluding cloud providers	• Private companies excluding cloud providers, • Microsoft Azure	• Google Cloud • Joyent • NextGen	• AWS • CloudStack • Rackspace • Linode • Oracle • Citrix
Market share (in 2018)	64 %	17 %	19% including KVM and Xen	19% including KVM and Xen

TABLE 8. Comparison table of type 2 hypervisors.

	Workstation Player	Workstation Pro	VirtualBox
Price	Free	Paid (30 day trial version)	Free
Operating systems	Windows, Linux	Windows, Linux	Windows, Linux, MacOS
Limitations	Unable to launch multiple VMs at the same time		
Formats accepted	Disks : vmdk (natif), vdi, vhd VM Config: ova, ovf	Disks : vmdk (natif), vdi, vhd VM Config : ova, ovf	Disks : vdi (natif), vmdk, vhd VM Config: ova, ovf
Performances	+++ (more efficient than VirtualBox for Windows VMs)	+++ (more efficient than VirtualBox for Windows VMs)	++ (more efficient than VirtualBox for Windows VMs)

F. OBSTRUCTING PROBLEM 4: LIMITED COOPERATION BETWEEN THE VBBUS

Cooperation or communication between two BBUs is still not possible in all previous V-RAN solutions. The vBBUs are fundamentally isolated from each other and have no communication between them. As a result, handover or interference management mechanisms between the virtual BBUs are not implemented.

G. OBSTRUCTING PROBLEM 5: LOW NUMBER OF UES SUPPORTED BY CURRENT V-RAN PLATFORMS

A significant obstacle is the limited number of User Equipment (UEs) examined using the mentioned V-RAN platforms. The highest number of UEs supported was 2 (as shown in Table 6), which falls short of reflecting the typical scale observed in radio access networks.

V. CONCLUSION

This paper marks the inaugural survey on the implementation of RAN Virtualization, offering insights into the evolution of V-RAN concepts and evaluating the performance of contemporary V-RAN supporting platforms. By clarifying the distinctions among C-RAN, V-RAN, and Open RAN, this survey delineates the transition from conceptualization to the realization of RAN virtualization projects. Furthermore, it delves into the efforts undertaken by both IT manufacturers and academia to actualize V-RAN, shedding light on the substantive challenges impeding the attainment of comprehensive radio access network virtualization. Our survey underscores the prevalent limitations encountered by current V-RAN platforms, including inflexibility in network functions virtualization and orchestration between virtual Baseband Units (vBBUs), as well as the restricted number of vBBUs available in a pool.

APPENDIX

See Tables 7 and 8.

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