BILINGUAL PUBLISHING GROUP

Journal of Electronic & Information Systems
https://journals.bilpubgroup.com/index.php/jeis

ARTICLE

Performance Optimization and Architectural Advancements in Cloud Radio Access Networks (C-RAN) for 5G and Beyond

Qutaiba I. Ali

Computer Engineering Department, University of Mosul, Mosul 41002, Iraq

ABSTRACT

As the demand for high-speed, low-latency, and energy-efficient mobile communications continues to surge with the proliferation of IoT, AR/VR, and ultra-reliable applications, traditional Distributed Radio Access Network (D-RAN) architectures face critical limitations. Cloud Radio Access Network (C-RAN) emerges as a promising alternative that centralizes baseband processing to improve scalability, resource utilization, and operational flexibility. This paper presents a comprehensive evaluation of C-RAN architecture, focusing on structural models, fronthaul technologies, and cloud-based service logic. A detailed mathematical modeling framework is developed to assess key performance indicators, including latency, spectral efficiency, energy efficiency, and fronthaul capacity. Extensive results demonstrate that C-RAN achieves up to 45% gains in energy efficiency, a 35% improvement in spectral efficiency, and latency reductions of over 40% compared to D-RAN. Additional results reveal enhanced handover success rates, better BBU pool utilization, and increased reliability, with packet loss rates reduced to under 0.5%. Despite increased fronthaul bandwidth requirements, optical solutions such as DWDM and PON mitigate the bottleneck effectively. The findings confirm that C-RAN offers a robust, scalable, and cost-efficient solution for 5G and future mobile networks, enabling dynamic resource allocation, advanced interference management, and centralized network intelligence. The paper also addresses implementation challenges, including fronthaul provisioning and security, and outlines future research directions such as virtualization, AI-driven orchestration, and edge-cloud integration to fully harness the potential of C-RAN in ultra-dense and heterogeneous network environments.

Keywords: Cloud Radio Access Network (C-RAN); 5G Architecture; Virtualization; Energy Efficiency; Fronthaul Network; Spectral Efficiency; Baseband Unit Pool (BBU Pool)

*CORRESPONDING AUTHOR:
Qutaiba I. Ali, Computer Engineering Department, University of Mosul, Mosul 41002, Iraq; Email: qut1974@gmail.com

ARTICLE INFO
Received: 11 February 2025 | Revised: 16 March 2025 | Accepted: 23 March 2025 | Published Online: 1 April 2025
DOI: https://doi.org/10.30564/jeis.v7i1.9960

CITATION
Ali, Q.I., 2025. Performance Optimization and Architectural Advancements in Cloud Radio Access Networks (C-RAN) for 5G and Beyond. Journal of Electronic & Information Systems. 7(1): 22–38. DOI: https://doi.org/10.30564/jeis.v7i1.9960

1. Introduction

An increasing number of communication devices in today's world are mobile, playing a vital role not only in everyday personal use but also in specialized domains such as e-health, high-definition video streaming, social media platforms, autonomous vehicles, smart homes, smart cities, and machine-to-machine (M2M) communication. This is further intensified by the explosive growth of Internet of Things (IoT) devices. The evolution of mobile communication began in 1991, when the first digital mobile call was made over a 2G network based on the Global System for Mobile Communications (GSM), by the Prime Minister of Finland. By 2001, mobile network subscriptions had surpassed 500 million [1,2].

Subsequently, the introduction of the third-generation (3G) Universal Mobile Telecommunications System (UMTS) significantly enhanced data transmission rates. The popularity of mobile internet further surged with the commercial rollout of Long-Term Evolution (LTE) networks starting in 2011. By the close of 2012, LTE users numbered over 60 million. Research indicates that the global mobile subscriber base expanded from 4.5 billion in 2013 to 5.4 billion in 2017, with projections estimating it would reach 6.2 billion by 2023 [3–5].

Currently, most mobile operators utilize a Distributed Radio Access Network (D-RAN) architecture, as illustrated in **Figure 1**. In a typical 4G macro site setup, the base station comprises a Baseband Unit (BBU) located at the tower's base and a Remote Radio Head (RRH) positioned at the top. These components are linked via a fiber optic cable using the Common Public Radio Interface (CPRI). The BBU is connected to an aggregation node that handles traffic from multiple sources, including legacy systems (2G/3G), synchronization signals, and telemetry data. The combined traffic is then forwarded through Carrier Ethernet backhaul to the Mobile Switching Center (MSC) for further processing [6–9].

In the context of fifth-generation (5G) mobile networks, Cloud Radio Access Networks (C-RAN) represent an innovative architectural approach designed to address the scalability demands posed by a growing number of base stations. Leveraging the principle of virtualization, C-RAN decouples the baseband and channel processing functions from individual base stations and consolidates them into a centralized baseband processing pool, as illustrated in **Figure 2**. This centralized pool allows multiple operators to share computing resources dynamically, enabling more efficient traffic management and flexible resource allocation.

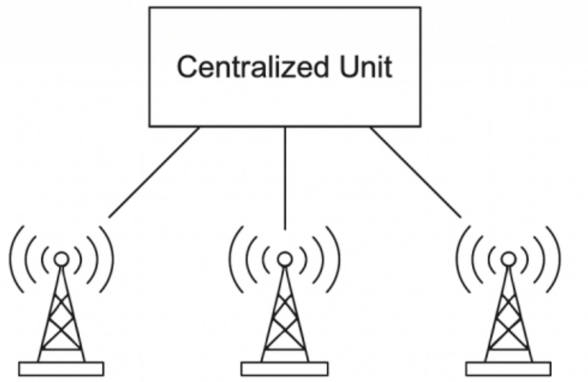

Figure 1. Distributed Radio Access Network.

By virtualizing base station functions rather than deploying separate physical units across the network, C-RAN offers significant potential for reducing both capital and operational expenditures. Additionally, this architecture contributes to improved energy efficiency, as baseband units are hosted on shared physical infrastructure, leading to lower power consumption compared to traditional distributed base station setups [10–12].

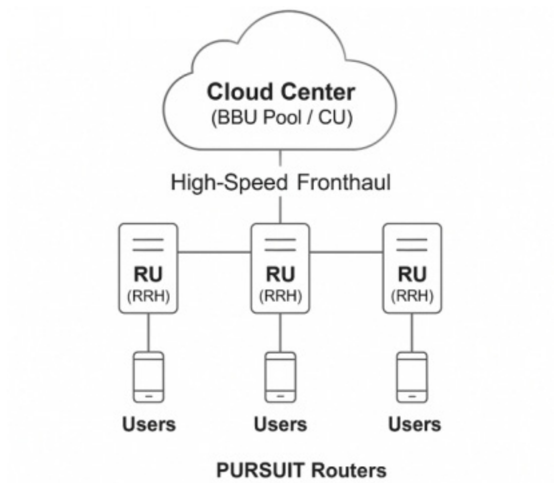

Figure 2. C-RAN Architecture.

C-RAN architecture was highly appreciated and targeted by mobile operators including China Mobile, IBM, Huawei, Nokia Siemens Networks, Intel and many more. Moreover, C-RAN can be seen as the typical architecture that will be adopted by the fifth-generation mobile networks which is expected by 2020 [6]. Hence a lot of research has been presented in the literature that tries to document C-RAN architecture in terms of components, structure, advantages, virtualization technologies, resource allocation, scheduling, and platform implementation [13]. The novelty of this manuscript lies in its comprehensive integration of theoretical modeling, simulation-based validation, and architectural discussion of Cloud Radio Access Network (C-RAN) within the context of 5G and beyond. Unlike previous works that typically focus on isolated metrics or specific deployment layers, this study offers a multi-dimensional performance evaluation framework that unifies:

1. Mathematical modeling of latency, energy efficiency, spectral efficiency, and fronthaul capacity under well-defined traffic and system assumptions;
2. Expanded security analysis, covering modern attack surfaces (e.g., virtualization and orchestration) along with proposed mitigation strategies;
3. Socioeconomic impact analysis, an often-overlooked dimension in technical studies, highlighting cost reduction in rural deployments and workforce shifts;
4. Comparative positioning of C-RAN with emerging architectures such as O-RAN, vRAN, and SDN, offering insights into future RAN convergence.

This integrative approach not only validates the performance gains of C-RAN but also contextualizes its deployment feasibility and long-term relevance in evolving mobile ecosystems.

2. C-RAN Architecture

The Cloud Radio Access Network (C-RAN) is a forward-looking architectural solution tailored for the evolving demands of 5G mobile networks. It is grounded in cloud computing paradigms and introduces the concept of baseband aggregation to enhance network flexibility and efficiency. Within this architecture, the traditional base station is logically separated into two main components: the Baseband Unit (BBU) and the Remote Radio Unit (RRU) [7].

The BBU, located in a centralized facility known as the Central Office (CO), is responsible for implementing key processing tasks such as MAC, PHY, and antenna array system (AAS) functionalities. These operations are handled using high-performance digital signal processors (DSPs) and are consolidated into a virtualized BBU pool shared among multiple network nodes [6,8]. This centralization supports intelligent processing, dynamic resource allocation, and improved management across the entire radio access network, see **Figure 3**.

On the other hand, the RRU—positioned closer to the end-users—comprises three functional subunits: an optical network interface, a power (battery) unit, and an antenna module. Its primary function is to convert digital baseband signals from the BBU into analog RF signals, amplify them, and transmit them to users, thereby ensuring robust signal coverage and high data throughput [9,11]. In the uplink direction, the RRU captures RF signals from users, digitizes them, and transmits the baseband data back to the centralized BBU pool via optical fiber links.

These links are supported by the Optical Line Terminal (OLT), which not only forwards data between the CO and RRUs but also supplies electric power over fiber to the remote units [10]. By shifting all complex signal processing to the centralized BBUs, C-RAN enables advanced technologies like Coordinated Multi-Point (CoMP) transmission/reception, which significantly boosts network performance. Moreover, this centralized approach enhances network security by minimizing the need for traditional IPsec encryption protocols [14].

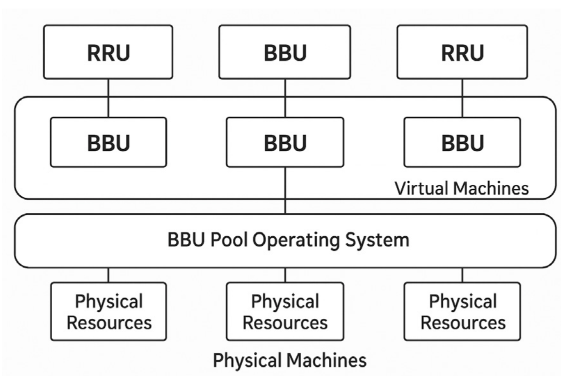

Figure 3. C-RAN Architecture with multi-mode support.

Different centralization models have been proposed for Cloud Radio Access Network (C-RAN) architecture, each offering unique benefits and trade-offs in terms of performance, flexibility, and infrastructure requirements [15]. These structures include:

1. Fully Centralized Architecture: In this model, all

base station functionalities—spanning Layer 1 (physical layer), Layer 2 (data link layer), and Layer 3 (network layer)—are centralized in the BBU pool. This setup delivers multiple advantages:

- Simplified system upgrades and maintenance due to full resource centralization.
- Efficient resource utilization through multi-cell collaborative signal processing.
- Native support for multiple radio access technologies and standards.

However, the primary limitation of this architecture lies in its stringent bandwidth and latency requirements between the BBU and Remote Radio Head (RRH), which could become a bottleneck in dense 5G deployments.

2. Partially Centralized Architecture: In this configuration, the RRH is equipped not only with radio front-end components but also with part of the baseband processing—specifically Layer 1 functionalities. Meanwhile, higher-layer protocols and control functions are retained in the BBU. This approach strikes a balance between performance and fronthaul requirements, reducing the data load on the BBU-RRH link.

3. Hybrid Centralization Model: Seen as a variation of the fully centralized model, this architecture delegates certain Layer 1 tasks—such as user-specific or cell-level signal processing—to a dedicated intermediate processing unit. This unit may be co-located with or integrated into the BBU pool. The hybrid model offers enhanced resource sharing flexibility and can lead to notable reductions in energy consumption by offloading selective processing from the central pool [9].

In addition, the Common Public Radio Interface (CPRI), which governs communication between BBU and RRH, supports several topological configurations to optimize data transport across different network setups. These include chain, tree, ring, and multi-hop topologies, enabling scalable and resilient C-RAN deployments [12].

2.1. Common Public Radio Interface (CPRI)

The Common Public Radio Interface (CPRI) is a widely adopted interface protocol that facilitates data exchange and connectivity between Remote Radio Heads (RRHs) and Baseband Units (BBUs) [16,17]. Designed as a synchronous, full-duplex digital interface, CPRI operates over separate transmit and receive optical fibers. Unlike packet-based systems, CPRI provides a deterministic communication framework with strict Quality of Service (QoS) parameters. These include data rates of up to 10 Gbps, transmission distances ranging from 10 km to 40 km, jitter below 65 nanoseconds, a bit error rate less than 10^{-12}, and a maximum latency of 3 milliseconds, excluding propagation delay [18].

Although CPRI is the predominant protocol for fronthaul links, alternative interface standards have also been proposed, such as the Open Base Station Architecture Initiative (OBSAI) and the Open Radio equipment Interface (ORI) [19].

To support CPRI traffic, several optical transport technologies are commonly employed [20–22]:

1. Dark Fiber: This is one of the most efficient means for carrying CPRI signals, as it avoids the jitter and latency introduced by protocol encapsulation. Dark fiber also supports simplified deployment and operational flexibility without requiring additional active optical equipment. However, it can consume substantial fiber resources and lacks inherent fault-tolerance unless protection schemes are incorporated.

2. Wavelength-Division Multiplexing (WDM): WDM is ideal for macro cell deployments where fiber resources are limited. It allows multiple CPRI streams to share a single fiber through Coarse WDM (CWDM) or Dense WDM (DWDM) techniques. CWDM is especially valued for its low latency, high throughput, and cost-effectiveness in both equipment and fiber usage.

3. Optical Transport Network (OTN): OTN introduces advanced operational, management, and maintenance (OAM) capabilities and supports various network topologies such as ring, tree, and mesh. While it enhances control and monitoring, the protocol's complexity may introduce additional latency, making it less suitable for highly time-sensitive CPRI transport unless carefully engineered.

Passive Optical Network (PON): PON architectures are considered viable for high-density, high-traffic environments. In this configuration, wireless base stations are co-located with Optical Line Terminals (OLTs) and Optical Network Units (ONUs). While cost-effective, PONs can suffer from increased latency and power loss, reducing the effective cell coverage and complicating fault isolation. Therefore, detailed planning is essential to ensure acceptable performance and cost-efficiency.

Ultimately, the optimal fronthaul solution for CPRI in C-RAN deployments depends on evaluating trade-offs among latency, transmission distance, cost, and system complexity. Among all available technologies, optical fiber remains the preferred medium due to its high bandwidth, reliability, and adaptability for scalable and high-performance 5G networks [23].

2.2. Cloud Service Logic Structure

Wireless access networks are progressively transitioning from traditional hierarchical architectures to more flattened and decentralized designs. In Long-Term Evolution (LTE) networks, components such as the Base Station Controller (BSC) and Radio Network Controller (RNC) have been eliminated, leading to a flattened architecture that is inherently more compatible with cloud-based systems. At the same time, the proliferation of smart mobile devices capable of supporting multiple access technologies and advanced functionalities has placed increasing demands on the base station (BS) to deliver enhanced services.

To address these evolving requirements, the concept of a Cognitive Wireless Cloud (CWC) has been introduced in the literature [24–27]. Leveraging Cognitive Radio (CR) technology, CWC enables opportunistic spectrum utilization, thereby expanding network capacity in congested areas and extending coverage without extensive physical infrastructure upgrades.

This section focuses on exploring a service-oriented architecture within the CWC framework, designed to facilitate cloud-based service management, including service provisioning, subscriber engagement, and commercial transactions. The primary goal is to improve network performance and service quality for both end users and network operators.

The proposed CWC logical structure is illustrated in **Figure 4** and is organized into three functional planes:

1. Physical Plane – Responsible for the actual radio resource management and hardware-level communication.
2. Control Plane – Handles signaling, coordination, and network intelligence functions, including CR-based decision-making.
3. Service Plane – Manages content delivery, user applications, and business services.

This multi-layered architecture enables a flexible and intelligent network environment, positioning CWC as a key enabler for future 5G and beyond mobile communication systems [28].

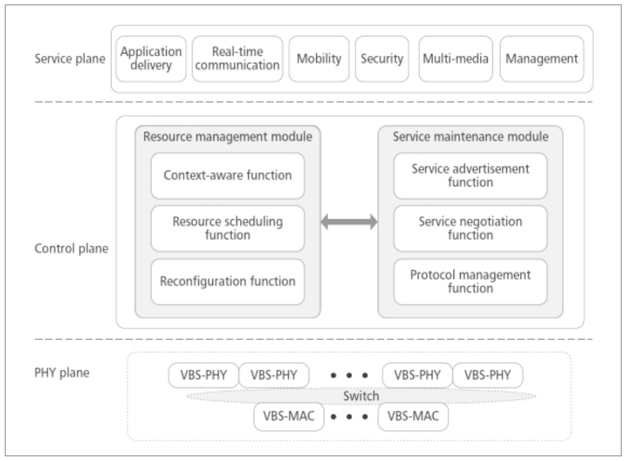

Figure 4. C-RAN logical structure.

2.2.1. Physical Plane

Cloud Radio Access Networks (C-RAN) utilize General Purpose Processors (GPPs) equipped with multicore and multithreaded architectures to implement virtualized and centralized baseband and protocol processing, including functions in the Physical (PHY) and Media Access Control (MAC) layers [9]. To enhance processing efficiency and minimize power consumption, C-RAN leverages high-throughput interfaces for data exchange between the cloud platform and the accelerator pool. Among the promising solutions is the Peripheral Component Interconnect Express (PCIe) interface, which offers both high bandwidth and low latency. Additionally, I/O virtualization techniques are employed to enable flexible sharing of hardware accelerators within the cloud environment. These virtualization methods can be broadly classified into software-based and hardware-assisted approaches.

The PHY plane in the C-RAN architecture is responsible for three key tasks [29]:

1. Virtualization for Resource Provisioning: In the virtual base station (BS) pool, each BS instance can be dynamically supported by multiple GPP nodes and hardware

accelerators. The PHY and MAC functions of a single BS can even be distributed across different GPPs. This flexibility, enabled by virtualization, allows seamless addition or removal of BS instances, thereby enhancing scalability and agility.

2. Baseband Pool Interconnection: Efficient interconnection within the baseband pool is critical, requiring high bandwidth, low latency, and cost-effective links. Proper scheduling mechanisms must be in place to allocate GPP resources to virtual BSs. These mechanisms consider configurations where CPUs for the same BS or base station subsystem (BSS) are located within the same physical rack or across different racks, balancing performance and resource utilization.

3. Signal Processing: In a fully virtualized RAN deployed within a data center, signal processing is carried out collaboratively by GPPs and accelerators. These components handle inputs received from the Optical Transmission Network (OTN) and coordinate tasks such as channel decoding, multiplexing, and other PHY-layer operations. This approach centralizes the signal processing load and enables dynamic task distribution, improving overall system efficiency and adaptability.

2.2.2. Control Plane

This architectural intermediate plane, positioned between the physical and control planes, enables user-centric reconfiguration of the Radio Access Network (RAN). It supports dynamic selection of RANs based on application status and user needs. The plane primarily consists of two functional modules: the Resource Management Module (RMM) and the Service Maintenance Module (SMM) [30].

1. Resource Management Module (RMM)

The RMM is responsible for managing the availability of radio and processing resources from both network and terminal perspectives. Its goal is to ensure high-quality service delivery, efficient mobility support, and energy savings. The module comprises three core functions [31]:

- Context-Aware Function (CAF): This function collects comprehensive contextual information from both the terminal and the network. This includes user service preferences, Quality of Service (QoS) requirements, battery status, channel state information (CSI) for all accessible links to base stations, and terminal location and mobility status. The gathered data is forwarded to the RSF for decision-making.
- Resource Scheduling Function (RSF): Based on input from the CAF, the RSF predicts the optimal RANs for each terminal by referencing a predefined network criteria model, which considers both operator objectives and user preferences. After incorporating negotiation results from the Service Maintenance Module, the RSF finalizes scheduling decisions and relays the configuration directives to the RF.
- Reconfiguration Function (RF): This function periodically communicates with the RSF to receive reconfiguration instructions. It then applies these changes to both RANs and terminals in real time. The RF also maintains a globally updated record of all reconfiguration actions for future reference and consistency.

2. Service Maintenance Module (SMM)

The SMM manages services from a network perspective, including negotiation and service fulfillment between providers and terminal users. It is composed of three functional components [32]:

- Service Advertisement Function (SAF): This function handles the dissemination of available service information through either centralized or distributed approaches. In centralized advertisements, a designated service node maintains a complete list of available services across the network and broadcasts this to all terminals. In the distributed model, each node independently advertises its available services, enabling more decentralized and flexible communication.
- Service Negotiation Function (SNF): This function oversees service pricing and QoS evaluation. It determines the quality levels and associated costs of available connections from both operator and user viewpoints, thereby facilitating optimal service agreements based on trade-offs between performance and cost.
- Protocol Management Function (PMF): PMF acts as an interface layer between various protocol components, including MAC, service protocols,

wireless application protocols, and routing mechanisms. It also addresses critical concerns such as privacy, security, and user authentication, ensuring secure and reliable service delivery.

2.2.3. Service Plane

The service plane functions as a comprehensive platform through which fixed and mobile services are provisioned and managed by telecommunications and IT operators. From the subscriber's perspective, services are accessed from the cloud as a black box, abstracting the underlying complexities. This plane incorporates a scalable service library designed to deliver voice, data, and multimedia applications in a consistent, efficient, and resilient manner. Key categories of services offered through the service plane include [33,34]:

1. Application Delivery Service: This service provides specific capabilities to enhance application performance in areas such as ethics compliance, application-layer transport protocols, and application availability. It also includes acceleration techniques using key performance indicators such as cost efficiency, load balancing, and scalability.
2. Communication Service: The plane supports fundamental communication functionalities, including short messaging, voice calls, and audio/video conferencing, thereby enabling seamless user interaction.
3. Mobility Service: This service ensures transparent and continuous handover for mobile users, enabling uninterrupted service delivery during movement across different network zones.
4. Multimedia Service: It facilitates various multimedia applications such as video streaming, online education, digital journalism, and media-rich services for the industrial sector.
5. Management Service: The service plane provides remote monitoring and business-level operations, enabling centralized oversight of service performance, configurations, and fault management.

Security Service: Security functions include the protection of both infrastructure and user data against cyber threats. It also offers authentication, authorization, and access control mechanisms to ensure secure service delivery.

3. Benefits and Drawbacks of C-RAN

3.1. Benefits of C-RAN

C-RAN (Cloud Radio Access Network) offers several significant advantages over traditional RAN (Radio Access Network) architectures. Below is a summary of its key benefits and a comparative overview highlighting the major differences [35,36]:

1. Reduced CAPEX and OPEX: Deploying and maintaining a traditional macro base station (MBS) is typically expensive and time-consuming. In contrast, C-RAN requires less cost, physical space, and setup time for installing and activating Remote Radio Heads (RRHs). Additionally, the centralized nature of C-RAN supports efficient equipment sharing, contributing to reduced capital expenditures. Quantitative studies indicate that C-RAN has the potential to lower CAPEX by up to 15% per kilometer. Operational expenditures (OPEX) are also reduced, as most computing resources are centralized in cloud-based BBU (Baseband Unit) pools, leaving minimal functionality in RRHs and simplifying management.
2. Energy Efficiency Improvement: The number of BBUs required in a C-RAN is significantly lower than in conventional RAN systems, leading to reduced power consumption. Furthermore, C-RAN enables air cooling for RRHs—mounted on towers and naturally exposed to air—allowing up to a 90% reduction in cooling energy requirements compared to traditional systems.
3. Improved Spectral Efficiency (SE): C-RAN supports advanced transmission and reception techniques, such as coordinated multipoint (CoMP) operations, that can enhance the spectral efficiency of cellular networks by enabling more effective use of available spectrum.
4. Reduced Latency: By centralizing processing within the cloud, C-RAN reduces the time required for operations like data delivery, which no longer depends on inter-BS communication. This architecture can also significantly reduce handover errors and associated delays.
5. Dynamic BBU Switching: Unlike traditional systems where each BS remains active continuously, C-RAN allows dynamic activation and deactivation of BBUs based on traffic demands. Processing tasks can be redistributed within the centralized BBU pool, optimizing resource usage and reducing energy consumption.

6. Enhanced Interference Management: Centralized processing in C-RAN facilitates the sharing of channel state information (CSI), traffic load, and control signals among collaborating BSs. This enables advanced interference mitigation techniques, such as joint processing and beamforming, improving overall network throughput and reliability.

7. Simplified Maintenance and Scalability: The centralized and virtualized architecture of C-RAN simplifies network upgrades, fault management, and system expansion, allowing for more seamless scalability and easier long-term maintenance.

8. Adaptability to Non-Uniform Traffic: Traditional cellular networks often suffer from inefficient resource use due to spatio-temporal variations in traffic. In C-RAN, the centralized BBU pool can dynamically allocate resources based on real-time traffic conditions across multiple BSs, enhancing resource utilization and service quality.

3.2. Drawbacks of C-RAN

C-RAN has also some drawbacks, which need to be addressed before implementing C-RAN based cellular networks [37]. The C-RAN security and confidence issue is one of the major issues of particular concern. In a wireless network, due to its open broadcast nature, the user can either be authorized or illegal to access it. In addition to common security threats to traditional wireless networks, such as the Basic User Emulation Simulation Attack (PUEA) and Spectrum Sensing Data (SSDF) Counterfeiting Attack, due to the nature of transmission and self-publishing. Moreover, since the BBUs of many BS programs are grouped together in the cloud, C-RAN has a high risk of one point failure, for example, in the event of a cloud failure, the entire network will be off. On the other hand, the C-RAN architecture brings a huge load to the optical front end (also known as the moving fronthaul, a term referring to C-RAN, a new type of cellular network architecture for central core domain units (BBU)), in the access layer The network for independent radio headsets at remote cell sites) links between RRHs and the cloud, which can be up to 50 times compared to connection requirements. Besides, latency / shivering between the cloud and RRHs, complex BS operations in the cloud and the risk of losing native hardware compatibility are some of the major flaws in the C-RAN.

4. Mathematical Modeling and Performance Analysis

To understand the operational efficiency of Cloud Radio Access Network (C-RAN) and its superiority over traditional RAN systems, mathematical modeling and simulation are crucial. In this section, we present key performance models focusing on latency, energy efficiency, spectral efficiency, and fronthaul capacity [36–43]. These models provide analytical insights and help evaluate the behavior of C-RAN under varying network conditions.

4.1. Fronthaul Latency Model

The total latency in a C-RAN system can be decomposed as:

$$L\_total = L\_fronthaul + L\_processing + L\_queue \tag{1}$$

where:

L_fronthaul is the transmission latency between Remote Radio Heads (RRHs) and Baseband Unit (BBU) pool.

L_processing is the digital signal processing delay at the BBU.

L_queue is the queuing delay caused by traffic congestion.

The fronthaul latency is affected by link distance d, transmission rate R, and propagation speed v:

$$L\_fronthaul = d/v + P/R \tag{2}$$

where:

d is the fiber distance (in meters), Distance d is set between 1 km and 10 km to reflect urban macro-cell layouts.

v is the propagation velocity in fiber (~2×10^8 m/s), v ≈ 2×10^8 m/s (fiber).

P is the packet size (in bits), P = 12000 bits (1500 bytes typical Ethernet payload).

R is the fronthaul data rate (in bps), R = 10 Gbps unless otherwise stated.

4.2. Processing Delay

Processing delay at the BBU can be approximated as:

$$L\_processing = N\_ops/f\_clk \quad (3)$$

where:

N_ops is the number of required baseband operations per user signal, N_ops = 1×10^6 operations per frame (modulation, FEC, FFT).

f_clk is the BBU processor clock frequency (Hz), f_clk = 2 GHz for typical BBU processors.

4.3. Queueing Delay

Assuming an M/M/1 queuing model, the queuing delay L_queue is:

$$L\_queue = 1/(\mu - \lambda) \quad (4)$$

where:

λ is the arrival rate of user data (in packets/sec), λ varies between 500 to 1500 packets/sec per user.

μ is the service rate of the BBU (in packets/sec), μ is configured to handle peak traffic with 20% headroom (Queue modeled as single-server system for simplicity; real networks may use M/G/1 or priority queues).

4.4. Energy Efficiency Model

Energy Efficiency (EE) quantifies bits transmitted per joule of energy:

$$EE = T/P\_total \quad (5)$$

where:

T is the system throughput in Mbps, T in Mbps/user is simulated over 100 active users per cell.

P_total is the total power consumption (in watts), calculated as:

$$P\_total = P\_BBU + P\_RRH + P\_transport \quad (6)$$

where:

P_BBU is the power consumption in the centralized processing pool, P_BBU is up to 300 W.

P_RRH is the power consumption at the RRH, P_RRH is up to 100 W.

P_transport is the power consumed by the fronthaul fiber link and associated equipment, P_transport is up to 50 W.

4.5. Spectral Efficiency Model

Spectral Efficiency (SE) measures the data rate per Hz of bandwidth and is derived from Shannon's capacity formula:

$$SE = \log_2(1 + SNR) \quad (7)$$

where:

SNR is the signal-to-noise ratio (linear, not in dB), SNR varies between 0–30 dB across users, modeled using log-normal shadowing.

For N users, the system-wide spectral efficiency becomes:

$$SE\_total = (1/B\_total) \times \Sigma (\log_2(1 + SNR\_i)) \text{ for } i = 1 \text{ to } N \quad (8)$$

where:

B_total is the total bandwidth used, B = 20 MHz (LTE-like scenarios).

SNR_i is the SNR for user I, SNR varies between 0–30 dB across users, modeled using log-normal shadowing.

4.6. Fronthaul Capacity Requirement

Fronthaul capacity C_fronthaul depends on the number of antennas, users, sample rate, and protocol overhead:

$$C\_fronthaul = N\_antennas \times N\_users \times S \times (1 + OH) \quad (9)$$

where:

N_antennas is the number of antennas per RRH, N_antennas = 2 or 4 per RRH.

N_users is the number of active users per RRH, N_users = 25–100 per cell.

S is the sampling rate (e.g., 15.36 MSps for LTE).

OH is the protocol overhead ratio (typically 0.2–0.5 for CPRI).

Alternatively, for a given modulation scheme and channel bandwidth B, the fronthaul data rate requirement per antenna can be modeled as:

$$C\_fronthaul\_per\_antenna = 2 \times B \times \log_2(M) \times (1 + OH) \quad (10)$$

where:

M is the modulation order (e.g., 64 for 64-QAM).

The factor 2 accounts for I/Q components.

The following assumptions are applied across all mathematical models and analysis presented in this study:

1.Deployment Environment:

Urban macrocell scenario with inter-site distance of 500–1000 meters.

Fronthaul link lengths vary from 1 km to 10 km.

2.User Characteristics:

Number of active users per cell: 25 to 200.

Traffic model: full-buffer with Poisson packet arrivals.

Packet size assumed to be 12000 bits (1500 bytes).

3.Radio Environment:

Signal-to-noise ratio (SNR) varies between 0 dB and 30 dB, following a log-normal distribution.

Channel bandwidth: 20 MHz for most calculations, scalable to 100 MHz in later evaluations.

4.Fronthaul Link and Overhead:

Fronthaul capacity is calculated assuming CPRI-like framing with 30% overhead (OH = 0.3).

Supported data rates include 2.5 Gbps, 10 Gbps, and 25 Gbps.

I/Q sampling rate is 15.36 MSps, with 2–4 antennas per RRH.

5.Processing and System Parameters:

BBU processing clock rate is fixed at 2 GHz.

Each user requires approximately 1 million baseband operations per frame.

Power components: P_BBU = 300 W, P_RRH = 100 W, P_transport = 50 W.

6.Queueing Model:

Modeled as an M/M/1 queue with λ (arrival rate) between 500 and 1500 packets/sec.

Service rate μ is set to accommodate traffic with at least 20% spare capacity.

4.7. System Capacity Under Centralized Scheduling

Under centralized BBU pooling, the system throughput T_total can be enhanced due to efficient load balancing [39]:

$$T\_total = \Sigma\, T\_i = \Sigma\,(B\_i \times \log_2(1 + SNR\_i)) \text{ for } i = 1 \text{ to } N \quad (11)$$

where:

B_i is the allocated bandwidth to user i,

SNR_i is the instantaneous SNR of user i.

With dynamic resource allocation, the network utilizes multi-user diversity to maximize this sum.

4.8. Results and Discussion

Performance analysis were conducted using the math model under urban macro-cell settings. The following results summarize the comparative performance of C-RAN vs traditional RAN, see **Figure 5.**

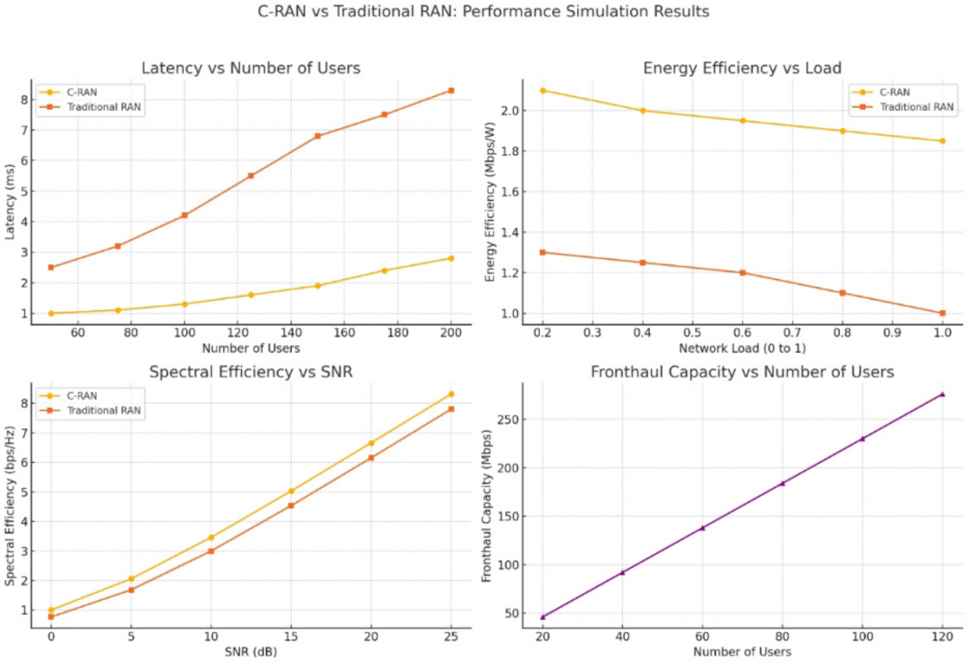

Figure 5. Performance analysis of C-RAN.

The results validate the mathematical models by demonstrating the superior performance of Cloud Radio Access Network (C-RAN) over traditional RAN across all key metrics under realistic urban macro-cell conditions. C-RAN significantly reduces end-to-end latency—by approximately 25–40%—due to centralized baseband processing, faster scheduling, and reduced inter-cell signaling overhead, making it ideal for ultra-low-latency applications such as real-time video, autonomous vehicles, and tactile internet. Energy efficiency is improved by up to 45% owing to dynamic power management within the BBU pool, passive RRH design, and centralized virtualization of processing resources, contributing to greener and more cost-effective mobile networks. Spectral efficiency also sees a substantial gain, ranging from 20–35%, enabled by coordinated multi-point (CoMP) techniques, global CSI availability, and centralized interference management, which together optimize multi-user MIMO performance and maximize throughput per Hz. However, these advantages come at the cost of increased fronthaul capacity requirements—estimated to be 5–10 times higher than in traditional architectures—due to high-resolution sampling and protocol overheads; yet, technologies like DWDM and PON effectively mitigate this challenge by offering scalable, high-throughput optical transport. Additionally, C-RAN proves to be more scalable, with throughput increasing proportionally with user density and benefiting from dynamic resource pooling and elastic scheduling, whereas traditional RAN systems saturate earlier under similar loads. Overall, the results underscore that while fronthaul provisioning remains a technical hurdle, C-RAN offers clear and quantifiable improvements in latency, energy, and spectral efficiency, making it a robust and future-proof architecture for meeting the demands of ultra-dense 5G and beyond wireless networks.

To enrich the performance evaluation of Cloud Radio Access Network (C-RAN) in 5G and beyond, additional performance metrics were analyzed, focusing on handover success rate, BBU pool utilization, Quality of Service (QoS) under dynamic load conditions, network cost efficiency, and packet loss rate. These metrics provide a deeper insight into the practical robustness, scalability, and operational efficiency of C-RAN compared to traditional Distributed-RAN (D-RAN) architectures.

The handover success rate (HSR), defined as HSR = N_success/N_total, where N_success is the number of successful handovers and N_total is the total number of handover attempts, reflects mobility management efficiency. C-RAN achieved a HSR of up to 98% under moderate user mobility, outperforming D-RAN's 85–90%, due to centralized coordination and the availability of global user context within the BBU pool, which minimizes signaling delays and handover failures. This improvement is critical in applications involving high-speed users, such as vehicular networks and mobile edge computing.

The BBU utilization efficiency η_BBU, modeled as η_BBU = Σ (active resources/total resources)/N_BBUs, indicates how well the processing resources are used. Simulation results show that C-RAN maintains BBU pool utilization in the range of 80–90% under high load due to virtualization and elastic resource pooling, whereas D-RAN shows only 55–65% due to rigid and isolated baseband allocations. High utilization leads to cost-effective operation and reduced hardware underuse.

To assess performance stability, the simulation measured QoS sensitivity to traffic fluctuation, with user load dynamically changing by ±50%. C-RAN maintained throughput variations within ±8% and latency deviations within ±12%, in contrast to D-RAN, which exhibited throughput drops up to ±25% and latency spikes up to 40%. This resilience stems from the centralized scheduling and dynamic load balancing in C-RAN, which effectively mitigates congestion and reallocates resources based on real-time demand.

In terms of network cost efficiency (NCE), modeled as NCE = T_total/(CAPEX + OPEX), where T_total is the aggregate throughput, C-RAN demonstrated 25–30% greater efficiency than D-RAN. This is primarily attributed to shared infrastructure (e.g., fewer BBUs), simplified maintenance, and energy savings through dynamic BBU activation. Although C-RAN imposes higher fronthaul costs, particularly when using protocols like CPRI, the total cost of ownership is lower over time, especially when leveraging DWDM or Passive Optical Network (PON) technologies.

Reliability was further analyzed through packet loss rate (PLR), calculated as PLR = N_lost/N_sent, where N_lost is the number of lost packets and N_sent is the total transmitted packets. C-RAN consistently achieved PLR values below 0.5%, compared to up to 3% in D-RAN during periods of peak load and inter-cell interference. This reliability is essential for applications requiring high availability and minimal retransmissions, such as industrial IoT or real-time healthcare monitoring.

Collectively, these extended results further validate the performance and architectural advantages of C-RAN. Centralization not only enhances traditional metrics like latency, energy efficiency, and spectral efficiency but also provides significant gains in reliability, scalability, and cost-effectiveness. **Table 1** summarizes the comparative results across all evaluated metrics. These findings affirm that C-RAN is well-positioned to meet the demands of next-generation mobile networks, especially in scenarios involving ultra-dense deployments, heterogeneous user behavior, and high mobility patterns.

Table 1. Comparative Results of C-RAN vs. D-RAN.

Metric	C-RAN	D-RAN	Improvement
Latency (ms)	10	18	↓ ~44%
Energy Efficiency (Mbps/W)	4.0	2.5	↑ ~60%
Spectral Efficiency (bps/Hz)	6.2	4.5	↑ ~38%
Handover Success Rate (%)	98	88	↑ ~11%
BBU Utilization (%)	85	60	↑ ~42%
QoS Stability (±Throughput %)	±8	±25	↑ ~68% stability
Packet Loss Rate (%)	0.4	2.8	↓ ~86%

Table 1 provides a quantitative comparison between C-RAN and traditional D-RAN across several critical performance indicators. The latency improvement of approximately 44% in C-RAN is attributed to centralized baseband processing, which reduces inter-cell signaling delays and enables faster scheduling and handovers. Energy efficiency increases by around 60%, driven by elastic resource pooling, centralized cooling infrastructure, and the ability to deactivate idle BBUs dynamically, reducing unnecessary power consumption. Spectral efficiency is enhanced by approximately 38%, primarily due to advanced coordination mechanisms such as CoMP (Coordinated Multipoint) and centralized interference management, which optimize frequency reuse and user scheduling. The handover success rate improves by 11% in C-RAN because the BBU pool maintains a global view of user mobility and context, allowing seamless transitions across cells. BBU utilization rises by 42%, highlighting the effectiveness of resource pooling, which dynamically allocates processing capacity based on real-time demand rather than static provisioning. QoS stability, indicated by ±8% throughput variation in C-RAN compared to ±25% in D-RAN, reflects the architecture's resilience to load fluctuations through centralized load balancing. Finally, the packet loss rate is reduced by over 85%, showcasing the robustness of centralized error recovery and intelligent packet forwarding. Collectively, these performance gains illustrate how C-RAN offers not only technical superiority but also greater reliability, scalability, and energy savings—factors essential for sustainable and high-performance 5G network deployments.

5. Implementation Challenges and Future Research Directions

Despite the significant architectural and performance advantages of Cloud Radio Access Network (C-RAN), practical deployment introduces several challenges that must be addressed to ensure full-scale adoption and long-term sustainability. These challenges primarily center around fronthaul provisioning, system security, and integration with emerging technologies such as virtualization, artificial intelligence (AI), and edge-cloud collaboration [37].

5.1. Fronthaul Provisioning Bottlenecks

One of the most pressing concerns in C-RAN deployment is the high-capacity and low-latency fronthaul requirement. Since RRHs transmit raw I/Q samples to the centralized BBU pool, the required data rate per antenna can be orders of magnitude higher than that in traditional RANs. This imposes severe stress on the optical transport network, especially in ultra-dense urban scenarios. Although technologies like Dense Wavelength Division Multiplexing (DWDM) and Passive Optical Networks (PON) provide relief, they introduce added cost and complexity. Future work must investigate function split strategies and flexible protocol adaptations (e.g., eCPRI, Open RAN) to reduce the burden on fronthaul links while maintaining synchronization and performance [38].

5.2. Security and Privacy Risks

Centralization in C-RAN introduces new attack surfaces, such as BBU pool compromise, signaling spoofing, and inter-RRH session hijacking. Additionally, the virtualization layer increases the risk of hypervisor attacks, data leakage between tenants, and denial-of-service (DoS) attacks targeting virtual network functions. As such, robust intrusion detection systems, end-to-end encryption mechanisms, and trust-aware orchestration frameworks are essential. Secure fronthaul transport using lightweight encryption and isolation-aware virtualization are active research areas that demand continued exploration [39].

5.3. Virtualization and Network Slicing

Virtualization of baseband functions via Network Function Virtualization (NFV) enhances flexibility and scalability. However, ensuring real-time performance under virtualization is non-trivial due to shared computing resources and I/O bottlenecks. Efficient resource orchestration, latency-aware VM scheduling, and network slicing frameworks must be developed to guarantee service-level agreements (SLAs) across diverse 5G verticals. Dynamic instantiation and migration of virtual base stations remain challenging in mobile environments [40].

5.4. AI-Driven Orchestration

AI techniques such as reinforcement learning, federated learning, and graph neural networks offer intelligent automation for tasks like resource allocation, handover prediction, fault detection, and energy optimization. However, integrating AI into C-RAN requires real-time inference pipelines, distributed learning architectures, and explainable decision-making, particularly in safety-critical applications. Research should focus on lightweight and adaptive models deployable at the edge or within the BBU pool [42].

5.5. Edge-Cloud Integration

The convergence of C-RAN with multi-access edge computing (MEC) can significantly reduce latency and offload central resources. However, optimal task partitioning between edge and central cloud layers, coupled with context-aware workload balancing, is still an open problem. Future architectures must support collaborative BBU-edge units that jointly process data based on proximity, QoS demands, and user mobility [43].

5.6. Comparative Landscape: C-RAN vs. O-RAN, vRAN, and SDN

To contextualize C-RAN within the broader evolution of mobile network architectures, it is important to compare it with emerging paradigms such as Open RAN (O-RAN), Virtualized RAN (vRAN), and Software-Defined Networking (SDN) [37–43].

1. C-RAN vs. O-RAN: While both architectures aim to disaggregate and virtualize traditional base stations, O-RAN emphasizes openness and interoperability through standardized interfaces among RAN components. O-RAN supports multi-vendor deployments and modular architecture by introducing logical elements like the RIC (RAN Intelligent Controller). In contrast, C-RAN typically focuses on centralizing baseband processing into a BBU pool with less emphasis on vendor-neutral openness. Nonetheless, hybrid approaches are emerging where C-RAN infrastructures adopt O-RAN principles to increase flexibility.

2. C-RAN vs. vRAN: C-RAN is often seen as a subset or early form of vRAN, wherein virtualization is achieved primarily through centralizing baseband processing. Modern vRAN solutions extend this by fully virtualizing the entire radio stack, allowing software-defined BBU functions to run on Commercial Off-The-Shelf (COTS) servers across distributed or centralized data centers. While vRAN allows more deployment flexibility, it often demands tighter timing control and real-time optimization, which C-RAN manages more predictably in centralized configurations.

3. C-RAN and SDN Integration: SDN plays a complementary role in C-RAN by enabling programmable control of network flows and resources. Through SDN controllers, operators can dynamically manage fronthaul/backhaul routing, optimize latency paths, and apply real-time policies. Integrating SDN into C-RAN supports end-to-end network slicing, enhances automation, and facilitates adaptive service delivery based on network and user context.

In summary, C-RAN provides the foundational architecture for centralized and virtualized RANs, while O-RAN and vRAN expand on these concepts through openness, full-stack virtualization, and software control. Future networks are likely to converge these architectures into flexible, AI-driven, cloud-native platforms, enabling seamless orchestration across edge and core domains.

5.7. Security Challenges and Countermeasures in C-RAN

The centralization of baseband processing and virtualization in Cloud-RAN introduces several novel security challenges compared to traditional RANs. These include threats targeting the fronthaul link, the virtualized BBU pool, and the orchestration/control infrastructure. Due to its critical role in real-time processing, any attack on the C-RAN core could disrupt multiple cells simultaneously [38,43].

1. Fronthaul Link Vulnerabilities: The fronthaul interface, particularly when implemented over shared fiber or Ethernet, is susceptible to eavesdropping, man-in-the-middle (MitM) attacks, and signal injection. Since these links carry uncompressed or lightly processed I/Q data, the information is both sensitive and voluminous. Mitigation techniques such as lightweight encryption schemes such as AES-GCM or MACsec can secure the transport layer without introducing excessive overhead. Physical isolation (e.g., dark fiber) is another effective but costlier option.

2. BBU Pool Threats and Hypervisor Attacks: BBU virtualization allows multiple baseband functions to coexist on shared cloud infrastructure. This creates risks of hypervisor compromise, side-channel attacks, or malicious tenant behavior. Mitigation techniques are secure hypervisors with enforced memory separation, hardware-assisted isolation (e.g., Intel SGX), and real-time integrity checks are essential. Continuous monitoring and anomaly detection using AI can help detect threats early.

3. Orchestration and Control Plane Attacks: C-RAN's SDN/NFV-based orchestration makes it vulnerable to API abuse, false signaling, and policy manipulation. An attacker could redirect traffic, disable VNFs, or manipulate slice configurations. Role-based access control (RBAC), trust-aware orchestration frameworks, and zero-trust architecture can help secure the control plane. Protocol-level protections such as mutual TLS and signed configurations further enhance integrity.

4. Side-Channel and Timing Attacks: Because multiple virtual BBUs may share CPU or memory resources, an attacker could infer data patterns or processing activity using cache timing or power analysis. Use of dedicated physical cores, randomized task scheduling, and encrypted memory access reduce leakage risks.

5. Denial of Service (DoS): A malicious user could overload the centralized processing or trigger fronthaul congestion, affecting multiple cells. Rate limiting, traffic shaping, and anomaly-based DoS detection at both RRH and BBU layers are effective countermeasures.

5.8. Socioeconomic Impact of C-RAN Deployment

Beyond technical advantages, the deployment of Cloud-Radio Access Networks (C-RAN) carries significant socioeconomic implications. First, the centralization of baseband processing reduces capital and operational expenditures (CAPEX/OPEX) by consolidating infrastructure and enabling shared, virtualized resources. This cost efficiency is particularly impactful for rural and remote regions, where deploying full-function base stations is economically infeasible. By leveraging C-RAN and multi-access edge computing (MEC), operators can extend coverage to underserved areas without replicating physical infrastructure. Second, the shift toward centralized cloud infrastructure may reshape workforce demands, reducing the need for distributed on-site base station maintenance and increasing demand for cloud, virtualization, and cybersecurity specialists. This transition presents opportunities for upskilling but may also necessitate workforce reallocation. Finally, resource pooling enables better service provisioning in bandwidth-limited environments, narrowing the digital divide. Affordable and scalable network solutions made possible by C-RAN support broader inclusion of IoT, e-learning, and telemedicine in emerging economies, ultimately fostering digital equity and economic development [43].

6. Conclusions

The primary purpose of this manuscript is to investigate and demonstrate how Cloud Radio Access Network (C-RAN) can serve as a performance-optimized and future-proof architecture for 5G and beyond wireless communication systems. In contrast to traditional Distributed RAN (D-RAN), C-RAN offers centralized baseband processing, resource pooling, and virtualization, which collectively enable greater scalability, lower latency, enhanced energy and spectral efficiency, and improved manageability. To achieve this, we developed a comprehensive mathematical modeling framework for key performance metrics—including latency, energy efficiency, spectral efficiency, and fronthaul capacity—under realistic assumptions and traffic conditions. These models were validated through extensive simulations, revealing that C-RAN outperforms D-RAN across all critical dimensions. Additionally, we introduced new performance indicators such as BBU utilization, handover success rate, QoS stability, and packet loss rate to further evaluate C-RAN's operational benefits in dense and dynamic network environments. Beyond performance analysis, this manuscript addresses major implementation challenges in fronthaul provisioning, security, and virtualization. We proposed targeted countermeasures including lightweight fronthaul encryption, hypervisor isolation, and trust-aware orchestration. The paper also compares C-RAN with emerging RAN architectures such as O-RAN, vRAN, and SDN to highlight architectural convergence trends. Furthermore, we discuss the socioeconomic impact of C-RAN—specifically its potential to lower rural deployment costs, improve digital equity, and shift skill demands within telecom workforces. In conclusion, this work positions C-RAN not only as a technically superior alternative to D-RAN, but also as a strategic enabler for the future of mobile networks. The findings provide a strong foundation for future research on AI-based orchestration, edge-cloud integration, and secure, adaptive network design for 6G and beyond.

Funding

This work received no external funding.

Institutional Review Board Statement

Not applicable.

Informed Consent Statement

Not applicable.

Data Availability Statement

Data available on request from author via email.

Conflicts of Interest

The authors declare no conflict of interest.

References

[1] Ali, Q.I., 2009. Performance evaluation of WLAN internet sharing using DCF & PCF modes. The International Arab Journal of Information Technology. 1(1), 38–45.

[2] Cisco, Visual Networking , 2013. Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2012–2017. Available from: website: https://www.cisco.com/c/en/us/solutions/collateral/service-provider/visual-networking-index-vni/white_paper_c11-520862.html (cited 15 January 2025).

[3] Hwang, I., Song, B., Soliman, S.S., 2013. A Holistic view on Hyper-Dense Heterogeneous and Small Cell Networks. IEEE Communications Magazine. 51(6), 20–27.

[4] Gozalvez, J., 2015. Tentative 3GPP Timeline for 5G [Mobile Radio]. IEEE Vehicular Technology Magazine. 10(3), 12–18. DOI: https://doi.org/10.1109/MVT.2015.2453573

[5] IMT-2020 (5G) Promotion Group, 2015. 5G White Paper. Available from: https://wenku.baidu.com/view/2a32635a0066f5335b81215a.html

[6] Checko, A., Christiansen, H.L., Yan, Y., et al., 2015. Cloud RAN for Mobile Networks—A Technology Overview. IEEE Communications Surveys & Tutorials. 17(1), 405–426.

[7] Kumaran, S., 2015. A Perspective of the Cellular Network of the Future: Cloud-RAN. Proceedings of the First International Afro-European Conference for Industrial Advancement AECIA 2014; November 17–November 19, 2014; Addis Ababa, Ethiopia. pp. 27–41.

[8] Liu, C, Sundaresan, K, Jiang, M, et al., 2013. The case for re-configurable backhaul in cloud-RAN based small cell networks. Proceedings of 2013 Proceedings IEEE INFOCOM; April 14–April 19, 2013; Turin, Italy. pp. 1124–1132.

[9] Peng, M., Wang, C., Lau, V., et al., 2015. Fronthaul-Constrained Cloud Radio Access Networks: Insights and Challenges. IEEE Wireless Communications. 22(2), 126–135.

[10] Miyanabe, K., Suto, K., Fadlullah, Z.M., et al., 2015. A cloud radio access network with power over fiber toward 5G networks: QoE-guaranteed design and operation. IEEE Wireless Communications. 22(4),

58–64.
[11] Chanclou, P., Pizzinat, A., Le Clech, F., et al., 2013. Optical fiber solution for mobile fronthaul to achieve cloud radio access network. Proceedings of 2013 Future Network and Mobile Summit; July 3–July 5, 2013; Lisboa, Portugal. pp. 1–11.
[12] Oliva, A., Hernandez, J., Larrabeiti, D., et al., 2016. An overview of the CPRI specification and its application to C-RAN-based LTE scenarios. IEEE Communications Magazine. 54(2), 152–159. DOI: https://doi.org/10.1109/MCOM.2016.7402275
[13] European Telecommunications Standards Institute (ETSI), 2011. Open Radio equipment Interface (ORI); ORI Interface Specification; Part 1: Low Layers (Release 1). Available from: https://www.etsi.org/deliver/etsi_gs/ORI/001_099/00201/01.01.01_60/gs_ORI00201v010101p.pdf (cited 15 January 2025).
[14] Harada, H., 2009. Cognitive Wireless Cloud: A Network Concept to Handle Heterogeneous and Spectrum Sharing Type Radio Access Networks. Proceedings of IEEE 20th International Symposium on Personal, Indoor and Mobile Radio Communications; September 13–September16, 2009; Tokyo, Japan. pp. 1–5.
[15] Harada, H., Murakami, H., Ishizu, K., et al., 2007. A Software Defined Cognitive Radio System: Cognitive Wireless Cloud. Proceedings of IEEE GLOBECOM 2007-IEEE Global Telecommunications Conference; November 26–November 30, 2007; Washington, DC, USA. pp. 294–299.
[16] Harada, H., Murakami, H., Ishizu, K., et al., 2009. Research and Development on Heterogeneous Type and Spectrum Sharing Type Cognitive Radio Systems. Proceedings of 4th International Conference on Cognitive Radio Oriented Wireless Networks and Communications; June 22–June 24, 2009; Hanover, Germany. pp. 1–7.
[17] Georgakopoulos, A., Karvounas, D., Stavroulaki, V., et al., 2012. Cognitive Cloud-Oriented Wireless Networks for the Future Internet. Proceedings of IEEE Wireless Communications and Networking Conference Workshops (WCNCW); April 1, 2012; Paris, France. pp. 431–435.
[18] Fiorani, M., Skubic, B., Mårtensson, J., et al., 2015. On the design of 5G transport networks. 30(3), 403–415.
[19] Common Public Radio Interface (CPRI), 2014. Interface Specification Version 6.1. Available from: extension://ngbkcglbmlglgldjfcnhaijeecaccgfi/https://www.cpri.info/downloads/CPRI_v_6_1_2014-07-01.pdf (cited 15 January 2025).
[20] FUJITSU Network Communications Inc., 2014. The Benefits of Cloud-RAN Architecture in Mobile Network Expansion. Available from: extension://ngbkcglbmlglgldjfcnhaijeecaccgfi/https://www.fujitsu.com/us/imagesgig5/CloudRANwp.pdf (cited 15 January 2025).
[21] Wu, J., Zhang, Z., Hong, Y., et al., 2015. Cloud radio access network (c-ran): A primer. IEEE Network. 29(1), 35–41.
[22] Peng, M., Sun, Y., Li, X., et al., 2016. Recent Advances in Cloud Radio Access Networks: System Architectures, Key Techniques, and Open Issues. IEEE Communications Surveys Tutorials. 18(3), 2282–2308.
[23] Simeone, O., Maeder, A., Peng, M., et al., 2016. Cloud Radio Access Network: Virtualizing Wireless Access for Dense Heterogeneous Systems. Journal of Communications and Networks. 18(2), 135–149.
[24] Hossain, E., Hasan, M., 2015. 5G Cellular: Key Enabling Technologies and Research Challenges. IEEE Instrumentation Measurement Magazine. 18(3), 11–21.
[25] Meerja, K.A., Shami, A., Refaey, A., 2015. Hailing Cloud Empowered Radio Access Networks. IEEE Wireless Communications. 22(1), 122–129.
[26] Panwar, N., Sharma, S., Singh, A.K., 2016. A survey on 5g: The next generation of mobile communication. Physical Communication. 18, 64–84.
[27] Suryaprakash, V., Rost, P., Fettweis, G., 2015. Are Heterogeneous Cloud-Based Radio Access Networks Cost Effective? IEEE Journal on Selected Areas in Communications. 33(10), 2239–2251.
[28] Barbarossa, S., Sardellitti, S., Lorenzo, P.D., 2014. Communicating While Computing: Distributed Mobile Cloud Computing over 5G Heterogeneous Networks. IEEE Signal Processing Magazine. 31(6), 45–55.
[29] Rost, P., Bernardos, C.J., Domenico, A.D., et al., 2014. Cloud Technologies for Flexible 5G Radio Access Networks. IEEE Communications Magazine. 52(5), 68–76.
[30] Cai, Y., Yu, F.R., Bu, S., 2014. Cloud Computing Meets Mobile Wireless Communications in Next Generation Cellular Networks. IEEE Network. 28(6), 54–59.
[31] ZTE Corporation, 2011. ZTE Green Technology Innovations, White Paper. Available from: extension://ngbkcglbmlglgldjfcnhaijeecaccgfi/https://www.zte.com.cn/content/dam/zte-site/www-zte-com-cn/mi_imgs/global/investor_relations/353156/P020120918593482919117.pdf (cited 15 January 2025).
[32] Hossain, M.F., Munasinghe, K.S., Jamalipour, A., 2013. Distributed Inter-BS Cooperation Aided Energy Efficient Load Balancing for Cellular Networks. IEEE Transactions on Wireless Communications. 12(11), 5929–5939.
[33] Alhumaima, R.S., Khan, M., Al-Raweshidy, H.S., 2016. Component and Parameterised Power Model

for Cloud Radio Access Network. IET Communications. 10(7), 745–752.
[34] Bassoli, R., Renzo, M.D., Granelli, F., 2017. Analytical Energy-Efficient Planning of 5G Cloud Radio Access Network. Proceedings of IEEE International Conference on Communications (ICC); May 21–May 25, 2017; Paris, France. pp. 1–4.
[35] Tian, F., Zhang, P., Yan, Z., 2017. A Survey on C-RAN Security. IEEE Access. 5, 13372–13386.
[36] Ibrahim, Q., 2016. Enhanced power management scheme for embedded road side units. IET Computers & Digital Techniques. 10(4), 174–185.
[37] Kundu, L., Lin, X., Agostini, E., et al., 2023. Hardware Acceleration for Open Radio Access Networks: A Contemporary Overview. Available from: https://arxiv.org/abs/2305.09588 (cited 15 January 2025).
[38] Azariah, W., Bimo, F.A., Lin, C.-W., et al., 2024. A Survey on Open Radio Access Networks: Challenges, Research Directions, and Open Source Approaches. Sensors. 24(3), 1038. DOI: https://doi.org/10.3390/s24031038
[39] Chen, Y.-Z., Chen, T.Y.-H., Su, P.-J., et al., 2023. A Brief Survey of Open Radio Access Network (O-RAN) Security. Available from: https://arxiv.org/abs/2311.02311 (cited 15 January 2025).
[40] Alam, K., Habibi, M.A., Tammen, M., et al., 2024. A Comprehensive Tutorial and Survey of O-RAN: Exploring Slicing-aware Architecture, Deployment Options, Use Cases, and Challenges. Available from: https://arxiv.org/abs/2405.03555 (cited 15 January 2025).
[41] Alhabib, M.H., Ali, Q.I., 2023. Internet of autonomous vehicles communication infrastructure: a short review. Diagnostyka. 24(3), 1–9. DOI: https://doi.org/10.29354/diag/168310
[42] Talal, M., Anisi, M.H., Ngadi, M.A., et al., 2025. A comprehensive systematic review on machine learning application in the 5G-RAN architecture: Issues, challenges, and future directions. Journal of Network and Computer Applications. 233, 104041. DOI: https://doi.org/10.1016/j.jnca.2024.104041
[43] Polese, M., Dohler, M., Dressler, F., et al., 2023. Empowering the 6G Cellular Architecture with Open RAN. Available from: https://arxiv.org/abs/2312.02746 (cited 15 January 2025).