Proceedings of the 5th International Conference on Signal Processing and Machine Learning
DOI: 10.54254/2755-2721/99/20251749

# *Advancing Wireless Network: The Role of C-RAN in 5G and Beyond*

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***Abstract:*** The rapid evolution of mobile communication technologies, particularly with the transition from 5G to 6G, has heightened the demand for higher data capacity, lower latency, and improved network reliability. Traditional Distributed Radio Access Networks (D-RAN) struggle to meet these requirements, creating a gap that has led to the adoption of Cloud Radio Access Network (C-RAN) as the mainstream deployment model. The approach involves a combination of literature review and technological evaluation to assess the scalability and security challenges posed by C-RAN. Simulation models were employed to evaluate the performance of Wavelength Division Multiplexing (WDM) and Free Space Optical (FSO)-millimeter-wave (mmWave) integration in terms of network resilience and resource optimization. Despite its advantages, such as enhanced spectral efficiency and reduced energy consumption, C-RAN faces significant challenges related to high fiber-optic infrastructure demands and complex data processing requirements. The findings highlight C-RAN's potential to meet the needs of 6G networks by optimizing resource allocation and enhancing network resilience. However, further advancements are required to overcome existing scalability and security issues. These insights underline C-RAN's pivotal role in the future of wireless communication, driving the evolution toward autonomous and highly adaptive network architectures in 6G, capable of meeting future communication demands.

***Keywords:*** C-RAN architecture, Mobile fronthaul network, WDM, FSO.

## 1. Introduction

The rapid evolution of mobile communication technologies, especially with the advent of 5G and the upcoming 6G, demands significantly enhanced data capacity, reduced latency, and improved reliability[1]. Unlike existing survey papers, this paper focuses more on the advancements in fronthaul networks, summarizes key technologies, and explores the potential future development and integration of these technologies. Traditional network architectures struggle to meet these requirements, necessitating the adoption of mainstream models like C-RAN, and significantly enhancing network performance and resource management. In comparison to the D-RAN architecture, the C-RAN architecture has represented significant technological innovation. The new C-RAN architecture has reconstructed the two-tier architecture of RRU and BBU into a three-tier architecture comprising the AAU, DU, and CU, corresponding to the division into fronthaul, midhaul, and backhaul networks[2]. Through the remote placement and centralized deployment of DUs, C-RAN offers advantages such as reduced energy consumption, space savings in equipment rooms, and

DOI: 10.54254/2755-2721/99/20251749

enhanced spectrum collaboration efficiency[3]. However, the development of the C-RAN network architecture still encounters several challenges. For instance, the demand for fiber optic infrastructure is high in C-RAN due to the need for high-bandwidth, low-latency connections between the BBU and RRU, which may present challenges in certain regions. Additionally, data processing capability remains a significant challenge, as a centralized BBU pool demands robust computing and data processing power to manage data streams from numerous RRUs. This necessitates the optimization of cloud computing and virtualization technologies. This paper provides an overview of C-RAN architecture, examining its development, key advantages, challenges, and future prospects in 5G and beyond. This study aims to solve the scalability and security issues of C-RAN in 5G/6G by in-depth analysis of its key technologies, and promote the optimization and evolution of wireless network architecture.

## 2. Basic concept and principles of C-RAN

Cloud Radio Access Network is a type of wireless access network architecture based on real-time cloud computing technology, collaborative radio, and centralized processing, enabling large-scale network deployment. It is an eco-friendly architecture designed to adapt to the evolving technological landscape and current network conditions[4]. A C-RAN architecture primarily consists of three components - a BBU pool containing multiple BBUs with centralized processors, remote radio heads (RRHs) with antennas and a fronthaul network that connects RRHs with the BBU pool. By centralizing the BBUs to the cloud, C-RAN forms a centralized baseband pool, which allows the radio resources of different BBUs to be shared to cope with the spatial and temporal dynamics of user demands[5]. Aiming to enhance network scalability and design flexibility while improving energy efficiency and reducing integration costs, the C-RAN achieves these goals by utilizing technologies including virtualization and collaboration, enabling resource sharing and dynamic scheduling.

### 2.1. Mobile fronthaul network

In the C-RAN architecture, Mobile Fronthaul (MFH) is an indispensable and important part, and its performance determines the rate and capacity ceiling of the whole architecture, playing a vital role in connecting remote radio units to centralized processing units and ensuring efficient data transmission in modern wireless communication systems. The access network architecture of 5G and even B5G is shown in FIG.1. Developing a robust MFH network is essential for advancing modern mobile communication technologies. In the development of access network, with the change of access network architecture, the functional positioning of the fronthaul network is also changing. As shown in Fig.2, in the 3G access network, the baseband processing unit and the remote wireless unit act as a whole, which are connected to the core network through the Backhaul network. In 4G era, BBU and RRU are separated, and the link between them is defined as Fronthaul network, which is generally carried by optical fiber. After the 5G era, the access network has been further split, and the BBU has been split into a central unit and a distribution unit[6]. A new link called Midhaul is formed between the CU and DU, and the RRU also evolves into the Radio Frequency unit due to the increased functionality.

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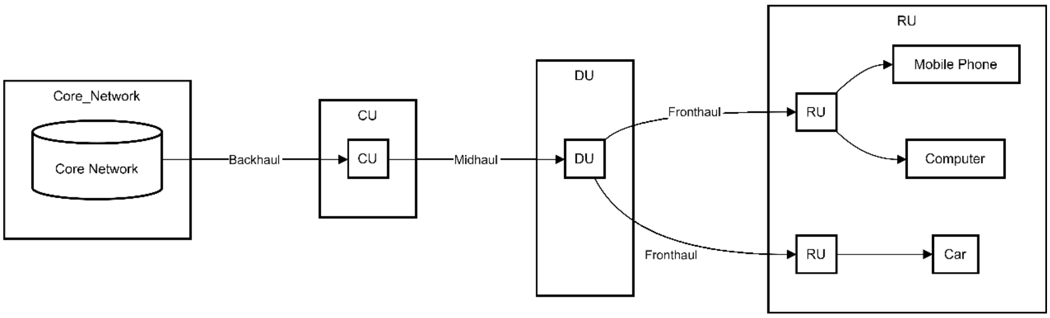


Figure 1: The access network architecture of 5G and even B5G.

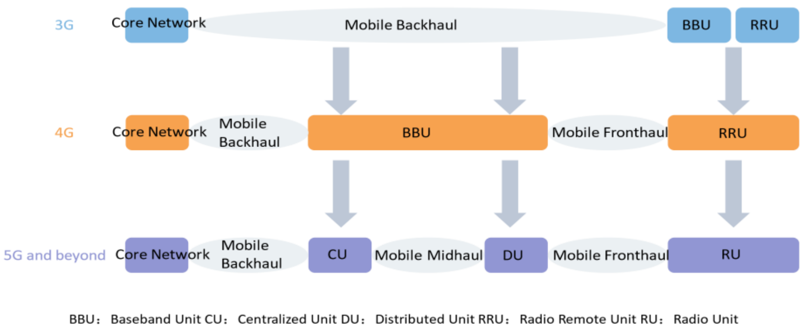


Figure 2: The fronthaul network architecture of different generations of mobile communication networks.

## 2.2. Extensive advantages of C-RAN in 5G

The advantages of C-RAN over existing architectures are summarized below:

- C-RAN can reduce latency when performing operations. For example, the time for handover will be reduced because the operation is performed in the cloud instead of between base stations, which also reduces the probability of handover failure. In addition, C-RAN can reduce the amount of signaling information sent to the core network, thus reducing the overall delay.
- The C-RAN architecture can significantly enhance the spectral efficiency of cellular networks. For instance, by implementing coordinated and collaborative transmission/reception strategies between RRHs connected to the same cloud, such as enhanced Inter-Cell Interference Coordination (eICIC) and Coordinated Multi-Point (CoMP) transmission, these strategies will become more streamlined and efficient, leading to higher spectral efficiency[5].
- The C-RAN has the adaptability to non-uniform traffic.Traffic in modern cellular networks is significantly diverse in time and space. However, the base stations are usually configured according to the demand during peak hours, which means that there is a waste of processing capacity during off-peak hours[7].

# 3. Challenges and solutions in the development of C-RAN

## 3.1. Security threats and trust issues

Some drawbacks still remain, including high costs, low scalability, and latency issues. This section introduces the security threats and trust issues. In C-RAN systems, especially when infrastructure is shared among multiple operators or private owners, some RUs may be untrusted. These untrusted RUs pose significant risks as they might intercept and store sensitive information transmitted between the core network and end-users. This makes the system vulnerable to internal eavesdropping. The distributed nature of RUs in C-RAN, combined with wireless broadcast characteristics, increases the risk of data leaks to external eavesdroppers. This is particularly concerning in scenarios where full-duplex (FD) communication is utilized, as both uplink and downlink data are susceptible to interception[8]. In response to the security challenges posed by untrusted RRUs in C-RAN, a novel approach involves using FD capable trusted RRUs to transmit a jamming signal towards the untrusted RRUs while simultaneously receiving UL signals. This jamming signal, known to the CU, can be subtracted from the UL communication to mitigate its impact on trusted RRUs, while it degrades the decoding capability at the untrusted RRUs[9]. The proposed solution integrates the design of fronthaul compression, jamming, and information transmission strategies into a unified optimization framework, enhancing privacy while maintaining network performance.

### 3.2. High requirement of fronthaul network

The fronthaul network in C-RAN systems faces significant challenges that can hinder the scalability and overall performance of the network. One of the primary issues is the limited capacity of fronthaul links, which becomes a bottleneck as the number of connected RRUs increases. This limitation is particularly problematic in FD C-RAN systems, where both uplink and downlink communications coexist, exacerbating the demand on fronthaul capacity. Additionally, to comply with the limited fronthaul capacity, quantization of the transmitted waveforms is necessary, which introduces quantization noise. While this noise can be leveraged to enhance security, it also complicates the design and optimization of the network, requiring sophisticated strategies to balance performance and security. The scalability of C-RAN is therefore significantly constrained by these fronthaul limitations, making it challenging to efficiently expand the network while maintaining the required quality of service[10]. Meeting capacity challenges requires fronthaul networks to support extremely high data rates. This often necessitates advanced fiber infrastructure, which can be costly and difficult to deploy in certain regions. However, deploying such infrastructure is costly and not necessarily feasible in all regions, especially in rural or underdeveloped areas where the cost and logistical challenges of laying fiber are often difficult to overcome[11]. This has become a significant barrier to the widespread adoption of C-RAN, limiting its deployment to areas with existing infrastructure or economic reasonability.

### 3.3. Wavelength Division Multiplexing(WDM) technology and the Aggregation of Free Space Optical(FSO) Communication and millimeter Wave (mmWave) Communication

For C-RAN scale networking,5G fronthaul needs to solve the problems of large consumption of terminal fiber resources and low cost control of dumb resources. WDM technology and system architecture are two key technologies[12]. To meet these challenges, the use of WDM technology to conserve fiber resources has become an industry consensus. Currently, based on different wavelength planning and ranges, four types of WDM technologies are present in 5G fronthaul networks: Coarse Wavelength Division Multiplexing(CWDM), Local Area Network Wavelength Division Multiplexing(LWDM), Medium Wavelength Division Multiplexing(MWDM), and Dense Wavelength Division Multiplexing(DWDM) and they are summarized in Table.1 below.

DOI: 10.54254/2755-2721/99/20251749

Table 1: Four Types of WDM Technologies.

| WDM Technology | Wavelength Range (nm) | Channel Spacing | Number of Channels | Key Advantages | Application |
|---|---|---|---|---|---|
| CWDM | 1271 - 1611 | 20 nm | 18 | Low cost, simple modules | Cost-effective short-distance fronthaul |
| LWDM | 1269.23-1318.35 | 800 GHz | 12 | Low dispersion costs, reuses existing laser sources | Reduced dispersion in 5G fronthaul |
| MWDM | 1271 - 1371 | Variable | 12 | Quick industrial maturity, reduced Four-Wave Mixing risk | Optimized cost for mid-range fronthaul |
| DWDM | C-band (1528.77 - 1563.86) | 50 or 100 GHz | 48 or 96 | High channel density, tunable lasers | High-capacity backbone and metro networks |

Each of these WDM technologies plays a vital role in optimizing fiber usage and ensuring that the network can scale effectively to meet the demands of 5G and beyond. In addition to WDM technologies, the system architecture of the WDM networks is also crucial. WDM systems can be categorized into three main types: Passive, Active, and Semi-active WDM systems, each offering different levels of performance, cost, and complexity. These architectures determine how WDM technology is implemented in the network and directly impact the overall efficiency and scalability of the 5G fronthaul. In addition to WDM technology, there are two crucial fronthaul technology based on analog signal transmission, Free Space Optical(FSO) communication and mmWave communication. FSO is an ideal choice for constructing mobile fronthaul networks(MFH). The transmission medium of FSO is laser light wave, which propagates directly through vacuum or atmosphere without using waveguide medium. Currently, transmission rates can reach hundreds of gigabits per second. FSO technology has several advantages, such as high bandwidth, low cost, abundant spectrum resources, and immunity from electromagnetic interference[12]. Another excellent scheme is mmWave communications. Millimeter wave belongs to high frequency electromagnetic wave. Its advantage lies in the rich spectrum resources, high communication bandwidth, strong directionality and reliability brought by high frequency. Because of this, mmWave technology plays a key role in the development of 5G[13]. Due to being a wireless propagation technology, mmWave communication is also susceptible to weather conditions just like FSO. In bad weather, the propagation loss of mmWave increases substantially, which is unfavorable for signal propagation. Therefore, many studies point out that FSO can be used in combination with mmWave to reduce the transmission loss. The aggregated communication between FSO and mmWave is utilizing both technologies simultaneously for information transfer. When encountering extreme weather, the device is able to switch between FSO and mmWave to reduce the adverse effects of the weather. The FSO-mmWave aggregated communication system adjusts the type and parameters of the transmitted signal according to the channel condition of the mmWave link through the transmitting controller, and the signal is received by the receiver through the transmitting antenna, channel and receiving antenna. By synchronously transmitting information in the laser band and the mmWave band, this aggregated communication system can effectively take the advantages of both

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technologies, thereby improving the transmission rate and system reliability, and adapting to different weather conditions[14].

## 4. The integration and development of C-RAN and future 6G

Future 6G systems will evolve from traditional self-organizing networks (SONS) to self-sustaining networks (SSNS) to cope with increasingly complex environments and application requirements. As a typical representative of centralized radio access network, C-RAN architecture will play a key role in this transformation. SSN networks should not only be able to adapt to different environmental states, but also need to maintain their long-term key performance indicators through energy harvesting and spectrum utilization. In addition, the design of 6G systems will not only be limited to communication, but also integrate multi-functional services including computing, control, positioning and sensing[13]. The new spectrum resources, especially the communication technology in terahertz band (0.1-10thz), have become one of the most concerned 6G core technologies due to the requirements of 6G ultra-wideband, ultra-low delay and extreme coverage. Terahertz communication has extremely rich application scenarios and is the key technology to realize ultra-high speed mobile wireless communication in the future. It has important strategic and economic value and becomes the commanding height of global scientific and technological competition. For instance, by integrating terahertz communication capabilities into FSO architectures, it can not only support higher data transmission rates, but also trigger the development of new applications such as space exploration[14]. Another aspect is massive URLLC. URLLC services in 5G focus on meeting the reliability and latency requirements of specific uplink IoE applications such as smart factories, for which previous research also provides the necessary foundation. But in the 6G era, the classic URLLC must be scaled at the device scale, resulting in a new massive URLLC (mURLLC) service that integrates 5G URLLC with traditional mMTC. mURLLC introduces the trade-off between reliability, latency, and scalability, which requires a departure from average based network design such as average throughput/delay. Accordingly, a scalable framework that can handle latency, reliability, packet size, architecture, topology (covering access, edge, and core), and decision making under uncertainty must be built[15].

## 5. Conclusion

The rapid evolution of mobile communication technologies, particularly from 5G to 6G, has underscored the limitations of traditional D-RAN, necessitating the development of more advanced network architectures. C-RAN has emerged as a key solution, addressing the growing demands for higher data capacity, reduced latency, and improved reliability. This study has examined the C-RAN architecture, highlighting its significant advantages over D-RAN, such as enhanced spectral efficiency, dynamic adaptability to traffic variations, and reduced energy consumption. The paper explored key enabling technologies within C-RAN, including WDM and the integration of FSO and mmWave communications, which collectively optimize resource utilization and network resilience. Despite these benefits, C-RAN faces critical challenges, particularly related to the high demand for fiber-optic infrastructure, complex data processing needs, and security issues associated with untrusted radio units. Innovative solutions like advanced fronthaul compression and jamming techniques are proposed to mitigate these challenges. Looking forward, the integration of C-RAN with 6G networks will be pivotal in the transition toward self-sustaining and highly adaptive network architectures. This evolution will expand C-RAN’s role beyond communication, incorporating multifunctional services such as computing, control, and sensing. Future research and technological advancements will be essential to fully realize C-RAN’s potential, particularly in harnessing new spectrum resources like the terahertz band to meet the ultra-high speed, low latency, and extensive

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coverage demands of next-generation wireless communication systems. The deficiency of this study is the lack of in-depth discussion on the specific implementation scheme of C-RAN security and large-scale deployment. Future research should focus on improving the security mechanism of C-RAN, optimizing resource allocation, and expanding its application in 6G.

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