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5G radio access networks: A survey

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The fifth generation (5G) technology improves the user experience and creates new possibilities for a variety of applications, including transportation, device-to-device communication, agriculture, and manufacturing. These new use-cases significantly increase the number of users, volume of traffic, throughput, and latency. Hence, there is a need to modify the radio access network (RAN) for the 5G system. This study investigates the various RAN architectures such as cloud-RAN (CRAN), heterogeneous cloud-RAN (HCRAN), and fog-RAN (FRAN). The architectures are examined in a variety of contexts, including system efficiency, spectrum and energy efficiency, fronthaul capacity, latency, resource sharing and allocation, and so on. Also, current issues with these architectures are highlighted, as well as some existing remedies.

1. Introduction

The COVID-19 pandemic has produced a significant influence on the global digital landscape. To halt the virus from spreading, some measures such as social isolation and lockdown have been implemented, emphasizing the necessity of an effective and inclusive digital economy, facilitated by increasing access to reliable, and suitable broadband for socioeconomic well-being. The fifth generation (5G) technology is a major component of the Fourth Industrial Revolution (4IR), which supports the use of integrated spectrum with traditional technologies. Unlike past generations of mobile networks, 5G aims at delivering enhanced mobile broadband (eMBB), massive machine-type communication (mMTC), and ultra-reliable and low-latency communication (uRLLC). Hence, 5G can be used for a variety of applications, including healthcare, automotive, entertainment, internet of things (IoT), and industrial internet of things (IIoT) applications that require ultra-low latency for maximum performance.

Moreover, the demand for internet resources increases at an exponential rate and thus, poses resource constraints and management challenges for the 5G networks. For instance, the industry revenue for IoT between 2017 and 2019 has increased from 100 to 212 billion dollars, with growth expected to reach 1.6 trillion dollars by 2025 [1]. According to IDC [2], about 50 billion of connected devices would be in use globally by 2030, yielding a vast network of linked devices encompassing anything from vehicles to smartphones, home appliances, and so on. Therefore, different designs and technological advances have been suggested in the literature, particularly in the area of Radio Access Network (RAN) for 5G networks. These designs are to meet the growing capacity needs, reduce Capital Expenditure (CAPEX) and Operational Expenditure (OPEX) networks, provide ultra low latency and higher bandwidth to multiple end-users, and integrate the existing technologies.

Cloud radio access network (CRAN) is an architecture that utilizes cloud computing to achieve the 5G objectives [3]. Moreover, issues such as security, and fronthaul and a centralized baseband unit (BBU) pool constraint reduce the CRAN capabilities. The centralized BBU processing is required to have fronthaul links with high bandwidth and ultra low latency in CRAN. However, the capacity of a link is usually limited and time-delayed in real-time applications. Thus, reducing the spectral and energy efficiency of the CRAN.

A heterogeneous CRAN (HCRAN), which separates the user plane is separated from the control plane was introduced in [4] to resolve the CRAN fronthaul issues. Uninterrupted coverage and other control plane duties are offered by high power nodes (HPNs), which are linked to the BBU pool through the backhaul to manage interference. On the other hand, user plane high-speed data transmission are provided using remote radio heads (RRHs). Nevertheless, real-time implementation of HCRANs remains an issue. The fronthaul links connecting RRHs and the centralized BBU pool increases, having several redundant traffic data due to the increased use of location-aware social applications and thus, the fronthaul burden of HCRAN increases. Edge devices such as RRHs and intelligent user equipments (UEs) that are capable of data storage and processing can be used to minimize the BBU pool and fronthaul link limitations. However, the edge devices are inadequately utilized during low-traffic periods, leading to a rise in the CAPEX/OPEX costs.

Fog radio access networks (FRAN) is one of the recent technologies that has swiftly emerged in short time. The technology offers opportunities for low-latency service in 5G by bring computing resources from

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BBU pool to the edge of the network. The FRAN handles the limitations of Cloud radio access network (CRAN) and Heterogeneous Cloud radio access network (HCRAN) with distinctive features of high mobility, enhanced radio resource allocation, enhanced service quality, and low latency [5]. However, there are still challenges with implementing the FRAN architecture in 5G networks, such as optimal resource allocation, ultra-low-latency, spectrum and energy efficiency, among others. Hence, a need to develop an enhanced resource management scheme for 5G Fog-RANs (5G FRAN). This is to minimize the IoT devices challenges while satisfying the industrial requirements.

In this article, an extensive comparative study of the different 5G-RAN architectures, that is, CRAN, HCRAN, and FRAN is presented. The survey aims at studying these RAN architectures from various perspectives such as energy and spectrum usage, CAPEX/OPEX, system level performance, and so on to provide enhanced user's quality of experience (QoE) and satisfy vertical industrial requirements.

The rest of this article is structured as follows. Section 2 introduces the basics of the 5G system, key milestones and Standard Development Organisations (SDOs). Section 3 discusses the 5G radio access network (5G RAN) architectures and limitations. Finally, Section 4 concludes with the key contributions and future work.

2. 5G mobile communication

The 5G mobile communications has created a significant impact on the society and industry. 5G allows for significant higher peak data rates, available almost anywhere and at any time, compared to previous cellular generations. Although, mobile broadband services are widely available today, 5G enables the next level of human connectivity and human to everything interaction, such as widespread use of virtual or augmented reality, free viewpoint video, and telepresence [6–8].

To enhance the 5G capabilities three major service types; eMBB, mMTC, and uRLLC, were proposed in the Mobile and wireless communications Enablers for Twenty-twenty (2020) Information Society (METIS) project [9]. The eMBB utilizes 5G as a progression from 4G LTE mobile broadband service, with faster connections, higher throughput, and more capacity. Thus, benefitting areas with high traffic such as cities, stadiums, and so on. On the other hand, uRLLC is considered as using the network for mission critical applications, that is, services that require uninterrupted and robust data transfer. In this case, short packet data transmission is used to satisfy the reliable and latency wireless communication networks. Moreover, mMTC is expected to be used for connecting many devices, especially the numerous connected IoT devices. These applications were further endorsed by International Telecommunication Union Radiocommunication Sector (ITU-R) Working Party 5D (WP5D) such that only eMBB was deployed in 2020.

Recently, ITU-R produced a new recommendation known as International Mobile Telecommunications (IMT) "IMT Vision Framework and overall objectives of future development for 2020 and beyond" [10,11]. Subsequently, standardization organizations such as 3rd Generation Partnership Project (3GPP), Institute of Electrical and Electronics Engineers (IEEE), and others transformed the ITU's objective to 5G standards. Moreover, other Standards Developing Organizations (SDOs) and industrial forums continue to develop competitive or complementary technologies to the 3GPP standards such as Broadband Forum (BBF), Open Radio Access Network (O-RAN), Small Cell Forum, etc. [12–15].

3. 5G radio access network architecture

Radio access network (RAN) is the most critical component of a mobile network. This is evident during the deployment phase, which is followed by the operational complexity, and cost. The RAN is a collection of interconnected base stations that are linked to the core network and provide coverage in a specific area based on radio access technologies (RATs). The traditional mobile networks depend on a distributed RAN architecture such that a single RRH is linked to a single and specific baseband unit (BBU). For instance, the RRH located on the tower's pole is linked to the BBU located at the tower's base using a common public radio interface (CPRI) or coax cable link. This one-to-one RRH-BBU design is neither cost nor energy-efficient. Thus, a need to evolve traditional RANs for diverse service requirements for the exponential growth in the number of connected devices and increasing data rates for the 5G standards. Despite improvements on the conventional distributed RANs, the architecture could not satisfy the requirements of 5G; therefore, the disruptive concept of a cloud RAN (CRAN) was presented in [16–18].

3.1. Cloud radio access network (CRAN)

The CRAN is a 5G mobile architecture that emerged from existing traffic patterns and technological developments. CRAN is based on centralized processing, collaborative radio, and real-time cloud infrastructure, that is, splitting the BBU pool and RRHs of the base stations (BS) to create a centralized pool as shown in Fig. 1. The centralized BBU has enhanced computation through virtualization and cloud computing technologies. The CRAN design aims to minimize the number of BS and reduce energy consumption in the network. More so, the CRAN utilizes collaboration and virtualization technology to enable dynamic resource allocation, enhanced spectrum efficiency, high bandwidth utilization, flexibility in design and operational efficiency.

The key concept of CRAN splitting the BS into BBU and RRH. The BBUs are responsible for intensive baseband signal processing activities, while RRHs are responsible for light computational tasks such as signal modulation and amplification [19]. This also disrupts the direct link between BBU and RRH, so that each RRH is dynamically allocated to the BBU pool. In [20], RRH sends and receives signals using a virtual BBU, while the virtual BS's processing capacity was enhanced based on the allocated processors in the real-time virtual allocation BBU pool.

3.1.1. Benefits of CRAN

Some important benefits of CRAN over the conventional RAN are discussed as follow.

- Enhanced Energy and Spectral Efficiency
  Unlike the traditional RAN, CRAN utilizes less numbers of BBUs, yielding significant reduction in power consumption [21,22]. Also, radio modules do not require a lot of site supporting equipments such as air conditioning since the RRHs can be naturally cooled by hanging on mast or building walls. Additionally, CRAN enables computational offloading of energy consuming data computations from UEs and BSs to a nearby cloud; thus saving their energy. Besides, the introduction of cooperative radio technology helps to reduce the distance between RRHs and UE, which minimizes interference among RRHs while decreasing computation of energy in 5G network. As part of the related studies on increasing spectrum efficiency by deploying the CRAN, [23] considered the advantages and disadvantages of using licensed and unlicensed spectrum of different technologies for the fronthaul of 5G-CRAN. More so, a coordinated and cooperative transmission technique for improved SE, such as enhanced inter-cell interference coordinated (eICIC) and coordinated multiple point transmission (CoIMP) over the RRHs, connected to the same cloud was investigated by [20,24].
- Reduced CAPEX/OPEX
  Mobile network operators (MNOs) can reduce CAPEX and OPEX of 5G-CRAN by virtualizing baseband processes in the cloud platform. The CRAN architecture requires low cost RRH spatial-time deployment, installation, and operation. In [25], the cost of deploying BSs, transport networks, and data center was examined based on several processes in the spatial domain. The analysis showed that CRANs can reduce CAPEX up to 15% based on the costs of BSs and the combination of backhaul methods for

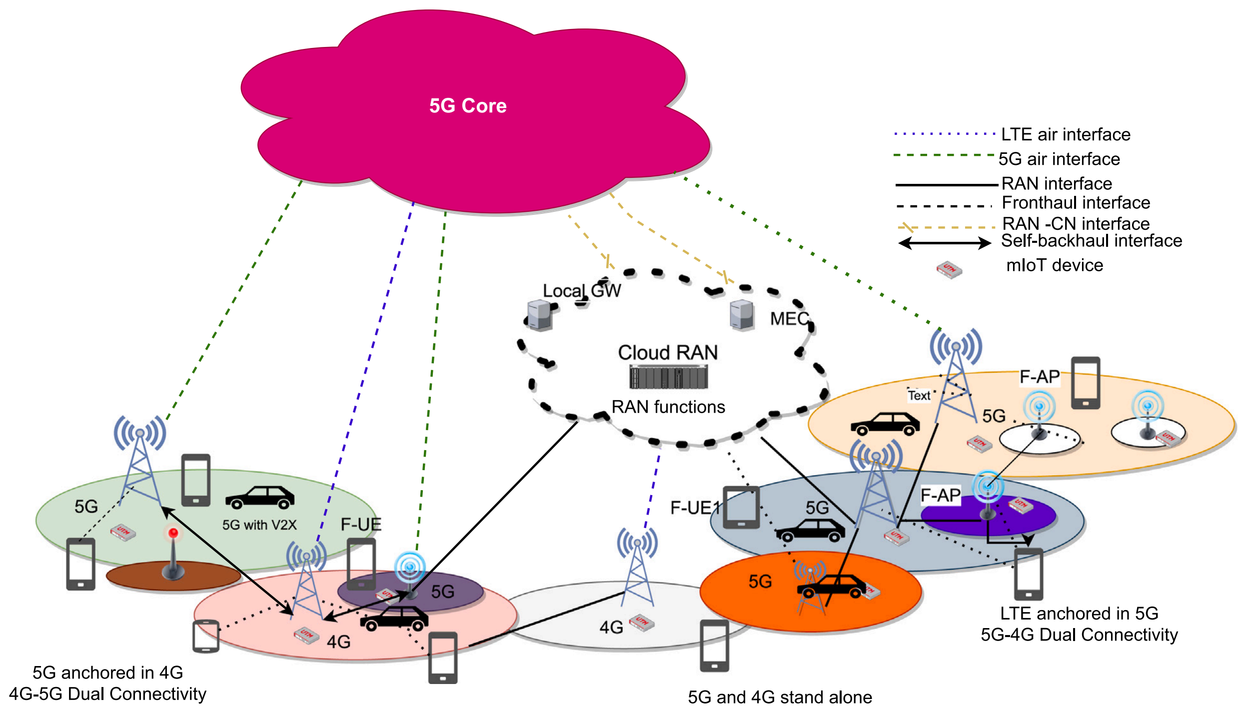

Fig. 1. 5G CRAN Architecture.

linking BSs with data centers. Likewise, a two-phase framework that finds optimal BS clustering scheme in CRAN was proposed in [26]. The framework exhibited a 12.88% reduction in the cost of deployment. In [27], the cost for BBU hotelling strategies: BBU stacking, BBU pooling, and CRAN BBU was modeled and the performance were compared. In [28], a network planning and provisioning framework was proposed to optimize the cost of deployment in CRAN. The framework utilized a mixed integer quadratic constrained programming (MIQCP) method, which maximizes the cost of deploying a virtualized 5G service chain.

- Enhanced Mobility Management
  An important benefit of BBU pooling is that it allows for dynamic allocation of BBU resources to RRHs for load balancing mobile traffic between the BBU pools. The load balancing capacity in the distributed BBU pool makes CRAN appropriate for dynamic distributed traffic. Despite that the serving RRH changes continually with respect to UE movement, the serving BBU remains in the same pool since the BBU's coverage is greater than that of a typical BS. As a result, UE-generated non-uniformly dispersed traffic can be routed through a virtual BS within the same BBU pool; thus, aiding the MNOs with mobility management. In [29], location based algorithms were presented for tower clustering, and BBU cluster categorization using mobility and traffic patterns prediction in the CRAN. There are several other benefits that the CRAN offers to 5G mobile communication system, which are discussed in detail in [30].

Table 1 summarizes some major benefits of CRAN in the 5G systems.

Table 1
5G CRAN benefits.

Benefits	Achievements	References
Enhanced energy and spectral efficiency	BBU pool reduces the number of physical equipment. No cooling needed. Use of licensed and unlicensed bands.	[20–24]
Reduced CAPEX/OPEX	BBU pool reduces the numbers of site locations. RRU reduces site footprints. Low maintenance cost.	[25–28]
High flexibility and performance	Improvement in the Backhaul transmission (fiber or high capacity microwave)	[31,32]
Enhanced mobility management	BBU pool enhances handover coordination	[29,30]

3.1.2. Challenges of CRAN

Apart from the benefits that CRAN contributes to 5G systems, there are still some limitations, which include:

- **Security**
  CRAN security issue has attracted concern since cyber-attacks are constantly on the rise. In addition to common security threats of traditional wireless networks such as primary user emulation attack (PUEA), CRAN faces more security threats, such as eavesdropping and jamming, media access control (MAC) spoofing, IP spoofing and hijacking, transmission control protocol (TCP) flooding attacks, and file transfer protocol (FTP) attacks [33]. CRAN security threats and mitigations have been investigated in studies such as [3,33–35].
- **Fronthaul Link Capacity**
  As the BBUs of multiple BSs are migrated to the cloud, it is possible that if the cloud fails, the entire network will be rendered inoperative. Fronthaul links provide a seamless connection between RRHs and BBU pool (centralized pool), while backhaul links offer a connection between BBUs and the core mobile network. Despite the benefits of CRAN, it still has performance due to fronthaul and backhaul link capacity constraints. Several studies on fronthaul compression have been conducted to address fronthaul issues relating to capacity for downlink and uplink CRAN [36–50]. The techniques aim at effective transmission on the fronthaul links. Two major transmission techniques; data sharing and compression techniques. These techniques depend on whether the joint encoding and precoding of information intended for mobile users is performed at individual BSs (data-sharing technique) or at the centralized BBU (compression technique). Generated signals

from the later are quantized and compressed before being sent to the RRH through fronthaul links [37]. A general form of compression technique was proposed for downlink CRAN in [36]. A finite-capacity fronthaul was developed to connect the BSs to a centralized processor. This method allows the centralized processor to centrally encode signals that will be broadcast by the BSs using the fronthaul links in a cooperative manner. In [37], a combined data-sharing and compression solution for downlink CRAN was introduced, allowing for better control over fronthaul/backhaul capacity usage. Moreover, the issue of jointly optimizing digital baseband beamforming and fronthaul compression techniques at the BBU alongside RF beamforming at the RRHs was studied in [39]. This joint design of fronthauling and hybrid beamforming ensures that the weighted downlink sum-rate and network energy efficiency of the CRAN system is maximized. A standard point-to-point fronthaul compression method was studied in [47], while several multivariate fronthaul was investigated in [48,49].

For uplink CRAN, [40,41] considered a joint fronthaul compression and transmit beamforming design for multi-antenna users. The users communicated with the centralized processor using multi-antenna BSs. The BSs were connected to the central processor through limited capacity digital fronthaul links. The authors in [40] investigated two different fronthaul compression techniques; single-user compression (point-to-point compression) and Wyner–Ziv coding for CRAN. They further proposed an optimization strategy for noise covariance matrix quantization. Each BS utilizes vector quantization to compress the received signals across different BSs in single-user compression. However, Wyner–Ziv coding fully uses the correlation of the received signals to achieve enhanced compression efficiency; thus, obtaining an improved overall performance. The joint design of CRAN with wireless fronthaul link and OFDMA access link was investigated in [44,50]. Moreover, the wireless fronthaul link used to communicate between multi-antenna RRHs and multi-antenna BBU pool was enhanced based on Intelligent reflecting surface in [41]. Each received signal at individual RRH was compressed using Wyner–Ziv coding. An adaptive compression method was proposed in [42] to minimize the fronthaul transmission rate; thus, maximizing the compression efficiency. Further in [43], fronthaul compression was performed at the RRH to transmit baseband signal over the fronthaul link to the centralized unit. The algorithm utilized the Charnes–Cooper transformation and Difference of Convex approach to optimize the power spectral density of quantization noise at the RRHs.

3.2. Heterogeneous Cloud Radio Access Network (HCRAN)

The need for dense 5G RANs has led to the concept of Heterogeneous Cloud RAN (HCRAN). The HCRAN is a cost efficient solution that utilizes the combination of heterogeneous networks (HetNets) and cloud computing as shown in Fig. 2. The HCRAN design in [4,51] incorporated different cells such as macro BSs, that is, the HPNs, micro BSs and RRHs. The macro BSs provide network control, mobility management, and system performance enhancement. On the other hand, micro BSs and RRHs improve capacity of the system and lower the power of transmission. The RRHs enable signal processing and radio frequency functions, whereas the BBU pool incorporates other physical processing functions of the baseband that are associated with the upper layers. Also, all physical and network layer functions are available in the HPNs. The HPNs send system broadcasting data and control signaling to the UEs, resulting to an improved fronthaul link capacity and reduced time delay in the HCRAN. Some benefits of HCRAN in 5G systems are discussed as follows.

3.2.1. Benefits of HCRAN

Several studies have been conducted on HCRAN presenting diverse perspectives such as energy efficiency, spectrum efficiency, resource allocation, cost management and load balancing, mobility management, performance enhancement and so on. This is because HCRAN exploits full advantage of the HetNets and cloud computing capabilities in the 5G system.

- **Enhanced Energy and Spectral Efficiency**
  The integration of HetNets with CRANs allows for the implementation of novel strategies for efficient energy and spectrum utilization. The cloud computing-based coordinated multipoint (CC CoMP) system described in [52] is an example of coordinated transmission and reception. This CC-CoMP enabled HCRAN is similar to a large distributed MIMO system in which femto, pico, and macro cells are essentially RRHs connected to a centralized baseband processing center where signals are combined. The joint processing in HCRANs becomes possible and economically practical by removing the rigorous backhaul and synchronization requirements among dispersed cells. The use of joint transmission coordinated multipoint (CoMP) transmission to mitigate inter-cell-interference was adopted in [53] to enhance spectral efficiency for cell edge users in NOMA based network. Moreover, in [4], the coverage area for HCRAN was carefully designed to enhance spectral efficiency by significantly shortening the communicating distance between serving RRH and desired mobile terminals.
- **Resource Sharing and Allocation**
  Resource sharing for HCRANs has been classified to three categories: spectrum sharing [54,55], infrastructure sharing [56,57], and network sharing [58,59]. The spectrum and infrastructure resources can be further divided to sharing entities, network slices, and logical connections [60]. A sharing entity represents a collection of accessible resources, such as a base station, a network of interconnected base stations, or a component of a base station. The allocation of available resources among two or more sharing entities is known as network slices. Whereas, at the network level, the HCRAN's spectrum and infrastructure are categorized to network slices based on parameters such as throughput and processing. In HCRAN, each of these steps allow for resource sharing benefits such as a dynamic pool of spectral resources, improved infrastructure coverage, and virtual networks suited to a certain service class.
- **Enhanced Mobility Management**
  The separate plane design of HCRAN enhances user mobility in 5G systems. Therefore, a cell outage management (COM) technique for HetNets with separated management and data BS layers was presented in [61]. The management BSs were used for control information transmission and user mobility while the data BSs were used to manage user data. Moreover, a cooperative cell outage detection (COD) approach for pico cells in conventional HetNet was proposed in [62]. Also, [63] adopted the COD and cell outage compensation (COC) algorithms for microcell and macrocell failures identification and mitigation in HetNet respectively. In highly densed HCRAN, the authors in [64] proposed a scheme for user equipments to directly select the cell with the highest priority in terms of cell features, mobile equipment, mobility features, and application features.
- **Enhanced Performance**
  System performance in HCRAN has been enhanced due to the central cloud computing controlling functionality, where various node entities interface. The HCRAN design in [4,51] separated the control and user planes to increase CRAN's functionality and efficiency. As a result, the spectrum and energy efficiency of CRAN may be considerably improved under HCRAN design. In [52], two separate HCRAN architectures with different sizes of cell

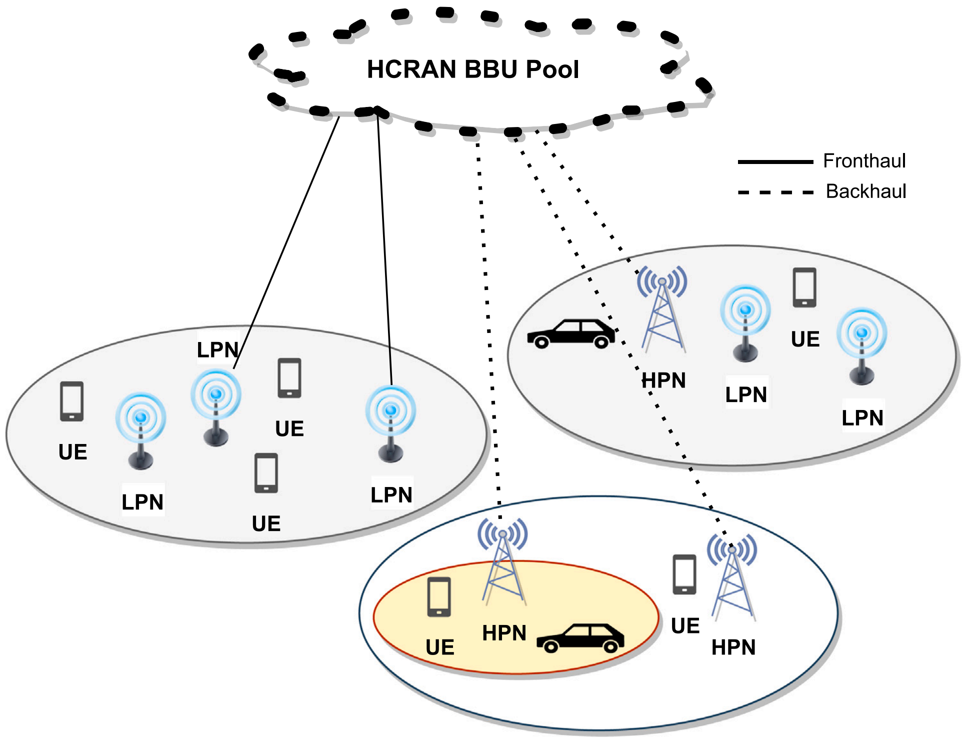

Fig. 2. HCRAN Architecture.

Table 2
5G HCRAN benefits.

Benefits	Achievements	References
Enhanced energy and spectral efficiency	Mitigates against inter-cell-interference and enhances spectral efficiency for cell edge users	[4,52,53]
Resource sharing and allocation	Enables network slices and dynamic pool of spectral resources. Improves infrastructure coverage	[54–60]
Enhanced mobility management	Flexible design allows for easy handover management.	[61–64]

was introduced. For a single cloud, wireless or optical backhaul links were used to connect the cloud to BSs from different layers. On the other hand, multiple clouds were connected using hybrid backhauling to a group of BSs. Moreover, a design that separates the HCRAN operation into unique layers; infrastructure, control, and application layers was proposed in [65]. The design incorporates massive MIMO (mMIMO) to enable broadband transmission. This method improves the scalability and flexibility of the system since RRHs become smaller and complex computations could be performed and managed by the BBU pool obtained by the mMIMO.

Table 2 summarizes some major benefits of HCRAN in 5G systems.

3.2.2. Challenges of HCRAN

Despite the above-mentioned advantages of heterogeneous networks and cloud computing in 5G systems, HCRAN has several limitations, which are detailed below and summarized in Table 3.

- **Energy Consumption**
  In HCRAN, ultra dense deployment of RRHs and micro BSs had been deployed to improve capacity while increasing energy usage of the system. Moreover, a radio resource management scheme based on non-orthogonal multiple access (NOMA) was presented to maximize the energy efficiency of HCRAN in [66]. The authors designed the network energy efficiency maximization problem as a mixed integer non-linear programming problem (MLNLP). In the approach, users accessed the network services using non-orthogonal resources, which improves the system's overall energy usage. Additionally, a pre-coding method was introduced to enhance energy usage of the HCRAN network in [67]. The scheme explored a macro/femto HetNet such that a high remote radio head (HRRH) represented the macro base stations (MBSs) while a low remote radio head (LRRH) represented the femto BS. As compared to the conventional HetNet without CRAN, the approach exhibited an increased throughput while utilizing low energy.
- **Backhaul Load Balancing**
  As cellular communication networks evolve to dense and dynamic HetNets, an increasing high volume of data transmission on the backhaul links between the BBU pool and RRHs is a major setback for the adoption of HCRAN's centralization [68]. The RRHs are unable to fully exploit existing radio resources in the HCRAN system due to inadequate backhaul capacity. Hence, there is a need to reduce and effectively balance transmission load on the backhaul links. Data compression approaches in the time and frequency domains have been well-studied to solve the HCRAN transmission backhaul issues. These methods enhance the efficiency of data compression but increase the complexity of the system. In [69], backhaul workload balancing was suggested as a solution to relieve HCRANs' backhaul data transmission demand. This approach requires collecting the number of active RRHs in a specific region and designing the area that each RRH is required to service as an optimization problem. However, there still exists the challenge of allocating data transmission among several users to either a macro BS or a RRH. Meanwhile, integrating HCRAN with CoMP transmission in ultra-dense heterogeneous cellular networks has been studied as a viable solution for challenges such as inadequate fronthaul bandwidth and excessive noise. Note

that some literature assumed lossless fronthaul links with infinite capacity, which is unrealistic for real-world capacity-constrained fronthaul links. Consequently, distributed compression techniques such as distributed Wyner–Ziv compression [70] with joint decompression and decoding [71] are generally used to enable transmission across capacity-constrained fronthaul links.

- **Latency**
As earlier mentioned, one of the key aim of the 5G system is to provide uRLLC services. Given the introduction of HCRANs to improve network management, resource management, and enhance throughput, other challenges such as achieving complete self-organization for ultra-low-latency networks still exist. In [72], end-to-end latency performance was enhanced using resource scheduling methods. This technique decreases data transmission delays at the system's air interface. Also, an access control policy that improves HCRAN system performance by reducing latency in backhaul of wired and wireless networks was introduced in [73]. Nevertheless, there still exits considerable delay in data transmission caused by signaling overheads in the air interface. Consequently, a delay-aware centric technique that avoids signaling overhead and enhances latency performance was suggested in [74]. The method utilizes a preemptive network, which combines devices of intelligent mobile machines (IMMs) that use CoMP. The approach was effective since the HCRAN design contains numerous access points (APs) for coverage and high power nodes (HPNs) for broader coverage. Furthermore, [75] discussed a design that lowers three forms of latency: air interface latency, radio resource optimization latency, and routing/paging procedures latency. The authors utilized a systematic design with unique open-loop radio access to reduce air interface latency. Likewise, an information-based resource optimization was implemented to reduce radio resource optimization delay while a social data cache-based routing/paging strategy was used to eliminate the latter type of latency. However, this design is not applicable for heterogeneous carrier communications over the HCRAN and remains as an open issue since the latency performance can be negatively affected by unreliable communication.
Additionally, [76] introduced a dynamic stochastic resource optimization model to obtain a tradeoff between energy efficiency and queue latency limitation. The approach utilized a simple Lyapunov optimization strategy based on local information at the transmitter. This method addressed the issues of energy efficiency optimization, power consumption of RRHs, and interference limitations to achieve near-optimal system stability by minimizing traffic congestion using a weighted minimal mean square error (WMMSE) technique. Thus, yielding a balance between time averaged energy efficiency and queue backlogs.
- **Interference Mitigation**
Interference control is intended to be more efficient in HCRANs compared to a typical HetNets since the centralized operation of CRAN allows collaborative signal processing across the networks and supports coordination between BSs. Moreover, controlling interference in HCRANs may be challenging due to the extensive heterogeneity of BSs, network size, and fronthaul/backhaul limitations. As a result, a number of studies have been carried out to address the HCRAN interference problem. In [77], an interference-conscious user association strategy based on cell sleeping approach was investigated such that a cloud computing unit was used to manage the operation status of the BSs. A suboptimal user association problem was introduced to optimize the aggregate user utility as such, a distributed heuristic algorithm was presented as a solution to the problem.
Moreover, a cooperative method that mitigates interference of cell edge users based on joint transmission CoMP clustering approach was introduced in [78]. The authors utilized a pseudo-dynamic clustering method to obtain two clusters of RRHs: measurement RRHs and coordinated RRHs. The former stores measured RRH data such as the received signal strength indicator (RSSI) and channel state information (CSI), while the latter collects and preprocesses user data. Similarly, [79] described a cooperative interference mitigation system between RRHs and MBSs based on a user weighted probability strategy for separating the spectrum into shared and dedicated portions. The strategy aids in the allocation of individual BS into appropriate spectrum portions based on QoS requirements, as well as the optimization of overall throughput for users at every tier.
Additionally, a contract-based interference coordination framework that mitigates inter-tier interference was presented in [80]. The approach categorized the period of downlink transmission into three stages: RRH with all UEs, RRH with individual UEs, RRH-MBS with separate UEs, according to three scheduling methods. The MBS, which acts as a decision agent, receives a contract request from the BBU pool of all RRHs (principal) and decides to accept or reject the contract based on a logical constraint. Given that both the principal and the agent have perfect CSI, an optimal contract design for rate-based utility maximization was implemented. Also, the study considered optimizing the contract for partial CSI. In [81], a collaborative processing and cooperative radio resource allocation (CRRA) technique was introduced for HCRAN inter-tier interference suppression. The method utilizes interference collaboration (IC) and beamforming (BF) schemes to mitigate inter-tier interference. CRRA optimization models was further developed for the IC and BF schemes to maximize the sum rates of users accessing RRHs based on power allocation.

Table 3
5G HCRAN challenges and solutions.

Challenges	Solutions	References
Energy consumption	NOMA based radio resource management scheme. Pre-coding approach	[66,67]
Backhaul load balancing	Data compression approach. Integrated HCRAN-CoMP scheme. Distribution compression method	[68–71]
Latency	Resource scheduling method. Access control policy. Delay-aware centric scheme. Systematic design with open-loop radio access and information-based resource optimization approach. Dynamic stochastic resource optimization model.	[72–76]
Interference mitigation	Interference-conscious user association strategy based on cell sleeping approach. Joint transmission CoMP clustering approach. User weighted probability strategy. Contract-based interference coordination framework. Collaborative processing and cooperative radio resource allocation (CRRA) scheme.	[77–81]

3.3. Fog radio access network (FRAN)

To solve the HCRAN difficulties and provide an enhanced QoS to the users, a new RAN design focusing on fog computing was recently studied in the literature. Based on the benefits of the CRAN and fog computing, fog computing-based RAN (FRAN) design aims to address the issue of rising traffic demands while also improving QoS for end-users. Given the current global demand for IoT end-user solutions,

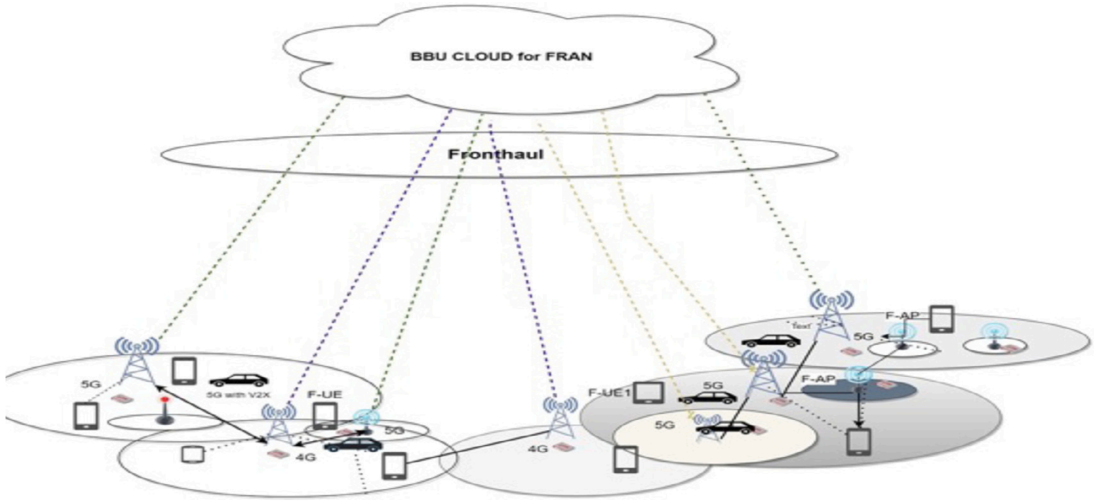

Fig. 3. 5G FRAN Architecture.

cloud computing is among the most suitable solutions, wherein data generated by IoT devices is stored, processed, managed, and analyzed by remote servers hosted on the internet. It allows organizations to concentrate on their main activities rather than planning, deploying, and maintaining network infrastructure [82]. However, the cloud storage approach is faced with issues such as long end-to-end delays, traffic congestion, huge data processing, and connectivity costs. As a result, [83] proposed a fog computing approach to replace the functionalities of the remote servers. This approach is used to expand cloud computing to the network edge, allowing for the allocation of a vast amount of computation, storage, communication, control, configuration, measurement, and management functions at the mobile network's edge.

Unlike CRAN that utilizes a centralized content storage architecture, [84] classified FRAN to distributed and centralized networks. Some of the BBU's task, including computing, caching, and resource management, are delegated to the RRHs and UEs in the distributed FRAN. On the other hand, the centralized FRAN makes use of software defined networking (SDN) and network virtualization to support logical centralized control planes, provide improved resource management, and simplified resource sharing.

Several studies [83,85–88] have examined the FRAN architecture and the consequences of major enabling techniques on the network. Fig. 3 shows a typical FRAN system architecture [86]. The FRAN architecture in [86] consists of three layers; terminal, access, and cloud computing layers. Specifically, the fog computing layer contains the fog UEs (F-UEs) and fog access points (F-APs) in the terminal layer and network layer respectively. Nearby F-UEs can interface with one another in the terminal layer using the D2D mode or mobile relay mode. Also, the F-UEs can access high power nodes (HPNs) to receive system signal information. Moreover, the HPNs and F-APs are found in the network access layer. The F-APs process the data received from F-UEs and send it to the cloud computing layer through fronthaul links. On the other hand, the HPNs connect to the BBU pool through the backhaul links. The BBU pool, which are suitable with the HCRAN's BBU pool and centralized caching are situated in the cloud computing layer. Note that allocating a huge proportion of collaboration radio signal processing (CRSP) and cooperative radio resource management (CRRM) functions to the F-APs and F-UEs reduces the fronthaul and BBU pool load constraints.

3.3.1. Benefits of FRAN

The FRAN technology for 5G mobile communication systems was examined from different contexts in the literature, including system level efficiency, energy usage, radio resource allocation, caching, service admission control and so on. An up-to-date survey of the FRAN's solutions in various contexts are discussed as follows with Table 4 summarizing the benefits.

- **System Level Efficiency**
  Several studies have been conducted on the efficiency of the FRAN system. Considering FRAN system with ultra-low applications such as IoT application, a tradeoff between system performance, computing, and communication costs in the FRAN system was discussed in [87]. The study demonstrates how critical it is to carefully choose these parameters to provide ultra-low latency services. In [89], a hierarchical content caching approach for FRANs was introduced to reduce constraints on the fronthaul capacity and transmit latency. To maximize the use of the central and edge caches in the approach, RRH clusters were created at the BBU pool based on a common centralized cloud, while local content was provided by F-APs. The system's ergodic rate was derived using stochastic geometry. Moreover, the waiting time and transmit latency were modeled using queueing theory. A system control technique for FRAN was developed utilizing the embedded game model in [90]. To maximize system efficiency, the approach considered a cooperative design of spectrum allocation, cache placement, and service admission algorithms.
  Furthermore, [91] suggested a hybrid cloud and edge processing method to reduce FRAN downlink latency, while channel encoding and fronthaul compression methods were employed to reduce fronthaul content delivery delay from the BBU to the requesting UEs. Similarly, in [92], a superposition coding approach that uses the fronthaul links in both hard and soft transfer modes was suggested for the delivery phase design of an arbitrary prefetching scheme. This design was used to generate caches of an enhanced RRH (eRRH) in [93]. In [94], the Markov chain was used to model and identify the impact of mobile social networks on the efficiency of FRAN edge caching. A combined distributed computing and content sharing approach was introduced in [95] to achieve ultra low latency by reducing fronthaul connectivity problems. Moreover, [96] proposed a dynamic resource balancing approach to enhance system reliability in the FRAN.
- **Spectrum and Energy Efficiency**
  The FRAN has been proposed in numerous publications as a solution to the CRAN issues and to improve spectral and energy efficiency of the 5G networks. Generally, allowing a single UE to access a specific group of nearby RRHs improves the spectral efficiency of CRANS. These group of surrounding RRHs are often

established using a disjoint clustering method or a user-centric clustering approach such that the cluster generation is dependent on the received power threshold of the reference signal. Although a disjoint clustering approach can reduce inter-cell interference, edge users may experience significant interference from surrounding clusters. Using the user-centric approach reduces interference between clusters since there are no edge users. Thus, CRAN performs power allocation and dynamical scheduling in addition to the massive CRSP to improve spectrum efficiency. Unlike the CRAN, users can easily access F-APs which with content caching capabilities. In the FRAN system, the distributing cluster is usually decided by the users' desired cached content and the received power of the reference signal from the F-AP to the UE. Thereafter, the spectral efficiency is improved based on user scheduling and power allocation.

In FRAN, the goal of recent research has been to create a tradeoff between fronthaul capacity and transmit power. This is because increasing spectral efficiency might put a lot of strain on the fronthaul, having limited data traffic capacity. Therefore, the study in [84] investigated a combined resource allocation and coordinated offloading scheme in a centralized FRAN. The aim was to use the least amount of energy possible to offload all of the UE's computational activities, taking into account each UE's delay tolerance, fronthaul and backhaul capacity, and available resource. An energy-saving method was proposed in [85], which considered maximum delay tolerance as well as fronthaul and backhaul capacity limits. For numerous UEs, the method resulted in improved computing resource allocation and effective transmission power allocation. In [97], an evaluation of the multicast FRAN downlink design was performed. In particular, information compression-based (soft) and information-sharing-based (hard) fronthauling were discussed. A storage module with unique bounded signal processing capabilities was assigned to each RRH. As a result, storing in-demand data during non-peak hours improved latency while lowering network energy usage. The challenges and performance of mmWave based FRAN access and fronthaul links were studied in [98]. The study examined energy-efficient power distribution in an orthogonal frequency-division multiple access network to manage interference. The optimization issue was presented as a nonlinear programming problem to improve the system's energy efficiency. To find the best solution for energy-efficient power allocation, a gradient-based iteration technique was proposed.

- **Resources Allocation**

The following studies [99–102] have looked on resource allocation for FRAN in a 5G system. In [99], a shared resource allocation and structured computation offloading scheme was proposed to reduce energy costs and enhance computational resource allocation for a range of user equipment (UE). Also, the approach aimed at minimizing the amount of transmission power and the splitting factor delivered to each UE. Furthermore, off-loading options and computational resource allocation were combined to increase the likelihood of UE relocation in [100]. The problem was solved using a mixed integer nonlinear programming (MINLP) approach while a Gini coefficient-based FCNs selection algorithm (GCFSA) was developed to provide a sub-optimal off-loading strategy. In addition, the authors employed a distributed resource optimization approach based on genetic algorithm (ROAGA) to solve the computing resource allocation problem. The authors in [101] developed a system control strategy and dynamic mode selection for the FRAN system using an embedded game model. Cache placement, spectrum allocation, and service admission algorithms were jointly designed to increase the system's performance. Similarly, [102] presented a joint mode selection and resource allocation approach for device-to-device (D2D) communication. The method improved energy efficiency while considering time and resource reuse constraints.

Table 4
FRAN benefits.

Benefits	Achievements	References
System level efficiency	Improved system performance, computing, and communication costs	[85,96,103]
Spectrum and energy efficiency	Improved spectrum and energy performance based on user scheduling and power allocation	[87–89,93,94,99,104]
Resources allocation	Reduced energy costs and enhanced computational resource allocation for a range of user equipment (UE). Minimized transmission power.	[99–102]

3.3.2. Challenges of FRAN

The FRAN, like other 5G RAN architectures, is still faced with some major research issues. Edge caching enhances FRAN performance by minimizing traffic congestion at the cloud server and enabling F-UEs to access and acquire content faster. Contrary to centralized caching schemes, the caching capacity of individual F-AP and F-UE is limited in FRAN. Edge caching strategies such as determining which content to cache and when to deliver caches in different edge devices need to be optimized to enhance overall caching performance in FRAN. More so, conventional rules for caching such as least recently and least frequently used, first-in-first-out should be improved to enhance the FRAN cache hit ratio.

Network functions virtualization (NFV) helps to virtualize the SDN controller to host a cloud server in FRAN. Thus, the server may be moved to other positions depending on the network's demands. Nevertheless, virtualizing the SDN controller in 5G F-RAN system remains uncertain. This is because of the characteristic of distribution in edge devices. Furthermore, security and privacy, computational complexity, scalability, core operational and maintenance compatibility with existing RAN designs, among other issues, remain unsolved research issues.

4. Conclusion

5G necessitates a complete rethinking of mobile network design, particularly the RAN architecture, because to the rapidly growing subscriber population, huge connectivity, massive data, and new expectations for extremely low latency and higher data rates. A evaluation of the current RAN designs for 5G mobile networks, especially CRAN, HCRAN, and FRAN, was undertaken as a response. The goal was to explore the benefits of CRAN and HCRAN while not disregarding the challenges that each network design encounters. Consequently, current CRAN and HCRAN solutions were investigated. For energy efficiency, fronthaul capacity, latency, and other factors, detailed summaries were supplied in tabular style. In the case of FRAN, a different method was followed, with the focus being on resource categories within the design layers and then an analysis of resource management system.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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