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ARTICLE

Performance Analysis of Bandwidth Aware Hybrid Powered 5G Cloud Radio Access Network

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ABSTRACT: The rapid growth in available network bandwidth has directly contributed to an exponential increase in mobile data traffic, creating significant challenges for network energy consumption. Also, with the extraordinary growth of mobile communications, the data traffic has dramatically expanded, which has led to massive grid power consumption and incurred high operating expenditure (OPEX). However, the majority of current network designs struggle to efficiently manage a massive amount of data using little power, which degrades energy efficiency performance. Thereby, it is necessary to have an efficient mechanism to reduce power consumption when processing large amounts of data in network data centers. Utilizing renewable energy sources to power the Cloud Radio Access Network (C-RAN) greatly reduces the need to purchase energy from the utility grid. In this paper, we propose a bandwidth-aware hybrid energy-powered C-RAN that focuses on throughput and energy efficiency (EE) by lowering grid usage, aiming to enhance the EE. This paper examines the energy efficiency, spectral efficiency (SE), and average on-grid energy consumption, dealing with the major challenges of the temporal and spatial nature of traffic and renewable energy generation across various network setups. To assess the effectiveness of the suggested network by changing the transmission bandwidth, a comprehensive simulation has been conducted. The numerical findings support the efficacy of the suggested approach.

KEYWORDS: 5G; bandwidth; renewable energy; energy efficiency; spectral efficiency; C-RAN

1 Introduction

The need for widespread and fast wireless communication has experienced a substantial rise in recent years owing to the extensive use of personal mobile computing devices such as tablets and smartphones, as well as the increasing prevalence of data-intensive mobile applications [1]. The next generation 5G cellular network is expected to need 1000 times the bandwidth, 100 times the data throughput, 100 times increases in spectral efficiency, and 1000 times increases in energy efficiency to address the rapidly increasing rate [2].

As a result, a technological revolution is required to meet these demands. The traditional cellular network was not designed to sustenance the capabilities required to handle the significant rise in data traffic and to reduce capital and operational expenses. To address these challenges, a new architecture called C-RAN has been introduced [3]. C-RAN represents a revolutionary redesign of the cellular architecture. In contrast, traditional base stations (BSs) in mobile networks consume a substantial amount of energy, 60%–80% of the total network's energy usage [4]. Moreover, BSs also have a negative impact on the environment due to the significant amount of carbon dioxide CO_2 emissions they generate. Therefore, it is prominent to optimize network energy efficiency, which is the key objective of this study. C-RANs have emerged as a viable solution for mitigating energy consumption. By centralizing the Baseband Units (BBUs) in C-RAN, there is a reduction in energy usage associated with site maintenance equipment and air conditioning systems. Furthermore, the central BBU pool effectively manages the signal processing for numerous dynamically deployed Remote Radio Heads (RRHs). The development of mobile commerce has increased energy consumption, which puts a great deal of strain on the resources of the traditional grid and also has a harmful impact on the ecological and economic aspects [5]. It is widely accepted that the cost of producing renewable energy is considerably lower than that of traditional grid electricity, and it has the advantage of no CO_2 emissions [6]. However, the combination of random renewable energy sources into the dynamics of energy consumption on wireless networks poses a significant challenge for next-generation fifth generation (5G) cellular networks. To address this issue, a viable approach has emerged in the form of powering BSs in cellular network architecture to enhance energy efficiency. This approach involves combining renewable energy sources with traditional grid supplies through an aggregation technique, which shows promise in achieving improved energy efficiency in the infrastructure of mobile networks.

1.1 Cloud Radio Access Network (C-RAN)

Base station duties are divided into two sections in C-RAN [7]. The RRHs are strategically positioned near the mobile users throughout the network, while the BBUs consist of high-speed processors and are utilized in the cloud for conducting baseband processing operations [8]. The central BBU effectively manages the RRHs through a cost-effective optical transport link with high bandwidth [9]. Although there are fewer cell sites in C-RAN since the BSs are centralized, there are also fewer additional site support devices that require air conditioning and electricity. Moreover, the central BBU pool lowers the expense of deploying and running BSs. Furthermore, the implementation of C-RAN enables efficient provision of services to a substantial user base through the utilization of network information within the BBU pool. However, it is important to consider the energy efficiency aspect, as the deployment of densely distributed RRHs may lead to increased energy consumption within the C-RAN system. This can impose a considerable burden on the electric grid and result in elevated operational expenses. This study offers a thorough understanding of C-RAN powered by hybrid supply, which can significantly contribute to greater improvements in energy efficiency by lowering total grid power usage.

1.2 Motivation & Contributions

The authors in [10] presented fundamental design concepts for mobile networks driven by green energy sources, while emphasizing the adaptability of green energy-powered BSs to accommodate the evolving demands of mobile data traffic. In [11], the authors investigated transmission mechanisms employed by BSs to reduce energy consumption of the network. Furthermore, in order to use green energy as much as possible, authors in [12] explored the distribution of traffic loads among BSs to effectively meet the traffic demands of all users. Lastly, authors in [13], examined user association schemes that take into consideration the availability of green energy sources. The fundamental goal of these research endeavors is to modify the transmission techniques of BSs using renewable energy sources. Nevertheless, the majority of these studies neither take energy storage into account nor do they examine potential energy storage techniques. The aforementioned authors have identified key research challenges and trends that are essential for the integration of energy harvesting as a facilitating technology for 5G systems. Given that 5G networks are expected to be highly dense, the issues of energy consumption and carbon dioxide emissions will assume global significance.

To address the previously mentioned problem, we propose a C-RAN that operates on renewable energy sources. This solution aims to reduce the power consumption of BS during specific periods and store excess energy for future use, thereby ensuring compliance with the network's outage restrictions. The existing study extensively inspects the potential advantages of solar energy in terms of mitigating energy consumption. The contribution of this paper are summarized as

- The difficulties of highly increasing BSs energy consumption is formulated and then explored the potential benefits of integrating renewable energy source with traditional grid supply to power these BSs.
- In order to coordinate the power control and energy allocation of the entire system, a hybrid energy provided C-RAN with energy cooperation is proposed.
- A power consumption model for C-RAN based on varying traffic load is proposed.
- An energy sharing dynamics is developed which can significantly contribute to greater improvements in energy efficiency by lowering total grid power usage.
- We examine the system performances in terms of several performance metrics such as energy efficiency, spectral efficiency, and average on-grid energy saving aiming to increase the EE and SE.
- Through extensive simulations, we evaluate the effectiveness of our framework by varying the transmission bandwidth.

The remainder of the manuscript is structured as follows. Section 2 contains a comprehensive assessment of related works. The network model is addressed in detail in Section 3, together with the solar energy model, path loss model, traffic model, and BS power model, among other things. Section 4 presents numerical findings as well as a thorough analysis. Finally, Section 5 concludes this study.

2 Related Works

Numerous surveys and reviews have previously examined the potential of future 5G C-RAN with hybrid supply to decrease energy consumption throughout the year. The following literature presents research conducted in this field. In [14], the authors proposed a novel model for C-RAN that incorporates an amalgamation of on-grid and renewable energy sources. In the context of 5G networks, the model accounts for the overall energy consumption of several network elements. Adiraju and Rao in [15] present a C-RAN network that dynamically distributes BBU resources to RRHs in accordance with the RRH's traffic loads. The network also minimizes the power consumption of the BBU by intelligently switching between active and inactive modes using the particle swarm optimization algorithm. Simulation outcomes show that the suggested network accomplishes significantly improved energy efficiency, with a 95% enhancement. Another study in [16], the authors proposed a hybrid C-RAN that integrates renewable energy and traditional grid power supply to create an energy-efficient 5G network. This combination reduces the effective grid power consumption and CO_2 emissions. Authors in [17] proposed an a mechanism that adjusts energy usage among base stations and allows for the hybrid power supply of additional subscribers using renewable energy sources. The authors also demonstrate how to maximize the usage of green energy during periods of high traffic, resulting in significant on-grid energy savings. Elhattab et al. in [18] focused on improving spectral efficiency and QoS without considering the issue of EE. The SE and throughput of the entire network will be increased by placing more RRHs in a single cell, but this could result in underutilized

RRHs and BBUs, which would increase energy consumption costs and decrease EE [19]. Consequently, it is believed that two competing objectives—maximizing throughput and decreasing the active RRHs are necessary to improve EE [20]. Additionally, very few studies consider the dynamics of the system within the scope of energy harvesting, while optimization often concentrates on a particular time period. In actuality, the time-varying data queues will impact the stability of the network because of the stochastic nature of the remote radio unit's data arrival. Because most prior work has neglected the static channel state, the operational scheme should be built with the assumption that the time-varying properties of the channel and the randomness of traffic arrivals would be taken into account [21–23]. On the other hand, Refs. [24–27] disregard the need for traffic load coordination, which could lead to an inadequate arrangement of renewable energy and traffic load. Furthermore, in order to minimize grid power consumption (GPC), authors in [28] proposed a combinatorial optimization technique to maximize system energy efficiency (EE). The strategy was shown to cut energy by almost 20% and boost EE by around 10% during collected energy scarcity among the BSs. However, this result disregards the existence of energy storage devices, and some of the energy may be squandered if it is not needed by any base station at a particular moment. All of these works do not address numerous concerns, though, and they need to be solved. In contrast to previous research, we propose a C-RAN network with hybrid power supply system with the goal of maximizing the use of solar energy. This approach is intended to enhance energy efficiency while simultaneously reducing reliance on conventional grid electricity through the implementation of energy cooperation and energy storage mechanisms. Comprehensive simulations are performed to assess the energy efficiency and spectral efficiency of the proposed model across diverse network scenarios.

While many existing hybrid C-RAN studies [14–28] focus on utilizing renewable energy sources or optimizing grid consumption, they largely neglect the role of energy storage. Our proposed C-RAN incorporates energy storage mechanisms, allowing the network to store surplus green energy during low-demand periods and utilize it when traffic demand peaks, thereby reducing reliance on the grid and improving energy self-sufficiency. Unlike previous works [24–27] that either do not coordinate traffic load or consider static scenarios, our design dynamically allocates energy to RRHs based on real-time traffic load and stochastic data arrivals. This ensures that green energy is used efficiently, while also maintaining network stability in time-varying conditions.

3 System Model

The suggested C-RAN is presented in this part along with a number of characteristics.

3.1 Network Model

As shown in Fig. 1, the configuration of a C-RAN powered by renewable energy source comprises a centralized BBU pool and a number of RRHs indicated by the set R = {1, 2, 3, . . ., m}. Moreover, the set K = {1, 2, 3, . . ., k} represents the number of active users, randomly distributed, that are served by the RRHs. Grid power and photovoltaic (PV) solar cells are employed to supply power to each Remote Radio Head (RRH). To ensure energy availability during periods when renewable energy sources are not accessible, each RRH is linked to an individual energy storage system, enabling energy storage for later use. Here, the downlink data transmission is taken into account. The BBU pool initially sends data across the wired fronthaul lines to the RRHs, and the RRHs subsequently provide data wirelessly to customers. The BBU pool can efficiently distribute data to multiple RRHs for data transfers by making use of the knowledge of RRHs' energy availability network topology.

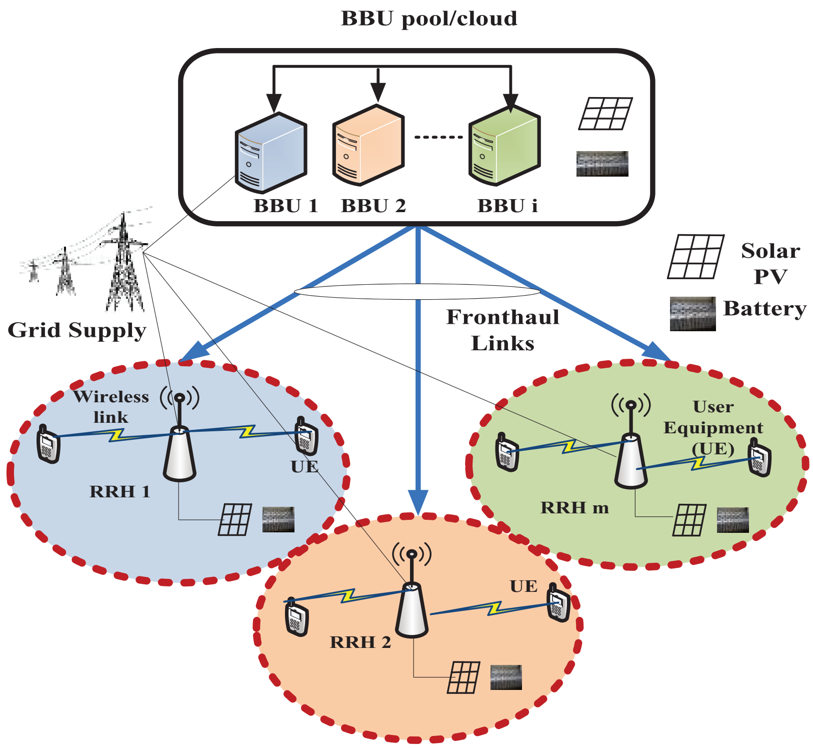

Figure 1: Layout of hybrid powered C-RAN

3.2 Solar Energy Model

Renewable energy sources are abundant, clean, and competitive energy sources. It offers the best chance of reducing on-grid electricity consumption. The diversity, quantity, and potential for usage of renewable energies make them unique in the world. In this case, solar photovoltaic (PV) technology has been taken into account because it is a crucial power generating technology on the path to green energy. The evaluation of solar power generation was previously conducted by means of the System Advisor Model (SAM) software. The below Fig. 2, generated using SAM [29], illustrates the characteristic periodic pattern of energy generation from a 1-kW solar panel (System Advisor Model (SAM), version 2025.4.16). The generation reaches its peak at 1:00 PM and is limited to the time frame between approximately 6 AM and 6 PM. The RRH must be managed by a grid-connected power source in order to avoid disruption when solar power is scarce due to the variability and unavailability of solar radiation.

3.3 Dynamics of Energy Sharing

The PV solar energy storing for each time slot under the proposed approach may be stated as,

$$\mu_i(t) = \alpha\mu_i(t-1) + g_i(t) - \partial_i(t) \tag{1}$$

where, $\mu_i(t)$ denotes the green energy storage for ith RRH at time slot t, $g_i(t)$ is the harvested solar energy for ith RRH at time slot t and $\partial_i(t)$ represents the required energy for ith RRH at time slot t. The factor α is limited between 0 and 1, indicates the proportion of stored energy that is still present after a unit of time. The on-grid energy usage and green utilization under various network situations of the ith RRH in different scenarios within the suggested network are outlined below.

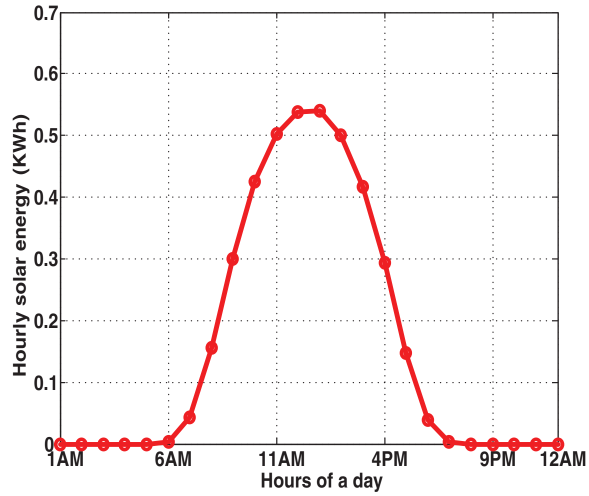

Figure 2: Average solar energy production per hour

Case I: If $\mu_i(t) \geq \partial_i(t)$, the ith RRH will be self-sufficient in terms of storage and will no longer rely on grid energy. After fulfilling the required demand, the remaining stored energy is denoted by $s_i(t)$, can be written as,

$$s_i(t) = \mu_i(t) - \partial_i(t) \tag{2}$$

Case II: The ith RRH will utilize energy sourced from the electrical grid if $\mu_i(t) < \partial_i(t)$. In this particular case, the on grid energy of ith RRH is denoted by ϵ_i (t), can be written as,

$$\epsilon_i(\mathrm{t}) = \partial_i(t) - s_i(\mathrm{t}) \tag{3}$$

3.4 Network Traffic Model

The network traffic has an impact on a mobile cellular network's power consumption. Therefore, it is crucial to have a clear comprehension of the mobile traffic load to analyze the power consumption of the network. Fig. 3 displays an approximate daily traffic load profile, which can be modeled as follows.

$$\lambda(\tau) = \frac{\rho(\tau,\sigma)}{\max[\rho(\tau,\sigma)]} \tag{4}$$

$$\rho(\tau,\sigma) = \frac{\sigma^{\tau}}{\tau!}e^{-\sigma} \tag{5}$$

where, $\lambda(\tau)$ represents the normalized traffic load at time slot τ, $\rho(\tau,\sigma)$ represents the Poisson probability of having τ arrivals (or traffic requests) when the average arrival rate is σ.

3.5 BSs Power Consumption Model

The power consumption model for the proposed C-RAN comprises three distinct components: (i) BBU pool power, denoted as P_{pp}, (ii) optical link power, denoted as P_{op}, and (iii) RRH power, denoted as P_{rp}. The total power (P_{total}) of the network is mathematically formulated as,

$$P_{total} = P_{pp} + P_{op} + P_{rp} \tag{6}$$

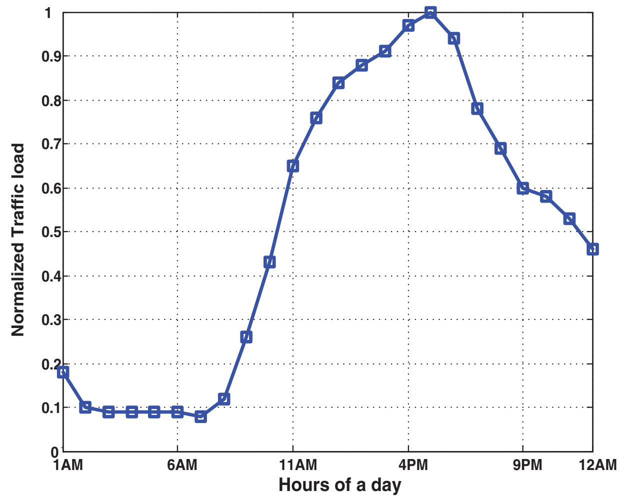

Figure 3: Daily traffic pattern of a residential area

3.5.1 BBU Pool Power

The computation of the BBU pool power (P_{pp}) incorporates the cooling power (P_{clp}) alongside the aggregate power consumption of the active BBUs, determined as follows.

$$P_{pp} = P_{clp} + \sum_{b=1}^{B} P_{BBU_b} + P_{CIP} \tag{7}$$

where, P_{CIP} denotes the common infrastructure power and P_{BBU_b} denotes the power consumption by the bth BBU can be presented as follows,

$$P_{BBU_b} = P_{st} + \Delta_P . P_{max}^{BBU_b} . \beta_{BBU_b} \tag{8}$$

Here, P_{st} is static power consumption, β_{BBU_b} denotes resource utilization factor of BBU_b. The active BBU within the BBU pool is accountable for serving the RRHs. The allocation of BBUs to RRHs can be adjusted dynamically according to the traffic conditions and the common infrastructure power refers to the power that integrates backhaul transmission power ($P_{backhaul}$), lighting power ($P_{lighting}$), and site monitoring power ($P_{monitoring}$). This is defined as [30],

$$\boldsymbol{P_{CIP} = P_{backhaul} + P_{lighting} + P_{monitoring}} \tag{9}$$

3.5.2 Fronthaul Power Consumption

It is expected that the fronthaul is a fiber connection. Each Remote Radio Head (RRH) is connected to the Base Station (BS) cloud via a single-mode optical fiber operating at a wavelength of 1310 nm. According to the findings presented in [30], the power required for a single 20 km connection is estimated to be approximately 5.39 dBW.

3.5.3 RRH Power Consumption

The power consumption of a RRH can be calculated by using the following equations [31].

$$P_{rp} = \begin{cases} T_{TRX}.\left(P_t + \Delta_p P_{tx}\left(\lambda - 1\right)\right), & 0 < \gamma \leq 1 \\ T_{TRX}.P_{sp}, & \gamma = 0 \end{cases} \tag{10}$$

where, $P_t = P_o + \Delta_p P_{tx}$ is the highest power used in an RRH. T_{TRX} represents the number of transceivers per RRH and P_{tx} is the instantaneous RF transmit power per transceiver. The parameter λ represents the traffic load, with $\lambda = 1$ corresponding to a fully loaded system and $\lambda = 0$ representing an idle system. P_{sp} denotes the sleep mode power consumption which is independent of traffic. It simply depends on the amount of power used by several BS characteristics, such as the baseband engine, RF transceiver, and power amplifier (PA). The parameters of the power consumption model for RRH utilized in this study are presented in Table 1 [32]. However, P_t can now be expressed as follow [33],

$$P_t = \frac{P_{bb} + P_{rf} + P_{pa}}{\left(1 - \partial_{dc}\right)\left(1 - \partial_{ms}\right)\left(1 - \partial_c\right)} \tag{11}$$

where the three loss components, denoted by ∂_{dc}, ∂_{ms} and ∂_c represent the losses resulting from DC conversion, main source, and active cooling, respectively. We set ∂_c to zero because RRH in C-RAN no longer requires a cooling system. The power consumption of the base band engine, radio frequency transceiver, and power amplifier are denoted by the symbols P_{bb}, P_{rf} and P_{pa}, respectively.

Table 1: Parameters for power consumption model [32,33]

SL	Parameter	Value
1	P_{tx}	20 W
2	T_{TRX}	6
3	Δ_P	2.8
4	P_o	84
5	P_{sp}	56 W
6	P'_{bb}	29.6 W
7	P'_{rf}	12.9 W
8	η_{pa}	31.1
9	∂_{dc}	7.5
10	∂_{ms}	9
11	∂_c	0

And the P_{bb} and P_{rf} can be define as [33],

$$P_{bb} = T_{TRX} \times \frac{B}{10\,\text{MHz}} \times P'_{bb} \tag{12}$$

$$P_{rf} = T_{TRX} \times \frac{B}{10\,\text{MHz}} \times P'_{rf} \tag{13}$$

where, B is the system bandwidth, 10 MHz is the normalization factor or reference bandwidth. P'_{bb} and P'_{rf} represents baseband processing power consumption and RF circuit power consumption per transceiver, respectively. Conversely, the P_{tx} and the power amplifier efficiency η_{pa} determine the P_{pa} as

$$P_{pa} = \frac{P_{tx}}{\eta_{pa}\left(1 - \partial_f\right)} \tag{14}$$

where probable feeder losses are represented by σ_f.

3.6 Path Loss Model

A specific channel model that has a shadow fading which is log-normally distributed is thought about in this paper. Path loss $\varphi(x)$ in decibels may be calculated using the following formula [16] if x represents the distance between the transmitter and receiver.

$$\varphi\ (x) = \varphi\ (x_o) + 10\ \beta \log_{10}\left(\frac{x}{x_o}\right) + X_\alpha \tag{15}$$

where, β denotes the exponent of path-loss, $\varphi(x_o)$ denotes the path-loss at a reference distance x_o and X_α denotes shadow fading. Consequently, the received power, denoted as $P_r^{i,k}$, in dBm, for a kth user equipment at a distance $d^{i,k}$ from a ith RRH can be expressed as follows,

$$P_r^{i,k} = P_t^{i,k} - \varphi\left(x\right) \tag{16}$$

where, $P_t^{i,k}$ is the transmitted power by the ith RRH in dBm. Subsequently, the received signal-to-interference-plus noise ratio $\gamma_{i,k}$ at the kth UE from the ith RRH can be expressed as [16],

$$\gamma_{i,k} = \frac{P_r^{i,k}}{I_{intra} + I_{inter} + P_{NP}} \tag{17}$$

where, I_{intra} and I_{inter} represent the intra-cell and inter-cell interference, respectively. P_{NP} denotes the noise power which can written as [16],

$$P_{NP} = -174 + 10\log_{10}\left(B\right) \tag{18}$$

where, B is the bandwidth in Hz.

3.7 Performance Metrics

3.7.1 Network Throughput

The total throughput may be determined by applying the following equation [34],

$$T_{total} = \sum_{k=1}^{K}\sum_{i=1}^{R} B\log_2\left(1 + \gamma_{i,k}\right) \tag{19}$$

Here, K represents the total number of users, and R signifies the total number of Remote Radio Heads (RRHs).

3.7.2 Energy Efficiency

The primary measure of performance for evaluating the proposed network is its energy efficiency. Energy efficiency is determined by the amount of power required to transmit a certain amount of data, with more efficiently resulting in less power usage. In this study, we evaluate the energy efficiency by calculating the ratio of the network's overall throughput to its net on-grid power consumption.

The EE, represented as η_{EE}, can be expressed as,

$$\eta_{EE} = \frac{T_{total}}{P_{grid}} \tag{20}$$

$$P_{grid} = \sum_{i=1}^{R} P_{total}(i,t) - \sum_{i=1}^{R} P_{solar}(i,t) \tag{21}$$

P_{grid} is the net grid energy in ith RRH, $P_{total}(i,t)$ is the is the power in ith RRH and $P_{solar}(i,t)$ is the harvested solar energy at time t.

3.7.3 Spectral Efficiency (SE)

In the proposed system, it is observed that each RRH has the potential to cause interference to other RRHs. Specifically, user $k \in$ K obtains information from the RRH $i \in$ R and obtains interference from other RRH $r \in$ R\{i}, where R represents the set of RRHs (R = {1, 2, 3, . . ., i}) and K represents the set of users (K = {1, 2, 3, . . ., k}). Consequently, the spectral efficiency (η_{SE}) can be mathematically expressed as follows,

$$\eta_{SE} = \frac{T_{total}}{B} \tag{22}$$

where, T_{total} and B are the total throughput and the bandwidth, respectively.

4 Result Analysis

4.1 Simulation Setup

A simulation layout with coverage area of 10 RRHs comprising of a maximum of 10 BBUs is taken into consideration. We considered that, up to 50 users per cell and the users are randomly distributed. The number of users in the cell follows the traffic profile as shown in Fig. 3. A single BBU can handle one or more RRHs, as long as the data is within its capacity. Using a Monte-Carlo method developed in MATLAB, the effectiveness of the suggested network is assessed. By doing 10,000 iterations and measuring the average outcomes, the network's performance is evaluated. It is assumed that the number of users connected to each RRH may change throughout the day. Furthermore, all users experience data transmissions from the RRHs at identical speeds. Equal transmit power is taken into account for all Resource Blocks (RB), and the same power profile parameters have been taken into account for all BS. The **standard proportional fair (PF) allocation mechanism is considered**, which is widely adopted in 5G network analysis. We also assumed that each user has access to a single resource block. The nearby allocating RRH is used to generate the inter-cell interference effect. The system's primary parameters are established in accordance with the LTE standard [19], and the entities are enumerated in Table 2.

Table 2: Parameters for simulation [34]

SL	Parameter	Value (Watt)
1	RRH radius	1000 m
2	Density of noise power	−174 dBm/Hz
3	Reference distance, x0	100 m
4	Exponent of path loss, β	3.574
5	Shadow fading, X_α	8 dB

4.2 Analysis

A comparison of the proposed system's throughput performance under various bandwidth conditions is shown in Fig. 4. It is evident that upper bandwidth results in improved throughput due to the allocation of a larger number of resource blocks (RBs). Furthermore, the disparity in throughput performance is more pronounced during periods of peak traffic demand, particularly in the evening. The depicted throughput curves align with the traffic distribution pattern depicted in Fig. 3. This correspondence can be attributed to the proportional variation in the total number of RBs associated with a cluster, which is influenced by the distribution of traffic load. In essence, the allocation of resource blocks at specific times of the day directly impacts the system's throughput performance. As observed, the throughput curves reach their peak during periods of high traffic volume in the early hours and *vice versa*.

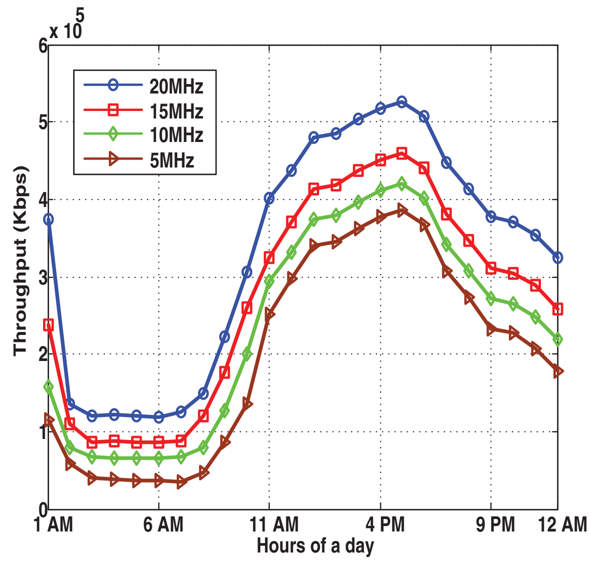

Figure 4: Throughput results with varying bandwidth during a 24-h period

Fig. 5 illustrates the comparison between the grid power consumption of the proposed network and the traditional network. The network is entirely powered until 6 a.m. by grid power when sunshine is not present. When incoming solar energy generation is available, on-grid consumption drops fast to zero. The data reveals that there is no grid energy usage during a substantial portion of the day, specifically from 8 a.m. to 7 p.m. Any surplus electricity generated during this time is stored in batteries after meeting the demands of the network. This observation suggests that the optimum utilization of green energy sources leads to a substantial reduction in grid consumption.

Fig. 6 depicts the principal performance metric of the system, specifically the energy efficiency as a function of bandwidth. The C-RAN's energy efficiency (EE) is determined by dividing its average throughput by the net on-grid power usage, expressed in bits per joule. Conversely, the net on-grid power consumption is determined by subtracting the power supplied from solar storage from the total power consumption. The total power consumption of C-RAN is sum of three distinct power: BBU pool power, RRH power and fronthaul power consumption, respectively. According to the definition, the RRH power consumption is proportional to the bandwidth. If the bandwidth increases, the RRH power consumption will increase. And if the RRH power consumption increases, the total power will increase. As a result grid power consumption will increase. The energy efficiency (EE) is inversely proportional to the power consumption of the grid. Because of the increasing grid power use at this time, the EE decreases as bandwidth increases. Compared to the C-RAN without a hybrid supply, the suggested C-RAN with a hybrid supply system had a 60% higher energy efficiency.

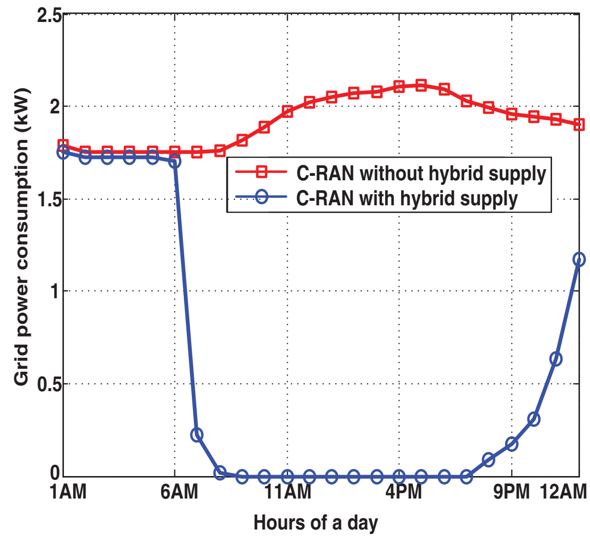

Figure 5: Comparison of grid power consumption over 24 h

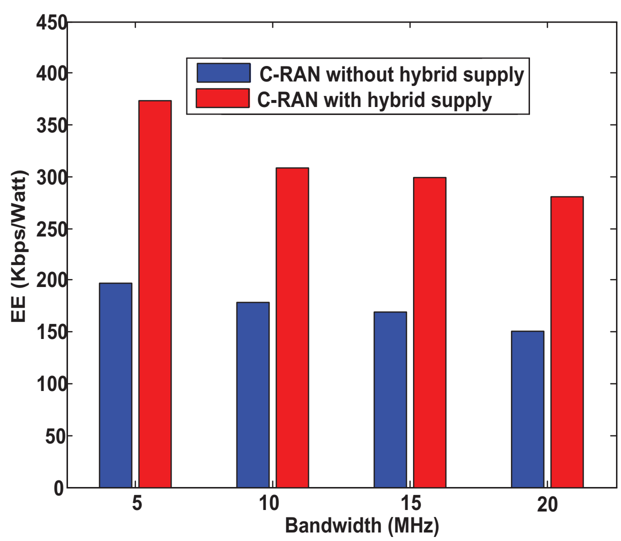

Figure 6: Performance of EE at various bandwidth

Another performance metric spectral efficiency is also inversely proportional to the bandwidth. Hence, if bandwidth increases, the spectral efficiency will decrease. Fig. 7 provide a thorough comparison of spectral efficiency at various bandwidths. With the higher system bandwidth a progressive decrease in SE has been seen. The proposed network achieves 46% more spectral efficiency than the conventional one.

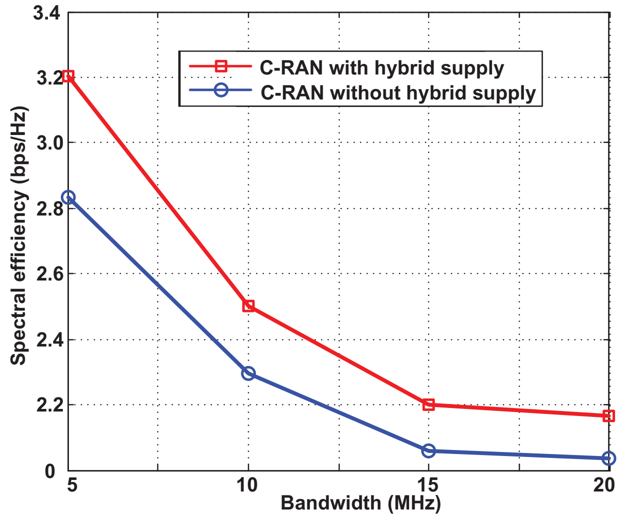

Figure 7: Comparison on spectral efficiency for different bandwidth

5 Conclusion

This research paper, hybrid energy powered C-RAN architecture is proposed with the aim of enhancing the EE and SE of networks. The proposed network utilizes solar PV with an energy storage device as the crucial energy source, while the grid supply serves as a subordinate source during periods of limited green power availability. The key aim of this paper is to improve EE and SE within the limitations of existing resources, while also maximizing the benefits of renewable energy harvesting. The execution of the system is evaluated through comprehensive Monte Carlo simulations, considering factors such as throughput, on grid power consumption, energy efficiency, and spectral efficiency, with varying system parameters such as bandwidth. The numerical results show that the bandwidth has the greatest influence on EE and spectral efficiency. Notably, the proposed system achieved 60% more EE and 46% more SE performance than the conventional scheme under the specific network settings. The weakness of the proposed scheme is we primarily examined the energy management of each individual RRH for simplicity. Future studies may investigate the coordinated sharing of surplus renewable energy among adjacent Remote Radio Heads (RRHs).

Moreover, as future extensions, the analysis could be broadened to include additional renewable energy sources such as wind or hybrid PV–wind systems, which would improve sustainability and resilience. The traffic model, currently based on a Poisson process, may also be refined by incorporating mobility-aware models and stochastic variations (e.g., bursty or correlated arrivals) to better reflect real user dynamics. In addition to technical performance, a techno-economic assessment that captures capital expenditure (CAPEX) and operational expenditure (OPEX) implications of renewable energy integration would provide a more comprehensive perspective on deployment feasibility. Finally, performance evaluation could be extended by benchmarking against optimization-based approaches, including heuristic methods and AI-driven resource allocation strategies, to demonstrate robustness and competitiveness relative to emerging intelligent solutions. Collectively, these directions would strengthen the practical relevance of the proposed framework and establish a broader foundation for future research.

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