ENERGY EFFICIENT HYBRID POWERED C-RAN ARCHITECTURES WITH DYNAMIC USER ASSOCIATION

by

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Rubina
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Mst. Rubina Aktar

DEDICATION

TO MY DEAREST PARENTS AND LOVING DAUGHTER

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First and Foremost praise is to Almighty Allah, the greatest of all, on whom eventually we depend for sustenance and guidance. I would like to thank Almighty for giving me opportunity, determination and strength to do my research. His continuous grace and mercy was with me throughout my life and ever more during the tenure of my research.

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ABSTRACT

During the last decade, there has been remarkable development in cellular networks market due to the ubiquitous availability of internet access in worldwide. The number of users and corresponding cellular traffic has escalated astronomically. To cope with the tremendous growth of data demand across the globe, cellular networks are deploying an increasing number of base stations (BSs) which leads to a voluminous inflation in energy consumption. Cloud radio access network (C-RAN) is new born mobile network architecture has the potential to reduce the power consumption compared to the traditional RAN network architecture. But, network densification in C-RAN places an extensive burden on the electric grid system. Concerns about global warming and increasing number of base stations (BSs) leading to rising energy consumption have prompted extensive research effort focusing on energy efficiency (EE) issue for cellular networks. The integration of renewable energy harvesting (REH) technology is expected to be pervasively utilized by telecom operators aiming to reduce carbon foot-prints and gird energy consumption. However, the dynamic nature of RE generation could lead to energy outage and service quality deterioration. Thus utilization of commercial grid supply in conjunction with RE generators is a more realistic option for sustainable network operations.

In this thesis we propose hybrid powered C-RAN architectures and required energy usage algorithms to enhance EE. Each RRH is equipped with renewable energy generators, such as solar panel along with a set of batteries as an energy storage device and also connected to grid energy supply. Afterward, dynamic user association policies integrated with the proposed model for further improving EE. The prime goal is to quantify the EE of various selection schemes namely distance-based, SINR-based, green energy-based and traffic aware-based under the proposed network model. An extensive simulation-based study is carried out for evaluating the EE performance of the proposed framework varying different system parameters. Numerical results validate the proposed network models compared to other counterparts.

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LIST OF ABBREVIATIONS

Symbol	**Meaning**
ARPU	Average Revenue Per User
AWGN	Additive White Gaussian Noise
BAP	Battery Assisted Passive
BB	Baseband
BBU	Base Band Units
BS	Base Stations
BW	Bandwidth
CAPEX	Capital Expenditure
CoMP	Coordinate Multipoint
CPRI	Common Public Radio Interface
C-RAN	Cloud Radio Access Network
DG	Diesel Generator
DPCs	Distributed Processing Centers
DU	Data Unit
EARTH	Energy Aware Radio and Network Technologies
EE	Energy Efficiency
EH	Energy Harvest
eICIC	Enhanced Inter-Cell Interference Coordination
eNB	Evolved Node B
GHG	Greenhouse Gas

GSM	Global System for Mobile Communications
HetNets	Heterogeneous network
ICI	Inter Cell Interference
ICT	Information and Communication Technology
IQ	In-Phase/Quadrature
IRC	Interference Rejection Combining
ITU	International Telecoms Union
LTE	Long-Term Evolution
LTE-A	Long-Term Evolution-Advanced
LTEUL	Long-Term Evolution Uplink
MAC	Medium Access Control
MIMO	Multiple-Input and Multiple-Output
MRC	Maximum Ratio Combining
NE	Network Elements
NFV	Network Functions Virtualization
NP	Non-Deterministic Polynomial-Time
OAM	Operations, Administration And Maintenance
OBSAI	Base Station Architecture Initiative
OFDMA	Orthogonal Frequency Division Multiple Access
OPEX	Operational Expenditure
ORI	Open Radio Equipment Interface
PV	Photovoltaic
QoS	Quality of Service

RAN	Radio Access Network
RB	Resource Blocks
RE	Renewable Energy
REH	Renewable Energy Harvesting
RF	Radio Frequency
RRH	Radio Remote Heads
RRM	Radio Resource Management
RRU	Remote Radio Unit
RU	Radio Units
SAM	System Advisory Model
SDH	Synchronous Digital Hierarchy
SDR	Software Defined Radio
SINR	Signal-to-Noise-Plus-Interference Ratio
TCO	Total Cost of Ownership
TD-SCDMA	Time Division Synchronous Code Division Multiple Access
TREND	Towards Real Energy-Efficient Network Design
UA	User Association
UE	User Equipment
UMTS	Universal Mobile Telecommunications Service
WCDMA	Wideband Code Division Multiple Access
WNC	Wireless Network Cloud
WiMAX	Worldwide Interoperability for Microwave Access

LIST OF SYMBOLS

Symbol	**Meaning**
Δ_p	Power Gradient
P_o	Static Consumption
P_{max}	Maximum Transmission Power
P_{sleep}	Sleep Mode Power
N_{TRX}	Number of Transceivers
γ	Traffic Load
$E_n(t)$	Harvested Energy
ε_{max}	Maximum Harvested Energy
$\Psi_n(t)$	Green Energy Storage
$\delta_n\,(t)$	Demand Energy
α	Percentage of Storage Energy
$S(t)$	Remaining Storage Energy
$g_n(t)$	Grid Consumption
PL	Path-Loss
δ	Path-Loss Exponent
X_σ	Zero-Mean Gaussian Random Variable
σ	Standard Deviation
N	Number of RRH

K	Number of User
P_t	Transmitted Power
P_r	Received Power
$I_{k,intra}$	Intra-Cell Interference
$I_{k,inter}$	Inter-Cell Interference
F_C	Carrier Frequency
d_o	Reference Distance
s_{max}	Maximum Storage Capacity
C_{total}	Total Throughput
μ	Storage Factor
η_{EE}	Energy Efficiency
P_{net}	On Grid Power Consumption

Chapter 1
Introduction

1.1 Introduction

A cellular network or mobile network is a communication network where the last link is wireless. The network is distributed over land areas called cells, each served by at least one fixed-location transceiver, but more normally three cell sites or base transceiver stations. These base stations provide the cell with the network coverage which can be used for transmission of voice, data, and other types of content. A cell typically uses a different set of frequencies from neighboring cells, to avoid interference and provide guaranteed service quality within each cell. Cellular network infrastructures and mobile devices proliferate and because of this an increasing number of users rely on cellular networks for their daily activities. Mobile networks are the major energy guzzlers of information and communication technologies infrastructures, and their contributions to global energy consumption are accelerating because of the ever-increasing traffic demand. This growing energy consumption not only escalates the operators' operational expenditure (OPEX) but also leads to a significant rise of their carbon footprints. Hence, greening of mobile networks is becoming a necessity to bolster social, environmental, and economic sustainability. This chapter describes the background and motivation for this research work describing the overview of the field and explaining the principle research problem. A brief summary of the contributions of this thesis also presented.

1.2 Background and present state of the problem

The recent rapid growth in the number of subscribers and applications leads to unprecedented rise of energy consumption in cellular networks. This has severe detrimental effect on both the economical and the environmental aspects [1]-[2]. Overall, the ICT sector currently contributes around 2% of the global carbon footprint, where cellular networks are the major stakeholders. In traditional cellular systems, base stations (BSs) in the radio access network (RAN) are the most energy hungry equipment amounting around 60% - 80% of the total consumption [3]-[6]. On the other hand, cloud RAN (C-RAN), a newborn mobile network architecture [7]-[8], is being considered as a strong contender for the future 5G cellular systems. In C-RAN, traditional BSs are decoupled into two parts - radio remote heads (RRHs) and base band units (BBUs), while the BBUs are clustered into a centralized cloud. C-RAN has several potential benefits including improved spectral efficiency, flexible interference management, lower power consumption, reduced latency and adaptability to non-uniform traffic [9]-[10]. However, expected densely deployed RRHs may also increase energy consumption of C-RANs [11]. Considering the potential savings of energy cost, mobile network operators are keen to deploy renewable energy (RE) sources, e.g., solar panel for improving network energy efficiency (EE) [12]-[14]. But, powering RANs by renewable sources only can severely degrade the network performance due to the strong tempo-spatial diversity in RE generation. Hence, investigations of EE performance of C-RAN with the joint use of hybrid supplies (a combination of RE with the conventional grid electricity) carry significant importance. Furthermore, designing techniques for hybrid-powered C-RAN systems for further enhancing EE is extremely critical.

1.3 Growth of global traffic and energy consumption in cellular networks

During the last decade, there has been tremendous growth in cellular networks market. With the introduction of Android and iPhone devices, use of ebook readers such as iPad and Kindle and the success of social networking giants such as Facebook, the demand for cellular data traffic and the number of subscribers has grown significantly in recent years. Figure 1.1 shows the growth of world‘s mobile traffic. Figure 1.2 shows how the numbers of users in cellular networks have increased. Hence, mobile operators find meeting these new demands in wireless cellular networks inevitable, while they have to keep their costs minimum. Such unprecedented growth in cellular industry has pushed the limits of energy consumption in wireless networks. There are currently more than 4 million base stations (BSs) serving mobile users, each consuming an average of 25MWh per year. Information and Communication Technology (ICT) already represents around 2% of

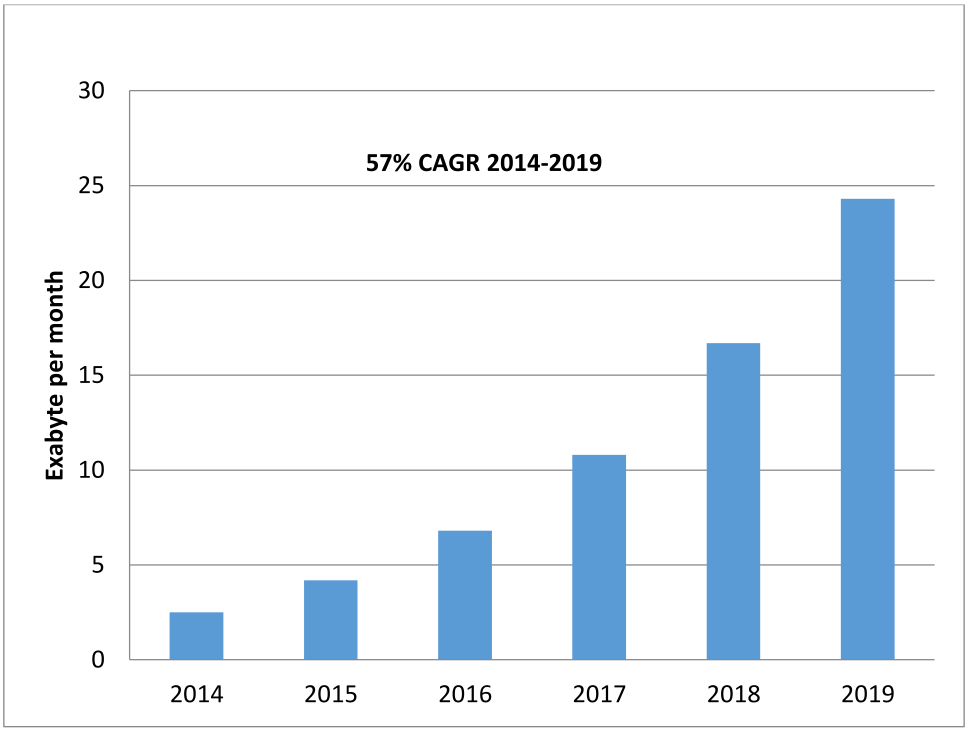

Figure 1.1: A forecast of mobile data traffic growth in coming year [1].

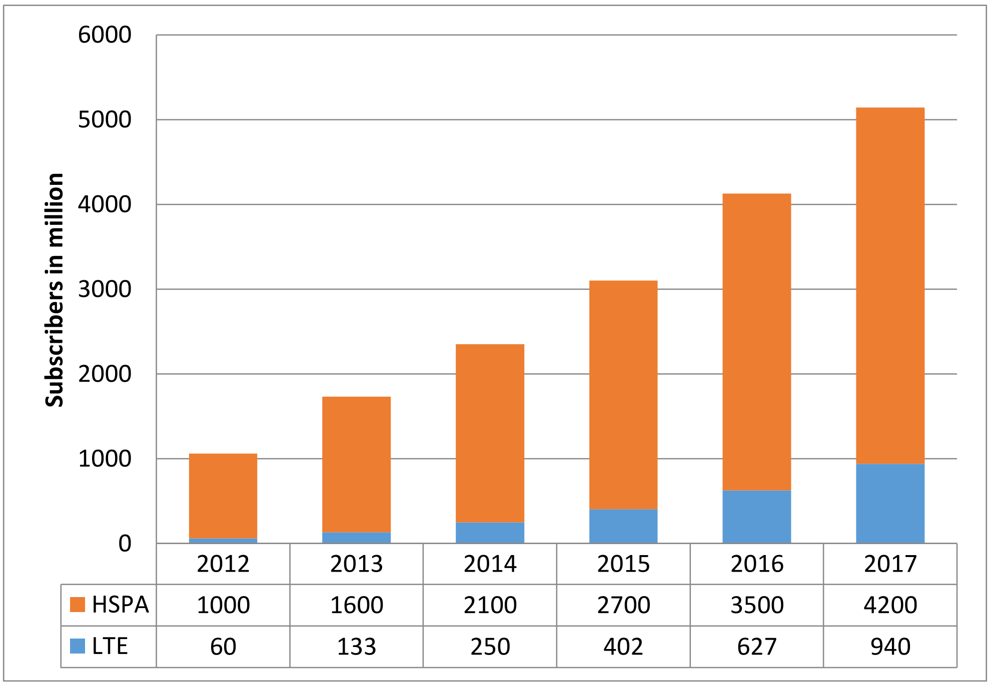

Figure 1.2: Subscriber growth for global HSPA and LTE subscriber [1].

total carbon emissions (of which mobile networks represent about 0.2%), and this is expected to increase every year. In addition to the environmental aspects, energy costs also represent a significant portion of network operators‘ overall expenditures

(OPEX). While the BSs connected to electrical grid may cost approximately 3000$ per year to operate, the off-grid BSs in remote areas generally run on diesel power generators and may cost ten times more. The rising energy costs and carbon footprint of operating cellular networks have led to an emerging trend of addressing energy efficiency amongst the network operators and regulatory bodies such as 3GPP and ITU [15] - [16]. This trend has stimulated the interest of researchers in an innovative new research area called ―green cellular networks". In this regard, the European Commission has recently started new projects within its seventh Framework Programme to address the energy efficiency of mobile communication systems, viz. ―Energy Aware Radio and NeTwork TecHnologies (EARTH)",―Towards Real Energy-efficient Network Design (TREND)" and ―Cognitive Radio and Cooperative strategies for Power saving in multi-standard wireless devices (C2POWER)" [17] - [19].

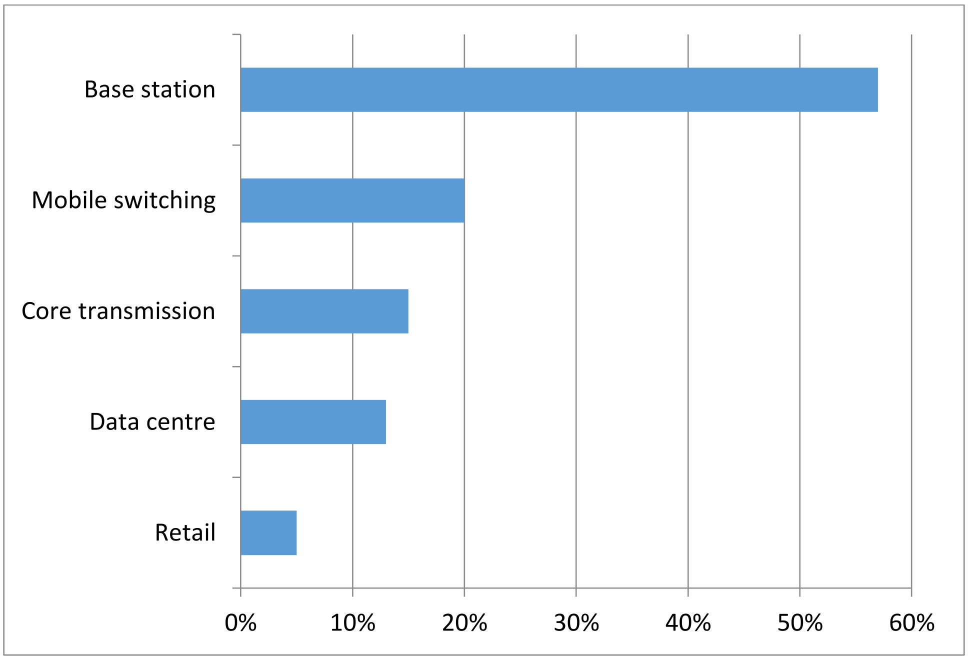

Figure 1.3: Power consumption of a typical wireless cellular network [2].

―Green radio" is a vast research discipline that needs to cover all the layers of the protocol stack and various system architectures and it is important to identify the fundamental trade-offs linked with energy efficiency and the overall performance [20]. Figures 1.3 and 1.4 shows a breakdown of power consumption in a typical cellular network and gives us an insight into the possible research avenues for reducing energy consumption in wireless communications.

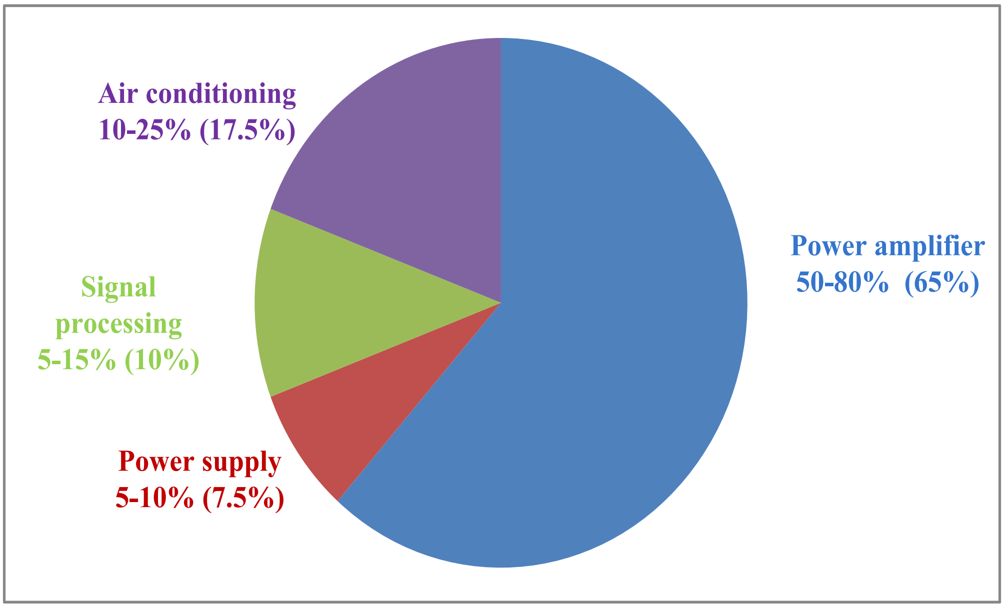

Figure 1.4: Power consumption distribution in radio base stations [2].

1.4 Energy efficiency in cellular network

Energy awareness in telecommunication networks is the perception and identification of all energy resources and characteristics gathered from all network elements (NE) in order to precede certain power adjustment and maximize networks energy efficiency (EE) and lifetime. Telecom sectors have been accused as the most energy-intensive consumer in ICT industry that is responsible for the amount of greenhouse gas (GHG) emissions and high operation cost. Energy efficiency in cellular networks is a growing concern for cellular operators to not only maintain profitability, but also to reduce the overall environment effects. This emerging trend of achieving energy in cellular network is motivating the standardization authorities and network operators to continuously explore future technologies in order to bring improvements in the entire networks infrastructure. Therefore, it has now become essential to include to, include energy efficiency as a major performance indictor in both the planning and the operation stages of cellular networks.

1.5 Literature review

Recently, cellular network has drawn deep attention among academia and mobile operator due to its ever-increasing energy demand in their infrastructures. In this regard, few researches have been conducted for energy-efficient wireless network with hybrid energy supplies [21]–[22]. A simple energy cooperation framework is proposed between two surrounded BSs with hybrid supplies addressing the EE metric [22]. Authors in [22], proposed an energy efficient algorithm that balances the energy consumption among BSs enabling more subscribers to be served with renewable energy sources under hybrid power supply. Authors also demonstrate the optimization of green energy utilization during the peak traffic hours and shows a significant amount of on-grid energy saving has been attained. To conserve the on-grid energy consumption, the hybrid energy-powered cellular networks have drawn increasing attentions recently [23]–[28]. Authors in [23] investigated user association and power control between two BSs to minimize the time-average on-grid energy consumption. Considering the lack of non-causal information of the energy harvesting EH process, the authors proposed a resource allocation algorithm which only requires instantaneous information of the channel fading and EH process. In [27], Sheng et al. investigated the energy sharing and load shifting among the BSs with energy harvesting capability. The authors formulate a NP-hard optimization problem to minimize the on-grid energy consumption. Authors in [28] developed a greedy algorithm to optimize the power control subject to network latency. In [26], Yang et al. investigated the tradeoff between the network throughput and on-grid energy consumption in a relay network, while considering the stochastic characteristics of renewable energy and mobile traffic. Authors in [29] proposed an energy optimization algorithm to minimize the on-grid consumption and thus enabling more users to be served using solar energy in heterogeneous wireless networks powered by hybrid supplies. But this article does not take into consideration the tempo-spatial variation of green energy generation and cellular traffic diversity. Authors in [30] proposed a simple energy-efficient hybrid model for green energy sharing among BSs via a resistive power line in consideration of traffic dynamics. Cell zooming is another method has the potential to balance the traffic load and reduce the energy consumption have proposed in [31]. However, there are many issues that these works do not tackle and remain to be addressed. To deploy renewable-powered BSs, it is important to understand the interaction/competition between the renewable energy supplier and the BS, especially considering the competition‘s impact on the QoS.

1.6 Motivation of the work

It is predicted that, increase global energy consumption in the future due to dramatic escalation of mobile traffic. Due to this exponential growth in the number of mobile users, the data traffic is increased incredibly leading to massive energy inflation and incur high OPEX. In traditional cellular architecture, BSs consumed about half of the total power in RAN infrastructure, while other half is used by other equipment‘s such as cooling device, RF unit, baseband signal processing unit etc. [32]. The ever growing energy consumption is pushing terrific pressure on the electricity grid supply and exerting detrimental impact to the atmosphere. This aptitude has drawn intensive attention for energy-efficient cellular networking and also has driven to address the EE.

C-RAN is a newborn mobile network architecture whose concept was first proposed in [39] has the potential to reduce the power consumption compared to the traditional RAN network architecture. Moreover, C-RAN can efficiently serve a large number of users, by implementing the knowledge of the network at the BBU pool. From the energy efficiency perspective, densely deployed RRHs may increase energy consumption of C-RANs, leading high OPEX and produce pollution intensive carbon footprints. Being inspired this issue, we are motivated to propose a renewable energy powered C-RAN for achieving an increased level of EE. Under the proposed network, all the network are powered by hybrid supplies combining traditional grid power and RE sources such as solar PV module with sufficient energy storage capacity. On the other hand, the C-RAN powered by only grid supply is considered as the conventional C-RAN. In the result section, we thoroughly investigate the proposed system performance using Monte-Carlo simulations and thereafter, we compare EE performance with the conventional C-RAN for further validation.

1.7 Objectives with specific aims and possible outcomes

The objectives of this thesis are:

1) To propose hybrid powered C-RAN architectures and required energy usage algorithms to enhance EE.
2) To propose various dynamic user association policies and integrate with the proposed architectures for further EE improvement.
3) To develop a simulation platform for evaluating the performance of the proposed C-RAN.
4) Finally, the performance of the proposed framework will be compared with that of the existing networks.

The possible outcome after the successful completion of the research work will support lower grid power consumption and higher EE. The simulation platform will be helpful to investigate and understand the effect of different network parameters on the performance of the proposed C-RAN system and thus can be used for energy efficient network design for C-RAN.

1.8 Organization of the thesis

This thesis consist of five chapters presenting the background material, reviews of the relevant literature, proposed hybrid model with thorough investigation and insightful analysis, summary of the key findings and potential future research opportunities.

Chapter 2 briefly describes the cloud radio access network with its different aspects.

Chapter 3 outlines the proposed network model along with network layout, network traffic model, power consumption model, energy storage dynamics, hybrid energy model, path loss model. Moreover, various dynamic user association policies integrate with the proposed architecture. Furthermore, the formation of performance metrics and details parameters of simulation setup has also been focused in this chapter.

Chapter 4 provides the simulation results on grid power consumption, DG power consumption, carbon footprint, surplus electricity, throughput, EE, EE gain and so on with insightful analysis.

Chapter 5 concludes the thesis by summarizing the major findings, as well as identifying several potential research opportunities for the improvement.

Chapter 2
Cloud Radio Access Network

2.1 Introduction

Today‘s mobile operators are facing a strong competition environment. The cost to build, operate and upgrade the Radio Access Network (RAN) is becoming more and more expensive while the revenue is not growing at the same rate. The mobile internet traffic is surging, while the ARPU is flat or even decreasing slowly, which impacts the ability to build out the networks and offer services in a timely fashion. To maintain profitability and growth, mobile operators must find solutions to reduce cost as well as to provide better services to the customers. On the other hand, the proliferation of mobile broadband internet also presents a unique opportunity for developing an evolved network architecture that will enable new applications and services, and become more energy efficient.

The RAN is the most important asset for mobile operators to provide high data rate, high quality, and 24x7 services to mobile users. Traditional RAN architecture has the following characteristics: first, each Base Station (BS) only connects to a fixed number of sector antennas that cover a small area and only handle transmission/reception signals in its coverage area; second, the system capacity is limited by interference, making it difficult to improve spectrum capacity; and last but not least, BSs are built on proprietary platforms as a vertical solution. These characteristics have resulted in many challenges. For example, the large number of BSs requires corresponding initial investment, site support, site rental and management support. Building more BS sites means increasing CAPEX and OPEX. Usually, BS‘s utilization rate is low because the average network load is usually far lower than that in peak load; while the BS‘s processing power can‘t be shared with other BSs. Isolated BSs prove costly and difficult to improve spectrum capacity. Lastly, a proprietary platform means mobile operators must manage multiple none-compatible platforms if service providers want to purchase systems from multiple vendors. Causing operators to have more complex and costly plan for network expansion and upgrading. To meet the fast increasing data services, mobile operators need to upgrade their network frequently and operate multiple-standard network, including GSM, WCDMA/TD-SCDMA and LTE. However, the proprietary platform means mobile operators lack the flexibility in network upgrade, or the ability to add services beyond simple upgrades.

In summary, traditional RAN will become far too expensive for mobile operators to keep competitive in the future mobile internet world. It lacks the efficiency to support sophisticated centralized interference management required by future heterogeneous networks, the flexibility to migrate services to network edge for innovative applications and the ability to generate new revenue from revenue from new services. Mobile operators are faced with the challenge of architecting radio network that enable flexibility. In the following sections, we will explore ways to address these challenges.

C-RAN is a novel mobile network architecture, which has the potential to answer the above mentioned challenges. The concept was first proposed in [39] and described in detail in [41]. In C-RAN, baseband processing is centralized and shared among sites in a virtualized BBU Pool. This means that it is well prepared to adapt to non-uniform traffic and utilizes resources, i.e., base stations, more efficiently. Due to that fact that fewer BBUs are needed in C-RAN compared to the traditional architecture, C-RAN also has the potential to decrease the cost of network operation, because power and energy consumption are reduced compared to the traditional RAN architecture. New BBUs can be added and upgraded easily, thereby improving scalability and easing network maintenance. A virtualized BBU Pool can be shared by different network operators, allowing them to rent Radio Access Network (RAN) as a cloud service. As BBUs from many sites are co-located in one pool, they can interact with lower delays – therefore mechanisms introduced for LTE-Advanced (LTE-A) to increase spectral efficiency and throughput, such as eICIC and CoMP are greatly facilitated. Methods for implementing load balancing between cells are also facilitated. Furthermore, network performance is improved, e.g., by reducing delay during intra-BBU Pool handover.

2.2 Background history

C-RAN architecture is targeted by mobile network operators, as envisioned by China Mobile Research Institute [41], IBM [39], Alcatel-Lucent [42], Huawei [43], ZTE [44], Nokia Siemens Networks [45], Intel [45] and Texas Instruments [47]. Moreover, C-RAN is seen as a typical realization of mobile network supporting soft and green technologies in fifth generation (5G) mobile networks. However, C-RAN is not the only candidate architecture that can answer the challenges faced by mobile network operators. Other solutions include small cells, being part of HetSNets and Massive MIMO. Small cells deployments are the main competitors for outdoor hot spot as well as indoor coverage scenarios. All-in-one small footprint solutions like Alcatel-Lucent‘s Light Radio [48] can host all base station functionalities in a several-liter box. They can be placed outdoors reducing cost of operation associated to cooling and cell site rental. However, they will be underutilized during low-activity periods and cannot employ collaborative functionalities as well as C-RAN. Moreover, they are more difficult to upgrade and repair than C-RAN. A brief comparison between C-RAN, Massive MIMO and HetSNets is outlined in [49]. Liu et al. in [50] prove that energy efficiency of large scale Small Cell Networks is higher compared with Massive MIMO. Furthermore, cost evaluation on different options needs to be performed in order for a mobile network operator to choose an optimal solution. Comparison of TCO including CAPEX and OPEX over 8 years of a traditional LTE macro base station, LTE C-RAN and LTE small cell shows that the total transport cost per Mbps is highest for macro cell deployments - 2200$, medium for C-RAN - 1800$ and 3 times smaller for small cell - 600$ [51]. Therefore the author concludes that C-RAN needs to achieve significant benefits to overcome such a high transportation cost. Collaborative techniques such as CoMP and eICIC can be implemented in small cells giving higher benefits in HetNet configuration instead of C-RAN. The author envisions that C-RAN might be considered for special cases like stadium coverage. However, C-RAN is attractive for operators that have free/cheap fiber resources available.

2.3 Base station architecture evolution

2.3.1 Traditional architecture

In the traditional architecture, radio and baseband processing functionality is integrated inside a base station. The antenna module is generally located in the proximity (few meters) of the radio module as shown in Figure 2.1 as coaxial cables employed to connect them exhibit high losses. This architecture was popular for 1G and 2G mobile networks deployment.

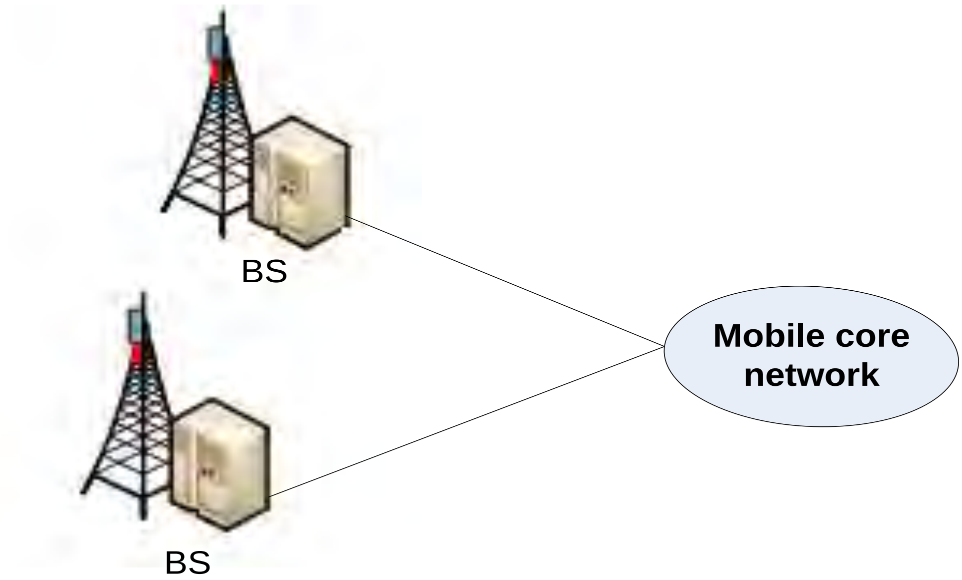

Figure 2.1: Traditional macro base station.

2.3.2 Base station with RRH

In a base station with RRH architecture, the base station is separated into a radio unit and a signal processing unit, as shown in Figure 2.2. The radio unit is called a RRH or Remote Radio Unit (RRU). RRH provides the interface to the fiber and performs digital processing, digital to analog conversion, analog to digital conversion, power amplification and filtering. The baseband signal processing part is called a BBU or Data Unit (DU). This architecture was introduced when 3G networks were being deployed and right now the majority of base stations use it. The distance between a RRH and a BBU can be extended up to 40 km, where the limitation is coming from processing and propagation delay. Optical fiber and microwave connections can be used. In this architecture, the BBU equipment can be placed in a more convenient, easily accessible place, enabling cost savings on site rental and maintenance compared to the traditional RAN architecture, where a BBU needs to be placed close

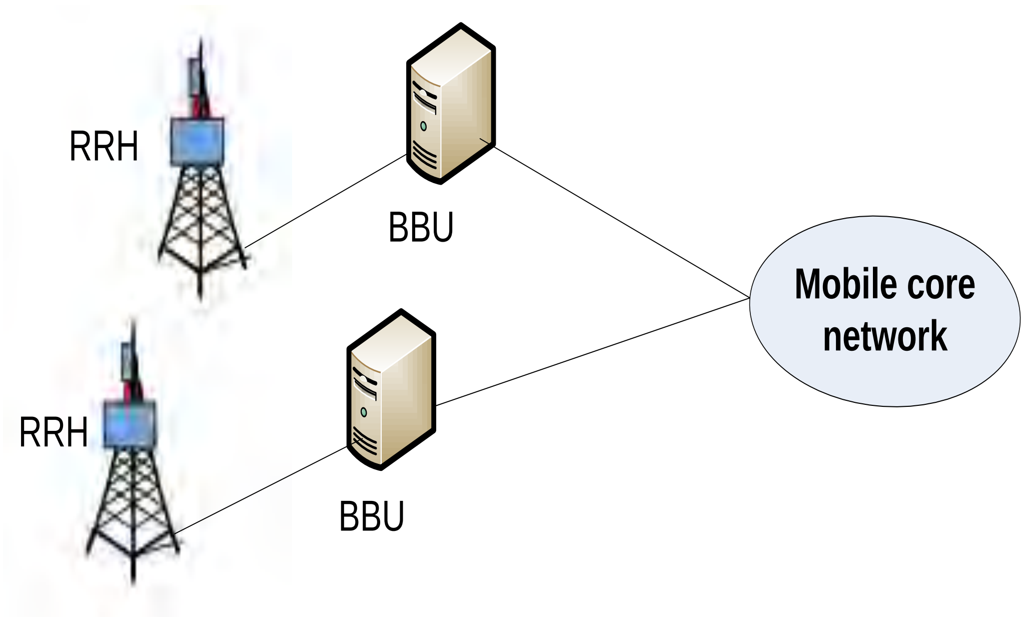

Figure 2.2: Base station with RRH.

to the antenna. RRHs can be placed up on poles or rooftops, leveraging efficient cooling and saving on air-conditioning in BBU housing. RRHs are statically assigned to BBUs similarly to the traditional RAN. One BBU can serve many RRHs. RRHs can be connected to each other in a so called daisy-chained architecture. An Ir interface is defined, which connects RRH and BBU.

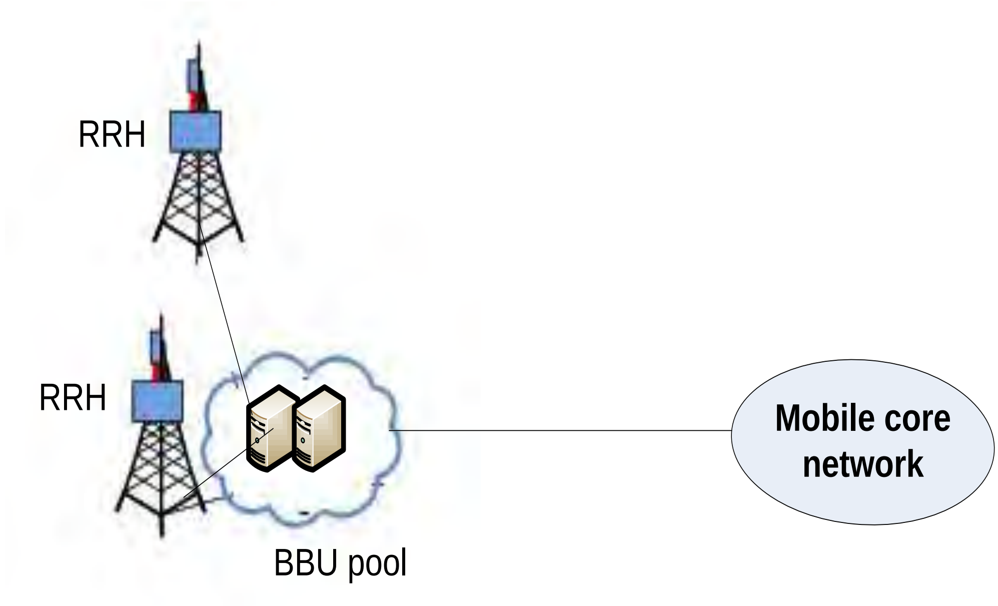

Figure 2.3: C-RAN

2.3.3 Cloud radio access network (C-RAN)

In C-RAN, in order to optimize BBU utilization between heavily and lightly loaded base stations, the BBUs are centralized into one entity that is called a BBU/DU Pool/Hotel. A BBU Pool is shared between cell sites and virtualized as shown in Figure 2.3. A BBU Pool is a virtualized cluster which can consist of general purpose processors to perform baseband (PHY/MAC) processing.

C-RAN is the term used now to describe this architecture, where the letter C can be interpreted as: Cloud, Centralized processing, Cooperative radio, Collaborative or Clean. Figure 2.3 shows an example of a C-RAN mobile LTE network. The fronthaul part of the network spans from the RRHs sites to the BBU Pool. The backhaul connects the BBU Pool with the mobile core network. At a remote site, RRHs are co-located with the antennas. RRHs are connected to the high performance processors in the BBU Pool through low latency, high bandwidth optical transport links. Digital baseband, i.e., IQ samples, are sent between a RRH and a BBU.

Table 2.1 Compares traditional base station, base station with RRH and base station in C-RAN architecture.

Architecture	Radio and base-band functionalities	Problem it addresses	Problems it Causes
Traditional base station	Co-located in one unit	-	High power consumption Resources are underutilized
Base station with RRH	Spitted between RRH and BBU. RRH is placed together with antenna at the remote site. BBU located within 20-40 km away.	Lower power consumption. More convenient placement of BBU	Resources are underutilized
C-RAN	Spitted into RRH	Even lower	Considerable

	and BBU. RRH is placed together with antenna at the remote site. BBUs from many sites are co-located in the pool within 20-40 km away.	power consumption. Lower number of BBUs needed cost reduction	transport resources between RRH and BBU

2.4 Architecture of C-RAN

It‘s a natural evolution of the distributed BTS, which is composed of the baseband Unit (BBU) and remote radio head (RRH). According to the different function splitting between BBU and RRH, there are two kinds of C-RAN solutions: one is called ‗full centralization‘, where baseband (i.e. layer 1) and the layer 2, layer 3 BTS functions are located in BBU; the other is called ‗partial centralization‘, where the RRH integrates not only the radio function but also the baseband function, while all other higher layer functions are still located in BBU. For the solution 2, although the BBU doesn‘t include the baseband function, it is still called BBU for the simplicity. The different function partition method is shown in Figure 2.4

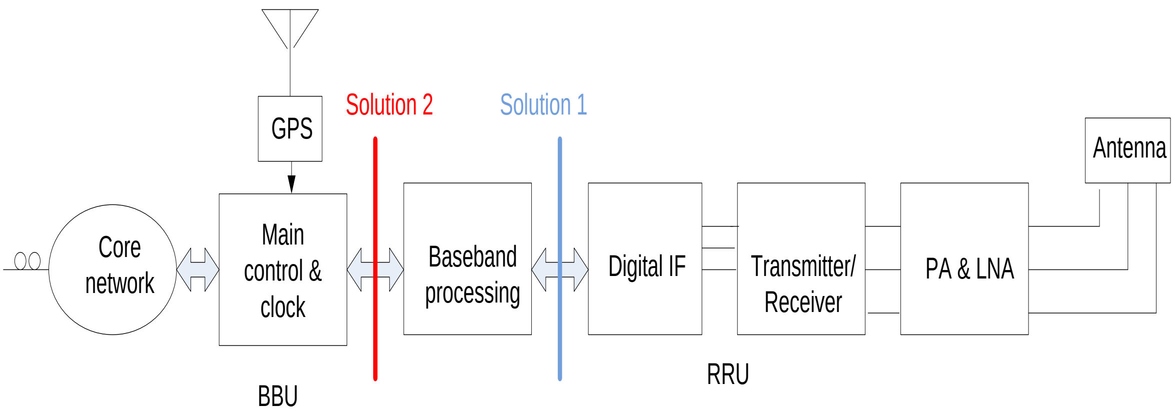

Figure 2.4: Different separation method of BTS functions [9].

Based on these two different function splitting methods, there are two C-RAN architectures. Both of them are composed of three main parts: first, the distributed radio units which can be referred to as Remote Radio Heads (RRHs) plus antennas which are located at the remote site; second, the high bandwidth low-latency optical transport network which connect the RRHs and BBU pool; and third, the BBU composed of high-performance programmable processors and real-time virtualization technology.

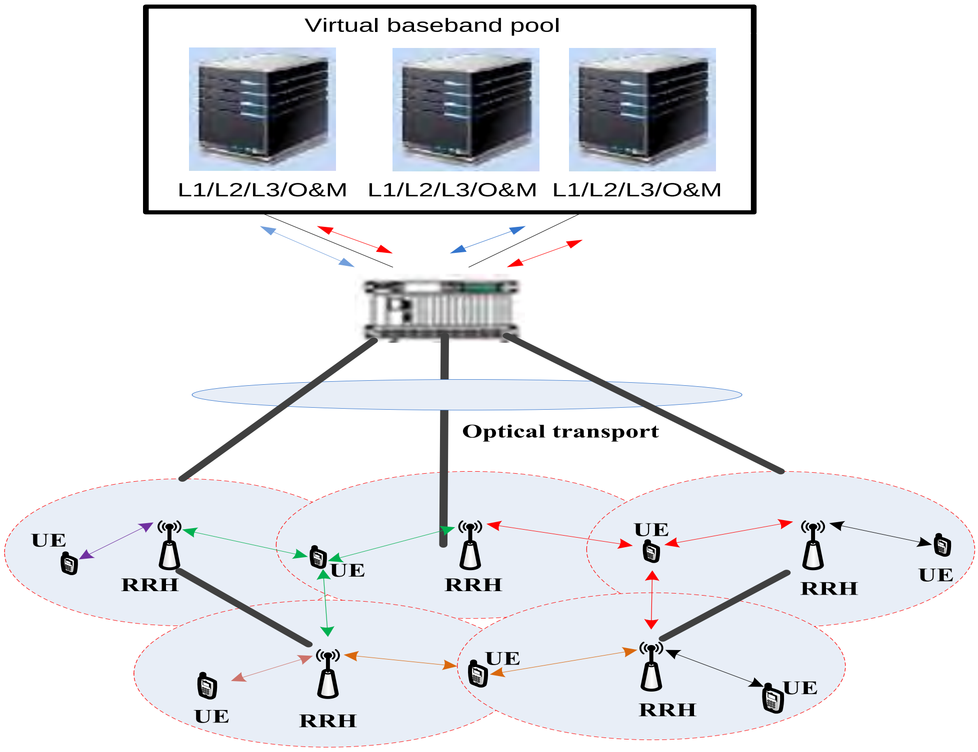

Figure 2.5: C-RAN Architecture 1: Fully centralized solution [8].

The ―fully centralized" C-RAN architecture, as shown in Figure 2.5, has the advantages of easy upgrading and network capacity expansion; it also has better capability for supporting multi-standard operation, maximum resource sharing, and it‘s more convenient towards support of multi-cell collaborative signal processing. Its major disadvantage is the high bandwidth requirement between the BBU and to carry the baseband I/Q signal. In the extreme case, a TD-LTE 8 antenna with 20MHz bandwidth will need a 10Gpbs transmission rate.

The ―partial centralized" C-RAN architecture, as shown in Figure 2.6, has the advantage of requiring much lower transmission bandwidth between BBU and RRH, by separating the baseband processing from BBU and integrating it into RRH. Compared with the ‗full centralized' one, the BBU-RRH connection only need to carry demodulated data, which is only 1/20~1/50 of the original baseband I/Q sample data. However, it also has its own shortcomings. Because the baseband processing is integrated into RRH, it has less flexibility in upgrading, and less convenience for multi-cell collaborative signal processing. With either one of these C-RAN architectures, mobile operators can quickly deploy and make upgrades to their network. The operator only needs to install new RRHs and connect them to the BBU pool to expand the network coverage or split the cell to improve capacity. If the network load grows, the operator only needs to upgrade the BBU pool's HW to accommodate the increased processing capacity.

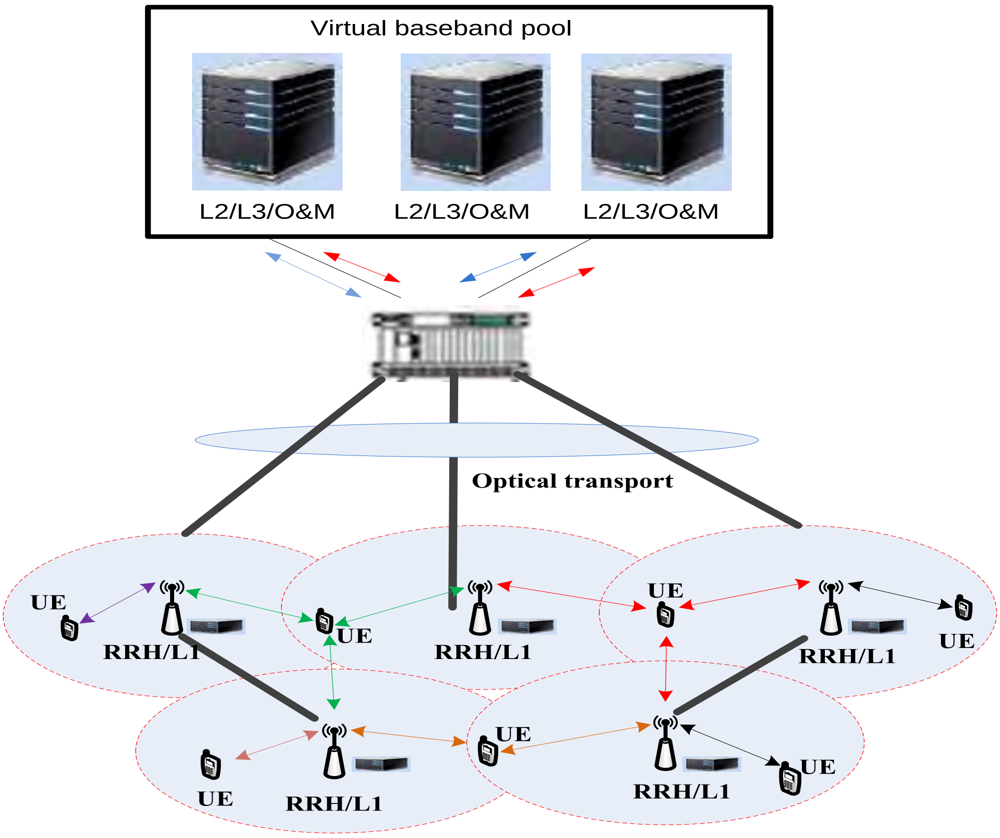

Figure 2.6: C-RAN Architecture 2: Partial centralized solution [8].

Moreover, the ‗fully centralized solution', in combination with open platform and general purpose processors, will provide an easy way to develop and deploy software defined radio (SDR) which enables upgrading of air interface standards by software only, and makes it easier to upgrade RAN and support multi-standard operation.

Different from traditional distributed BS architecture, C-RAN breaks up the static relationship between RRHs and BBUs. Each RRH does not belong to any specific physical BBU. The radio signals from /to a particular RRH can be processed by a virtual BS, which is part of the processing capacity allocated from the physical BBU pool by the real-time virtualization technology. The adoption of virtualization technology will maximize the flexibility in the C-RAN system.

2.5 Advantages of C-RAN

2.5.1 Adaptability to non-uniform traffic and scalability

Typically, during a day, users are moving between different areas, e.g., residential and office. Figure 2.7 illustrates how the network load varies throughout the day. Base stations are often dimensioned for busy hours, which mean that when users move from office to residential areas, the huge amount of processing power is wasted in the areas from which the users have moved. Peak traffic load can be even 10 times higher than during off-the-peak hours [41]. In each cell, daily traffic distribution varies, and the peaks of traffic occur at different hours. Since in C-RAN baseband processing of multiple cells is carried out in the centralized BBU pool, the overall utilization rate can be improved. The required baseband processing capacity of the pool is expected to be smaller than the sum of capacities of single base stations. The ratio of sum of single base stations capacity to the capacity required in the pool is called statistical multiplexing gain.

In [52] an analysis on statistical multiplexing gain is performed as a function of cell layout. The analysis shows that in the Tokyo metropolitan area, the number of BBUs can be reduced by 75% compared to the traditional RAN architecture.

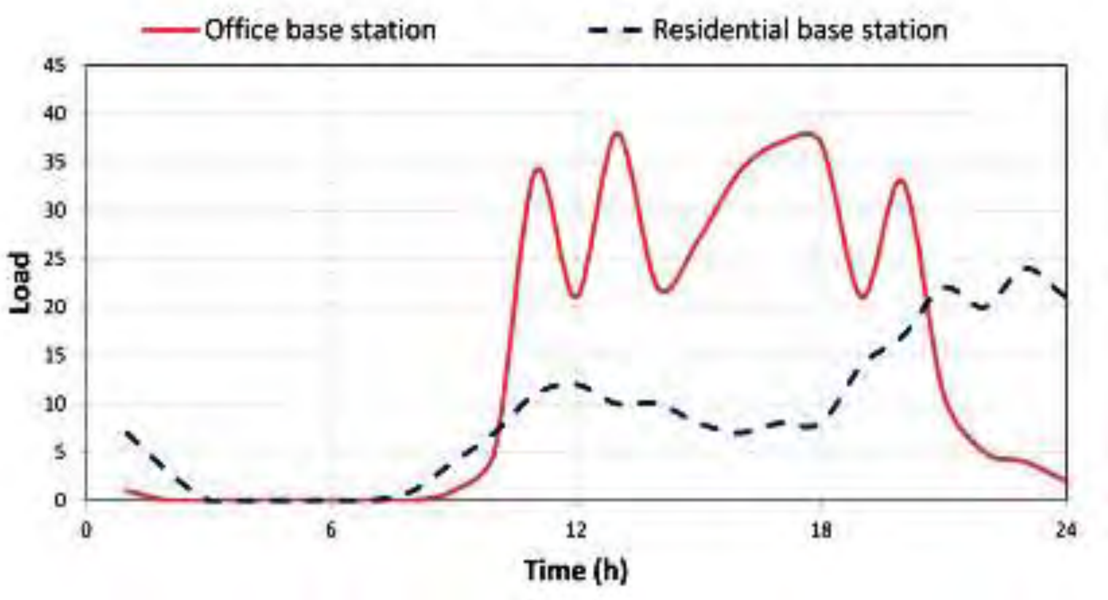

Figure 2.7: Daily load on base stations varies depending on base station location. Data source: [9]

Coverage upgrades simply require the connection of new RRHs to the already existing BBU Pool. To enhance network capacity, existing cells can then be split, or additional RRHs can be added to the BBU Pool, which increases network flexibility. Deployment of new cells is in general more easily accepted by local communities, as only a small device needs to be installed on site (RRH) and not a bulky base station. If the overall network capacity shall be increased, this can be easily achieved by upgrading the BBU Pool, either by adding more hardware or exchanging existing BBUs with more powerful ones.

As BBUs from a large area will be co-located in the same BBU Pool, load balancing features can be enabled with advanced algorithms on both the BBU side and the cells side. On the BBU side, BBUs already form one entity, therefore load balancing is a matter of assigning proper BBU resources within a pool. On the cells side, users can be switched between cells without constraints if the BBU Pool has capacity to support them, as capacity can be assigned dynamically from the pool.

2.5.2 Energy and cost savings coming from statistical multiplexing gain in BBU Pool and use of virtualization

By deploying C-RAN, energy, and as a consequence, cost savings, can be achieved. 80% of the CAPEX is spent on RAN [41], therefore it is important to work towards reducing it.

Energy in mobile network is spent on power amplifiers, supplying RRH and BBU with power and air conditioning. 41% of OPEX on a cell site is spent on electricity [1]. Employing C-RAN offers potential reduction of electricity cost, as the number of BBUs in a C-RAN is reduced compared to a traditional RAN. Moreover, in the lower traffic period, e.g., during the night, some BBUs in the pool can be switched off not affecting overall network coverage. Another important factor is the decrease of cooling resources, which takes 46% of cell site power consumption [41]. Due to the usage of RRHs air conditioning of radio module can be decreased as RRHs are naturally cooled by air hanging on masts or building walls. ZTE estimates that C-RAN enables 67%-80% power savings compared with traditional RAN architecture, depending on how many cells one BBU Pool covers, which stays in line with China Mobile research claiming 71% power savings [53].

Civil work on remote sites can be reduced by gathering equipment in a central room, what contributes to additional OPEX savings. In total, 15% CAPEX and 50% OPEX savings are envisioned comparing to RAN with RRH [54] or traditional RAN architecture. However, the cost of leasing the fiber connection to the site may increase CAPEX. IQ signal transported between RRHs and BBUs brings up a significant overhead. Consequently, the installation and operation of transport network causes considerable costs for operators.

Moreover, virtualization helps to reduce cost of network deployment and operation, at the same time enabling operators to offer additional services, not only serve as pipelines for carrying user date.

2.5.3 Increase of throughput

eICIC and CoMP are important features of LTE-A that aim at minimizing inter cell interference and utilizing interference paths constructively, respectively. If all the cells within a CoMP set are served by one BBU Pool, then a single entity doing signal processing enables tighter interaction between base stations. Therefore interference can be kept to lower level and consequently the throughput can be increased. It has been proven that combining clustering of cells with CoMP makes more efficient use of the radio bandwidth [55]. In [56] Huiyu et al. discuss the factors affecting the performance of CoMP with LTE-A in C-RAN uplink (UL), i.e., receiver algorithm, reference signals orthogonality and channel estimation, density and size of the network. In [41] authors present simulation results which compare spectrum efficiency of intra-cell and inter-cell JT to non-cooperative transmission. 13% and 20% increase in spectrum efficiency was observed, respectively. For a cell edge user, spectrum efficiency can increase by 75% and 119%, respectively.

2.5.4 Decrease of the delays

The time needed to perform handovers is reduced as it can be done inside the BBU Pool instead of between eNBs. In GSM, the total average handover interrupt time is lower and the signaling is reduced due to better synchronization of BBUs. In UMTS signaling, Iub transport bearer setup and transport bandwidth requirements are reduced, however, the performance improvement may not be sensed by the user. For LTE X2-based inter-eNB handover the delay and failure rate are decreased. Moreover, the general amount of signaling information sent to core mobile network is reduced, after being aggregated in the pool.

2.5.5 Ease in network upgrades and maintenance

C-RAN architecture with several co-located BBUs eases network maintenance: not only C-RAN capacity peaks and failure might be absorbed by BBU Pool automatic reconfiguration, therefore limiting the need for human intervention, but whenever hardware failures and upgrades are really required, human intervention is to be done only in a very few BBU pool locations. On the contrary for traditional RAN, the servicing may be required at as many cell sites as there are in the network. C-RAN with a virtualized BBU Pool gives a smooth way for introducing new standards, as hardware needs to be placed in few centralized locations. Therefore deploying it can be considered by operators as a part of their migration strategy. Co-locating BBUs in BBU Pool enables more frequent CPU updates than in case when BBUs are located in remote sites. It is therefore possible to benefit from the IT technology improvements in CPU technology, be it frequency clock (Moore‘s law) or energy efficiency (as currently seen in Intel mobile processor road map or ARM architecture). Software Defined Radio (SDR) is a well-known technology that facilitates implementation in software of such radio functions like modulation/demodulation, signal generation, coding and link-layer protocols. With such technology, C-RAN BBU Pool can support multi-standard multi-system radio communications configured in software. Upgrades to new frequencies and new standards can be done through software updates rather than hardware upgrades as it is often done today on non-compatible vertical solutions. Multi-mode base station is therefore expected to alleviate the cost of network development and Operations, Administration and Maintenance (OAM).

2.6 Challenges of C-RAN

Before the commercial deployment of C-RAN architectures a number of challenges need to be addressed: A. High bandwidth, strict latency and jitter as well as low cost transport network needs to be available, B. Techniques on BBU cooperation, interconnection and clustering need to be developed as well as C. Virtualization techniques for BBU Pool need to be proposed.

2.6.1 A need for high bandwidth, strict latency and jitter as well as low cost transport network

The C-RAN architecture brings a huge overhead on the optical links between RRH and BBU Pool. Comparing with backhaul requirements, the one on fronthaul are envisioned to be 50 times higher [34]. IQ data is sent between BBU and RRH as shown in Figure 2.2. The main contributors to the size of IQ data are: turbo coding (e.g., in UMTS and LTE 1:3 turbo codes is used resulting in three times overhead), chosen radio interface (e.g., CPRI) IQ sample width and oversampling of LTE signal. For example, 30.72 MHz sampling frequency is standardized for 20 MHz LTE, which is more than 20 MHz needed according to Nyquist - Shannon sampling theorem. Total bandwidth depends also on number of sectors and MIMO configuration. Equation 2.1 summarizes factors that influence IQ bandwidth. Scenario of 20 MHz LTE, 15+1 CPRI IQ Sample width, 10/8 line coding, 2x2 MIMO transmission resulting in 2.4576 Gbps bit rate in fronthal link is often treated as a baseline scenario. Consequently, for

20 MHz 4x4MIMO, 3 sector base station, the expected IQ throughput exceeds 10 Gbps. Examples on expected IQ bit rate between cell site and BBU in LTE-A, LTE, Time Division Synchronous Code Division Multiple Access (TD-SCDMA) and GSM

Table 2.2: IQ bit rates between a cell site and centralized BBU Pool [9]

Cell configuration	Bit rate
20 MHz LTE, 15+1 CPRI IQ Sample width, 10/8 line coding, 2x2 MIMO	2.5 Gbps
5x20 MHz LTE-A, 15 CPRI IQ Sample width, 2x2 MIMO, 3 sectors	13.8 Gbps
20 MHz LTE, 4x2 MIMO, 3 sectors	16.6 Gbps
TD-LTE, 3 sectors	30 Gbps
1.6 MHz TD-SCDMA, 8Tx/8Rx antennas, 4 times sampling rate	330 Mbps
TD-SCDMA S444, 3 sectors	6 Gbps
200 kHz GSM, 2Tx/2Rx antennas, 4x sampling rate	25.6 Mbps

networks can be found in Table 2.2. The centralized BBU Pool should support 10 - 1000 base station sites [1], therefore a vast amount of data needs to be carried towards it.

IQ Bandwidth = sampling Frequency • sample Width •2 • line Coding • M IM O • no Of Sectors. (2.1)

The transport network not only needs to support high bandwidth and be cost efficient, but also needs to support strict latency and jitter requirements. Below different constraints on delay and jitter are summarized:

i. The most advanced CoMP scheme, JT, requires 0.5µs timing accuracy in collaboration between base stations, which is the tightest constraint. However, it is easier to cope with synchronization challenges in C-RAN compared to traditional RAN due to the fact that BBUs are co-located in the BBU Pool.

ii. According to [41], regardless of the delay caused by the cable length, round trip delay of user data may not exceed 5 μs, measured with the accuracy of 16.276ns on each link or hop [33].

iii. The sub-frame processing delay on a link between RRHs and BBU should be kept below 1ms, in order to meet HARQ requirements. Due to the delay requirements of HARQ mechanism, generally maximum distance between RRH and BBU must not exceed 20-40 km [41].

2.6.2 BBU cooperation, interconnection and clustering

Cooperation between base stations is needed to support CoMP in terms of sharing the user data, scheduling at the base station and handling channel feedback information to deal with interference. Co-location of many BBUs requires special security and resilience mechanisms. Solutions enabling connection of BBUs shall be reliable, support high bandwidth and low latency, low cost with a flexible topology interconnecting RRHs. Thus, C-RAN must provide a reliability that is better or comparable to traditional optical networks like Synchronous Digital Hierarchy (SDH), which achieved high reliability due to their ring topology. Mechanisms like fiber ring network protection can be used. Cells should be optimally clustered to be assigned to one BBU Pool, in order to achieve statistical multiplexing gain, facilitate CoMP, but also to prevent the BBU Pool and the transport network from overloading. One BBU Pool should support cells from different areas such as office, residential or commercial. After analyzing interferences a beneficial assignment of cells to one BBU Pool can be chosen.

To achieve optimal energy savings of the C-RAN, base stations need to be chosen in a way that will optimize the number of active RRHs/BBU units within the BBU Pool. Proper RRH aggregation and assignment to one BBU Pool can also facilitate CoMP.

To achieve optimal throughput on the cell edges cooperative transmission/reception schemes are needed to deal with large Inter Cell Interference (ICI), improving spectrum efficiency. The resource sharing algorithms have been developed by the research community. They need to be combined with an algorithm clustering the cells to reduce scheduling complexity. Therefore, the well-designed scheduler in C-RAN also has an impact on the spectrum efficiency.

2.6.3 Virtualization technique

A virtualization technique needs to be proposed to distribute or group processing between virtual base station entities and sharing of resources among multiple operators. Any processing algorithm should be expected to work real time - dynamic processing capacity allocation is necessary to deal with a dynamically changing cell load. Virtualization and cloud computing techniques for IT applications are well defined and developed. However, C-RAN application poses different requirements on cloud infrastructure than cloud computing. Table 2.3 compares cloud computing and C-RAN requirements on cloud infrastructure.

Table 2.3: Requirements for cloud computing and C-RAN applications [54]

	IT - Cloud computing	**Telecom - Cloud RAN**
Client/base station data rate	Mbps range, bursty, low activity	Gbps range, constant stream
Latency and Jitter	Tens of ms	< 0.5 ms, jitter in ns range
Life time of in-Formation	Long (content data)	Extremely short (data symbols and received samples)
Allowed recovery time	s (second) range (some-times hours)	ms (milliseconds) range to avoid network outage
Number of clients per centralized location	Thousands, even millions	Tens, maybe hundreds

2.7 Chapter Summary

With the arrival of the mobile Internet era, today‘s RAN architecture is facing more and more challenges that the mobile operators need to solve: mobile data flow increase drastically caused by the popularization of smart terminals, very hard to improve spectrum efficiency, lack of flexibility to multi-standard, dynamic network load because of ―tides effect" and expensive to provide ever increasing internet service to end users. Mobile operators must consider the evolution of the RAN to high efficient and lost cost architecture.

C-RAN is a promising solution to the challenges mentioned above. By using new technologies, we can change the network construction and deployment ways, fundamentally change the cost structure of mobile operators, and provide more flexible and efficient services to end users. With the distributed RRH and centralized BBU architecture, advanced multipoint transmission/reception technology, SDR with multi-standard support, virtualization technology on general purpose processor, more efficient way of dealing with the tides effect and service on the edge of the RAN, C-RAN will be able to provide today‘s mobile operator with a competitive infrastructure to keep profitable growth in the dynamic market environment.

Chapter 3

The Proposed Model and Performance Metrics

3.1 Introduction

This chapter presents the proposed network layout and other key features with mathematical model in the context of next-generation mobile networks. Green energy model, energy storage principle, RRH power consumption model and different UA policies are also presented. Moreover, overviews of performance metrics are also discussed in this section.

3.2 System model

We consider a hybrid powered C-RAN architecture consisting of BBU pool and radio units (RUs). The RUs consist of N numbers of RRH that are jointly support K numbers of users. Let, R = {R_1, R_2, R_3.......,N} and K = {K_1, K_2, K_3……,K} be the set of RRHs and randomly located active users, respectively. All the RRHs are connected to BBU pool i.e., the central controller; through the high bandwidth wired front-haul links. Based on the network topology and energy availability at RRHs, the central controller schedules and distributes the data properly to various RRHs. The BBU pool and all RRHs are powered by both the grid power/DG and RE source. Each RRH is also connected with its own energy storage device such as battery bank to store surplus electricity for future use. The grid power is supplied to the network entities through energy router. Here, the main functions of energy router include the interconnection of energy unit, energy distribution, the demand management of the load side. However, RRH switched on to grid power supply/DG in the absence of storage energy in order to ensure reliability as well as zero outage. A segment of proposed network model shown in Figure 3.2 and Figure 3.3.

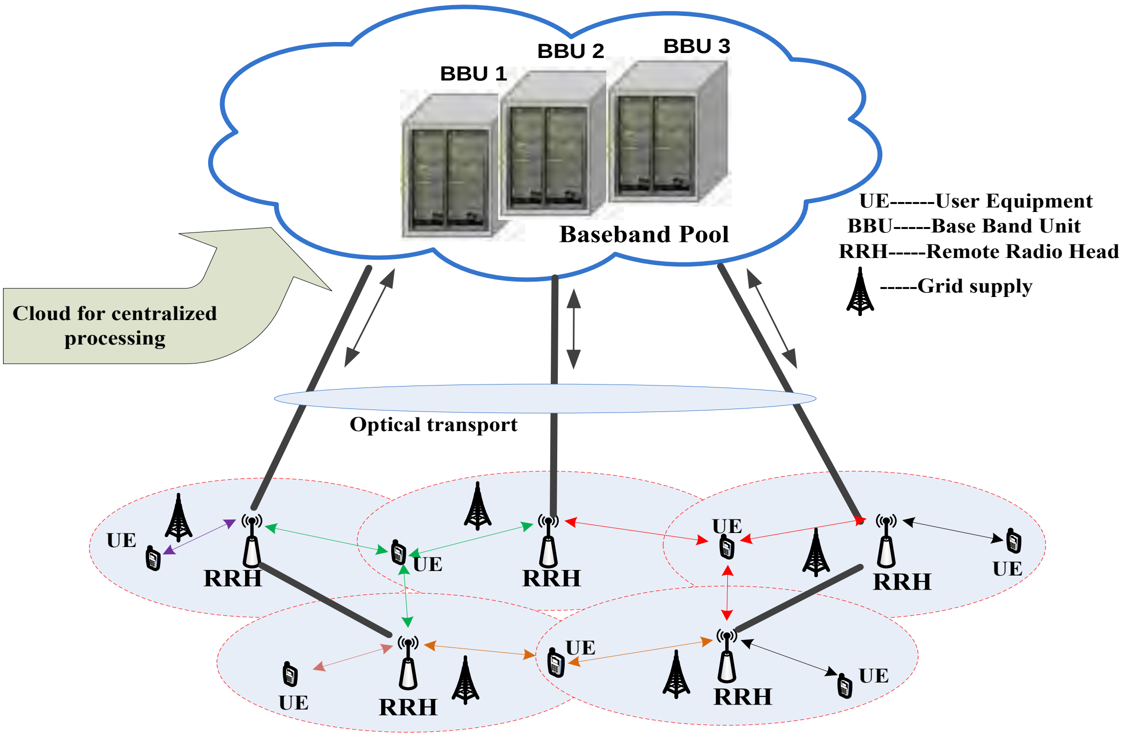

Figure 3.1: Conventional C-RAN.

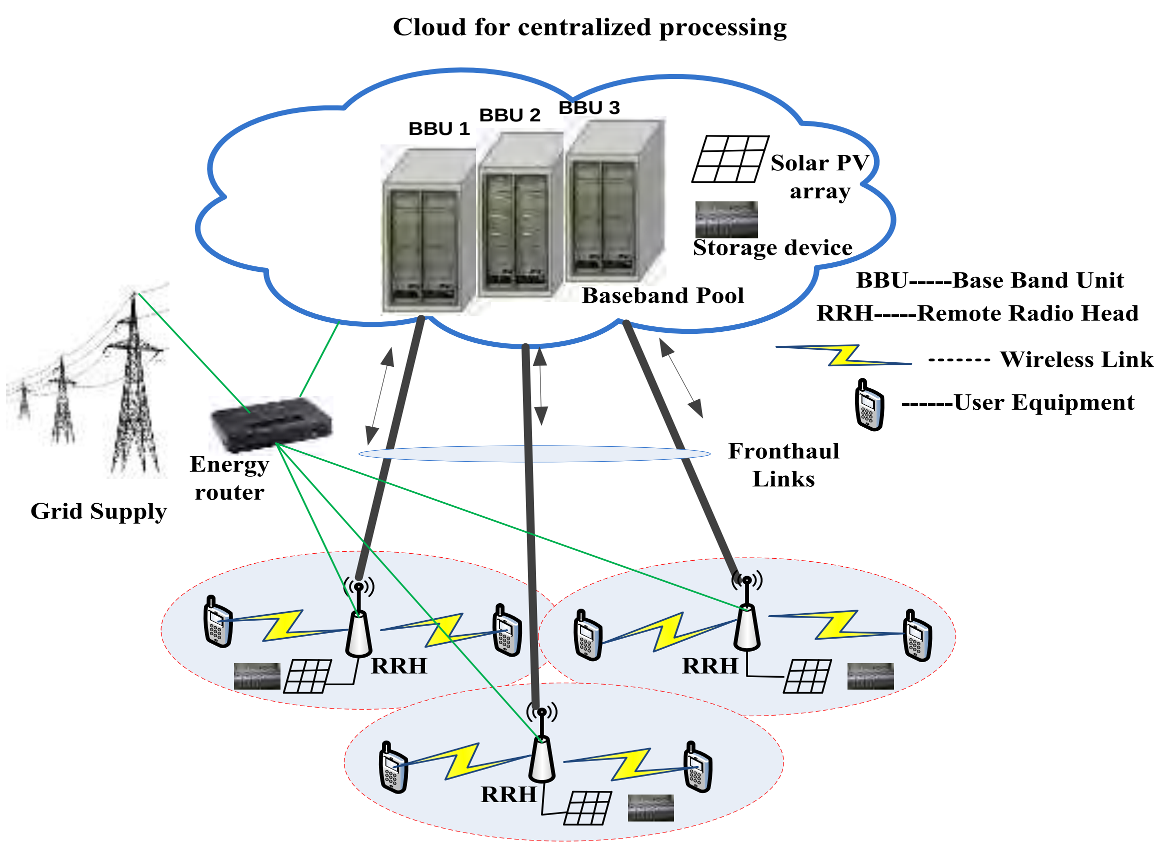

Figure 3.2: The proposed hybrid network model with grid supply.

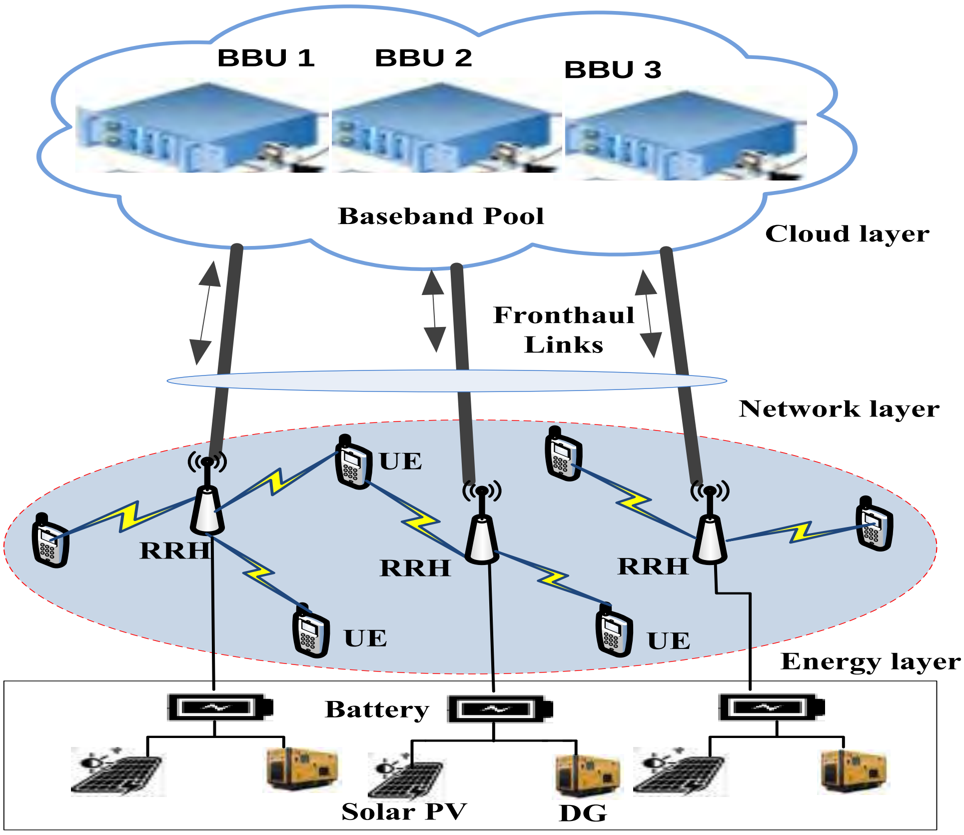

Figure 3.3: Proposed hybrid network model with diesel generator.

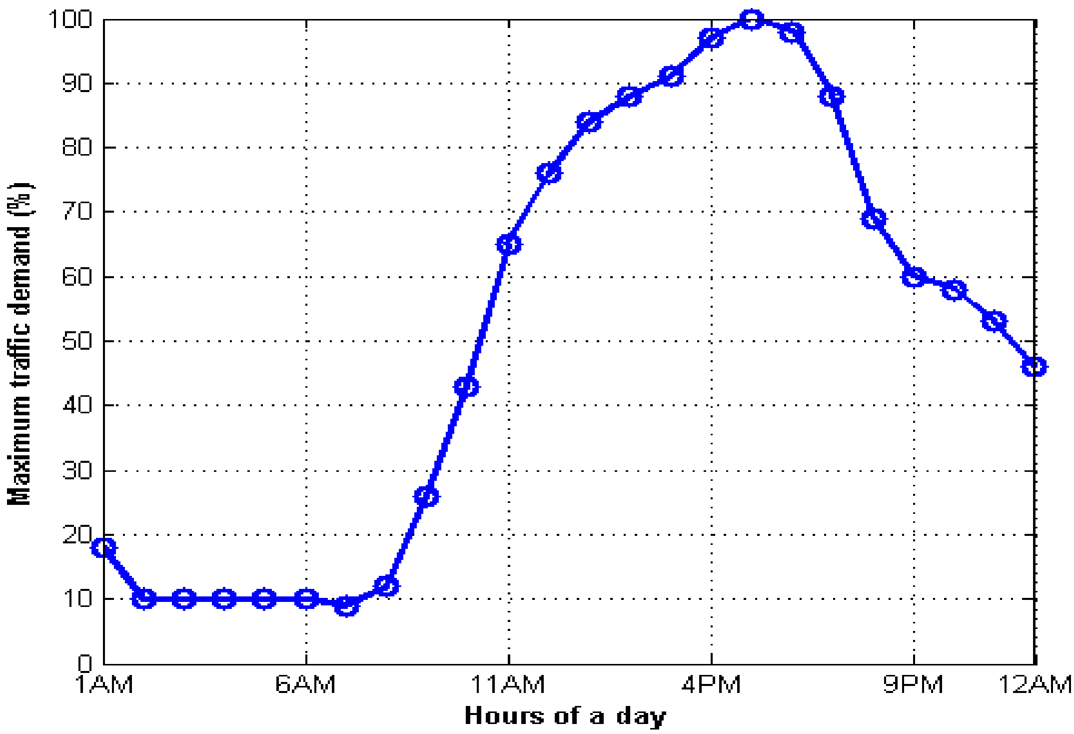

Figure 3.4: Daily traffic profile of a residential area.

3.3 Network traffic model

It is worth mentioning that the power consumption depends on the traffic load and that the mobile traffic distribution exhibits both temporal and spatial diversity [57]. The total number of mobile users in the system varies at different time slots— the temporal diversity of the mobile traffic. Also, the number of users on individual BSs are different—the spatial diversity of mobile traffic. Figure 3.4 shows the typical daily traffic intensity under a cellular network. Assuming all the mobile users are randomly distributed in the area and the RRHs transmit data to all the users with the same data rate.

3.4 RRH power consumption model

The total supply power of a RRH can be approximated as an affine function of transmission power [58]. In other words, it can be expressed as a sum of load dependent share (dynamic consumption) which increases linearly by a power gradient Δ_p and load independent (static consumption) share (P_o). According to Figure 3.5, when BS operating at transmission power (P_{max}), the supply power consumption is reached at maximum (P_1). In contrary, RRH may enter at sleep mode (P_{sleep}) when power consumption is extremely low. Here, we take a power consumption model of RRH, in which the total power consumption in a RRH is a function of traffic distribution.

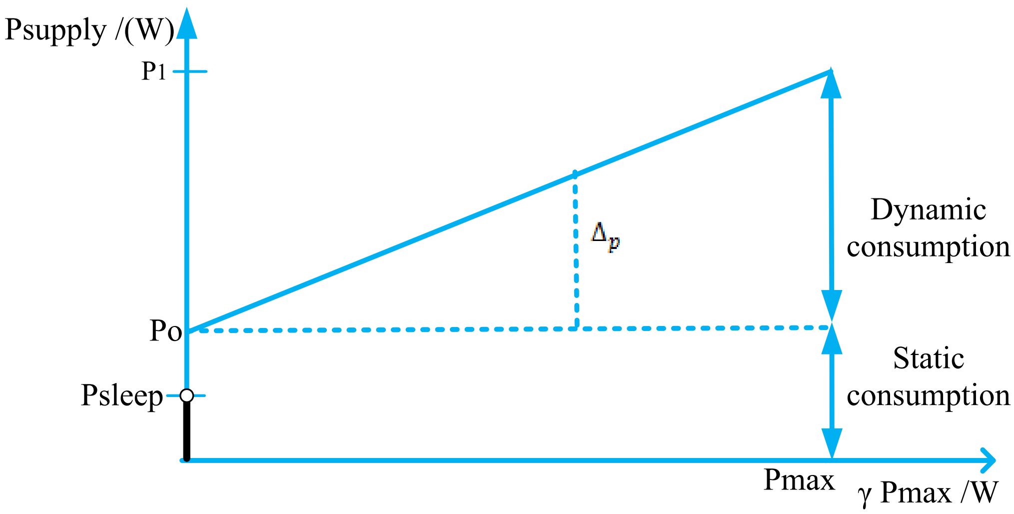

Figure 3.5: Load-dependent power model [58].

$$P_c = \begin{cases} N_{TRX}.\left(P_1 + \Delta_p P_{max} (\gamma - 1)\right), & 0 < \gamma \leq 1 \\ N_{TRX}.P_{sleep}, & \gamma = 0 \end{cases}$$

(3.1)

where N_{TRX} is the number of transceivers per RRH, $P_1 = P_o + \Delta_p P_{max}$ is the maximum power consumption in a RRH. The parameter γ is the traffic load, where γ = 1 indicates that a fully loaded system, e.g. RRH transmitting at full power and at full bandwidth, and γ = 0 indicates an idle system. The idle mode power consumption does not depend on traffic. It depends on only power consumption of different parameters of BSs like as power amplifier (PA), radio frequency (RF) transceiver, baseband (BB) engine. Now, P_1 can be expressed as below [58],

$$P_1 = \frac{P_{BB} + P_{RF} + P_{PA}}{(1-\partial_{DC})(1-\partial_{MS})(1-\partial_{cool})} \tag{3.2}$$

where ∂_{DC}, ∂_{MS} and ∂_{cool} are the three loss factor represents the losses incurred by DC-DC conversion, main supply and active cooling respectively. In C-RAN, as there is no longer require any cooling arrangement for RRH, hence we set ∂_{cool} to a zero value. P_{BB} , P_{RF} and P_{PA} are the power consumption of BB engine, RF transceiver and PA respectively. However, both the power consumption P_{BB} and P_{RF} scales linearly with the number of transceiver N_{TRX} and bandwidth BW. For some basic consumptions, P'_{BB} and P'_{RF} , we thus define;

$$P_{BB} = N_{TRX} \times \frac{BW}{10MHz} \times P'_{BB} \tag{3.3}$$

and $$P_{RF} = N_{TRX} \times \frac{BW}{10MHz} \times P'_{RF} \tag{3.4}$$

On the other hand, The PA power consumption P_{PA} depends on the maximum transmission power per antenna and the PA efficiency η_{PA} ,

$$P_{PA} = \frac{P_{TX}}{\eta_{PA}\,(1-\partial_{feed})} \tag{3.5}$$

where σ_{feed} is the possible feeder losses. RRH power consumption model parameters are summarized in Table 3.1 and Table 3.2.

Table 3.1: Power consumption breakdown

Parameters	**Value**
Feeder loss, ρ_{feed}[dB]	0
PA efficiency, η_{PA} (%)	31.1
BB power, P'_{BB} [W]	29.6
RF Transceiver power, P'_{RF} [W]	12.9
PA power, P'_{AF}[W]	64.4
DC-DC, ρ_{DC} (%)	7.5
Cooling, ρ_{cool} (%)	0
Main supply, ρ_{MS} (%)	9

3.5 Hybrid energy model

Renewable energy generation is most promising approach for minimizing on grid power consumption and also reducing greenhouse gasses. Here, we consider solar PV as the green energy generators at each RRH. Solar energy generation is depends on some factors, such as temperature, solar light intensity, panel materials, and the geographic location of the solar panels. Figure 3.6 shows the average hourly solar energy generation for full year in Dhaka city using System Advisory Model (SAM) software.

Table 3.2: Power consumption model parameter

Antenna pattern	N_{TRX}	P_{TX}**(Watt)**	P_0**(Watt)**	Δ_p	P_{sleep}
Omnidirectional	1	20	84	2.8	56.0
	1	40			
Tri-sector 2/2/2	6	20			
	6	40			

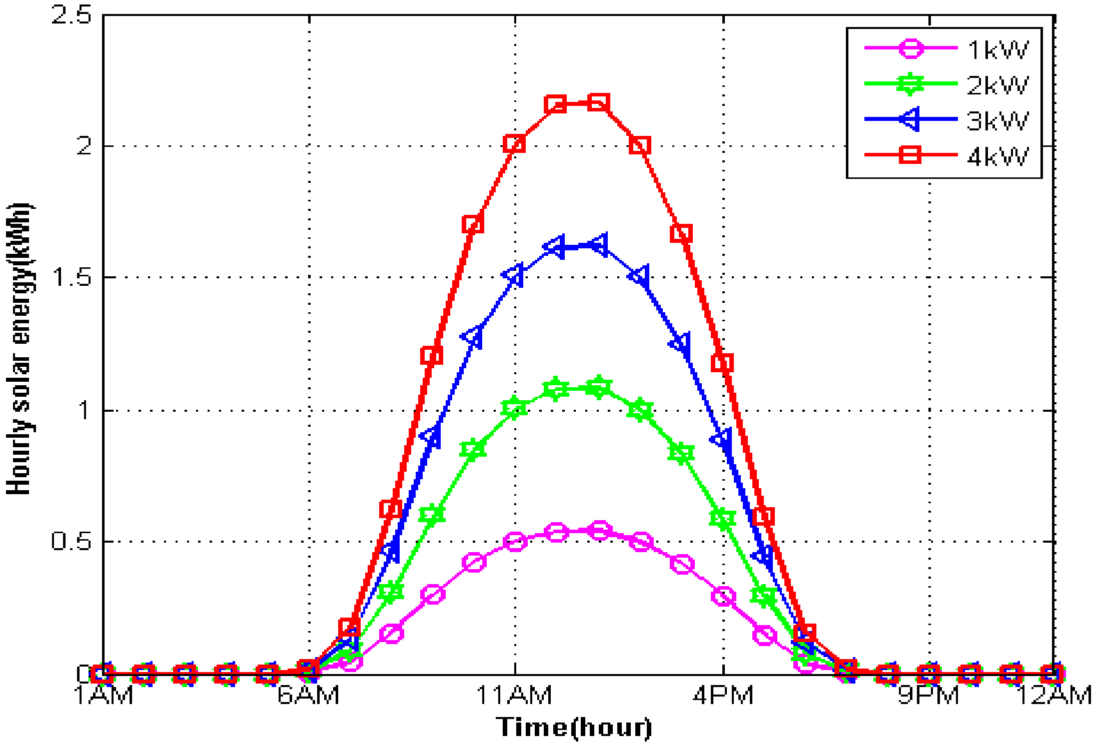

Figure 3.6: Average hourly solar energy generation.

It is observed that, solar energy generation start from around 6:00 AM. The energy generation remains increasing and reaches at peaks at around 1:00 PM, and ends at about 6:00 PM. Due to the variation in energy generation, the available solar energy may not always guarantee the sufficient energy supplies to the RRHs. In that case, on grid power supply is required to run the RRH in order to avoid outage.

3.6 Energy storage dynamics

RUs can harvest energy from the renewable energy source buying energy from the grid supply. Let, $E_n(t)$ is the harvested energy by n^{th} RRH in time slot t. The following energy harvest constraint holds in each time slot:

$$E_n(t) \le \varepsilon_n(t) \le \varepsilon_{\max}$$

where $\varepsilon_n(t)$ denotes the amount of ambient energy. Due to the impact of environmental changes, the value of $\varepsilon_n(t)$ diametrically changes across time slots, which is upper limited by $\varepsilon_{\max}$. Denote by $\psi_n(t)$ the green energy storage of the n^{th} RRH at time t. The following green energy saving holds each time slot [59]:

$$\psi_n(t) = \alpha\psi_n(t-1) + E_n(t) - \delta_n(t) \tag{3.6}$$

where δ_n(t) is the demand energy of a specific RRH .The factor α indicate the percentage of storage energy retained after unit period of time, which is bounded by $0 \le \alpha \le 1$.

Under the proposed network, the green utilization and on-grid energy consumption of n^{th} RRH under different scenarios are as follows:

Case I: If $\psi_n(t) \ge \delta_n(t)$, then the n^{th} RRH will be served by its own storage and there is no longer requiring of grid energy consumption. The total storage energy remaining after fulfilling demand by itself can be expressed as,

$$s(t) = \psi_n(t) - \delta_n(t) \tag{3.7}$$

Case II: If $\psi_n(t) \le \delta_n(t)$, then n^{th} RRH will take energy from grid supply. In this case, the on grid consumption of n^{th} RRH can be written as,

$$g_n(t) = \delta_n(t) - \psi_n(t) \tag{3.8}$$

3.7 Path loss model

In this paper, we consider a channel model with log normally distributed shadow fading. If d is the distance between transmitter and receiver, then path loss in dB can be formulated as [37],

$$PL(d) = PL(d_o) + 10\delta \log_{10}(\frac{d}{d_o}) + X_\sigma, \quad \text{dB} \tag{3.9}$$

where δ is the path-loss exponent and $PL(d_o)$ is the path-loss in dB at a reference distance d_o in km. Usually, $PL(d_o)$ is computed assuming free space propagation model. X_σ is zero-mean Gaussian random variable with standard deviation σ which is also in dB.

Thus, received power in dBm for k^{th} UE at a distance $d^{k,n}$ from n^{th} RRH is given by

$$P_r^{n,k}(dBm) = P_r^{n,k}(dBm) - PL(d) \tag{3.10}$$

where $P_r^{n,k}$ is the transmitted power by the n^{th} RRH in dBm. Then the received signal-to-noise-plus-interference ratio $SINR_{n,k}$ for k^{th} UE can be given by

$$SINR_{n,k} = \frac{P_r^{n,k}}{I_{k,\text{intra}} + I_{k,\text{inter}} + P_N} \tag{3.11}$$

where $I_{k,\text{intra}}$ is intra-cell interference and $I_{k,\text{inter}}$ is inter-cell interference. P_N is additive white Gaussian noise (AWGN) power given by $P_N = -174 + 10\log_{10}(\Delta f)$ in dBm where (Δf) is the bandwidth in Hz. Orthogonal frequency division multiple access (OFDMA) technique nullify the intra-cell interference ($I_{k,\text{intra}}$).

3.8 Performance metrics

EE is the key performance indicators that assess the feasibility of a cellular network given in terms of bit per joule. In particular, EE metric measures how efficiently data can be transmitted per unit energy consumption. The low power consumption to transmit the same amount of data implies the more energy efficient operations. In this paper, we evaluate EE performance metric for the proposed RE-CRAN as the ratio of total throughput of the network to that of the net on-grid power consumed by the network. The total network throughput can be formulated by Shanon's capacity theorem as

$$C_{total} = \sum_{k=1}^{K} \sum_{n=1}^{N_B} \Delta f \log_2(1 + SINR_{n,k}), \quad \text{kbps} \tag{3.12}$$

where K is the total number of UE and N_B is the total number of transmitting RRHs for serving k^{th} user.

Now the EE metric denoted as η_{EE} can be written as

$$\eta_{EE} = \frac{C_{total}}{P_{net}}, \quad \text{bit/joule} \tag{3.31}$$

where, P_{net} is the net on grid power consumption, as the difference between total input power consumption and the solar storage power.

However, EE gain is another useful metrics is used to compare the network performance under different scenarios. EE gain can be defined as the ratio of the considered system and baseline reference. Here, conventional C-RAN as shown in Figure 3.1 is considered as reference system.

3.9 User association (UA) policy

UA means the UE connects to a RRH in a suitable way to receive best signal quality. Associating users with the closest RRH does not always ensure the best SINR due to the randomness of shadow fading. Different UE-RRH connection algorithm has been adopted in this paper.

3.9.1 SINR-based

A user orders the neighbouring RRHs in a descending manner depending on received signal quality. Thereafter, user connects to a RRH that provides maximum SINR among neighbouring cells. It is noteworthy that a single RRH is assumed for data transmission each association policy. Therefore, dynamic point selection coordinated multipoint scheme is carried out in this paper varying four different user connection policies.

3.9.2 Traffic aware-based

A similar concept of sleep-mode based mechanism is followed under this scheme. It is widely recognized that incoming traffic arrival varies both time and space. The considered RRHs operating under below threshold traffic are shift into sleep mode for further energy saving. However, the remaining incoming request will be taken care by neighbouring active RRH intending to zero outage. For instance, RRH_1 is currently operated under low traffic mode switch their traffic into RRH_2 that served least number of traffic load. In this case, the RRHs are ranked in ascending manner based on traffic demand. Provided that RRH_2 reached their maximum demand, then the rest of incoming request will be transferred to the next possible RRH from the RRH set.

3.9.3 Distance-based

In a conventional scheme, a UE generally connects to nearest RRH. Under this policy, UE categorized the surrounding RRHs in an ascending order. Notably, the nearest RRH may not always supports the UE owing to the random shadow fading effect.

3.9.4 Green energy-based

The green energy generation exhibits tempo-spatial diversity. Therefore, each RRH may have different storage capability due to variation of solar generation and traffic dynamics. Under the green energy-aware UA scheme, a user categorizes the RRH in a subsiding way. According to definition, UE associates the RRH that have highest green energy storage capability

3.10 Chapter summary

In this chapter, we have proposed a frame work for an energy efficient cellular network with hybrid powered RRHs, where PV solar module acts as the main energy source for a RRH and the grid/DG remains as the standby. Mathematical modeling of the energy generation system, SINR expression and energy storage algorithm have been clearly presented in this chapter. This chapter has also entailed discussion of the different performance metrics in order to assess the achievement of entire cellular networks.

Chapter 4

Results and Analysis

4.1 Introduction

Energy efficiency (EE) is a key concern in diverse domains of next-generation mobile networks due to dramatic surge of energy consumption. Both the energy savings and network performance subsequently form the basis of EE metrics. The simulation results of the proposed hybrid model are described in this chapter. The simulation setup and various simulated results such as on grid power consumption, throughput, EE, EE gain performance and so on are shown in the section 4.2 and section 4.3.

4.2 Simulation setup

A MATLAB based Monte-Carlo method is conducted to evaluate the system performance and the results are calculated by taking mean of 10000 iterations. The considered networks are assumed to be deployed with omnidirectional antenna with hexagonal fashion. We assume the number of users on each RRH is different over a day and they are randomly distributed. The RRHs transmit data to all the users with the same data rates. We further assume that one resource block is allocated to one user. Inter-cell interference effect is taken from the neighboring serving RRH. According to the LTE standard [60], the key model parameters of the system are set which are summarized in table 4.1.

4.3 Results and discussions

4.3.1 Energy efficiency analysis of the proposed hybrid network with grid supply

This section analyzes the performance of the proposed network in terms of grid power consumption and energy efficiency for different solar PV capacities (1kW, 2kW, 3kW and 4kW) with respect to conventional C-RAN. Here, the conventional C-RAN scheme defines the cellular system is powered by only traditional grid supply without

RE source integration. Figure 4.1 illustrates the grid power consumption varying installed on-site solar capacity over a day. Until 6AM, the RRH is fully run by grid supply when the sunlight is not available or empty energy storage in the battery bank.

Table 4.1: Simulation parameters

Parameters	Value
Resource block	180 kHz
System bandwidth, BW	10 MHz
Carrier frequency, fc	2 GHz
Cell radius	1000 m
BS transmit power	43 dBm
Noise power density	-174 dBm/Hz
Cell layout	Hexagonal
Reference distance, d_0	100m
Path loss exponent, δ	3.574
Shadow fading, X_σ	8 dB
Maximum storage capacity, s_{max}	4 kWh
Storage factor, μ	0.92 i.e. 8% loss
Traffic model	Tempo-spatial diversity

On-grid consumption sharply falls down to zero level with the availability of incoming solar energy generation. As observed, the grid energy consumption is zero for a prolonged period of time (i.e., 8AM to 7PM for 1kW panel capacity). During day time the batteries store excess electricity generation for future use after fulfill the RRH demand. As seen, grid energy savings are widen for the higher solar PV capacity leading to substantial improvement of network performance. On the other hand, once again grid electricity is required to serve associated UEs in the absence of green energy storage. However, 4kW solar panel attains an improved performance as evident form the figure. It can be concluded that the maximum utilization of green energy significantly reduces grid consumption. In contrary, conventional C-RAN always tends to run using grid power and thereby, our proposed system shows superior performance. Figure 4.2 presents the throughput performance of C-RAN over

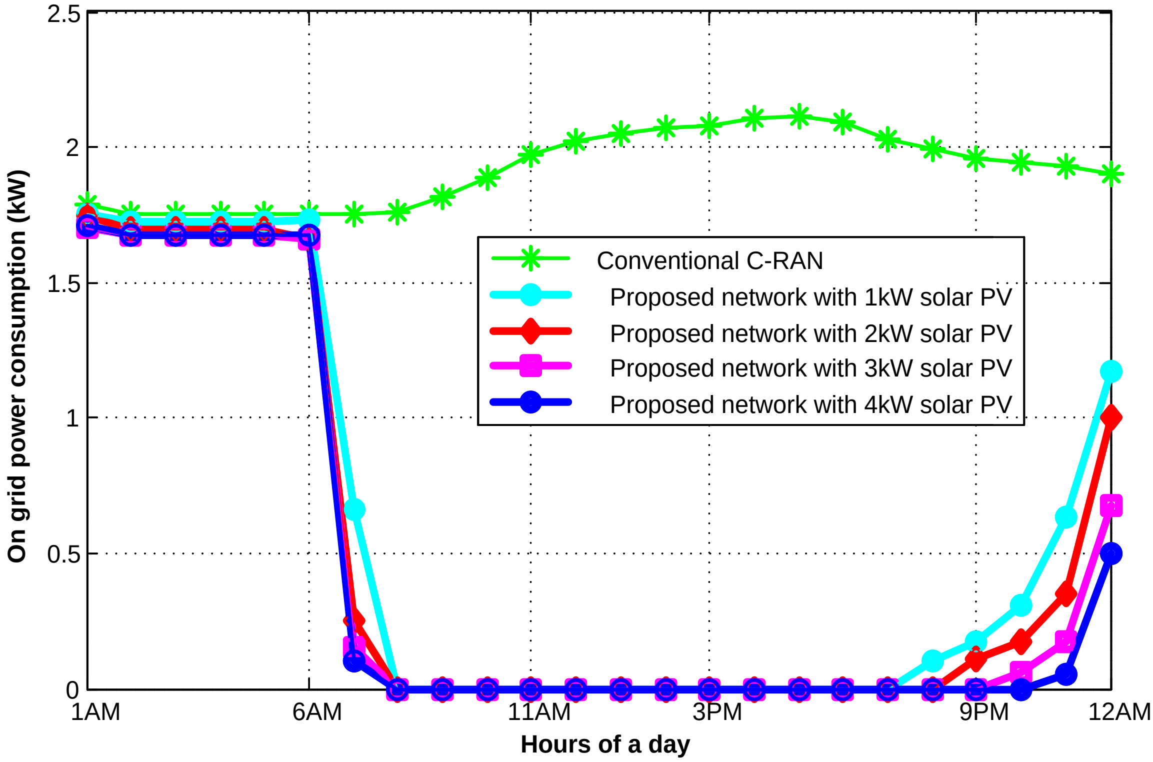

Figure 4.1: Comparison of on grid power consumption of the proposed C-RAN with different solar module capacity and conventional C-RAN.

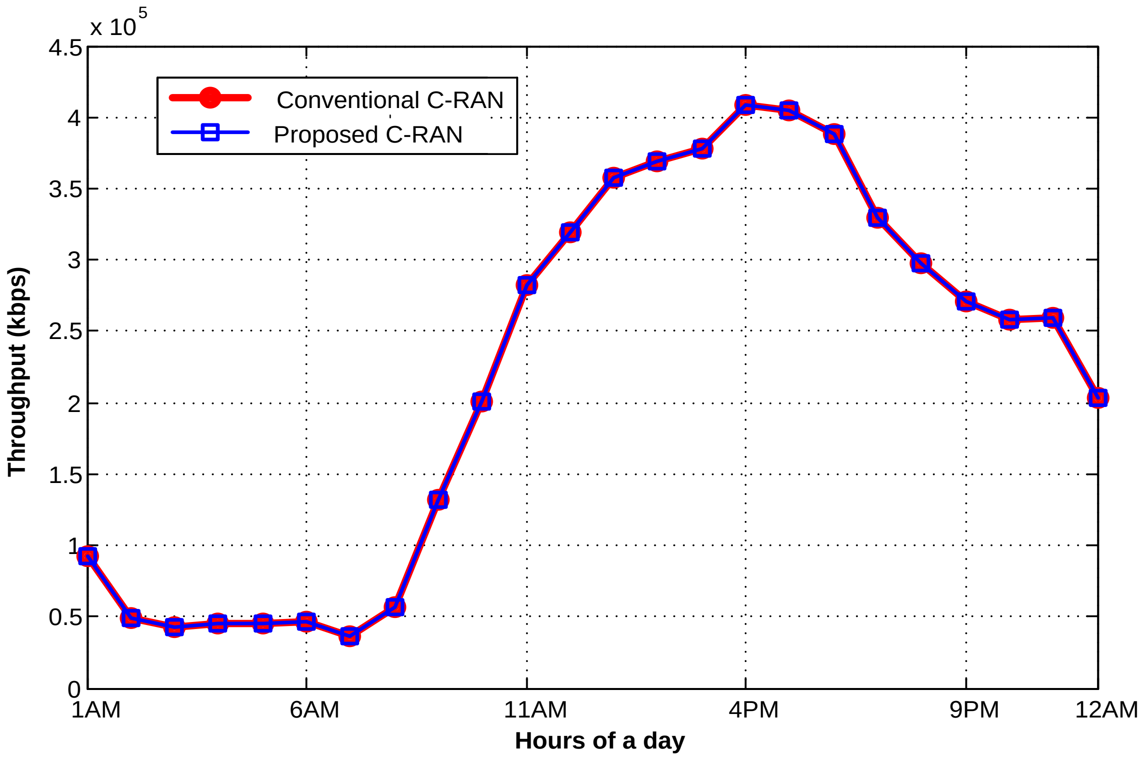

Figure 4.2: Throughput of the proposed C-RAN and conventional C-RAN.

a day. The throughput curve apparently follows the given traffic demand graph as observed from the figure. In addition, the throughput curves for both the proposed system and conventional C-RAN overlap with each other. This is due to the throughput is entirely depends on system bandwidth as well as resource blocks (RB) and independent on power consumption. We assume one user occupies one RB and thus, it follows the given traffic distribution. Therefore, the nature of power consumption by RRH doesn't make any change on data transmission rate.

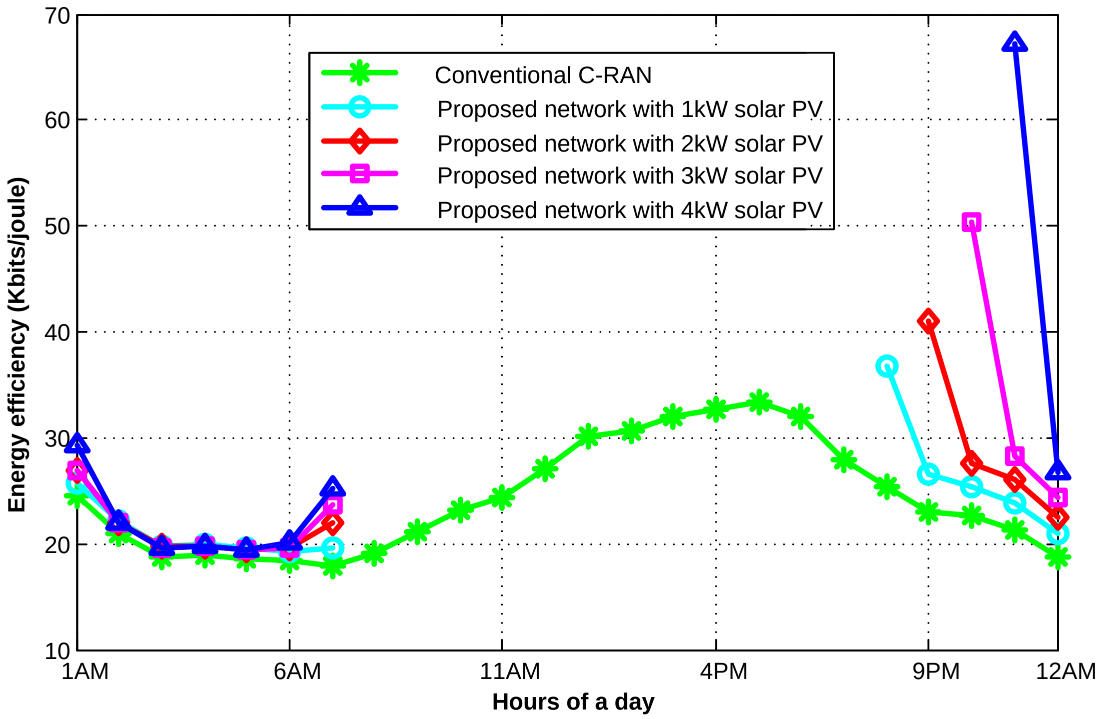

Figure 4.3: Comparison of EE perfomance between proposed C-RAN and conventional C-RAN.

Figure 4.3 demonstrates the comparison of EE performance the proposed model with conventional C-RAN over a period of a day. According to the definition, EE is inversely related to the net grid power consumption (P_{net}). The minimum grid power consumption is found for 4kW solar panel in Figure 4.1 and hence, superior EE performance is obtained under this condition as clearly seen from the figure. However, all the four curves involved with hybrid scheme follows a similar pattern. During midnight to early morning, EE falls down due to the absence of sunlight and is found to reach infinity for the prolonged period with the solar energy availability. The break lines identify the infinity region that indicates there is no on-grid energy consumption. Under this condition, the RRHs are fully powered by stored solar energy implying the best EE performance is achieved. As mentioned in table 4.2, during some period on grid power consumption (P_{net}) goes to zero as the stored solar energy at that period fully neutralized the demand of on-grid consumption. Since the throughput is same for all hybrid schemes, EE of proposed network varies with an installed solar capacity. The figure also includes the EE metric curve of the conventional C-RAN scheme which shows inferior performance compared to our proposed model. However, the empty region of the proposed C-RAN hybrid model is comparatively wider for 4kW energy harvester capacity compared to others. Therefore, the proposed network with 4kW solar PV exhibits better EE performance. On the other hand, EE curves shifts downward once again as the stored green energy is much lower to feed RRH load demand during night. Furthermore, EE gap is more noticeable in night time due to the variation of energy storage capability.

Table 4.2: Comparison of power consumption

Network model	**Solar PV capacity**	**Hours of a day**	**On grid consumption**
Proposed RE-CRAN	1kW PV	08.00AM – 07.00PM	Nill
	2 kW PV	08.00AM – 08.00PM	Nill
	3 kW PV	08.00AM – 09.00PM	Nill
	4 kW PV	08.00AM – 10.00PM	Nill
Conventional C-RAN	No solar PV used	01.00 AM– 12.00 AM	Always Present

Figure 4.4 illustrates the energy efficiency gain of our proposed model for different solar capacities. As seen, the proposed hybrid system with 4kw solar capacity has been identified as 129% more energy efficient C-RAN than the 1kW PV capacity. From the aforementioned analysis, it can be easily inferred that proposed C-RAN with greater solar capacity is a preferred in the context of green cellular communication.

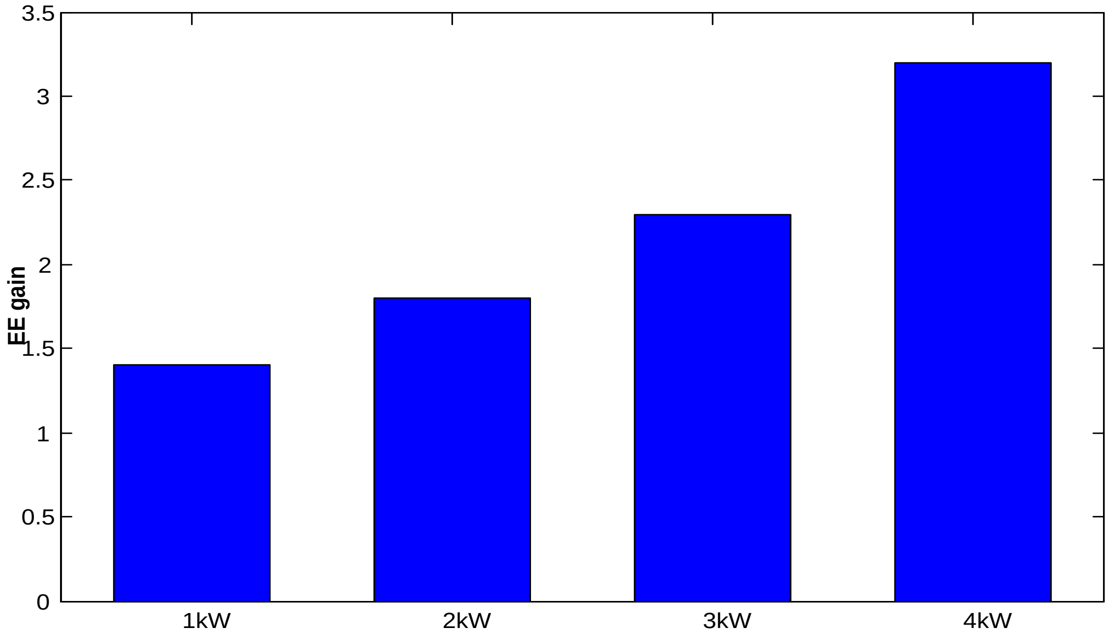

Figure 4.4: Energy efficiency gain for the proposed C-RAN network varying solar capacity.

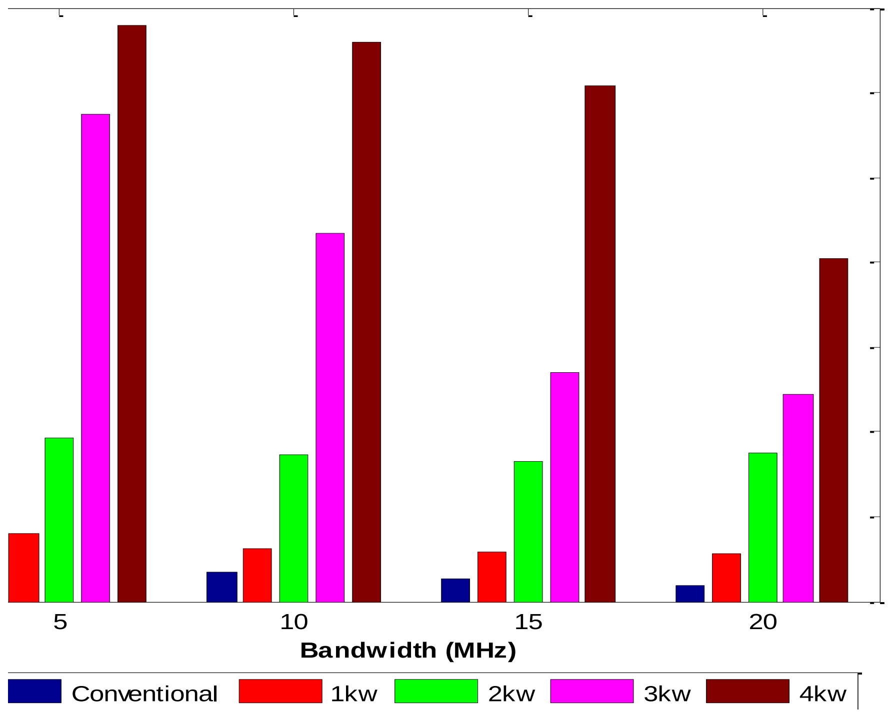

Figure 4.5: Comparison on EE performance of Macrocell RRH with bandwidth varying solar module capacity.

A comparison of key network performance metric, i.e., EE with bandwidth for conventional system and different solar module capacity is demonstrated in Figure 4.5. The EE decreases with the increment of bandwidth because the grid power consumption is increased at this time. Therefore, the proposed network with 4kW solar PV exhibits better EE performance. Because, 4kW solar PV has muchmore energy harvester capacity compared to others.

4.3.2 Energy efficiency analysis of the proposed hybrid network with DG supply

This section also analyze the proposed network performance in terms of diesel power consumption, excess electricity, Greenhouse gas (GHG) emissions impact and energy efficiency for different solar PV capacities (1kW, 2kW, 3kW and 4kW). However, the results presented in this section are analyzed for two different BS type varying transmission power.

Figure 4.6 illustrates the input power consumption for omnidirectional and tri-sector 2/2/2 configurations with 2 different transmission power (i.e., 43 dBm and 46 dBm

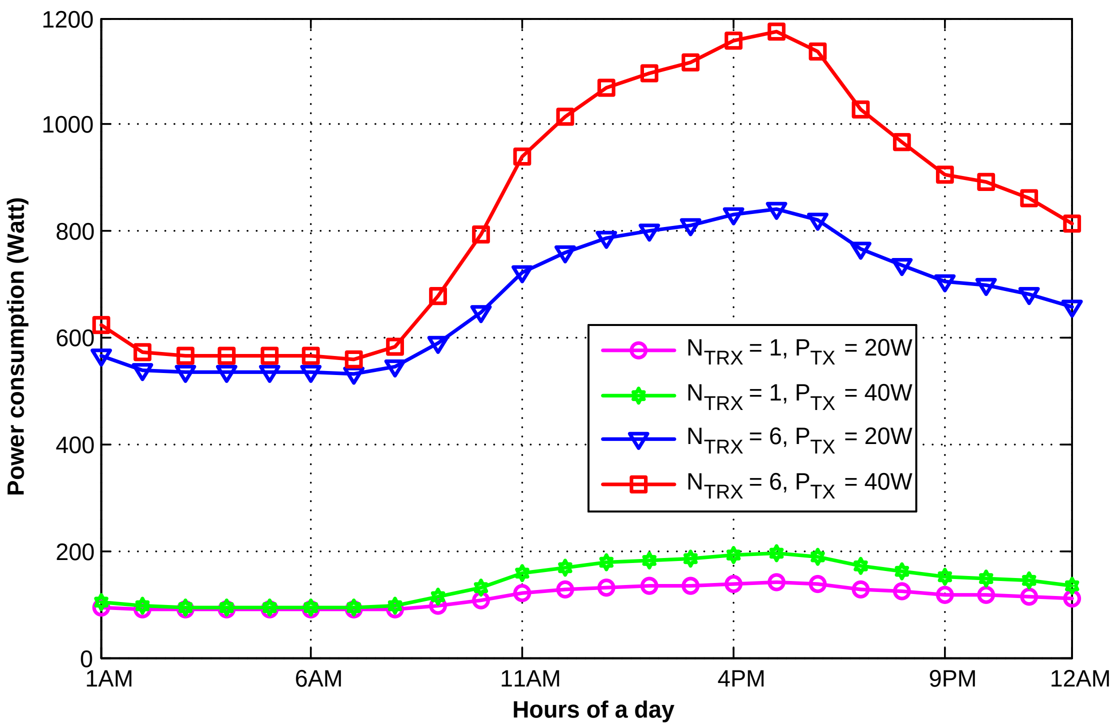

Figure 4.6: Input power consumption for a single RRH with two different transmitting power and antenna pattern.

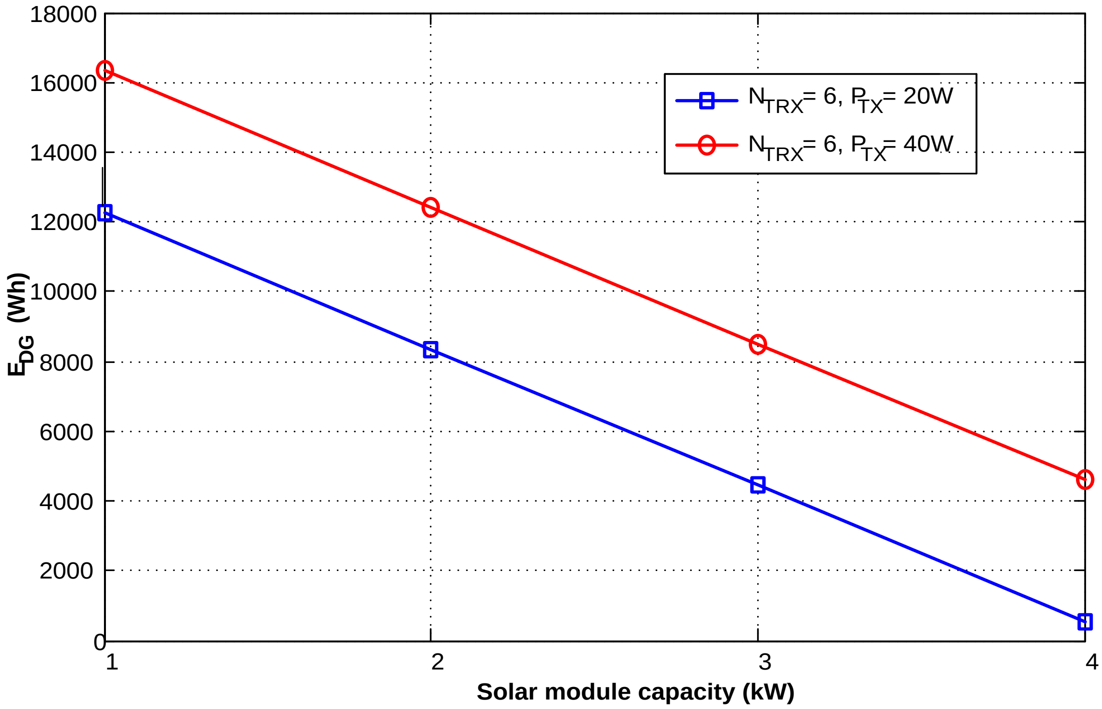

Figure 4.7: Comparison of diesel power consumption with two different transmission powers.

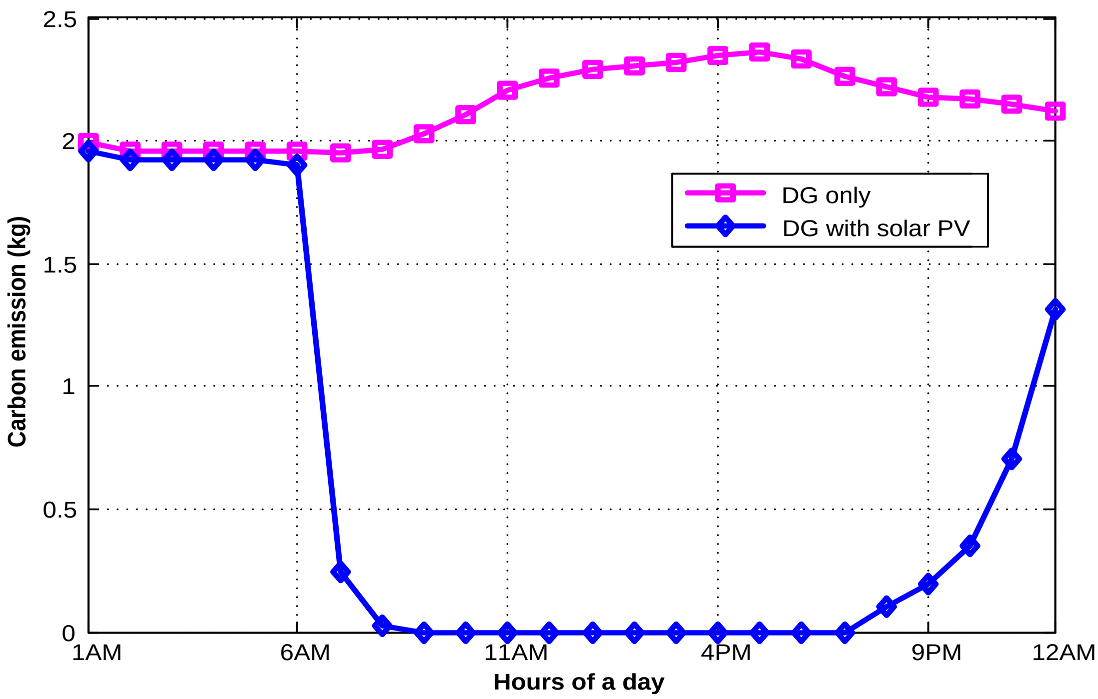

Figure 4.8: Comparison of CO_2 emission of the proposed hybrid network with non-hybrid network.

over a day. A BS with 2/2/2 pattern implies that each macrocell are configured with three sectors and each sector have two antennas. As expected, power consumption of

2/2/2 is higher than the omnidirectional configuration. Besides, a high the value of transmission power (P_{TX}) resulting in higher input power consumption.

Figure 4.7 illustrates the DG energy production with installed solar panel capacity for tri-sector RRH enabled macrocell RRH varying transmission power. As observed, a higher value of solar module capacity indicates lower value of diesel consumption.

A comparison of pollution intensive carbon emissions of proposed hybrid (DG + PV) network with non-hybrid (DG only) network is demonstrated in Figure 4.8. It is clear from figure, the proposed system attains an improved performance as it produces lower amount of greenhouse gas emission.

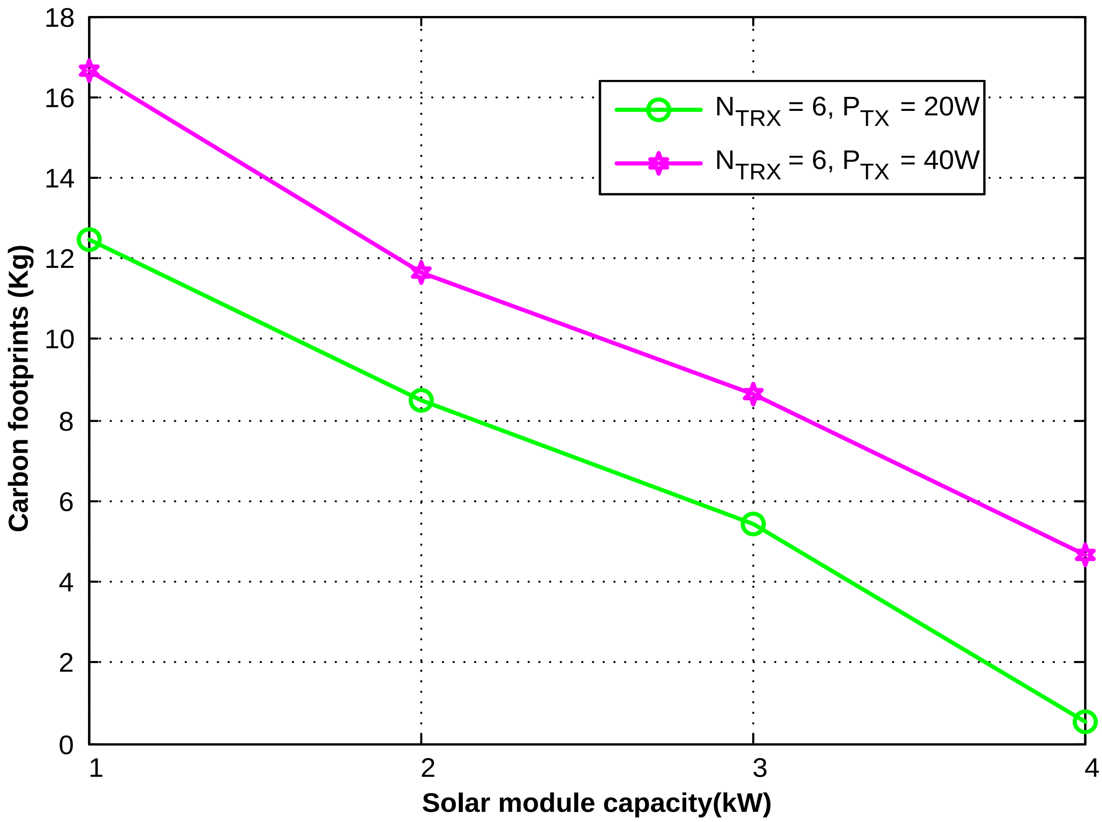

Figure 4.9: Comparison of CO_2 emission with two different transmission power.

Figure 4.9 demonstrates the pollution intensive carbon emissions with different solar module capacity for two different transmission power. Both curves are rapidly goes down to reach their minimum value with the increment of PV array capacity and follows similar pattern of Figure 4.7 as explained beforehand. Since high P_{TX} results greater power consumption and consequently pushed the DG operating hour to cope with the BS load demand. In addition, GHG emission factor is linearly scaled with E_{DG} as well as operating hours. As a result, P_{TX} = 40W produces greater amount of CO_2 emissions compared to P_{TX} = 20W transmission power as mentioned in table 4.3. On the other hand, the amount of CO_2 emissions is found lower for the higher PV array capacity. Solar EH can alone carry the BS load demand for omni- directional configuration where no DG module is required. This is because, the energy consumption for P_{TX} = 20W and P_{TX} = 40W is 2694Wh and 3373Wh respectively. Whereas 1kW solar panel with dual tracking mode produce 3910Wh according to (1). Therefore, surplus energy is remained in battery bank for further use in the absence of solar energy. In other words, the C-RAN with omnidirectional configuration fully run by green energy sources and hence emits zero carbon emission that considered as an eco-friendly solution. The challenges of RE variability can be mitigated by storing surplus electricity to the energy storage system.

Table 4.3: Comparison of CO_2 emission with two different transmission powers.

Solar module capacity (kW)	Energy produced from DG, E_{dg} (kWh)		DG fuel consum-ption (L/kWh)	Required diesel (L)	Co_2 Emissi-on (Kg/L)	Carbon footprints (Kg)	
	N_{TRX} = 6, P_{TX} = 20W	N_{TRX} = 6, P_{TX} = 40W				N_{TRX} = 6, P_{TX} = 20W	N_{TRX} = 6, P_{TX} = 40W
1	12.258	16.33	0.38	4.65804	2.68	12.48355	16.63047
2	8.348	12.42		3.17224		8.501603	12.64853
3	4.438	8.51		1.68644		5.45361	8.666584
4	0.528	4.6		0.20064		0.537715	4.68464

From Figure 4.10 it is clearly observed that, greater the module capacity resulting in higher the surplus energy. The amount of surplus electricity improves the system reliability ensuring the zero outage. The excess solar energy can be shared to the neighboring BS via physically installed power cables for further enhancing EE.

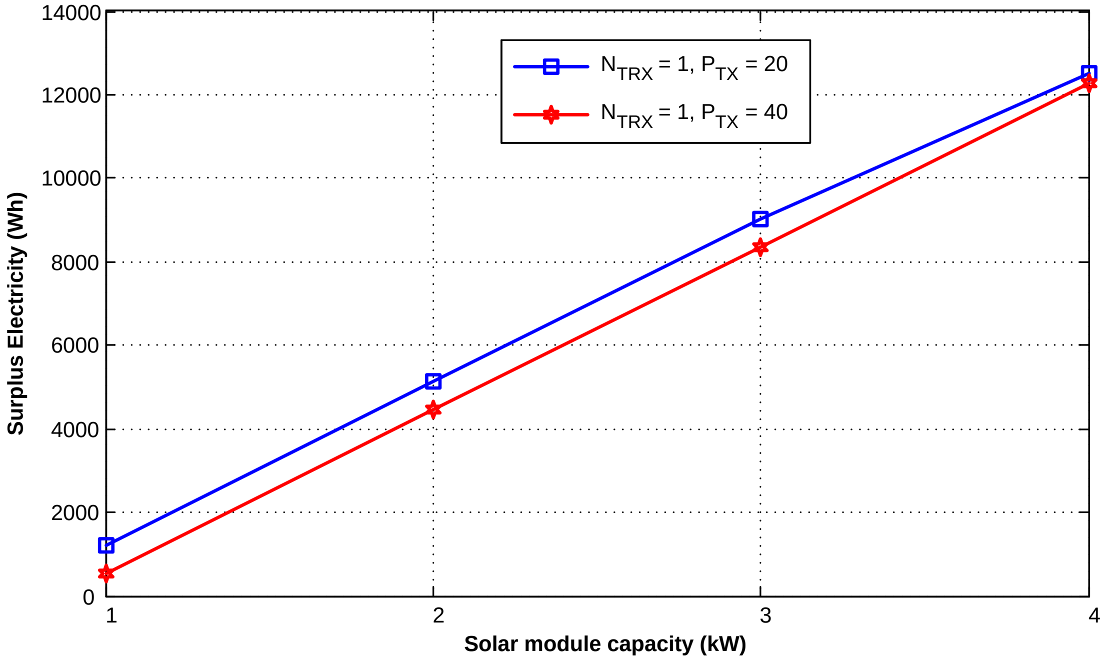

Figure 4.10: Comparison of excess energy generation for omnidirectional configuration.

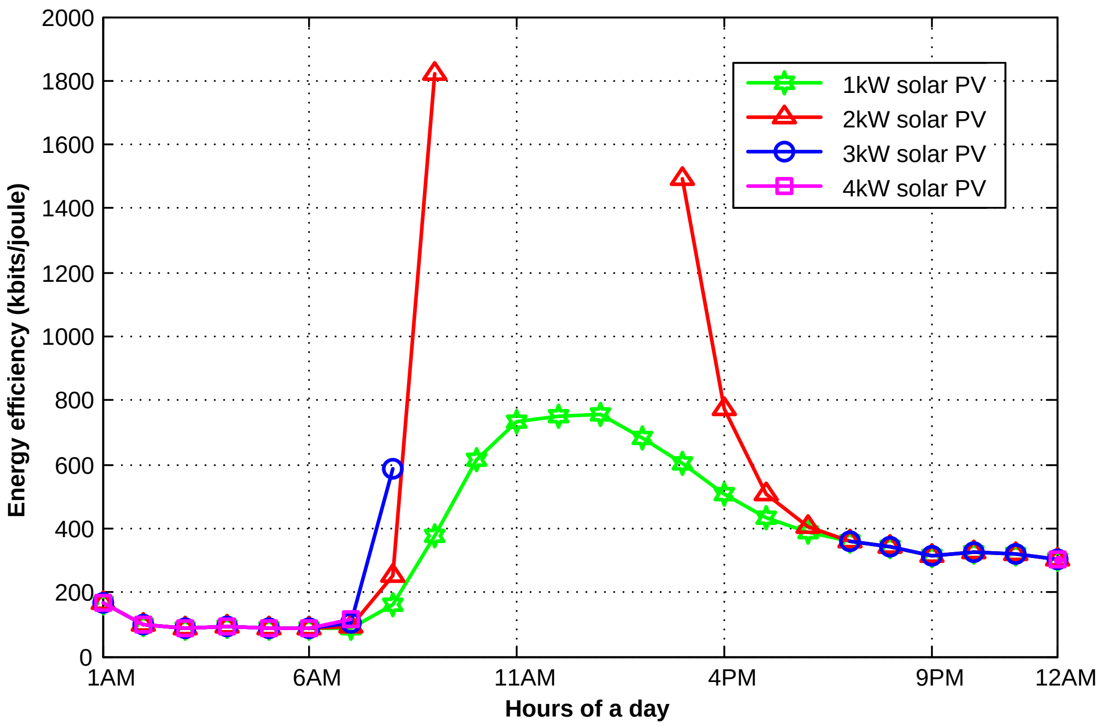

Figure 4.11: Comparison on EE performance varying solar module capacity for a RRH with 2/2/2 tri-sector antenna.

Figure 4.11 represents the EE performance of a RRH with 2×2×2 tri-sector antenna. Until 6AM, the RRH is fully run by DG supply whatever the solar module capacity. Because, the sunlight is not available at this time. The DG consumption sharply falls down to zero level with the availability of incoming solar energy generation. The minimum DG power consumption is found for 4kW solar panel in Figure 4.7 and hence, superior EE performance is obtained under this condition. However, all the four curves follows a similar pattern. During midnight to early morning, EE falls down due to the absence of sunlight and is found to reach infinity for the prolonged period with the solar energy availability. The break lines identify the infinity region that indicates there is no DG consumption. However, 4kW solar panel attains an improved performance as evident form the figure. It can be concluded that the maximum utilization of green energy significantly minimizes the DG consumption.

4.3.3 Energy efficiency analysis of proposed hybrid network under different UA schemes

Figure 4.12 presents the comparison of throughput among the different UA schemes of the proposed network over a day along with conventional schemes. As seen from

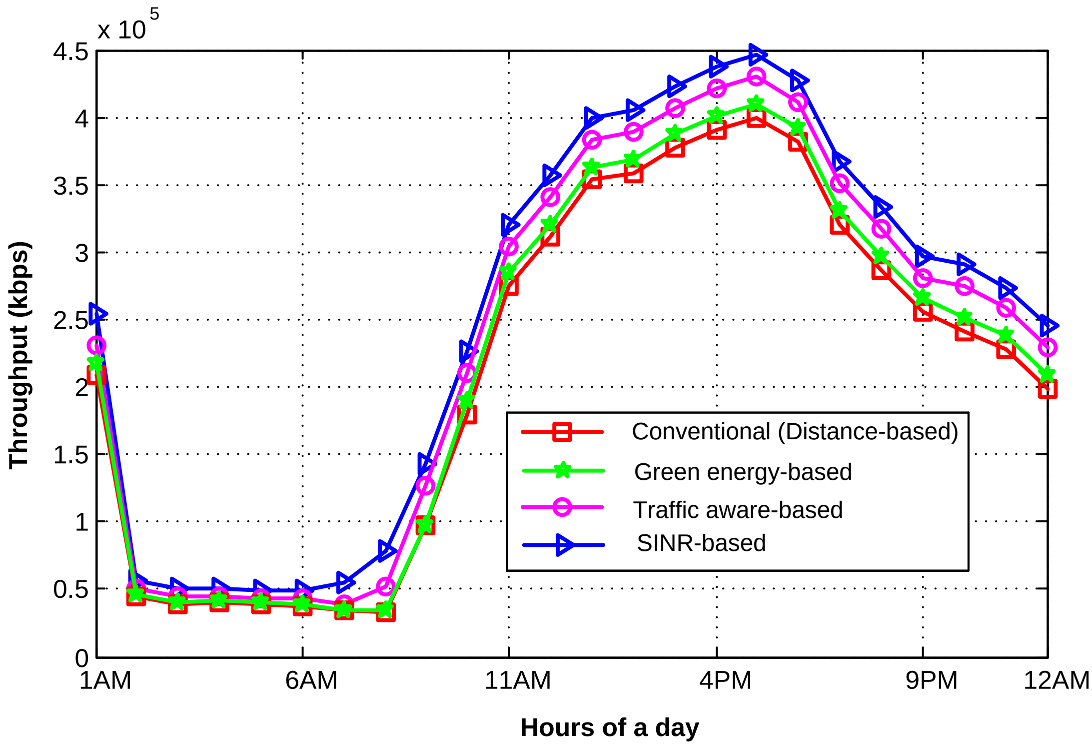

Figure 4.12: Throughput of the proposed C-RAN and conventional C-RAN.

the figure, throughput curves clearly follow the traffic pattern in a day. It is also observed that, the throughput at peak traffic hour is higher than the low traffic hour. From the all hybrid proposed models along with the conventional distance-based model, the SINR-based model gives the highest throughput performance for its improved SINR performance.

Figure 4.13 demonstrates the EE comparison of the proposed model with the conventional C-RAN over a period of a day. In accordance with the definition, EE is directly proportional to the throughput. Since SINR-based UA provides higher throughput, hence it provides higher EE than other hybrid schemes. The figure also shows that the EE curve of energy-based scheme gives inferior performance compared to our other proposed model. This is because, the installed 4kW solar capacity is not sufficient to run a RRH in whole day solely as shown in Figure 4.1. However, all the four curves involved with hybrid scheme follows a similar pattern. Between midnight to early morning, EE falls owing to the absence of sunlight and is found to reach infinity for the prolonged period with the solar energy availability. The break lines identify the infinity region that indicates there is no grid energy consumption.

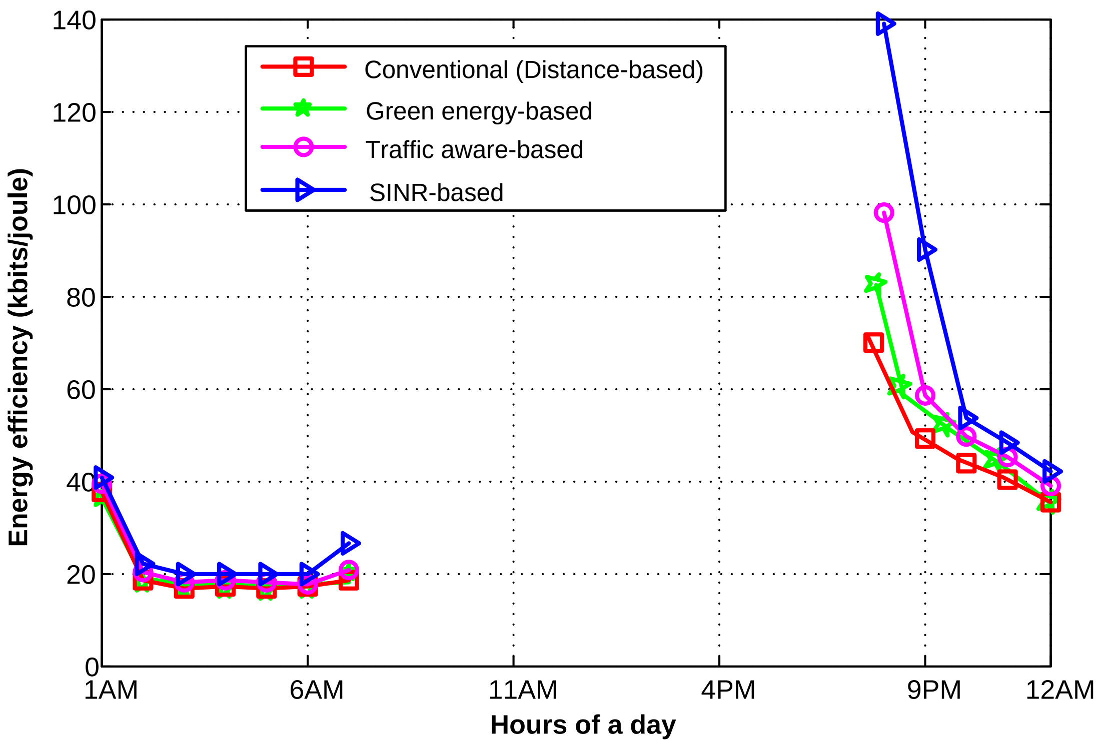

Figure 4.13: Comparison of EE perfomance between proposed C-RAN and conventional C-RAN.

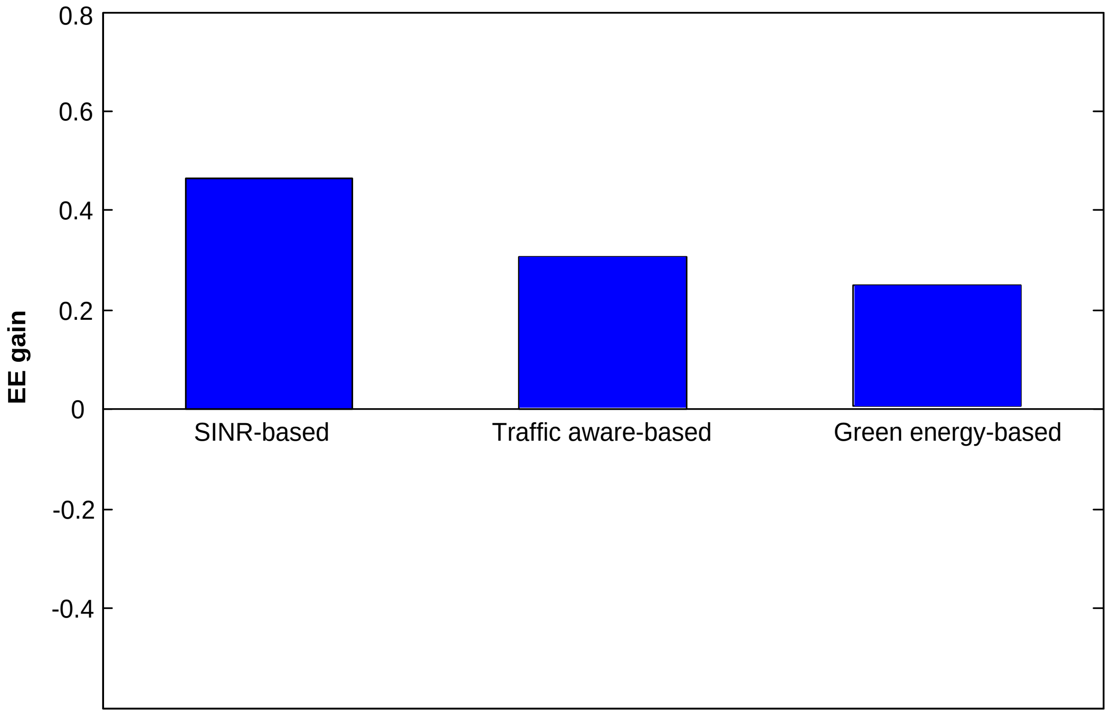

Figure 4.14: Energy efficiency gain for the proposed C-RAN network with different UA policies for 4kW solar PV.

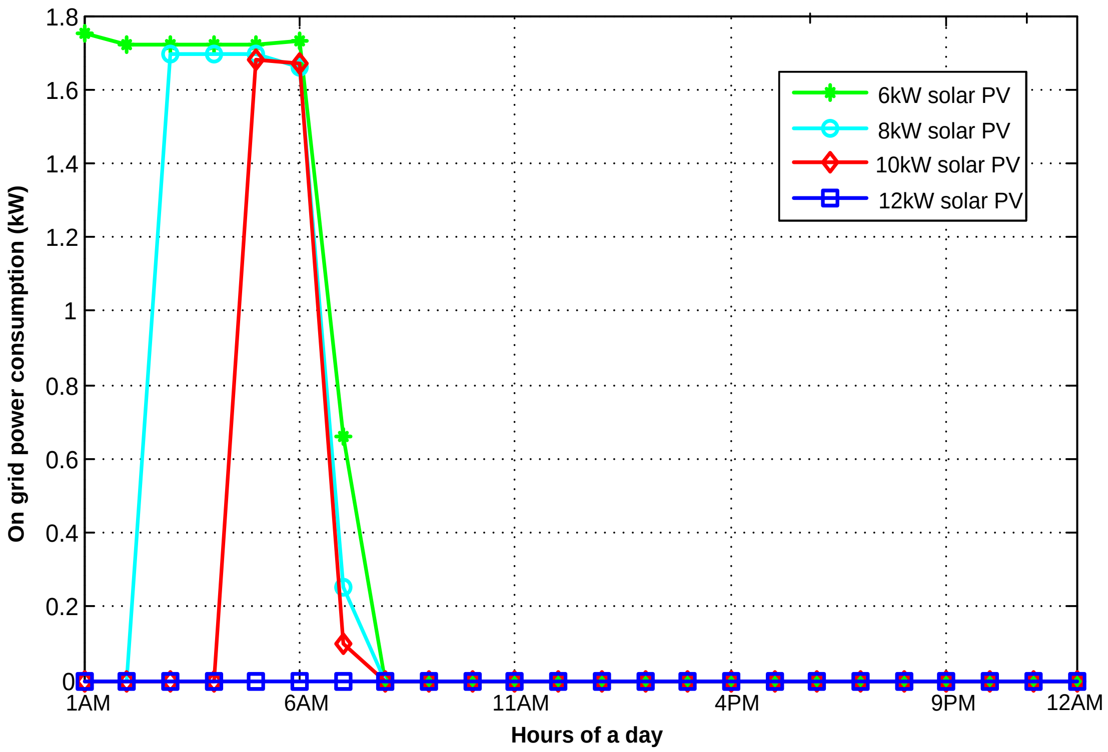

Figure 4.15: Comparison of on grid power consumption of proposed C-RAN with different solar module capacity.

Figure 4.14 shows the energy efficiency gain of proposed model for different UA policies. As seen, the proposed hybrid system with SINR-based has been identified as 62% and 83% more energy efficient than the traffic aware and green energy-based algorithm.

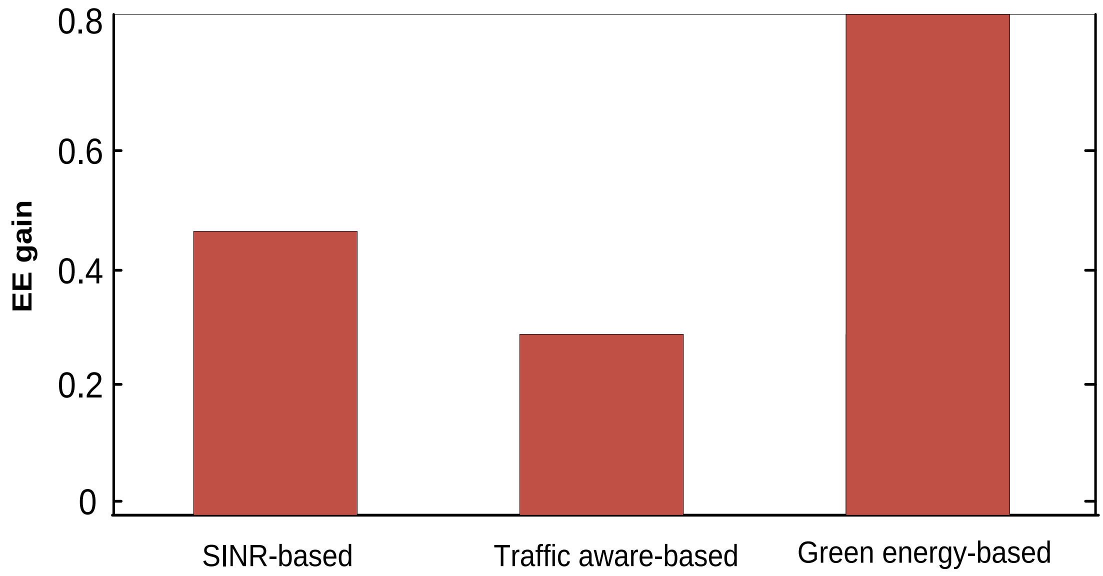

Figure 4.16: Energy efficiency gain for the proposed C-RAN network with different UA policies for 12kW solar PV.

Another quantitative comparison of the energy efficiency gain of proposed model for different UA policies is demonstrated in Figure 4.16. It has been observed that, the proposed hybrid system with green energy-based is now identified as 72% and 180% more energy efficient than the SINR-based and traffic aware-based algorithm. This is because, the installed 12kW solar capacity is sufficient to run a RRH in whole day solely as shown in Figure 4.15.

It can be concluded that, if the installed solar module capacity is sufficient to run a RRH in whole day, the green energy-based UA scheme will provides superior performance than the others schemes.

4.4 Chapter summary

In this chapter, a comprehensive results analysis have thoroughly been investigated in order to measure the effectiveness of the proposed system model in terms of EE and

EE gain metrics varying system parameters such as throughput, bandwidth, solar module capacity, on-grid power consumption, etc. under different user association policies. Furthermore, details parameters of simulation setup has also been focused. Thereafter, a comprehensive Monte-Carlo based MATLAB simulations considering both tri-sector and omnidirectional antenna with hexagonal cell layout have been carried out to evaluate the EE performance.

Chapter 5
Conclusions and Future works

5.1 Conclusions

In order to cope up with fast growing and ubiquitous mobile data usage, cellular network has to be expanded worldwide. Consequently more and more BSs are needed to be deployed. As BSs is the main energy hungry elements in a network power usage in cellular network would also increase tremendously. For this concern energy efficiency discussion is one of the paramount issues of today‘s high speed cellular network system.

This thesis has proposed and investigated an energy efficiency of C-RAN with hybrid supplies. In addition, different UA schemes integrate with the proposed architectures for further EE improvement. The system performance has thoroughly been investigated using Monte Carlo based MATLAB simulation taking into account several limiting factors. Finding for different analysis of this thesis are summarized as below.

i. This thesis has proposed and investigated hybrid powered C-RAN architectures to enhance EE. More specifically, various dynamic user association policies and integrate with the proposed architectures for further EE improvement.
ii. On-grid energy consumption of the proposed hybrid system has been observed. The maximum utilization of green energy significantly reduces grid consumption.
iii. A comparison of pollution intensive carbon emissions of proposed hybrid (DG + PV) network with non-hybrid (DG only) network has been demonstrated and the proposed hybrid system has improved performance than the non-hybrid network.

iv. EE performance and EE gain performance of the considered hybrid scheme with different solar PV modules capacities has been observed. C- RAN with 4kW PV capacity has been identified as 129% more energy efficient than with 1kW PV capacity.

v. EE and EE gain has been improved significantly with different UA schemes.

vi. SINR-based UA scheme has been identified as 62% and 83% more energy efficient than the traffic aware and green energy-based algorithm respectively when there is insufficient green energy to run RRH during the whole day.

vii. Green energy-based UA scheme has been identified as 72% and 180% more energy efficient than the SINR-based and traffic aware-based algorithm respectively when there is sufficient green energy to run RRH during the whole day.

5.2 Future works

At the current stage of the propose research, developed dynamic network operation mechanism have much room for being improved and extended in several interesting directions. Some of these potential researches opening are summarized below.

- **Cost assessment:** In C-RAN architecture, the optical fiber between BBU pool and RRHs has to carry a large amount of total cost. Hence, future work will focus on the generalized algorithms for C-RAN architecture with cost assessment.
- **Energy cooperation:** Energy cooperation among RRHs is the key to achieve higher energy efficiency. A renewable energy cooperation of C-RAN networks paradigm can be explored for improving energy efficiency performance.
- **User association in heterogeneous C-RAN:** A User-RRH pairing and resource allocation strategy in heterogeneous C-RAN can be improved energy efficiency. A stochastic geometry model for user association in H-CRAN can be improved which can be considered as a future focus for thorough study.

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