Green Energy Driven Cellular Networks with JT CoMP Technique

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***Abstract*—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. As a result, cellular operators are increasingly deploying renewable energy (RE) sources in BSs as a promising way to reduce the on-grid consumption and operational expenditure. In this paper, we propose a novel framework on green energy driven cellular networks aiming to maximize the utilization of the green energy and minimize the grid energy consumption considering stochastic traffic demand profile. Each BS 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 commercial grid supply. In addition, joint transmission (JT) coordinated multi-point (CoMP) transmission technique is integrated with the proposed model for selecting the best serving BSs for a user equipment (UE). The prime goal is to quantify the EE of various selection schemes namely, distance based, SINR based and SINR-distance based JT CoMP techniques under the proposed network model. Provision of sleep mode approach in BSs is also considered. A thorough investigation in the downlink of LTE-Advanced (LTE-A) cellular system is carried out for evaluating EE performance of the proposed framework under a wide range of network settings. Numerical results validate the proposed network models demonstrating a considerable enhancement in network EE compared to other counterparts.**

***Keywords*— Energy Efficiency, Energy Harvesting, Green Cellular Network, Coordinated Multipoint, Hybrid Power Supply.**

I. Introduction

Over the last few decades, the revolutionary success of Information and Communication Technologies (ICT) has made information highly accessible and led to increased productivity to unprecedented levels. This rapid growth of ICT industry is due to the increases in a number of mobile users and their diverse data applications. It is expected that the demand is increasing continually in the future as smartphones and other wireless devices become affordable for everyone [1]. To cater for this demand, cellular network operators are installing more number of base stations (BSs) in order to increase capacity and coverage for maintaining the quality of service (QoS). As the indication of this trend, a massive inflation in energy consumption of cellular networks happens in ICT sector, which pushes up the operational expenditures (OPEX) [2]. Apart from the financial aspects, this remarkable rise in energy consumption is exerting tremendous pressure on the environment. It is estimated that the ICT sector is responsible for 2-2.5% of total global carbon footprint generated by human activity and this is expected to increase every year with the exponential growth of the mobile traffic [3]. BSs in the radio access network (RAN) of cellular networks are the most dominant energy hungry equipment consuming around 60-80% of the total energy consumption [4], [5]. On the other hand, energy inflation in RAN infrastructure is expected to increase approximately by a factor of ten in every five years, leading a terrific pressure on energy demand [6]. However, traditional cellular wireless networks were designed with the purpose of providing high spectral efficiency without any provisions of energy efficiency (EE).

Therefore, EE in radio access networks has drawn intensive attention with the enormous awareness of managing the profitability of cellular operators and global warming aspects. As a consequence, severe concerns about the greenhouse gas emission and rising energy cost indicates the substantial importance for green cellular communications in ICT circle. Several recent studies [7]–[9] have been carried out by academia, mobile operators and vendors focusing on integrating the utilization of green energy sources in networks, which can drastically reduce the grid energy consumption and improve network EE. On the other hand, authors in [10] presented a tractable mathematical framework to analyze the SE and EE for the heterogeneous deployment especially for cell-edge UEs.

Powering cellular networks with energy harvesting from renewable energy sources e.g., solar panels, wind turbines, etc. has become a promising alternative for reducing global carbon footprint and can even completely phase out the consumption from the conventional grid supply leading to improved EE. Currently, most cellular industries worldwide are implementing renewable energy generators in their infrastructure to make greener the networks with minimum cost solution [11]–[13]. It is widely believed that green energy is much cheaper than conventional grid energy and does not produce carbon emissions. It thus becomes interesting to tackle the issue of on-grid consumption through maximizing the green energy utilization. The ultimate objective of green cellular networking is to maximize the usage of solar energy while minimizing the conventional grid consumption. However, RE generation is highly variable both in time and space depending on several factors. To this end, powering RAN infrastructures by hybrid supplies including both traditional grid energy and green energy has become a remarkable solution for achieving improved EE in cellular networks. In other words, a step towards green communications requires the RE generators to be easily used in conjunction with the traditional grid system.

A. Coordinated Multi-Point Techniques

Recently, the concept of coordinated multipoint (CoMP) transmission proposed by third generation partnership project (3GPP) for both uplink and downlink in LTE-Advanced (LTE-A) has been widely focused on many studies [14]–[16]. CoMP enables the dynamic coordination of transmission and reception over a variety of different BSs leading to improved overall service quality for UEs as well as the system capacity. With the introduction of CoMP, multiple coordinated BSs serve a single UE in a best possible way for improving received signal quality. A CoMP-enabled UE can communicate with single BS or multiple BSs located at different points according to best-received signal quality. Performance gain by CoMP depends on the proper information coordination among BSs via backhaul links. To tackle the inter-cell interference, cooperative transmission has shown a remarkable aptitude. It has been found that CoMP has the potential to improve network performance in terms of interference management, cell edge throughput and overall spectral efficiency (SE) as well as EE [15]. The downlink CoMP can be categorized into three types based on data availability at multiple BSs; joint transmission (JT), dynamic point selection (DPS) and coordinated scheduling/coordinated beamforming (CS/CB) as outlined by 3GPP [14]. In JT CoMP technique, information is transmitted to a UE simultaneously from different coordinated BSs in order to improve received signal quality and strength. Additionally, JT CoMP actively cancels interference effect from transmissions that are intended for other UEs. This form of CoMP mechanism places a heavy demand on the backhaul networks as joint processing data needs to be sent to all of the BSs involved in the CoMP. In contrary, under DPS CoMP technique, only a single BS having maximum SINR is selected for data transmission to a particular UE. On the other hand, in CS/CB technique, the signal is transmitted from only one BS, where UE beamforming decisions are made through proper scheduling among coordinated BSs. This paper provides a deep insight of different categories of JT CoMP technique into the current hybrid cellular networks and can substantially lead more enhancements in SE as well as EE and overall system performance through proper interference management with better cooperative coordination strategies.

B. Motivations & Contributions

In our previous work [17], EE of homogeneous cellular networks was presented considering SINR and distance based JT CoMP only. The system restricts energy saving during off period traffic. In addition, the selection of BSs for distributing traffic is entirely dependent on the instantaneous traffic arrivals, while SINR-distance based UE-BS association scheme is completely ignored. Not only that, the system model is evaluated for two BSs only and is not compared with other combination of JT CoMP schemes for providing a benchmark. In light of these key considerations, this paper proposes and explores the potential of JT CoMP based UE-BS association for improving EE of modern cellular networks, which is free from all aforementioned issues. To the best of our knowledge, this hybrid framework with JT CoMP feature is not analyzed in any literature. The main contributions of this paper are summarized as below:

- A generalized hybrid framework is developed for improving EE of the modern cellular networks. Under the proposed framework, BSs possess RE sources such as PV solar panel and adequate storage capabilities. Moreover, solar energy is the primary energy source to feed the BS demand, whereas traditional grid energy is assumed as the standby energy source for running BSs in the case of green energy deficit. Different UE association schemes, namely, SINR, distance and SINR-distance based JT CoMP techniques are employed in the proposed framework, which has not been investigated yet in literature.
- A heuristic energy management framework is developed taking into account of the temporal and spatial behavior of traffic demand and RE generation. However, inter-cell interference, shadow fading along with path loss model and load-dependent BS power model are responsible for affecting the system performance. All of these limiting factors are taken into consideration throughout the paper.
- Extensive simulations are carried out for analyzing system performance in terms of EE, energy consumption index (ECI), energy reduction gain (ERG), on-grid energy savings, throughput, etc. by varying different system parameters. Finally, the system performance is compared with the non-CoMP based existing schemes.

The rest of the paper is organized as follows. A through review of related works is discussed in section II. Section III presents the detailed discussion of system model along with solar energy model, wireless propagation model, BS power model, etc. User association algorithms are described in section IV. In Section V, we show numerical results with an insightful discussion. Finally, this paper is concluded in Section VI.

II. Related Works

Due to the apparent ever-increasing energy demand in cellular networks has received deep attention among academia and mobile operators. As a consequence, several efforts have been paid by cellular industries and academia to reduce the increasing trend of energy consumption [18]–[20]. Various techniques have been used to achieve higher energy efficiency such as turning off some selective BSs during low traffic hours [4], [21], [22], radio resource management [23], [24], and energy harvesting from renewable sources to power BSs [11], [12], [25]. However, the scope of using RE in cellular networks has been thoroughly investigated in [3], [26], [27]. Authors in [3] categorized energy savings via cooperative networks, adopting renewable energy resources, deployment of heterogeneous networks and efficient usage of spectrum. To tackle the tempo-spatial randomness of distributed RE harvested at cellular BSs, authors [26] proposed three approaches namely, energy cooperation, communication cooperation, and joint energy and communication cooperation. In [27], authors suggest that RANs are powered by renewable energy resources may be the most promising solution to reduce grid energy consumption. However, numerous researches [28]–[30] have carried out in literature to investigate energy efficiency of cellular networks with hybrid power supplies. Authors investigated the optimization of green energy utilization during peak traffic periods without counting the uncertainty of RE generation [28]. EE performance of DPS CoMP enabled LTE-A cellular networks with hybrid supplies has been thoroughly analyzed in the literature of [29]. Authors in [30] proposed

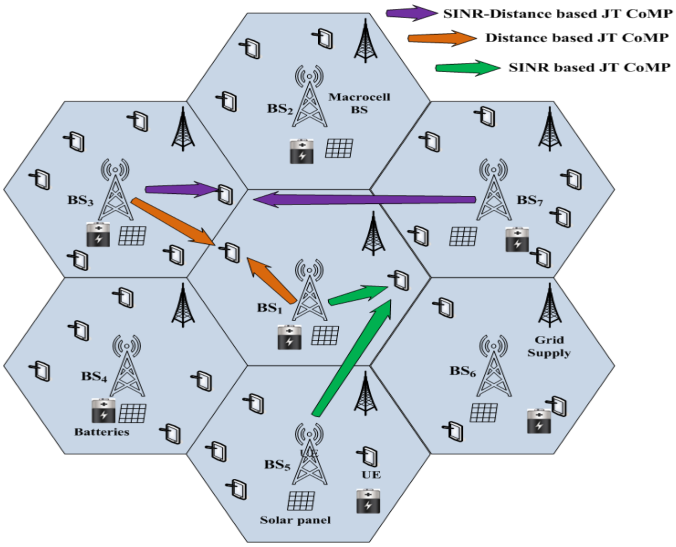

Fig. 1. A Section of the proposed network model with hybrid energy supply.

a joint paradigm of energy and communication approach via smart grid for exchanging grid energy. Huang *et. al.* [31] studies energy-aware cooperation among BSs for enhancing SE under CoMP based green cellular networks. Authors [32] has analyzed cell-edge user throughput under both homogeneous and heterogeneous cellular networks considering SINR based JT CoMP only. The SE performance of dynamic JT CoMP based next-generation green cellular networks has been extensively analyzed in [33]. The proposed paradigm studies only SE in the context of uplink 5G cellular networks without investigating EE. However, Shams *et. al.* [34] developed a renewable powered CoMP based simulator is for the LTE-A cellular networks addressing the aforementioned issues, which offered a free license for academic research and non-commercial use.

III. System Model

This section presents the proposed system model along with solar energy generation model and BS power consumption model. Moreover, wireless propagation model and formulation of performance metrics are also presented in the same section.

A. Network Layout

We consider the downlink of a LTE-A based cellular network consisting N BSs $\mathbb{B} = \{\mathcal{B}_1, \mathcal{B}_2, ..., \mathcal{B}_N\}$ covering an area $\mathcal{A} = \{\mathcal{A}_1 \cup \mathcal{A}_2 \cup ... \cup \mathcal{A}_N\} \subset \mathbb{R}^2$. Here, $\mathcal{A}_i$ is the coverage area of BS $\mathcal{B}_i$, $\forall i \epsilon \{1, ..., N\}$. Each BS is assumed to be deployed using omnidirectional antenna in a hexagonal grid layout with a set of orthogonal resource blocks (RBs), while the same RBs are reused among the BSs. We consider a finite-horizon time-slotted system with slot index, $1 \leq n \leq T$, where T denotes the total number of time slots.

All the BSs in the considered cellular network are powered by hybrid supplies, namely solar energy and conventional grid energy. Each BS is equipped with on-site renewable energy generating equipment such as PV solar panels and energy storage devices capability e.g., battery bank. The commercial grid is connected to each BS that enables to meet its energy deficit in absence of solar energy. A segment of the proposed network model with seven macrocells is illustrated in Fig. 1. The considered network deploys JT CoMP transmission technique for choosing the best serving BSs for UEs as discussed in section IV. On the other hand, users are assumed to be uniformly distributed throughout the network. Moreover, any BS during off-peak hours are switched into sleep mode for saving energy.

B. Link Model

This paper considers a channel model with log-normally distributed shadow fading. For a separation d between transmitter and receiver, path-loss in dB at a distance d can be expressed as

$$PL(d) = PL(d_0) + 10\alpha log(\frac{d}{d_0}) \tag{1}$$

where $PL(d_0)$ is the path-loss in dB at a reference distance d_0 and α is the path-loss exponent. $PL(d_0)$ can be calculated using the free-space path-loss equation.

Thus, the received power in dBm for k^{th} UE at a distance $d = d^{i,k}$ from i^{th} BS $\mathcal{B}_i$ is given by

$$P_{rx}^{i,k} = P_{x}^{i,k} - PL(d) + X_\sigma \tag{2}$$

where $P_{tx}^{i,k}$ is the transmitted power in dBm and X_σ is the amount of shadow fading modeled as a zero-mean Gaussian random variable with a standard deviation σ dB. The transmit power $P_{tx}^{i,k}$ from BS i to UE k satisfies $\sum_{k \epsilon U} P_{tx}^{i,k} \leq P_i^{max}$, where P_i^{max} is RF output power of BS $\mathcal{B}_i$ at its maximum traffic load and U is the number of active UE in this BS. For instance, two coordinated BSs serve a single UE jointly on the same frequency band simultaneously under JT CoMP transmission technique. Then, the received power at CoMP-UE can be expressed as

$$P'_{rx} = P_{rx}^{1,k} + P_{rx}^{2,k} \tag{3}$$

Here $P_{rx}^{1,k}$ and $P_{rx}^{2,k}$ are the received power in dBm from the two coordinating active BSs respectively. On the other hand, the adjacent channel interference can be expressed as:

$$\mathcal{I}_{k,inter} = P_{inter}^{i,k} = \sum_{m \neq 1,2} (P_{rx}^{m,k}) \tag{4}$$

Then the received SINR $\gamma_{i,k}$ at k^{th} UE from BS $\mathcal{B}_i$ can be given by

$$\gamma_{i,k} = \frac{P_{rx}^{i,k}}{\mathcal{I}_{k,inter} + \mathcal{I}_{k,intra} + \mathcal{P}_N} \tag{5}$$

where $\mathcal{I}_{k,inter}$ is the inter-cell interference, $\mathcal{I}_{k,intra}$ is the intra-cell interference, $\mathcal{P}_N$ is the additive white Gaussian noise (AWGN) power given by $\mathcal{P}_N = -174 + 10log_{10}(\Delta f)$ in dBm with Δf is the bandwidth in Hz. However, LTE-A system employs orthogonal frequency division multiple access (OFDMA), which results in zero intra-cell interference.

C. Solar Energy Generation Model

This paper considers the PV solar panel as the on-site renewable energy generator. The solar energy generation profile is highly variable in time and space depending on several factors, such as temperature, solar light intensity, panel materials, generation technology and the geographic location of solar panel. The daily solar energy generation shows temporal dynamics over a period of a day in the given area and exhibits spatial dynamics with geographical location. Due to the temporal randomness of solar energy generation, the available solar

TABLE I
SOLAR PANEL AND STORAGE DEVICE PARAMETERS

Parameters	Type (Value)
Solar module type	Photovoltaic (Distributed)
Generation technology	CSP PV cell
Solar panel capacity	1 kWdc
DC to AC ratio	0.9
Array type	Fixed roof mount
Tilt	20 degrees
Azimuth	180 degrees
Storage type	Lead-acid battery
Storage capacity	2000 Wh
Storage factor	0.96

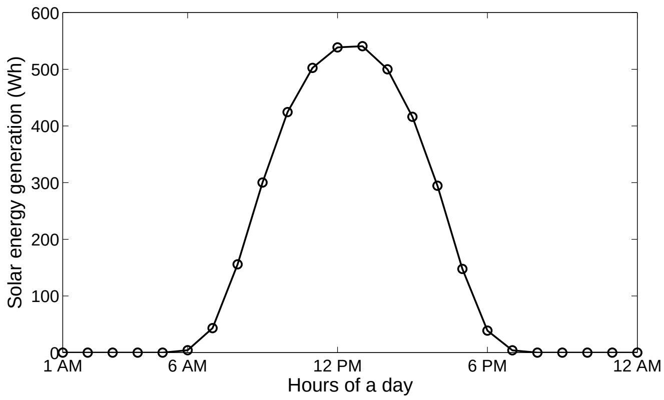

Fig. 2. Average hourly solar energy generation.

energy may not guarantee the adequate energy supplies for a BS to run for a whole day.

RE generated at BS $\mathcal{B}_i$, $i \in \{1, ..., N\}$ during time slot n is a random variable denoted by $r_i(t) \in [0, {r_i}^{max}]$, where ${r_i}^{max}$ is the maximum available solar energy generation by $\mathcal{B}_i$. The green power generation can be defined as $\int_{(n-1)\tau}^{n\tau} b_i(t)dt = r_i(t)$, where $b_i(t)$ is obtained from the instantaneous solar power profile as depict in Fig. 2 and τ is the duration of each time slot. Hence, this energy quantities represent the temporal averages over the corresponding time slots. The time varying average solar energy generation $\bar{r_i}(t)$ in BS $\mathcal{B}_i$ can be characterized by the following model [35]

$$\bar{r_i}(t) = \frac{{r_i}^{max} exp^{-(n-\beta_i)^2}}{\delta_i^2} \tau \tag{6}$$

In this model, the parameter β_i represents the position in time of the peak generation, chosen to be noon, i.e. 12 hours, $\forall i \in \{1, ..., N\}$, δ_i indicates the shape width at half maximum of the peak, chosen to be 3 hours, $\forall i \in \{1, ..., N\}$, and the time duration of each time slot τ is one hour.

Average hourly solar energy generation profile for full year in Dhaka city of Bangladesh is shown in Fig. 2. Here, solar energy profile for a particular region is estimated by adopting System Advisory Model (SAM) [36]. The curve indicates that the green energy generation starts at around 6:00 AM, reaches peak value at noon and falls down at zero level at about 6:00 PM. SAM supports various solar power generation technologies. However, without losing the generality, distributed type concentrated solar power (CSP) PV technology with 1 kW solar panel is used for generating the shown curve. On the other hand, though solar batteries, such as Ni-Cd, Ni-MH, Li-ion, Sodium Nickel Chloride, etc. are available for using in solar systems, lead-acid batteries are most commonly used in solar powered BSs. The parameters of the solar generation and storage systems for the considered solar module are summarized in Table I.

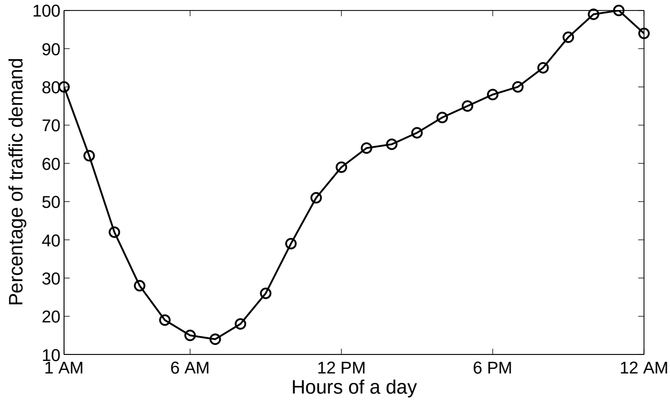

Fig. 3. Daily traffic load profile of a residential area.

D. BS Power Consumption Model

Energy consumption of BSs directly varies with their respective traffic demand, i.e., with the number of active UEs. Mobile traffic volume exhibits both temporal and spatial diversity. It is assumed that BSs transmit data to all users with the same data rate and each BS experiences different traffic intensity for a given period. Under the sleep mode operation scheme, BSs switch to sleep mode from an active mode that are currently not serving any UEs. Sleep mode operation of BSs by deactivating some hardware components can save a considerable amount of energy needed since a great portion of energy is required to operating BSs in active mode. As a result, a reduced operational energy consumption is attributed whenever the sleep mode operation is applied. Based on internal surveys on operator traffic data within the EARTH project [9], the daily traffic demand in the network is characterized by the normalized traffic profile illustrated in Fig. 3.

Energy consumption of BSs can be sub-divided into two parts: the static energy consumption and the dynamic energy consumption. The energy consumption of BS $\mathcal{B}_i$ at time slot $n \in T$ is given by [37]

$$E_{in}(t) = \sum_{i=1}^{N} \{P_i^{act} y_i(t)\tau + P_i^{sleep}(1 - y_i(t))\tau\} + \sum_{i=1}^{N}\sum_{k=1}^{U} \Delta_i P_{tx}^{i,k}(t) x_{i,k}(t)\tau \tag{7}$$

where P_i^{act} and P_i^{sleep} account for the power consumption of BS $\mathcal{B}_i$ operating in active and sleep modes respectively, Δ_i is the slope of load dependent power consumption of BS $\mathcal{B}_i$. The binary variable $x_{i,k}$ models the association between BS $\mathcal{B}_i$ and k^{th} user UE_k as in the following

$$x_{i,k} = \begin{cases} 1, & \text{if } UE_k \text{ is served by } \mathcal{B}_i, \quad \forall i, \forall k \\ 0, & \text{otherwise} \end{cases} \tag{8}$$

On the other hand, the activity status of BS $\mathcal{B}_i$ is modeled by the binary variable y_i(t) such that

$$y_i(t) = \begin{cases} 1, & \text{if } \mathcal{B}_i \text{ is active,} \quad \forall i \\ 0, & \text{if } \mathcal{B}_i \text{ is in sleep mode} \end{cases} \tag{9}$$

By collecting terms, (7) can be reinterpreted as

$$E_{in}(t) = E^{dym}(t) + E^{sta} \tag{10}$$

where $E^{dym}(t)$ and E^{sta} represent the dynamic and static energy consumption of E_{in} respectively as given below.

$$E^{dym}(t) = \sum_{i=1}^{N}\{P_i^{act} - P_i^{sleep}\}y_i(t)\tau + \sum_{i=1}^{N}\sum_{k=1}^{U}\Delta_i P_{tx}^{i,k}(t)x_{i,k}(t)\tau \tag{11}$$

$$E^{sta} = \sum_{i=1}^{N} P_i^{sleep}\tau \tag{12}$$

However, the authors in [9] approximated the operating power of a BS as a linear function of RF output power P_{MAX} and BS loading parameter χ, which can be given by

$$P_{in} = \begin{cases} M_{sec}[P_1 + \triangle_p P_{MAX}(\chi - 1)], & \text{if } 0 < \chi \leq 1 \\ M_{sec}P_{sleep}, & \text{if } \chi = 0 \end{cases} \tag{13}$$

where the expression in the square brackets represents the total power requirement for a transceiver (TRX) chain, M_{sec} is the number of sectors in a BS and P_1 is the maximum power consumption in a sector. The load dependency is accounted for by the power gradient $\triangle_p$. The loading parameter $\chi = 1$ indicates a fully loaded system, i.e., BS transmitting at full power with all of their LTE RBs occupied and and $\chi = 0$ indicates idle state. Furthermore, a BS without any traffic load enters into sleep mode with lowered consumption P_{sleep}. Now P_1 can be expressed as below [9]

$$P_1 = \frac{P_{BB} + P_{RF} + P_{PA}}{(1-\sigma_{DC})(1-\sigma_{MS})(1-\sigma_{cool})} \tag{14}$$

where P_{BB} and P_{RF} are the power consumption of based-band unit and radio frequency transceiver respectively. Losses incurred by DC-DC power supply, mains supply and active cooling can be approximated by the loss factors σ_{DC}, σ_{MS} and σ_{cool} respectively. Power consumption in the power amplifiers is represented by P_{PA} which depends on the maximum transmission power and power amplifier efficiency η_{PA} and can be given as follows [9]

$$P_{PA} = \frac{P_{MAX}}{\eta_{PA}(1-\sigma_{feed})} \tag{15}$$

BS power consumption model parameters used in this paper are summarized in Table II.

TABLE II
BS POWER CONSUMPTION MODEL PARAMETERS [9]

Parameters	Value
BS Type	Macro
η_{PA}	0.306
γ	0.15
$P_{BB}[W]$	29.4
$P_{RF}[W]$	12.9
σ_{feed}	0.5
σ_{DC}	0.075
σ_{MS}	0.09
σ_{cool}	0.1
Number of sectors, M_{sec}	1
Maximum transmit power, $P_{MAX}[dBm]$	43
$\triangle_p$	4.2
$P_{sleep}[W]$	54

E. Solar Energy Storage Model

Energy harvested from renewable source is stored in the battery for future use by the BS. During operation, storage devices keep charging and discharging according to the pattern of solar generation and BS consumption. The stored green energy at $\mathcal{B}_i$ is determined by the green energy consumption and generation of the previous time slot. For the proposed system, the amount of residual green energy of $\mathcal{B}_i$ at time t can be given by [38]

$$s_i(t) = \mu s_i(t-1) + r_i(t) - d_i(t) \tag{16}$$

where s_i is the green energy storage, r_i is the harvested green energy from PV solar panel, d_i is the energy demand of the BS and $0 \leq \mu \leq 1$ is the storage factor i.e., the percentage of storage energy retained after unit period of time. For example, $\mu = 0.9$ indicates that 10% energy will be lost in the storage during the time interval. It is to be noted that the stored energy can not exceed the maximum storage capacity. Therefore, if the generation is higher than the storage capacity, that amount of energy is considered as wastage. The initialization condition for the batteries is $s_i(0) = 0$, $\forall i \in \{1, ..., N\}$.

The net renewable energy available at a typical BS, denoted by $N_i(t)$ is the difference between RE generation and BS demand. That is $N_i(t)$ = $r_i(t)$ - $E_{in}(t)$. This quantity can be positive or negative, where positive quantity representing a surplus energy available and negative quantity implies a deficit. The traditional grid energy will be used to fulfill the deficit whenever the allocated green energy is inadequate. Let $h_i(t)$ be the indicator function of using two different energy sources as below

$$h_i(t) = \begin{cases} 1, & H_i(t) \geq E_{in}(t) \\ 0, & H_i(t) < E_{in}(t) \end{cases} \tag{17}$$

where $H_i(t)$ is the green energy available at BS_i at time t. If $h_i(t)$ = 1, the BS $\mathcal{B}_i$ is powered by green energy at time t; otherwise this BS is powered by conventional grid energy. Under the proposed model, the green energy utilization and on-grid energy consumption of $\mathcal{B}_i$ under different scenarios are as follows:

Case I: If $s_i(t) \geq d_i(t)$, then BS $\mathcal{B}_i$ will be served by its respective storage. Hence, no on-grid energy will be consumed whatsoever. The total green energy remains in the storage after fulfilling the demand, $g_i(t)$ can be expressed as

$$g_i(t) = s_i(t) - d_i(t) \tag{18}$$

After that, for the next period of time slot, the stored energy of BS $\mathcal{B}_i$ can be given by

$$s_i(t+1) = \mu g_i(t) + r_i(t+1) \tag{19}$$

Case II: If $s_i(t) < d_i(t)$, then BS $\mathcal{B}_i$ feeds itself from its remaining own storage; though its not sufficient to meet the demand fully. However, on-grid consumption is required to mitigate the shortage energy demand in the absence of sufficient green energy storage. Thus, the conventional grid energy consumption $c_i(t)$ by BS $\mathcal{B}_i$ is now

$$c_i(t) = d_i(t) - s_i(t) \tag{20}$$

In other words, the electrical grid is used to offset the remaining energy consumption whenever the allocated green energy is insufficient.

F. Performance Metrics

EE performance metric of a network given with the proposed CoMP technique in terms of bits per joule can be defined as the ratio of the aggregate throughput to the total power required for running the network. In this paper, we define the EE metric of the proposed network models with CoMP techniques and hybrid power supply as the ratio of the total throughput of the network to that of the net on-grid power consumed P_{net} by the network. Total achievable throughput in a network at time t can be calculated by Shanon's capacity formula as given below

$$R_{total}(t) = \sum_{k=1}^{U}\sum_{i=1}^{N_k} \Delta f log_2(1+\gamma_{i,k}), \text{ bps} \tag{21}$$

where N_k is the number of transmitting BSs simultaneously for serving k^{th} UE and U is the total number of UEs in the network. Thus, the EE metric denoted as η_{EE} for time t can be written as

$$\eta_{EE}(t) = \frac{R_{total}(t)}{P_{net}}, \text{ bits/joule} \tag{22}$$

where $P_{net} = \sum_{i=1}^{N} P_{in}(i,t) - \sum_{i=1}^{N} P_s(i,t)$ is the net on-grid power consumption in all the BSs at time t, $P_{in}(t)$ is the required total power in BS $\mathcal{B}_i$ at time t and $P_s(t)$ is the green solar power utilized by the BS $\mathcal{B}_i$ at time t.

An alternative performance metric for evaluating the EE of a BS is Energy Consumption Index (ECI) defined in [9], which can be given by

$$ECI = \frac{P_{in}}{KPI} \tag{23}$$

where P_{in} refers to the total input power of a BS, whereas KPI (Key Performance Indicator) indicates the total throughput of the BS. In other words, ECI is the reciprocal of EE and hence for the proposed networks, it can be evaluated by taking the inverse of (22), while a lower value of ECI implies better EE and vice versa. ECI is more suitable for better visualization of network behavior when the denominator of (22) becomes zero.

On the other hand, Energy Consumption Ratio (ECR) is an equipment level metric, which is the ratio of energy consumption to the effective system capacity. The ECR is evaluated for the whole radio access network (RAN) for a given average RF transmission power and a given average throughput in the network, measured in units of Watt/bps. The ECR metrics quantifies the amount of energy required for transmitting one bit of information. A system with a lower ECR is more energy efficient in its energy use, as each bit consumes less power for transmission. However, Energy Consumption Gain (ECG) in green cellular communication can be defined as a ratio of the ECR metrics of the two systems under consideration. For example, hybrid powered cellular network without CoMP mechanism is a baseline reference system and SINR based JT CoMP enabled hybrid system with a more energy efficient network architecture. Consequently, the ECG metric measures the energy consumption improvement compared to a reference baseline system [17]. Furthermore, another green performance metric named Energy Reduction Gain (ERG) is sometimes preferable in the context of energy efficient analysis in cellular networks. The ERG metric is derived from the ECG metric as [17]

$$ERG = (1 - \frac{1}{ECG}) \times 100\% \tag{24}$$

TABLE III
SUMMARY OF THE NOTATIONS USED IN THE ALGORITHMS

$\mathcal{RB}_t$	Total number of LTE RBs for a BS
$\chi_{i,j}$	Traffic demand of i^{th} BS $\mathcal{B}_i$ in j^{th} hour
N	Total number of BSs
T	Total number of time slots
U	Total number of UEs
BS_{n1}	First top BS among N BSs
BS_{n2}	Second top BS among N BSs
$d_{k\forall i}$	Distance of k^{th} UE (UE_k) from $\mathcal{B}_i, \forall i$
$\gamma_{k\forall i}$	Received SINR for k^{th} UE (UE_k) from $\mathcal{B}_i, \forall i$
$\gamma_{k,n1}$	Received SINR for k^{th} UE from BS BS_{n1}
$\gamma_{k,n2}$	Received SINR for k^{th} UE from BS BS_{n2}
T_j^D	Throughput for distance based JT scheme on j^{th} hour
T_j^S	Throughput for SINR based JT scheme on j^{th} hour
T_j^{S-D}	Throughput for SINR-distance based JT scheme on j^{th} hour

IV. User-BS Association Schemes and Algorithms

The term user association implies connecting a UE with BS(s) for receiving quaity service. Conventionally, a UE is connected to one of the serving BSs supporting the best signal quality, whereas a CoMP enabled UE can communicate simultaneously with more than one BSs located at different points based on association scheme. CoMP is an inter-cell cooperation technology specifically aiming to enhance throughput of UEs at the cell edge and mitigates inter-cell interference [15] as described in section I-A. Aiming to leverage the best possible way of UE-BS association, JT CoMP technique has been adopted throughout this paper. In JT CoMP, two or more than two BSs are simultaneously selected among the cooperating BSs as transmission points for better reception of UEs. In this paper, JT CoMP is carried out in three categories - distance based, SINR based and SINR-distance based as outlined below.

Distance based JT CoMP: A UE ranks the macrocells in an ascending order of the distance between the UE and the BSs. Then the UE is connected to the top m BSs in the list. For instance, in a network with 2-BS JT system, top two (i.e., $m = 2$) nearest BSs are selected for associating a UE, which jointly transmits data to the UE. In this paper, we name this scheme as Distance-Distance JT CoMP in the results section below.

TABLE IV

UE ASSOCIATION ALGORITHM FOR DISTANCE-DISTANCE BASED JT COMP SCHEME

Initialize: $\mathcal{RB}_t, \tau, \chi_{i,j}, k \in 1, 2, ...U$
for $j = 1 : T$
  for $i = 1 : N$
    Locations of $U = \chi_{i,j}\mathcal{RB}_t$ associated with $\mathcal{B}_i$ are updated
    Compute $d_{k\forall i}$
      for $k = 1 : U$
        Sort $d_{k\forall i}$ in ascending order
        Connect UE_k to BSs, BS_{n1} and BS_{n2} with minimum distances
        $T_j^D = T_j^D + 180[\log_2(1 + \gamma_{k,n1}) + \log_2(1 + \gamma_{k,n2})]$
        Update $\chi_{i,j}$
      end for
  end for
end for

TABLE V

UE ASSOCIATION ALGORITHM FOR SINR-SINR BASED JT COMP SCHEME

Initialize: $\mathcal{RB}_t, \tau, \chi_{i,j}, k \in 1, 2, ...U$
for $j = 1 : T$
  for $i = 1 : N$
    Downlink transmit power for U = $\chi_{i,j}\mathcal{RB}_t$ associated with $\mathcal{B}_i$ are updated
    Compute $\gamma_{k\forall i}$
      for $k = 1 : U$
      Sort $\gamma_{k\forall i}$ in descending order
        Connect UE_k to BS_{n1} and BS_{n2} with maximum SINR
        T_j^S = T_j^S + 180 [$\log_2$ (1+$\gamma_{k,n1}$)+$\log_2$(1+$\gamma_{k,n2}$)]
        Update $\chi_{i,j}$
      end for
  end for
end for

TABLE VI

UE ASSOCIATION ALGORITHM FOR SINR-DISTANCE BASED JT COMP SCHEME

Initialize: $\mathcal{RB}_t, \tau, \chi_{i,j}, k \in 1, 2, ...U$
for $j = 1 : T$
  for $i = 1 : N$
    Locations and downlink transmit power for U = $\chi_{i,j}\mathcal{RB}_t$ associated with $\mathcal{B}_i$ are updated
    Compute $d_{k\forall i}$ and $\gamma_{k\forall i}$
      for $k = 1 : U$
      Sort $\gamma_{k\forall i}$ in descending order
      Sort $d_{k\forall i}$ in ascending order
        Connect UE_k to BS_{n1} with maximum SINR and connect BS_{n2} with minimum distance
        T_j^{S-D} = T_j^{S-D} + 180 [$\log_2$ (1+$\gamma_{k,n1}$)+$\log_2$(1+$\gamma_{k,n2}$)]
        Update $\chi_{i,j}$
      end for
  end for
end for

SINR based JT CoMP: A UE ranks the BSs in a descending order of the received SINR. A UE is then associated with the top m BSs in the list. Once again, for a network with 2-BS JT system, top two BSs offering the highest and the next highest SINR values are then selected to serve the UE, which is termed as a SINR-SINR JT CoMP in the legend of figures described in results section.

Hybrid SINR and Distance based JT CoMP: It is a combination of the two earlier JT CoMP based UE-BS association schemes. For example, in a 2-BS JT cellular network, data intended for a particular UE comes simultaneously from two different coordinated BSs. More specifically, a UE is connected jointly with a BS that provides the highest SINR and the other BS having the shortest path among multiple coordinated BSs. This scheme is specified as SINR-Distance JT CoMP. On the other hand, 2 Distance - 1 SINR JT CoMP implies that three different BSs are selected to serve a UE in the considered hybrid network model. In this scheme, a BS offering the highest SINR and two other BSs having the shortest distance from the UE are picked for serving a UE. Nevertheless, an additional processing is required for involving more number of BSs, which may lead to increasing delays (i.e. latency).

A comprehensive comparison among the different user association schemes in terms of several network performance metrics is demonstrated in Sec V-B. Pseudo codes of the three different user association schemes with 2-BS JT schemes are presented in Table IV, V and VI respectively.

V. Performance Analysis

A. Simulation Setup

Performance of the proposed green powered JT CoMP based cellular network is evaluated through extensive Monte-Carlo simulations on a platform developed using MATLAB. Each calculated data point corresponds to the average value obtained from over 10,000 independent iterations. The network is deployed by using a hexagonal grid layout of BSs, which are erquiped with omnidirectional antennas. All the results presented in this section considered inter-cell interference contributions by neighboring BSs positioned in the two surrounding tiers. We assume same BS power profile parameters for all the BSs, while equal transmit power is considered for all RBs. UEs are considered uniformly distributed over the geographical area. Performance of the proposed network model for any non-uniform UE distribution can also be evaluated in a similar way. A summary of the system parameters of the simulated network considered in reference to the LTE standards [14] is presented in Table VII.

In the MATLAB environment, we set the input parameters according to the Table VII and Table VII. We then calculate the path loss and eventually received SINR at UEs according to (1) and (2) respectively. After that, we compute throughput based on received SINR for the three different JT CoMP schemes as specified in Table IV, V, and VI respectively. Unless otherwise specified, 2-BS JT scheme is used for the simulations of the proposed network models.

Under the analysis of energy issues, BS power consumption is estimated according to (13) based on the daily traffic profile as shown in Fig. 3. We also calculate its associated energy storage in batteries using (16) at each iteration. Basically, we adopt an energy storage policy during simulations, where the surplus green energy is stored in the battery bank for future use. A BS fulfills its own demand from green solar energy as it is kept as the primary source and is powered by commercial grid supply during scarcity of green energy. Based on the above mechanism as described, we further calculate different performance metrics as described in Section III-F.

TABLE VII
SIMULATION PARAMETERS

Parameters	Value
RB bandwidth	180 kHz
System bandwidth, $\mathcal{BW}$	10 MHz (50 RBs), 600 subcarriers
Carrier frequency, f_c	2 GHz
Duplex mode	FDD
Cell radius	1000 m
BS transmit power	43 dBm
Noise power density	-174 dBm/Hz
Number of antennas	1
Reference distance, d_0	100m
Path loss exponent, α	3.574
Shadow fading, σ	8 dB
Access technique	OFDMA
Traffic model	Temporal and spatial diversity

B. Result Analysis

Fig. 4 illustrates the empirical cumulative distribution function (ECDF) of received SINR showing the distribution of SINR throughout the network coverage. For benchmarking, we consider different UE association schemes based on JT CoMP technique and the network is assumed to be fully loaded (i.e. $\chi = 1$). From the figure, a clear difference in SINR distribution is noticed for different JT CoMP based hybrid systems. As seen, SINR based JT CoMP enabled hybrid system keeps its optimistic nature achieving comparatively stronger SINR ranging from -2dB to 80dB. On the other hand, a distance based JT CoMP hybrid scheme has the worst SINR performance as it spreads out over a larger range compared to other techniques. SINR performance of the SINR-distance based JT CoMP system lies in between the SINR based and distance based JT CoMP systems as it also selects at least one BS supporting the best signal quality. This phenomenon can be explained as below. For 2-BS JT cases, under SINR-SINR based JT CoMP technique, a particular UE receives the best signal quality than the other JT schemes. The path loss occurred in SINR-SINR JT CoMP is inherently lower than other scheme which results in improved SINR performance. On the other hand, the nearest BS is never fully guaranteed to provide the best possible SINR due to the random nature of shadow fading. Thus, under the SINR-distance based JT CoMP transmission, a UE may receive the strongest signal from a BS, but another BS may not provide the best signal quality. The simulation results imply the same results. From the figure it can also be readily identified that compared to the 'Hybrid without CoMP' model, UEs experience significantly better signal quality under all the proposed network models. Here, the 'Hybrid without CoMP' model defines the conventional network model without any CoMP transmission mechanism,

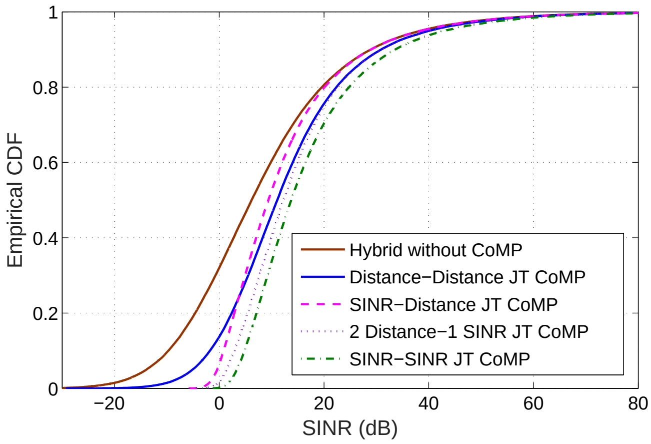

Fig. 4. Empirical CDF of received SINR among different hybrid systems for $\chi = 1$.

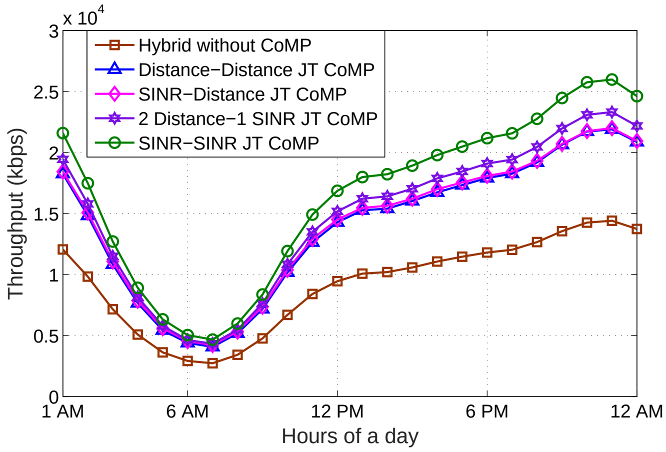

Fig. 5. Throughput comparison of a single BS among different hybrid models.

but the BSs are powered by both green solar energy and grid energy.

Fig. 5 presents the throughput performance over a day of the proposed model along with other hybrid schemes. From the figure, it is clearly observed that throughput curves apparently follows the given traffic pattern in a day (as depicted in Fig. 3). We presume one UE occupies one RB and hence, the total number of occupied RBs in a BS varies with traffic distribution. Throughput is directly varied with the number of RBs. During peak traffic arrivals, a higher number of RBs are allocated to the users resulting in higher throughput and vice versa as seen in the figure. Out of all the proposed schemes including the conventional 'Hybrid without CoMP' model, SINR based JT CoMP hybrid model provides the best throughput performance due to its improved SINR performance (as seen in Fig. 4) and thus enhances overall SE over other hybrid schemes as clearly evident from the figure.

A comparison of key network performance metric, i.e., EE for different hybrid models is demonstrated in Fig. 6 over a period of a day. As throughput is directly related to received signal quality (i.e. SINR), improved SINR guarantees better throughput. As a result, under the proposed network models, total throughput increases leading to direct improvement of EE. Therefore, as seen from the figure, our proposed network models show better EE performance compared to the other

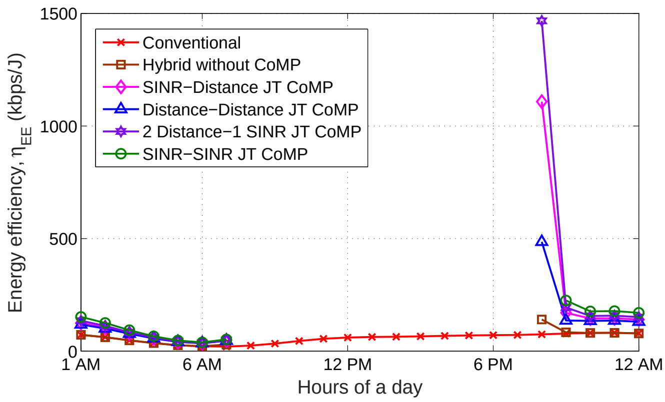

Fig. 6. EE comparison among diffrent hybrid models.

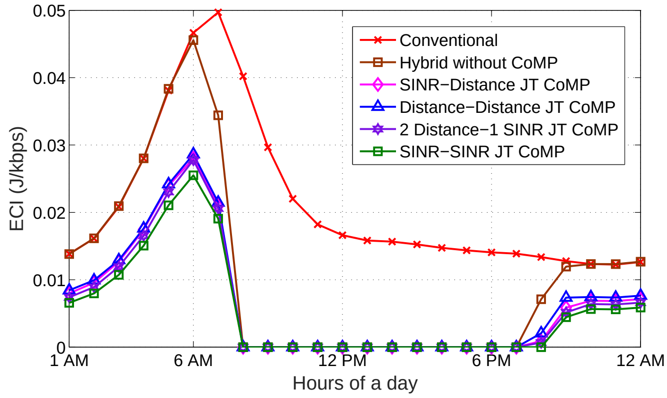

Fig. 7. ECI comparison among different hybrid models for a single BS.

models. As seen, EE of the 'Conventional' scheme is inferior compared to our proposed models. Here, 'Conventional' model implies a cellular network with BSs, which are powered by utilizing only traditional grid energy (i.e., no RE source). In addition, each UE is served by only one of the BSs, i.e., no CoMP mechanism is involved. However, all the curves except the conventional one follow similar patterns. As observed, during midnight to morning energy efficiency falls down due to the unavailability of sunlight. As time goes, EE raises slightly with the increasing solar intensity. With the further solar energy generation, EE curve reaches to infinity between 7 AM to 8 PM signifying that BSs do not consume any on-grid energy. This infinity EE horizon is marked by drawing no line in the figure. During this period, BSs are run by the green energy only. As net power consumption P_{net} from grid goes to zero due to the sufficiency of green energy, EE becomes infinity according to (22). We also observe the down trending nature of EE curves for all the hybrid models during night, which indicates that the stored green energy becomes increasingly insufficient at each BS due to the unavailability of sunlight. Finally, at the empty green energy storage condition, EE curve shows almost flatter response. On the other hand, the infinity region of the proposed hybrid network models is comparatively wider than the 'Hybrid without CoMP' system implying higher savings of grid energy consumption. Out of all the proposed hybrid models with JT CoMP, SINR based one has the widest infinity region. Therefore, it can be concluded that the SINR based JT CoMP hybrid network model provides the best EE performance.

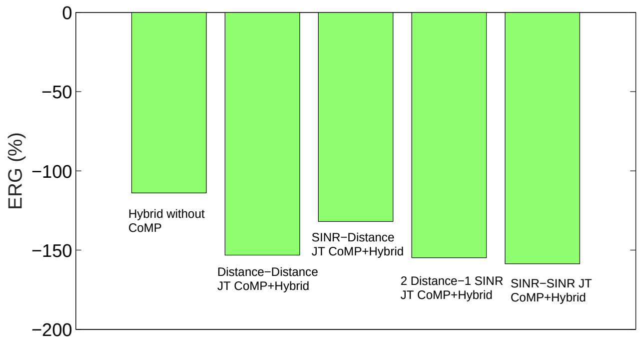

Fig. 8. ERG comparison among different hybrid models with the existing scheme for a single BS.

Fig. 7 compares the ECI metric variation among the different hybrid models over the duration of a day. During low traffic arrivals, ECI increases sharply up to a certain point and then takes sudden fall beyond that point. The up-trending behavior of ECI curve indicates the higher grid energy consumption while the amount of solar intensity is negligible. After the early morning period, ECI curves tend to push downward with the increase of sunlight. During 8 AM to 8 PM, ECI curve falls to zero implying maximum EE is achieved (i.e., on-grid energy consumption is nearly zero). With the decrease of solar energy generation, batteries discharge faster and once again after 8 PM, grid energy is required for powering the BSs in order to maintain network coverage. Comparison among the proposed JT CoMP based hybrid models, this figure once again demonstrates the optimistic nature of SINR based JT CoMP hybrid system in which UEs receive better signal quality, while the most pessimistic performance is obtained by distance based JT CoMP hybrid one.

A detail quantitative comparison of the energy reduction gain (ERG) performance of different hybrid models is demonstrated in Fig. 8. According to the definition of ERG in section III-F, it evaluates the reduction of on-grid energy consumption relative to the reference system and here hybrid scheme without CoMP is considered as a baseline. It has been observed that, the proposed network model achieves about 29% energy reduction gain over non-CoMP hybrid system. Moreover, only 4% and 2.6% energy consumption gain is attain through SINR based JT model over distance based JT CoMP and 2 distance - 1 SINR based JT CoMP hybrid models respectively. Therefore, it can be concluded that SINR based UE association policy attains superior network performance as clearly observed from Figs. 4-8. Therefore, the rest of the results presented in this paper are analyzed considering the proposed SINR based JT CoMP Hybrid scheme.

Fig. 9 presents the variation of total network power consumption of the proposed SINR based model with the number of coordinated transmitting BSs. Simulations for this figure including the following twos are done considering both tempo-spatial traffic diversity, i.e., traffic variation is considered among the BSs. Temporal traffic variation is incorporated by using the traffic pattern over a day as shown in Fig. 3. Whereas, spatial traffic variation is simulated by modeling BS loading parameter χ in (13) as a uniformly distributed random variable in $[0, 1]$. A total number of 19 BSs with one BS at the center and 18 others surrounding the center one placed in two neighboring tiers are considered for evaluating the total network power over a day. It is widely recognized that network power consumption increases with the traffic load and number of transmitting points as well. As seen, for a transmit power of 43 dBm, network power consumption starts to increase rapidly from 1500W and eventually reaches a constant value around 2800W for a certain number of BSs. This is due to the fact that all the transmitting BSs are considered to be in active mode always and the BSs which are far away from the UE have negligible chance to be selected for joint transmission. On the other hand, performance of the proposed SINR based JT CoMP network model by incorporating sleep mode approach is also included in the figure demonstrating improved performance over the non-sleep based system. Sleep mode mechanism is the most popular idea to minimize BS energy consumption by monitoring the traffic load. This is due to the fact that all most all the power hungry equipment in a BS remain shut off during sleep mode operations, which leads to a significant reduction of overall grid consumption in a RAN infrastructure. Moreover, the results are further analyzed for the two different transmit power settings. Proposed cellular networks certainly consumes much higher power for 46 dBm case over 43 dBm transmit power under both sleep mode and non-sleep mode mechanism as evident from the figure.

A comparison of throughput distribution with the transmitting BSs including sleep mode access is demonstrated in Fig. 10. In general, data intended for a particular UE from multiple number of BSs leads to a higher throughput performance. As seen from the figure, throughput starts to increase rapidly for the smaller number of transmitting BSs. As the number of BSs increases, throughput curve continually follows decreasing manner and eventually reaches to a constant value. The UEs usually ranks the BSs in descending order based on SINR and tends to connect the BSs offering highest SINR. As a consequence, the RBs of top serving BSs are occupied in a faster rate and hence the next upcoming UEs will connect to BSs having lower SINR which may be located at a further distance. To this end, when the number of BSs reaches its optimal value, the throughput then tends to decrease. Nevertheless, a number of transmitting BSs corresponding to the first peak in the throughput curve indicates the optimal number of BSs to be selected that maximizes the number of bits transmitted per second. From the figure, it can readily be identified the optimal number BSs is equal to 2 in which throughput performance is the best. In other words, the SINR based JT CoMP hybrid cellular network model selecting top two BSs offering maximum SINR for transmission reveals improved network performance as explained beforehand. It is to be noted that when the number of serving BSs is equal to one, the curve indicates that only DPS CoMP technique is carried out. However, the throughput curve starts to fall down beyond the optimal point and eventually reaches to a nearly constant value showing inferior throughput performance compared to DPS CoMP association policy. This is because, BSs which are far away from the UE has a negligible contribution to the throughput as the SINR contribution becomes very low. On the other hand, under the sleep mode approach, the proposed network model has shown superior throughput performance. Furthermore, results for two different transmit power settings (43 and 46 dBm) are also included in this figure. However, due to the change in transmission power,

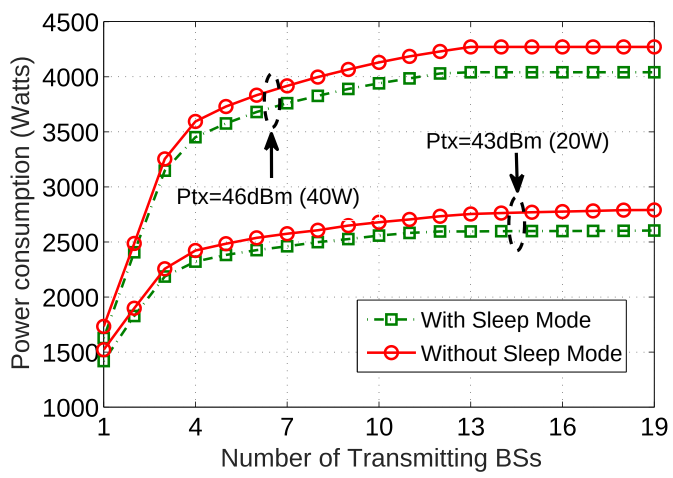

Fig. 9. Network power consumption with the number of jointly transmitting BSs for the proposed SINR based model.

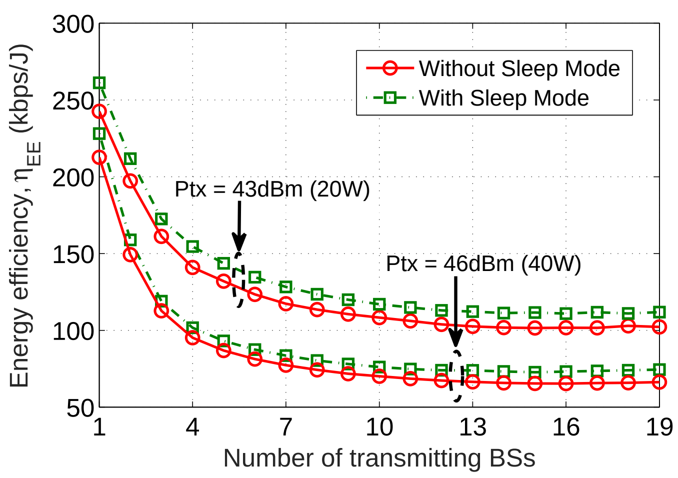

Fig. 11. EE performance with the number of jointly transmitting BSs for the proposed SINR based model.

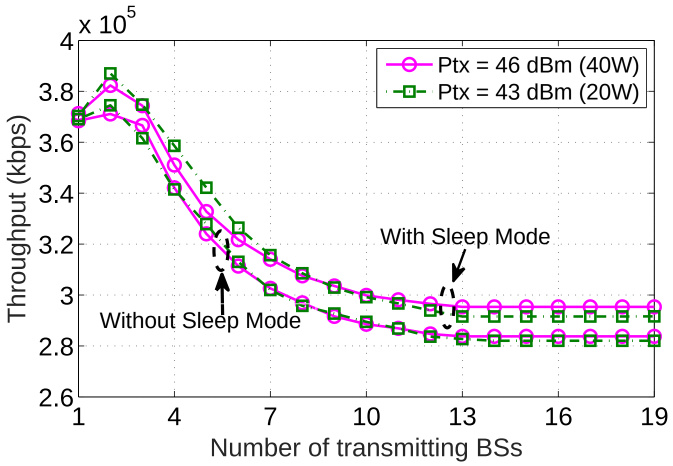

Fig. 10. Total throughput with the number of jointly transmitting BSs for the proposed SINR based model.

inter-cell interference also changes with the received signal power simultaneously. As a consequence, a very insignificant change of throughput performance is observed between the two different transmission power settings.

Dependency of EE on the active number of BSs with and without sleep mode approach is illustrated in Fig. 11. As expected, the EE metric curve clearly shows a downward trend with the increase of the number of transmitting BSs due to decreasing throughput. Unlike the optimal point in the case of throughput curve, EE metric curve shows almost the similar pattern. However, with the rising number of servicing BSs leading to linearly increasing total energy consumption and decreased throughput eventually forces EE metric to drop down as seen from the figure. Notably, both the curves have a similar pattern reaching their constant bottom values at their respective number of transmitting BSs. Furthermore, the EE performance for the low power transmission mode exhibits better performance due to low power consumption.

VI. Conclusion

In this paper, we have proposed a novel energy efficient multi-cell cellular network framework to improve EE with hybrid supplies. Envisioning the BSs to be powered by green energy sources has shown a remarkable aptitude for improving EE performance. The proposed framework has integrated JT CoMP technique with various selection schemes for selecting best user-association method. We particularly investigate three individual cases in which user connects with BSs based on distance, SINR and SINR-distance JT CoMP techniques. Network performance in terms of throughput, ECI, ERG and EE performance has been evaluated through extensive Monte-Carlo simulations. Numerical results illustrate the huge potential of the proposed cellular network models in substantially improving the total energy reduction gain being over 29% compared to the existing hybrid system model. Moreover, simulation results have identified that SINR based JT CoMP UE-BS connection policy achieves the best EE performance by maximizing the system throughput. BS sleep mode provision has also been investigated demonstrating improved EE performance compared to that of without sleep mode approach. Future extension of this work will focus on developing generalized algorithms and analytical modeling for heterogeneous networks and the verification of the network performance with the simulation results.

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