

Traffic Skewness-aware Performance Analysis of Dual-powered Green Cellular Networks

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Abstract—Solar-powered and power grid connected green cellular networks are becoming attractive due to low carbon footprint and cost-effectiveness in providing uninterrupted service. In this paper, we analyze the performance of such dual-powered multi-cell network in presence of skewed traffic load across the different base stations (BSs). Cell coverage is decided at the network design stage based on long-term average traffic intensity across the various regions of a multi-cell coverage area. In presence of dynamically-changing skewness of traffic loads across different cells, we propose to adjust the cell coverage to accommodate the traffic and energy availability imbalance in the cells, while the demand for residual energy deficiency for serving the customers is fulfilled through the power grid connectivity. Network service provider's cost with the proposed coverage adjustment based strategy is compared with that of the conventional approach where the individual BSs do not undergo any cell coverage adjustment and seek to provide the maximum network performance. Our analysis and simulation-based performance results demonstrate, that the network performance as well as monetary gains of the service provider are significantly higher with our proposed strategy. For example, at a moderate (30%) traffic skewness, the proposed strategy offers about 4% gain in operator's annual profit, while serving about 8% more users on average at the peak hour. At a very high (80%) skewness, these numbers are respectively about 50% and 39%.

Index Terms—Dual-powered base station, solar energy harvesting, energy load balancing, green communication

I. INTRODUCTION

Traffic load management along with reducing the base station (BS) power consumption have been long-standing problems towards the development of green cellular networks [1], [2]. While solar-enabled BS is a key enabler towards realizing green communication systems, it is not economically viable to eliminate the energy-outage in pure solar-powered BS. Hence, dual-powered cellular networks with the ability to draw power on demand is a cost-effective alternative. In this work, we focus on such dual-powered BS clusters and study cellular operation strategies to maximize the service provider's revenue while fulfilling user service guarantee.

A. Related works and research gap

The continually increasing user service requirements, demand a re-look at the network problems from the network operator's perspective of economics and logistics, and not solely from the traditional user's perspective. The work in [3] provided a general tractable coverage framework for flexible user association, BS capacity, and spectral efficiency within a conventional grid powered multi-tier network from the user's

perspective. Some pertinent works towards energy-sustainable BSs were [4], [5], and [6]. The work in [4] tended towards realizing green BSs by dimensioning the BS power generator and energy storage with Photo Voltaic (PV) panels and batteries respectively. A simpler approach was considered in [5], where the renewable energy being harvested, was modeled as a discrete-time Markov chain. Similarly, the study in [7] was significant in finding out the distribution of the difference between harvested and consumed energies through a Gaussian mixture model approach while, [8] characterized the solar harvested energy for sensor node operations.

Energy harvesting strategies to power small cell networks was studied in [9], investigating its feasibility and network issues. The study in [10] moved a step ahead towards designing green energy and delay aware networks, for determining user-BS association in off-grid systems. Network centric strategies like Dynamic BS ON/OFF were discussed in [6] to reduce the net power consumption in the network, while the authors in [11] and [12] proposed cell zooming techniques for reducing the energy consumption of the network. Lately, there have been some considerable efforts towards improving the interaction between grid and BSs by providing cost benefits in return of ancillary services in [13].

We observe that, while green energy provisioning in cellular networks as well as on-demand energy usage from the power grid have been investigated, the traffic heterogeneity aware resource allocation, along with traffic skewness aware BSs' energy availability imbalance and the associated power grid interaction requirement have not been analyzed and optimized.

B. Motivation and contributions

The spatio-temporal variation in user traffic in a dual-powered wireless network with a given solar dimensioning could result in an energy-traffic imbalance that is addressable at the cellular level, where some BSs maybe energy deficient while its neighboring ones may be energy surplus. Further, the differential service requirements suggest that, while some traffic (e.g., voice/multimedia) may require a minimum rate guarantee, some others (e.g., data) may not require any rate guarantee. It is anticipated that, accounting for traffic heterogeneity will also aid in optimizing the energy usage, thus increasing the service provider's revenue.

In view of the above motivations, key contributions of this work are as follows: (1) To deal with traffic skewness-dependent energy availability imbalance at the neighboring

BSs, a novel energy balancing scheme is proposed wherein the radio network controller (RNC) adjusts the various cell coverage areas as a function of the individual BS's energy availability and user density at a given time. Power grid connectivity for drawing or supply of power is invoked subsequently, which aids in service provider's revenue maximization. (2) In serving skewed user traffic, their service classes are considered, to optimize the energy resource requirement, which also aids in revenue earning. (3) The proposed energy-and-traffic-aware coverage adjustment based network performance is compared with the conventional approach, where the individual BSs do not have the flexibility to modify their coverage areas, even though can interact with the power grid when subjected to skewed traffic. Our performance results demonstrate significant gain in revenue as well as network performance with the proposed traffic heterogeneity aware energy load balancing, which is a function of the traffic skewness.

C. Organization

The paper layout is as follows. The cellular system model is presented in Section II, followed by a mathematical analysis of traffic heterogeneity aware resource allocation in Section III. Section IV presents the algorithm for resource allocation in a conventional dual-powered network without cell coverage adjustment (WCA), followed by the algorithm in the proposed coverage adjustment (CA) scheme. Section V contains simulation results on network service performance and revenue. Section VI concludes the paper.

II. SYSTEM MODEL

Let the users in a closed system, of fixed area A be distributed as a Poisson Point Process (PPP) with density λ_u , resulting in the total number of users distributed in the area to be $N = \lambda_u \cdot A$. This PPP distribution of the users represent the long term average user distribution. Based on the user locations and, the number of BSs considered, the optimum centroid coordinates for the K dual-powered BSs are calculated using K-Means clustering algorithm, and this set of BSs is represented as $\mathbf{B} = \{BS_j\}$. Based on this long-term average PPP distribution of the users, at the design and deployment stage, the transmit power of all the K BSs are assigned to be equal, i.e, $\mathbf{P} = \{P\} \forall j \in \{1, 2, \dots, K\}$ such that $(0 \leq P \leq P_{max})$. The system model is shown in Fig.1(a).

The users are assumed to associate with the BSs following the maximum received power level criterion, using which the cell radii are calculated for each BS at the design/deployment stage, ensuring no coverage void in the entire area with minimum overlap. Let the design level cell radii be represented as $R_{des} = \{R_1 \dots R_K\}$. The net traffic profile ρ_t considered for the entire area is shown in Fig. 1(b) has been generated from the data collected in [14]. Thus the traffic intensity ρ_{tj} for the j^{th} BS is highly skewed at any hour of the day.

For studying the effects of various levels of traffic skewness, a full day of 24 hour duration is granularized into six windows of four hours each and a BS is subjected to skewed traffic in any one window such that some other BS experiences

the skewed traffic as the day progresses. The various traffic skewness levels considered for one window in our analysis are shown in Fig.1(i). Our analysis includes all the possible permutations for these skewness levels. Although the long term average traffic across all BSs follow the same pattern as shown in Fig. 1(c), it is considered that at different hours of the day, the traffic distribution is rather skewed, with some BSs experiencing more than long-term average traffic load whereas some others have less than their long-term average load. This is due to the practical reason of cellular users activity related displaced location during different parts of the day. As an example, for demonstration and generating numerical results, the closed location of area A is considered to be covered by 6 BSs, as depicted in Fig. 1(c) through Fig. 1(h).

The traffic intensity subjected to a BS is further classified as delay-tolerant and delay-constrained. For a preliminary study it is considered that for any BS j at hour t , the delay-tolerant traffic intensity ρ_{tj}^{DT} and the delay-constrained traffic intensity ρ_{tj}^{DC} are 50% each, such that $\rho_{tj} = \rho_{tj}^{DC} + \rho_{tj}^{DT}$ and $\rho_t = \sum_{j=1}^K \rho_{tj}$. The number of active users associated with a BS j at hour t is denoted as $N_{tj} = N\rho_{tj}$, out of which $N\rho_{tj}^{DT}$ and $N\rho_{tj}^{DC}$ are the number of active users generating delay-tolerant and delay-constrained traffic respectively. This skewed traffic system model framework will be used throughout this paper in all subsequent analysis and calculations.

III. ANALYSIS OF RESOURCE ALLOCATION

This section presents traffic heterogeneity aware resource allocation and BS downlink transmit power calculation.

A. Per user power allocation based on traffic class

Let the net available bandwidth be denoted as BW . Assuming Fractional frequency reuse (FFR) at the BSs, we consider that each user gets an equal amount of Bandwidth BW_{tj}/N_{tj} , where $BW_{tj} = BW\rho_{tj}$ is the portion of bandwidth allotted to BS j by the RNC at the t^{th} hour depending on the traffic intensity at each BS. Thus, the rate offered at a location $x \in A$, at a radial distance r_{jx} from BS j , is given as $\psi_{jx} = \frac{BW_{tj}}{N_{tj}} \log_2(1 + SNR_{jx})$, where the Signal-to-Noise Ratio (SNR) at the radial location x is given by $SNR_{jx} = \frac{g_{jx}P_{jx}}{r_{jx}^2 \sigma^2}$. σ^2 denotes the additive noise power level, g_{jx} is the channel gain between the user location and BS j taking the path-loss and shadowing loss into account, and P_{jx} is the portion of transmit power being allocated to the user at that location depending on the channel condition. It is notable that inter-cell interference does not arise as each BS has a different set of frequencies owing to FFR.

From the physical layer perspective the delay-constrained traffic mandates a certain rate threshold to be maintained, on the other hand, even though, the delay-tolerant traffic does not mandate a rate threshold, it needs a certain SNR threshold to be met for some nominal rate requirement. Let the rate guarantee for delay-constrained traffic be represented as r_{th} while the SNR threshold for delay-tolerant traffic be τ . Let the probabilities that the rate requirement of a delay-constrained

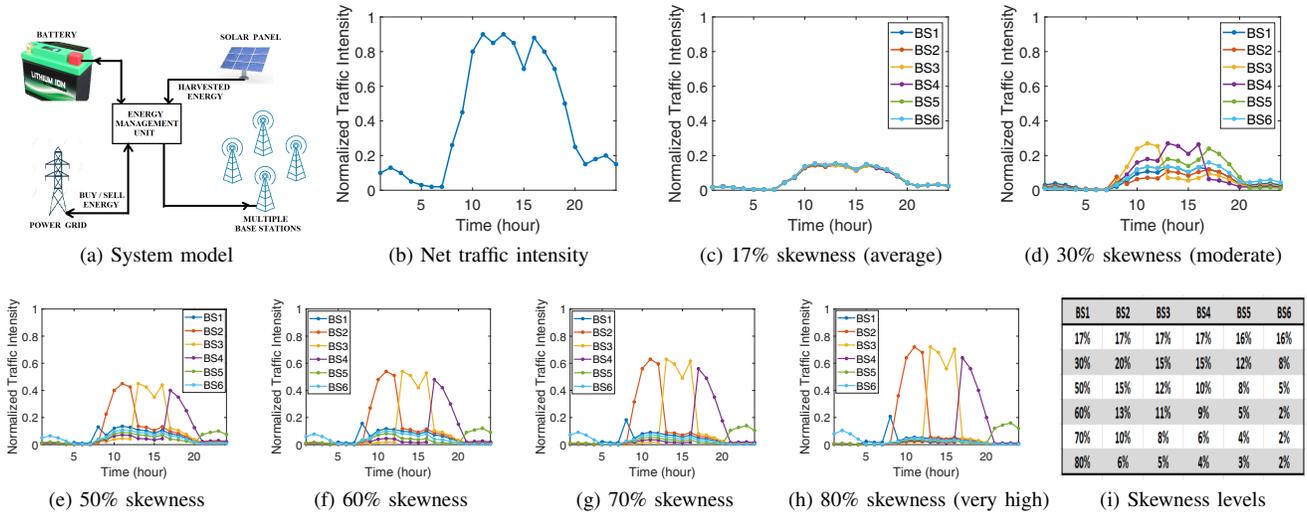


Fig. 1: (a) System model; (b)-(i) Net traffic intensity and the various traffic skewness levels subjected on the BSs.

user is satisfied and the SNR threshold of a delay-tolerant user is met be p_0 and q_0 , respectively.

The mathematical expression of power allocation for quality of service (QoS) guarantee to delay-constrained traffic considering Rayleigh distributed channel gains with unit mean is given by:

$$\mathbf{P}(\psi_{jx} \geq r_{th}) \geq p_0 \quad (1)$$

$$\text{i.e., } \mathbf{P}\left(g_{jx} \geq \frac{[2^{\frac{r_{th} N_{tj}}{BW_{tj}}} - 1] r_{jx}^2 \sigma^2}{P_{jx}}\right) \geq p_0$$

$$\text{or, } \exp\left(-\frac{[2^{\frac{r_{th} N_{tj}}{BW_{tj}}} - 1] r_{jx}^2 \sigma^2}{P_{jx}}\right) \geq p_0$$

$$\text{or, } P_{jx} \geq \frac{[2^{\frac{r_{th} N_{tj}}{BW_{tj}}} - 1] r_{jx}^2 \sigma^2}{\ln(\frac{1}{p_0})} \quad (2)$$

where P_{jx} is the minimum required transmit power to a user at radial distance r_{jx} . Similarly, the mathematical representation for QoS guarantee to the delay-tolerant traffic is:

$$\mathbf{P}(SNR_{jx} \geq \tau) \geq q_0 \quad (3)$$

$$\text{i.e., } \mathbf{P}\left(g_{jx} \geq \frac{\tau r_{jx}^2 \sigma^2}{P_{jx}}\right) \geq q_0$$

$$\text{or, } \exp\left(-\frac{\tau r_{jx}^2 \sigma^2}{P_{jx}}\right) \geq q_0$$

$$\text{or, } P_{jx} \geq \frac{\tau r_{jx}^2 \sigma^2}{\ln(\frac{1}{q_0})} \quad (4)$$

(2) and (4) represent the minimum power allocation by a BS to a delay-tolerant/constrained user depending on its location and channel condition to meet QoS requirements.

B. BS Downlink transmit power calculation

Since the users are distributed following a PPP, the probability density function (pdf) of user locations around a BS is

given as $f_X(x) = 2\pi\lambda_u x e^{-\lambda_u \pi x^2}$. Thus the average power consumed with the long-term traffic distribution within the associated BS coverage radius $R_{tj} = R_{des} = \{R_1 \dots R_K\}$ is given by $P_{avg} = \int_0^{R_{tj}} P_{jx} f_X(x) dx$. Depending on the traffic class to be delay-constrained traffic or delay-tolerant, solving the integral using (2) and (4) respectively, along with binomial negative exponential approximation gives:

$$P_{avg}^{DC} = \left(\frac{[2^{\frac{r_{th} N_{tj}}{BW_{tj}}} - 1]}{\ln(p_0)}\right) \sigma^2 (1 - \lambda_u \pi R_{tj}^2) \left(R_{tj}^2 + \frac{1}{\lambda_u \pi}\right) \quad (5)$$

$$\text{and, } P_{avg}^{DT} = \frac{\tau \sigma^2 (1 - \lambda_u \pi R_{tj}^2)}{\ln(q_0)} \left(R_{tj}^2 + \frac{1}{\lambda_u \pi}\right) \quad (6)$$

Using the hourly traffic intensities for either traffic class at each BS, the downlink transmit power level for the j^{th} BS at the t^{th} hour is expressed as:

$$P_{tj} = P_{avg_t} = (P_{avg_t}^{DT} \rho_{tj}^{DT}) + (P_{avg_t}^{DC} \rho_{tj}^{DC})$$

$$\text{or, } P_{tj} = P_{avg_t}^{DT} + P_{avg_t}^{DC} \quad (7)$$

Thus, the hourly dynamic downlink transmit power level required to be radiated by a BS in the network, to fulfil the QoS requirements of all its cell users has been calculated as a function of traffic intensity and cell radius.

IV. CELL COVERAGE ADJUSTMENT AND GREEN ENERGY ALLOCATION

This section presents two possible network operation scenarios in the current skewed-traffic aware framework.

A. Proposed coverage model versus conventional model

The inability of a BS to guarantee the required QoS to all its active cell users if subjected to skewed traffic at any hour can lead towards two possible network operation strategies. In the conventional approach, the BSs tend to increase their transmit power level (up to P_{max}) to fulfil the QoS requirements of as many of its cell users, without having any flexibility of coverage adjustment. It is notable that the user density at any

given hour for any cell is constant. This is because the users are distributed as a PPP in the area and it is followed even during displacement of users among the cells at any intensity. This conventional without-coverage adjustment model (WCA) is presented in Part I of Algorithm (1) where, for the BS subjected to skewed traffic, the radius is decremented by a unit distance and the corresponding number of users getting unserved (Uns_{tj}) are calculated, recursively checking the transmit power constraint and updating the unserved users and new active number of users N_{tj}^n .

The proposed strategy follows Part I. The energy deficient BS which has been unable to fulfil the QoS of all its users due to the skewed traffic rely on its adjacent BSs to accommodate its unserved users. The adjacent BSs being energy-surplus, expand their coverage area by incrementing their radius by a unit distance till the distance the skewed traffic BS had shrunk, recursively maintaining the transmit power constraint and updating their active number of users. In this strategy, the user is assigned to a neighbouring BS in accordance with the received signal strength at his location w.r.t the neighbouring BSs. The proposed algorithm for this coverage-adjustment model (CA) is shown in of Part II of Algorithm (1). Here, adj_j represents an adjacent matrix, comprising of the indices of the adjacent BSs (w) to each BS and $served_{tw}$ denotes the total number of users, who were earlier associated with the skewed BS and are now being accommodated by the w^{th} neighbour. The first two rows in Table I shows the average fraction of users served during peak hours (when $Uns_{tj}! = 0$ in Fig.2(d) and (e)) with both the models demonstrating that the fraction of users getting served in our proposed model of adjustment is significantly higher than the conventional no-coverage adjustment model.

B. Energy harvesting model

Green energy is allocated on an hourly basis to the BSs once the RNC adjusts their cell sizes in to further energy-balancing. Annual solar radiation data provided by National Renewable Energy Laboratory, is fed into System Advisor Model [15] to get hourly energy generated (H_{tj}) by a 1KW rated PV panel. Thus the total energy harvested per hour for a BS containing N_{sol} unit rated panels is ($N_{sol}H_{tj}$). The net energy consumed by a BS per hour includes a static power consumption ($P_0 = 118.7W$) in addition to the dynamic hourly consumption due to varying traffic. This net energy consumption can be represented as $E_{tj}^c = N_{TRX} (P_0 + P_{tj})$ [5] for BS j at hour t , with $N_{TRX} = 6$ being the number of transceivers. The capacity of each battery is taken to be B_{cap} , resulting in a net battery capacity of $B_{max} = N_B B_{cap}$ with each BS having N_B number of batteries. The critical level below which energy can not be extracted from the storage is given as $B_{cr} = (DoD N_B B_{cap})$, where DoD is depth of discharge decided by the operator to avoid battery degradation.

The green energy distribution to each BS by its battery storage is done in accordance with the traffic variation (ρ_{tj}) and the net energy being consumed by the BS (E_{tj}^c). E_{bud}^j is the net green energy capacity per BS at the beginning of the

Algorithm 1: Traffic skewness aware-coverage adjustment algorithm

Result: $Uns_{tj}, P_{tj}, R_{tj}^n, N_{tj}^n$

1 Part I - WCA model

2 Input: $K, N, BW, \sigma^2, \tau, r_{th}, p_0, q_0, R_{des} = R_{tj}, \rho_{tj}, P_{max}$

3 Initialize: $\rho_{tj}^n = \rho_{tj}, N_{tj}^n = N_{tj}, R_{tj}^n = R_{tj}, BW_{tj}^n = BW_{tj}, Uns_{tj} = 0, \Delta R_{tj} = 0$

4 for $t = \{1 \dots 24\}$ **do**

5 for $j = \{1 \dots K\}$ **do**

Obtain P_{tj} as in Sec. III for given ρ_{tj} & R_{des}

if $P_{tj} \geq P_{max}$ **then**

while $P_{tj} \geq P_{max}$ **do**

$R_{tj}^n = R_{tj}^n - 0.001$

$\Delta R_{tj} = R_{tj} - R_{tj}^n$

update N_{tj}^{DC} and N_{tj}^{DT}

$\rho_{tj}^{DC} = N_{tj}^{DC} / N$ and $\rho_{tj}^{DT} = N_{tj}^{DT} / N$

$\rho_{tj}^n = \rho_{tj}^{DC} + \rho_{tj}^{DT}$

$BW_{tj}^n = BW \rho_{tj}^n$

$N_{tj}^n = N \rho_{tj}^n$

$Uns_{tj} = N_{tj} - N_{tj}^n$

Calculate P_{tj} till false

end

else

Parameters are unchanged as initial

end

Part II - CA model

if $Uns_{tj}! = 0$ **then**

for $w = \{1 \dots K\}$ **do**

if $w \in adj_j$ **then**

while $P_{tw} \leq P_{max}$ **do**

if $\Delta R_{tw} \leq \Delta R_{tj}$ **then**

$R_{tw}^n = R_{tw}^n + 0.001$

$\Delta R_{tw} = R_{tw}^n - R_{tw}$

update N_{tj}^{DC} and N_{tj}^{DT}

get ρ_{tj}^{DC} and ρ_{tj}^{DT}

update $served_{tw}$

$N_{tw}^n = N_{tw} + served_{tw}$

$\rho_{tw}^n = \frac{N_{tw}^n}{N}$ & $BW_{tw}^n = BW \rho_{tw}^n$

Calculate P_{tw} till false

else

exit

end

end

else

parameters unchanged

end

end

$Uns_{tj} = Uns_{tj} - \sum_w served_{tw}$

else

parameters unchanged

end

end

TABLE I: Examples of performance trends at various traffic skewness

Traffic skewness level \rightarrow	17%	30%	50%	80%
Percent users served with WCA	100%	91.26%	80.94%	55.09%
Percent users served with CA	100%	99.18%	96.06%	93.91%
Gain in traffic served with CA	0%	7.92%	15.12%	38.82%
Gain in revenue earned with CA	0%	3.9%	16.84%	43.14%
Net profit gain with CA	0%	4.21%	18.68%	50.71%

day and is given by $E_{bud}^j = B_{ini}^j - B_{cr} + \sum_{t=1}^{24} H_{tj} - E_{exc}^j$, where B_{ini}^j is the initial battery level chosen randomly for each BS and E_{exc}^j refers to the excess energy harvested by the BS which can be sold back to the power grid. The expected battery level at each hour is given as $B_j^t = B_j^{t-1} + H_j^t - E_{tj}^c$. If $B_j^t \geq B_{max}$, then the difference energy is termed as excess energy E_{exc}^j and if $B_j^t \leq B_{cr}$, then the difference energy is termed as deficient energy E_{def}^j . The energy being allocated to the BS in any hour t is given as, $E_{tj}^{alc} = E_{bud}^j \frac{E_{tj}^c}{\sum_{t=0}^{24} E_{tj}^c}$.

V. SIMULATION RESULTS AND COMPARATIVE COST ANALYSIS

The annual cost analysis includes both investments and revenue earned by the operator. Capital Expenditure (CAPEX) refers to the investments borne by the operator related to dimensioning the BSs while ignoring the other initial investment costs. Considering the cost of PV panels ($C_{sol} = \text{USD } 1300\text{\$}$) [16] and storage batteries ($C_B = \text{USD } 216\text{\$}$) [17] it can be calculated as $CAPEX = C_{sol}N_{sol} + C_B N_B$. Operational Expenditure (OPEX) refers to dynamic costs incurred during the operation of the BS. Since, we are doing an annual cost analysis, no component replacement costs will be incurred, and only the cost of buying unit energy $c_{buy} = \text{USD } 0.079\text{\$}$ [18] from the grid is considered to be OPEX, which is given as $OPEX = c_{buy} E_{def}^j$. Revenue has been earned by the operator by serving the users in the network. If $c_{serv} = \text{USD } 1.31\text{\$}$ [19] is the revenue earned by serving a user for 1 month, then R_{serv} is calculated according to the number of users served annually throughout the network. The net annual profit of the system can be calculated as $Net_{pr} = R_{serv} - CAPEX - OPEX$.

A. Energy and traffic load balancing performance

For simulation purpose, we have considered deployment of six single operator BSs, enabled with 12 unit rated solar panels and 12 batteries in total, around a fixed area of $A = 1 \text{ km}^2$ and $\lambda_u = 1500$. The batteries are considered to be $12V - 205Ah$, flooded lead acid batteries. The net bandwidth spectrum available is $BW = 10 \text{ MHz}$ and the noise floor has been taken to be -150dBm/Hz . The constants used in the calculations are, $\tau = 20 \text{ dB}$, $p_0 = q_0 = 0.9$, $r_{th} = 800 \times 10^3$, $DoD = 0.3$, and $P_{max} = 40W$. Our results pertain to the analysis of skewed traffic network performance and cost comparison between the proposed CA and conventional WCA models. The network performance has been gauged by the average fraction of users being served by the network in its peak hours, which has been shown in first two rows of Table I, demonstrating that the average (17%) traffic skewness results in 100% users being served, without the need for any

coverage adjustment. With increasing skewness, its observed that the network performance degrades for the WCA model. In contrast, the CA model offers a better network performance at all higher traffic skewness levels, providing on average about 8% gain in moderate (30%) skewness and about 39% gain at 80% traffic skewness, as depicted in the third row of Table I. The fraction of users whose QoS cannot be fulfilled in the WCA and CA models for the various traffic skewness are shown in Figs. 2 (d) and (e).

Further, an annual comparative cost analysis comprising of the investments (CAPEX and OPEX) and the overall revenue R_{serv} is performed from the operator's perspective. The comparative plots are shown in Figs. 2 (a)-(c). As discussed in the previous paragraph, the average traffic skewness results in 100% users being served through the conventional model, resulting in maximum revenue for the network operator. It is observed from Fig. 2(a) that the revenue earned R_{serv} decreases in both models with increase in traffic skewness. The percent gain in R_{serv} in the proposed CA model over the conventional WCA is presented in fourth row of Table I again demonstrating that CA based approach is significantly better over the conventional WCA approach in generating revenue for the service provider. When the OPEX incurred to the service provider is compared as in Fig. 2(b), we find that the proposed CA model incurs a higher OPEX as compared to the WCA model for all traffic skewness.

However, even though the service provider incurs a larger OPEX in the proposed model, the annual revenue generated in the proposed model is significantly higher than the net investment made by the service provider. The net profit earned by the service provider can be observed from Fig. 2(c) and the corresponding percent gain to the service provider with the CA model over WCA can be observed in fifth row of Table I, showing a profit gain of about 4% at moderate (30%) skewness and gaining over 50% at a very high (80%) skewness.

Inter-BS energy balancing taking place in the network due to the proposed CA approach in presence of skewed traffic can be seen in Figs. 2 (f)-(g). These plots show the BS downlink transmit power levels in the WCA approach and the proposed CA approach at 80% traffic skewness. It can be observed that the skewness in traffic results in, a potential energy difference between the BS subjected to skewed traffic and its neighboring ones, resulting in the neighboring BSs increase their respective transmit power levels to guarantee QoS to the users who otherwise would have been left out.

VI. CONCLUSION

The paper has investigated the performance of a dual-powered cellular system subjected to skewed traffic, wherein cell coverage adjustment has been proposed before deciding on deficit or surplus power for guaranteeing the user QoS at the different BSs. The framework calculates the power requirement for serving each user in the system depending on its traffic class, and further computes the BS downlink transmit power level depending on the number of users getting served in that hour. Skewness in traffic results in

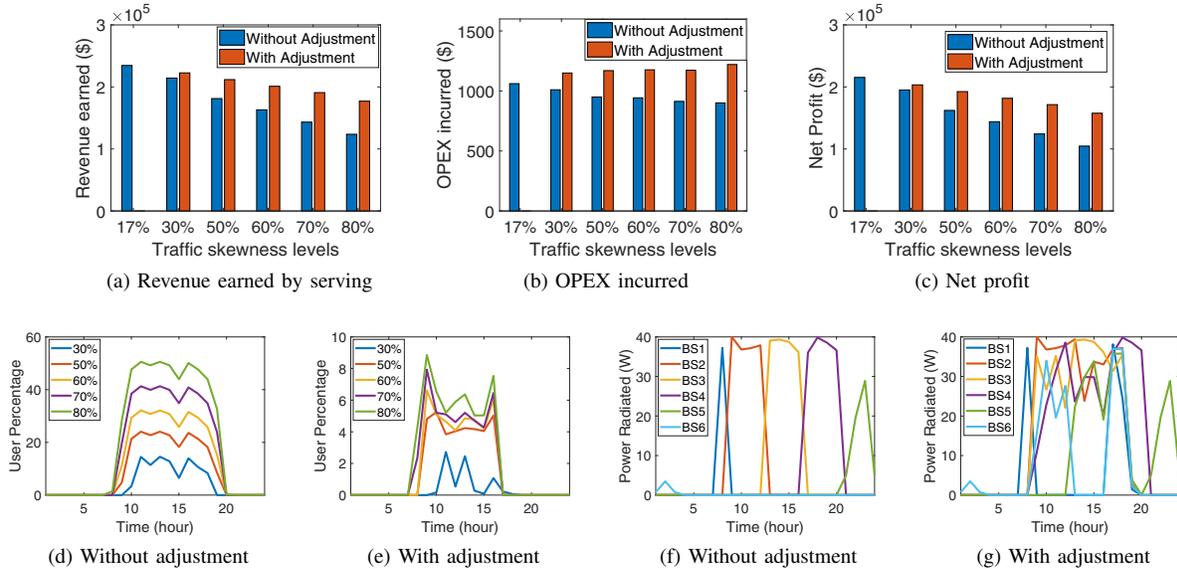


Fig. 2: (a)-(c) Cost comparative analysis; (d)-(e) Fraction of users unserved; (f)-(g) BS downlink transmit power level variation.

the energy surplus neighboring BSs, thus suggesting on increasing their coverage area and accommodating most of the edge users that normally cannot have a guaranteed QoS by the BS that is subjected to skewed traffic at that hour. A network performance comparison between the conventional WCA model and the proposed CA model has been evaluated in terms of the fraction of users getting served at the peak hours, showing a significant gain in it through our proposed energy and traffic aware coverage-adjustment model. Finally, a comparative cost analysis has been performed for computing the service provider's net expenditure in terms of his earnings and investments. Simulation studies demonstrate that, while the conventional approach incurs less OPEX compared to the proposed coverage adjusted case, the overall revenue earned in the proposed approach is consistently higher. However, the net profit as well as revenue earned reduce as the traffic skewness increases, thus capturing the limits of energy balancing.

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REFERENCES

- [1] H. Wu, C. Qiao, S. De, and O. Tonguz, "Integrated cellular and ad hoc relay systems: iCAR," *IEEE J. Sel. Areas in Commun.*, vol. 19, no. 10, pp. 2105–2115, Oct. 2001.
- [2] S. Agarwal, S. De, S. Kumar, and H. M. Gupta, "QoS-aware downlink cooperation for cell-edge and handoff users," *IEEE Trans. Vehicular Technol.*, vol. 64, no. 6, pp. 2512–2527, Jun. 2015.
- [3] H. Jo, Y. J. Sang, P. Xia, and J. G. Andrews, "Heterogeneous cellular networks with flexible cell association: A comprehensive downlink sinr analysis," *IEEE Trans. Wireless Commun.*, vol. 11, no. 10, pp. 3484–3495, 2012.
- [4] M. A. Marsan, G. Bucalo, A. Di Caro, M. Meo, and Y. Zhang, "Towards zero grid electricity networking: Powering bss with renewable energy sources," in *Proc. IEEE ICC Wksp., Budapest, Hungary*, 2013.
- [5] S. Suman and S. De, "Solar-enabled green base stations: Cost versus utility," in *Proc. IEEE 18th Int. Symp. WoWMoM, Macau, China*, 2017, pp. 1–8.
- [6] E. Oh, K. Son, and B. Krishnamachari, "Dynamic base station switching-on/off strategies for green cellular networks," *IEEE Trans. Wireless Commun.*, vol. 12, no. 5, pp. 2126–2136, 2013.
- [7] S. Suman and S. De, "Low complexity dimensioning of sustainable solar-enabled systems: A case of base station," *IEEE Trans. Sustain. Comput.*, pp. 1–1, 2019.
- [8] K. Kaushik, D. Mishra, and S. De, "Stochastic solar harvesting characterization for sustainable sensor node operation," *IET Wirel. Sens. Syst. J.*, vol. 9, no. 4, pp. 208–217, 2019.
- [9] Y. Mao, Y. Luo, J. Zhang, and K. B. Letaief, "Energy harvesting small cell networks: feasibility, deployment, and operation," *IEEE Commun. Mag.*, vol. 53, no. 6, pp. 94–101, 2015.
- [10] V. Chamola, B. Krishnamachari, and B. Sikdar, "Green energy and delay aware downlink power control and user association for off-grid solar-powered base stations," *IEEE Syst. J.*, vol. 12, no. 3, pp. 2622–2633, 2018.
- [11] Z. Niu, Y. Wu, J. Gong, and Z. Yang, "Cell zooming for cost-efficient green cellular networks," *IEEE Commun. Mag.*, vol. 48, no. 11, pp. 74–79, 2010.
- [12] R. Balasubramaniam, S. Nagaraj, M. Sarkar, C. Paolini, and P. Khaitan, "Cell zooming for power efficient base station operation," in *Proc. 9th IWCMC, Sardinia, Italy*, 2013, pp. 556–560.
- [13] H. Al Haj Hassan, D. Renga, M. Meo, and L. Nuaymi, "A novel energy model for renewable energy-enabled cellular networks providing ancillary services to the smart grid," *IEEE Trans. Green Commun. Netw.*, vol. 3, no. 2, pp. 381–396, 2019.
- [14] Yi Zhang, . Budzisz, M. Meo, A. Conte, I. Haratcherev, G. Koutitas, L. Tassiulas, M. A. Marsan, and S. Lambert, "An overview of energy-efficient base station management techniques," in *Proc. 24th TIWDC, Genoa, Italy*, 2013, pp. 1–6.
- [15] System Advisor Model: National Renewable Energy Laboratory. [Online]. Available: <https://www.sam.nrel.gov>
- [16] Economic Times-Solar Panel Cost: Price range of different types of solar panels and how much govt. subsidy you can avail for installing one. May '14. [Online]. Available: <https://economictimes.indiatimes.com>
- [17] Batteries for solar systems-Renewable Energy Batteries. [Online]. Available: <https://www.thesolarbiz.com/batteries.html>
- [18] True Cost of Providing Energy to Telecomm Towers in India. [Online]. Available: <https://www.gsma.com>
- [19] Antennae Location Methodology for a Telecomm Operator in India, IIM-B, Working paper no. 454. [Online]. Available: <https://www.iimb.ac.in>