Achieving energy sustainable and scalable networks: A joint load-energy balancing paradigm

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Outline

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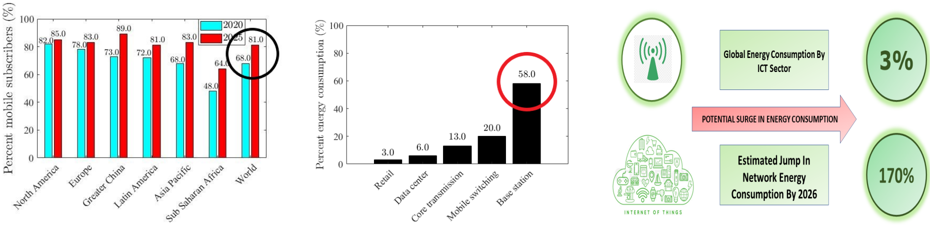
2. Leveraging Imbalances through Energy Balancing
3. Joint Traffic and Green Energy Balancing
4. Conclusion
5. Publications

Why Need Green Communication Networks?

- IoT coupled with beyond 5G (B5G) communications: significant rise in mobile subscribers by 13% (Fig. 1(a))
- Base station (BS) is most energy consuming device, consumes 58% of the network energy (Fig. 1(b))
- The increase in user QoS/QoE due to B5G communications ⟶ BS densification [1], increasing network energy consumption



(a) Estimated increase in number of mobile subscribers

(b) Energy consumption by ICT components

(c) Estimated rise in network energy consumption

Figure 1: Illustrating need for green communication.

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[1] J. G. Andrews et al., "What Will 5G Be?," in IEEE Journal on Selected Areas in Communications, vol. 32, no. 6, pp. 1065-1082, June 2014.

Powering BSs: Smart Grid Connected and Solar Powered Networks

- Traditional power grid connectivity
    - Powered by carbon generating power plants
- Purely solar enabled base stations[a]
    - Off-grid, standalone
    - Carbon free
    - High CAPital EXpenditure (CAPEX) to the operator
    - Not scalable
- Need to analyze both energy-efficiency and cost to mobile operator

- Smart-grid connected and solar powered base stations
    - Each BS is individually solar powered and grid connected
    - "Dual powered"
- Designing dual-powered BSs is challenging
    - Stochasticity in energy harvest
    - Stochastic behaviour of traffic
    - Leads to 'traffic-energy imbalances' across the network

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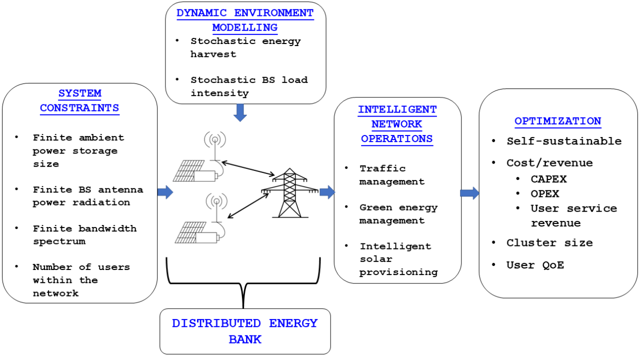
[a] V. Chamola, B. Krishnamachari, and B. Sikdar, "Green Energy and Delay Aware Downlink Power Control and User Association for Off-Grid Solar-Powered Base Stations," IEEE Syst. J., vol. 12, no. 3, pp. 2622–2633, 2018.

The Challenge: Traffic-Energy Imbalances



DYNAMIC ENVIRONMENT MODELLING

- Stochastic energy harvest
- Stochastic BS load intensity

SYSTEM CONSTRAINTS

- Finite ambient power storage size
- Finite BS antenna power radiation
- Finite bandwidth spectrum
- Number of users within the network

DISTRIBUTED ENERGY BANK

INTELLIGENT NETWORK OPERATIONS

- Traffic management
- Green energy management
- Intelligent solar provisioning

OPTIMIZATION

- Self-sustainable
- Cost/revenue
  - CAPEX
  - OPEX
  - User service revenue
- Cluster size
- User QoE

Figure 2: Overview of system design.

- Traffic energy imbalances
  - Space-time stochastic variation of green energy harvest and BS load
  - A BS may experience the imbalances in any degree of skewness

- Effects of traffic-energy imbalances
  - Degrade user QoS
  - Reduces operator revenue
  - Improper green energy utilization in the network
  - Higher grid energy purchase, despite green energy usage potential in the network

Motivation: Why Joint Load-Energy Balancing?

Key features:

- Aim to fully utilize the green energy potential in network
- Traditionally, traffic management (Fig. c) and energy management (Fig. b)
- Finite battery capacity per BS limits energy balancing, finite BS radiation level limits load balancing
- Proposed CASE strategy involves joint traffic & energy management (Fig. d)
- The energy management framework follows the traffic management framework
- BSs operations
  - Coverage adjustment flexibility
  - Energy transfer flexibility
  - Energy trade with power grid

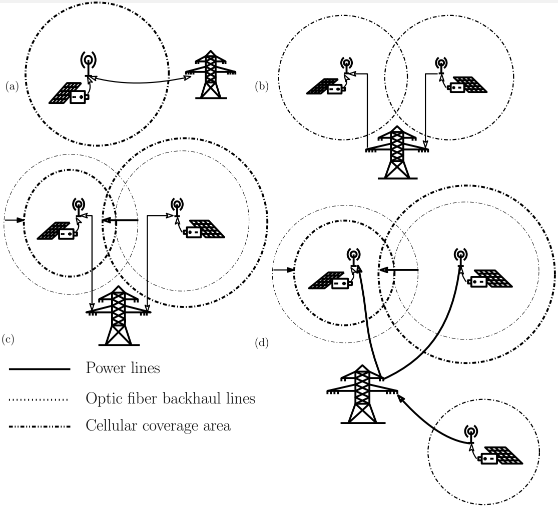


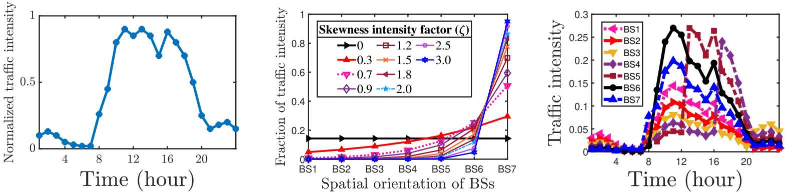
Figure 3: Illustrating (a) grid connected and solar powered BS, (b) sharing of energy (SE) based framework, (c) coverage adjustment (CA) based load management framework , (d) proposed CASE framework.

Leveraging Imbalances: A Load Aware Cooperative Energy Transfer Framework

- **Why Energy Transfer?**
  - It is not feasible to modify antenna power levels frequently
  - Coverage adjustment cannot fully utilize the green potential in the network
  - Some BSs might still have surplus green energy with them, if their neighbouring BSs are subjected to low load
- **System Features**
  - Solar BSs can transfer green energy among each other via grid infrastructure
  - BSs can trade energy with the power grid
- **Objective**
  - To minimize grid energy procurement and study it's tradeoff with operator revenue maximization

Modeling Skewed Traffic

1. Finite BSs in the network → the BSs are subjected to skewed traffic
2. At the design and deployment stage, BSs located assuming homogeneous, balanced traffic
3. Skewed traffic: BS experiences traffic relatively higher than the balanced load scenario



(a) Net traffic profile

(b) Illustrating skewness levels.

(c) Illustrating space-time varying of skewed traffic.

Figure 4: Skewed traffic profile modeling

4. A localized closed area A, having U users following a homogeneous binomial point process of density λ, such that the users can displace within the area and not move out of it.
5. Net area traffic[2], $\rho(t)$
6. The traffic is distributed among the BSs using a skewness intensity factor, ζ

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[2] Yi. Zhang, et al., "An overview of energy-efficient base station management techniques", in Proc. TIWDC, 2013

Grid Energy Procurement Minimization

1. The OEMC classifies the BSs at each hour as energy-deficient and energy-sufficient

2. Let I out of $\mathfrak{B}$ BSs be energy-deficient (battery level $\beta_b(t) < \beta_c$) and the remaining $J = (\mathfrak{B} - I)$ BSs be energy-sufficient

3. For the I energy-deficient BSs, the total deficit energy in the network is

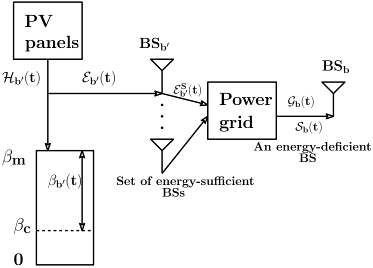
$$\mathcal{D}(t) = \sum_{b=1}^{I} \mathcal{D}_b(t) = \sum_{b=1}^{I} \left(\beta_c - \beta_b'(t)\right) \tag{1}$$

4. The J energy-sufficient BSs $(\beta_b(t) \geq \beta_c)$ contribute, net sharable energy available in the network as

$$\mathcal{E}^S(t) = \sum_{b'=1}^{J} \mathcal{E}^S_{b'}(t) = \sum_{b'=1}^{J} \left(\beta_{b'}'(t) - \beta_c\right) \tag{2}$$

5. An energy-deficient BS can meet its deficit energy requirement by
   - energy sharing through the energy-sufficient BSs
   - energy procurement through the power-grid
   - Selling price < Energy transfer price < Energy purchase price (incentivize more energy transfer among networked BSs)

1. The grid energy procured by a deficit BS $\mathcal{G}_b(t) = \left(\underbrace{\mathcal{D}_b(t)}_{\text{deficit energy}} - \underbrace{\mathcal{S}_b(t)}_{\text{deficit met by sharing}}\right)$
2. Problem is solved by transforming the problem into a quadratic optimization problem to derive the closed form expressions.



Lemma

For a dual-powered network consisting of $\mathfrak{B}$ BSs, the minimum power grid energy procurement required by an energy deficient BS b is

$$\mathcal{G}_b(t) = \begin{cases} 0, & \text{if } \sum_{b=1}^{I} \mathcal{D}_b(t) \leq \sum_{b'=1}^{J} \mathcal{E}^S_{b'}(t) \\ \mathcal{D}_b(t) \left(\frac{\sum_{b=1}^{I} \mathcal{D}_b(t) - \sum_{b'=1}^{J} \mathcal{E}^S_{b'}(t)}{\sum_{b=1}^{I} \mathcal{D}_b(t)} \right), & \text{if } \sum_{b'=1}^{J} \mathcal{E}^S_{b'}(t) < \sum_{b=1}^{I} \mathcal{D}_b(t) \end{cases} \tag{3}$$

and the maximum energy that can be shared to a energy deficient BS is given as

$$\mathcal{S}_b(t) = \begin{cases} \mathcal{D}_b(t), & \text{if } \sum_{b=1}^{I} \mathcal{D}_b(t) \leq \sum_{b'=1}^{J} \mathcal{E}^S_{b'}(t) \\ \left(\mathcal{D}_b(t) \sum_{b'=1}^{J} \mathcal{E}^S_{b'}(t)\right) / \sum_{b=1}^{I} \mathcal{D}_b(t), & \text{if } \sum_{b'=1}^{J} \mathcal{E}^S_{b'}(t) < \sum_{b=1}^{I} \mathcal{D}_b(t) \end{cases} \tag{4}$$

Operator Revenue Maximization

- Cost metrics associated with the system design
  - CAPEX
  - OPEX to the operator: cost of energy transfer + cost of energy procurement, $-(\mathcal{C}_{share} + \mathcal{C}_{buy})$
  - Revenue earned by selling energy to the grid, $\mathcal{R}_{sell}$
  - Revenue earned by serving users, $\mathcal{R}_{serv}$
- The annual net revenue $\mathcal{R}_o$ earned by the mobile operator

$$\mathcal{R}_o = \mathcal{R}_{serv} + \mathcal{R}_{sell} - \mathcal{C}_{share} - \mathcal{C}_{buy} - CAPEX \tag{5}$$

- For a fixed BS solar provisioning (i.e., CAPEX), the two decision variables are
  1. Number of Users serviced by a BS
  2. Amount of energy transferred in the network among the BSs
- Hence, maximizing user service and maximizing green energy utilization in the network shall lead to increasing the operator revenue.
- Maximizing green energy utilization ⟶ reduces OPEX (less grid purchase) in addition to reduced CAPEX per BS.

- Note: $\mathcal{R}_{serv}$ is constant for a given skewness factor
- Price of energy sharing lower than grid purchase price, but higher than energy selling price, $C_{se} < C_{sh} < C_b$
- Problem is solved by transforming the problem into a quadratic optimization problem to derive the closed form expressions.

Theorem

For a given CAPEX, the OPEX incurred in the grid energy procurement minimization problem is identical to the operator revenue maximization problem. That is, the solution of $\mathcal{P}5$ is

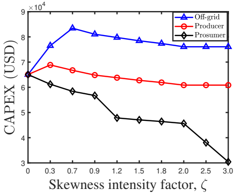
$$\mathcal{S}_b(t) = \begin{cases} \mathcal{D}_b(t), & \text{if } \sum_{b=1}^{I} \mathcal{D}_b(t) \leq \sum_{b'=1}^{J} \mathcal{E}_{b'}^{S}(t) \\ \left(\mathcal{D}_b(t) \sum_{b'=1}^{J} \mathcal{E}_{b'}^{S}(t)\right) / \sum_{b=1}^{I} \mathcal{D}_b(t), & \text{if } \sum_{b'=1}^{J} \mathcal{E}_{b'}^{S}(t) < \sum_{b=1}^{I} \mathcal{D}_b(t). \end{cases} \tag{6}$$

Optimal CAPEX in Networked Scenario

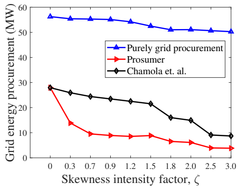
Two proposed modes of network operation:

- Energy producer mode
    - Carbon free
    - BSs act as a distributed energy producer to the power grid
    - BSs cannot procure energy from the grid
    - BSs can share energy amongst each other and/or sell energy to the power grid
- Energy prosumer mode
    - Not carbon free
    - BSs act as energy producers to the grid (i.e., sell energy to the grid) as well as energy consumers (i.e., procure energy from the grid)
    - BSs can procure energy or sell to grid
    - BSs can also share energy
- Optimal CAPEX varies for both the proposed modes of network operation
- Optimal CAPEX computation involves optimizing the number of BSs in the network in addition to the solar provisioning per BS.

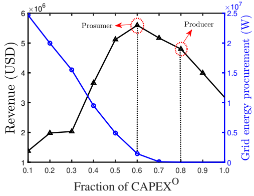
Pure energy balancing framework results



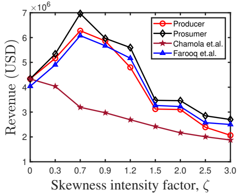
(a) Variation of optimal CAPEX



(b) Reduction in grid procurement



(c) Revenue and grid procurement variation; $\zeta = 1.2$.



(d) Optimum operator revenue variation, compared to [a],[b]

- Parameter values: $\mathcal{A} = 1$ km^2, $\mathcal{B} = 7$, $\mathcal{P}_m = 40$ W, $\mathbb{B}_c = 2460$ Wh, $\delta = 0.3$, $BW = 20$ MHz, $\sigma^2 = -150$ dBm/Hz, $r_0 = 300 \times 10^3$ bps, $p_0 = 0.9$, $C_{PV} = 1300$ USD, $C_B = 216$ USD, $C^{sel} = 0.015$ USD, $C^{buy} = 0.079$ USD, $C^{sh} = 0.057$ USD
- Cooperative networked energy transfer among the BSs significantly reduces the CAPEX (Fig. a) and OPEX (Fig. b) incurred by the operator
- Prosumer mode gains around 60% CAPEX savings over the off-grid mode at extreme skewness (Fig. a)
- The proposed energy producer mode achieves self sustainability (Fig. c)
- The energy prosumer mode provides significant revenue gains up to 42% (Fig. d)

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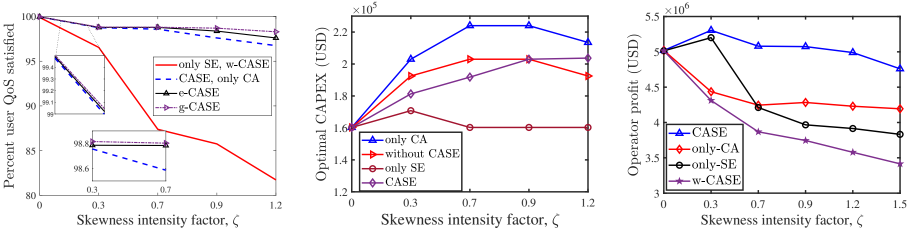
[a] V. Chamola, et.al., "Delay Aware Resource Management for Grid Energy Savings in Green Cellular Base Stations With Hybrid Power Supplies," in IEEE Trans. Commun., 2017

[b] M. J. Farooq, et.al., "A Hybrid Energy Sharing Framework for Green Cellular Networks," in IEEE Trans. Commun., Feb. 2017.

Joint load-energy balancing results



(a) Percentage gain in user QoS satisfied (b) Variation of optimal CAPEX to achieve sustainability (c) Variation in green energy utilization

Figure 7: Key results.

- CASE: coverage adj. & sharing of energy; only SE: only sharing of energy; only CA: only coverage adj.; w-CASE: without CASE; e-CASE: expected CASE; g-CASE: global CASE
- The proposed CASE framework significantly improves user QoS as well as green energy utilization
- The proposed CASE framework is very effective in providing self-sustainable network at a much lower CAPEX in addition to net revenue gains
- From a technical perspective, CASE and only-CA are similar (Fig. 18(a)), but from an economic perspective - CASE performs better than only-CA (Fig. 18(c)). Thus showing the importance of energy balancing in addition to traffic balancing.

Conclusion

- We study the prospect of designing green scalable networks through an ambient powered and grid connected communication framework.
- From a system design perspective, we outline the inherent challenges, system requirements, and physical constraints involved.
- A joint load-energy balancing framework has been discussed in detail with an aim to fully utilize the green energy potential in the network by leveraging the inherent dual stochasticity.
- Illustrate the associated techno-economic trade-offs involved in network design.
- It is inferred that two frameworks may perform similarly technically but may have different revenue models.

Research publications

Journals:

1. **A. Balakrishnan**, S. De, and L.-C. Wang, “Networked energy cooperation in dual powered green cellular networks,” in *IEEE Trans. Commun.*, Oct. 2022. **[Best journal award, ICST, NYCU]**
2. **A. Balakrishnan**, S. De, and L.-C. Wang, “CASE: A joint traffic and energy optimization framework for grid connected green future networks”, in *IEEE Trans. Netw. Serv. Manag.*, Feb. 2024.
3. **A. Balakrishnan**, S. De, and L.-C. Wang, “Network operator revenue maximization in dual powered green cellular networks,” in *IEEE Trans. Green Commun. Netw.*, vol. 5, no. 4, Dec. 2021.
4. **A. Balakrishnan**, S. De, and L.-C. Wang, “Distributed energy bank optimization towards outage aware sustainable cellular networks”, in *IEEE Trans. Sust. Comput.*, accepted Oct. 2024.

Conferences:

1. **A. Balakrishnan**, S. De, and L.-C. Wang, “HAPS-aided power grid connected green communication framework: Architecture and optimization”, in *Proc. IEEE ICC,* Denver, CO, USA, June 2024.

3. **A. Balakrishnan**, S. De, and L.-C. Wang, “Toward green residential systems: Is cooperation the way forward?”, *in Proc. IEEE GLOBECOM*, pp. 1-6, Rio de Janeiro, Brazil, Dec. 2022.

4. **A. Balakrishnan**, S. De, and L.-C. Wang, “Energy sharing based cooperative dual-powered green cellular networks”, *in Proc. IEEE GLOBECOM*, pp. 1-6, Madrid, Spain, Dec. 2021.

5. **A. Balakrishnan**, S. De, and L.-C. Wang, “Traffic skewness-aware performance analysis of dual-powered green cellular networks,” in *Proc. IEEE GLOBECOM,* pp. 1-6, Taipei, Taiwan, Dec. 2020.

Thank You

Questions, Suggestions?

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