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HAPS-aided Power Grid Connected Green Communication Network: Architecture and Optimization

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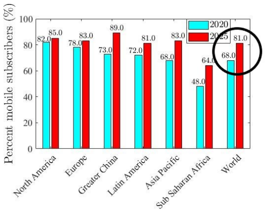
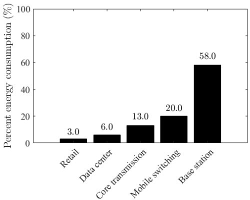
Why Need Green Future Networks?

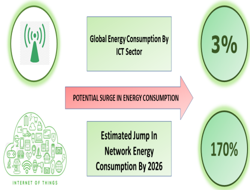
- IoT coupled with beyond 5G communications: significant rise in network users by 13% (Fig. 1(a)).
- BS is most energy consuming device, consumes 58% of the network energy (Fig. 1(b)).
- The increase in user QoS/QoE due to B5G communications ⟶ BS densification[1], increasing network energy consumption.



(a) Estimated increase in number of mobile subscribers



(b) Energy consumption by ICT components



(c) Estimated rise in network energy consumption

[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.

Aerial assisted and Grid connected, Ambient powered Networks

- Traditional power grid connectivity
  - Powered by carbon generating power plants
- Purely solar enabled base stations
  - 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
- Possible solution: Grid connected and ambient powered BSs

Integrating with aerial BSs

- Terrestrial Macro BSs (tMBS) can meet the QoS guarantee of limited users
- They are governed by FCC guidelines on downlink power radiation
- Thus, there is a requirement for additional capacity injection, in addition to energy sustainability
- HAPS is averse to energy constraints and latency occurring in drone based UAVs and satellites, respectively
- HAPS are flexible as compared to small cell based HetNets, provides coverage to a much larger area

Key Contributions and System Model

1. We propose a HAPS aided, solar powered, and smart grid connected green communication network.
2. Aim to offload excess users to the hMBS in the event of low energy harvest or high user density rather than grid energy procurement.
3. The power grid infrastructure is utilized only for selling surplus green energy harvested back to the power grid.
4. Explore the extent of user offloading to an energy and capacity constrained hMBS.
5. The inherent communication and energy network are studied and jointly modeled as a six state DTMC.
6. The tMBS operates in full frequency reuse mode, having access to the entire BW. The hMBS has limited capacity, having access to a fraction $f\%$ of total BW for the considered area.

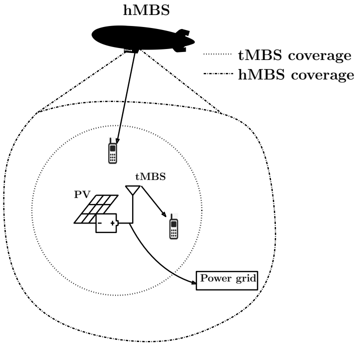


Figure 2: Illustration of HAPS aided, grid connected, and solar powered communication network.

Communication and Energy Network Modelling

Communication network

- With each user having a QoS r_{th}, the minimum power required per user by a tMBS is

$$P_{ub}^{T}(t) \geq \frac{\exp\left(r_{th}\ln 2/W_{ub} - 1\right)\left(d_{ub}^{2}(W_{ub}\sigma^{2}) + I\right)}{\ln(1/p_o)}. \quad (1)$$

- The net power consumption of the tMBS is

$$\sum_{u} \pi_{ub} P_{ub}^{T}(t) = P_{b}^{T}(t) = f(\mathbf{U}, \mathbf{g}, \mathbf{d}) \leq P_{max}. \quad (2)$$

- A communication system can be modeled as a two state Markov model as described below.
  - *QoS satisfied (QS)* state: If the QoS of all active users are met by the tMBS, i.e.,

$$r_{ub}(t) \geq r_{th} \ \forall \ u \in \mathbf{U} \text{ such that, (2).} \quad (3)$$

  - *QoS violation (QV)* state: If the QoS of all active users are not being met by the tMBS, i.e.,

$$r_{ub}(t) < r_{th} \ \forall \ u \in \mathbf{U}' \subset \mathbf{U} \text{ such that, (2).} \quad (4)$$

Energy network

- Depending on the green energy harvest and traffic profile being experienced by a tMBS, the energy network can be modeled as a three state system.
- The green energy storage level at tMBS b is defined as

$$B_b'(t) = B_b(t-1) + H_b(t) - E_b(t),$$
$$B_b(t) = \min\{\max\{B_b'(t), \beta_{cr}\}, \beta_{max}\}. \quad (5)$$

- Here, $E_b(t) = N_{TRX}\left(P_s + \theta_1 P_b^T(t)\right)$ denotes the net energy consumption by the tMBS.
- Depending on the battery level, the energy network can be discretely modeled as
  - *Deficit (D)* state: In this state, $B_b'(t) < \beta_{cr}$. This state signifies that the tMBS becomes energy-deficient thereby affecting user service.
  - *Intermediate (I)* state: In this state, $\beta_{max} \geq B_b'(t) \geq \beta_{cr}$.
  - *Surplus (S)* state: In this state, $\beta_{max} < B_b'(t)$, signifying that the storage battery cannot store excess energy

Integrated Markov Modelling

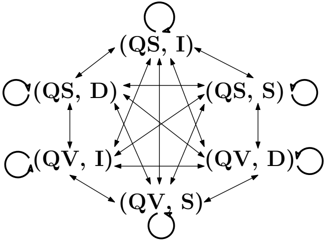


Figure 3: Proposed Markovian model.

Possible service provider network operations.

1. Energy selling back to grid: The tMBS can sell excess energy in its storage back to grid.
2. Excess user offloading to hMBS: In the event that the tMBS is unable to satisfy QoS of all temporal active users, some users will be offloaded to the hMBS.

1. (QS, D): tMBS satisfies QoS requirements of the temporally active users. But battery level is critical, *offload some users to the hMBS.*
2. (QS, I): tMBS satisfies QoS requirements, and the battery level is in intermediate state. *No offloading or energy selling needed.*
3. (QS, S): tMBS satisfies QoS requirements, and battery level is in surplus state. *Sell energy back to grid, no offloading required.*
4. (QV, D): tMBS is insufficient to satisfy temporal QoS, the battery level is also in deficit state. *Hence, excess user offloading to hMBS required.*
5. (QV, I): tMBS is insufficient to satisfy temporal QoS, the battery level is in I state. *Hence, excess user offloading to hMBS required.*
6. (QV, S): tMBS is insufficient to satisfy temporal QoS, and the battery storage is overflowing. *Excess user offloading and energy selling to the grid.*

Performance Computation

The rate maximization problem is

$$\mathcal{P}1 \max_{\pi_{ub},\pi_{uh},\mathbf{P}} (\pi_{ub}(t) r_{ub}(t) + \pi_{uh}(t) r_{uh}(t)) \;\; \forall u \in \mathbf{U}$$
$$\text{such that, } \pi_{ub}, \pi_{uh} \in \{0,1\}$$
$$r_{ub}(t), r_{uh}(t) \geq r_{th} \tag{6}$$

- Solved algorithmically after relaxing the integer constraints.
- Net profit $\mathcal{P}_1 = R_{ser} + R_{sell} - CAPEX^H - CAPEX^B$
- Here, $CAPEX^B = (C_{PV} N_{PV} / L_{PV} + C_B N_B / L_B)$ denote the CAPEX of solar provisioning tMBS.
- $CAPEX^H = C_{PV} N_{PV}^H / L_{PV} + C_B N_B^H / L_B \sim f(N_{TRX}^H)$ denotes solar provisioning of hMBS for RAN operations

Algorithm 1: User association and offloading

```
Result: N = Σ_u π_ub + Σ_u π_uh, P
Input: U, ρ(t), g(t), W, f, σ^2, P_max
Initialize: N = 0
for t = {1, ..., T} do
    for u = {1, ..., U(t)} do
        d_ub ⟵ sqrt((x_u − x_bs)^2 + (y_u − y_bs)^2)
        Compute SINR_ub from (1)
        r_ub(t) ⟵ W_ub log_2(1 + SINR_ub(t))
        if (r_ub(t) ≥ r_th) then
            N ⟵ N + 1
            π_ub ⟵ 1
            Compute P_ub, P_b^T from (10)
        end
        else
            Compute P_r from hMBS using (1) – (8)
            Compute r_uh = f log_2(1 + SINR_uh)
            if (r_uh(t) ≥ r_th) then
                π_uh ⟵ 1, N ⟵ N + 1
                else
                    user remains unserved
                end
            end
        end
    end
end
```

Figure 4: User association and offlocation algorithm.

Results

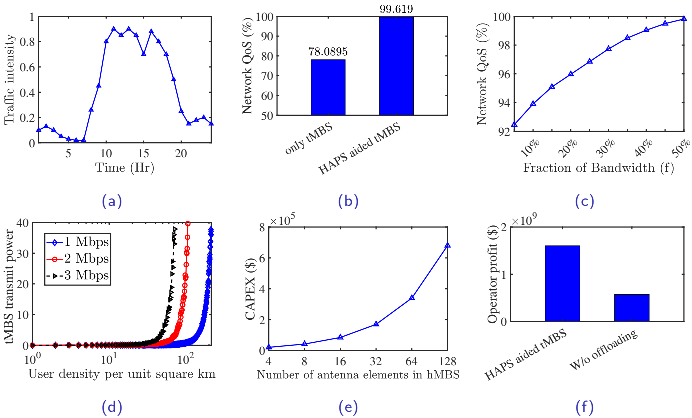


Figure 5: (a) Traffic profile, (b) Network QoS variation at peak hours (9 AM - 6 PM, hMBS operating at 50% capacity), (c) Network QoS variation in peak hours with limited hMBS capacity, (d) Effect of minimum QoS on variation of tMBS transmit power level, (d) Variation of hMBS CAPEX for RAN with number of antenna elements equipped with hMBS, (e) Comparison of operator revenue.

Research Output

Journals:

1. **A. Balakrishnan**, S. De, and L.-C. Wang, "Designing ambient powered green future networks: Architectures and optimization", (under review, *IEEE Wireless Communications*, May 2024).
2. **A. Balakrishnan**, S. De, and L.-C. Wang, "Distributed Energy Bank Optimization Towards Outage Aware Sustainable Cellular Networks", (under review *IEEE Trans. Sust. Comput.*, major revision submitted , May 2024).
3. **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.
4. **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]**
5. **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.

Conferences:

1. **A. Balakrishnan**, S. De, and L.-C. Wang, "Design and Optimizations Toward Cost Aware Green Future Networks", in *IEEE COMSNETS,* Bengaluru, India, Jan. 2024. **[Best paper award]**
2. **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.
3. **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.
4. **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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