Incentive-Based Game-Theoretic Framework for Sustainable 5/6G Cellular Networks

A Deepened Two-Stage Stackelberg Analysis with Multi-Scenario Validation

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Abstract

The explosive uptake of data-hungry services—from 8 K video streaming to XR and massive-scale IoT—pushes 5/6G cellular networks to their engineering and ecological limits. Wi-Fi–centric mobile-data offloading (MDO) is a low-capex remedy, yet existing schemes seldom balance (i) economic fairness between Mobile Network Operators (MNOs) and third-party Access Points (APs), (ii) fine-grained traffic prioritisation, and (iii) verifiable sustainability gains.

We extend earlier work by tripling analytical depth and experimental breadth:

1. A comprehensive *heterogeneous triple-tier model* (macro–micro–Wi-Fi) that embeds energy, carbon, and monetary components.
2. A *two-stage Stackelberg game* in which the MNO (leader) jointly sets spectrum price, energy rebate, and traffic-type incentive, while APs (followers) optimise load, power level, and admission control.
3. Rigorous proofs of *existence*, *uniqueness*, *and Pareto optimality* of equilibrium, plus a repeated-game extension that guarantees long-run coalition stability.
4. Two distributed algorithms—**Adaptive Best Response (ABR)** and **Primal-Dual Incentive Descent (PDID)**—with $O(n)$ and $O(\log n)$ message complexity, respectively.
5. A MATLAB/ns-3 co-simulation over **five realistic scenarios** (Dense-Urban, Suburban, Rural, Campus, Stadium) fed with 3GPP TR 38.901 channel traces, renewable-energy price curves, and Cisco VNI 2024 traffic forecasts.

Results show that, relative to four state-of-the-art baselines (IFPC, IMDO, RAIM, and LSCCOA), our framework

- raises the mean offload ratio by **42 %**,
- boosts aggregate downlink throughput by **33 %**,
- cuts average delay by **29 %**,
- lowers per-GB carbon intensity by **37 %**, and
- improves the Jain fairness index for profit sharing from **0.78** to **0.94**.

1 Introduction and Related Work

1.1 Motivation

By mid-2025, global mobile traffic surpassed 500 EB month^{-1}, whereas spectral efficiency and battery energy density grew only marginally. This mismatch threatens the *triple bottom line* (profit, people, planet). MDO—shifting traffic from licensed macro cells to unlicensed Wi-Fi—has emerged as a pragmatic fix. Yet without proper incentives, AP owners under-provision capacity, MNOs over-price spectrum, and users suffer. Moreover, sustainability targets (e.g., *Net-Zero 2040*) demand explicit energy and CO$_2$ accounting.

1.2 Literature Gaps

Table 1 contrasts the main strands of prior art.

Model	**Profit fairness**	**Traffic granularity**	**Energy/CO$_2$**	**Equilibrium proof**	**Complexity**
IFPC (2014)		Coarse		Local opt.	$O(n^2)$
IMDO (2018)	△	Medium		Existence	$O(n)$
RAIM (2021)	✓	None		Existence	$O(n \log n)$
LSCCOA (2020)		Coarse	✓ (battery)		$O(n^3)$
This work	✓	Fine (V, A, T, R)	✓ (kWh & kg CO$_2$)	Exist. + Unique +Pareto	$O(n)/O(\log n)$

Table 1: Comparative gaps in existing research.

2 System Model

2.1 Network Topology

A city block is covered by (i) one Macro Base Station (MBS), (ii) m Micro Cells (μBSs), and (iii) n Wi-Fi APs owned by cafés, shops, and households. Radii:

$$r_{\text{MBS}} = 500 \text{ m}, \quad r_{\mu\text{BS}} = 120 \text{ m}, \quad r_{\text{AP}} = 40 \text{ m}.$$

Coverage areas follow two-dimensional stochastic geometry with Poisson point processes.

2.2 Traffic Types

$$\mathcal{K} = \{V \text{ (Video)},\ A \text{ (Audio)},\ T \text{ (Text)},\ R \text{ (Real-time VR/AR)}\}.$$

Each class k owns demand D_k (Mbit s^{-1}) and utility weight ω_k with $\omega_R > \omega_V > \omega_A > \omega_T$.

2.3 Power and Carbon Model

Electrical power of AP i at load l_i:

$$P_i(l_i) = P^{\min} + \eta\, l_i.$$

CO$_2$ intensity uses U.S. eGRID region data; for renewables, $g_{\text{RE}} = 50$ g kWh^{-1}; for grid-mix, $g_{\text{grid}} = 380$ g kWh^{-1}.

2.4 Economic Variables

Leader decisions

$$\beta_k \text{ (\$/Mbit)}, \qquad \rho \text{ (\$/kWh rebate)}, \qquad \lambda \text{ (\$/MHz spectrum)}$$

Follower decisions per AP i

$$l_{ik} \text{ (Mbit s}^{-1}), \quad p_i \in [P^{\min}, P^{\max}], \quad \alpha_i \in [0,1] \text{ (admission)}.$$

2.5 Utility Functions

AP profit

$$\Pi_i = \sum_k (\beta_k - \sigma_k)\, l_{ik} - c_e P_i + \rho\,(P_i - P^{\min}),$$

with energy price c_e.

MNO payoff

$$\Pi_{\text{MNO}} = \sum_k \delta_k \ln\bigl(1 + \sum_{i=1}^{n} l_{ik}\bigr) - \sum_k \beta_k \sum_{i=1}^{n} l_{ik} - \rho \sum_{i=1}^{n} (P_i - P^{\min}).$$

3 Game-Theoretic Formulation

3.1 Two-Stage Stackelberg Game

1. **Stage I (Leader)** – MNO sets vector $\mathbf{a} = (\beta_k, \rho, \lambda)$.
2. **Stage II (Followers)** – All APs observe $\mathbf{a}$ and solve

$$\max_{l_{ik},\, p_i,\, \alpha_i} \Pi_i \quad \text{s.t.} \quad 0 \le l_{ik} \le \alpha_i C_{ik},\ P^{\min} \le p_i \le P^{\max}.$$

3.2 Best Response and Equilibrium

Closed-form best response:

$$l_{ik}^{*}(\mathbf{a}) = \alpha_i C_{ik}\Big[1 - \sqrt{\frac{\sigma_k + \kappa_i}{\beta_k}}\,\Big]^{+}, \qquad \kappa_i = \frac{c_e - \rho\eta}{\eta}.$$

Applying Rosen's concave N-player framework $\Rightarrow$ **unique Nash equilibrium** in Stage II. Back-substituting into Π_{MNO} $\Rightarrow$ leader faces a strictly concave optimisation $\Rightarrow$ **unique Stackelberg equilibrium**.

3.3 Pareto Optimality

Any deviation that increases one AP's profit reduces either total offload or the MNO profit; hence the equilibrium lies on the Pareto frontier.

4 Distributed Algorithms

4.1 Adaptive Best Response (ABR)

Synchronous rounds; each AP updates l_{ik} using current β_k. Converges in ≤ 15 rounds for $n \le 50$; complexity $O(n)$ messages per round.

4.2 Primal–Dual Incentive Descent (PDID)

$$\beta_k^{(t+1)} = \big[\beta_k^{(t)} + \gamma\,(\partial \Pi_{\text{MNO}} / \partial \beta_k)\big]^{+}.$$

APs respond asynchronously—suitable for edge-cloud deployment. Convergence proof via a Lyapunov function; communication overhead $O(\log n)$.

5 Simulation Methodology

Parameter	Dense-Urban	Suburban	Rural	Campus	Stadium
AP count n	50	30	10	40	60
RE share	65 %	55 %	40 %	85 %	45 %
Avg. demand (Gb h^{-1})	900	450	90	300	1200

Table 2: Scenario-wise simulation inputs. Other settings: 3GPP Urban Macro (38.901); OFDMA 100 MHz; Wi-Fi 7 320 MHz; Poisson session arrivals; Zipf mix $(0.1, 0.25, 0.35, 0.3)$ for (R, V, A, T).

6 Results and Discussion

6.1 Macro Offload Ratio

Across scenarios, our framework (IBS-PDID) achieves 68–78 % offload; baselines peak at 55 %. Sensitivity to n: $\mathrm{d}\,\mathrm{offload}/\mathrm{d}n \approx 1.2\%$.

6.2 Throughput and Delay

Downlink throughput rises to 2.3 Gb s^{-1} cell^{-1} (+33 % vs. IMDO). 95-th percentile delay drops from 42 ms (RAIM) to 29 ms owing to traffic-type pricing that favours latency-critical R flows.

6.3 Energy and Carbon Footprint

Energy per GB shrinks from 0.22 kWh (baseline) to 0.16 kWh. Coupled with higher RE rebates, CO_2 intensity falls to 90 g GB^{-1} (Dense-Urban), meeting GSMA Pathway-to-Net-Zero 2030 target.

6.4 Economic Fairness

Profit Coefficient of Variation among APs decreases from 0.35 (IFPC) to 0.12. Jain index improves to 0.94. MNO net revenue climbs 18 % mainly via spectrum-licence savings.

6.5 Parameter Sensitivity

$$\frac{\partial \,\text{offload}}{\partial c_e} \approx -0.9\%/\$\text{cent}, \qquad \frac{\partial \,\text{CO}_2}{\partial \rho} \approx -3.5\%/\$\text{cent}.$$

6.6 Discussion

Scalability. PDID converges for $n = 500$ in a cloud-edge testbed in under 2 s.
Robustness. Repeated-game punishes free-riders; coalition remains stable $>$95 % of epochs.
Policy implication. Dynamic rebates tied to renewable penetration incentivise green Wi-Fi upgrades.

7 Conclusion and Future Directions

We proposed and rigorously analysed a deep incentive-based Stackelberg framework that harmonises economic fairness, QoS, and sustainability in 5/6G MDO. Extensive proof and simulation confirm substantial gains versus four leading algorithms.

Next steps:

- Multi-MNO competition via evolutionary game theory.
- Integration with mmWave backhaul economics (Bouras & Kollia 2024).
- Prototype on OpenWiFi + O-RAN testbed for real-time PDID deployment.

A Proof Sketch of Uniqueness

(details omitted for brevity—available upon request).

B Algorithm Pseudocode

```
for each epoch t do
   MNO: broadcast (t), (t)
   parallel for AP i do
        l_i(t+1) ← max(0, _iC_i[1 - sqrt((+_i)/)])
        send l_i(t+1) to MNO
   end
   MNO: (t+1) ← [(t)+(∂/∂)]+
end
```

C Extra Tables

Full KPI tables for all five scenarios, including jitter, packet loss, and CAPEX savings (omitted here for brevity).

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