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Predictive Energy-Aware Uplink Antenna and Link Selection for Multi-Network Cellular User Equipment

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Abstract: Modern cellular user equipment (UE) increasingly supports multiple switchable antenna panels and concurrent connectivity to both terrestrial networks (TN) and non-terrestrial networks (NTN), including low-earth-orbit (LEO) satellite links. Existing uplink antenna and link selection schemes suffer from three fundamental limitations: they rely on downlink reference signal measurements as proxies for uplink path quality; they delegate selection to the network via capability reporting and scheduling commands; or they minimize only transmit power without accounting for the transient energy costs of antenna switching, retuning, and baseband chain activation. These limitations render existing approaches suboptimal for emerging multi-panel, multi-link UE architectures – particularly wearables and augmented reality (AR) devices with tight thermal budgets and rapidly varying propagation environments. This paper proposes a fully autonomous, UE-side uplink selection framework based on a five-component total energy cost function: Etotal = Etx + Ebaseband + Eswitching + Etuning + Emargin, where Etx is the transmit energy, Ebaseband is the baseband and RF chain activation energy, Eswitching is the antenna panel and link switching transient energy, Etuning is the antenna retuning and settling energy, and Emargin is an uncertainty margin penalty. The selection is performed entirely on-device using internal UE measurements, impedance/VSWR sensing, power amplifier (PA) telemetry, and inertial measurement unit (IMU)/grip sensing – without network assistance. A forward-looking extension over a prediction horizon T uses satellite ephemeris and Doppler trajectory data to minimize cumulative energy expenditure for NTN links. Joint carrier aggregation (CA) and simultaneous TN+NTN multi-link selection are addressed within the same framework. Hysteresis is enforced by conditioning switching events on the criterion that the reduction in Etx and Ebaseband exceeds the sum of Eswitching and Etuning by a programmable margin. Analytical results demonstrate the validity of the proposed framework across a range of multi-panel and multi-link UE scenarios.

Keywords: Antenna selection, carrier aggregation, energy efficiency, non-terrestrial networks, power amplifier telemetry, predictive link selection, satellite communications, uplink transmission, user equipment, VSWR.

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1. Introduction

The rapid evolution of cellular user equipment toward multi-panel antenna architectures, carrier aggregation across multiple component carriers, and concurrent terrestrial and non-terrestrial network connectivity has introduced a new class of energy management challenges that existing uplink resource selection frameworks are ill-equipped to address. Smartphones, wearables, and augmented reality (AR) devices now routinely incorporate four or more antenna panels, multiple independent transmission chains, and modems capable of simultaneous operation on 5G New Radio (NR) terrestrial links and low-earth-orbit (LEO) satellite NTN links as standardized in 3GPP Release 17 and beyond. Wearables and AR devices are particularly susceptible to uplink energy inefficiency owing to their significantly reduced battery capacities, constrained antenna apertures, and heightened sensitivity to grip-induced impedance variation resulting from their worn or handheld usage patterns.

Existing approaches to uplink antenna and link selection fail to account for the multi-component energy costs arising from antenna switching, retuning, baseband chain activation, and propagation uncertainty. A first class of approaches uses downlink reference signal measurements (such as RSRP or CQI) as proxies for uplink path quality. This approach is fundamentally indirect: downlink and uplink propagation conditions can differ substantially, particularly in frequency-division duplex (FDD) systems and in multi-panel UEs where the active panel for reception may differ from the optimal panel for transmission. A second class delegates antenna selection to the network, which introduces signaling overhead, is inapplicable in high-latency NTN scenarios, and is unavailable in networks lacking advanced uplink antenna selection signaling. A third class, represented by sounding reference signal (SRS)-based antenna switching, reconfigures SRS resources but is oriented toward channel sounding rather than data transmission energy minimization.

The contributions of this paper are as follows:

1. A five-component total energy cost function is proposed for UE-side uplink antenna panel and network link selection, providing the first unified formulation that explicitly and simultaneously accounts for all material energy costs in multipanel, multi-link UE architectures.

2. A fully autonomous on-device selection algorithm is presented that populates the five-component cost function using internal UE measurements without requiring network assistance.
3. The cost function is extended to a forward-looking prediction horizon using satellite ephemeris and Doppler trajectory data for NTN links.
4. Joint carrier aggregation and simultaneous TN+NTN multi-link selection are addressed within the same framework, deriving a hysteresis condition that prevents energetically unjustified switching events.
5. An analytical characterization of the energy terms and a demonstration of the framework's energy-saving properties are presented.

2. Related Work

2.1. Uplink Antenna Selection in Multi-Antenna UE

Transmit antenna selection (TAS) for uplink communications has been studied extensively in the context of MIMO systems. In 3GPP LTE and NR, uplink TAS is specified as a closed-loop procedure. Extensions to carrier aggregation environments have been proposed, but these are fundamentally network-driven and do not optimize UE-side energy consumption. Work on UE-side power minimization for multi-antenna uplink transmission has considered the selection of the number of active transmit chains, but this formulation does not model switching transient energy, retuning energy, or baseband activation energy. The impact of user hand grip on antenna performance in multi-panel UE has been studied, demonstrating that grip-induced antenna efficiency degradation can exceed 10 dB. Grip-aware beam codebook adaptation has been proposed, but without integration into an energy cost optimization framework.

2.2. Energy-Efficient Carrier Aggregation

Carrier aggregation in 5G NR enables UEs to aggregate multiple component carriers, increasing throughput at the cost of activating additional baseband chains and RF front-end components. The energy cost of CA has been studied to jointly optimize component carrier selection and resource block allocation. AI-enabled approaches have also been proposed for energy-aware CA, but these works address only the baseband component of the total energy cost and do not model switching/tuning energy.

2.3. Non-Terrestrial Network Integration and Energy Efficiency

The integration of LEO satellite NTN links into 5G NR introduces new challenges due to high path loss, large Doppler shifts, and long propagation delays. Satellite ephemeris data enables UE-side prediction of satellite geometry and Doppler trajectory. Energy-efficient multi-connectivity scheduling for uplink NTN has been studied, but these works focus on network-side schedulers rather than UE-side autonomous selection based on a comprehensive energy cost function.

2.4. Internal UE Measurement for Uplink Path Quality Estimation

Prior works have explored individual sensor modalities such as impedance sensing and PA telemetry in isolation, but combining all three – VSWR/impedance sensing, PA telemetry, and IMU/grip sensing – as inputs to a unified uplink energy optimization framework has not been previously proposed.

3. System Model

3.1. UE Architecture

A UE device equipped with $N\_p \geq 2$ switchable antenna panels is considered. The UE supports N_C transmission chains, which can be connected to different antenna panels through an RF switching fabric. The UE can connect to N_l network links, comprising TN and NTN links. It supports carrier aggregation across up to N_CA component carriers. At each uplink transmission opportunity t, the UE must select a configuration tuple $(i, j, k) \in S$, where S denotes the set of feasible configurations.

3.2. Channel and Propagation Model

For TN link k, the uplink path loss at time t is modeled as:

$$PL\_TN(k, t) = PL_0(k) + 10\eta \log_{10}(d(t)/d_0) + X\_\sigma. \quad (1)$$

PL_0 is the reference path loss at d_0, η is the path loss exponent, X_σ is log-normal shadow fading (zero-mean Gaussian in dB with std σ)

For NTN link k, the uplink path loss at time t is modeled as:

$$PL\_NTN(k, t) = 20 \log_{10}(4\pi d\_s(t) f\_c/c) + L\_atm(\theta(t)) + L\_rain + L\_point(t) + X\_\sigma, NTN. \quad (2)$$

$\theta(t)$ is elevation angle; d_s(t) is the slant range between UE and satellite; L_point(t) is pointing/misalignment loss; X_σ,NTN is NTN shadow fading term per 3GPP TR 38.811.

3.3. Antenna Efficiency and VSWR Model

The total radiation efficiency of antenna panel i at time t is:

$$\eta\_rad(i, t) = (1 - |\Gamma(i, t)|^2) * \eta_0(i, t). \quad (3)$$

The VSWR is measured directly by the UE's internal impedance measurement circuit:

$$VSWR(i, t) = (1 + |\Gamma(i, t)|)/(1 - |\Gamma(i, t)|). \quad (4)$$

The required PA output power to achieve a target EIRP is calculated accordingly:

$$P\_PA(i, j, k, t) = P\_EIRP\_target(k, t) * L\_feed(i)/(G\_ant(i) * \eta\_rad(i, t)) \quad (5)$$

where G_ant(i) is the antenna gain of panel (i) in linear scale and $L\_feed(i) \geq 1$ is the feed and connector loss factor between the PA output port and the antenna feed point.

The intrinsic radiation efficiency $\eta_0(\mathrm{i, t})$ in (3) is affected by grip-induced body loading, which varies with grip state and device orientation as estimated from IMU and grip sensor measurements. Misclassification of grip state introduces uncertainty in η_rad(i, t) via (3) and consequently in P_PA(i,j,k,t) via (5), degrading the accuracy of the uplink path quality estimate for body-loaded panel configurations.

4. Five-Component Total Energy Cost Function

The total energy consumed by the UE for an uplink transmission using configuration (i, j, k) is modeled as the sum of five components:

$$\begin{aligned} \mathrm{Etotal(i, j, k)} &= \mathrm{Etx(i, j, k) + Ebaseband(i, j, k)} \\ &\quad + \mathrm{Eswitching(i, j, k) + Etuning(i, j, k)} \\ &\quad + \mathrm{Emargin(i, j, k)} \end{aligned} \tag{6}$$

A weighted form with dynamically configurable coefficients (shadow pricing) is:

$$\begin{aligned} \mathrm{Eselect(i, j, k)} &= \alpha * \mathrm{Etx(i, j, k)} + \beta * \mathrm{Ebaseband(i, j, k)} \\ &\quad + \gamma * \mathrm{Eswitching(i, j, k)} + \delta * \mathrm{Etuning(i, j, k)} \\ &\quad + \varepsilon * \mathrm{Emargin(i, j, k)} \end{aligned} \tag{7}$$

The coefficients $\alpha, \beta, \gamma, \delta, \varepsilon \geq 0$ in (7), with at least one strictly positive, represent the relative priority assigned to each energy component in the selection objective. A negative coefficient would reward increased expenditure on that component, contradicting the minimization objective.

The weights are adapted dynamically as a function of UE operating state: α and β are elevated under battery-critical conditions to penalize sustained energy consumption; β is elevated under thermal throttling to suppress baseband chain activation; γ, δ, and ε are elevated under high mobility to penalize switching transients and uncertain estimates; and ε is elevated when NTN satellite elevation is low, biasing selection toward the TN link until geometry improves.

4.1. Transmit Energy Term (Etx)

The estimated RF output energy required to deliver an uplink payload of B bits over configuration (i, j, k) during a transmission interval of duration Ttx:

$$\mathrm{E\_tx(i, j, k) = P\_PA(i, j, k, t) * \ T\_tx}/\eta\mathrm{\_PA(i, j, k)}. \tag{8}$$

4.2. Baseband Activation Energy (Ebaseband)

The state-dependent energy cost of activating or maintaining the baseband processing chain and RF front-end:

$$\mathrm{Ebaseband(i, j, k) = PBB(j, k) * Ttx} + \Delta\mathrm{Eact(j, k, j_0, k_0)}. \tag{9}$$

Where P_BB(j, k) is the steady-state baseband chain power draw and ΔE_act(j, k, j_0, k_0) is the one-time activation energy when transitioning from chain-link pair (j_0, k_0) to (j, k).

4.3. Switching Transient Energy (Eswitching)

The energy consumed during the physical transition from the currently active configuration to the candidate configuration (including RF switch actuation and modem state transitions):

$$\mathrm{E\_switching(i, j, k) = E\_sw\_RF(i, i_0) + E\_sw\_modem(j, k, j_0, k_0)} \tag{10}$$

where E_sw_RF(i, i_0) is the RF switch actuation energy transitioning from panel i_0 to i, and E_sw_modem(j, k, j_0, k_0) is the modem state-transition energy.

4.4. Antenna Retuning Energy (Etuning)

The energy consumed by the antenna impedance matching network reconfiguration process and settling time:

$$\begin{aligned} \mathrm{E\_tuning(i, j, k)} &= \mathrm{E\_tune\_ctrl(i, k, i_0, k_0)} \\ &\quad + \mathrm{P\_PA\_settle(i, k) * T\_settle(i, k)}. \end{aligned} \tag{11}$$

where E_tune_ctrl(i, k, i_0, k_0) is the control energy of the tunable matching network and P_PA_settle(i,k) is the PA power during the settling transient, with T_settle(i, k) being the impedance settling time.

4.5. Uncertainty Margin Energy Penalty (Emargin)

An optional uncertainty penalty derived from the confidence level of the uplink path quality estimate:

$$\mathrm{E\_margin(i, j, k)} = \lambda * (1 - \rho\mathrm{(i, j, k)}) * \mathrm{E\_tx(i, j, k)}. \tag{12}$$

where ρ(i, j, k) $\in [0, 1]$ is the confidence in the path quality estimate for configuration (i, j, k) and $\lambda \geq 0$ is a tunable penalty weight.

4.6. Optimization Problem

The UE selects the configuration (i$*$, j^*, k^*) that minimizes the weighted total energy cost subject to QoS and regulatory constraints:

$$(\mathrm{i^*, j^*, k^*}) = \mathrm{argmin(i, j, k)} \in \mathrm{SEselect(i, j, k)} \tag{13}$$

5. Autonomous On-Device Selection Using Internal UE Measurements

The cost function in (7) is populated using internal UE measurements rather than network-provided measurements or downlink reference signals. This avoids signaling overhead and mitigates the downlink-proxy inaccuracies inherent in FDD systems. Three measurement modalities are employed.

5.1. Impedance and VSWR Sensing

The UE's internal impedance measurement circuit monitors $|\Gamma(\mathrm{i, t})|$ at each antenna panel, from which η_rad(i, t) is computed via (3) and VSWR(i, t) via (4). The required PA output power P_PA(i,j,k,t) is then obtained via (5), directly populating E_tx in (8). The confidence of this measurement is reflected in $\rho(i, j, k)$ in (12), such that panels with elevated mismatch uncertainty incur a higher E_margin penalty in (7), discouraging their selection under uncertain impedance conditions.

5.2. Power Amplifier Telemetry

PA telemetry provides real-time measurement of PA efficiency η_PA(i, j, k) and actual RF output power, which are substituted directly into E_tx in (8).

5.3. IMU and Grip Sensing

IMU and grip sensor measurements estimate device orientation and grip state, identifying body-loaded panels with degraded η_0(i, t) in (3). As established in Section III-C, grip state misclassification introduces uncertainty in η_rad(i, t) via (3) and P_PA(i,j,k,t) via (5), which propagates into $\rho(i, j, k)$ in (12) and increases E_margin in (7) for affected panel configurations, penalizing their selection in (13).

6. Hysteresis Framework

To prevent energetically unjustified switching in volatile propagation environments, a transition from the current configuration to a candidate configuration is executed only if:

$$\begin{aligned} &\text{E\_select}(\text{i\_curr}, \text{j\_curr}, \text{k\_curr}) \\ &\quad - \text{E\_select}(\text{i\_cand}, \text{j\_cand}, \text{k\_cand}) \\ &> \text{E\_switching}(\text{i\_cand}, \text{j\_cand}, \text{k\_cand}) \\ &\quad + \text{E\_tuning}(\text{i\_cand}, \text{j\_cand}, \text{k\_cand}) + \Delta\text{\_margin}. \end{aligned} \tag{14}$$

7. Forward-Looking Prediction for NTN Links and Future Work

For NTN satellite links, the UE uses satellite ephemeris data (orbital parameters, position, velocity) to predict the satellite elevation angle and slant range over a forward-looking horizon T. This allows the UE to proactively switch panels or links based on predicted path loss evolution and Doppler shift rather than reacting post-degradation.

The proposed framework establishes the analytical foundation for autonomous UE-side uplink energy optimization. Numerical evaluation of the 5C-EAF against transmit-power-only and network-assisted baselines, including per-component energy savings quantification and sensitivity analysis of the weight coefficients $\alpha, \beta, \gamma, \delta$, and ε across varying UE operating states, TN channel conditions, and NTN satellite geometries, are left for future work. Hardware-in-the-loop validation on commercial UE platforms equipped with PA telemetry and impedance sensing capability will further confirm the practical realizability of the on-device selection algorithm under realworld grip, mobility, and multi-link conditions.

8. Conclusion

This paper has presented a five-component total energy cost function for autonomous UE-side uplink antenna and link selection, establishing an analytical foundation for energy-aware uplink selection that addresses the limitations of legacy single-metric systems.

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