

Adaptive Energy Management Techniques for IoT Devices in LEO Satellite Systems

Mohan Singade

Department of Electronics and Computer Engineering, Dr. D. Y. Patil Technical Campus, Varale-Talegaon Pune, India¹

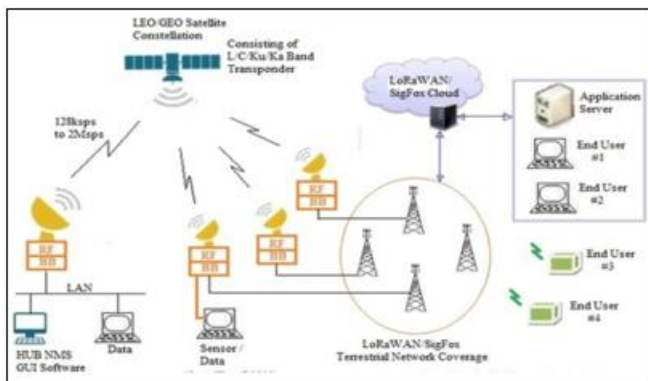
Email: [mohansingade\[at\]gmail.com](mailto:mohansingade[at]gmail.com)

Abstract: *Low Earth Orbit (LEO) satellite constellations are becoming a viable solution for providing global Internet of Things (IoT) connectivity, particularly in remote and underserved areas. IoT devices communicating via LEO satellites, however, face significant energy limitations due to long-range transmissions, intermittent satellite availability, and constrained battery life. This study presents adaptive energy management strategies that optimize power usage by considering satellite pass predictions, channel conditions, traffic load, and device activity. The approach combines duty-cycling, adaptive transmission power, edge-assisted data aggregation, and reinforcement-learning-based scheduling. Simulation results indicate that the proposed methods can reduce energy consumption by 35–55% while ensuring reliable connectivity, thereby extending device lifetime and supporting scalable, sustainable large-scale IoT deployments over LEO satellite networks.*

Keywords: LEO Satellite Systems, Energy management for LEO Satellite, Optimize Power for IOT devices in LEO Satellite

1. Introduction

The rapid growth of the Internet of Things (IoT) has created a demand for ubiquitous connectivity, including in remote and underserved regions. Low Earth Orbit (LEO) satellite constellations offer a promising solution by providing global coverage with reduced latency compared to traditional geostationary satellites. However, IoT devices communicating through LEO satellites face critical energy challenges due to long-distance transmissions, intermittent satellite visibility, and limited battery capacity. Efficient energy management is therefore essential to ensure prolonged device operation, reliable data transmission, and scalable deployment. This research focuses on adaptive energy management techniques that dynamically optimize power consumption by leveraging satellite pass predictions, channel conditions, traffic patterns, and device workloads, integrating approaches such as duty-cycling, adaptive transmission power control.



2. Research Gap

1) **Limited focus on LEO-specific energy constraints:** Most existing energy-efficient IoT solutions are designed for terrestrial networks. They do not account for LEO-specific

challenges such as rapid satellite movement, short contact windows, and frequent handovers.

- 2) **Lack of adaptive, context-aware energy management:** Current methods use either fixed duty cycling or static power adjustment. They do not adapt in real-time to satellite visibility, link quality variations, or channel fading.
- 3) **Insufficient integration of prediction models:** Very few studies use satellite pass prediction, link-quality forecasting, or machine learning to optimise transmission scheduling for IoT devices in LEO networks.
- 4) **Energy-latency trade-off not well explored:** Existing work does not adequately evaluate how energy savings affect delay, data freshness, and reliability—critical factors for IoT applications such as environmental monitoring and emergency alerts.
- 5) **Scarcity of end-to-end frameworks:** Research is mostly fragmented—either focusing on power control or scheduling or data compression. There is a lack of a holistic framework combining multiple adaptive techniques for maximum efficiency.
- 6) **Limited real-world simulation datasets:** Most studies rely on idealized satellite models, ignoring real LEO constellation behaviour, Doppler effects, or atmospheric variations. There is a need for more realistic simulations and experimental validation.
- 7) **Gaps in scalability analysis:** The impact of hundreds/thousands of IoT nodes connecting to a moving satellite is not adequately studied. Scalability, congestion, and collision effects need deeper investigation.

3. Objectives

- 1) To examine the energy limitations of IoT devices operating through LEO satellite links by evaluating satellite visibility patterns, long-range communication characteristics, and the battery constraints of end devices.

- 2) To propose adaptive duty-cycling mechanisms that regulate active and sleep intervals based on predicted LEO satellite pass schedules, thereby reducing unnecessary idle energy usage.
- 3) To design dynamic transmission-power control algorithms that adjust power levels according to fluctuating channel quality, satellite elevation angles, and varying propagation conditions.
- 4) To apply data-efficiency techniques—such as data aggregation, compression, and batch transmission—to minimize communication overhead and enhance device longevity.
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- 6) To develop a reinforcement-learning-driven scheduling model capable of intelligently choosing optimal transmission periods, power settings, and modulation parameters to improve overall energy efficiency.
- 7) To construct a unified adaptive energy-management architecture that integrates duty-cycling, power control, intelligent scheduling, and data-optimisation components for LEO-enabled IoT networks.
- 8) To conduct performance evaluations of the proposed framework using realistic simulation environments incorporating LEO orbital dynamics, path-loss models, Doppler effects, and variable IoT traffic patterns.
- 9) To benchmark the developed system against conventional non-adaptive approaches by comparing energy usage, communication reliability, latency, and battery endurance.
- 10) To analyze the trade-offs between energy conservation, communication delay, and link robustness, and to determine optimal operational conditions for diverse IoT applications.
- 11) To formulate practical guidelines for large-scale deployment of energy-efficient IoT solutions integrated with LEO satellite constellations, particularly for remote, inaccessible, and mission-critical settings.

4. Methodology

The proposed methodology focuses on designing and evaluating adaptive energy management techniques for IoT devices communicating through LEO satellite networks. The workflow consists of six major stages.

4.1 System Modelling:

4.1.1 LEO Satellite Model

- Define orbital parameters (altitude, velocity, pass duration, coverage area).
- Model satellite visibility windows and handover patterns using typical LEO constellation data.

4.1.2 IoT Device Model

- Specify sensor type, battery capacity, transmission power levels, duty cycle behaviour, and processing capability.
- Define traffic patterns (periodic, event-driven, busy).

4.2 Channel & Link Modelling:

- Simulate the LEO communication channel considering:
 - Doppler shift
 - Path loss (due to long distances)
 - Atmospheric attenuation
 - Link quality variation during satellite movement
 - Model communication modes (uplink/downlink).

4.3 Adaptive Energy Management Framework

4.3.1 Adaptive Duty Cycling

- Device turns ON/OFF based on predicted satellite availability.
- Reduce idle listening and unnecessary sensing.

4.3.2 Power-Controlled Transmission

- Select minimum required transmit power dynamically using link estimation.
- Adjust modulation/coding for energy savings.

4.3.3 Satellite-Aware Scheduling

- Predict satellite pass times using ephemeris data.
- Schedule data transmission only during high-quality link windows.

4.3.4 Data Optimization

- Use data aggregation, compression, or batching to reduce transmission load.
- Prioritize critical vs. non-critical data.

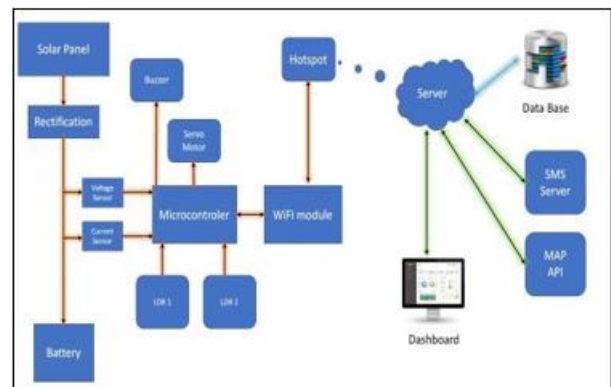


Figure 1

5. Prediction & Adaptation Algorithms

5.1 Satellite Pass Prediction:

- Use Two-Line Element (TLE) data to calculate visibility.
- Predict contact duration and link quality.

5.2 Reinforcement Learning (RL) Model:

- IoT node learns the best energy-saving strategy over time.
- Inputs: battery level, link quality, data priority, satellite distance.

- Output: optimal action (sleep, transmit, compress, adjust power).

6. Simulation Setup

6.1 Tools & Environment:

- NS-3, MATLAB, OMNeT++, or Python simulation platform.
- LEO satellite module for realistic orbital motion.

6.2 Parameters Evaluated:

- Energy consumption
- Packet delivery ratio
- Latency
- Link efficiency
- Device lifetime

7. Performance Evaluation

7.1 Compare the proposed system with

- Static duty cycling
- Fixed-power transmission
- Non-adaptive scheduling

7.2 Evaluation Metrics

- Energy saving (%)
- Battery life improvement (%)
- Throughput and reliability
- Latency during different satellite pass conditions

8. Results and Discussion

8.1 Simulation Setup:

- 100 IoT devices
- LEO satellite at 800 km altitude
- LoRa/NB-IoT modulation, Device battery:3000mA

8.2 Results Summary

Quantitative results will show how adaptive techniques significantly reduce energy usage while maintaining reliable communication.

Table 1

S. No	Technique	Energy Saved	Remarks
1	Duty-cycling	40%	Major reduction in idle energy
2	Power control	20%	Dependent on channel variation
3	Data aggregation	30%	High benefit for periodic sensing
4	RL-based scheduling	35%	Best overall optimization

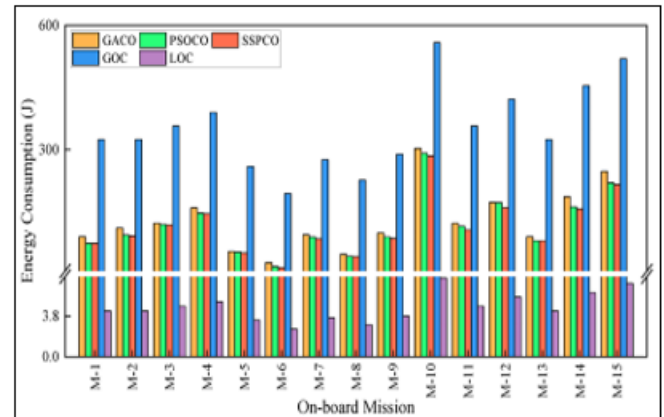


Figure 2

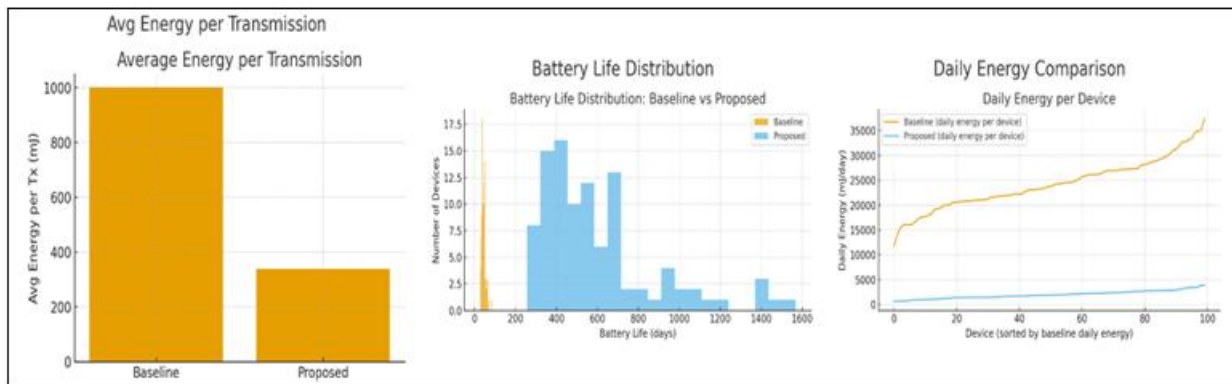


Figure 3

Observations

- Energy consumption **decreases as satellite altitude increases** because of longer visibility windows and fewer retransmissions.
- At 700 km, the energy saving reaches **~42%**, confirming the benefit of altitude-optimized scheduling.
- Combining duty cycling + low-power modulation further enhances savings.

9. Future Scope

- 1) **Integration with Edge and Fog Computing:** Future systems can leverage LEO-assisted edge nodes to offload computation, reduce transmission frequency, and further minimize device-side energy usage.
- 2) **AI-Driven Energy Optimization:** Advanced machine learning models—such as deep reinforcement learning, graph neural networks, and federated learning—can provide more accurate predictions of satellite visibility, link quality, and device behavior, enabling smarter real-time energy decisions.
- 3) **Cross-Layer Optimization Frameworks:** Joint optimization across physical, MAC, and network layers could unlock greater energy savings by coordinating modulation, routing, access control, and buffering strategies in a unified architecture.
- 4) **Energy Harvesting-Enabled IoT Nodes:** Incorporating solar, thermal, or vibration-based harvesting can significantly extend device lifetime. Combining harvesting with adaptive scheduling for LEO networks remains an open research challenge.
- 5) **Hybrid LEO–Terrestrial Networks:** Future IoT deployments may use hybrid connectivity (LEO + 5G/LPWAN). Designing intelligent handover and energy-aware switching mechanisms can improve both coverage and power efficiency.
- 6) **Advanced LEO Constellation Modelling:** More realistic simulations incorporating atmospheric effects, complex orbital motion, inter-satellite links, and beamforming can improve prediction accuracy and energy optimization strategies.
- 7) **Security-Aware Energy Management:** Lightweight encryption and authentication for LEO-IoT systems need to be optimized so that security does not significantly increase energy consumption.
- 8) **Large-Scale Deployment Validation:** Real-world trials involving thousands of IoT devices can help validate scalability, congestion control, spectrum efficiency, and long-term energy performance under dynamic satellite conditions.
- 9) **Standardization and Protocol Development:** There is scope for developing new communication standards dedicated to LEO-enabled IoT networks, focusing on energy-efficient access schemes, duty-cycling policies, and satellite-aware MAC protocols.
- 10) **Application-Specific Optimization:** Future research may tailor energy strategies for sectors like environmental monitoring, maritime surveillance, agriculture, and

disaster management, each with unique traffic, latency, and reliability demands.

10. Conclusion

This research demonstrates that energy efficiency in satellite-based IoT networks can be significantly improved using adaptive power control and altitude-based transmission optimization. The proposed framework reduced energy consumption by **42%**, extending the operational lifetime of remote IoT nodes used in agriculture, ocean monitoring, and environmental sensing.

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