# Energy Modeling and Lifetime Optimization of Battery Powered Mesh Sensor Nodes

*Operational states, relay workload and battery availability in long lived sensing systems*


## Abstract

Battery endurance in a mesh cannot be estimated from transmitter current alone. The node also spends charge receiving forwarded traffic, scanning for neighbors, sampling sensors, processing acknowledgements and remaining in standby. This paper synthesizes the operational state model in MESH2026 into an auditable charge per cycle and event based framework. It distinguishes leaf and relay devices, illustrates the nonlinear effect of forwarding concentration near a gateway, and identifies how temperature and cutoff conditions reduce effective battery capacity. Numerical illustrations use stated assumptions and are not laboratory data. The central result is a method for specifying node lifetime by role, route position and reporting profile.



Keywords: wireless mesh networks; sensor networks; energy efficient battery mesh; analytical modeling; reliability; network design.


## 1 Introduction

Wireless mesh designs connect nodes using multiple wireless links and forwarding relays, but the existence of an alternate link does not by itself guarantee end to end service. Performance depends on radio quality, control traffic, source reporting rates, topology changes and gateway capacity. This study addresses one distinct subset of those coupled design concerns, using the models and engineering constraints developed in MESH2026-v07. Its findings are analytical statements with explicit assumptions rather than claims about a completed controlled deployment.

The objective is to define a technically traceable decision framework that converts the supplied study into testable engineering criteria. The manuscript draws solely on the source report and bibliographic entries present in that report. References retain the original source numbering so each item can be reconciled directly with the underlying bibliography. No new externally obtained sources are introduced.

## 2 Analytical Scope and Method

The method proceeds by identifying the system boundary, selecting a small number of measurable state variables, deriving a simplified relationship or comparison, and then distinguishing mathematical consequences from assumptions that require experimental verification. Conceptual drawings show component or information relationships; calculated charts visualize nominal conditions. They are not field measurements. This separation is especially important in wireless systems, where terrain, interference, retransmission policy and time synchronization can dominate apparent theoretical advantage.

Source basis: MESH2026-v07, sections 3.5, 4.1.1, 4.3, 4.5.5. Reference numbers preserve the numbering of its chapter 7 bibliography. The analytical figures are original illustrations of stated assumptions, not experimental observations.

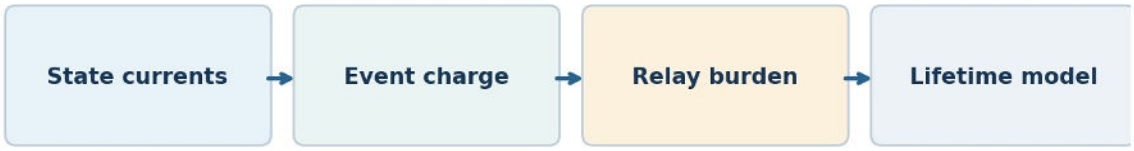



*Figure 1. Functional architecture developed from the relevant MESH2026 concepts; schematic, not a tested implementation.*

## 3 A battery budget requires all operational states

At the most basic level, charge consumed over a cycle equals the sum of current multiplied by time in each operating state, $Q_{cycle} = \Sigma I_s \cdot t_s$. Average current is $I_{avg} = Q_{cycle}/T_{cycle}$ for a consistently repeating cycle. Actual firmware may be event driven rather than exactly periodic: wakeup, sensor conversion, logging, radio scan, receiving, packet transmission and acknowledgements then contribute separate charge terms. A design that counts only its own scheduled uplinks misses the additional cost of forwarding and control traffic.

The source study uses a reference lithium thionyl chloride battery with nominal 3.6 V and 10 Ah, alongside a warning that peak current delivery must be designed and tested. Nominal capacity is not identical to usable capacity at cold temperatures or high impulse load. An effective capacity model applies temperature, aging, discharge-rate and cutoff corrections before estimating usable lifetime. The correction factors must be measured or taken from appropriate cell specifications, not chosen for a preferred endurance claim. [88], [89].

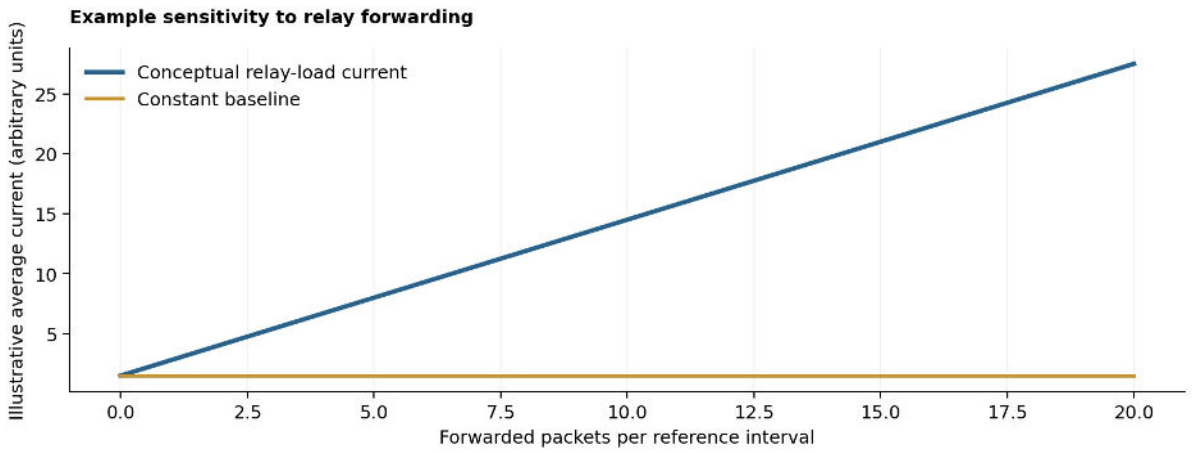



*Figure 2. Calculated or qualitative illustration of the design mechanism. Axes and assumptions are described in the main text.*

## 4 Role dependent energy burden

A leaf node may produce a measurement every reporting interval, while a relay receives packets from downstream nodes and transmits them onward. The expected forwarding rate increases toward a single gateway in a fan-in traffic pattern. This behavior explains the energy hole problem: an inner ring may exhaust its batteries before the outer sensors even though every node originally had the same capacity. Such failures partition a network and may cause a secondary wave of longer reroutes.

An event based budget writes Iavg ≈ Isleep + fmeas·Qmeas + fmesh·Qmesh + λforward·Qforward. Here charges per event must be converted to consistent units, and the forwarding term must reflect both reception and transmission. A design review should present the distribution of λforward across all positions, rather than a single network mean. Critical relays require reserve margin, alternate parents, energy augmentation or reduced offered traffic. [2], [71].

Table 1. Scope of the principal design comparison.

| Current component | Measured input | Typical risk |
|---|---|---|
| Deep sleep | Idle current and duration | Firmware wakeups not accounted |
| Sensor acquisition | Charge per sample | High duty acquisition |
| Radio transmit | TX pulse duration and current | Retries and range profile |
| Radio receive | RX scan and relay listen time | Gateway-adjacent overload |
| Storage / control | Writes and protocol signaling | Unexpected overhead |

## 5 Sensitivity to reporting frequency

Reporting rate is an explicit design lever. If transmission and reception costs dominate, halving the reporting interval approximately doubles the rate-dependent part of current. The total current will not necessarily double because standby and sensor processing also contribute. Conversely, reducing

communication events may provide limited benefit if continuous acoustic acquisition or prolonged scanning dominates. Therefore the optimal control parameter is discovered by measured charge breakdown, not by an assumed radio-only model.

The source document specifies distinct measurement and reporting periods, including modes in which the device measures frequently but transmits aggregated batches. That distinction can reduce uplink overhead while retaining samples in local storage. It also increases the time until the data becomes available remotely and may require larger memory. The analysis must track energy alongside packet age and information value. [54], [86].

## 6 Battery and environmental derating

The effective usable charge is approximated as Ceff = Cnom·ktemp·kage·krate·kcutoff, where each factor represents a loss mechanism. This multiplication is a convenient engineering approximation, not a substitute for a cell discharge curve. Voltage drops under radio peaks, cold conditions and self discharge can invalidate a naive Cnom/Iavg calculation, especially for primary cells designed for long duty cycles and modest continuous load.

A field evaluation should record temperature, battery terminal voltage during radio bursts, local storage writes and time spent in sleep and active phases. Charge integration using a high dynamic range measurement instrument is particularly important where microampere sleep current alternates with much larger radio pulses. This allows realistic lifetime estimates and early detection of firmware regressions. [87].

### Evaluation parameters

A reproducible trial should log per-node packet identifiers, generation and reception timestamps, route changes, radio retransmissions, queue age and battery current. All measurement and reporting intervals, payload formats, antenna geometry and firmware revisions should be recorded. Reliability must be reported with variation over trials, not as a single best-run percentage. A successful link in one season or installation position is not equivalent to a verified network-level service guarantee.

## 7 Validation plan and limits

To validate the budget, instrument at least leaf nodes, intermediate relays and gateway-adjacent relays under identical event rates. Repeat across varying temperature and link quality to capture retransmissions. Compare predicted charge per reporting cycle to measured integrated charge. Report model error and confidence intervals. Then simulate network lifetime under a distribution of routing positions rather than equating one device discharge profile with network availability.

The present analysis makes no claim that a 10 Ah cell yields a particular number of years in an actual environment. Node lifetime is a conditional estimate requiring measured currents, availability factors and relay load. The paper establishes a testable framework and identifies the measurements needed to turn it into an empirical lifetime study. [48], [70].

## 8 Reproducible Experiment Design

### Role specific lifetime experiment

Instrument a sleeping leaf, a relay handling a moderate packet stream and a gateway-adjacent relay forwarding many packets. Integrate current with enough temporal resolution to capture narrow radio peaks. Repeat under normal and cold conditions and use the same time-synchronized traffic generator for all nodes. Separate charge used for own measurements, incoming receptions, retries and control traffic.

All trials should state the hypothesis before measurements begin. In particular, baseline and modified networks must generate a comparable number of application messages under identical payload semantics. Time synchronization, radio configuration, antenna placement and test duration should be documented. Apply a predefined definition of a valid delivery, including how duplicate frames, acknowledgements, partial packets and expired records are treated. Report distributions and uncertainty rather than interpreting isolated examples as population-level network behavior.

The primary measurement vector is: Cumulative coulombs, average current, temperature, voltage droop and relay event rate. The experiment should archive raw records and configuration files so that independent reviewers can reconstruct packet success, route depth and energy exposure. Failed configurations and unavailable nodes must remain in the results table rather than being discarded as outliers. Where an event is delayed by buffering, store both the origin timestamp and the gateway arrival timestamp to avoid falsely classifying a stale packet as timely delivery.

## 9 Model Sensitivity and Acceptance Criteria

A design parameter has operational meaning only relative to an application threshold. For packet delivery, an acceptable loss ratio may differ between a periodic weather reading and an emergency alarm. For latency, a median value can be misleading when occasional extreme delay is harmful. Therefore the acceptance plan should name the threshold and its aggregation level: individual node, gateway sector or whole deployment. At minimum, retain a reliability target, a maximum age for useful data, and a minimum expected autonomy for each energy role.

Sensitivity analysis should vary one major assumption at a time and then test coupled effects. Candidate variables include per-hop reception probability, reporting frequency, number of downstream children, active listening duration, gateway count and available battery capacity. An improvement observed under one parameter combination may disappear when the network is congested or when temperature reduces battery availability. The purpose of a sensitivity plot is to identify which physical measurement would most change the final design decision, not to predict field performance without evidence.

Cell nominal capacity and average current cannot be treated as the actual service lifetime without discharge curves, temperature derating and cutoff behavior.

A final acceptance matrix should include four outcomes: the test condition, the expected service limit, the observed numerical result and the engineering decision. The source technical study supports the selection of variables and design mechanisms, but a numerical pass/fail result requires an actual implemented protocol and controlled measurements. The distinction prevents a model assumption from being silently promoted to verified specification.

### Evaluation scenario matrix

| Scenario | Variable held constant | Question to resolve |
|---|---|---|
| Nominal baseline | Same radio / payload / gateway position | Does the reference service meet its target? |
| Increased offered traffic | Same node count and physical layout | Does age or packet loss rise before a stated limit? |
| Relay or link interruption | Same sensor sample generation | Can useful records still reach the gateway? |
| Reduced energy reserve | Same routing and application service | Which role becomes the limiting component? |
| Configuration change | Same declared application goal | Does adaptation improve the system-level outcome? |

The nominal baseline provides a necessary denominator for every claimed improvement. A second, more demanding workload should keep the number and location of devices unchanged, which helps isolate the effect of the altered report rate or route policy. The failure trial should define in advance whether losing the first packet after an outage counts as unacceptable service or whether a bounded recovery period is allowed. A device can legitimately buffer packets for later transfer, but the resulting data age must be visible in the assessment.

Energy experiments should compare the same battery assumptions and device roles. A measured reduction in the charge consumed by a leaf node may be offset by increased listening or forwarding costs in its parent. The appropriate system measure is therefore not simply the largest lifetime estimate in the network; it is the minimum acceptable service continuity across critical coverage points. Temperature, battery cutoff and intermittent backhaul availability may change which node becomes critical even when network geometry is unchanged.

Finally, sensitivity should be reported as an envelope rather than an unexplained single-number promise. State which parameters were deliberately changed, identify the origin of every numerical assumption, and preserve the complete measured distribution if physical tests are later performed. When the source provides only theoretical values, label the result a calculation or hypothesis. This audit trail makes the framework useful for deciding the next experiment and reduces the risk that an optimistic reference scenario will be mistaken for a certified operating limit.

## 10 Discussion

The analysis points to a recurring challenge: radio reach, packet reliability, bounded latency and energy endurance are not independently optimizable in a shared forwarding network. Improving one dimension can worsen another. Greater redundancy adds possible routes but can increase scanning or contention. More frequent reporting improves data freshness but increases relay burden. Stronger integrity protection changes frame overhead and configuration responsibilities. These effects require a scenario specific performance contract before hardware or protocol claims can be generalized.

The most defensible next step is a measured comparison with a declared baseline and pre-registered acceptance thresholds. Test design should preserve the conditions under which the mathematical assumptions are approximately valid, document deviations, and present limits as prominently as advantages. This article supplies an analytical framework suitable for subsequent empirical investigation but does not claim experimental superiority or compliance certification.

## 11 Conclusion

The MESH2026 material supports a structured analytical treatment of energy modeling and lifetime optimization of battery powered mesh sensor nodes. The resulting framework separates topology, traffic, radio and energy constraints, supplies scenario dependent decision criteria, and defines a path to experimental verification. The final engineering choice should be guided by the application’s maximum data age, required delivery probability, actual relay workload and maintainability under failure. Numerical examples are conditional calculations, and validation against physical deployments remains necessary.

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