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Energy-Efficient Modulation and Communication Technologies for Internet of Things Networks: A Focused Comparative Review and Research Agenda

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ABSTRACT—

Energy efficiency in Internet of Things (IoT) communications cannot be inferred from transmit power alone. It depends on modulation, airtime, receiver sensitivity, protocol overhead, connection procedure, retries, sleep scheduling, topology, and the delivery target of an application. This focused review compares four widely deployed IoT connectivity families: LoRaWAN based on chirp spread spectrum (CSS), Bluetooth Low Energy (BLE) based on Gaussian frequency-shift keying (GFSK), IEEE 802.15.4/Zigbee based on offset-QPSK with direct-sequence spread spectrum (O-QPSK/DSSS), and cellular narrowband IoT (NB-IoT), for which QPSK is a representative physical-layer modulation option. Rather than declaring a universal winner, the review organizes the evidence around energy per successfully delivered packet, coverage, latency, reliability, scalability, topology, and infrastructure dependence. The analysis shows that long range and low instantaneous transmit power do not guarantee minimum energy per delivered bit; the governing trade-off is the total radio-state and protocol cost required to meet an application service constraint. Key research gaps include inconsistent energy boundaries, non-comparable workloads, missing delivery-conditioned metrics, weak treatment of density and link quality, and limited trace-calibrated cross-technology studies. A cross-layer decision framework and a research agenda are proposed to enable fairer evaluation and application-aware technology selection.

Keywords—Internet of Things, energy efficiency, LoRaWAN, Bluetooth Low Energy, Zigbee, IEEE 802.15.4, NB-IoT, modulation techniques.

1. Introduction

IoT systems connect sensors, actuators, meters, wearables, and industrial assets that commonly operate for months or years from small batteries. The communication subsystem is frequently the dominant and most variable energy consumer because radio use includes not only payload transmission but also receive windows, channel access, synchronization, control signaling, retry, and idle listening. Consequently, a comparison that reports only a nominal transmit power or a peak data rate can select an inappropriate technology for real deployment. Broad surveys recognize that IoT connectivity options occupy distinct short-, local-, and wide-area niches rather than a single performance continuum [1], [2].

Four connectivity families are central to contemporary low-power IoT design. LoRaWAN combines long-range CSS at the physical layer with a wide-area star-of-stars network architecture. BLE uses GFSK and is optimized for energy-conscious short-range personal-area connectivity. IEEE 802.15.4 provides a low-rate wireless foundation often used by Zigbee mesh networks, including an O-QPSK/DSSS mode in the 2.4 GHz band. NB-IoT is a licensed cellular IoT technology whose performance is shaped by cellular access, signaling, coverage enhancement, and operator infrastructure. Their design targets overlap in some applications but diverge sharply in link budget, bandwidth, latency, topology, and operational cost [1], [2], [9].

This article is a focused comparative review rather than a meta-analysis. It synthesizes peer-reviewed surveys, representative comparative studies, and the relevant technology specifications to answer three questions: (i) how do modulation and protocol mechanisms change the energy budget, (ii) what conditions determine an appropriate technology choice, and (iii) what experimental gaps prevent fair cross-technology conclusions? The review also supplies a research agenda that directly motivates trace-calibrated simulation studies, including the companion LoED-based empirical study planned in this research program.

2. Review Scope and Evaluation Perspective

A fair energy comparison must specify the service outcome rather than treating radio transmission as an isolated event. The appropriate primary metric is delivery-conditioned energy, $E_{del} = E_{cycle} / P_s$, where E_{cycle} is the energy expended during sensing and communication for a reporting cycle and P_s is the probability of successful application-level delivery. The communication portion is expanded as $E_{comm} = E_{tx} + E_{rx} + E_{idle} + E_{sleep} + E_{ctrl} + E_{retx}$. The expression makes two facts explicit: a short transmission may be inefficient if it requires frequent connection activity or retries, while a long-airtime transmission can remain attractive when it permits deep sleep, high link success, and low reporting frequency.

The review therefore evaluates technologies along six common dimensions: (1) energy per successful packet, (2) coverage and penetration, (3) latency and data-rate adequacy, (4) reliability under loss, interference, and congestion, (5) scalability at realistic node density, and (6) deployment and infrastructure dependence. These dimensions should be evaluated under equivalent payload sizes, reporting intervals, link-quality classes, and reliability constraints. Without these controls, apparent technology advantages may result only from different test workloads or different definitions of delivery.

TABLE I. Representative IoT technologies and their energy-relevant communication characteristics

Technology	Representative modulation and architecture	Energy-relevant strengths	Principal limitation / best fit
LoRaWAN	CSS PHY; star-of-stars LPWAN; unlicensed spectrum.	High receiver sensitivity and wide coverage can reduce gateway count; sleep-dominated sparse sensing is favorable.	Long airtime, duty-cycle constraints, and ALOHA-type contention can limit latency and density. Best for sparse, low-data, wide-area monitoring.
BLE	GFSK PHY; short-range star, broadcast, or connected operation in 2.4 GHz.	Short packets, low protocol overhead for local links, and efficient intermittent operation.	Range and building penetration depend on local infrastructure; 2.4 GHz coexistence can affect reliability. Best for wearables, peripherals, and gateway-assisted sensing.
IEEE 802.15.4 / Zigbee	O-QPSK/DSSS in common 2.4 GHz mode; local star or mesh.	Low-rate sensor networking with multi-hop reachability and device interoperability.	Mesh forwarding, receiver duty cycle, and routing maintenance can increase network energy. Best for local buildings and industrial sensor fields.
NB-IoT	Licensed cellular IoT; QPSK is a representative PHY mode; scheduled wide-area access.	Managed spectrum, strong coverage mechanisms, and operator QoS/security support.	Attachment, control-plane, repetition, and network configuration can dominate low-duty-cycle energy. Best for operator-covered metering and managed wide-area assets.

3. Technology and Modulation Foundations

3.1 LoRa CSS and LoRaWAN

LoRa uses chirp spread spectrum (CSS), in which information is represented by chirps whose frequency varies over time. The spreading factor, bandwidth, and coding rate jointly shape airtime, receiver sensitivity, and useful bit rate. LoRaWAN defines the MAC and network operation for battery-powered end devices, normally using a star-of-stars architecture in which gateways relay frames to a network server [3], [6]. The combination is attractive for low-rate, wide-area sensing because a gateway can serve geographically dispersed devices without per-device mesh relays.

Its energy benefit is conditional. Increasing the spreading factor improves robustness at weak links but increases time on air and collision exposure. Adaptive data rate can reduce airtime when a link margin permits, while high-density deployments require careful allocation of spreading factor, frequency, and channel resources [4], [5]. Therefore, LoRaWAN is highly suitable for sparse monitoring, agriculture, and city-scale telemetry, but it should not be selected solely from a range claim when frequent reporting, low latency, confirmed messages, or dense contention are central requirements.

3.2 BLE GFSK

BLE employs GFSK at the low-energy physical layer; the Bluetooth specification defines a Gaussian bandwidth-bit period product of 0.5 and the associated modulation index requirements [7]. Its design favors short packets, advertising, connection events, and a sleep-heavy duty cycle. The physical range is shorter than that of LPWAN systems, but a nearby phone, hub, or gateway can make BLE extremely attractive when low latency, user-device interaction, or frequent local reporting is required.

BLE energy must be assessed at the connection procedure level. Advertising intervals, connection interval, data length, channel map, retransmission, and the role of a hub affect the radio-state budget. A comparison against LoRaWAN that ignores the energy of the BLE gateway or assumes identical range is not meaningful. BLE is best viewed as a local-access technology that can be combined with another backhaul technology in multi-radio IoT designs [1], [7].

3.3 IEEE 802.15.4/Zigbee O-QPSK/DSSS

IEEE 802.15.4 defines low-rate wireless networks across several frequency bands. In its widely used 2.4 GHz mode, the standard includes O-QPSK with DSSS, which supports robust low-rate local communications; Zigbee builds network and application-layer capabilities around the underlying standard [8]. A local mesh can extend reach around obstacles, improve path diversity, and support distributed building or industrial deployments.

The energy cost of a mesh is not the energy of one radio hop. Routing discovery, neighbor maintenance, receiver wake-up schedules, and relay forwarding need to be included. Mesh routing can reduce the required link margin per hop but may consume more total network energy than a single-hop alternative for sparse layouts. Therefore, IEEE 802.15.4/Zigbee is usually most compelling when a local network already exists and the ability to route around obstructions is more valuable than wide-area coverage.

3.4 NB-IoT and cellular QPSK-based operation

NB-IoT is designed for massive low-rate connectivity through licensed cellular infrastructure. Unlike unlicensed LPWAN options, it benefits from managed spectrum and network-scheduled access, while its device energy is affected by synchronization, random access, control signaling, discontinuous reception, power-saving mechanisms, and coverage-enhancement repetitions. QPSK is a representative modulation option within LTE/NB-IoT physical-layer operation; the relevant cellular specifications define modulation mapping and physical procedures [9], [11].

The practical implication is that payload airtime alone may severely underestimate NB-IoT energy. Experimental and analytical literature reports strong latency-energy interactions when repetitions and scheduling are used under poor coverage [9], [12]. NB-IoT should consequently be evaluated as an end-to-end managed service. It is a strong candidate where operator coverage, assured security, deep indoor reach, and managed availability outweigh the infrastructure dependency and connection overhead.

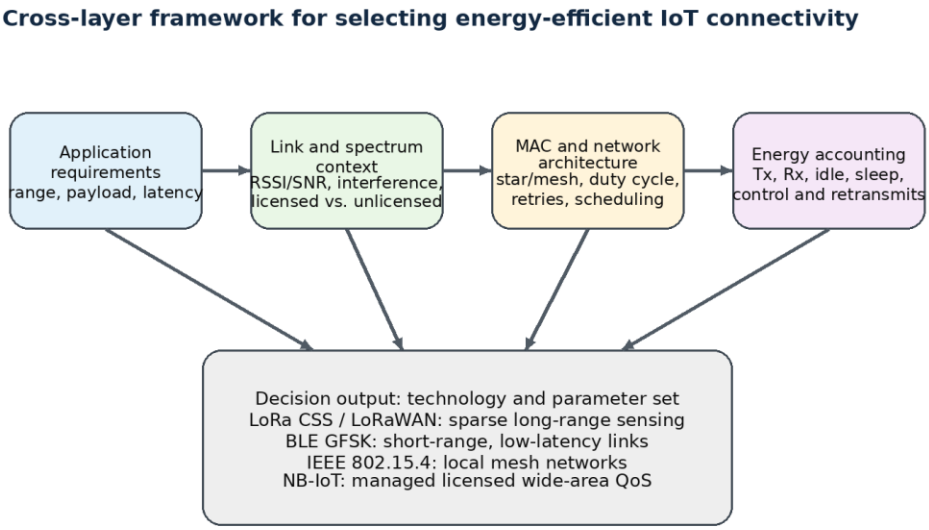


Fig. 1. Cross-layer technology selection framework. A valid choice follows application constraints, link context, architecture, and full-cycle energy accounting.

4. Comparative Energy and Communication Trade-offs

4.1 Airtime, sensitivity, and packetization

Modulation changes both the energy spent during a radio-on period and the probability that a packet is delivered. CSS can trade a lower useful rate for improved sensitivity, whereas GFSK and O-QPSK/DSSS favor higher local data rates and short burst transmission. In cellular NB-IoT, scheduled operation and coverage enhancement introduce additional state transitions and, at difficult links, repetitions. Consequently, the relevant denominator is a delivered application packet or a fulfilled service objective, not a nominal bit transmitted.

Packetization is equally important. Small payloads sent frequently can make headers, synchronization, and access procedures that dominate energy. Aggregating readings can reduce overhead but may raise latency and loss cost. For LoRaWAN, a larger spreading factor or coding rate can increase robustness but also airtime. For BLE and IEEE 802.15.4 systems, wake-up and listening schedules can dominate sparse traffic. For NB-IoT, the access and control sequence can dominate a very short payload. These mechanisms make application reporting intervals a first-class experimental variable.

4.2 Topology, infrastructure, and density

Topology shifts where energy is consumed. LoRaWAN places most infrastructure burden at gateways and keeps the end device simple, although uncoordinated access can create collisions at high offered load. BLE commonly assumes a local collector, and a BLE design should account for collector availability and backhaul. IEEE 802.15.4/Zigbee may distribute energy among relay-capable nodes, while NB-IoT transfers infrastructure complexity to the cellular network but retains device-level signaling costs. Thus, a study must distinguish end-device energy, network energy, and deployment cost instead of reporting one without the others.

Scalability is also technology specific. LoRaWAN capacity is strongly shaped by airtime, spreading-factor distribution, frequency allocation, and the likelihood of simultaneous transmissions [4], [5]. Mesh networks are constrained by relay load, routing churn, and channel contention. Cellular NB-IoT can schedule access but may exhibit delay and energy penalties under coverage enhancement. A fair scalability test must therefore increase node count while keeping the per-node reporting process, payload, and required reliability fixed.

TABLE II. Common comparability problems in energy-efficiency studies and recommended remedies

Issue	Why it biases conclusions	Recommended review / experiment practice
Transmit-power-only comparison	Omit airtime, receive windows, access signaling, idle listening, and retransmissions.	Report full-cycle end-device energy and energy per successfully delivered application packet.
Unequal workloads	Payload size, reporting interval, and acknowledgment policy change protocol overhead.	Fix service workload across technologies; separately report workload sensitivity.
No link-quality stratification	One technology can be tested on an easier RSSI/SNR range than another.	Use good, moderate, and poor link groups or a common propagation model.
Ignoring topology	Mesh relay energy and gateway/collector requirements are hidden.	State whether results are device-only, network-wide, or lifecycle-based.
Single-run conclusions	Random access, interference, and channel variation create run-to-run uncertainty.	Use repeated runs, confidence intervals, and corrected pairwise testing.

Issue	Why it biases conclusions	Recommended review / experiment practice
Generic “best technology” claim	Application constraints differ fundamentally across IoT sectors.	Provide a scenario-aware decision guide rather than a universal ranking.

5. Application-Aware Selection Guidance

Technology selection should begin with a service constraint. A sparse agricultural sensor that sends a small measurement every hour prioritizes coverage, device simplicity, and sleep-dominated energy; LoRaWAN is usually a natural candidate. A wearable that exchanges small bursts with a nearby smartphone prioritizes local availability, low latency, and modest packet overhead; BLE is generally more appropriate. A building with many rooms, obstacles, and local actuators may benefit from an IEEE 802.15.4/Zigbee mesh when routing value exceeds relay overhead. A utility meter requiring managed carrier connectivity and predictable operator support may justify NB-IoT.

However, this guidance is conditional, not prescriptive. LoRaWAN can be inefficient at unfavorable spreading factors or high confirmation rates. BLE can become impractical when a collector is unavailable. Zigbee can incur relay and maintenance energy in a thinly populated network. NB-IoT can consume substantial energy for very small, infrequent reports if access and coverage mechanisms are not configured carefully. The correct result is a technology-parameter pair: for example, LoRaWAN with a suitable spreading-factor policy, BLE with a specific connection interval, Zigbee with a bounded relay duty cycle, or NB-IoT with an appropriate power-saving and repetition configuration.

TABLE III. Scenario-aware qualitative technology-selection guide

Scenario	Primary service need	Most plausible option(s)	Key condition to validate
Smart agriculture / environmental sensing	Kilometer-scale coverage; small infrequent payloads.	LoRaWAN; NB-IoT where operator coverage and QoS are essential.	Spreading factor, duty-cycle compliance, gateway density, and low-rate reliability.
Wearables / personal sensing	Low-latency local link; phone or hub integration.	BLE.	Advertising/connection interval, coexistence, hub availability, and user mobility.
Smart building / local automation	Multi-room coverage, actuators, local resilience.	IEEE 802.15.4/Zigbee; BLE mesh in appropriate ecosystems.	Relay energy, routing stability, receiver duty cycle, and interference.
Utility metering / managed assets	Wide-area reach, managed service, deep coverage.	NB-IoT; LoRaWAN in privately deployed networks.	Access energy, coverage enhancement, carrier availability, and lifecycle cost.
Dense urban sensing	Scalability, heterogeneous links, data aggregation.	LoRaWAN with capacity control; NB-IoT; multi-RAT design.	Contention, gateway/base-station coverage, link-quality distribution, and traffic peaks.

6. Research Gaps and Future Research Agenda

6.1 Trace-calibrated and service-equivalent evaluation

Many published comparisons use nominal parameters or small laboratory layouts. This is useful for isolated validation, but it does not fully capture the temporal variation of packet arrivals, link margin, gateway diversity, and congestion seen in operational networks. A stronger approach is to extract payload, reporting interval, RSSI/SNR, spreading factor, and packet-success patterns from real traces, then use them to calibrate technology-neutral simulation scenarios. The LoED date-wise capture collection used in the associated empirical paper offers precisely this type of calibration basis for urban LoRaWAN behavior. Cross-technology results should then be generated under equal service workloads, not borrowed directly from unrelated testbeds.

6.2 Multi-RAT operation rather than winner-takes-all design

Literature increasingly supports the idea that no single radio access technology can optimize all IoT states. A device may need a low-energy local link for routine operation, a wide-area option for mobility or gateway failure, and a managed cellular path for urgent or guaranteed delivery. Multi-RAT research should quantify the cost of radio switching, scanning, provisioning, and redundancy, because a second radio is valuable only if it improves delivered service more than it increases standby and management energy. The value of combining LoRaWAN and NB-IoT has been demonstrated conceptually and experimentally for selected payload and link-quality conditions [13].

6.3 Reproducible energy models and statistics

Future work should publish the radio-state current traces or equivalent state-power parameters used to calculate energy. The boundary must be explicit: device-only energy, device plus gateway, or system lifecycle energy. Simulations should include at least transmit, receive, idle, sleep, control, and retransmission states, report random seeds and repetitions, and provide confidence intervals. When many configurations are compared, an omnibus test and corrected pairwise comparisons are needed. These practices are especially important when nominal differences are small or when stochastic contention creates large uncertainty.

6.4 Security, maintenance, and carbon-aware metrics

Energy efficiency must not reduce secure operation to an afterthought. Authentication, encryption, key rotation, firmware updates, and monitoring create communication work that should be budgeted for long-lived devices. Similarly, replacement visits, battery changes, gateway electricity, and network maintenance determine lifecycle impact. A mature evaluation should therefore add maintenance frequency and carbon-aware infrastructure metrics alongside joules per packet. These topics are particularly relevant for deployments scaled to thousands of devices and multi-year operation.

7. Conclusion

The authors of this focused review show that the development of efficient (energy-wise) IoT communications is a multi-layered (cross layer) design issue. Each of the technologies mentioned in this paper has its own strengths/advantages, but these will depend on how well the requirements of an application fit with the assumptions made about the conditions of use at the time they were developed. In particular, LoRaWAN/CSS are good for supporting large scale sparse sensor applications; BLE/GFSK have strong possibilities as very-low-power connections between devices close together; Zigbee/O-QPSK/DSSS are suitable for very-low-rate mesh networking among nearby nodes; and NB-IoT has attractive possibilities for providing reliable licensed wide area connectivity to all nodes. There should be no assumption that one technology can support all possible requirements. Instead, the most useful way to compare them would be by measuring the amount of energy required to deliver one packet of data from source to destination under equivalent service constraints. A research agenda has been proposed which includes trace calibrated workloads, comprehensive radio state energy measurements, link quality stratified metrics, multiple replications (measurement/simulation), and recommendations based on scenarios.

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