

BLE Optimization: A Review

Omkar Shrivare

Electronics & Telecommunication

JSPM's Rajarshi Shahu College Of Engineering , Pune
Pune, India shrivareomkar1244@gmail.com

Sakshi Karvande

Electronics & Telecommunication

JSPM's Rajarshi Shahu College Of Engineering , Pune
Pune, India karvandesakshi@gmail.com

Dr. S. M. Joshi

Electronics & Telecommunication

JSPM's Rajarshi Shahu College Of Engineering , Pune
Pune, India smjoshi_entc@rscoe.edu.in

Arati Patil

Electronics & Telecommunication

JSPM's Rajarshi Shahu College Of Engineering , Pune
Pune, India patilarati2773@gmail.com

Aparna Sontakke

Electronics & Telecommunication

JSPM's Rajarshi Shahu College Of Engineering , Pune
Pune, India sontakkeaparna16@gmail.com

Abstract

Bluetooth Low Energy (BLE) is one of the most widely used wireless technologies in Internet of Things (IoT) applications, owing to its low power consumption, low implementation cost, and short-range communication capability. Yet most conventional BLE deployments rely on fixed communication parameters, wasting energy when operating conditions change. This paper reviews adaptive, machine-learning-assisted, and hardware-level approaches to energy-efficient BLE communication, and proposes a Smart Adaptive BLE Module for IoT Applications that tunes transmission power, advertising interval, connection interval, and PHY mode dynamically in response to link quality, battery state, and application requirements. A mathematical energy and link-budget model is developed to relate transmission time, supply voltage, current consumption, packet-delivery ratio, and retransmission behavior to overall energy efficiency. Numerical examples show that reducing transmit power below the point needed for reliable delivery can increase, rather than decrease, energy per successfully delivered byte due to retransmissions. The reviewed literature is compared across communication method, key control variables, validation approach, and remaining limitations. Based on this review, an EFR32BG22-based hardware implementation is proposed as a suitable platform for a compact, energy-efficient adaptive BLE module, with a defined measurement plan for future experimental validation.

Index Terms

Bluetooth Low Energy, Internet of Things, Energy Efficiency, ESP32, EFR32BG22, Adaptive Communication, Low-Power Wireless Communication, Battery Life

1. INTRODUCTION

The rapid growth of the Internet of Things (IoT) has raised the demand for wireless technologies that deliver reliable connectivity while drawing minimum power. IoT devices are typically battery-operated and are expected to run for long stretches without frequent battery replacement, which makes

energy efficiency a central design consideration for smart sensing, healthcare monitoring, wearable devices, industrial automation, smart homes, and environmental monitoring.

Bluetooth Low Energy has emerged as a natural fit for these applications because it combines low-power communication with low implementation cost and compatibility across a wide range of smart devices. However, conventional BLE configurations rely on fixed communication parameters that do not adapt to the situation at hand. A device sitting close to its receiver does not need high transmission power, yet a fixed configuration supplies it anyway. A device under poor signal conditions, by contrast, may need increased transmission power or a more robust communication mode than the default. Similarly, transmitting data at a fixed interval wastes energy when the sensed information hardly changes.

Several research groups have investigated ways to improve the energy efficiency and reliability of BLE-based systems, including adaptive PHY selection, transmission-power optimization, connection-interval optimization, lightweight machine-learning-based adaptation, and BLE mesh networking [2]–[8]. These studies consistently show that dynamically adjusting BLE communication parameters to match operating conditions can cut energy consumption without sacrificing performance. Nevertheless, many of these methods optimize a single parameter or target one specific scenario, leaving room for a more flexible, integrated solution.

2. REVIEW METHODOLOGY

The review for the proposed Smart Adaptive BLE Module for IoT Applications followed five steps:

- **Methodology analysis.** The methods used by different researchers were studied, including adaptive PHY se-

lection, transmission power control, connection-interval optimization, and BLE Mesh communication.

- **Parameter identification.** The key BLE parameters affecting energy and communication performance were identified: transmission power, advertising interval, connection interval, PHY mode, RSSI, and packet size/data rate.
- **Performance parameters.** The following metrics were chosen for evaluating BLE performance: energy consumption, battery lifetime, packet delivery ratio, latency, throughput, communication range, and packet loss.
- **Comparison of existing methods.** The advantages and limitations of different approaches were compared to decide which techniques suit a low-power IoT BLE system best.
- **Research gap identification.** The review showed that most existing approaches focus on one parameter or one application, leaving clear room for a flexible system that adapts multiple BLE parameters to changing operating conditions.

3. LITERATURE REVIEW

A. Energy-Efficient BLE Extended Advertisements for Large Sensor Data

Gautam and Kumar investigate the use of BLE extended advertisements for energy-efficient, reliable transmission of large sensor datasets in monitoring applications [1]. Their study targets high-sampling-rate motion sensing, where legacy advertisements fall short due to limited payload capacity, forcing many small transmissions. The authors experimentally compare legacy and extended advertisements and show that extended advertisements become more energy efficient as application data size grows, while legacy advertisements remain preferable for very small payloads. The study explores sending up to 1650 bytes in a single extended advertising event via chained secondary-channel packets and evaluates the reliability-energy trade-off under different congestion levels and chain lengths. Data loss generally remains 2–4% for large data transfers, although higher losses can occur when the receiving link layer rejects partially received chains.

B. Baseline BLE Performance Evaluation

Tosi et al. provide a systematic review of BLE performance, reporting that practical throughput, range, power consumption, latency, and supported node count all depend on configuration and implementation conditions [2]. This study serves as a baseline: BLE performance cannot be captured by a single number such as nominal data rate; an application must balance several metrics simultaneously.

C. Data-Transfer Efficiency

Bulic' et al. investigated the energy consumption and data throughput of different BLE versions and connection parameters [3]. Their experiments show that the connection interval strongly influences performance, but the effect differs across transaction types, supporting application-specific parameter selection over a universal fixed setting.

D. Joint Runtime Adaptation

Park et al. introduced AdaptaBLE, which jointly controls connection interval, data rate, and transmission power using local link measurements [4]. The work is notable for evaluating the approach on real embedded hardware rather than simulation alone, reporting roughly a five-fold reduction in QoS failures compared with a reference parameter-control scheme, while keeping energy consumption similar.

E. Large-Scale BLE Communication

Nikodem et al. studied BLE deployments in which many devices communicate in the same area [5]. In connectionless operation, multiple nodes may compete for spectrum access, producing collisions, extending the energy-efficiency problem from a single link to network-scale coexistence.

F. BLE Mesh Energy Modeling

Darroudi et al. developed a model for BLE Mesh energy consumption [6]. Mesh operation introduces relay-related activity beyond a simple point-to-point link, making energy modeling essential when extending a compact BLE module to multi-node systems.

G. Machine-Learning-Assisted Adaptation

The SMART-A-BLE work reported a decision-tree-based method that predicts an appropriate connection interval from link- and traffic-related features, balancing latency, retransmission behavior, and current consumption [7]. This direction is promising for future adaptive modules but introduces model-selection, memory, and computation overheads that must be weighed on resource-constrained hardware.

H. Ultra-Low-Power Radio Architecture

Abdelatty et al. review radio-level techniques for reducing wireless energy consumption and discuss the joint importance of protocol and radio architecture [8], highlighting that transceiver energy can dominate the budget of battery-powered or battery-less IoT nodes.

4. RESEARCH GAP ANALYSIS

The reviewed literature points to several recurring gaps. First, many studies optimize one parameter or a limited subset, even though practical IoT operation depends on the interplay between transmission power, data rate, connection interval, traffic, and link quality. Second, algorithmic improvements are not always accompanied by the complete hardware and power-management design needed for a deployable module. Third, performance is often reported using selected metrics; a fuller evaluation should jointly report energy, PDR, latency, throughput, range, and battery lifetime.

The project underlying this review identifies the need for a flexible system that adapts multiple BLE parameters to changing operating conditions. Its proposed decision variables are RSSI, battery level, data activity, and application requirements, while the target control variables are transmission power, advertising/connection interval, and PHY mode.

TABLE I
COMPARATIVE ANALYSIS OF REVIEWED APPROACHES

Study	Main Focus	Key Variables	Validation	Main Limitation / Gap
Gautam & Kumar	Extended advertisements	Payload size, chain length, congestion	Experimental	Literature
Tosi et al.	BLE performance review	Power, latency, throughput, range	Experimental	Optimal chain size is data/network dependent No new integrated adaptive module
Bulic' et al.	Data-transfer efficiency	Connection interval, version, traffic	BLE Real BLE hardware	Parameter effects depend on transaction type
Park et al.	Joint adaptation	Connection interval, rate, TX power	Experimental/simulation	Communication-only; no full module/PCB design
Nikodem et al.	Large-scale BLE	Advertising/collision behavior, node count		Network-scale focus only
Darroudi et al.	BLE Mesh energy model	Relay/network activity, energy	Analytical/model based	Mesh-specific; not a compact hardware design
SMART-A-BLE packet features	ML-based adaptation	Latency, link quality	Algorithm + BLE ML/resource overhead on constrained hardware	
Abdelatty et al. behavior	ULP radio architecture	RX/TX current, wake-up	Testbed Literature review	Trade-off with range/latency not quantified

A further practical gap is the separation between communication from the final EFR32BG22 PCB are explicitly illustrative research and compact PCB implementation. A module intended assumptions.

for real IoT deployment must consider power regulation, decoupling, clock sources, RF matching, antenna implementation, firmware, measurement access, and application interfaces together. The literature supports the need for low-power, adaptive operation, but does not by itself provide a complete, application-specific hardware design.

I. IMPLICATIONS FOR A COMPACT ADAPTIVE BLE MODULE

Based on the reviewed literature, a practical module can be organized around an adaptive control loop. The node first observes link and application conditions – RSSI or other link-quality information, battery condition, traffic activity, and latency requirements. It then selects an operating point for transmission power, connection/advertising interval, and PHY/data-rate configuration. The resulting performance can be evaluated using energy per useful payload, PDR, latency, throughput, and battery-life estimates.

For the proposed project hardware, the EFR32BG22 is a suitable implementation target, as the device family is explicitly designed for energy-efficient Bluetooth LE IoT products [9]. Silicon Labs specifies low transmit and receive current, an Arm Cortex-M33 core, multiple BLE PHY options, and low-power operating modes – directly relevant to the gap identified above – although actual module-level performance must be measured on the fabricated PCB rather than inferred from datasheet values. The measurement plan should include current consumption in sleep, advertising, receive, and transmit states; PDR at different distances; latency under different connection intervals; throughput under different PHY/data-rate configurations; and battery-life estimation from measured average current.

II. MATHEMATICAL DESIGN CALCULATIONS

This section presents the engineering analysis used to evaluate the proposed module. All numerical values not measured

A. Basic Electrical Power Calculation

For a DC-powered BLE module, instantaneous electrical power is $P = VI$. Assuming a regulated supply of $V = 3.3$ V and an active radio current of $I = 8.5$ mA:

$$P_{TX} = 3.3 \text{ V} \times 8.5 \text{ mA} = 28.05 \text{ mW} \quad (1)$$

If the radio remains active for 1 ms during one communication event:

$$E_{TX} = P_{TX} \times t = 28.05 \text{ mW} \times 1 \text{ ms} = 28.05 \mu\text{J} \quad (2)$$

A real BLE event may contain transmit, receive/acknowledgement, processing, and possible retransmission periods, so the final measured event energy will differ.

B. Payload Transmission-Time Calculation

The payload transmission time can be estimated as

$$T_{payload} = (D \times 8)/R. \text{ For } D = 20 \text{ bytes and } R = 1 \text{ Mbit/s:}$$

$$T_{payload} = \frac{20 \times 8}{1,000,000} = 160 \mu\text{s} \quad (3)$$

For the same payload at 2 Mbit/s, $T_{payload} = 80 \mu\text{s}$. In practice, PHY overhead, packet scheduling, and retransmissions mean the complete event time will not be exactly half.

C. Packet-Overhead and Useful-Efficiency Calculation

Assuming a 20-byte application payload and 10 bytes of lower-layer overhead, total packet size = 30 bytes, and protocol efficiency = $20/30 \times 100 = 66.67\%$. Sending 100 bytes as five 20-byte payload packets gives total transmitted bytes = $5 \times 30 = 150$ bytes, so application-data efficiency remains $100/150 = 66.67\%$.

TABLE II

RESEARCH DIRECTIONS AND REMAINING ISSUES

Research direction	Primary objective	Useful parameter(s)	Remaining issue
BLE performance evaluation	Characterize system behavior	Power, latency, throughput, range	No adaptive control
Extended advertisements	Reliable large-payload transfer	Chain length, congestion	Optimal chunking is data-dependent
Adaptive PHY	Select PHY from link state	RSSI, PHY, outage, throughput	Limited parameter scope
	Balance latency and current	Connection interval, traffic	Application dependent
Joint adaptation	Optimize multiple link connections	Interval, rate, TX power needed	Hardware-specific validation
Dense BLE	Reduce collisions and loss	Node count, advertising	Scalability/environment effects
BLE Mesh	Estimate lifetime and energy/bit	Relay activity, traffic	Mesh-specific behavior
ML adaptation point	Predict suitable operating point	Latency, retransmissions, packet data	Model overhead and training data
ULP radio design	Reduce intrinsic radio energy	RX/TX architecture, wake-up	Trade-off with range/latency

D. Average Current from Duty Cycle

For periodic communication, average current is approximated by

$$I_{avg} = \frac{I_{active} t_{active} + I_{sleep} (T - t_{active})}{T} \quad (4)$$

With $I_{active} = 8.5 \text{ mA}$, $I_{sleep} = 0.005 \text{ mA}$, $t_{active} = 1 \text{ ms}$, and $T = 30 \text{ ms}$:

$$I_{avg} = \frac{(8.5 \times 1) + (0.005 \times 29)}{30} \approx 0.288 \text{ mA} \quad (5)$$

giving $P_{avg} = 3.3 \times 0.288 \approx 0.950 \text{ mW}$. For $T = 60 \text{ ms}$ with the same active event:

$$I_{avg} \approx 0.147 \text{ mA}, \quad P_{avg} \approx 0.485 \text{ mW} \quad (6)$$

E. Duty-Cycle Calculation

Duty cycle = $t_{active}/T_{interval} \times 100$. For 1 ms active time and $T = 30 \text{ ms}$: duty cycle = 3.33% ; for $T = 60 \text{ ms}$: duty cycle = 1.67% .

F. Energy per Useful Byte with Retransmissions

Assuming $28.05 \mu\text{J}$ per attempt and a 20-byte payload, energy per byte without retransmission is $1.4025 \mu\text{J}/\text{byte}$.

At 90% delivery probability, expected attempts = $1/0.90 = 1.111$, giving expected energy $\approx 31.17 \mu\text{J}$, or $\approx 1.558 \mu\text{J}/\text{byte}$. At 70% delivery probability, expected attempts = 1.429 , expected energy $\approx 40.07 \mu\text{J}$, or $\approx 2.004 \mu\text{J}/\text{byte}$. This shows that the lowest transmit power is not automatically the most energy-efficient operating point: excessive failures increase total delivery energy through retransmission.

G. Packet Delivery Ratio from a Test

For $N_{sent} = 1000$ and $N_{received} = 965$: $\text{PDR} = 96.5\%$, packet loss = 3.5% . For a second configuration with 985 received packets, $\text{PDR} = 98.5\%$, a 2.0-point improvement, corresponding to a relative packet-loss reduction of $(3.5 - 1.5)/3.5 \times 100 \approx 57.1\%$.

H. Throughput Calculation

Throughput = useful data delivered / measurement time. For $80,000$ bits in 2 s , throughput = 40 kbit/s ; if retransmissions extend this to 2.5 s , throughput drops to 32 kbit/s despite an unchanged nominal PHY rate.

I. Latency Calculation

For $T_{CI} = 30 \text{ ms}$, maximum scheduling wait $\approx 30 \text{ ms}$; for $T_{CI} = 60 \text{ ms}$, $\approx 60 \text{ ms}$. Adding 2 ms for processing/transmission gives worst-case estimates of $\approx 32 \text{ ms}$ and $\approx 62 \text{ ms}$ respectively.

J. Battery-Lifetime Calculation with a Safety Factor

$L_{ideal} = C_{battery}/I_{avg}$. For a 220-mAh battery and $I_{avg} = 0.288 \text{ mA}$: $L_{ideal} = 763.9 \text{ h} = 31.8 \text{ days}$. With a conservative usable-capacity factor of 0.80 (176 mAh): $L_{practical} \approx 611.1 \text{ h} \approx 25.5 \text{ days}$.

K. Link-Budget Calculation

$$P_{RX}(\text{dBm}) = P_{TX} + G_{TX} + G_{RX} - PL - L_{misc} \quad (7)$$

Assuming $P_{TX} = 0 \text{ dBm}$, 0 dBi antenna gains, and 2 dB miscellaneous loss, at 10 m and 2.4 GHz :

$$PL_{FS} = 20 \log_{10} \frac{4\pi df}{c} \approx 60.05 \text{ dB} \quad (8)$$

Therefore $P_{RX} \approx -62.05 \text{ dBm}$. With a hypothetical receiver sensitivity of -90 dBm , the link margin is 27.95 dB . Real module range must be measured, since walls, orientation, PCB loss, enclosure effects, multipath, and interference can substantially reduce this margin.

DIAGRAM

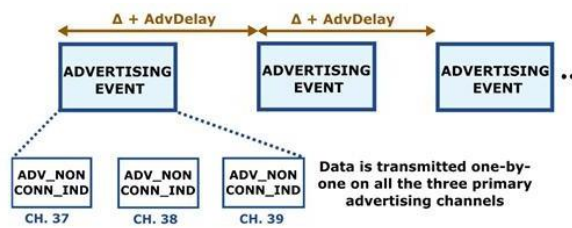


Fig. 2. Data transfer through BLE legacy advertisements.

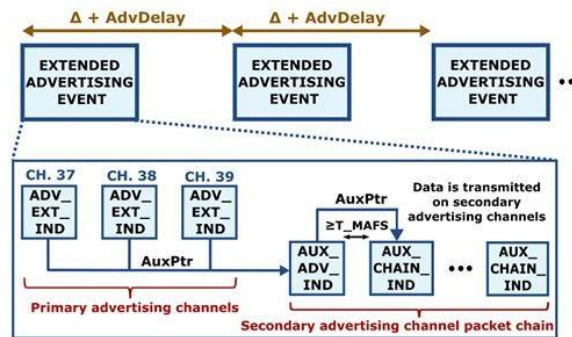


Fig. 3. Data transfer through BLE extended advertisements.

CONCLUSION

This review examined adaptive, machine-learning-assisted, and hardware-level approaches to energy-efficient BLE communication and identified a consistent gap: existing work optimizes individual parameters or single scenarios rather than providing an integrated, hardware-validated adaptive module. The proposed mathematical framework quantifies how transmit power, connection interval, duty cycle, and packet reliability jointly determine energy per delivered byte, showing that overly aggressive power reduction can increase total energy through retransmissions. Future work will implement and measure the proposed EFR32BG22-based adaptive BLE module against the performance parameters and calculations defined here.

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