Towards Quality of Service Guarantees in Bluetooth A Cross-Layer Framework for LE and Classic Coexistence in the 2.4 GHz IoT Ecosystem

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Abstract Bluetooth technology has become foundational for short-range communication in a wide range of Internet of Things (IoT) applications, encompassing both Bluetooth Low Energy (LE) and Classic protocols [1], [2]. With the 2.4 GHz ISM band increasingly congested by coexisting technologies such as Wi-Fi, Zigbee, and proprietary wireless protocols [3], [4], Bluetooth now faces critical challenges in delivering consistent Quality of Service (QoS) for time-sensitive and bandwidth-intensive use cases [5]. In contrast to Wi-Fi, which benefits from robust QoS frameworks like IEEE 802.11e and Wi-Fi Multimedia (WMM) [6], [7], Bluetooth's current design lacks built-in mechanisms for traffic prioritization, deterministic latency, or adaptive scheduling. This paper identifies core limitations of Bluetooth's transport architecture under interference-prone conditions and proposes a novel cross-layer QoS framework. Our design introduces traffic classification at the application layer, connection event prioritization at the link layer, coexistence-aware adaptive frequency hopping, and enhanced controller-host coordination through vendor-specific HCI extensions. We validate the proposal using simulations and empirical tests involving mixed BLE/Classic traffic and controlled Wi-Fi interference. The results demonstrate improvements in latency, jitter, and reliability, especially for critical IoT use cases such as voice, telemetry, and health monitoring. The framework provides a scalable path forward for integrating Bluetooth QoS into future specifications and enabling its use in high-density, real-time applications [8]–[12].

***Index Terms*—Bluetooth Low Energy (BLE), Bluetooth Classic, Quality of Service (QoS), 2.4 GHz ISM band, wireless coexistence, latency-sensitive applications, link-layer scheduling, traffic prioritization, connection event management, interference mitigation, IoT reliability, Wi-Fi interference, cross-layer optimization, vendor-specific HCI, Bluetooth mesh, real-time communication, LE Audio, industrial IoT (IIoT), adaptive frequency hopping, multi-radio systems.**

I. Introduction

Bluetooth technology has become a cornerstone of modern wireless communication, particularly in the Internet of Things (IoT) ecosystem. It enables a diverse range of applications, from wearable health monitors and smart home automation to industrial sensing and LE Audio streaming. Bluetooth Low Energy (BLE), introduced in Bluetooth 4.0, emphasizes energy efficiency, while Bluetooth Classic supports higher-throughput applications like audio streaming and serial data communication [1], [2]. Despite their functional differences, both operate within the crowded 2.4 GHz Industrial, Scientific, and Medical (ISM) band, sharing spectrum with Wi-Fi, Zigbee, cordless phones, and microwave ovens [3].

As the number of Bluetooth-enabled devices continues to rise—projected to exceed 7 billion by 2027 [4]—so do the challenges in ensuring robust and predictable wireless performance. In dense wireless environments, Bluetooth's reliance on frequency hopping alone is insufficient to mitigate packet loss, delay, and jitter. These limitations are particularly problematic for emerging real-time use cases, including voice assistants, industrial closed-loop control, and connected healthcare devices, where low-latency and high-reliability communication is critical [5], [6].

In contrast, IEEE 802.11-based Wi-Fi systems benefit from well-defined Quality of Service (QoS) mechanisms, including traffic classification, contention window tuning, and queue prioritization through frameworks such as Enhanced Distributed Channel Access (EDCA) and Wi-Fi Multimedia (WMM) [7], [8]. Bluetooth, however, provides no formal support for application-level traffic prioritization, dynamic latency control, or end-to-end service guarantees. Its connection-oriented model, based on static connection intervals and best-effort delivery, offers limited flexibility to dynamically adapt to network congestion or interference [9].

The lack of QoS support becomes especially pronounced in scenarios involving multi-protocol coexistence. Devices that support both Wi-Fi and Bluetooth—such as smartphones, smartwatches, and AR/VR headsets—often face contention for airtime, leading to performance degradation for latency-sensitive services like audio streaming or real-time alerts [10]. While mechanisms such as Adaptive Frequency Hopping (AFH) and Packet Scheduling exist, they are primarily reactive and do not account for service-specific performance requirements [11], [12].

This paper addresses the fundamental absence of a QoS framework in Bluetooth. We propose a modular, cross-layer QoS architecture that enables traffic classification, link-layer scheduling enhancements, coexistence-aware frequency adaptation, and host-controller coordination through vendor-agnostic HCI extensions. The proposed framework is evaluated using both simulations and empirical testing under varying interference and traffic loads. Our results demonstrate significant gains in latency predictability, packet delivery ratio, and energy efficiency for real-time applications.

The rest of the paper is structured as follows: Section 2 reviews related work; Section 3 defines the system model and problem formulation; Section 4 presents the proposed QoS framework; Section 5 evaluates its performance under different scenarios; Section 6 discusses implementation challenges and future work; and Section 7 concludes with key findings and recommendations.

II. Related work

Efforts to enhance the Quality of Service (QoS) in wireless technologies have been historically centered around Wi-Fi, cellular systems, and industrial protocols. Comparatively, Bluetooth's support for QoS—particularly in dynamic and interference-heavy environments—remains limited. This section reviews relevant research and specifications from Bluetooth, Wi-Fi, and industrial wireless systems to highlight gaps and motivate our proposed framework.

2.1 Wi-Fi QoS Mechanisms

Wi-Fi's evolution toward service differentiation began with the IEEE 802.11e standard [1], which introduced the Enhanced Distributed Channel Access (EDCA) mechanism. EDCA assigns different priority levels (Access Categories) to various types of traffic such as voice, video, best effort, and background [2]. These are implemented in practice through the Wi-Fi Multimedia (WMM) specification by the Wi-Fi Alliance [3]. These mechanisms enable low-latency communication for real-time services, offering a model for potential Bluetooth adaptation.

2.2 Bluetooth Transport and Scheduling

Bluetooth Classic and Low Energy were originally designed for point-to-point best-effort communications. The Bluetooth Core Specification [4] defines connection intervals and supervision timeouts but does not include mechanisms for traffic prioritization or scheduling across applications. Connection events are assigned statically, and retransmissions are handled at the link layer without traffic differentiation [5].

LE Isochronous Channels, introduced in Bluetooth 5.2, are the closest Bluetooth analog to QoS-aware transmission. They support time-bounded data for LE Audio use cases, ensuring deterministic latency and minimal jitter [6]. However, this feature is application-specific and not generalized to all BLE traffic classes.

2.3 BLE Performance Under Interference

Several studies have highlighted BLE's vulnerability to interference in the 2.4 GHz band. Petrova et al. [7] and Sikora et al. [8] demonstrated degradation in BLE throughput and reliability when operating concurrently with Wi-Fi. Adaptive Frequency Hopping (AFH) was introduced to mitigate these effects, but it lacks predictive adaptation or QoS prioritization based on application need [9].

Gomez et al. [10] explored the performance of LE Audio and noted that while isochronous channels reduce latency, their deployment remains niche and does not solve the broader need for generalized QoS in BLE networks. Similarly, Boggia et al. [11] introduced a feedback-based approach for dynamic interval control, but this mechanism operates independently of application-level priority information.

2.4 Industrial Wireless QoS

Protocols like Wireless HART and ISA100.11a offer time-synchronized channel hopping, traffic shaping, and deterministic delivery guarantees for industrial sensor networks [12]. These standards serve as mature examples of QoS-driven design, where critical control messages are prioritized over background telemetry. Zigbee Pro includes enhancements such as the MAC-level Guaranteed Time Slots (GTS) for predictable delivery [13].

Bluetooth Mesh attempts to offer scalable IoT support, but its flooding-based routing and lack of deterministic scheduling make it unsuitable for low-latency applications [14].

2.5 Bluetooth/Wi-Fi Coexistence

Research in coexistence mechanisms has been extensive. Lansford et al. [15] proposed time-slicing and AFH strategies to reduce mutual interference. Guo et al. [16] further proposed adaptive hopping algorithms based on spectral scanning to dynamically avoid busy channels. While effective in reducing collisions, these approaches are reactive and do not tie into application-aware QoS policies.

Summary

Despite incremental progress in BLE audio and industrial wireless networks, a comprehensive QoS framework for general-purpose Bluetooth use remains absent. Current mechanisms either address niche use cases (LE Audio) or offer coarse, reactive interference mitigation. This motivates our proposal for a cross-layer QoS model for Bluetooth that incorporates traffic classification, connection event prioritization, and coexistence-aware spectrum adaptation.

III. System model and problem statement

3.1 System Model

We consider a heterogeneous wireless communication environment operating in the 2.4 GHz Industrial, Scientific, and Medical (ISM) band. The system includes:

- Bluetooth Classic devices using Asynchronous Connection-Less (ACL) and Synchronous Connection-Oriented (SCO/eSCO) links for streaming and control applications.
- Bluetooth Low Energy (BLE) devices operating with connection-oriented events and periodic advertising for low-power sensor and peripheral communication.
- Wi-Fi (IEEE 802.11 b/g/n) devices using EDCA-based QoS for prioritized multimedia traffic.
- Other 2.4 GHz devices, including Zigbee and proprietary low-power radio links, contributing to cross-technology interference.

The Bluetooth stack, as defined by the Core Specification [1], is composed of the Host and Controller. The Host runs the application logic and upper protocols (e.g., GATT, L2CAP), while the Controller handles physical and link-layer operations (e.g., HCI, baseband scheduling). BLE operates using time-slotted Connection Events, with fixed or negotiated Connection Intervals (CI), Supervision Timeouts, and Slave Latency [2].

We assume:

- Multiple Bluetooth applications may coexist on the same host (e.g., LE Audio, BLE Sensor, BLE HID).
- Bluetooth and Wi-Fi radios may coexist on a shared antenna or chipset, leading to coordinated or uncoordinated airtime contention.
- The Bluetooth Controller may support Adaptive Frequency Hopping (AFH), but without knowledge of higher-layer traffic types or priorities.

3.2 Problem Statement

Bluetooth was originally designed for short-range, low-bandwidth applications with limited concurrency and no explicit need for service differentiation. However, the rise of multi-application Bluetooth nodes and cross-technology congestion has exposed fundamental limitations in Bluetooth’s ability to provide predictable QoS. These include:

(a) Lack of Traffic Prioritization

Bluetooth lacks native mechanisms for classifying or prioritizing traffic types. All data within a connection (or even across connections) is treated equally at the link layer, regardless of application semantics (e.g., voice vs telemetry) [3].

(b) Static Connection Scheduling

BLE connections use fixed connection intervals negotiated during pairing or updated via LL_CONNECTION_PARAM_REQ. These intervals are static until explicitly renegotiated, preventing dynamic adaptation to traffic conditions or latency constraints [4].

(c) Uncoordinated Airtime Sharing

When multiple Bluetooth profiles (e.g., HID, audio, telemetry) coexist on the same device, they compete for airtime without coordination or policy enforcement. This can lead to starvation of lower-priority or lower-power applications [5].

(d) Reactive and Non-Deterministic Coexistence

Current coexistence mechanisms (e.g., AFH, Wi-Fi coexistence interface) are largely reactive and based on instantaneous interference observations. They do not account for application-level QoS needs, such as guaranteed latency for control packets or jitter tolerance for audio [6].

(e) Lack of Cross-Layer Coordination

There is no standardized interface for the Host to inform the Controller about traffic priorities or service requirements. HCI packets do not contain metadata about urgency or deadlines. As a result, the Controller cannot schedule events intelligently to meet timing constraints [7].

3.3 Motivating Scenarios

- Smart Home Gateway: A BLE-enabled hub receives temperature sensor data, while also acting as a bridge for Classic audio streaming to smart speakers. Temperature updates experience >1s latency during heavy audio use.
- Industrial IoT Node: A BLE mesh node transmitting critical alerts gets delayed due to congestion from firmware updates or bulk telemetry traffic.
- AR Headset: Bluetooth handles simultaneous BLE HID input, voice uplink, and LE Audio, competing with Wi-Fi 6E AR streaming. Voice data suffers jitter spikes due to unsynchronized scheduling.

These limitations demonstrate that Bluetooth's current transport model is inadequate for emerging applications that require real-time, service-aware communication. To address this, we propose a cross-layer QoS framework in the next section.

IV. Proposed QoS Framework

To enable Quality of Service (QoS) for Bluetooth in dense, multi-service IoT environments, we propose a cross-layer QoS framework that introduces enhancements across the Bluetooth Host-Controller architecture. Our design aligns with the layered Bluetooth protocol stack and is compatible with both Classic and Low Energy (LE) modes. The framework consists of four core components:

- Traffic Classification Layer
- Link-Layer Scheduling Enhancements
- Coexistence-Aware Channel Adaptation
- Host-Controller QoS Coordination Interface

4.1 Traffic Classification Layer

Bluetooth currently lacks a mechanism for applications to signal the urgency or importance of their data. Inspired by Wi-Fi's Access Categories (AC_VO, AC_VI, etc. [1]), we introduce a classification scheme where each application tags its traffic with a Bluetooth Traffic Class (BTC), defined as:

Class	Description	Priority	Target Use Case
BTC0	Critical Control	Highest	BLE HID, emergency alerts
BTC1	Real-Time Audio/Video	High	LE Audio, voice chat, Classic SCO
BTC2	Periodic Telemetry	Medium	Sensor readings, mesh updates
BTC3	Best-Effort/Background Sync	Low	File transfers, OTA updates

Applications tag L2CAP channels or ATT characteristics with a BTC identifier through extended API interfaces at the Host. These tags are carried into the Host-Controller Interface (HCI) as metadata for informed scheduling.

4.2 Link-Layer Scheduling Enhancements

Bluetooth LE's link layer uses Connection Events (CE) at negotiated intervals, but they are statically scheduled. We propose:

- Dynamic CE Prioritization: Within each CE, packets tagged with higher BTCs are transmitted earlier using a weighted fair queuing policy.
- Adaptive Interval Adjustment: High-priority connections can request shorter connection intervals or receive CE extensions during congestion.
- Latency-Aware CE Insertion: Controllers can opportunistically insert additional CEs for BTC0/BTC1 connections under low-duty cycles.

For Classic Bluetooth, LMP-level modifications can prioritize SCO/eSCO packet scheduling and adjust inter-packet spacing based on tagged importance.

4.3 Coexistence-Aware Channel Adaptation

Although Adaptive Frequency Hopping (AFH) is defined in the Core Spec, current implementations focus only on observed interference, not traffic urgency [2]. We extend this with:

- QoS-Aware AFH (QAFH): Channels used by high-priority connections are maintained longer in the channel map, even under moderate interference.
- Spectral Rebalancing: BLE channels carrying BTC0/BTC1 traffic are preferentially assigned frequencies furthest from congested Wi-Fi bands (e.g., avoid channels 1–6 under 802.11b/g [3]).
- Predictive Channel Blacklisting: Based on past PER and collision history with respect to traffic class.

This approach ensures that critical traffic is not only prioritized in time but also in frequency allocation.

4.4 Host-Controller QoS Coordination Interface

To facilitate real-time coordination between application-layer service policies and link-layer behavior, we define a QoS Coordination Interface (QCI) with the following features:

- QoS Metadata in HCI Packets: Modified ACL and ISO HCI data packets carry BTC IDs.
- QoS Hints via Vendor-Specific HCI Commands:
  - HCI_Set_QoS_Profile(conn_handle, BTCx, latency, reliability)
  - HCI_Request_Priority_Slot(BTCx)
- Feedback Loop: Controller reports channel usage, delay statistics, and PER back to Host for adaptive decision making.

This interface is minimally invasive and backward-compatible; if unsupported, Host falls back to standard best-effort transmission.

4.5 Integration with Multi-Radio Devices

On devices with integrated Bluetooth and Wi-Fi (e.g., smartphones, smartwatches), the QCI is extended to interface with Wi-Fi QoS schedulers:

- Cross-Radio Airtime Budgeting: Share airtime based on cumulative BTCs and Wi-Fi WMM queues.
- Synchronized Sleep-Wakeup Windows: Bluetooth latency-sensitive events can preempt or align with Wi-Fi delivery windows.

This coordination prevents contention and improves QoS predictability across radios sharing the same antenna and processor.

Summary

Our QoS framework enables Bluetooth to move beyond best-effort delivery. By introducing traffic classification, prioritized scheduling, adaptive spectrum management, and host-controller signaling, we provide a scalable path toward service differentiation in Bluetooth-enabled IoT systems. This design is especially suited for applications requiring low-latency, high-reliability, or coexistence robustness.

V. Simulation and Evaluation

To validate the effectiveness of the proposed QoS framework, we conducted both simulation-based and empirical evaluations across realistic Bluetooth Low Energy (BLE) and Bluetooth Classic traffic scenarios. The goal was to quantify improvements in latency, packet delivery, and coexistence robustness under interference-rich environments.

5.1 Experimental Setup

Simulation Environment:

- Simulator: Custom-built NS-3 module extended with Bluetooth LE and Classic models, including support for traffic classes (BTC0–BTC3) and coexistence-aware AFH.
- Topology: Multiple BLE and Classic connections simulated alongside IEEE 802.11g/n traffic at 2.4 GHz.
- Metrics Measured: Latency (ms), Jitter (ms), Packet Delivery Ratio (PDR), and Energy Consumption (mJ).
- Traffic Profiles:
    - BTC0: BLE HID (10 ms periodic)
    - BTC1: LE Audio (40 ms)
    - BTC2: BLE telemetry (500 ms)
    - BTC3: Background OTA (asynchronous)

Hardware Evaluation:

- Devices: Nordic nRF52840 DK (BLE), CSR8670 (Classic), and ESP32 (Wi-Fi 802.11n emulator)
- Testbed: Anechoic chamber with programmable interference via USRP B200 SDR
- Coexistence Scenarios:
    - Scenario A: BLE + Wi-Fi
    - Scenario B: BLE + Classic + Wi-Fi
    - Scenario C: BLE only, with increasing background BLE noise

5.2 Latency and Jitter Reduction

In the baseline BLE stack, traffic experiences non-deterministic delays due to contention and lack of scheduling granularity. With QoS enabled:

- BTC0 packets (e.g., HID input) saw 70% reduction in average latency, from 45 ms to 13 ms.
- BTC1 packets (e.g., LE Audio) showed 52% jitter reduction, improving intelligibility in simulated voice playback (Figure 4a).
- Under high contention, inserted connection events reduced end-to-end delay variance by over 60%.

5.3 Packet Delivery Ratio (PDR)

PDR was measured under 30% Wi-Fi airtime load in the 2.4 GHz band. Results show:

Traffic Class	**Baseline PDR**	**QoS Framework PDR**
BTC0	87.3%	98.4%
BTC1	81.1%	96.7%
BTC2	93.8%	95.2%
BTC3	96.1%	90.5% (intentionally deprioritized)

The trade-off in BTC3 performance is intentional and reflects the QoS scheduling decisions prioritizing latency-sensitive traffic.

5.4 Coexistence Robustness

Under Wi-Fi interference on channels 1–6:

- QoS-aware AFH blacklisted congested frequencies for BTC1/0 while preserving more tolerant BTC3 traffic in these bands.
- BTC0 throughput was maintained above 90% even under 40% overlapping channel utilization by Wi-Fi.
- BLE telemetry (BTC2) experienced minimal degradation, while Classic SCO packets under BTC1 retained continuous transmission without dropouts due to coordinated scheduling.

5.5 Energy Consumption

BLE power profiles were analyzed for a wearable scenario:

- Dynamic connection interval adjustment for BTC1 resulted in 12–15% higher energy consumption, justified by latency improvements.
- BTC3 saw up to 30% energy savings, as it was deprioritized during active BTC0/1 transmissions.

5.6 Summary of Results

Metric	Baseline Bluetooth	With Proposed QoS Framework
Average Latency (BTC0)	45 ms	13 ms
Jitter (BTC1, LE Audio)	18 ms	8.7 ms
PDR (BTC1, with Wi-Fi)	81.1%	96.7%
Energy per bit (BTC3)	7.1 µJ	4.8 µJ
Scheduling fairness	Round-robin	Priority-weighted

These results demonstrate that the proposed framework enables differentiated service levels for diverse applications while maintaining efficiency and scalability.

VI. Discussion

The proposed QoS framework addresses long-standing gaps in Bluetooth's ability to deliver service differentiation across diverse and interference-prone IoT environments.

While simulation and experimental results demonstrate significant improvements in latency, reliability, and energy efficiency, several practical considerations, trade-offs, and deployment challenges must be discussed.

6.1 Compatibility with Existing Bluetooth Specifications

The framework is intentionally designed to be backward-compatible with the Bluetooth Core Specification. By introducing traffic classification and scheduling hints as metadata—rather than modifying fundamental protocol structures—it enables incremental adoption:

- Devices that do not recognize BTC tags will default to best-effort behavior.
- QoS-aware controllers can honor enhanced scheduling only when capabilities are negotiated.
- Use of vendor-specific HCI commands ensures no disruption to legacy applications.

However, broader adoption will likely require formal standardization through the Bluetooth SIG, particularly for the definition of traffic classes, HCI extensions, and coexistence coordination mechanisms.

6.2 Controller Complexity and Stack Bloat

Introducing traffic prioritization and adaptive scheduling at the Controller layer increases implementation complexity, especially in resource-constrained SoCs:

- Scheduling logic must dynamically balance multiple BTC-tagged streams while maintaining compliance with supervision timeouts and fairness.
- Power and memory overheads for tracking QoS state may be non-trivial in low-cost embedded platforms.

To address this, a tiered compliance model could be introduced:

- Tier 1: Basic support for BTC tagging and fair queuing.
- Tier 2: Full support with dynamic CE insertion, QAFH, and controller feedback loops.

6.3 Security and Fairness Concerns

QoS introduces opportunities for resource abuse, particularly in multi-tenant or third-party ecosystems:

- Applications might falsely tag data as BTC0 to gain priority.
- Without verification or policing mechanisms, this could lead to QoS starvation for legitimate background flows.

To mitigate this, we propose:

- Traffic policy enforcement in the Bluetooth Host, where only privileged system components may tag traffic as BTC0/BTC1.
- Optional integration with Bluetooth Mesh security models to ensure traffic tags are bound to application permissions.

6.4 Coexistence with Wi-Fi and Other Radios

Bluetooth devices that share RF front ends with Wi-Fi face unique challenges:

- Coordinating airtime for simultaneous BLE audio and Wi-Fi video requires cross-radio scheduling, which is not natively supported in Android/Linux/RTOS Bluetooth stacks.
- Existing coexistence interfaces (e.g., PTA/3-Wire) are hardware-limited and lack semantic awareness of traffic class.

Future devices could adopt cross-stack resource brokers or middleware that mediate airtime allocations based on traffic class mappings (e.g., BTC0 ↔ WMM_AC_VO). Bluetooth could inform Wi-Fi schedulers of expected CE timing for alignment.

6.5 Applicability to Bluetooth Mesh and Broadcast

While this work focuses on connection-oriented Bluetooth transport (LE and Classic), the concepts of QoS classification and channel adaptation can be extended to connectionless modes:

- Bluetooth Mesh: Traffic relaying and retransmission budgets can be prioritized for emergency or time-bounded messages.
- Periodic Advertising with Responses (PAwR): QoS hints can influence advertiser timing and anchor slot prioritization.
- LE Audio Broadcast: BTC tagging can help listeners prioritize decoding under multi-stream conditions.

These extensions would require tighter integration with Bluetooth 5.3/5.4 features and potential updates to mesh relay logic and advertising controller behavior.

6.6 Future Standardization and Deployment Path

Realizing Bluetooth QoS at scale will require coordinated efforts across chip vendors, OS maintainers, and OEMs:

- Standardization through Bluetooth SIG: A working group could be established to define formal QoS classes, signaling formats, and controller APIs.
- Reference Implementations: Open-source stacks (e.g., Zephyr, BlueZ, Android) can serve as pilots for adoption and performance validation.
- Target Use Cases: Initial deployments may focus on wearables, healthcare, and smart home gateways, where QoS demands are urgent and consistent.

Summary

The proposed QoS framework bridges the gap between best-effort Bluetooth transport and the demands of modern real-time, multi-application wireless systems. Its modularity allows for selective implementation, while its compatibility ensures interoperability with legacy devices. Future standardization and ecosystem collaboration will be key to achieving its full potential.

VII. Conclusion

Bluetooth has become a foundational technology for short-range communication in the Internet of Things (IoT), supporting a wide range of applications from wearable health monitors and smart home devices to LE Audio and industrial telemetry. However, its existing transport model—built on best-effort delivery, static scheduling, and limited coexistence awareness—fails to meet the performance demands of modern latency-sensitive and high-reliability use cases.

In this paper, we proposed a modular cross-layer QoS framework for Bluetooth, applicable to both Low Energy (LE) and Classic modes. Our design introduces:

- A traffic classification system (BTC0–BTC3) for expressing application-level service needs;
- Link-layer scheduling enhancements to dynamically prioritize connection events and reduce latency;
- Coexistence-aware channel adaptation that aligns spectral use with traffic class urgency;
- A QoS coordination interface (QCI) between Host and Controller for signaling and feedback.

Through extensive simulation and real-device testing under realistic interference and traffic scenarios, we demonstrated that this framework significantly improves latency, jitter, and packet delivery ratio for critical Bluetooth traffic, while maintaining energy efficiency and spectrum compatibility.

Importantly, the proposed solution is backward-compatible, incrementally deployable, and aligns with architectural practices in Wi-Fi and industrial wireless networks. It provides a clear path forward for Bluetooth to evolve from a best-effort protocol to a service-differentiated, scalable wireless solution suitable for dense, heterogeneous, and mission-critical environments.

As Bluetooth continues to scale into new markets—such as audio sharing, automotive, healthcare, and mixed-reality systems—the need for predictable, policy-driven transport behavior will only grow. This work provides both the foundation and a call to action for future standardization, implementation, and ecosystem adoption of Bluetooth QoS.

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