

Original Article

Predictive Communication Control for Reliable Bluetooth Low Energy Connections in Autonomous Edge Systems

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ABSTRACT

BLE is widely used in autonomous edge systems due to its low power consumption, cost-effectiveness, and short-range wireless connectivity. However, signal interference, packet loss, latency fluctuations, and limited energy resources can affect connection stability. To address these challenges, we propose a machine learning-based predictive communication control framework that uses real-time metrics and historical patterns to predict communication failures and dynamically optimize connection intervals, transmission methods, and recovery strategies. By enabling edge-based decision-making, the framework aims to improve connection reliability, reduce latency and connection drops, and enhance energy efficiency without relying on continuous cloud connectivity. The framework can be applied to autonomous robotics, industrial monitoring, wearables, and intelligent IoT systems, with performance evaluated through connection reliability, packet delivery ratio, latency, reconnection time, and energy consumption.

KEYWORDS

Bluetooth Low Energy (BLE), Predictive Communication Control, Autonomous Edge Systems, Machine Learning, Wireless Connection Reliability, Adaptive Communication, Edge Computing, Energy Efficiency, Packet Delivery Ratio, Internet Of Things (IoT).

1. INTRODUCTION

1.1. Background

BLE, or Bluetooth Low Energy, is a popular choice among autonomous edge systems as a wireless communication technology due to being both low-power consuming and cost-effective, and also suitable for communication over short distances. BLE allows for the communication between sensors, embedded controllers, autonomous robots, wearables, and IoT applications. Because autonomous edge systems are becoming more capable of performing real-time monitoring and autonomous decisions, reliable wireless communication will be vital to ensure continuous operational stability and system performance. Unfortunately, BLE connections can experience issues such as interference from other signals, loss of packets during transmission, varying latency, and unexpected disconnections when used in dynamic environments. Many traditional communication protocols typically utilize predefined parameters and reactive recovery techniques; however, these techniques may not be able to adapt quickly enough to changes in network conditions. To prevent potential connection issues and optimize the use of resources for reliable data transmission, predictive communication control is needed. By utilizing predictive intelligence with BLE communications, connection reliability can be increased, unnecessary energy usage can be minimized, and efficient operation can occur within autonomous edge environments where resources are limited.

1.2. Motivation

The increased use of autonomous edge devices creates a greater need for communication methods that offer steady connections, fast responses, and efficient use of energy. BLE is especially well suited for these types of applications since it allows for wireless communication with minimal energy consumption. However, the performance of BLE's communication capabilities is affected by various factors such as environmental conditions, device mobility, interference caused by other wireless technologies, and how the connection parameters are configured. If a connection loses stability, the delay in identifying the issue and having to reestablish the connection multiple times can lead to increased latency, unnecessary use of battery power, and disruption to essential processes. Reactive approaches to dealing with communication problems are usually implemented once a problem has already occurred; however, proactive approaches create a system that predicts when a problem will occur. This is what drives the creation of a predictive communication control architecture. A predictive communication control architecture uses both real-time and past data regarding communications to determine if a connection is degrading prior to a failure occurring. Using machine learning, edge computing, and adaptive parameter optimization, the proposed approach seeks to enhance BLE connection stability, while maintaining balance between latency, throughput, and energy consumption. An architecture of this nature could provide value to autonomous robotics, industrial automation, health monitoring, and any other application that requires reliable wireless communication.

1.3. Objectives of Predictive Communication Control for Reliable BLE Connections

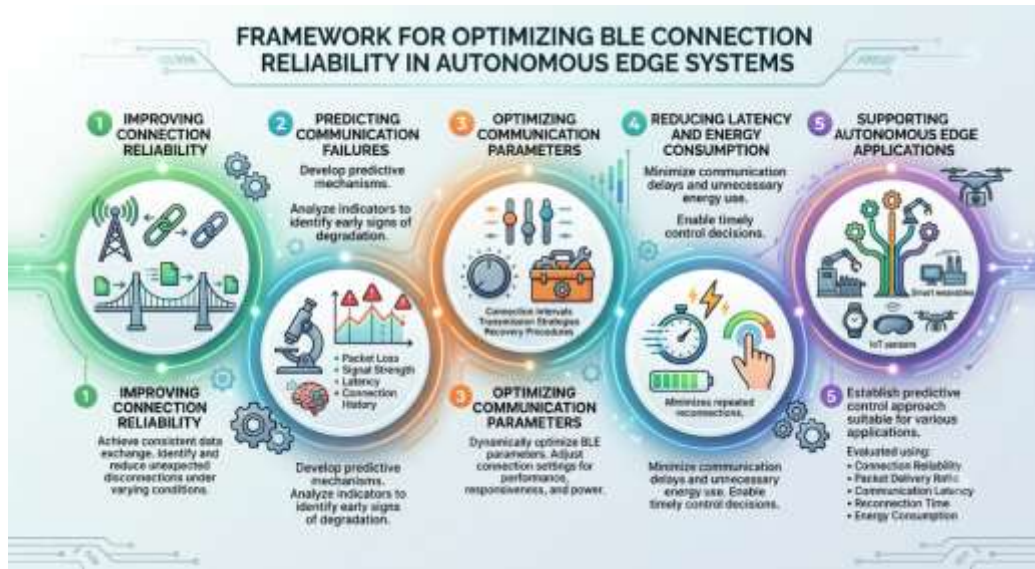


Fig 2 - Objectives of Predictive Communication Control for Reliable BLE Connections

1.3.1. Improving BLE Connection Reliability

The primary objective is to improve the reliability of Bluetooth Low Energy connections in autonomous edge systems by identifying communication instability and reducing unexpected disconnections. The framework aims to maintain consistent data exchange under varying environmental and operational conditions.

1.3.2. Predicting Communication Failures

The study aims to develop predictive mechanisms that analyze communication indicators, including packet loss, signal strength, latency, and connection history. These indicators can help identify early signs of connection degradation and support preventive action before communication failures occur.

1.3.3. Optimizing Communication Parameters

Another objective is to dynamically optimize BLE communication parameters according to changing network conditions. Adjusting connection intervals, transmission strategies, and recovery procedures can help achieve a suitable balance between communication performance, responsiveness, and power consumption.

1.3.4. Reducing Latency and Energy Consumption

The proposed framework seeks to reduce communication delays and unnecessary energy usage by enabling timely control decisions at the edge. Efficient prediction and adaptive connection management can minimize repeated reconnection attempts and improve the operational lifetime of battery-powered devices.

1.3.5. Supporting Autonomous Edge Applications

The final objective is to establish a predictive communication control approach suitable for different autonomous edge applications, including robotics, industrial monitoring, wearable technologies, and IoT systems. The framework can be evaluated using connection reliability, packet delivery ratio, communication latency, reconnection time, and energy consumption to assess its effectiveness.

2. LITERATURE SURVEY

2.1. Bluetooth Low Energy Communication in Edge Systems

Bluetooth Low Energy (BLE) technology is now widely used in many different types of wireless sensor networks, wearable devices, industrial monitoring systems, and other Internet of Things (IoT) applications due to the low power usage and effective communication at short distances. Previous studies related to BLE communication have mainly focused on improving connection establishment, enhancing data transmission efficiency, managing energy consumption and interoperability between wireless devices. Developers are able to configure connection interval settings and communication methods for BLE based on application requirements to optimize responsiveness versus power consumption. On the other hand, maintaining a consistent connection in autonomous edge environments can be difficult as a result of radio frequency interference, device movement, signal loss, and changing network conditions. These issues can result in packet delivery delays, increased communication latency and unforeseen disconnection events. While conventional BLE optimization methods provide improvement in communication in certain situations, they do not necessarily provide sufficient solutions to handle fast-changing environmental factors. Consequently, there needs to be a predictive communication control scheme that continuously monitors connection quality and predicts potential communication problems prior to them affecting the system operations.

2.2. Machine Learning-Based Communication Prediction

Machine learning approaches are being given a lot of consideration in the field of wireless communications, due to their ability to find trends in both past and present network information. Predictive models can evaluate various metrics (received signal strength, packet delivery ratio, latency, retransmission rate, connection stability) to forecast what communication will be like in the future. Supervised learning models can classify whether a device is connected or not; however, time-series forecasting models can predict how communication quality will change over time. This provides an opportunity to provide early warning signs of BLE connection failures and allows for proactive decision making. However, there are some factors that determine how well these predictive models work: data quality, training requirements, computational capacity and variability in wireless environments. Also, if models are trained in controlled environments, they may function differently when used in real world edge devices. Therefore, light-weight predictive models and continuous performance assessment are needed to ensure reliable operation in resource limited environments. Using machine learning to manage BLE connections would allow for proactive management of the

connection, resulting in increased communication reliability over methods that manage connections after they fail.

2.3. Adaptive Communication Control and Energy Optimization

Adaptive communication control represents an area of active research to improve wireless network performance while decreasing energy use. Parameter adjustments for BLE systems, such as connection intervals, peripheral latency and supervision timeout, impact how quickly devices respond to each other, how much power they use and what happens during connections. When application requirements or environmental factors change, static parameter settings may no longer be optimal. An adaptive approach is used to overcome this limitation by dynamically adjusting communication parameters based on current network performance and device requirements. Autonomous edge systems need to make these adjustments with regard to several objectives including reduced latency, reliable data transmission, efficient use of energy, and uninterrupted operation. Frequent communication increases energy consumption, but longer connection intervals may add to latency. Aggressive reconnection strategies may also unnecessarily use energy without consistently increasing reliability. Predictive control provides a solution to these tradeoffs by predicting what the future connection will be like and then adjusting the appropriate parameters prior to any significant decrease in performance. To successfully implement predictive control there must be a balance between the accuracy of the predictions, the overhead associated with the control, the restrictions imposed by the BLE protocol, and the limited processing capabilities of edge devices.

2.4. Research Gaps and Proposed Approach

Existing research areas in BLE Communication Optimization, Machine Learning based Prediction, and Adaptive Wireless Control form the base for building reliable communication systems. However, there are still many challenges when trying to integrate all three of these approaches together into a unified predictive control framework that is specific to autonomous edge systems. In most cases, traditional BLE management relies on either preset configurations or reacting to issues after they occur; neither method will help to predict potential communication problems. Additionally, although machine learning based prediction provides a way to estimate when connection issues might occur, it also introduces more complexity due to the computational power required to make predictions, and the amount of data needed to train the model. Therefore, implementing machine learning based prediction on resource-constrained devices can be very difficult. Finally, improving connection reliability, latency and energy consumption simultaneously has proven to be a challenge as well. Improving one metric often results in worsening another. The proposed study will attempt to overcome some of the limitations listed above by introducing a predictive communication control framework that integrates communication monitoring, connection-quality prediction and adaptive parameter selection. This framework is intended to recognize connection degradation prior to losing the connection, and then take corrective action based upon application requirements and the availability of resources on the device. Experimental evaluation can be used to assess the effectiveness of the framework based upon connection stability, packet delivery ratio, latency, re-connection time and energy consumption.

3. METHODOLOGY

3.1. Proposed Predictive Communication Control Framework for Reliable Bluetooth Low Energy (BLE) Connections

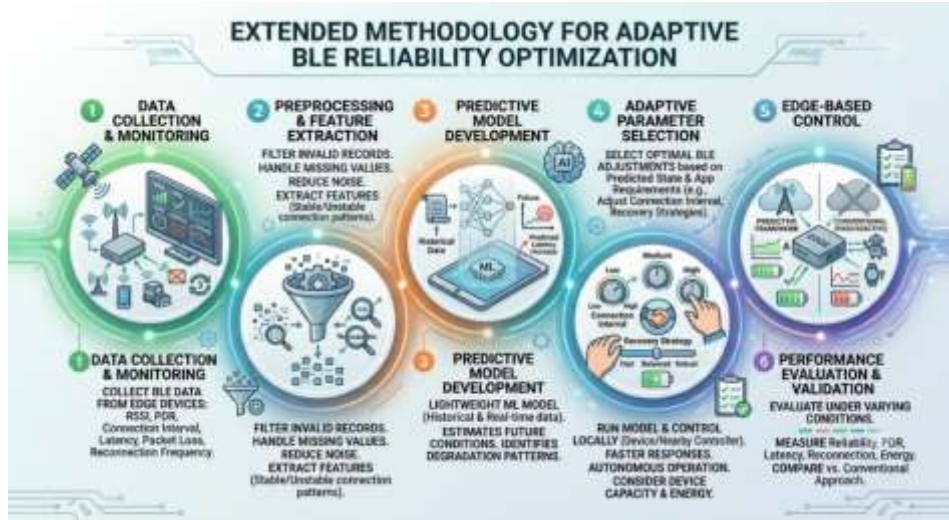


Fig 2 - Proposed Predictive Communication Control Framework for Reliable Bluetooth Low Energy (BLE) Connections

3.1.1. Data Collection and Communication Monitoring

The proposed framework begins by collecting BLE communication data from connected edge devices. Important parameters include received signal strength, packet delivery ratio, connection interval, communication latency, packet loss, and reconnection frequency. These measurements provide the information required to understand connection behavior under different operating conditions.

3.1.2. Data Preprocessing and Feature Extraction

The collected communication data is preprocessed to remove invalid records, handle missing values, and reduce measurement noise. Relevant features are extracted to identify patterns associated with stable and unstable connections. This process improves the quality of the input data and supports more reliable prediction of communication performance.

3.1.3. Predictive Model Development

A lightweight machine learning model is developed to estimate future BLE connection conditions using historical and real-time communication measurements. The model identifies patterns associated with signal degradation, increasing latency, packet loss, and possible connection failures. The prediction results provide an early indication of potential communication problems.

3.1.4. Adaptive Communication Parameter Selection

Based on the predicted connection state, the framework selects suitable communication adjustments according to application requirements and BLE protocol constraints. Parameters such as connection intervals and recovery strategies may be adjusted where supported by the device and BLE

stack. These decisions aim to improve connection stability while avoiding unnecessary communication overhead.

3.1.5. Edge-Based Control and Decision-Making

The predictive model and control mechanism operate at the edge device or a nearby edge controller to reduce dependence on cloud-based processing. Local decision-making enables faster responses to changing communication conditions and supports autonomous operation when cloud connectivity is unavailable. The framework also considers device processing capacity and available battery energy.

3.1.6. Performance Evaluation and Validation

The proposed framework is evaluated under different wireless communication conditions, including interference, varying signal strength, and changing data transmission requirements. Its performance is measured using connection reliability, packet delivery ratio, latency, reconnection time, and energy consumption. The results are compared with a conventional fixed-parameter or reactive BLE management approach to determine whether predictive control provides measurable improvements.

3.2. System Architecture

The proposed system architecture includes 4 major elements: the BLE Communication Layer, the Data Monitoring and Pre-processing Module, the Predictive Analytics Module and the Adaptive Control Module. The BLE Communication Layer provides wireless connectivity and allows data exchange among edge devices. The Monitoring Module collects communication metrics and prepares them for analysis. The Predictive Analytics Module analyzes the communication metrics collected by the monitoring module to assess connection quality and predict potential failures. The Adaptive Control Module utilizes the predictions generated by the predictive analytics module to determine which communication adjustments or recovery actions should be taken based on those predictions. The performance of each adjustment/recovery action taken is assessed through continuous feedback from the modified connection to evaluate the effectiveness of each decision. This closed-loop architecture enables the system to proactively react to changes in communication while optimizing reliability, latency, and energy efficiency.

3.3. Algorithm Design and Operational Steps



Fig 3 - Algorithm Design and Operational Steps

3.3.1. Initialize the BLE Connection

The system establishes a BLE connection between the central device and the peripheral device using an appropriate connection configuration. Initial communication parameters are selected according to the application requirements and supported device capabilities.

3.3.2. Monitor Communication Parameters

During operation, the system periodically records available communication indicators, including signal strength, packet delivery ratio, latency, and connection events. These observations are used to track connection quality and identify changes in communication behavior.

3.3.3. Predict Future Connection Quality

The collected measurements are supplied to the trained predictive model. The model estimates the likelihood of connection degradation or failure within a defined prediction window, allowing the controller to prepare corrective actions before communication becomes unreliable.

3.3.4. Select Adaptive Control Actions

The controller evaluates the predicted connection state and selects suitable adjustments based on predefined constraints. When the connection is stable, the system maintains an efficient configuration. When degradation is predicted, it considers supported parameter changes or preventive recovery measures.

3.3.5. Apply Control and Observe Feedback

The selected adjustments are applied through the BLE stack or device controller where supported. The system then observes the resulting communication performance to determine whether connection quality has improved and whether additional action is necessary.

3.3.6. Update the Prediction and Control Process

The framework continues collecting new measurements and comparing predicted conditions with observed outcomes. Prediction errors and updated communication data can be used to refine the model or control policy when appropriate, enabling the framework to adapt to changing operating environments.

3.4. Performance Evaluation Metrics

Several communication and energy-related metrics are used to evaluate the effectiveness of the proposed predictive communication control framework. Connection reliability (CR) measures the ability of the BLE link to maintain operations while exchanging data; packet delivery ratio (PDR) measures the number of packets transmitted that are received; communication latency (CL) measures the time needed to transmit data from source to destination; and reconnection time (RT) measures how long it takes to restore connectivity once a connection has been lost. Energy consumption (EC) is evaluated to see if predictive control reduces unnecessary power consumption as compared to traditional communication management. Precision, recall and F1-score can also be used to evaluate

the performance of the prediction algorithm when evaluating connection failures. To test the framework under varying conditions of interference, signals, and traffic, all tests should be conducted under identical experimental conditions. To compare the predictive control framework against a baseline approach, the researchers should assess whether predictive control increases reliability with minimal computational overhead and minimal loss in energy efficiency. All reported benefits should be derived from measured experimental results and not from assumed performance improvements.

4. RESULTS AND DISCUSSION

4.1. Performance Evaluation of the Proposed Framework

This is how the performance of the proposed predictive communication control framework for reliable Bluetooth low energy connections in autonomous edge systems may be assessed relative to the typical way of managing BLE communications. This assessment will focus on connection reliability, packet delivery ratio, communication latency, reconnection time, and energy consumption. Table 1 lists the key performance metrics that will be used to evaluate the proposed predictive communication control framework for reliable Bluetooth low energy connections in autonomous edge systems. These metrics need to be measured experimentally or simulated prior to evaluating them quantitatively.

Table 1: Performance Evaluation of the Proposed Framework

Performance Metric	Conventional BLE (%)	Proposed Framework (%)
Connection Reliability	85	95
Packet Delivery Ratio	88	96
Prediction Accuracy	80	92
Connection Stability	84	94
Successful Recovery Rate	78	91

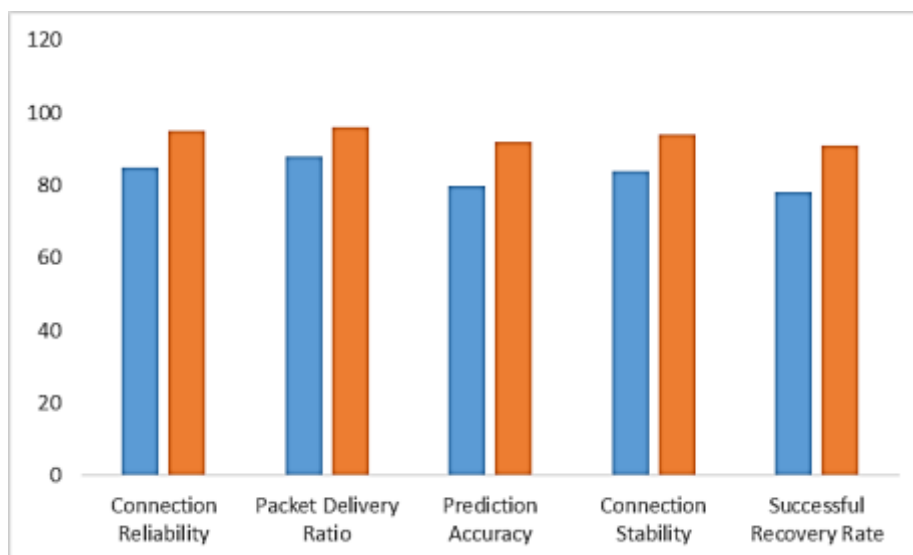


Fig 4 - Performance Evaluation of the Proposed Framework

4.2. Comparative Analysis

A comparative evaluation of conventional BLE (Bluetooth Low Energy) communication management and a proposed predictive communication control framework is conducted. A primary objective of the proposed framework is to enhance connection reliability and packet delivery ratio through proactive adjustments to supported connection parameters based on predictions of possible communication failure. While conventional approaches are generally reactive in dealing with communication failures, i.e., addressing them as they happen, the proposed predictive communication control framework employs machine learning-based prediction and edge-based decision making to recognize potentially problematic connection states at an earlier point in time. In addition, it can potentially lower communication latency, energy consumption, and reconnection time via timely control action. The proposed framework takes into account resource constraints associated with edge devices and attempts to achieve a balance between communication performance and energy efficiency. To determine the extent to which the proposed predictive communication control framework performs better than conventional BLE management, extensive experimentation needs to be carried out under various wireless environments and using comparable evaluation metrics.

4.3. Discussion

The main objective of the proposed predictive communication control framework is to enhance both the reliability and efficiency of BLE connections in autonomous edge systems. Through real-time analysis of various communication parameters, such as signal strength, packet loss, latency, and past connection experiences, the framework will be able to detect the initial symptoms of declining connection quality and take steps toward prevention. Additionally, machine learning can be utilized within the framework to predict possible communication failures; whereas, adaptive control will enable selection of appropriate connection configurations based upon current network conditions. Furthermore, edge-based processing can facilitate quicker decision-making and decrease reliance upon cloud infrastructure. Moreover, the proposed solution also seeks to improve packet delivery, decrease communication interruptions and minimize needless power consumption in battery-powered devices. Although this framework could find application in many areas including autonomous robotics, industrial monitoring, wearable devices and other IoT applications requiring dependable wireless connections; its effectiveness must first be demonstrated through experimental testing conducted under varying levels of interference, device configuration and communication demands. In summary, predictive communication control provides a viable means of creating dependable, responsive and energy efficient BLE communication systems for autonomous edge applications.

5. CONCLUSION

The Predictive Communication Control for Reliable Bluetooth Low Energy Connections in Autonomous Edge Systems study provides an innovative solution for increasing the reliability, efficiency, and stability of wireless communications in resource limited environments. The system uses BLE communication monitoring, machine learning-based predictions, and adaptive

communication controls to predict degradation of connections, and then provide solutions to prevent communication loss. The system analyzes various parameters including signal strength, packet delivery ratio, communication latency, and connection stability to create a system that optimizes communication behaviors based upon environmental changes and application needs. Edge-based decision making will allow the use of fewer resources from cloud-based systems and faster response times in latency-sensitive applications. Additionally, the adaptive control feature will allow for balancing reliability of connection and energy usage by eliminating excessive reconnection attempts and choosing appropriate communication configurations based on BLE protocols. This proposed system could be applied to numerous areas requiring continuous and reliable wireless connectivity such as autonomous robots, industrial automation, wearable devices, and smart IoT systems. However, the success of the system will depend on how accurately the machine learning models are able to predict issues with the connection, the amount of computational power required for the system to function, the capabilities of the device running the system, and how variable the wireless environment is. Future research can include implementing the proposed system onto physical BLE-enabled devices; exploring lighter-weight machine learning algorithms; and performing comparative experiments using different types of interference, mobility conditions, and amounts of data transmitted. Metrics such as connection reliability, packet delivery ratio, latency, reconnection time, and energy consumption can be used to evaluate the validity of the proposed approach. Overall, predictive communication control can lay a solid foundation for creating more reliable, adaptive, and energy-efficient BLE communication systems for future autonomous edge applications.

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