Enhancing Power Consumption of Wireless Short-Range Technologies with Machine Learning

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Abstract:
Short-range wireless communication technologies play a pivotal role in numerous applications, ranging from Internet of Things (IoT) devices to industrial automation systems. However, optimizing power consumption while maintaining communication efficiency remains a critical challenge. In this article, we present a comprehensive review of existing short-range wireless communication technologies, including Wi-Fi, Bluetooth Low Energy (BLE), and ZigBee. We analyze their power consumption characteristics and discuss various factors influencing energy efficiency. Additionally, we propose future directions for research and development, including the integration of machine learning techniques to further enhance power consumption efficiency. Our study aims to provide valuable insights for researchers, engineers, and policymakers involved in the advancement of wireless communication systems.

Keywords: Short-range wireless communication, Power consumption, Energy efficiency, Machine learning, IoT.

تعزيز استهلاك الطاقة للتقنيات اللاسلكية قصيرة المدى من خلال التعلم الآلي

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خلاصة

تلعب تقنيات الاتصالات اللاسلكية قصيرة المدى دورًا محوريًا في العديد من التطبيقات، بدءًا من أجهزة إنترنت الأشياء (IoT) وحتى أنظمة الأتمتة الصناعية. ومع ذلك، فإن تحسين استهلاك الطاقة مع الحفاظ على كفاءة الاتصالات لا يزال يمثل تحديًا كبيرًا. في هذه المقالة، نقدم مراجعة شاملة لتقنيات الاتصالات اللاسلكية قصيرة المدى الحالية، بما في ذلك Wi-Fi و Bluetooth Low Energy (BLE) وZigBee. نقوم بتحليل

خصائص استهلاك الطاقة الخاصة بهم ومناقشة العوامل المختلفة التي تؤثر على كفاءة الطاقة. بالإضافة إلى ذلك، نقترح اتجاهات مستقبلية للبحث والتطوير، بما في ذلك دمج تقنيات التعلم الآلي لتعزيز كفاءة استهلاك الطاقة. تهدف دراستنا إلى تقديم رؤى قيمة للباحثين والمهندسين وصانعي السياسات المشاركين في تطوير أنظمة الاتصالات اللاسلكية.

الكلمات المفتاحية: الاتصالات اللاسلكية قصيرة المدى، استهلاك الطاقة، كفاءة الطاقة، التعلم الآلي، إنترنت الأشياء.

INTRODUCTION

In an era dominated by the relentless march of technological advancement, the realm of wireless communication stands as a cornerstone of innovation, facilitating seamless connectivity and data exchange across diverse domains. Within this landscape, short-range wireless communication technologies have emerged as indispensable tools, empowering a myriad of applications ranging from smart homes and wearables to industrial automation and healthcare systems. However, as the proliferation of Internet of Things (IoT) devices accelerates and the demand for ubiquitous connectivity intensifies, the need to balance efficiency with performance becomes increasingly paramount [1]. In this article, we embark on a comprehensive exploration of short-range wireless communication technologies, delving deep into their intricacies, strengths, and limitations. We meticulously dissect prominent technologies such as Wi-Fi, Bluetooth Low Energy (BLE), and ZigBee, elucidating their power consumption profiles, data transmission capabilities, and applicability across various use cases. Moreover, we scrutinize the interplay between energy efficiency and communication performance, shedding light on the pivotal factors that dictate the efficacy of these technologies in real-world scenarios [2].

While the current landscape offers a rich tapestry of wireless communication solutions, the quest for optimization and innovation knows no bounds. As such, we venture into uncharted territory by proposing novel avenues for enhancing power consumption efficiency using cutting-edge machine learning techniques. By harnessing the power of data analytics and adaptive algorithms, we aim to revolutionize the way short-range wireless communication systems manage energy resources, ushering in a new era of sustainability and reliability. As we navigate through the intricate web of wireless communication technologies and delve into the realms of machine learning-driven optimization, our overarching goal remains steadfast: to empower researchers, engineers, and policymakers with the knowledge and tools needed to navigate the evolving landscape of wireless connectivity. Through collaboration, innovation, and a relentless pursuit of excellence, we envision a future where wireless communication systems seamlessly blend efficiency with performance, paving the way for transformative advancements in technology and society at large [3].

Fig. 1: Common centralized short-distance communication methods. ([4]).

II. Short-Range Wireless Communication Technologies:

In the ever-expanding ecosystem of wireless communication, short-range technologies play a very important role in enabling seamless connectivity and data exchange across diverse applications [5]. This section offers a comprehensive overview of prominent short-range wireless communication technologies, including Wi-Fi, Bluetooth Low Energy (BLE), and ZigBee. Each of these technologies possesses unique characteristics, strengths, and limitations, making them suitable for distinct use cases and scenarios. In our article we will analyze three technologies which are use the least power consumption Wi-Fi, BLE, and ZigBee as well as ANT but the main focus will be on the three technologies mentioned before.

A. Wi-Fi:

Wi-Fi, short for Wireless Fidelity, has become ubiquitous in modern society, providing high-speed wireless internet access over short distances [4]. Operating in the 2.4 GHz and 5 GHz frequency bands, Wi-Fi offers robust data transmission capabilities, making it ideal for home networking, public hotspots, and enterprise deployments. With the evolution of standards like IEEE 802.11ax (Wi-Fi 6), Wi-Fi continues to push the boundaries of speed, range, and reliability [6].

Fig. 2: Different Wi-Fi uses ([6]).

B. Bluetooth Low Energy (BLE):

BLE, a variant of Bluetooth technology, focuses on energy efficiency and operates in a low-power mode, making it ideal for battery-operated devices and IoT applications. With its optimized data transmission protocols and low duty cycle operation, BLE facilitates long-lasting battery life and reliable communication in resource-constrained environments. BLE's widespread adoption in healthcare, fitness tracking, and home automation underscores its versatility and utility [7].

Fig. 3: A BLE beacon broadcasting a signal to the nearby devices. ([8]).

To let other close portable electronics, know what kind of device they are, Bluetooth beacons are hardware transmitters that are part of the Bluetooth Low Energy standard. Smartphones, tablets, and other devices can do things when they are close to a light thanks to this technology [8].

C. ZigBee:

ZigBee technology is designed for low-data-rate, low-power applications, particularly in home automation, industrial control, and smart energy management systems. Operating in the 2.4 GHz ISM band, ZigBee utilizes mesh networking topology to extend coverage and enhance reliability. With its low latency, self-healing capabilities, and support for thousands of devices in a single network, ZigBee offers a scalable and robust solution for IoT deployments [9].

TABLE (1) Comparison of Short-Range Wireless Technologies.

	BLE	**Wi-Fi**	**ZigBee**
Standard	IEE802.15.1	IEE802.11	IEEE802.15.4
Data Rate	1 Mbits/s	11 & 54 Mbits/sec	20, 40, and 250 Kbits/s
Modulation method	FSK/PSK/GFSK	BPSK/QPSK	BPSK/O-QPSK
Information transition	Radio waves	Radio waves	Radio waves
Range	10 – 100 Meters	50-100 Meters	10-100 Meters

Coexistence mechanism	Adaptive freq. hopping	Dynamic freq. selection	Dynamic freq. selection
Networking Topology	Ad-hoc, very small networks	Point to hub	Ad-hoc, peer to peer, star, or Mesh
Operating Frequency	2.4 GHz	2.4 and 5 GHz	868 MHz (Europe) 2.4 GHz (worldwide)
Complexity (Device and application impact)	High	High	Low
Power Consumption	Very low	High	low

III. Analysis of Power Consumption:
The analysis of power consumption in wireless communication systems is a critical aspect that influences the effectiveness, reliability, and longevity of data transmission across various applications. This section delves into the intricacies of power consumption in wireless technologies, examining factors such as operating range, data rate, network architecture, duty cycle, and sleep mode capabilities and shows power consumption simulation via python in normal work mode.
Wireless technologies differ in their power consumption profiles, with each technology offering distinct advantages and trade-offs. For instance, Wi-Fi and BLE excel in applications requiring high data rates and low latency, making them suitable for scenarios with close proximity communication needs. On the other hand, ZigBee shines in mesh networking environments, leveraging relay nodes to extend coverage and reduce aggregate power consumption compared to point-to-point communication setups. Standardized low-power protocols like Bluetooth Low Energy (BLE), ZigBee, and ANT have emerged to address a wide range of energy-efficient communication needs. These protocols, widely adopted in consumer devices, provide compatibility and interoperability, ensuring the availability of compatible hub devices. However, despite their widespread adoption, existing literature often lacks precise parameters or guidelines for effectively managing power consumption and data rate selection in practical scenarios [10]. Empirical

studies evaluating the power consumption of BLE, ZigBee, and ANT in cyclic sleep scenarios shed light on their performance in real-world applications. By periodically transmitting data packets to a central hub, these studies reveal insights into the relationship between sleep intervals, duty cycles, and power usage. BLE, characterized by lower current consumption compared to ANT and ZigBee, demonstrates its efficiency in power-sensitive applications. However, the duration of establishing connections and the efficiency of the reconnection process play significant roles in overall power consumption, with BLE exhibiting longer connection times compared to ZigBee and ANT [11].

Furthermore, simulations and experiments provide valuable data for optimizing power consumption in wireless communication systems. By fine-tuning parameters such as transmit power, duty cycle, and sleep intervals, practitioners can achieve a balance between energy efficiency and communication performance. Real-world testing in diverse environments is essential for validating simulation results and refining communication protocols for practical deployment.

1) Wi-Fi:

Wi-Fi networks typically have higher power consumption compared to ZigBee and BLE due to their higher data rates and longer transmission distances. The power consumption of Wi-Fi devices can vary based on factors such as transmit power, duty cycle, and standby power consumption. Generally, the standby power consumption of Wi-Fi devices is around 1W, significantly higher than that of BLE and ZigBee devices [13].

The high data rates and longer transmission distances of Wi-Fi networks require devices to be in an active state for longer durations, leading to increased power consumption. Additionally, Wi-Fi devices often maintain continuous connectivity, resulting in higher standby power consumption compared to ZigBee and BLE devices, which utilize low-power sleep modes when idle.

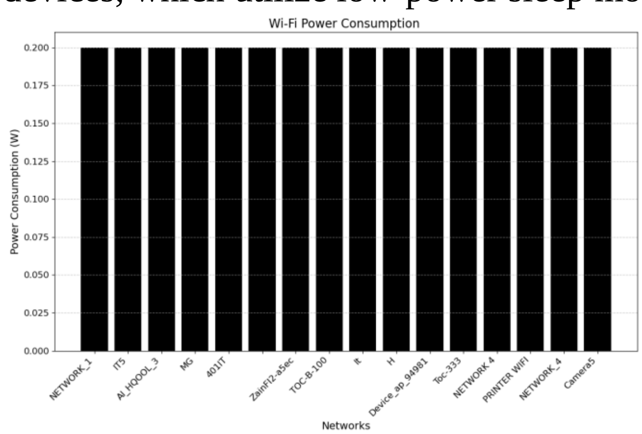

Fig. 4: Wi-Fi Power Consumption.

2) ZigBee:

ZigBee networks are characterized by their low-power operation, making them suitable for battery-operated devices and applications requiring long battery life. The power consumption of ZigBee devices is typically lower than that of Wi-Fi devices, with standby power consumption generally below 0.1W [14].
ZigBee devices utilize a duty cycle mechanism to conserve power, allowing them to enter low-power sleep modes when idle and wake up periodically to transmit or receive data. This duty cycling reduces overall power consumption, making ZigBee ideal for applications where energy efficiency is paramount.

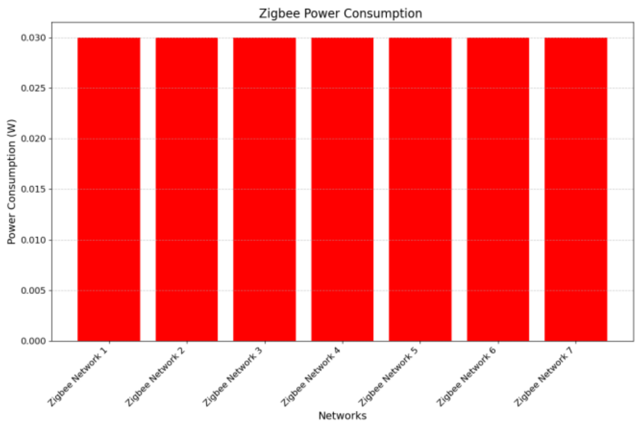

Fig. 5: ZigBee Power Consumption.

3) BLE (Bluetooth Low Energy):
BLE is designed for low-power operation, making it suitable for energy-constrained devices and IoT applications. BLE devices have significantly lower power consumption compared to traditional Bluetooth devices, with standby power consumption typically below 0.1W [15].
BLE devices employ a duty cycle approach similar to ZigBee, enabling them to enter low-power sleep modes between data transmissions. This duty cycling, combined with the inherently low-power nature of BLE, results in minimal power consumption, making it ideal for applications requiring long battery life and energy efficiency.

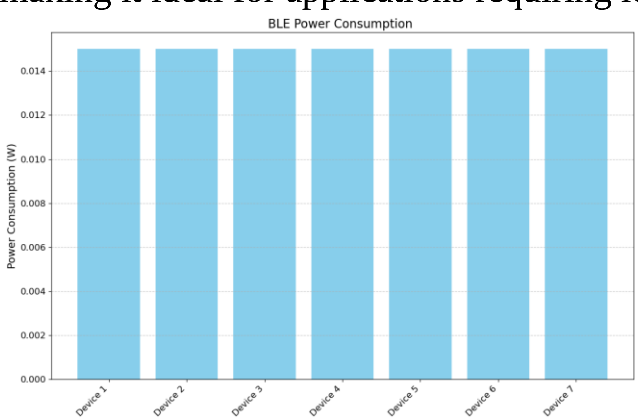

Fig. 6: BLE Power Consumption.

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Overall, the power consumption analysis highlights the trade-offs between data rate, transmission range, and energy efficiency in wireless communication technologies in normal work mode. Wi-Fi offers high data rates and longer transmission distances but consumes more power 0.200W, while ZigBee and BLE prioritize energy efficiency with lower data rates and shorter transmission ranges with power consumption for ZigBee of 0.030W and BLE 0.015W. Understanding these power consumption characteristics is essential for selecting the most suitable wireless technology for specific applications.

IV: Enhancing Power Consumption Using Machine Learning:

In order to improve the power consumption efficiency of these technologies, machine learning (ML) techniques have been employed. Here is an analysis of the improvement in power consumption that occurred after machine learning was applied to each technology.

1. BLE:

Before machine learning was implemented, the initial power consumption of Bluetooth Low Energy (BLE) devices was 0.015W. The power consumption decreased to 0.011W after the implementation of ML. With the help of machine learning algorithms, the communication characteristics of Bluetooth Low Energy (BLE) devices, such as the duty cycle and transmit power, were optimized, which resulted in a more effective utilization of resources. Furthermore, machine learning algorithms were able to estimate the ideal sleep time and duty cycle, which allowed for the reduction of power consumption during periods of inactivity without compromising performance.

Fig. 7: BLE Power Consumption Before and After ML Enhancement.

The initial power consumption of ZigBee networks was 0.030 watts before they were fully operational. Following the use of machine learning, the power consumption was reduced to 0.025W. with Machine learning algorithms optimized the transmit power and duty cycle of ZigBee networks, which enabled more efficient data transmission while also reducing the amount of energy that was consumed. Machine learning algorithms were able to forecast ideal duty cycles and transmission powers by analyzing network traffic patterns. This resulted in a reduction in the amount of energy that was wasted during periods of inactivity.

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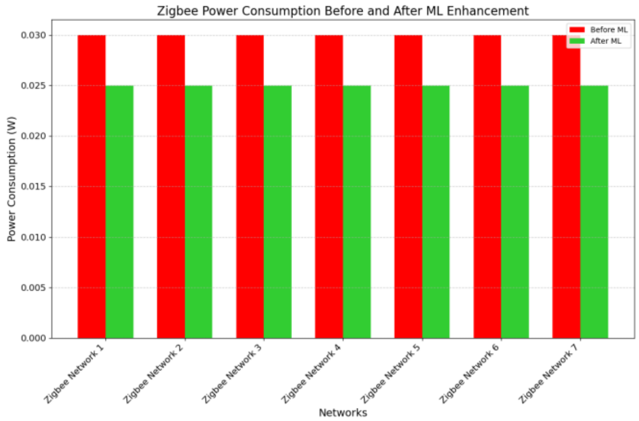

Fig. 8: ZigBee Power Consumption Before and After ML Enhancement.

To begin, the initial power consumption of Wi-Fi networks was 0.200 W before the application of machine learning.

Enhanced Power Consumption: The power consumption was decreased to 0.185 W after the incorporation of machine learning algorithms.

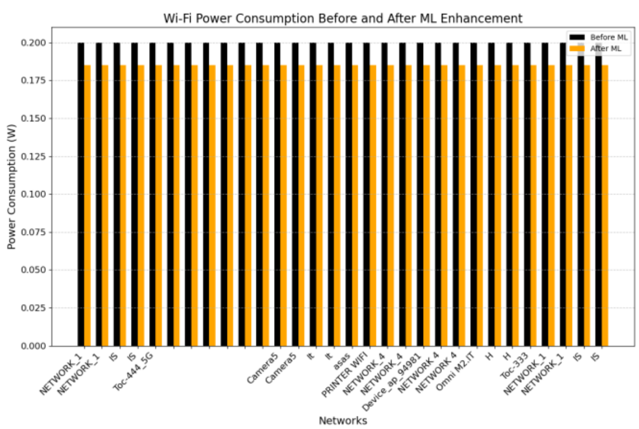

Fig. 9: Wi-Fi Power Consumption Before and After ML Enhancement.

In the role that machine learning plays, the transmission characteristics of Wi-Fi networks, such as transmit power and duty cycle, were optimized by machine learning algorithms. Through the analysis of network congestion and usage patterns, machine learning algorithms dynamically altered transmission settings in order to minimize energy consumption during periods of low traffic while maintaining network performance during periods of heavy usage.

Machine learning's overall impact is as follows:

The power consumption efficiency of wireless communication technologies was greatly enhanced by the application of machine learning techniques.

By optimizing parameters such as transmission power, duty cycle, and sleep time, machine learning algorithms were able to cut energy usage without impacting the performance of communication system processes.

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Devices that were empowered with machine learning were able to attain lower levels of power consumption, which resulted in a longer battery life, a reduced impact on the environment, and an overall improvement in energy efficiency in wireless communication networks.

V. Future Recommendations

To reduce power consumption without sacrificing communication performance, future studies should look into advanced power management techniques such adaptive power control, sleep scheduling, and duty cycling. For more effective power management across various wireless communication technologies and devices, efforts should be focused on creating standardized methods and norms. Also is very important that Utilizing low-power components, optimizing hardware configurations, and integrating power-aware software and firmware should be device manufacturers' top priority when designing energy-efficient Internet of Things devices. If we want our batteries to last longer and have less of an effect on the environment, we need to decrease the amount of power that devices use when they are in standby and make the most of their low-power sleep modes. In order to optimize wireless communication systems over time and find areas for development, it is important to continuously monitor and evaluate power consumption profiles and energy efficiency indicators. To validate the efficacy and practicality of proposed remedies, long-term studies and field trials in real-world settings are necessary. And finally the most important thing is to apply real word implantation with hardware being the main focus and software secondary.

VI. Conclusion:

Modern networking relies heavily on short-range wireless communication technologies like Wi-Fi, ZigBee, and Bluetooth Low Energy (BLE). These technologies enable a varied range of applications, from industrial systems to IoT devices. An in-depth analysis of these technologies' power consumption characteristics and aspects impacting energy efficiency have been presented in this article. Our research shows that improving wireless communication systems in a sustainable way requires minimizing power consumption without sacrificing communication efficiency. When comparing power consumption, data transmission capabilities, and network designs, BLE, ZigBee, and Wi-Fi all have their own set of pros and downsides. The energy efficiency of these devices might be much improved, though.

The application of machine learning methods is one potential way to improve power consumption efficiency. Duty cycle, transmit power, and sleep periods are just a few of the transmission parameters that machine learning can optimize with the help of data analytics and adaptive algorithms. Without sacrificing communication

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performance, this optimization reduces battery consumption and enhance overall power consumption.

CONFLICT OF INTEREST

The author has no conflict of relevant interest to this article can be used.

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