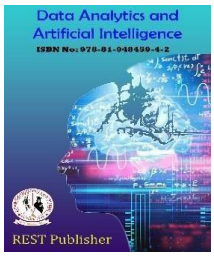
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Multi-Criteria Decision Analysis for Embedded Systems Selection with COPRAS

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Abstract: *Embedded Systems Introduction: Embedded systems, also known as specialized computer systems, are built to efficiently perform specific functions within larger equipment. They are more reliable than general-purpose computers. Real-time operation, and energy efficiency. These systems integrate hardware and software, including microcontrollers, sensors, and memory, to execute dedicated functions seamlessly. Widely Used in industrial automation, consumer electronics, automotive and healthcare, embedded systems power devices like smartphones, medical monitors, and smart appliances. With advancements in artificial intelligence, IoT, and machine learning, embedded systems continue to evolve, enabling automation and smarter technology. Their role remains crucial in shaping the future of intelligent and connected systems. Research significance: Research in embedded systems is crucial as these systems form the backbone of modern technology, driving advancements in automation, communication, healthcare, and industrial applications. Studying embedded systems helps improve energy efficiency, real-time processing, and security, ensuring reliable and high-performance solutions for critical applications. With the integration of IoT, AI, and machine learning, research in embedded systems enables smarter, autonomous devices, enhancing productivity and innovation. Additionally, advancements in low-power computing and reconfigurable hardware contribute to cost-effective and scalable solutions. The continuous evolution of embedded systems research is essential for shaping the future of intelligent and connected technologies. Methodology: The methodology for designing and developing embedded systems involves a structured approach to ensure efficiency, reliability, and real-time performance. It begins with requirement analysis, where system specifications and constraints such as power consumption, processing speed, and memory are defined. Hardware selection includes choosing suitable microcontrollers, processors, and sensors, while software development involves writing optimized code, typically in C or assembly language. Testing and debugging are crucial to ensure functionality and stability. Simulation tools, prototyping, and real-time operating systems (RTOS) are often used. Finally, integration and validation ensure the embedded system meets performance and security standards before deployment. Alternative: Bluetooth, LTE, Z-wave, Wi-Fi, ZigBee Evaluation preference: Transmission Speed, Transmission Range, Power Usage, Development Cost Results: Hash Table It occupies the first place in the table. Graph is getting last place of the table.*

Keywords: *Bluetooth, LTE, Transmission Speed, Transmission Range*

1. INTRODUCTION

A small microprocessor and a small amount of software are the main components of embedded which things like and Professionals working with embedded systems often use data collection tools and sensors. Many work with cross-development and debugging tools, often in the C language, and are active in programming and debugging. Real-time controls are desirable for embedded systems, and future research is expected to increase their importance. In addition, embedded systems also include a large number of hard real-time systems. [1] One of the greatest challenges and opportunities to revitalize computer science is to establish a strong embedded systems design discipline. As embedded systems become increasingly pervasive in everyday life, this presents a unique opportunity to advance the field. In the following discussion, we outline what we consider to be the embedded systems design challenge. Successfully managing the interactions between computation and various controls to meet specific requirements is central to the design of embedded systems. Like most computing systems, embedded systems integrate hardware, software, and their operating environment. [2] The unique challenges of embedded systems require innovative security approaches that encompass Everything from design to implementation to architecture. The "battery gap", which arises from the mismatch between the slow progress of battery technology and the increasing energy requirements for safe operation, is another critical problem in battery-powered embedded systems. Because embedded systems often perform critical functions, they are

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vulnerable to potential attacks from malicious entities. As a result, designers of emerging embedded systems must integrate a variety of security solutions to effectively address multiple security needs. [3] Embedded systems, often referred to as pervasive or ubiquitous computers, are specialized computer systems designed for specific tasks. Many of these systems are highly reliable and perform predictably. Although almost invisible, embedded systems are ubiquitous and have had a significant impact on how businesses operate. One of the most notable examples is the Internet, which consists of a vast network of interconnected embedded systems using various networking technologies. Backbone gigabit switches and network routers are examples of key maintaining this infrastructure. [4] An often-overlooked aspect of embedded systems is their remarkable longevity, with many products remaining in use for a decade or more. This longevity requires continued support for older product versions. While I don't place much emphasis on metrics, tracking bugs is essential because of their significant impact on embedded systems. Unlike desktop applications, embedded systems offer unique capabilities, especially in real-time operations. Most embedded systems include at least one or two interrupt-driven devices, and few designers bring their products to market without addressing the challenges associated with interrupt service routines (ISRs). [5] This book is intended for researchers, practitioners, and students interested in learning, understanding, or refining the fundamental principles of intelligence and their application in designing next-generation embedded systems and applications. Ensuring optimal performance while meeting constraints is a critical challenge for intelligent embedded systems and applications, as they must adapt to uncertain, dynamic, and ever-evolving real-world environments. [6] In recent years, the field of embedded systems has grown to encompass a wide range of products, including digital cameras, sensor networks, and medical imaging systems. As a result, engineers are constantly working to create smaller, faster devices that meet stringent power requirements. With the increasing demand for lower with faster time to market and lower costs, these designs constraints present significant challenges for embedded system designers. Reconfigurable hardware provides a flexible and efficient solution to meet the requirements of performance, cost, and energy efficiency in embedded systems. This article provides an overview of reconfigurable computing in embedded systems, highlighting its benefits, existing applications, design considerations, and challenges that hinder its widespread adoption. [7] The primary challenge is the lack of rigorous methodologies for the design of embedded systems. On one end, computer science research has largely ignored embedded systems, often relying on abstractions that ignore physical constraints. On the other hand, Embedded system design goes beyond conventional knowledge electrical engineers, as it involves a great deal of computation and software. However, embedded systems design remains a peripheral topic in both computer science and electrical engineering curricula. Establishing a dedicated discipline for the design of embedded systems has the potential to develop professionals with combined expertise in both fields. [8] The field of Embedded systems are growing rapidly as gadgets such as smartphones, PDAs, smart cards, and digital music players become an essential part of everyday life. Future developments in wearable technology and embedded network sensors promise even deeper human-machine interactions. The security architecture of embedded systems differs from that of conventional workstations and servers due to some features. One such unique challenge is differential power analysis (DPA), which is well suited to embedded systems due to their inherent accessibility. [9] As a result, the findings will contribute to the development of Fault-tolerant, high-performance, adaptive embedded systems that can dynamically adjust to real-time constraints. In the event of failures or timing constraints, these systems can guarantee predetermined system-level performance guarantees and graceful degradation. Many embedded systems use commercial real-time operating systems. Applications, including avionics, medical devices, communication systems, consumer electronics, and instrumentation. [10] As more embedded systems are connected to the Internet, the risks associated with vulnerabilities increase significantly. Cost sensitivity is a major factor in embedded computer design, and even a five-cent difference can be significant when millions of units are manufactured annually. As a result, most CPUs in embedded computers rely on 4- and 8-bit processors, which offer minimal capability for security overhead. Because many embedded systems interact directly with the physical world, security breaches can lead to serious consequences such as property damage, personal injury, or loss of life. Additionally, embedded systems typically operate without a dedicated system administrator, making security management more challenging. [11] By comparing We will explore the key characteristics of embedded and corporate systems varying motivations and technical requirements behind the use of computer virtual machines. Our analysis reveals significant disparities, showing that virtualization has failed to fully address the unique needs of embedded systems. Traditionally, embedded systems have been Relatively straightforward, single-use gadgets are severely limited by hardware parameters such as memory size, computer speed, and battery life. [12] We introduce nesC, a programming language designed for networked embedded systems, which provides a new design paradigm for application developers. This paper presents nesC as a computer programming language that is suitable for networked embedded devices such as mods. nesC integrates a programming model that seamlessly integrates environmental responsiveness, synchronization, and communication. These improvements significantly reduce memory usage and overhead, which are important for embedded systems. However, we believe that the associated runtime overhead makes this model unsuitable for networked embedded systems. [13] The design of modern embedded systems requires trained professionals with broad and deep expertise. As with VLSI system design, embedded system designers must understand the entire design process to make informed, global decisions, rather than focusing on isolated components. While hardware and software can be developed independently, embedded systems are often designed to support product improvements through software upgrades. However, it is important to recognize how architectural choices in hardware and software influence each other. Since students in the course do not have prior knowledge of

computer architecture, the curriculum covers the fundamentals of instruction set processors with concepts specific to embedded systems. [14] With these tools and with Programming Embedded Systems, Second Edition you will have a comprehensive framework for fully exploring embedded systems. A timer that is commonly discussed in embedded systems is the watchdog timer. In many cases, there are more tasks that need to be executed at specific intervals than there are timers assigned to each task. Engineers often use the term "real-time" to refer to computational challenges where a late response is as problematic as an incorrect response. Such problems are characterized by strict deadlines, and embedded systems often operate on them. [15] In recent years, security in embedded systems has received significant attention in both industry and academia. These systems are increasingly used in a variety of applications, from managing safety-critical functions to collecting data in challenging environments. Because they are implanted, they are naturally vulnerable operational issues and targeted attacks. This article provides an overview of embedded system security, highlighting how their unique characteristics contribute to specific vulnerabilities. These fundamental characteristics directly impact many security concerns and challenges. [16] Memory considerations are critical in embedded system design, significantly impacting performance, power consumption, and overall implementation cost. Because embedded systems are designed for specific purposes, they allow for intensive optimization techniques that utilize extensive application knowledge. Unlike Memory upgrades for embedded systems are designed to meet predictable patterns of code execution and data usage, unlike conventional memory-related hardware and software upgrades, which must support a range of general-purpose applications. [17] Embedded systems are an integral part of everyday life, appearing in household appliances, State-of-the-art automation systems, adaptive control systems, electrical devices, and nonlinear compensation techniques. Compared to traditional computer platforms, embedded systems typically have less computational power and limited memory capacity. They are generally defined as software integrated into hardware to perform specific real-time functions. For many years, microcontrollers and microprocessors have been the primary means of implementing embedded systems due to their programmability and performance. [18] The increasing number of information security breaches in recent years has highlighted the urgent need for secure electronic systems. Embedded systems, which are widely used to capture, store, process, and access sensitive data, present diverse and complex security challenges. This article aims to familiarize embedded system designers and tool developers with the key challenges in designing secure embedded systems. [19] This paper examines the design of reactive real-time embedded systems that integrate various processing technologies and design approaches, such as combining hardware ASICs with embedded software. The concurrent design process for these systems addresses challenges in specification, verification, and synthesis. Reactive real-time embedded systems are widely used in the electronics industry, with applications in automotive control, consumer electronics, communication systems, remote sensing, and home appliances. In these domains, evolving specifications and the need for rapid time-to-market play a key role in determining success. [20]

2. MATERIAL AND METHOD

Alternative: Bluetooth: Bluetooth is a popular short-range wireless communication method for connecting devices in embedded systems. It facilitates low-power, cost-effective communication between gadgets sensors by operating in the 2.4 GHz frequency spectrum. Applications that require low power consumption, such as smart home automation and wearable health monitors, benefit greatly from Bluetooth Low Energy (BLE). LTE (Long-Term Evolution): Mobile and Internet of Things applications are key uses for the high-speed wireless communication standard LTE. It is suitable for smart transportation, industrial automation, and remote healthcare applications because it provides reliable, high-bandwidth connectivity for real-time data transfer. LTE-based embedded systems benefit from extensive network coverage, ensuring seamless communication across long distances. Z-Wave: Z-Wave is a low-power wireless communication technology developed for automation and smart home systems. It improves network reliability and reduces interference by operating in the sub-1 GHz frequency band. Z-Wave facilitates efficient communication between security systems, lighting, and smart home devices. thermostats, supporting mesh networking for extended coverage. Wi-Fi: A widely used wireless technology called Wi-Fi provides fast internet access for embedded systems. It is ideal for applications requiring large data transfers, such as smart TVs, security cameras, and industrial monitoring systems. Wi-Fi-enabled embedded devices benefit from broad compatibility and seamless integration with existing network infrastructures. ZigBee: ZigBee is a low-power, low-data-rate wireless communication protocol used in embedded systems for home and business automation. It facilitates mesh networking, which increases network coverage and enables efficient communication between multiple devices. ZigBee is often used in energy management, smart lighting, and sensor-based monitoring systems due to its scalability and energy efficiency.

Evaluation preference: Transmission Speed: Transmission speed is a critical factor in evaluating embedded communication technologies, as it determines how quickly data can be transferred between devices. High-speed communication, such as Wi-Fi and LTE, is essential for applications requiring real-time data processing, video streaming, or industrial automation. Slower transmission speeds, like those in ZigBee and Z-Wave, may be more suitable for low-bandwidth applications such as smart home automation and sensor networks. Transmission Range: The effectiveness of an embedded system depends on its ability to transmit data over a required distance. Technologies like LTE provide long-range communication, making them ideal for mobile applications and IoT devices operating over vast

areas. In contrast, Bluetooth and ZigBee have shorter transmission ranges but are well-suited for local connectivity, such as in smart homes and personal devices. Z-Wave offers a balance with extended range through mesh networking, improving device coverage. Power Usage: Power consumption is a key consideration, especially for battery-operated embedded systems. Technologies such as Due to their low power consumption, ZigBee and Z-Wave are suitable for sensor-based and Internet of Things applications. Another useful choice for wearable technology and health monitoring systems is Bluetooth Low Energy (BLE). However, Wi-Fi and LTE, while offering high transmission speeds, tend to consume more power, requiring efficient power management solutions for long-term operation. Development Cost: The cost of development plays a significant role in selecting an embedded communication technology. Low-power, short-range protocols like Bluetooth and ZigBee typically have lower development and implementation costs, making them ideal for consumer electronics and smart home applications. LTE and Wi-Fi, while offering superior performance, may require higher investment due to infrastructure and licensing costs, making them more suitable for industrial and enterprise-level applications.

3. COPRAS

This study uses the fuzzy COPRAS (COPRAS-F) approach, which is a fuzzy multi-criteria decision-making tool that establishes criterion weights and assesses the importance of alternatives in light of the complexity of the problem and inherent uncertainty. To demonstrate the capabilities and effectiveness of the model in classifying risks related to critical infrastructure, a case study is carried out. Compared to the traditional RAMCAP method, the proposed model exhibits significant improvements. Zavadskas and Antucheviciene (2007) evaluated options for revitalizing abandoned structures in rural Lithuania using the fuzzy COPRAS approach. [1] This restriction was removed by the COPRAS (complex proportional assessment) approach. Although widely used in Lithuania, the primary characteristics of COPRAS are not well defined or explained. Understanding and explaining these properties has significant theoretical and practical value. Despite the widespread use of these methods, many of their aspects remain unexplored. This study conducts a detailed investigation and comparison of the SAW and COPRAS methods. [2] To effectively solve this problem, multi-criteria evaluation is required by decision makers, considering various alternatives. In this study, the COPRAS method is used to evaluate the performance of research assistants. The complex proportionality evaluation (COPRAS) method, developed by the authors, is designed to solve this problem. It works on the principle that the importance and utility of the evaluated alternatives are directly and proportionally dependent on the set of criteria that accurately describe them, with assigned values and weights. The final ranking, confirmed by the COPRAS method, is shown with a numerical example demonstrating the applicability and effectiveness of the proposed approach. [4] The second step is to develop a fuzzy COPRAS approach and complex proportionality estimator of alternatives with gray relations (COPRAS-G) to evaluate performance metrics in TPM. The original feature of this study is the introduction of new TPM performance metrics and their evaluation using the fuzzy COPRAS approach, which eliminates the defusification stage to avoid data loss. All calculations in the proposed fuzzy COPRAS method are carried out using fuzzy arithmetic concepts. [5] This research presents a collaborative decision-making evaluation framework that integrates the weighted interval approximate number (WIRN) method with the WIRN-based complex proportional estimation (COPRAS) model for hotel rating and ranking to resolve subjectivity and inconsistencies. To illustrate the applicability of the framework, an empirical example and a real-world case study from the Indian tourism industry are presented. The proposed WIRN-based COPRAS method provides a more intelligent and adaptive method for handling uncertainty situations compared to conventional COPRAS model. [6] Using SWARA and COPRAS-G methods, this work attempts to present an integrated approach to criterion weights are determined using the SWARA method, and the COPRAS-G method is used for selection. optimal machine tool alternative. The choice of this study is motivated by the existing literature, which includes research on evaluating and selecting machine tools. The COPRAS-G method improves decision-making by providing a scoring mechanism that provides deep insights to decision-makers by considering both the differences and similarities between alternatives with respect to the best and worst options. [7] This paper presents an integrated approach that combines are solve MCDM problems. evaluate the relative importance of criteria, and the COPRAS approach is used to make decisions. The paper presents a recommended algorithm for solving MCDM problems and gives a complete explanation of the COPRAS approach. A complete framework for selecting the best maintenance plan is provided by fuzzy AHP and COPRAS. [8] This study evaluates the construction sectors Considering the EU countries using statistical economic data, the COPRAS method is used to sort the sector priority and to obtain the criterion weights. The main objective is to use the COPRAS approach to classify European countries based on six important construction-related parameters. Interests, goals and influencing factors are taken into account when choosing risk assessment indices. affecting construction capacity and real estate price growth. Both TOPSIS gray and COPRAS-G methods are used to analyze and model the problem. [9] This study uses an integrated strategy combining fuzzy AHP and COPRAS to assess the performance and ranking of seven Indian Institutes of Technology (IITs) according to stakeholders' preferences. Each IIT is ranked using the COPRAS technique and given an overall score, which helps decision makers in selecting the optimal option considering multiple irrelevant factors. This study assesses the performance of this top the integrated framework. [10]

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4. RESULTS AND DISCUSSION

TABLE 1. Embedded Systems

	Transmission Speed	Transmission Range	Power Usage	Development Cost
Bluetooth	1.66	1.44	3.3	2.89
LTE	0.3	1.62	4.83	4.34
Z-wave	1.27	0.67	1.18	0.19
Wi-Fi	3.85	4.4	1.58	4.63
ZigBee	2.13	3.85	2.89	4.73

The performance of embedded communication technologies varies across key factors such as transmission speed, range, power usage, and development cost. Wi-Fi demonstrates the highest transmission speed (3.85) and range (4.4), making it suitable for data-intensive applications but comes with a high development cost (4.63). Bluetooth, with moderate speed (1.66) and range (1.44), offers low power usage (3.3) and cost efficiency (2.89), making it ideal for short-range applications. LTE excels in range (1.62) but has the highest power consumption (4.83) and development cost (4.34), making it suitable for mobile and industrial applications. Z-wave, with the lowest cost (0.19) and power consumption (1.18), is optimized for smart home applications. ZigBee balances speed (2.13), range (3.85), and power efficiency (2.89), making it a strong choice for IoT networks.

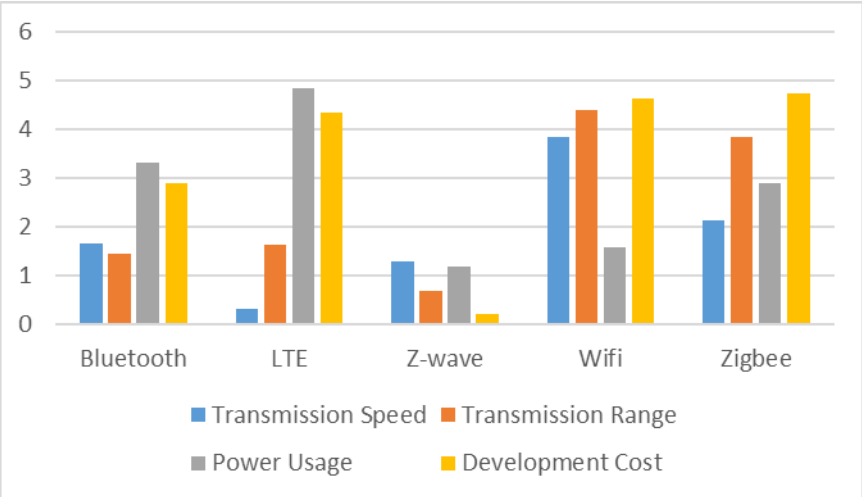


FIGURE 1. Embedded Systems

The bar chart compares five communication technologies—Bluetooth, LTE, Z-Wave, Wi-Fi, and ZigBee—based on transmission speed, transmission range, power usage, and development cost. Wi-Fi demonstrates the highest transmission speed, making it ideal for data-heavy applications, while LTE has the lowest speed but excels in transmission range, making it suitable for long-distance communication. Z-Wave shows minimal development cost and power usage, making it the most efficient for low-energy smart home applications. ZigBee balances all factors, performing well in range and cost-efficiency, making it an excellent choice for IoT networks. Bluetooth offers moderate performance across all parameters, making it ideal for short-range, low-power applications. This comparative analysis highlights the strengths and trade-offs of each technology, helping in selecting the most suitable option based on application needs.

TABLE 2. Normalized Data

Normalized Data				
	Transmission Speed	Transmission Range	Power Usage	Development Cost
Bluetooth	0.1802	0.1202	0.2395	0.1722
LTE	0.0326	0.1352	0.3505	0.2586
Z-wave	0.1379	0.0559	0.0856	0.0113
Wi-Fi	0.4180	0.3673	0.1147	0.2759
ZigBee	0.2313	0.3214	0.2097	0.2819

The normalized data highlights the relative strengths and weaknesses of different communication technologies based on transmission speed, range, power usage, and development cost. Wi-Fi leads in transmission speed (0.4180) and range (0.3673), making it ideal for high-speed data applications, though it has a moderate power usage (0.1147) and high

development cost (0.2759). Bluetooth offers balanced performance with moderate speed (0.1802) and power efficiency (0.2395), making it suitable for short-range, low-power applications. LTE has the highest power consumption (0.3505) and a significant development cost (0.2586) but provides reliable long-range communication (0.1352). Z-wave stands out for its low development cost (0.0113) and minimal power usage (0.0856), making it ideal for smart home applications. ZigBee strikes a balance with strong range (0.3214) and efficient power usage (0.2097), making it well-suited for IoT networks.

TABLE 3. Weight

Weight				
	Transmission Speed	Transmission Range	Power Usage	Development Cost
Bluetooth	0.25	0.25	0.25	0.25
LTE	0.25	0.25	0.25	0.25
Z-wave	0.25	0.25	0.25	0.25
Wi-Fi	0.25	0.25	0.25	0.25
ZigBee	0.25	0.25	0.25	0.25

In this evaluation, equal weight (0.25) is assigned to all four criteria—transmission speed, transmission range, power usage, and development cost—ensuring a balanced assessment of each technology. Wi-Fi, with its high transmission speed and range, remains a strong option for data-intensive applications but comes with higher power consumption and development costs. Bluetooth, offering moderate performance across all criteria, is a cost-effective and energy-efficient choice for short-range communication. LTE provides reliable long-range connectivity but at the expense of higher power consumption and cost. Z-wave, with its low power usage and minimal development cost, is ideal for smart home automation. ZigBee offers a well-rounded performance, making it a viable choice for IoT applications. With equal weighting, the most suitable technology depends on specific application requirements and constraints.

TABLE 4. Weighted normalized decision matrix

Weighted normalized decision matrix				
	Transmission Speed	Transmission Range	Power Usage	Development Cost
Bluetooth	0.05	0.03	0.06	0.04
LTE	0.01	0.03	0.09	0.06
Z-wave	0.03	0.01	0.02	0.00
Wi-Fi	0.10	0.09	0.03	0.07
ZigBee	0.06	0.08	0.05	0.07

The weighted normalized decision matrix provides a comparative evaluation of embedded communication technologies based on key performance criteria. Wi-Fi scores the highest in transmission speed (0.10) and range (0.09), making it a strong candidate for high-speed applications, despite moderate power usage (0.03) and development cost (0.07). Bluetooth, with balanced values across all criteria, offers a reliable and energy-efficient solution for short-range communication. LTE, while excelling in power usage (0.09), has relatively lower values in speed (0.01) and range (0.03), making it more suitable for long-range but power-intensive applications. Z-wave, with the lowest values in cost (0.00) and power (0.02), remains an optimal choice for smart home automation. ZigBee provides a well-rounded option with strong range (0.08) and moderate power efficiency (0.05), making it ideal for IoT networks.

TABLE 5. Bi, Ci, Min (Ci)/Ci

	Bi	Ci	Min (Ci)/Ci
Bluetooth	0.075	0.103	0.2355
LTE	0.042	0.152	0.1592
Z-wave	0.048	0.024	1.0000
Wi-Fi	0.196	0.098	0.2482
ZigBee	0.138	0.123	0.1972

The Bi, Ci, and Min (Ci)/Ci values provide insights into the relative performance of different communication technologies. Z-Wave achieves the highest Min (Ci)/Ci value (1.0000), indicating its strong suitability for cost-effective and low-power applications like smart home automation. Wi-Fi, with high Bi (0.196) and Min (Ci)/Ci (0.2482), demonstrates strong performance in high-speed data transmission but comes with higher costs and power consumption. Bluetooth maintains a balanced profile with Bi (0.075) and Min (Ci)/Ci (0.2355), making it a reliable option for short-range, low-power communication. LTE, despite having a moderate Ci (0.152), has the lowest Min (Ci)/Ci (0.1592), reflecting its higher power usage and cost. ZigBee presents a well-rounded alternative, excelling in Ci (0.123) and maintaining a competitive Min (Ci)/Ci (0.1972), making it an ideal choice for IoT applications.

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TABLE 6. Qi, Ui

	Qi	Ui
Bluetooth	0.139	43.4442
LTE	0.085	26.6096
Z-wave	0.320	100.0000
Wi-Fi	0.264	82.3839
ZigBee	0.192	59.8881

The Qi and Ui values highlight the relative efficiency and utility of each communication technology. Z-Wave ranks highest in both Qi (0.320) and Ui (100.0000), making it the most effective option, particularly for smart home automation and low-power IoT applications. Wi-Fi follows closely with a strong Qi (0.264) and Ui (82.3839), reinforcing its suitability for high-speed data transmission and networked applications. ZigBee, with Qi (0.192) and Ui (59.8881), offers a balanced solution for IoT and industrial automation. Bluetooth, with Qi (0.139) and Ui (43.4442), remains a reliable choice for short-range, energy-efficient applications. LTE, despite its widespread use in mobile communications, has the lowest Qi (0.085) and Ui (26.6096), reflecting its higher power consumption and cost, making it less favorable for low-energy embedded systems.

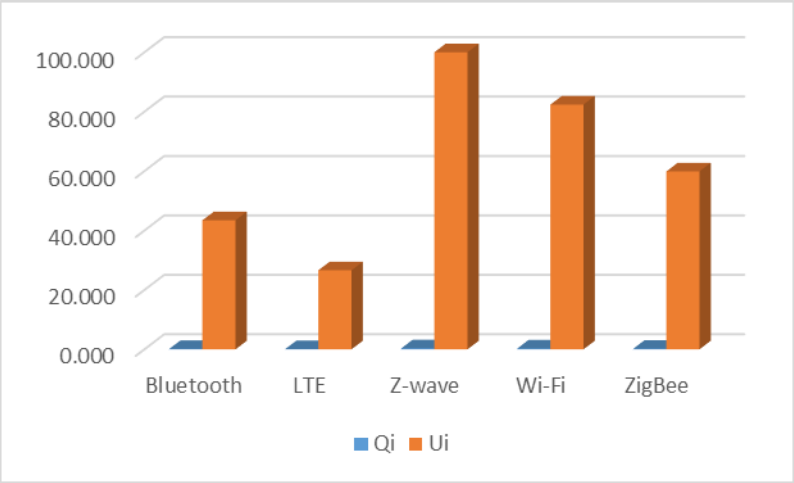


FIGURE 2. Qi, Ui

The bar chart compares five communication technologies—Bluetooth, LTE, Z-Wave, Wi-Fi, and ZigBee—based on Qi (quality index) and Ui (utility index) values. Z-Wave ranks the highest in Ui, indicating its strong efficiency and suitability for low-power applications like smart home automation. Wi-Fi follows closely, demonstrating high UI, making it ideal for high-speed data transmission. ZigBee performs well, offering a balanced approach with moderate Qi and Ui, making it a reliable choice for IoT networks. Bluetooth has a lower UI, reflecting its suitability for short-range, low-power communication. LTE, with the lowest Ui, indicates higher power consumption and development costs, making it less ideal for energy-sensitive embedded applications. This evaluation highlights Z-Wave and Wi-Fi as the most effective technologies based on efficiency and utility value.

TABLE 7. Rank

Rank	
Bluetooth	4
LTE	5
Z-wave	1
Wi-Fi	2
ZigBee	3

Based on the evaluation criteria, Z-Wave ranks first, making it the most efficient choice, particularly for smart home automation and low-power IoT applications due to its minimal energy consumption and cost-effectiveness. Wi-Fi secures the second position, excelling in transmission speed and range, making it ideal for high-speed data applications despite higher power consumption. ZigBee, ranked third, offers a well-balanced solution with moderate speed, range, and power efficiency, making it a strong contender for industrial automation and IoT networks. Bluetooth is placed fourth, providing reliable short-range communication with low power usage, making it ideal for wearables and consumer electronics. LTE, ranked fifth, has the highest power consumption and development cost, making it more suitable for mobile and long-range applications rather than energy-sensitive embedded systems.

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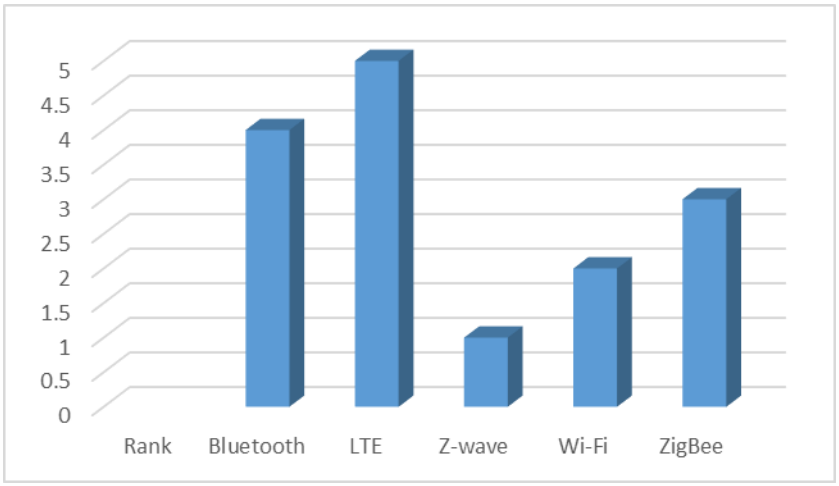


FIGURE 3. Rank

The bar chart presents the ranking of five communication technologies—Bluetooth, LTE, Z-Wave, Wi-Fi, and ZigBee—based on their overall performance. Z-Wave secures the top position with the lowest ranking score, indicating its superior efficiency in low-power and cost-sensitive applications, making it ideal for smart home automation and IoT networks. Wi-Fi ranks second, highlighting its strength in high-speed data transmission and broad network coverage, although it has higher power consumption. ZigBee holds the third position, offering a balanced approach for industrial and IoT applications. Bluetooth ranks fourth, making it a reliable choice for short-range, low-power communication. LTE is ranked the lowest due to its higher power consumption and development costs, making it less suitable for energy-sensitive embedded applications. This ranking helps identify the most suitable technology based on specific application requirements.

5. CONCLUSION

Embedded systems have become an essential part of modern technology, playing a critical role in various domains such as Communication networks, industrial automation, medical equipment, automobile systems, and consumer electronics. These systems are designed to efficiently complete specific tasks, often in real time. constraints, limited power consumption, and minimal hardware resources. The continuous advancements in embedded systems have led to the development of smarter, faster, and more efficient devices that enhance everyday life. One of the main difficulties of embedded systems is optimizing performance while maintaining cost-effectiveness and energy efficiency. Designers must balance hardware and software components to ensure reliability, security, and scalability. Combining and the into has further expanded their capabilities, enabling automation, data processing, and intelligent decision-making in real-time applications. Security remains a significant concern, as embedded systems are increasingly connected to networks and exposed to potential cyber threats. Ensuring robust security mechanisms, such as encryption, authentication, and secure booting, is crucial to protecting sensitive data and preventing unauthorized access. Additionally, the adoption of reconfigurable hardware, such as FPGAs, provides flexibility in embedded system design, allowing for efficient updates and enhancements. The future of embedded systems is promising, with ongoing research and innovation aimed at improving their performance, power efficiency, and adaptability. As embedded technology continues to evolve, it will drive advancements in autonomous systems, smart infrastructure, and next-generation computing solutions. Embedded systems will remain at the forefront of technological progress, shaping the way industries and individuals interact with intelligent and connected devices. In conclusion, Modern technology relies heavily on embedded systems and their continuous development will significantly impact various sectors. By addressing design challenges, enhancing security, and leveraging emerging technologies, embedded systems will continue to revolutionize industries and improve the efficiency of daily operations.

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