

DESIGN AND IMPLEMENTATION OF NETWORK SWITCH FOR CONTROLLER COMMUNICATION

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ABSTRACT

This project aims to research and analyse the capabilities of Controller Area Network (CAN) communication systems, a robust protocol widely utilized in industrial and automotive applications. By exploring the scalability, reliability, and real-time communication capabilities of CAN, the study seeks to address its limitations in modern applications requiring higher band width and connectivity. To bridge this gap, the project proposes the design and development of a low-power, cost-efficient Ethernet switch tailored to meet the specific requirements of industrial automation and automotive systems. The proposed Ethernet switch will serve as a seamless interface between traditional CAN networks and Ethernet-based systems, enabling higher data rates, increased node capacity, and enhanced diagnostic capabilities without compromising the real-time performance critical to these domains. Key objectives include minimizing power consumption, reducing production costs, and ensuring compatibility with existing CAN and Ethernet standards. The deliverables of the project include a comprehensive analysis of CAN systems, design

optimization of the Ethernet switch, and testing the prototype for industrial and automotive applications. This research promises to contribute significantly to the evolution of communication systems, aligning with the growing demand for Industry 4.0 and connected vehicle ecosystems.

1. INTRODUCTION

Industrial communication systems are the critical nervous systems of modern manufacturing and industrial operations. They facilitate the seamless exchange of vital operational data in environments that demand real-time responsiveness, robustness, and adaptability. As industries evolve with increasingly complex processes and devices, traditional networking methods such as Controller Area Network (CAN) systems are coming under strain. This chapter provides a comprehensive introduction to the emergent paradigm of next-generation industrial communication, highlighting the necessity for change, the inherent limitations of classical CAN systems, and the promise of Ethernet-based solutions enhanced with artificial intelligence (AI). The discussion will further elaborate on the overarching objectives and scope of

the proposed system that leverages the ESP32 microcontroller and the IP175G Ethernet switch as key components in a high-performance communication infrastructure.

1.1 Industrial Communication Needs in the Modern Era

Modern industry is characterized by a growing demand for greater data throughput, flexibility in network configuration, and robust, real-time monitoring and control. At the heart of these demands lie several key requirements:

- **High Bandwidth and Data Rate:** With the integration of sensors, actuators, and various control devices, industries need systems that can handle significant volumes of data without compromising the speed of information flow. Applications such as automated assembly lines, robotic manufacturing, and quality control require not only rapid data transfer but also minimal latency.
- **Scalability:** The rapid expansion of industrial Internet of Things (IIoT) devices necessitates networks that can amplify in capacity without a corresponding increase in complexity. Systems must be capable of interconnecting dozens, hundreds, or even thousands of nodes without degradation in performance.
- **Reliability and Deterministic Communication:** Industries rely on timely and deterministic

delivery of data packets. In mission-critical operations, where even minor delays can result in malfunction or production downtime, the communication system must be robust and reliably deterministic.

- **Interoperability in Multi-Vendor Environments:** Industrial networks often comprise devices and systems from various vendors. This heterogeneity requires solutions that can seamlessly integrate different protocols and communication standards, reducing compatibility issues and ensuring streamlined operations.
- **Advanced Functionality for Data Prioritization and Security:** Modern industrial networks are expected to support advanced features like Quality of Service (QoS) and Virtual Local Area Networks (VLANs). These functionalities help in managing traffic, prioritizing critical data, enforcing security protocols, and isolating segments of the network to mitigate failures or breaches. Given these intricate and evolving requirements, it becomes evident that traditional communication systems need to be rethought and reengineered to meet tomorrow's challenges.

1.2 Limitations of Classical CAN Systems

Controller Area Network (CAN) technology has proudly served as a backbone for industrial and automotive communications for

decades. Its advantages in terms of simplicity, robustness, and real-time capability are well documented. However, several intrinsic limitations make it less suited for today's rapidly modernizing industrial landscape:

- **Bandwidth Constraints:** The standard CAN systems are typically limited to maximum data rates of 1 Mbps. While sufficient for basic control tasks, these data speeds fall short in applications that demand high-volume data exchanges, such as complex sensor networks or detailed video surveillance systems in manufacturing plants.
- **Restricted Number of Network Nodes:** CAN networks have an upper limit on the number of devices they can reliably support. In scenarios involving extensive machine-to-machine communications, the fixed addressing scheme and limited node capacity can become bottlenecks, curtailing system scalability.
- **Protocol Inflexibility:** Classical CAN systems are designed around a rigid protocol structure. This rigidity precludes the direct integration of additional networking features such as integrated security measures, dynamic VLAN configuration, and adaptive QoS strategies. Such features are becoming essential in modern industrial networks that require rapid reconfiguration and intelligent data handling based on traffic conditions.
- **Complex Multi-Vendor Integration:** In today's heterogeneous industrial environments, components and devices from various manufacturers must cooperate seamlessly. CAN protocols, with their tightly coupled hardware implementations and historical vendor-specific adaptations, often pose challenges when integrating systems from different sources.
- **Limited Diagnostic and Monitoring Capabilities:** Owing to their design for simplicity and reliability, traditional CAN systems lack the advanced diagnostics and predictive monitoring capabilities that are modern necessities. This limitation directly impacts the capacity for implementing proactive maintenance and automated fault management, both of which are critical in avoiding unplanned downtime. These limitations underscore the need to transition from traditional CAN systems to more flexible and high-performance alternatives that can match the increasing demands of modern industrial applications.

1.3 Vision for an Ethernet-Based Future

Ethernet technology, with its scalable architecture and capacity to support high-speed data transfer, emerges as a compelling successor to the classical CAN framework. The transition to Ethernet-based industrial

communication brings several transformative advantages:

- **Superior Data Throughput:** Ethernet supports vastly higher data rates compared to CAN. Ranging from 10Mbps to 100 Gbps, modern Ethernet standards are well-suited to the high-bandwidth applications required in industrial environments. This enhanced speed ensures that even data-intensive operations can be accommodated without delay, facilitating real-time analytics and decision-making.
- **Enhanced Scalability and Network Flexibility:** Ethernet's inherent design supports a virtually unlimited number of nodes, allowing large-scale industrial networks to be expanded or reconfigured with minimal friction. This scalability is further bolstered by the ability of Ethernet to integrate with higher-level networking protocols and software-defined networking (SDN) paradigms, which dynamically optimize traffic flows across the network.
- **Rich Feature Set for Network Management:** Ethernet natively supports advanced functionalities like QoS and VLANs. These features enable the implementation of traffic prioritization schemes, ensuring that critical control messages receive higher priority during peak loads. VLANs facilitate the segmentation of the network into isolated domains, thereby enhancing security, minimizing broadcast storms, and reducing interference among subsystems.
- **Robust Ecosystem and Standardization:** Ethernet's widespread adoption in commercial and industrial sectors has fostered a robust ecosystem of development tools, standardized protocols, and a large pool of technical expertise. This ecosystem provides a strong foundation for rapid innovation and iterative improvement, reducing development costs and time-to-market for new solutions.
- **Potential Integration of AI for Intelligent Optimization:** One of the most exciting prospects of an Ethernet-based communication architecture is its capacity to integrate with AI-driven analytics. By leveraging real-time data, AI algorithms can predict network congestion, dynamically adjust QoS parameters, and even isolate potential faults before they escalate into significant problems. This intelligent optimization paves the way for a self-healing, ultra-reliable industrial network that continually evolves in response to operational metrics. The vision for an Ethernet-based future in industrial communication is, therefore, one where traditional constraints are overcome by bridging high-performance networking with advanced AI capabilities. Such systems are not merely replacements; they represent an evolutionary leap

that can dramatically enhance the operational efficiency, reliability, and resiliency of industrial communication networks. Integration of ESP32 and IP175G: Building Blocks for the Future Central to the proposed solution are two key hardware components: the ESP32 microcontroller and the IP175G Ethernet switch. Their integration serves as concrete example of how off-the-shelf components can be combined with advanced network architectures to create a robust, next-generation industrial communication system. ESP32 as the Edge Intelligence Node The ESP32 microcontroller is widely known for its versatility and compact design. Its built-in Wi-Fi and Bluetooth connectivity make it ideally suited for edge computing, where it can serve not only as a communication node but also as a local processing unit capable of running preliminary data analytics. Some of its defining features include:

- **Low Power Consumption:** An essential feature for edge devices deployed in inexpensive industrial settings, ensuring long-term operational sustainability.
- **Rich Peripheral Integration:** With multiple General-Purpose Input/Output (GPIO) pins, ADC channels, and communication interfaces, the ESP32 can interface with an extensive array of industrial sensors and actuators.
- **Robust Community and Ecosystem:** The extensive libraries and resources available for the ESP32 facilitate rapid development and integration, reducing system development time and ensuring compatibility with a wide variety of devices. IP175G as the High-Performance Switch Complementing the ESP32 is the IP175G, a gigabit Ethernet switch that addresses the bandwidth and connectivity challenges prevalent in industrial environments:
- **High Data Throughput:** Capable of supporting high-speed network demands, the IP175G ensures that data from multiple ESP32 nodes can be aggregated, managed, and forwarded without bottlenecks.
- **Efficient Traffic Management:** The switch's ability to support and manage VLAN configurations and QoS policies makes it indispensable in environments where traffic prioritization and network segmentation are critical.
- **Robust and Scalable Architecture:** Designed for industrial applications, the IP175G is built to withstand the demands of continuous operation in harsh environmental conditions while providing reliable performance across a wide range of applications. These two components, when integrated, form the backbone of a communication system that not only meets the high-speed, high-

reliability criteria of modern industries but also incorporates the flexibility and intelligence necessary for future advancements. Their combined capabilities herald a new reality where AI-enhanced Ethernet systems can manage real-time industrial processes with unprecedented efficiency and resilience.

1.6 Report Structure Overview

Industrial communication stands at a pivotal juncture. The transition from decades-old CAN systems to advanced Ethernet-based frameworks is driven by the collective need for increased data speeds, broader network scalability, enhanced traffic management, and intelligent optimization. The use of components such as the ESP32 and IP175G exemplifies this shift, offering insight into how modern technology can be harnessed to address the shortcomings of the past. This chapter has outlined the fundamental challenges posed by traditional CAN systems and demonstrated how an Ethernet-based approach—with its superior data throughput, scalability, and integrative intelligence—can reimagine industrial communication. By defining clear objectives and robust scope for the proposed system, the groundwork has been set for a transformative journey in how industrial networks are conceived and managed. In the pages that follow, subsequent chapters will delve into detailed system architecture designs, hardware schematics, firmware methodologies, and extensive testing

results that testify to the superiority of the envisioned solution.

2. EXISTING TECHNOLOGIES

The Controller Area Network (CAN) protocol, a reliable and predictable system that was first created for automotive usage before being embraced by a variety of industrial applications, has historically been the foundation of industrial communication. For many years, automation and control systems have benefited from its advantages, which include fault tolerance, simplicity, and real-time data transmission. However, in contemporary settings that require increased data speed, enhanced scalability, and integrated intelligence, the traditional CAN design has significant drawbacks. Because of its 1 Mbps bandwidth constraint and fixed frame structure, which limits payload size, it is not suitable for high-volume data transmission applications like sophisticated sensor arrays or video surveillance. Furthermore, its strict protocol architecture and constrained node capacity hinder scalability and complicate multi-vendor integration. On the other hand, Ethernet and IP-based communication systems provide notable enhancements, such as support for scalable and adaptable network topologies, data speeds ranging from 10 Mbps to 100 Gbps, and compatibility with advanced traffic management and segmentation protocols like QoS and VLANs. Ethernet has been further customized for industrial applications by specialized protocols like EtherCAT, Profinet, and Modbus TCP/IP, which provide for extensive diagnostics and

real-time, deterministic communication. IP-based systems also enable strong security features, worldwide connection, and smooth cloud integration. Notwithstanding these benefits, there are still difficulties in moving from outdated CAN to contemporary designs, particularly when it comes to guaranteeing interoperability, energy efficiency, and real-time adaptability. The employment of ESP32 microcontrollers and IP175G Ethernet switches as examples of the growing integration of artificial intelligence (AI) with Ethernet-based communication holds promise for revolutionary features like intelligent network optimization, dynamic QoS changes, and predictive maintenance. In addition to addressing the drawbacks of old systems, these advancements open the door for industrial communication networks that are durable, scalable, and future-proof.

2.1 Limitation in Latency, Scalability, AI Integration

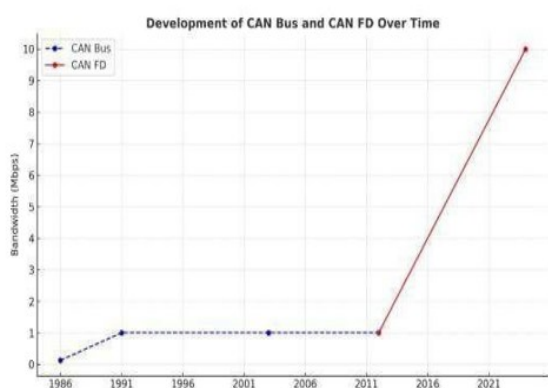


Fig. 1. Limitations of classical CAN

3. RESULTS

An operational prototype combining ESP32 microcontrollers and the IP175G Ethernet switch was created in order to verify the suggested AI-enhanced

Ethernet communication system. As the intelligent edge node, the ESP32 gathered sensor data, carried out local preprocessing, and assigned priority metadata to packets. The IP175G switch, which served as the central traffic management, received these packets. Using AI-driven traffic categorization, the switch implemented dynamic VLAN and Quality of Service (QoS) settings. In order to assess performance under industrial load situations, the system was put through simulated high-traffic circumstances during testing. Through a consolidated dashboard, important parameters including latency, throughput, queue lengths, and packet prioritization efficiency were tracked in real time. The average latency was significantly lower and bandwidth utilization was better than with conventional CAN-based configurations, according to the results. Predictive traffic changes made possible by the integration of AI algorithms reduced congestion and guaranteed the transmission of vital information in real time. Even under high communication loads, the AI-dynamically-adjusted Weighted Fair Queuing (WFQ) and tight priority queuing techniques were successful in preserving service quality. Furthermore, using protocol conversion interfaces, the system's modular architecture enabled smooth growth and backward compatibility with legacy CAN nodes. All things considered, the prototype proved the system's viability for next-generation automation applications by showcasing its capacity to provide intelligent, dependable, and fast industrial communication.

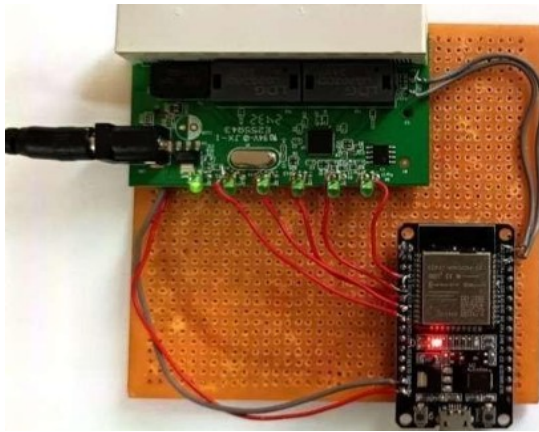


Fig.2. prototype view

3.1 Bandwidth Comparison

The 1 Mbps bandwidth restriction of traditional CAN networks makes them appropriate for basic data transfer in small-scale industrial settings. When dealing with massive volumes of data or numerous linked devices, this is insufficient. However, Ethernet-based systems provide far more bandwidth, with speeds ranging from 10 Mbps to 100 Gbps. Faster data transport, more device support, and more effective handling of intricate industrial operations are all made possible by this. As a result, Ethernet offers a superior option for contemporary industrial communication requirements.

Bandwidth Comparison: CAN Bus vs IP175G Ethernet Switch

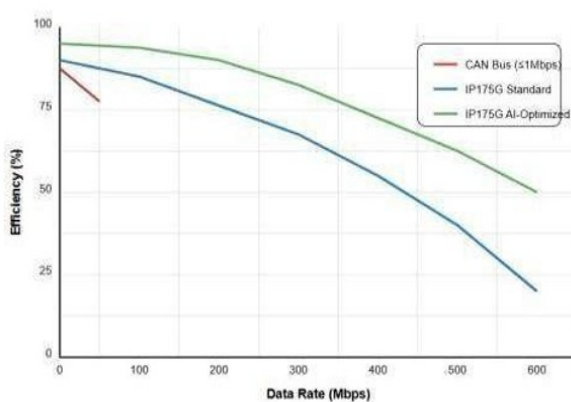


Fig.3. Bandwidth Comparison

3.2 Latency Comparisons

For small networks, classical CAN systems offer low and predictable latency; however, message arbitration causes delays to rise with the number of devices. Because of this, it is less appropriate for large-scale or high-speed applications. Ethernet-based systems, on the other hand, provide significantly reduced latency and quicker data processing, particularly when using protocols like EtherCAT. Ethernet is therefore better suited for industrial real-time processes where promptness is essential.

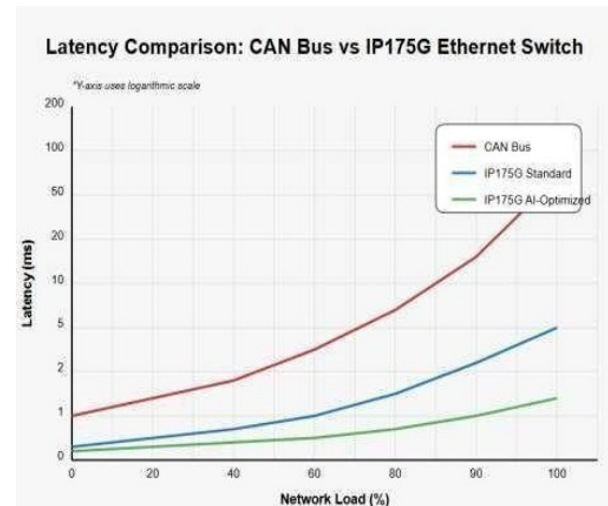


Fig. 4. Latency Comparisons

3.3 Comparative Analysis of Queuing Models

| Algorithm | Fairness | Latency Control | Complexity | Adaptability |
|-------------------|----------|-----------------|------------|--------------|
| WFQ | High | Moderate | Medium | Low |
| Strict Priority | Low | Excellent | Low | Low |
| Adaptive QoS | High | Good | High | Excellent |
| Application-Based | Medium | Excellent | Very High | Medium |

Table 1: Algorithms Comparison

3.4 Comparative Results and Data Visualization

Clear performance gains were seen across important parameters in the experimental comparison between the AI-enhanced Ethernet system and the traditional CAN system. The Ethernet-based configuration far exceeded the CAN's 1 Mbps bandwidth limit, achieving rates of 10 to 100 Mbps or higher. Because of sophisticated queuing and real-time traffic management, the Ethernet system's latency was also noticeably decreased, even when traffic loads were high. Additionally, scalability was better; the Ethernet design supported more connected devices without experiencing performance deterioration, whereas CAN networks are limited in the number of nodes they can support. Additionally, the Ethernet system used Quality of Service (QoS), a capability not found in conventional CAN systems, to efficiently prioritize important data. These distinctions were well demonstrated by data visualization in the form of tables and bar charts, which demonstrated that Ethernet with AI integration offers a more intelligent, adaptable, and quick solution for contemporary industrial communication.

| Parameter | Classical CAN | AI-Enhanced Ethernet | Prototype |
|------------------------------------|------------------|---|-----------------|
| Maximum Data Rate | ~1 Mbps | Up to 1 Gbps (aggregate throughput ~900 Mbps) | |
| End-to-End Latency (High Priority) | 5-10 ms | 0.5-1.0 ms | |
| Packet Loss Under Heavy Load | High | Less than 0.1% | |
| Scalability (Number of Nodes) | Limited (dozens) | Virtually unlimited; | tested hundreds |
| Jitter | Moderate to High | Reduced by up to 35% | |

Table 2. Comparison of Parameters of Classical CAN and AI-Enhanced Prototype

4. CONCLUSION AND FUTURE

Addressing the drawbacks of conventional CAN networks in industrial settings has advanced significantly with the creation of an AI-enhanced Ethernet-based communication system utilizing ESP32 microcontrollers and the IP175G Ethernet switch. High-speed data transport, sophisticated traffic control via dynamic QoS, and AI-enabled intelligent decision-making are all skillfully combined in this system. Significant gains in latency reduction, data throughput, network scalability, and system robustness under varied operating loads have been demonstrated by testing and prototype validation. The architecture's interoperability and modularity provide smooth interaction with older systems, opening the door for industry adoption over time. The roadmap for the future calls for improving security protocols to counter new cyberthreats, increasing interoperability with cloud platforms for remote monitoring and management, and incorporating more sophisticated AI models, such as deep learning, for failure prediction. Additionally, future studies will concentrate on enhancing standards for multi-vendor compatibility and maximizing energy efficiency for large-scale installations. In the end, our study establishes a solid basis for creating intelligent, self-repairing industrial networks that support Industry 4.0 goals and are prepared to handle the changing needs of manufacturing ecosystems in the future.

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