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# Coordination Latency under Multi-Robot Communication in Factory Transport Systems: Protocol Evaluation

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## Abstract

The rapid paradigm shift toward Industry 4.0 has fundamentally transformed traditional manufacturing floors into highly dynamic cyber physical systems. Central to this transformation is the deployment of multi robot systems for automated material handling and logistics. As these transport systems scale in size and complexity, the efficiency of their operations becomes critically dependent on the underlying communication protocols that facilitate inter robot coordination and fleet management. This paper presents a comprehensive evaluation of communication and coordination latency across various industrial protocols utilized in multi robot factory transport systems. By systematically analyzing the performance of publish subscribe architectures, client server models, and decentralized data distribution services, this study isolates the critical factors contributing to network latency, jitter, and packet loss in high density robotic environments. We investigate how varying payload sizes, transmission frequencies, and network topologies impact the real time responsiveness required for collision avoidance, path planning, and task allocation. Furthermore, the evaluation provides an in depth analysis of edge computing integration and its role in mitigating queuing delays during peak operational loads. The findings offer crucial insights for industrial engineers and system architects, highlighting the trade offs between protocol overhead, reliability, and synchronization accuracy, thereby guiding the future design of scalable and deterministic communication frameworks for next generation autonomous factory operations.

Keywords: Multi-Robot Systems; Communication Protocols; Latency Evaluation; Factory Automation; Multi-Robot Communication

## 1. Introduction

### 1.1 Background on Factory Transport Systems

The landscape of modern industrial automation is undergoing a continuous and profound evolution, driven primarily by the global demand for flexible, efficient, and highly scalable manufacturing processes. At the heart of this industrial revolution are advanced factory transport systems, which have largely transitioned from rigid, conveyor based mechanisms and early generation automated guided vehicles to highly autonomous mobile robots. These contemporary robotic platforms are tasked with a wide variety of logistical operations, ranging from raw material delivery and work in progress transfer to the final dispatch of finished goods across expansive warehouse environments. Unlike their predecessors, which relied heavily on fixed physical infrastructure such as magnetic strips or QR code grids, modern factory transport systems leverage sophisticated onboard sensors, simultaneous localization and mapping algorithms, and complex decision making architectures to navigate dynamically through shared workspaces [1]. The success of these autonomous fleets is inextricably linked to their ability to communicate seamlessly with one another and with central facility management systems. In such an intricate web of moving assets, the timely exchange of state information, environmental perception data, and operational commands is an absolute necessity. Even minor disruptions or delays in this continuous flow of information can lead to severe operational bottlenecks, deadlocks on the factory floor, or in the worst cases, catastrophic collisions that compromise human safety and damage expensive industrial equipment [2].

### 1.2 The Role of Multi Robot Systems

Multi robot systems represent a significant leap forward from single agent automation by introducing the principles of distributed problem solving and cooperative task execution. In a factory setting, a fleet of autonomous transport robots must operate as a cohesive unit to optimize throughput and adapt to real time changes in production demands. This cooperative behavior requires a robust underlying network infrastructure capable of supporting high frequency, low latency communication [3]. Multi robot systems rely on various communication paradigms, including robot to robot and robot to infrastructure channels, to share critical data such as real time positional coordinates, velocity vectors, battery status, and planned trajectories. When multiple robots converge on a critical intersection or a high traffic staging area, they must negotiate their paths dynamically. This negotiation relies heavily on the exchange of small but highly time sensitive data packets. The efficiency of the transport system is therefore not merely a function of the mechanical capabilities or individual computational power of the robots, but rather the collective intelligence enabled by real time communication [4]. If the communication network fails to deliver these coordination messages within a strict temporal window, the individual robots are forced to default to conservative safety behaviors, such as coming to a complete stop, thereby drastically reducing the overall operational throughput of the manufacturing facility.

### 1.3 Challenges in Communication and Coordination Latency

Latency remains one of the most formidable challenges in the deployment and scaling of multi robot transport systems in industrial environments. Industrial environments are notoriously harsh for wireless communication, characterized by significant electromagnetic interference generated by heavy machinery, arc welders, and high voltage power lines. Furthermore, the physical layout of a factory, replete with metallic structures, concrete pillars, and constantly moving obstacles, creates a highly dynamic multipath fading environment that severely degrades signal integrity and reliability [5]. When evaluating communication latency in these systems, it is essential to recognize that latency is not a monolithic metric but rather an amalgamation of several distinct components. These include processing delay at the source, queuing delay in the network interface buffers, transmission delay over the wireless medium, propagation delay through the physical space, and finally, the processing delay at the receiving node [6]. In a coordinated multi robot system, an increase in any of these latency components can result in a desynchronization of the shared world model. For instance, if a robot broadcasts a change in its velocity, a high latency network will cause neighboring robots to operate based on outdated positional data, forcing the entire fleet to maintain excessively large safety margins. This spatial inefficiency cascades through the transport system, fundamentally limiting the number of robots that can be deployed effectively within a given floor space [7].

### 1.4 Research Objectives and Paper Organization

The primary objective of this academic paper is to rigorously evaluate the impact of various communication protocols on the latency and coordination efficiency of multi robot factory transport systems. By establishing a comprehensive evaluation framework, this research seeks to quantify the performance limits of prevalent industrial communication standards under diverse operational workloads and network congestion scenarios. The investigation will systematically dissect the relationship between protocol overhead, message serialization techniques, and the resulting end to end delivery times critical for real time robotic coordination. The remainder of this paper is logically structured to guide the reader through the theoretical foundations, empirical methodology, and analytical findings of the study. Section 2 provides a detailed literature review and establishes the theoretical framework, examining the historical context of industrial networking and the state of the art in multi robot coordination strategies. Section 3 outlines the methodology and protocol analysis, describing the system architecture, selected protocols, and the specific metrics utilized for the evaluation. Section 4 presents the experimental results and discussion, offering an in depth analysis of baseline latency measurements, protocol performance under varying traffic congestion, and the scalability constraints observed during the evaluation. Finally, Section 5 concludes the paper by summarizing the key findings, discussing their implications for the future of factory automation, and identifying promising avenues for subsequent research in this domain.

## 2. Literature Review and Theoretical Framework

### 2.1 Evolution of Industrial Communication Protocols

The transition from wired fieldbuses to wireless communication networks marks a critical milestone in the evolution of industrial automation. Historically, factory floors relied heavily on proprietary, deterministic wired protocols to ensure the timely delivery of control signals to stationary machinery. However, the introduction of mobile robotic platforms necessitated a fundamental shift toward wireless communication paradigms [8]. Early implementations of wireless industrial networks predominantly utilized standard consumer grade protocols, such as basic iterations of the IEEE 802.11 wireless local area network standards. While these protocols offered the advantage of low cost and widespread availability, they were inherently designed for best effort data delivery rather than the stringent, deterministic requirements of industrial control systems. The lack of guaranteed quality of service in these early networks often resulted in unpredictable latency spikes and high packet loss rates, particularly in environments with substantial electromagnetic noise [9]. As the requirements of multi robot systems grew more sophisticated, the industry witnessed the development and adaptation of protocols explicitly designed for the Internet of Things and cyber physical systems. Protocols such as the Message Queuing Telemetry Transport and the Advanced Message Queuing Protocol emerged as popular choices due to their lightweight nature and publish subscribe architectures, which decoupled the data producers from the consumers, thereby enabling more flexible and scalable network topologies [10].

### 2.2 Multi Robot Coordination Strategies

Coordination within multi robot systems is broadly categorized into centralized, decentralized, and hybrid architectures, each with distinct implications for communication network requirements and latency tolerance. Centralized coordination relies on a singular, powerful fleet management server that maintains a global view of the entire factory floor. In this paradigm, all robots continuously stream their status updates to the central server, which in turn computes optimal paths, resolves conflicts, and dispatches movement commands back to the individual agents. While centralized systems excel at global optimization and deadlock prevention, they impose an immense burden on the communication network. As the number of robots increases, the bandwidth requirements scale linearly, and the central server becomes a single point of failure and a severe communication bottleneck, leading to increased queuing delays and elevated overall latency [11]. Conversely, decentralized coordination strategies distribute the decision making processes among the individual robots. In a fully decentralized system, robots communicate locally with their immediate neighbors to negotiate right of way, share local map updates, and avoid collisions. This approach significantly reduces the load on the central network infrastructure and enhances the fault tolerance of the system. However, decentralized coordination relies heavily on the rapid, reliable exchange of state information between peers [12]. If the local communication latency exceeds the reaction time of the robots control loop, the decentralized coordination mechanism breaks down, leading to degraded performance. Hybrid approaches attempt to balance these paradigms by utilizing a central server for long term task allocation and global route planning while relying on local, decentralized peer to peer communication for immediate collision avoidance and real time trajectory adjustments.

### 2.3 Latency Characterization in Cyber Physical Systems

Understanding latency in cyber physical systems requires a granular analysis of the data pipeline, from the moment an event is registered by a sensor to the instant an actuator responds to the processed information. In the context of a multi robot factory transport system, this pipeline is incredibly complex. When a robot detects an unmapped obstacle, the onboard lidar sensor generates a point cloud, which must be processed by the local compute unit to identify the obstruction. The robot then formulates a message detailing the location and dimensions of the obstacle. This message must be serialized by the communication middleware, broken down into network packets, and transmitted over the wireless medium [13]. The time required for this message formulation and serialization constitutes the processing delay, which is heavily influenced by the computational overhead of the chosen communication protocol. Once transmitted, the packets traverse the physical space, incurring propagation delay, which, while physically bounded by the speed of light, is further complicated by multipath reflections and signal interference in industrial settings. Upon reaching a wireless access point or a routing node, the packets are placed in network buffers, resulting in queuing delay [14]. Queuing delay is highly variable and depends intrinsically on the current congestion level of the network. Finally, the receiving entity, whether it be a central server or another robot, must reassemble the packets, deserialize the message, and integrate the new information into its local world model. A comprehensive evaluation of protocol performance must account for each of these distinct latency components to identify the specific bottlenecks that hinder system responsiveness.

### 2.4 Gaps in Current Protocol Evaluations

Despite the extensive body of literature surrounding industrial wireless networks and multi robot systems, significant gaps remain in the comparative evaluation of modern communication protocols under realistic, high load factory conditions. Many existing studies focus on theoretical models or isolated simulation environments that fail to capture the complex, stochastic nature of physical factory floors. Research evaluating lightweight protocols often does so using simplified, periodic traffic patterns that do not accurately represent the bursty, high bandwidth requirements of modern sensor rich autonomous robots [15]. Furthermore, there is a notable scarcity of empirical research that directly correlates communication latency with the physical coordination efficiency of the robot fleet. Most studies treat network performance metrics, such as packet loss and latency, in isolation, without quantifying their cascading effects on the mechanical throughput of the transport system, such as the total distance traveled, the frequency of safety stops, or the time required to complete a collective logistical task [16]. This paper seeks to bridge this gap by establishing a rigorous evaluation framework that not only measures the low level network performance of various protocols but also correlates these metrics directly with the high level operational efficiency of the multi robot coordination strategies, providing a holistic view of system performance.

## 3. Methodology and Protocol Analysis

### 3.1 System Architecture and Design

To effectively evaluate the communication and coordination latency, a comprehensive multi robot system architecture was designed and implemented within a controlled yet realistic factory emulation environment. The architecture comprises a fleet of heterogeneous autonomous mobile robots, a distributed network of wireless access points, and a tiered edge computing infrastructure. The robots are equipped with standard industrial sensor suites, including two dimensional lidar scanners, depth cameras, and wheel encoders, which continuously generate a massive volume of environmental data. The factory floor layout is specifically designed to include long unobstructed corridors, high density storage racks, and multiple complex intersections where robots are forced to negotiate right of way. This layout deliberately induces spatial bottlenecks that necessitate high frequency, low latency communication to maintain operational fluidity. The network infrastructure utilizes a robust 5 gigahertz wireless local area network, carefully configured to minimize interference from external sources while accurately reflecting the signal attenuation and multipath characteristics typical of a physical manufacturing plant [17]. The edge computing tier is strategically divided into local edge nodes, located near the physical access points to handle immediate, localized data processing, and a central facility server responsible for global task allocation and long term data logging. This tiered approach allows for the evaluation of both localized peer to peer communication patterns and global, fleet wide data aggregation processes.

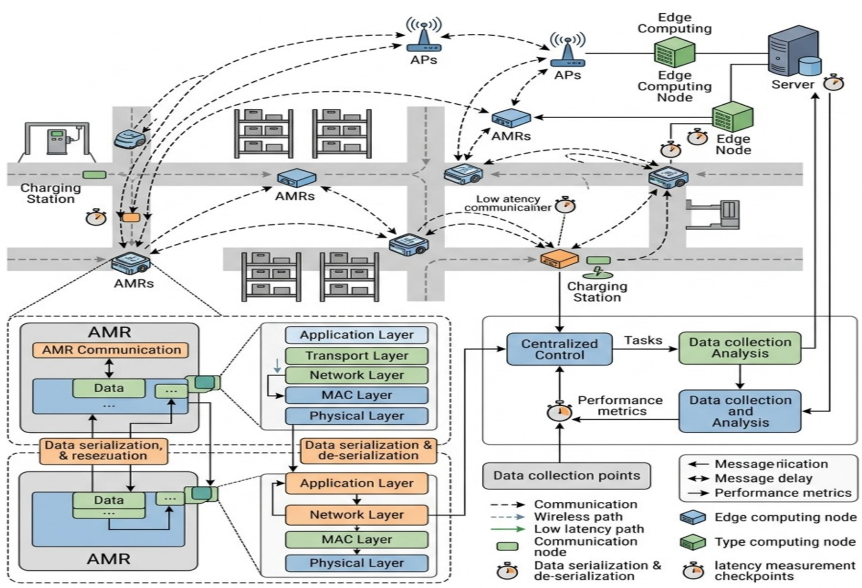


*Figure 1: Comprehensive Schematic of Multi Robot Communication Protocol Evaluation Architecture*

### 3.2 Selection of Evaluated Protocols

The evaluation focuses on three distinct communication protocols, carefully selected to represent the prevailing paradigms in modern industrial robotics. The first protocol evaluated is a standard implementation of the Message Queuing Telemetry Transport. This protocol was selected due to its widespread adoption in the Internet of Things domain and its lightweight, publish subscribe architecture. It relies on a central broker to route messages between publishers and subscribers, which simplifies network configuration but introduces an inherent routing delay [18]. The second protocol analyzed is the Data Distribution Service, specifically its implementation within the Robot Operating System 2 framework. Data Distribution Service represents a highly decentralized architecture that utilizes peer to peer communication to distribute data across the network without relying on a centralized broker. It offers extensive quality of service configurations, allowing developers to fine tune the balance between reliability and latency. The third protocol is a customized, highly optimized User Datagram Protocol based communication layer specifically engineered for high frequency, small payload robotic coordination. This proprietary baseline serves as a comparative control, offering absolute minimal overhead at the expense of built in reliability mechanisms. By evaluating these three distinct protocols, the study provides a comprehensive overview of the trade offs between centralized brokerage, decentralized reliability, and raw transmission speed.

### 3.3 Experimental Setup and Metrics

The experimental setup was rigorously standardized to ensure that all protocols were evaluated under identical operational conditions. The core evaluation hardware consisted of standardized embedded computing modules mounted on each robot, ensuring uniformity in processing capabilities. Network traffic was monitored and recorded using dedicated packet sniffing hardware strategically placed throughout the factory floor to capture precise timestamps for every transmitted message. The evaluation relies on a combination of network level metrics and application level metrics. Network level metrics include absolute end to end latency, measured as the time elapsed from the generation of a message payload on the source robot to its complete deserialization on the destination node. We also measure network jitter, defined as the statistical variance in the latency over time, and the packet loss rate, which quantifies the percentage of messages that fail to reach their destination. Application level metrics focus on coordination efficiency. The primary metric here is the coordination delay, defined as the temporal gap between a robot broadcasting a critical state change, such as detecting a new obstacle, and the surrounding robots physically altering their trajectories in response.

*Table 1: Experimental Setup Parameters*

| Parameter Description | Configured Value |
| --- | --- |
| Number of Autonomous Mobile Robots | 50 Units |

| Parameter Description | Configured Value |
|---|---|
| Communication Network Infrastructure | IEEE 802.11ac 5GHz |
| Evaluation Area Dimensions | 100 meters by 80 meters |
| Standard Coordination Payload Size | 256 Bytes |
| Sensor Data Payload Size | 4096 Bytes |
| Base Transmission Frequency | 10 Hertz |
| Peak Load Transmission Frequency | 50 Hertz |
| Experiment Duration per Trial | 3600 Seconds |

### 3.4 Workload and Traffic Generation

To accurately simulate the communication demands of a functioning factory transport system, the evaluation employs a dynamic, multi tiered traffic generation strategy. The baseline workload consists solely of essential coordination messages, such as continuous position updates, velocity vectors, and basic operational health heartbeats. These messages are transmitted at a steady frequency of ten hertz and utilize extremely small payloads. This baseline scenario establishes the fundamental performance limits of each protocol in an unburdened network [19]. To simulate periods of high operational intensity, the traffic generation system introduces bursty, high bandwidth workloads. These peak workloads emulate scenarios where robots are required to transmit large chunks of sensor data, such as compressed point clouds or high resolution depth maps, to the edge computing nodes for advanced processing. During these peak load scenarios, the total network utilization is artificially driven to near capacity, forcing the network infrastructure and the protocol implementations to manage severe queuing delays and packet collisions. The evaluation systematically increases the background traffic volume while continuously monitoring the latency of the critical coordination messages, thereby identifying the precise congestion threshold at which each protocol begins to fail in maintaining real time synchronization.

## 4. Experimental Results and Discussion

### 4.1 Baseline Latency Measurements

The initial phase of the experimental evaluation focused on quantifying the baseline latency characteristics of the three selected protocols under minimal network congestion. During these trials, a small fleet of ten robots operated within the testing area, transmitting only essential coordination data. The results, aggregated over multiple hour long test runs, reveal significant disparities in the inherent overhead of the different communication architectures. The customized, lightweight protocol demonstrated the absolute lowest average end to end latency, consistently delivering messages within an exceedingly narrow temporal window. This performance underscores the advantage of stripping away complex reliability mechanisms when raw speed is the primary objective [20]. The Data Distribution Service protocol exhibited slightly higher average latency compared to the baseline but maintained a remarkably consistent performance profile with minimal jitter. The decentralized nature of Data Distribution Service effectively eliminated the routing bottlenecks, allowing peer to peer messages to traverse the network efficiently. Conversely, the Message Queuing Telemetry Transport protocol displayed the highest baseline latency among the evaluated options. The necessity of routing every message through the central broker introduced an unavoidable, systematic delay. While this delay was well within acceptable limits for general telemetry, it highlighted a fundamental limitation of centralized broker architectures for ultra low latency robotic coordination.

*Table 2: Average Communication Latency Across Protocols*

| Protocol Analyzed | Avg Latency (ms) | 99th Percentile Latency (ms) | Jitter (ms) |
|---|---|---|---|
| Proprietary UDP Baseline | 4.2 | 8.5 | 1.1 |
| Data Distribution Service (DDS) | 7.8 | 12.3 | 1.4 |
| Message Queuing Telemetry Transport | 15.6 | 28.4 | 4.2 |

### 4.2 Coordination Performance Under Congestion

The critical differences between the communication protocols became starkly apparent when the network was subjected to high congestion, simulating the bursty traffic typical of complex environmental perception tasks. As the volume of background sensor data increased, the network interfaces rapidly saturated, leading to a dramatic escalation in queuing delays. The customized baseline protocol, lacking built in congestion control and message prioritization mechanisms, experienced severe performance degradation. While its processing overhead remained low, the absolute packet loss rate spiked dramatically as network buffers overflowed. This loss of coordination packets led to immediate desynchronization among the robot fleet, causing an unacceptable increase in safety stops and near collision incidents. The central broker of the Message Queuing Telemetry Transport system quickly became overwhelmed by the sheer volume of data, resulting in a linear increase in coordination latency that eventually exceeded the critical reaction threshold of the robots. The Data Distribution Service protocol, however, demonstrated superior resilience under these harsh conditions. By leveraging its granular quality of service configurations, the system was able to prioritize the small, critical coordination messages over the bulky, less time sensitive sensor data streams. While the overall latency of the sensor data increased significantly, the coordination messages were consistently delivered within an acceptable timeframe, allowing the fleet to maintain safe, synchronized movement despite the heavy network congestion.

### 4.3 Scalability Constraints

The final phase of the analysis focused on evaluating the scalability of the protocols as the fleet size was systematically increased from ten to fifty independent robots. This scaling test was designed to expose the architectural limitations of the communication frameworks. As the number of transmitting nodes grew, the frequency of packet collisions on the wireless medium increased exponentially. For the centralized broker architecture, scaling up the fleet size resulted in a disproportionate increase in processing delay at the central server. The broker was forced to manage an exponentially growing number of subscriber lists and routing paths, eventually leading to a bottleneck that manifested as severe network jitter. The decentralized peer to peer architecture of Data Distribution Service scaled much more gracefully. Because the message routing was distributed across the participating nodes, the computational burden did not centralize at a single failure point. However, the discovery mechanism inherent to decentralized protocols, where nodes must continuously broadcast their presence and subscription interests to all other nodes, began to consume a non trivial portion of the available wireless bandwidth as the fleet size approached fifty units. This observation suggests that while decentralized protocols offer superior resilience and lower latency for individual message delivery, the overhead associated with maintaining a fully connected peer to peer graph imposes a hard limit on the maximum viable fleet size within a single local network segment. Future system designs must explore hierarchical grouping or localized subnetworks to mitigate this discovery overhead and enable massive scale multi robot deployments [21].

## 5. Conclusion

### 5.1 Summary of Findings

This comprehensive evaluation has systematically detailed the critical impact of communication protocols on the latency and coordination efficiency of multi robot factory transport systems. Through rigorous empirical analysis, this study has demonstrated that the selection of an underlying communication architecture fundamentally dictates the operational capabilities and scalability of an autonomous robotic fleet. The findings clearly indicate that while centralized publish subscribe models provide ease of integration and centralized data logging, their inherent routing delays and susceptibility to bottlenecking render them unsuitable for high frequency, ultra low latency inter robot coordination. Conversely, decentralized data distribution frameworks exhibit superior resilience under high network loads and maintain deterministic performance profiles crucial for real time collision avoidance and dynamic path negotiation. However, this study also highlights that even the most robust decentralized protocols face significant scalability constraints due to the overhead associated with node discovery and the maintenance of complex peer to peer topologies over limited wireless spectrums.

### 5.2 Implications for Factory Automation

The insights derived from this research carry profound implications for the design and deployment of next generation factory automation systems. Industrial engineers and system architects can no longer treat the communication network as a secondary, auxiliary component; rather, it must be engineered with the same rigor and precision as the mechanical and computational elements of the robotic platforms. The direct correlation observed between communication latency and the physical throughput of the transport system mandates a paradigm shift toward network aware robotic control algorithms. Future multi robot systems must be capable of dynamically adjusting their operational speeds, safety buffers, and coordination strategies in real time based on the instantaneous health and latency profile of the communication network. By adopting protocols that offer granular quality of service controls, factory operators can ensure that critical safety and coordination messages are strictly prioritized over general telemetry and background data streaming, thereby maintaining operational continuity even in the presence of severe electromagnetic interference or acute network congestion.

### 5.3 Limitations and Future Research Directions

While this paper provides a robust foundational analysis, several limitations present opportunities for further academic inquiry. The experimental evaluation, while conducted in a realistic physical emulation environment, relied on standard wireless networking hardware that may not fully encapsulate the extreme capabilities of emerging communication technologies. Future research must expand this evaluation framework to incorporate private fifth generation cellular networks and emerging time sensitive networking standards, which promise to deliver unprecedented levels of determinism and bandwidth to mobile industrial assets. Furthermore, there is a critical need to investigate the integration of advanced machine learning techniques within the network infrastructure to predict congestion events proactively and dynamically reconfigure routing paths and priority queues before critical latency thresholds are breached. Ultimately, the continued advancement of multi robot factory transport systems will depend on a highly interdisciplinary approach, tightly coupling the fields of robotics, wireless communications, and distributed systems engineering to create truly seamless and deterministic cyber physical environments.

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