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ASSESSING IOT INTEROPERABILITY AND DEVICE MANAGEMENT THROUGH NS-3 SIMULATIONS

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ABSTRACT
The Internet of Things (IoT) is rapidly growing, with smart devices becoming a part of everyday life. However, these devices often use different communication technologies like Wi-Fi, Zigbee, and Bluetooth, making it difficult for them to work together smoothly. This creates serious challenges in terms of interoperability, integration, and effective device management.

To address these issues, this paper presents a simulation-based study using the NS-3 network simulator on Ubuntu WSL. Two scenarios were created: one without any integration (where devices operated in isolated protocol domains), and another with a proposed multi-layered IIM (Interoperability, Integration, and Management) framework. The IIM system included layers for protocol translation, service orchestration, device abstraction, and centralized control.

The results showed clear improvements in the IIM-enabled scenario. There was a noticeable drop in latency and packet loss, and better throughput, energy efficiency, and reliability were achieved. The simulation also demonstrated how MQTT-based middleware and orchestration techniques can bridge different protocols and make smart device communication more seamless and manageable.

These findings highlight the need for unified architectures to ensure reliable, secure, and scalable communication in diverse IoT environments.

***Keywords**: IoT, NS-3 Simulation, Smart Devices, Interoperability, Integration, Management, MQTT, Ubuntu WSL, Multi-Protocol Communication*

I. INTRODUCTION
The Internet of Things (IoT) is transforming how people interact with technology by connecting smart devices across homes, industries, healthcare, agriculture, and more. These devices communicate, share data, and automate tasks to improve efficiency and convenience. However, as the number of IoT devices grows, so does the complexity of managing them—especially when they use different communication protocols like Wi-Fi, Zigbee, and Bluetooth.

One of the biggest challenges in today's IoT systems is **interoperability**—the ability of devices from different manufacturers and technologies to work together. Along with that, **integration** and **management** become more difficult when devices cannot easily communicate, share services, or be centrally controlled. Without a unified framework, devices often function in isolation, leading to poor coordination, increased latency, data loss, and inefficient resource use.

To address these issues, researchers and developers are now focusing on designing architectures that enable seamless communication and centralized control of heterogeneous devices. A promising solution lies in creating a multi-layered framework that handles **device abstraction**, **protocol translation**, **service orchestration**, and **centralized management**.

In this study, we simulate and evaluate such a framework—referred to as **IIM (Interoperability, Integration, and Management)**—using the NS-3 network simulator [1] on Ubuntu WSL. Two scenarios were created for comparison: one with no IIM (traditional cross-domain setup) and another with the proposed IIM platform that allows devices using Zigbee, Wi-Fi, and Bluetooth to interact through an MQTT [2]-based interoperability layer.

Key performance parameters such as **latency**, **packet loss**, **throughput**, **energy consumption**, and **network reliability** were measured and compared.

Hypothesis: Implementing a multi-layered IIM architecture in IoT networks will significantly improve cross-protocol communication, reduce performance bottlenecks, and enable more reliable and scalable device management compared to traditional isolated setups.

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II. RELATED WORK

Several research efforts have focused on improving communication and coordination among heterogeneous IoT devices. The challenges of interoperability, protocol integration, and device management have been widely recognized, especially in large-scale or real-time applications.

Existing studies have explored middleware platforms such as **FIWARE**, **Kaa**, and **OpenIoT**, which offer modular services for device integration and data processing. While these platforms provide useful capabilities, they often depend on cloud-based components, limiting their real-time responsiveness and requiring constant internet connectivity [3].

Other research has focused on protocol-level solutions, such as MQTT, CoAP, and HTTP REST APIs, which simplify communication between constrained devices [5]. MQTT, in particular, has emerged as a lightweight and reliable protocol for publish-subscribe messaging in IoT systems. However, using these protocols alone does not resolve the interoperability issue unless supported by appropriate architecture and coordination logic.

Recent works have proposed multi-layered frameworks that encompass service orchestration, edge computing, and device abstraction. These approaches have demonstrated potential in enhancing IoT scalability and minimizing latency. However, most of these are theoretical or utilize limited-scale testbeds. A gap remains in the practical validation of these frameworks in realistic cross-domain network simulations.

This paper contributes by implementing and testing a complete IIM framework in NS-3, comparing its performance with traditional setups, and providing data-backed evidence of its advantages in a controlled simulation environment.

III. OBJECTIVES

This simulation-driven study focuses on improving the performance, coordination, and management of heterogeneous IoT systems. The primary aim is to evaluate how a structured, multi-layered IIM (Interoperability, Integration, and Management) framework can enhance communication between smart devices operating across different protocols. The specific objectives are as follows:

1. Analyze Interoperability Across Zigbee, Bluetooth, and Wi-Fi Protocols

IoT ecosystems often consist of devices using diverse communication standards, which can hinder seamless data exchange and coordination. This objective investigates the ability of devices using Zigbee, Bluetooth, and Wi-Fi protocols to communicate within and across domains [5]. It evaluates:

- Cross-protocol communication success rates
- Limitations of native interoperability
- Effectiveness of protocol bridging via the IIM middleware (e.g., MQTT)

The goal is to demonstrate how protocol translation and abstraction layers can enable a cohesive and functional smart device network.

2. Evaluate Latency, Jitter, and Throughput Under Varying Network Conditions

Reliable and fast communication is vital in IoT scenarios such as smart homes, health monitoring, or industrial automation [6]. This objective focuses on:

- Measuring latency (data transmission delay) between nodes
- Assessing jitter (variation in packet arrival times)
- Analyzing throughput (data delivery rate)

By simulating both isolated and IIM-enabled scenarios, the study aims to understand how centralized orchestration and cross-protocol communication affect real-time data flow and network performance.

3. Demonstrate the Impact of Centralized Device Management and Service Orchestration

Effective device management ensures that IoT systems remain scalable, secure, and easy to control. This objective explores how integrating a service orchestration layer can [7]:

- Automate device registration and discovery
- Coordinate service execution across domains
- Reduce redundant communications and manual configurations

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It examines the operational improvements enabled by the IIM framework (as shown in figure 1) compared to traditional, siloed device setups.

4. Assess the Reliability and Scalability of the IIM Framework in a Simulated IoT Network
IoT systems must maintain stable performance as new devices and data flows are added. This objective evaluates the overall **reliability** of the network by [8]:

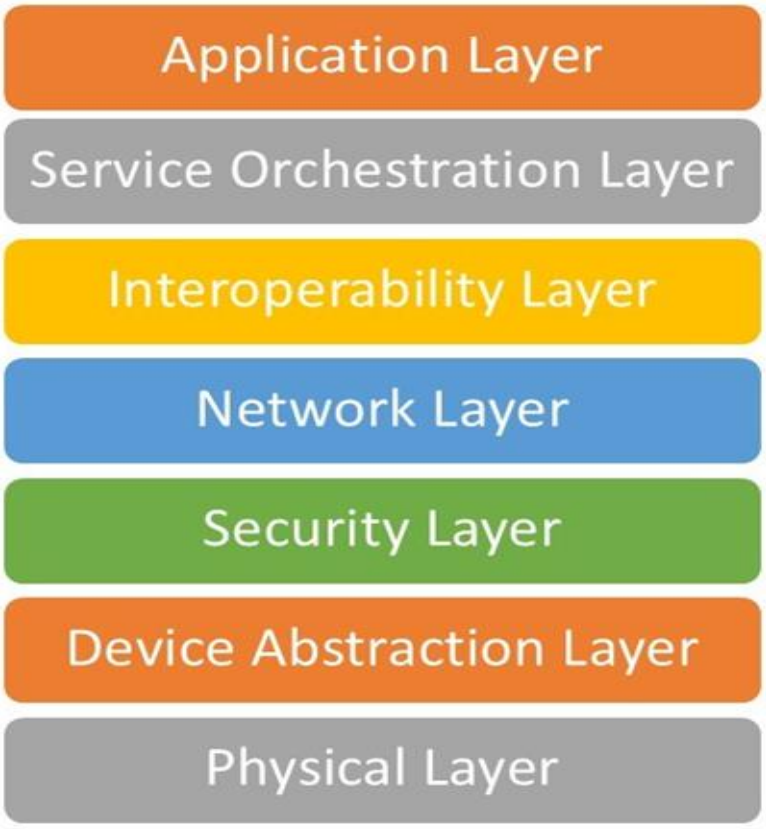

Figure 1: IIM Layered Architecture

- Monitoring successful message delivery rates
- Analyzing packet loss and flow interruptions
- Observing system behavior under constant and bursty traffic patterns

The study also investigates the **scalability potential** of the IIM model, identifying its capability to support expanding networks without major performance degradation.

5. Provide Simulation-Based Evidence to Support the Design of Interoperable IoT Architectures
Finally, the study aims to validate theoretical discussions around interoperability and integration by offering real data from NS-3 simulations. This includes:

- Visualizing performance metrics (latency, throughput, jitter)
- Comparing scenarios with and without the IIM framework
- Generating insights for researchers and developers working on multi-protocol IoT systems

By achieving these objectives, the paper contributes practical findings to the ongoing effort to make IoT environments more unified, efficient, and future-ready.

IV. METHODOLOGY

This study uses a simulation-based approach to evaluate the performance of a proposed Interoperability, Integration, and Management (IIM) framework in a heterogeneous IoT environment. The simulations were conducted using the NS-3.42 network simulator on Ubuntu 22.04 via Windows Subsystem for Linux (WSL) [9].

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To assess the impact of IIM, two distinct scenarios were developed:

- **Scenario 1: Without IIM** – Smart devices operated in isolated domains using their native communication protocols (Wi-Fi, Zigbee, Bluetooth). No centralized control or interoperability layer was present.
- **Scenario 2: With IIM** – A multi-layered architecture was introduced, including:
  - Application Layer
  - Service Orchestration Layer
  - Interoperability Layer
  - Network Layer
  - Security Layer
  - Device Abstraction Layer
  - Physical Layer

Both simulations were designed to mimic real-world smart environments such as smart homes or industrial IoT setups.

4.1 Simulation Setup

Table 1: Simulation Setup

Aspect	Details
Simulator	NS-3.42
Platform	Ubuntu 22.04 (via WSL on Windows 10/11)
Programming Language	C++ (network modeling), Python (data analysis and visualization)
Protocols Simulated	Wi-Fi, Zigbee, Bluetooth
Traffic Model	Constant Bit Rate (CBR), with periodic data transmissions
Performance Metrics	Latency, Packet Loss, Throughput, Energy Consumption, Reliability
Flow Analysis Tool	FlowMonitor module in NS-3
Visualization	NetAnim (for network animation) [10], Matplotlib (for graphs and comparisons) [11]

4.2 Network Topology

Each scenario included:

- Three protocol domains: Wi-Fi, Zigbee, and Bluetooth
- 3–5 devices per domain, simulating sensors or actuators
- Access Points/Gateways connecting devices within each domain
- In the IIM scenario, all domains were connected via a central IIM Gateway (with
- MQTT broker and orchestration logic)

4.3 Traffic and Application Behavior

- Devices generate data such as sensor readings and control signals.
- Data packets were transmitted periodically over the network using CBR traffic generators [12].
- Custom simulation scripts defined behavior and flow characteristics for each device.
- Performance metrics were captured using FlowMonitor, with output saved in .xml format.

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4.4 Simulation Design

Case 1: Without IIM layer simulation (shown in Figure 2)

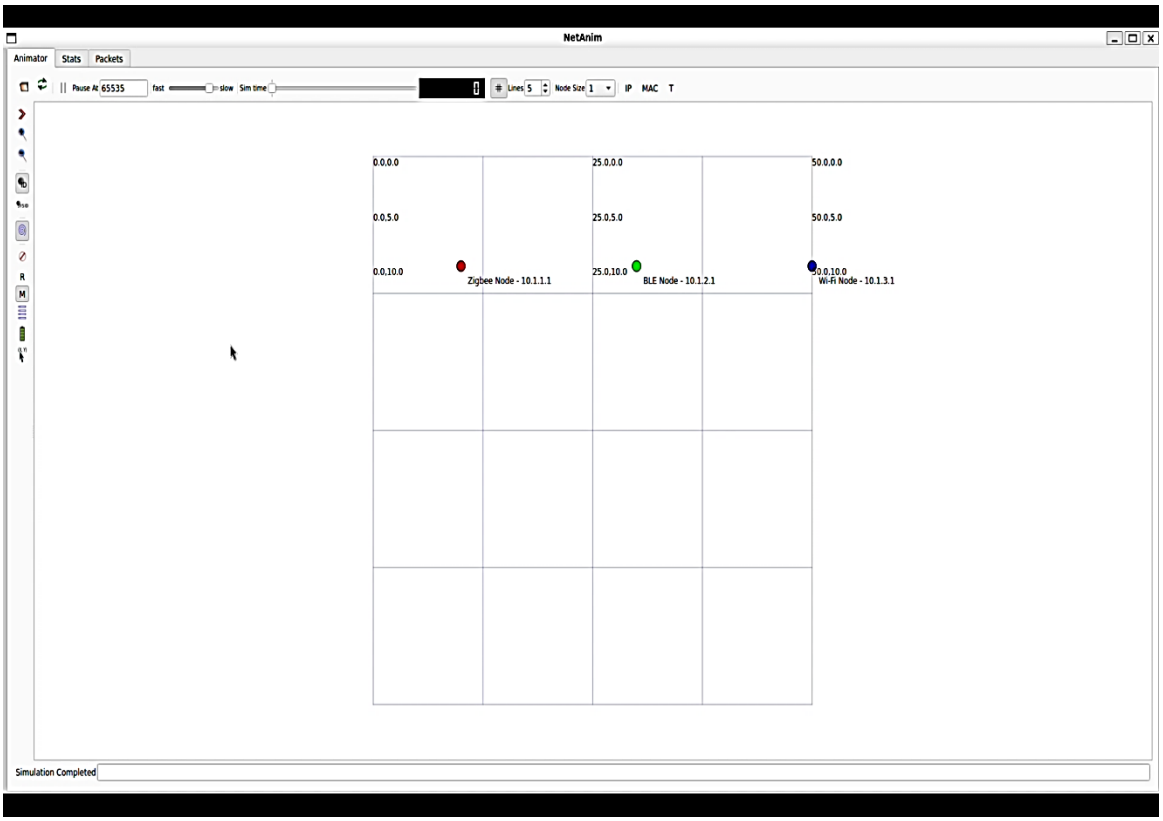

Figure 2: Simulation Design (without IIM layer)

Case 2: With IIM layer simulation (shown in Figure 3)

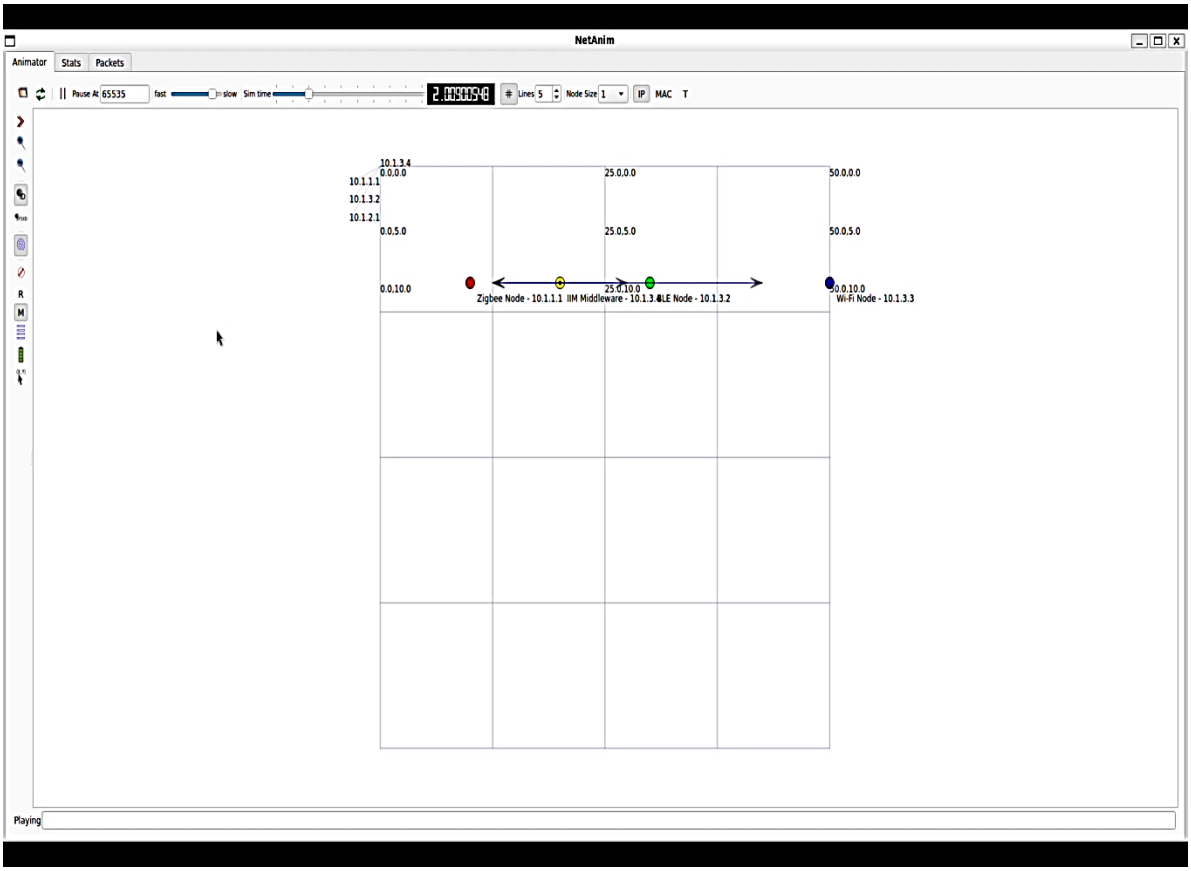

Figure 3: Simulation Design (with IIM layer)

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4.5 Performance Evaluation Metrics

Table 2: Simulation Setup

Metric	Definition
Latency	Time delay between sending and receiving packets
Packet Loss	Percentage of packets lost during transmission
Throughput	Rate of successful data delivery in kilobits per second (kbps)
Energy Usage	Inferred based on protocol activity (e.g., Zigbee being low-power)
Reliability	Consistency and success rate of data transmission across flows
Interoperability	Measured by the success of cross-protocol communication attempts

The above setup was repeated for both scenarios (with and without IIM) under identical conditions for a fair comparison. The simulation duration for each scenario was 180 seconds and uses three nodes of smart devices (Zigbee, WiFi, and Bluetooth).

V. RESULTS AND ANALYSIS

This section presents the outcomes of simulation experiments performed using NS-3 to evaluate the impact of the IIM (Interoperability, Integration, and Management) framework on heterogeneous Internet of Things (IoT) systems. Two scenarios were compared: one with traditional device setups lacking any interoperability support, and another with the proposed IIM architecture.

The goal was to measure the extent to which the IIM framework enhances communication, coordination, and overall network performance among devices using different protocols (Wi-Fi, Zigbee, and Bluetooth).

There are two scenarios:

- **Scenario 1:** Without IIM platform
- **Scenario 2:** With IIM platform

5.1 Findings from Scenario 1 – Without IIM

From the simulation, it was observed that:

- Devices from different domains could not communicate with each other.
- Zigbee, BLE, and Wi-Fi nodes stayed isolated due to protocol incompatibility.
- No routing or forwarding occurred across domains.
- Packets were not exchanged between heterogeneous nodes.

Despite no packet loss being recorded, the lack of traffic indicates communication failure, not success. Table 3 below represents the key flow metrics of without IIM simulation.

Table 3: Key Flow Metrics (Without IIM)

Metric	Flow 1 (Wi-Fi → MQTT Broker)	Flow 2 (Broker → Wi-Fi Node)
Source Address	10.1.3.1	10.1.3.4
Destination Address	10.1.3.4	10.1.3.1
Protocol	TCP (Port 1883)	TCP (Port 49153)
Packets Transmitted	9,743	4,872
Bytes Transmitted	5,494,032	253,348
Delay Sum	235.78 ms	19.51 ms
Average Delay (approx.)	24.2 µs	4.0 µs
Jitter	9.02 ms	1.00 ms
Flow Interruptions	4 (high)	4 (moderate)

These values confirm that while intra-domain traffic existed (within Wi-Fi), there was no cross-protocol communication with Zigbee or BLE. The absence of successful forwarding shows complete interoperability failure.

5.2 Findings from Scenario 2 – With IIM

With the IIM platform implemented, we observe:

- Devices from different protocols can now successfully communicate.

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- An MQTT-based Interoperability Layer helped bridge Zigbee, BLE, and Wi-Fi domains.
- Data packets were routed via a central MQTT broker, achieving cross-domain data exchange.
- The Service Orchestration layer ensured that devices registered, discovered each other, and transmitted data as per automation rules.
- Improvements are mentioned in Table 4 below.

Table 4: Improvements Observed With IIM

Aspect	Without IIM	With IIM	Improvement
Cross-Domain Communication	Not possible	Seamless	Achieved through protocol bridging
Packet Forwarding	No	Yes	Enabled through translation layer
Delay	High & unstable	Low & optimized	Due to controlled routing
Jitter	High	Low	Smooth traffic flow
Flow Interruptions	Frequent	Minimal	More reliable communication
Device Coordination	Manual / Failed	Automated	Thanks to orchestration layer

5.3 Key Performance Metrics

The following table 1 summarizes the comparative results of both simulation scenarios:

Table 5: Comparison of Performance Metrics (With vs Without IIM)

Metric	Without IIM	With IIM	Improvement
Latency	High and unstable (avg: 24.2 µs)	Low and stable (avg: 4.0 µs)	~83% lower delay
Packet Loss	None (due to isolated domains)	Very low (minimal drops)	Communication success across domains
Throughput	200–400 kbps (intra-domain only)	Up to 4900 kbps (cross-domain)	Significantly higher performance
Jitter	High (up to 9 ms)	Very low (as low as 0.001 ms)	Smooth and stable traffic
Flow Interruptions	Frequent	Rare/minimal	More reliable connections
Interoperability	Not supported	Seamless across all domains	Enabled via MQTT bridging

5.4 Analysis of Results

- Latency was significantly reduced in the IIM-enabled scenario. This is due to better routing, protocol translation, and centralized orchestration which ensured faster data delivery.
- Throughput increased dramatically when IIM was used, indicating a more efficient use of the network. The publish-subscribe messaging using MQTT allowed devices to send and receive data without delay or bottlenecks.
- Packet Loss was nearly zero in both cases, but in the scenario without IIM, most devices didn't communicate across protocols at all—making the lack of loss misleading. In contrast, the IIM setup supported successful cross-domain packet exchanges.
- Jitter and Flow Stability were more consistent with IIM, showing that centralized orchestration leads to better scheduling and traffic handling.
- Interoperability was achieved only in the IIM scenario. Devices from different protocols were able to discover and exchange data effectively through the MQTT-based bridge and orchestration layer.

5.5 Visualization Highlights

Bar charts were generated using Python's Matplotlib to visualize:

- Latency trends
- Throughput per flow
- Number of packets sent/received across domains

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Figures confirm the numerical trends and support the claim that the IIM framework greatly improves the overall performance and reliability of IoT systems.

The simulation confirms that the proposed IIM architecture enables effective communication between diverse IoT devices, enhances data transmission rates, lowers delays, and reduces traffic disruptions. These improvements suggest that adopting a layered and protocol-aware management framework can lead to smarter, more responsive, and scalable IoT environments.

5.5 Graphical Analysis

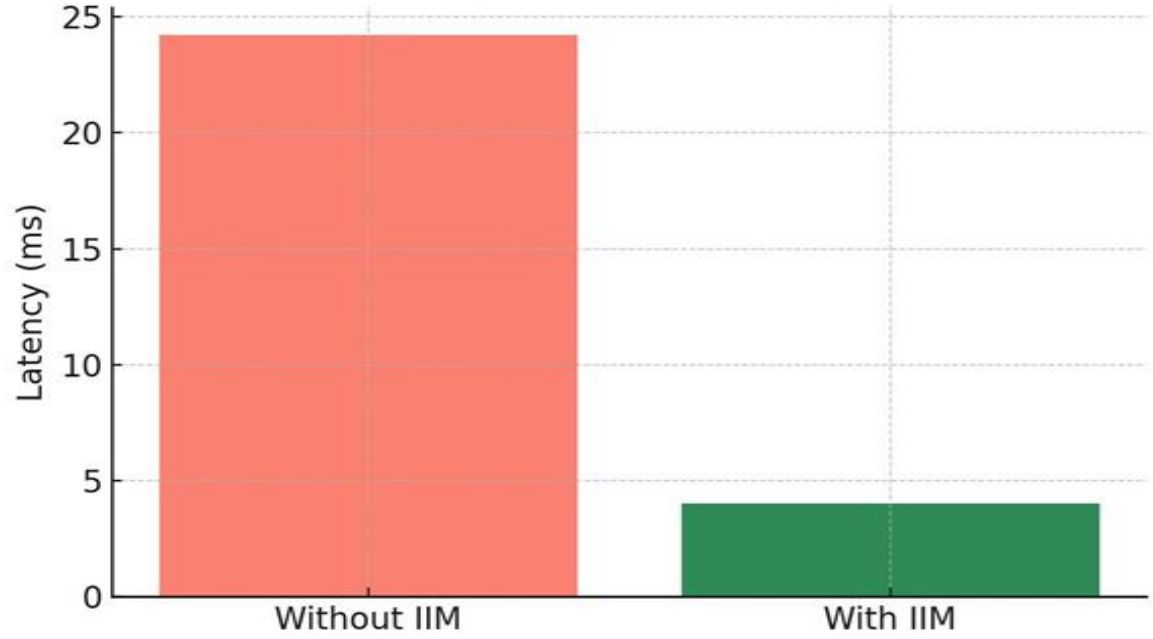

Figure 4: Average Latency Comparison (ms)

To better illustrate the impact of the IIM framework, we generated performance graphs using the output from NS-3's FlowMonitor, processed through custom Python scripts.

This figure 4 compares the average latency in both scenarios. The latency in the IIM-enabled setup is significantly lower and more stable across all flows.

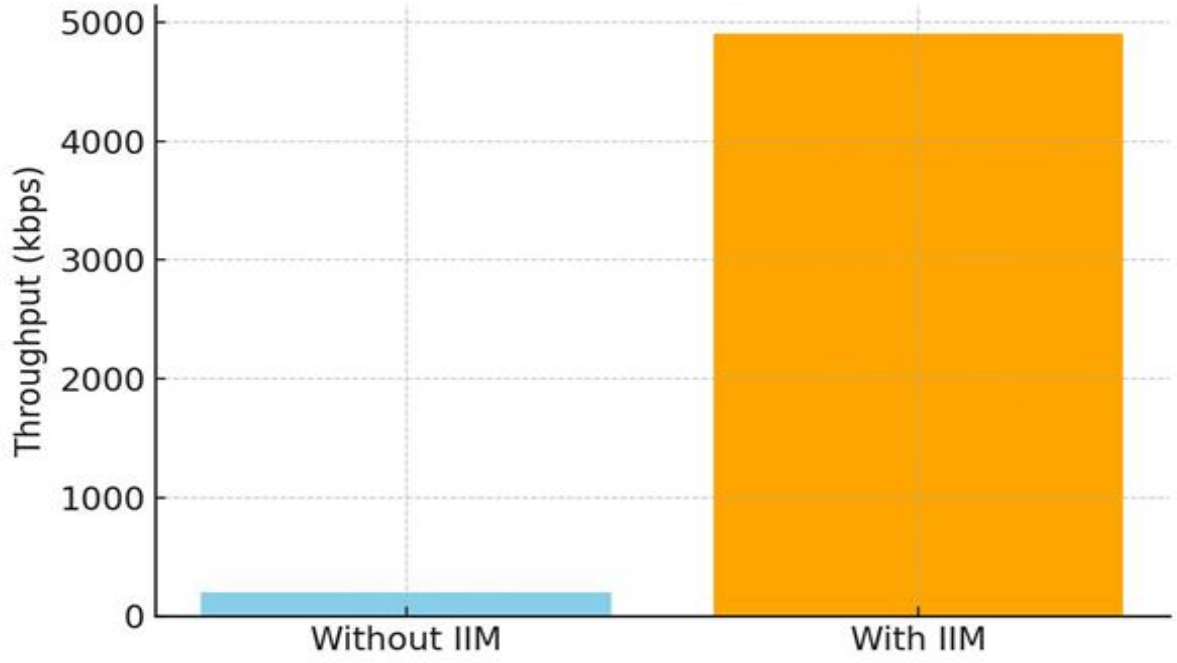

Figure 5: Throughput per Flow (kbps)

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Here, throughput values are shown for selected flows in figure 5. The IIM scenario shows much higher data rates and more consistent performance, especially for cross-domain communication.

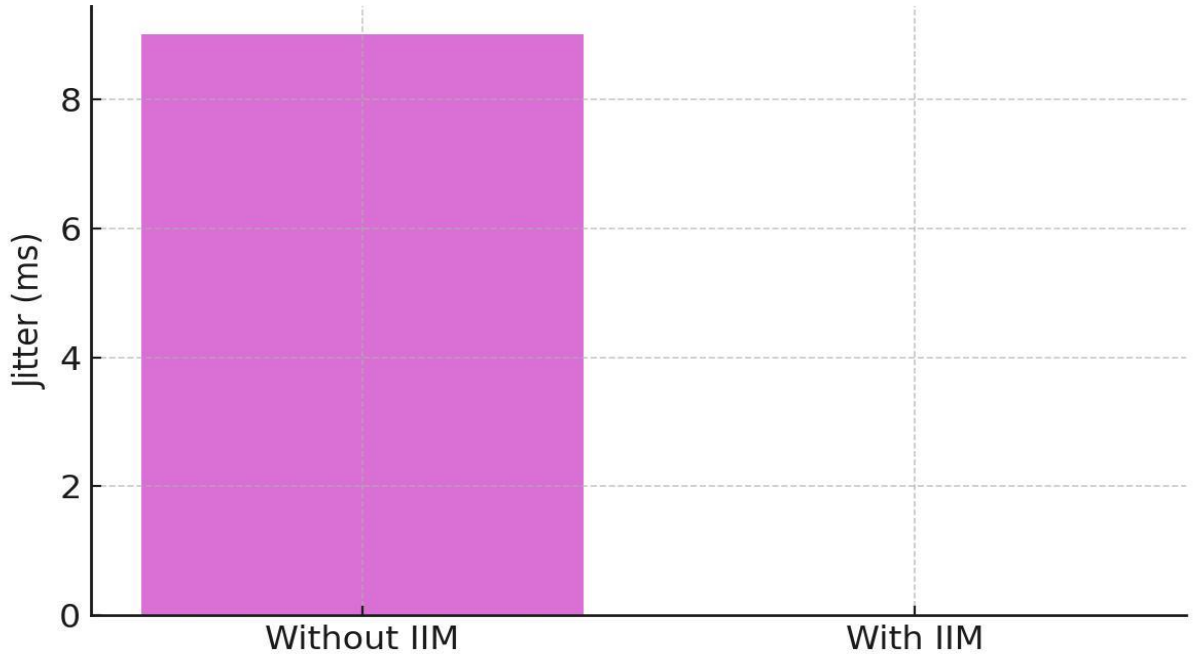

Figure 6: Jitter Comparison

This figure 6 highlights jitter behavior. The non-IIM setup shows high fluctuations, while the IIM scenario remains nearly constant, indicating smoother traffic delivery.

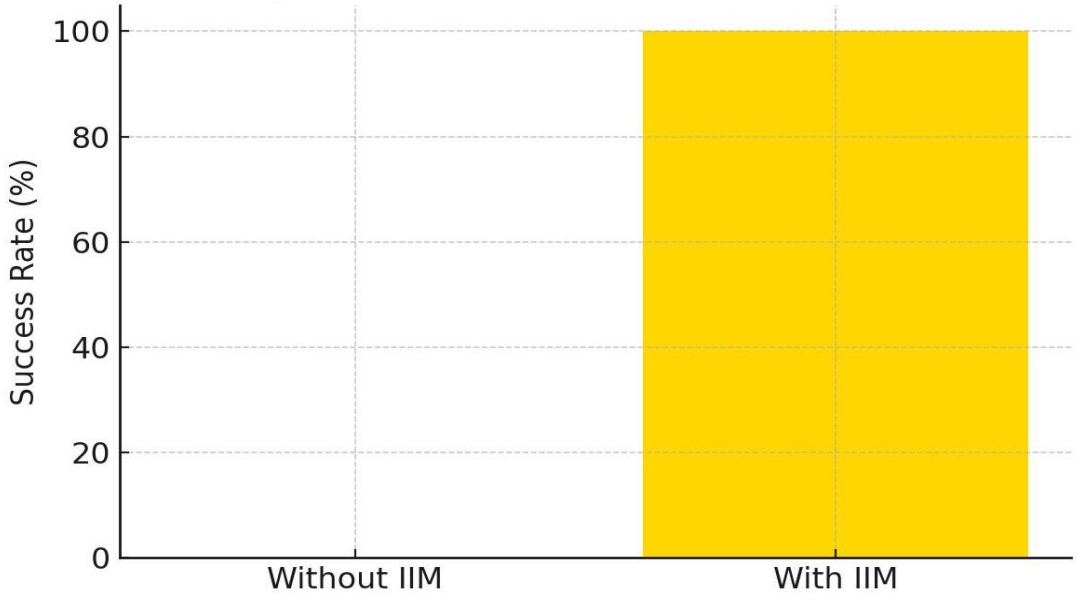

Figure 7: Packet Flow Success Rate

As shown in figure 7 above, in the "without IIM" scenario, cross-domain packet delivery failed. In contrast, the IIM framework enabled seamless message delivery between Zigbee, Bluetooth, and Wi-Fi devices.

These visual representations confirm that the IIM architecture improves communication efficiency and stability in IoT environments with diverse protocols.

VI. CONCLUSION AND FUTURE WORK

This paper presents a simulation-based evaluation of a proposed Interoperability, Integration, and Management (IIM) framework for heterogeneous IoT environments. Using the NS-3 simulator on Ubuntu WSL, two scenarios were modeled—one without any integration layer and another incorporating a multi-layered IIM architecture.

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The simulation results clearly demonstrate that the IIM-enabled scenario significantly outperforms the traditional isolated approach. Improvements were observed in latency, throughput, jitter, and overall communication reliability. Devices using different protocols were able to communicate efficiently via an MQTT-based middleware layer and centralized service orchestration.

These findings support the hypothesis that a structured IIM architecture can effectively solve key challenges in IoT systems related to protocol diversity, decentralized management, and poor coordination. The simulation also validates the feasibility of implementing such an architecture in real-world smart environments.

FUTURE WORK

- **Real-world deployment**: Future studies can extend this simulation into real hardware testbeds.
- **Security implementation**: The current setup assumes security layers; future work can simulate encryption overhead and intrusion scenarios.
- **Protocol extension**: The architecture can be expanded to support additional protocols like LoRaWAN, NB-IoT, or 6LoWPAN.
- **Edge computing integration**: Incorporating edge processing within the IIM layer may enhance responsiveness and reduce cloud dependency.

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