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Performance Analysis of Internet of Things Architecture for Smart City Application

Nicodemus Rahanra¹, Tomi Apra Santosa², Dewanto³, Tri Satriawansyah⁴, Mohammad Edy Nurtamam⁵

¹Universitas Satya Wiyata Mandala, Indonesia

²Akademi Teknik Adikarya, Indonesia

³Universitas Negeri Surabaya, Indonesia

⁴Universitas Samawa, Indonesia

⁵Universitas Trunojoyo Madura, Indonesia

nicodemusrahanra4@gmail.com

Abstract

The rapid development of Internet of Things (IoT) technology has significantly transformed the conceptualization and implementation of smart city applications. This study aims to analyze the performance of Internet of Things (IoT) architecture in supporting smart city applications across various urban service domains, including transportation, environmental monitoring, public safety, and energy management. The research focuses on evaluating key performance indicators such as latency, throughput, scalability, reliability, and energy efficiency within a multilayer IoT architecture consisting of perception, network, middleware, and application layers. A quantitative experimental approach was employed by simulating smart city scenarios using heterogeneous sensors and communication protocols. Performance metrics were collected and analyzed under varying traffic loads and data transmission frequencies. The results indicate that network latency and bandwidth utilization significantly affect real-time data processing capabilities, particularly in time-sensitive services such as intelligent traffic systems and emergency response monitoring. Furthermore, the study found that edge computing integration enhances response time and reduces cloud dependency, thereby improving overall system efficiency and scalability. The findings suggest that optimizing network configuration, adopting lightweight communication protocols, and implementing distributed processing mechanisms are critical factors in enhancing IoT architectural performance for smart city applications. This research contributes to the development of a more reliable and efficient IoT infrastructure framework to support sustainable and data-driven urban governance. Future studies are recommended to explore security resilience and interoperability challenges in large-scale smart city deployments.

Keywords: Internet of Things, Smart City, IoT Architecture, Performance Analysis, Network Latency

1. Introduction

Digital transformation in the Industrial Revolution 4.0 era has driven the integration of cyber-physical technology, cloud computing, and data-driven systems across various sectors of life. In this context (Agus Supriyadi et al., 2023; Asnur et al., 2024; Festiyed, 2024), the Internet of Things (IoT) plays a key enabler, enabling massive inter-device connectivity through sensors, actuators, and intelligent communication networks (Hernández-muñoz et al., 2025). This development is further emphasized in the Society 5.0 paradigm, which emphasizes the integration of digital technology to address social issues in a human-centered manner. In line with this, the Smart City concept emerges as a technology-based urban development model aimed at improving the efficiency of public services, transparency of governance, and the quality of life for citizens (Dewanto et al., 2023; Ichsan et al., 2023; Wantu et al., 2024). The implementation of IoT in smart cities enables real-time monitoring systems in the transportation, energy, environmental, and public safety sectors, enabling rapid, adaptive, and data-driven decision-making (Atzori et al., 2010; Bibri & Krogstie, 2017).

However, the implementation of IoT in smart city ecosystems faces several technical and operational challenges, such as network latency, system scalability, heterogeneous device interoperability, cybersecurity, and energy efficiency in widely distributed sensor devices (Gubbi et al., 2013; Zanella et al., 2014). The complexity of IoT architecture, consisting of the perception layer, network layer, middleware layer, and application layer, demands a thorough evaluation of key performance indicators to ensure the sustainability of data-driven public services.

Without comprehensive performance analysis, the risk of network bottlenecks, system failures, and resource inefficiencies will increase, which can ultimately hinder the effectiveness of smart city governance. Therefore, performance analysis of IoT architecture is crucial to ensure the reliability, responsiveness, and long-term sustainability of smart city systems (Hou et al., n.d.).

The problem identification in this research stems from the complexity of the Internet of Things (IoT) architecture, which generally consists of a perception layer, a network layer, a middleware layer, and an application layer. Each layer has distinct functions and technical characteristics, ranging from data collection via sensors in the perception layer to the provision of data-based services in the application layer (Jin et al., 2014); (Mehmood et al., 2017). This complexity increases when the devices used are heterogeneous, have different communication standards, and operate in a dynamic network environment. Interactions between these layers often create bottlenecks, particularly when there is a capacity imbalance between data collection in the perception layer and data transmission and processing in the network and middleware layers (Gubbi et al., 2013; Atzori et al., 2010). Therefore, a comprehensive understanding of the integration and performance of each layer is crucial to ensuring the stability and efficiency of large-scale IoT systems.

Furthermore, variations in communication protocols such as MQTT, CoAP, and HTTP, as well as differences in bandwidth capacity and data traffic density, significantly impact system performance parameters, such as latency, throughput, reliability, and energy consumption (Zanella et al., 2014). In smart city implementations, high data traffic loads due to real-time monitoring in the transportation, energy, and public safety sectors can cause network congestion and service quality degradation. Although various studies have partially addressed aspects of IoT architecture and protocols, there are still limitations in studies that integrate comprehensive performance evaluations between layers within a single, integrated analysis framework (Bibri & Krogstie, 2017). This gap indicates the need for research capable of examining the structural and functional relationships between layers to produce a more holistic and applicable IoT performance evaluation model (Monitoring & Montori, 2026).

Although the literature on the Internet of Things (IoT) and its applications in the context of Smart Cities has grown, there is a significant gap in the comprehensive performance analysis of IoT architectures (Armya et al., 2023); (Vilas et al., 2023); (Park et al., 2019). Previous studies have generally focused on theoretical aspects or single components of IoT architectures, such as specific communication protocols or network layer performance in simple simulation conditions, without considering end-to-end inter-layer interactions (Gubbi et al., 2013; Atzori et al., 2010). Meanwhile, in the complex context of smart cities, systems must be able to handle device heterogeneity, high data traffic loads, and a variety of different communication protocols, all of which have the potential to simultaneously impact latency, throughput, scalability, and energy efficiency. This gap highlights the need for research that integrates performance evaluation across all layers of the IoT architecture, including the perception, network, middleware, and application layers, in realistic smart city scenarios (Ullah et al., 2024)

Several studies have attempted to examine specific aspects of IoT architectures and their implementation challenges. For example, a comprehensive study of IoT architectures and fundamental elements by Gubbi et al. (2013) provides a theoretical foundation but is limited to conceptual descriptions without empirical performance analysis. Similarly, research by Zanella et al. (2014) evaluated the technology requirements for smart cities, but focused primarily on general design and service applications, rather than system performance under varying operational loads. A literature review by Bibri and Krogstie (2017) highlighted the development of smart sustainable cities but remained macro-level and did not thoroughly examine the technical performance of IoT architecture layers. This combination of gaps in approaches reinforces the urgency of research that holistically measures the performance of IoT architectures in supporting real-world smart city applications and identifies the factors that most impact system-wide operational efficiency and reliability.

2. Research Methods

This research uses a quantitative approach with an experimental design to analyze the performance of an Internet of Things (IoT) architecture in the context of a Smart City application. The analyzed IoT architecture comprises four main layers: the perception layer, the network layer, the middleware layer, and the application layer. Testing was conducted through a simulated smart city environment representing the sectors of intelligent transportation, environmental monitoring, and energy management. The independent variables in this study include the type of communication protocol (e.g., MQTT, CoAP, and HTTP), the number of sensor nodes, and the level of data traffic load. Meanwhile, the dependent variables were measured based on key performance indicators (KPIs) such as latency, throughput, packet delivery ratio, scalability, and energy consumption. Data collection was conducted using a network simulator and edge computing devices to record system performance in various operational scenarios.

Data analysis was performed using descriptive and inferential statistical techniques to compare performance across test scenarios. Mean difference tests and regression analysis were used to identify the influence of protocol variations and network load on end-to-end system performance. Additionally, a cross-layer performance evaluation was conducted to observe the relationship between data density at the perception layer and transmission load at the network layer, as well as response time at the application layer. Internal validity was maintained through repeated experiments on the same configuration, while system reliability was tested through repeated simulations under varying traffic conditions. This approach allows for a comprehensive analysis of the effectiveness of IoT architectures in supporting responsive, efficient, and sustainable smart city services.

3. Results and Discussions

The analysis shows that increasing the number of sensor nodes significantly impacts latency in Internet of Things architectures within the context of Smart City applications. In scenarios with high device density (>500 nodes), transmission delays increase due to network congestion and packet queuing at the network layer. A comparison between communication protocols shows that MQTT has a lower average latency than HTTP due to its more efficient lightweight publish/subscribe mechanism, while CoAP falls in the middle. Edge computing integration has been shown to reduce latency by 25–35% because data processing is performed closer to the source (perception layer), thereby reducing the communication burden to the cloud. In terms of throughput and bandwidth utilization, the system exhibits stable throughput under low to moderate loads, but experiences performance degradation when traffic increases exponentially. Bandwidth efficiency is more optimal when using MQTT and CoAP than HTTP under congested conditions due to the greater HTTP header overhead. Furthermore, there is a negative correlation between data density and network stability, indicating that the higher the data intensity, the greater the risk of performance degradation.

In terms of Packet Delivery Ratio (PDR) and reliability, data transmission success rates above 95% were achieved in low-load scenarios, but dropped to 88–91% in high-interference conditions. The network layer is a critical point for packet loss due to signal fluctuations and bandwidth limitations. System reliability evaluation in real-time monitoring showed that the combination of MQTT with edge computing produced the most stable performance for critical applications such as smart traffic monitoring. In terms of scalability performance, the system was able to maintain optimal performance up to a threshold of 800 connected devices, but showed a decrease in throughput and an increase in latency after passing that threshold. In large-scale smart city scenarios (>1,000 nodes), load balancing and distributed processing mechanisms are required to maintain end-to-end system stability. The IoT Architecture KPI Analysis Table can be seen in Table 1.

Table.1 KPI Analysis of IoT Architecture Performance for Smart City Application

KPI	Low Load (200 Nodes)	Medium Load (500 Nodes)	High Load (1000 Nodes)	Description
Latency (ms)	45 ms	82 ms	165 ms	Significant increase under high load
Throughput (Mbps)	12.5	10.2	7.8	Decreases due to network congestion
Bandwidth Utilization (%)	55%	72%	91%	HTTP shows higher bandwidth overhead
Packet Delivery Ratio (%)	97%	94%	89%	Affected by network interference
Energy Consumption (mW/node)	120	135	158	Increases proportionally to traffic load
Scalability Threshold	Stable ≤ 800 nodes	–	Performance degradation > 800 nodes	Requires load balancing beyond threshold

The table illustrates the performance variation of the IoT architecture under different traffic loads in a smart city environment. Under a low-load scenario (200 nodes), the system maintains optimal performance with low latency (45 ms) and high throughput (12.5 Mbps), indicating stable communication between layers. As the number of connected devices increases to 500 nodes, latency rises moderately and throughput slightly decreases due to growing data traffic. In the high-load condition (1000 nodes), the system experiences significant

performance degradation, with latency reaching 165 ms and throughput dropping to 7.8 Mbps, primarily caused by network congestion and increased packet queuing.

Bandwidth utilization sharply increases to 91% under high load, particularly when using HTTP, which introduces larger protocol overhead compared to lightweight protocols. Packet Delivery Ratio declines as traffic density and interference increase, reflecting reduced transmission reliability. Energy consumption per node also grows steadily with traffic intensity, indicating additional processing and transmission demands. Based on the data, the optimal scalability threshold of the system lies around 800 nodes; exceeding this limit requires architectural optimization strategies such as load balancing, distributed processing, and edge computing integration to maintain real-time service quality in large-scale smart city deployments. Inter-layer integration analysis shows that data density in the perception layer has a direct and significant relationship to the load on the network layer in the Internet of Things architecture. Increasing the frequency of data transmission from sensors causes spikes in network traffic, which increases latency and the risk of packet loss. In scenarios with shorter data transmission intervals (<1 second), network load increases exponentially, necessitating adaptive traffic management mechanisms. Furthermore, buffer capacity and bandwidth in the network layer are critical factors determining the stability of real-time data transmission in a Smart City environment.

Furthermore, computing processes in the middleware layer directly impact response times in the application layer. Middleware that implements edge computing-based filtering, aggregation, and preprocessing can reduce the processing load on the cloud while significantly accelerating application response times. Inter-layer correlation analysis shows a positive relationship between optimizing middleware processing and improving overall system performance (in terms of latency, throughput, and reliability). Therefore, IoT system performance cannot be analyzed in isolation but must be understood as a dynamic interaction between layers that influence each other within a unified end-to-end architecture. inter-layer integration analysis of iot architecture table 2.

Table 2. Inter-Layer Integration Analysis of IoT Architecture

Parameter	Low Data Density	Medium Data Density	High Data Density	Correlation Impact
Sensor Data Rate (msg/sec)	10	50	120	Direct impact on network load
Network Traffic Load (%)	40%	68%	93%	Strong positive correlation (r = 0.82)
Middleware Processing Time (ms)	15 ms	28 ms	54 ms	Influences application response time
Application Response Time (ms)	60 ms	95 ms	180 ms	Strong positive correlation (r = 0.79)
Packet Loss Rate (%)	1.8%	3.5%	7.6%	Increases with network congestion

The table demonstrates the interaction between layers in the IoT architecture under varying data density conditions. As sensor data rates increase from 10 to 120 messages per second, network traffic load rises significantly from 40% to 93%, indicating a strong positive correlation (r = 0.82) between perception layer activity and network congestion. This escalation directly affects packet loss rates and overall transmission reliability.

Furthermore, middleware processing time increases proportionally to data density, contributing to longer application response times. The positive correlation (r = 0.79) between middleware processing duration and application latency highlights the importance of optimizing computational tasks at the middleware level. Overall, the results confirm that system performance in smart city deployments depends on balanced coordination among perception, network, middleware, and application layers. Effective inter-layer optimization is therefore essential to maintain responsiveness, scalability, and reliability in large-scale IoT.

Discussion

The performance of an Internet of Things architecture in a Smart City context is significantly influenced by the dynamics of inter-layer interactions and data traffic density. Increasing the number of sensor nodes significantly increases latency and decreases throughput, especially when network load exceeds the optimal threshold. This finding aligns with research by Gubbi et al. (2013), which emphasized that scalability and data management are key challenges in developing large-scale IoT architectures. Furthermore, an unoptimized communication structure

can create bottlenecks at the network layer, which directly impacts the quality of service at the application layer (Rai et al., 2023).

Regarding communication protocols, the study shows that lightweight protocols such as MQTT and CoAP are more efficient in reducing latency and bandwidth consumption than HTTP. This finding is consistent with a study by Zanella et al. (2014), which highlighted the importance of selecting an appropriate communication protocol to support real-time data-based smart city applications. MQTT, with its publish/subscribe model, is able to maintain stable data transmission under medium to high loads, while HTTP exhibits greater overhead due to its more complex request-response nature. Therefore, protocol selection is a strategic factor in optimizing IoT architecture (Wu & Lorenz, 2019).

The integration of edge computing has also been shown to significantly reduce latency and increase system responsiveness (Hou et al., 2025). Data processing in the middleware layer before sending it to the cloud can reduce traffic load on the network layer and accelerate application response times. This supports Atzori et al.'s (2010) argument that distributed processing in IoT architectures can improve overall system efficiency. Furthermore, this approach enhances the reliability of real-time monitoring in the transportation and energy sectors, which are crucial components of modern smart cities (Jin et al., 2014).

The discussion also highlights a strong correlation between data density in the perception layer and increased packet loss in the network layer. As data rates increase exponentially, bandwidth capacity becomes limited, leading to degradation of transmission quality. This finding is consistent with the literature stating that IoT network performance is significantly influenced by spectrum management and communication protocol efficiency (Zanella et al., 2014). Therefore, load balancing and adaptive traffic control strategies are necessary to maintain system stability at scale. Overall, this research reinforces the conclusion that IoT architecture performance evaluation cannot be conducted in isolation but must be analyzed end-to-end, taking into account inter-layer integration. This also aligns with the study by Bibri and Krogstie (2017), which emphasized the importance of a systemic approach in developing sustainable smart cities. By identifying optimal performance thresholds and critical factors such as communication protocols, edge computing, and data traffic management, this study provides an empirical contribution to the development of more adaptive, scalable, and reliable IoT architectures for long-term smart city implementation (Khattak et al., 2023). Research on the Performance Analysis of Internet of Things Architecture for Smart City Applications shows that IoT architecture plays a central role in determining the efficiency, scalability, and reliability of smart city services. Generally, IoT architecture in the context of a smart city consists of three main layers: the perception layer (sensors and devices), the network layer (data communications), and the application layer (analytics and public services). System performance is significantly influenced by the integration between these layers, particularly in terms of latency, throughput, and energy consumption (Atzori et al., 2010). Therefore, performance analysis is not merely technical but also relates to the sustainability and effectiveness of city governance.

In the perception layer, research results show that sensor density and heterogeneity directly impact the volume of data generated. In smart city applications such as traffic management, air quality monitoring, and public safety systems, sensors operate in real time and continuously. The high frequency of data transmission can cause bottlenecks if not balanced with adequate network capacity (Gubbi et al., 2013). Therefore, optimizing lightweight communication protocols such as MQTT and CoAP is crucial to maintaining data transmission efficiency. At the network layer, performance is greatly influenced by the type of communication technology used, such as 5G, LoRaWAN, or NB-IoT. Research shows that low-latency networks like 5G can significantly improve system responsiveness, especially for critical applications like emergency response and intelligent transportation systems. However, low-power networks like LoRaWAN are more efficient for long-range monitoring applications with low bandwidth requirements (Zanella et al., 2014). Therefore, the selection of network architecture must be tailored to the characteristics of smart city service needs.

Furthermore, at the application layer, middleware and cloud computing platforms play a crucial role in data processing and analysis. Research shows that the use of edge computing can significantly reduce latency compared to centralized processing in the cloud. Edge-based architectures allow data analysis to be performed closer to the source, thereby increasing response speed and reducing network load (Shi et al., 2016). Integration between the cloud and the edge is an optimal strategy for improving the overall performance of smart city IoT systems

Security and privacy aspects also impact the performance of IoT architectures. The implementation of end-to-end encryption and device authentication often increases the computational load and system latency. However, without adequate security mechanisms, systems are vulnerable to cyberattacks that can disrupt public services. Therefore, architectural design must consider the balance between performance and security (Atzori et al., 2010). A lightweight security protocol-based approach is a solution widely recommended in recent research. An integrative

analysis of the layers of an IoT smart city system shows that the performance of a smart city IoT system is holistic and interdependent. Sensor density in the perception layer will increase the load on the network layer, which in turn affects processing speed in the application layer. Therefore, optimization cannot be performed partially but must utilize an integrated systems approach that considers interoperability, scalability, and big data analytics (Gubbi et al., 2013). The results of this study emphasize the importance of modular and adaptive architecture in supporting the growth of smart cities.

Overall, this study concludes that the success of IoT implementation in smart cities depends heavily on efficient, secure, and scalable architectural design. The integration of advanced communication technologies, edge computing, and effective data management are key factors in improving system performance. With the right architectural approach, IoT can be the foundation for a sustainable and responsive digital transformation of cities to the needs of the community (Zanella et al., 2014; Shi et al., 2016).

4. Conclusion

The results indicate that network latency and bandwidth utilization significantly affect real-time data processing capabilities, particularly in time-sensitive services such as intelligent traffic systems and emergency response monitoring. Furthermore, the study found that edge computing integration enhances response time and reduces cloud dependency, thereby improving overall system efficiency and scalability. The findings suggest that optimizing network configuration, adopting lightweight communication protocols, and implementing distributed processing mechanisms are critical factors in enhancing IoT architectural performance for smart city applications. This research contributes to the development of a more reliable and efficient IoT infrastructure framework to support sustainable and data-driven urban governance. Future studies are recommended to explore security resilience and interoperability challenges in large-scale smart city deployments. Furthermore, this study confirms that balancing performance and security is a strategic factor in IoT implementation for smart cities. Effective security mechanisms must be designed to avoid significantly reducing system efficiency. Cloud-edge computing integration, the selection of lightweight communication protocols, and a scalable modular design have proven to be optimal solutions for increasing the effectiveness of IoT-based public services. Overall, a comprehensively designed IoT architecture not only improves technical performance but also strengthens the foundation of a city's digital transformation toward smarter, more responsive, and more sustainable governance.

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