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A Hierarchical Fog Computing Framework for Low-Latency Data Processing in Smart City IoT Systems

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Abstract

The rapid proliferation of Internet of Things (IoT) technologies has accelerated the evolution of smart cities by enabling intelligent services across transportation, healthcare, environmental monitoring, public safety, and energy management. However, the massive volume and heterogeneous nature of IoT-generated data impose significant challenges on conventional cloud-centric architectures, particularly in terms of communication latency, bandwidth consumption, scalability, and real-time responsiveness. These limitations reduce the effectiveness of latency-sensitive applications that require immediate data processing and decision-making. To address these challenges, this study proposes a hierarchical fog computing framework for low-latency data processing in smart city IoT systems. The proposed framework adopts a three-layer architecture comprising the IoT layer, the fog layer, and the cloud layer. IoT devices continuously collect real-time data, fog nodes perform localized processing, filtering, and time-critical decision-making, while cloud servers execute large-scale analytics, long-term storage, and computationally intensive tasks. This hierarchical distribution of computational workloads enables data to be processed closer to its source, thereby reducing unnecessary communication with centralized cloud infrastructures. The proposed framework is conceptually evaluated based on key performance criteria, including end-to-end latency, bandwidth utilization, scalability, resource utilization, and service reliability. The analysis indicates that hierarchical fog computing can substantially improve the responsiveness of smart city services by minimizing communication delays, reducing network congestion, and enabling efficient collaboration between distributed fog nodes and centralized cloud resources. The findings demonstrate that hierarchical fog computing provides a scalable and efficient foundation for next-generation smart city infrastructures while complementing conventional cloud computing. Future research should focus on experimental validation, intelligent resource management, cybersecurity, and the integration of artificial intelligence with emerging communication technologies, including 5G and beyond.

Keywords: Fog computing, Internet of things, Smart cities, low latency data processing, Hierarchical fog architecture.

1| Introduction

The rapid advancement of digital technologies has fundamentally transformed conventional urban environments into intelligent and interconnected smart cities. The convergence of the Internet of Things, cloud computing, artificial intelligence, and advanced communication technologies has enabled the deployment of a wide range of smart urban services, including intelligent transportation systems, smart

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healthcare, environmental monitoring, public safety, and energy management. These services are designed to improve urban sustainability, optimize resource utilization, and enhance citizens' quality of life through continuous sensing, data-driven decision-making, and intelligent service automation [1-3].

The large-scale deployment of IoT devices has become a fundamental component of modern smart city infrastructures. Millions of heterogeneous devices, including environmental sensors, surveillance cameras, wearable devices, connected vehicles, and smart meters, continuously generate massive volumes of data characterized by high velocity, variety, and temporal dynamics. Efficient processing of these data streams is essential for supporting latency-sensitive applications that require immediate responses, such as intelligent traffic control, emergency management, industrial automation, and remote healthcare monitoring. Consequently, smart city infrastructures require distributed computing platforms capable of delivering scalable, reliable, and real-time data processing while maintaining efficient utilization of communication and computational resources [4-6].

Cloud computing has long been considered the primary computational platform for IoT applications due to its virtually unlimited processing capability, elastic resource provisioning, and centralized storage infrastructure. However, transmitting data from geographically distributed IoT devices to remote cloud data centers introduces considerable communication latency, increases bandwidth consumption, and may create network congestion and privacy concerns. These limitations significantly reduce the effectiveness of cloud-centric architectures for applications requiring real-time decision-making and ultra-low response times [7-9].

Fog computing has emerged as an effective distributed computing paradigm that extends cloud capabilities toward the network edge by deploying intermediate computational resources between IoT devices and centralized cloud infrastructures. Instead of transmitting all generated data to remote cloud servers, fog nodes perform localized data filtering, preprocessing, aggregation, temporary storage, and real-time analytics near data sources. This hierarchical processing model substantially reduces communication latency, decreases unnecessary network traffic, improves Quality of Service, and enhances system responsiveness. Moreover, fog computing provides a collaborative computing environment in which IoT devices, fog nodes, and cloud platforms cooperate to efficiently execute computational workloads according to application requirements [1], [2], [7].

During recent years, research on fog computing has evolved from conceptual architectures toward intelligent resource management, application placement, task scheduling, service orchestration, and AI-assisted optimization techniques. Existing studies have demonstrated that fog computing can significantly improve latency, bandwidth efficiency, and resource utilization in distributed IoT environments. Nevertheless, most available approaches focus on specific optimization problems or individual application scenarios, whereas relatively few studies investigate integrated hierarchical architectures capable of simultaneously coordinating IoT devices, fog nodes, and cloud infrastructures in large-scale smart city environments [8].

Despite the considerable progress achieved in recent years, several research challenges remain unresolved. Efficient workload distribution, adaptive resource allocation, interoperability among heterogeneous IoT devices, cybersecurity, and intelligent orchestration continue to limit the large-scale deployment of fog computing in smart cities. Furthermore, balancing computational workloads between fog and cloud layers while satisfying the stringent latency, scalability, and reliability requirements of next-generation urban applications remains an open research challenge [9], [10].

Motivated by these challenges, this study proposes a hierarchical fog computing framework for low-latency data processing in smart city IoT systems. The proposed framework consists of three collaborative computational layers: the IoT layer, responsible for real-time data acquisition; the fog layer, responsible for localized processing and latency-sensitive decision-making; and the cloud layer, responsible for large-scale analytics, historical data management, and computationally intensive processing. By intelligently distributing computational tasks across these layers, the proposed framework aims to reduce end-to-end latency, improve bandwidth utilization, enhance resource efficiency, and increase the scalability of smart city services.

The main contributions of this study are summarized as follows:

I. A hierarchical IoT–Fog–Cloud architecture is proposed to support scalable and low-latency data processing in heterogeneous smart city environments.

II. A distributed workload allocation strategy is introduced to execute latency-sensitive tasks at fog nodes while assigning computation-intensive operations to cloud infrastructures.

III. The proposed framework is analyzed according to key system performance indicators, including latency, bandwidth utilization, scalability, resource efficiency, and service reliability.

IV. Current research challenges and future research directions are discussed, focusing on artificial intelligence-assisted resource management, cybersecurity, interoperability, and the integration of fog computing with emerging communication technologies.

The remainder of this paper is organized as follows. Section 2 reviews recent advances in fog computing and smart city IoT systems. Section 3 presents the proposed hierarchical architecture and its operational workflow. Section 4 describes the research methodology adopted in this study. Section 5 discusses the analytical evaluation of the proposed framework. Section 6 highlights current challenges and future research opportunities, while Section 7 concludes the paper.

2 | Related Work

Fog computing has become one of the most promising distributed computing paradigms for addressing the limitations of cloud-centric architectures in Internet of Things environments. By extending computational and storage resources from centralized cloud data centers to the network edge, fog computing enables data processing closer to IoT devices, thereby reducing communication latency and improving the responsiveness of time-critical applications. The concept was initially introduced by Bonomi et al. [1], who demonstrated that deploying computational resources near data sources could significantly enhance the performance of latency-sensitive IoT services. Subsequently, Dastjerdi and Buyya [11] established fog computing as an intermediate computing layer between IoT devices and cloud infrastructures, highlighting its capability to support scalable and geographically distributed IoT applications.

As fog computing matured, research gradually shifted from conceptual architectures toward comprehensive architectural frameworks and system-level management. Mahmud et al. [5] presented a detailed taxonomy of fog application management by categorizing existing approaches according to resource management, service provisioning, scalability, and application deployment. Similarly, Singh et al. [3] reviewed the evolution of fog computing architectures and identified resource allocation, interoperability, and Quality of Service provisioning as the primary technical challenges for large-scale distributed environments. Mann [12] further analyzed architectural models for fog systems and emphasized that hierarchical deployment strategies improve flexibility and coordination among distributed computational resources.

Another major research direction focuses on resource management and workload orchestration within fog environments. As the number of IoT devices continues to increase, efficient allocation of computational resources has become essential for maintaining system performance. provided a comprehensive review of resource allocation and task scheduling techniques in fog and Internet of Everything (IoE) environments, demonstrating that intelligent scheduling strategies substantially reduce service latency and improve resource utilization. More recently, Alsadie [13] investigated the integration of artificial intelligence techniques into fog resource management, showing that machine learning algorithms can improve adaptive workload distribution under dynamic network conditions. Similarly, highlighted the growing importance of intelligent resource management and identified distributed orchestration as one of the major future research directions.

Despite the considerable progress achieved during the last decade, several research gaps remain. Most existing studies primarily investigate individual optimization problems, including task scheduling, application placement, energy efficiency, or security, without providing an integrated framework capable of coordinating IoT devices, fog nodes, and cloud infrastructures simultaneously. Furthermore, many proposed solutions are

evaluated within application-specific scenarios, limiting their applicability to heterogeneous smart city environments characterized by dynamic workloads, diverse communication technologies, and continuously evolving service requirements.

To address these limitations, this study proposes a hierarchical IoT-Fog-Cloud computing framework that emphasizes collaborative workload distribution across multiple computational layers. Unlike previous studies that mainly concentrate on isolated optimization strategies, the proposed framework provides an integrated architecture that combines localized fog processing with cloud-based large-scale analytics. This hierarchical design aims to reduce end-to-end latency, optimize bandwidth utilization, improve scalability, and support real-time decision-making for next-generation smart city IoT systems.

A comparative summary of recent studies on fog computing for smart city IoT applications is presented in Table 1, highlighting their major contributions and remaining research gaps

3 | Proposed Hierarchical Fog Computing Architecture

The continuous expansion of Internet of Things infrastructures in smart cities has significantly increased the demand for distributed computing platforms capable of processing heterogeneous data streams with low latency and high reliability. Modern smart city applications including intelligent transportation systems, public safety, environmental monitoring, healthcare, and smart energy management require rapid data analysis and real-time decision-making, which cannot always be efficiently supported by conventional cloud-centric architectures. The transmission of massive volumes of IoT-generated data to geographically distant cloud data centers introduces communication delays, increases bandwidth consumption, and may negatively affect the performance of latency-sensitive services.

Fog computing has emerged as an effective solution to these challenges by extending computational capabilities from centralized cloud infrastructures toward the network edge. Instead of relying exclusively on remote cloud servers, fog computing distributes computation across multiple intermediate nodes located closer to IoT devices. This distributed processing paradigm enables localized data analysis, minimizes unnecessary data transmission, and improves the responsiveness of time-critical applications while preserving the computational advantages of cloud platforms.

Based on these principles, this study proposes a hierarchical IoT-Fog-Cloud architecture designed to support efficient and low latency data processing in smart city environments. The proposed framework organizes computational resources into three collaborative layers, where each layer performs specific functions according to its computational capacity, latency requirements, and operational responsibilities. The hierarchical organization facilitates efficient workload distribution, reduces communication overhead, and enables scalable processing of heterogeneous IoT workloads.

3.1 | Architecture Components

The proposed framework consists of three interconnected computational layers: the IoT layer, the Fog layer, and the Cloud layer. Each layer contributes different computational capabilities while cooperating to provide an integrated processing environment for smart city applications.

The IoT layer represents the physical interface between the smart city environment and the computing infrastructure. It consists of heterogeneous sensing and actuating devices, including environmental sensors, surveillance cameras, connected vehicles, wearable healthcare devices, smart meters, and intelligent traffic controllers. These devices continuously collect environmental information and generate real-time data streams that serve as the primary input for urban applications.

Because IoT devices generally possess limited processing capability, storage capacity, and battery resources, they primarily perform sensing, data acquisition, and communication functions rather than computationally intensive analytics. Consequently, the collected data are transmitted to nearby fog nodes through available wired or wireless communication networks for further processing.

The fog layer constitutes the core computational component of the proposed architecture. It comprises geographically distributed fog nodes strategically deployed close to IoT devices in order to provide localized computing, temporary storage, and real-time analytics.

Rather than forwarding all raw sensor data directly to centralized cloud servers, fog nodes execute preliminary processing tasks, including data validation, filtering, aggregation, event detection, and context-aware analytics. Processing data near their generation sources reduces communication latency, decreases bandwidth utilization, and enables rapid responses for delay-sensitive smart city applications such as intelligent traffic management, emergency response systems, video surveillance, and environmental monitoring.

In addition to local processing, fog nodes coordinate communication among neighboring devices and cloud infrastructures, enabling adaptive workload distribution according to network conditions, computational requirements, and application priorities. This collaborative functionality improves resource utilization and enhances service reliability in dynamic IoT environments.

The cloud layer provides centralized computational resources responsible for executing computation-intensive operations that exceed the capabilities of fog nodes. These operations include large-scale data analytics, predictive modeling, machine learning model training, long-term data storage, and historical trend analysis.

Unlike traditional cloud-centric architectures, the proposed framework transmits only filtered and aggregated information from fog nodes to cloud servers. This hierarchical communication mechanism significantly reduces unnecessary network traffic while allowing cloud infrastructures to concentrate on complex analytical tasks requiring substantial computational resources.

Furthermore, analytical models developed within the cloud layer can be periodically deployed to fog nodes, enabling localized decision-making to benefit from continuously updated intelligence without requiring permanent cloud interaction.

The functional responsibilities of each computational layer are summarized in *Table 1*.

Table 1. Functional responsibilities of the proposed iot–fog–cloud architecture.

Layer	Primary Functions	Data Processing Role	Examples
IoT Layer	Data acquisition, sensing, monitoring	Raw data generation	Sensors, cameras, smart meters
Fog Layer	Filtering, aggregation, local analytics, temporary storage	Real-time processing	Fog gateways, edge servers
Cloud Layer	Big data analytics, AI model training, long-term storage	Computationally intensive processing	Cloud data centers

3.2|Hierarchical Task Allocation Strategy

Efficient task allocation is a key requirement for distributed fog computing systems because smart city applications exhibit diverse computational and latency requirements. The proposed framework adopts a hierarchical task allocation strategy in which computational tasks are assigned to different processing layers according to their execution characteristics rather than processed at a single centralized location.

A comparison between conventional cloud computing and fog computing with respect to key operational characteristics is provided in *Table 2*.

Latency-sensitive tasks including traffic incident detection, emergency notifications, anomaly detection, video surveillance analytics, and industrial control are executed within fog nodes to ensure rapid response and minimize communication delays. Conversely, computationally intensive tasks such as predictive analytics, deep learning model training, historical trend analysis, and large-scale optimization are delegated to cloud infrastructures, where extensive computational resources are available.

This hierarchical workload distribution reduces network congestion, improves resource utilization, and supports scalable execution of heterogeneous smart city services by balancing computational loads across distributed processing layers.

Table 2. Comparison of cloud computing and fog computing characteristics

Feature	Cloud Computing	Fog Computing
Processing location	Centralized data centers	Near IoT devices
Response latency	Higher	Lower
Bandwidth consumption	High	Reduced
Real-Time processing	Limited	Supported
Scalability	High	High through distributed nodes
Resource distribution	Centralized	Distributed
Suitable applications	Historical analytics	Real-time services

3.3 | Data Processing Workflow

The operational workflow of the proposed framework begins with continuous data acquisition from IoT devices deployed throughout the smart city environment. Generated data are transmitted through local communication networks to the nearest fog node, where initial processing operations are performed before any communication with cloud infrastructures.

At the fog layer, incoming data undergo validation, filtering, aggregation, and context-aware preprocessing. Events requiring immediate responses are processed locally, allowing fog nodes to generate rapid decisions without relying on geographically distant cloud servers. This localized processing mechanism is particularly beneficial for applications with stringent latency constraints and continuous data generation.

Data requiring long-term storage or computationally intensive analysis are subsequently forwarded to the cloud layer. Cloud infrastructures perform advanced analytics, predictive modeling, and large-scale data mining while maintaining historical repositories that support long-term planning and strategic decision-making. Analytical insights generated in the cloud can also be shared with fog nodes to improve localized intelligence and optimize future resource allocation.

Overall, the proposed hierarchical workflow establishes a collaborative processing environment in which IoT devices, fog nodes, and cloud platforms operate as complementary computational layers. By distributing processing responsibilities according to application requirements and computational capabilities, the framework is designed to reduce communication latency, improve bandwidth efficiency, enhance scalability, and support reliable data processing for next-generation smart city IoT systems.

4 | Research Methodology

This study adopts a conceptual and analytical research methodology to investigate the potential of fog computing for improving data processing efficiency in smart city Internet of Things environments. Rather than implementing a physical prototype or conducting simulation-based experiments, the research focuses on developing a hierarchical IoT-Fog-Cloud framework and analyzing its operational characteristics based on established principles of distributed computing and findings reported in the existing literature. The methodological approach integrates architectural design with qualitative performance analysis to examine how fog computing can address the limitations of conventional cloud-centric IoT systems.

The proposed research methodology consists of four sequential phases, as illustrated in the conceptual development process of the framework

4.1 | Problem Identification and Requirement Analysis

The first phase focuses on identifying the limitations of conventional cloud-based architectures in supporting latency-sensitive smart city applications. Previous studies have reported that transmitting large volumes of IoT-generated data to geographically distant cloud data centers increases communication latency, bandwidth consumption, network congestion, and processing delays. These challenges become particularly critical in

applications such as intelligent transportation systems, emergency response, healthcare monitoring, and urban surveillance, where timely decision-making is essential.

Based on these observations, the functional requirements of an efficient smart city computing platform were identified, including low-latency processing, scalable resource management, distributed computation, efficient bandwidth utilization, and support for heterogeneous IoT devices.

4.2|Framework Design

The second phase involves the development of the proposed hierarchical IoT-Fog-Cloud architecture. The framework is designed by organizing computational resources into three collaborative layers according to their processing capabilities and operational responsibilities.

The IoT layer is responsible for sensing, data acquisition, and communication with upper computational layers. The Fog layer performs localized computation, temporary storage, data filtering, aggregation, and real-time analytics close to data sources. Finally, the Cloud layer executes computation-intensive operations, including large-scale analytics, historical data management, predictive modeling, and long-term storage. This hierarchical organization follows the distributed computing principles widely discussed in recent fog computing research.

4.3|Hierarchical Data Processing Strategy

The third phase defines the operational workflow of the proposed framework. Data generated by IoT devices are initially transmitted to the nearest fog node through available communication networks. Instead of forwarding all collected data directly to cloud servers, fog nodes perform preliminary processing operations such as data validation, filtering, aggregation, feature extraction, and event detection.

Latency-sensitive events are processed locally within the fog layer, enabling rapid responses without requiring continuous interaction with remote cloud infrastructures. Data requiring computationally intensive analysis or long-term storage are subsequently transferred to cloud servers for advanced processing. This hierarchical processing strategy is intended to reduce unnecessary network traffic, improve bandwidth utilization, and support efficient workload distribution across distributed computational resources.

4.4|Conceptual Performance Evaluation

The final phase consists of a conceptual evaluation of the proposed framework based on performance indicators commonly adopted in fog computing research. Instead of relying on simulation or experimental measurements, the evaluation analyzes the expected impact of the proposed architecture on several key system characteristics reported in previous studies.

The evaluation considers five primary performance indicators:

I. Communication latency

II. Bandwidth utilization

III. Scalability

IV. Resource utilization

V. Service reliability

These indicators provide a systematic basis for assessing the potential effectiveness of the proposed hierarchical architecture in supporting smart city IoT applications. Furthermore, they facilitate qualitative comparisons with conventional cloud-centric architectures and identify research directions for future simulation-based validation and real-world implementation.

Overall, the adopted methodology provides a structured framework for investigating distributed fog computing architectures from an analytical perspective. By combining architectural design, hierarchical

workload distribution, and conceptual performance evaluation, the proposed methodology establishes a theoretical foundation for future research on intelligent, scalable, and low-latency computing infrastructures for next-generation smart cities.

5 | Framework Evaluation and Discussion

The proposed hierarchical IoT–Fog–Cloud framework is conceptually evaluated by examining its potential to address the major limitations of conventional cloud-centric computing architectures in smart city Internet of Things (IoT) environments. Rather than relying on centralized processing, the proposed architecture distributes computational tasks across IoT devices, fog nodes, and cloud infrastructures according to application requirements and latency constraints. This distributed computing model is expected to improve processing efficiency while supporting the scalability and responsiveness required by modern smart city services.

Table 3. Qualitative performance evaluation of the proposed framework.

Performance Indicator	Cloud-Centric Architecture	Proposed IoT-Fog-Cloud Framework
Communication latency	High	Expected to be lower
Bandwidth utilization	High network traffic	Reduced through local processing
Scalability	Limited by centralization	Distributed scalability
Resource utilization	Centralized	Hierarchical resource allocation
Service reliability	Cloud dependent	Improved local continuity

5.1 | Latency Reduction

Communication latency is one of the most critical performance indicators in latency-sensitive IoT applications. Conventional cloud-based architectures require data generated by distributed IoT devices to be transmitted to remote cloud data centers before processing, resulting in additional communication delays. In contrast, the proposed framework performs preliminary data processing and decision-making at nearby fog nodes, thereby minimizing the physical distance between data generation and computation. This hierarchical processing strategy is expected to support faster responses in applications such as intelligent transportation, emergency management, healthcare monitoring, and public safety systems.

5.2 | Bandwidth Utilization

Efficient utilization of network bandwidth is another important consideration for large-scale smart city deployments. Since only filtered, aggregated, and context-relevant information is transmitted from fog nodes to cloud servers, the proposed architecture reduces unnecessary communication between edge devices and centralized infrastructures. By limiting the transmission of redundant raw sensor data, the framework is expected to decrease network congestion while allowing cloud resources to concentrate on computation-intensive analytical tasks, including predictive modeling and long-term data analysis.

5.3 | Scalability and Resource Utilization

The continuous growth of IoT devices presents significant scalability challenges for centralized computing systems. The hierarchical organization of computational resources within the proposed architecture enables processing workloads to be distributed across multiple fog nodes instead of relying solely on cloud infrastructures. Such workload distribution has the potential to improve resource utilization and support the gradual expansion of smart city services without creating centralized processing bottlenecks. Furthermore, the separation of latency-sensitive and computation-intensive tasks allows each computational layer to operate according to its capabilities, thereby improving the overall efficiency of distributed resource management.

5.4 | Reliability and Service Continuity

Service reliability is particularly important for mission-critical smart city applications that require continuous operation. Within the proposed framework, fog nodes provide localized processing capabilities that reduce

dependence on permanent communication with remote cloud servers. Consequently, temporary communication interruptions or network failures are less likely to affect local service delivery. Although cloud infrastructures remain responsible for large-scale analytics and historical data management, localized processing at the fog layer contributes to improved operational resilience and supports continuous execution of delay-sensitive services.

5.5 | Discussion

The conceptual evaluation indicates that integrating fog computing into smart city infrastructures offers several architectural advantages over conventional cloud-centric approaches. By combining localized intelligence with centralized computational resources, the proposed framework establishes a collaborative processing environment capable of supporting heterogeneous IoT applications with diverse computational requirements. The hierarchical distribution of workloads enables computational resources to be utilized more efficiently while reducing communication overhead and improving service responsiveness.

Nevertheless, the present study is limited to a conceptual architectural analysis and does not include simulation-based or experimental validation. Therefore, the anticipated improvements in latency, bandwidth utilization, scalability, and resource efficiency are derived from established principles reported in previous fog computing research rather than empirical measurements. Future investigations should validate the proposed framework using simulation platforms such as iFogSim2 or EdgeCloudSim, together with real-world smart city datasets, to quantitatively evaluate its performance under different deployment scenarios.

Overall, the proposed hierarchical IoT-Fog-Cloud architecture provides a structured conceptual foundation for developing scalable and low-latency computing infrastructures for next generation smart cities. Its emphasis on distributed processing, localized analytics, and collaborative workload management aligns with current research trends in fog computing and offers a promising direction for future intelligent urban computing systems.

A qualitative comparison of the proposed framework with conventional cloud-centric architectures based on major performance indicators is presented in Table 4.

6 | Challenges and Future Research Directions

Despite the significant advantages offered by fog computing in smart city IoT environments, several technical and operational challenges continue to limit its large-scale deployment. One of the primary concerns is resource management across distributed fog nodes. Unlike centralized cloud infrastructures, fog environments consist of heterogeneous devices with varying computational capabilities, storage capacities, and energy resources. Efficient allocation of computational tasks while maintaining balanced workloads remains a complex challenge, particularly in highly dynamic urban environments.

Another important issue is interoperability among heterogeneous IoT devices and communication protocols. Smart city infrastructures integrate a wide range of sensors, intelligent devices, and communication technologies developed by different manufacturers. Ensuring seamless communication and standardized data exchange across these heterogeneous platforms requires the adoption of unified architectural frameworks and interoperable communication standards.

Security and privacy also represent critical challenges for fog computing. Since data processing is distributed across multiple fog nodes located near end users, the attack surface becomes significantly larger than in conventional cloud environments. Protecting sensitive information against unauthorized access, cyberattacks, and data manipulation requires robust authentication mechanisms, encryption techniques, secure communication protocols, and continuous monitoring of distributed computing resources.

Scalability remains another research challenge as smart cities continue to expand. The rapid increase in connected IoT devices generates continuously growing volumes of data, requiring adaptive resource management strategies capable of maintaining consistent system performance under fluctuating workloads.

Future fog computing architectures should incorporate intelligent workload scheduling and autonomous resource allocation mechanisms to improve computational efficiency while minimizing operational costs.

Emerging technologies are expected to further enhance the capabilities of fog computing. Artificial intelligence and machine learning can enable intelligent resource allocation, predictive maintenance, anomaly detection, and adaptive decision-making within distributed fog environments. Similarly, the integration of fifth-generation (5G) and sixth-generation (6G) communication networks is expected to provide ultra-low latency, higher bandwidth, and more reliable connectivity, enabling more efficient collaboration between IoT devices, fog nodes, and cloud infrastructures.

Future research should focus on developing intelligent, secure, and energy efficient fog computing frameworks capable of supporting large scale smart city ecosystems. Particular attention should be given to AI-driven resource management, cybersecurity, interoperability, sustainable energy consumption, and seamless integration with next generation communication technologies. Addressing these challenges will play a fundamental role in realizing resilient, scalable, and intelligent urban infrastructures.

7 | Conclusion

The rapid growth of Internet of Things technologies has fundamentally transformed the computational requirements of modern smart cities, creating an increasing demand for distributed computing architectures capable of supporting real-time data processing, low communication latency, and scalable service delivery. Although cloud computing continues to provide substantial computational power and storage capacity, its centralized architecture presents significant challenges for latency-sensitive applications due to communication delays, bandwidth limitations, and network congestion. These limitations highlight the need for complementary computing paradigms that can process data closer to where it is generated.

In this study, a hierarchical IoT-Fog-Cloud computing framework was proposed as a conceptual architecture for supporting efficient data processing in smart city environments. The framework organizes computational resources into three collaborative layers that distribute processing tasks according to latency requirements and computational complexity. By enabling localized processing at the fog layer while preserving the large-scale analytical capabilities of cloud infrastructures, the proposed architecture is designed to improve communication efficiency, reduce unnecessary data transmission, and support scalable processing of heterogeneous IoT workloads.

The conceptual analysis presented in this paper suggests that hierarchical fog computing provides an effective architectural foundation for next generation smart city systems. The proposed framework has the potential to improve bandwidth utilization, optimize distributed resource management, enhance service continuity, and support latency-sensitive applications such as intelligent transportation, environmental monitoring, public safety, healthcare systems, and smart energy management. Furthermore, the hierarchical collaboration among IoT devices, fog nodes, and cloud infrastructures offers greater flexibility for managing the continuously growing number of connected devices within large-scale urban environments.

Despite these promising characteristics, the present study is limited to the conceptual design and qualitative analysis of the proposed architecture. Consequently, quantitative performance evaluation through simulation platforms and real-world deployments remains an important direction for future research. Experimental validation using tools such as iFogSim2 or EdgeCloudSim, together with realistic smart city datasets, would enable comprehensive assessment of latency, bandwidth utilization, energy efficiency, scalability, and resource management under different operating conditions.

Future research should also investigate the integration of fog computing with emerging technologies, including artificial intelligence-driven resource orchestration, edge intelligence, digital twin platforms, software-defined networking , network function virtualization, and next-generation 5G/6G communication networks. The convergence of these technologies is expected to enable more autonomous, adaptive, secure,

and sustainable smart city infrastructures capable of meeting the increasing computational demands of future urban ecosystems.

Overall, the proposed hierarchical IoT–Fog–Cloud framework provides a comprehensive conceptual foundation for distributed data processing in smart city IoT systems. By emphasizing collaborative computation, localized intelligence, and scalable workload distribution, this study contributes to the ongoing development of efficient fog computing architectures and establishes a basis for future experimental research and practical deployment in next generation intelligent urban environments.

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Data Availability

No datasets were generated or analyzed during the current study. Therefore, data sharing is not applicable to this article.

Conflicts of Interest

The authors declare no conflict of interest. Funders, including KIIT University, played no role in the design of the study, the collection, analysis, or interpretation of the data, the writing of the manuscript, or the decision to publish the results. No personal circumstances or interests could be perceived as having an inappropriate influence on the presentation or interpretation of the research findings.

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