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Article

Enhancing IoNT performance with fog computing: A hybrid architecture for real-time data processing

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Abstract: The rapid evolution of the Internet of Nano Things (IoNT) and Fog Computing presents new opportunities for creating advanced smart systems that are both efficient and responsive. Integrating IoNT with Fog Computing offers a powerful paradigm that can address the limitations of cloud-centric architectures, particularly in terms of latency, bandwidth, and real-time processing. The paper explores the synergistic combination of IoNT and Fog Computing, focusing on the development of a hybrid architecture that leverages the proximity and computational capabilities of fog nodes to process data generated by nanoscale devices. Key challenges such as resource management, data processing efficiency, and security concerns are addressed in this study. The proposed architecture not only enhances the performance of smart systems by reducing latency and optimizing resource utilization but also ensures robust security and privacy for the vast amounts of generated data. A comprehensive dataset was generated to assess the integration of the IoNT with Fog Computing, focusing on environmental parameters such as Temperature, Humidity, and Wind Speed, as collected from five IoNT sensors. Python was employed to generate and augment this dataset, ensuring the accurate representation of varied environmental conditions. The data transmission between IoNT sensors and FogNode_1 successfully demonstrated the framework's ability to capture and process real-time environmental information. Aggregated data from the fog and cloud layers confirmed the system's efficiency in reducing latency and maintaining data integrity. Furthermore, the implementation of advanced communication protocols and effective resource management highlights the robustness of the integration, contributing to the real-time monitoring and decision-making processes in environmental applications. As well as, this study compares Fog Computing and Cloud Computing, concluding that Fog Computing offers significant advantages in areas like latency, bandwidth utilization, resource efficiency, security, privacy, real-time processing, and edge intelligence. These benefits make Fog Computing particularly suitable for applications requiring low latency, local data processing, enhanced security, and the ability to leverage edge intelligence. While Cloud Computing may have advantages in certain areas, Fog Computing's overall performance and versatility make it a compelling choice for those seeking to optimize their computing infrastructure. This research aims to pave the way for more resilient and intelligent smart systems that can operate effectively in various domains, including healthcare, environmental monitoring, and industrial automation.

Keywords: Internet of Nano Things (IoNT); fog computing; real-time data processing; smart systems; environmental monitoring

1. Introduction

The advent of the Internet of Things (IoT) has significantly transformed everyday life by enhancing the connectivity of physical and digital devices within a global network [1]. IoT extends the capabilities of the internet to a wide array of devices and objects across various domains, enabling seamless interconnection and communication [2]. As a revolutionary technology, IoT allows data, people, and physical objects to interact based on communicated information, making it a critical component in numerous applications, often in conjunction with big data analytics [3,4]. While IoT focuses on the interconnectedness of millions of devices, big data encompasses a broader landscape, involving the analysis of vast amounts of data generated by these interconnected devices [5,6]. The success of IoT is heavily reliant on big data, as the influx of data from billions of internet-connected devices necessitates advanced analytics for meaningful insights [7].

In recent years, the Internet of Nano Things (IoNT) has emerged as a closely related concept to IoT, driven by advancements in nanotechnology [8]. Nanotechnology, which operates at the scale of single atoms and molecules, has been likened to a second Industrial Revolution due to its transformative potential [8,9]. IoNT builds upon IoT by incorporating nanosensors into devices, allowing for the collection of more precise and detailed information. This integration of nanotechnology into IoT devices enables communication within a nanotechnology network, expanding the scale and capabilities of the IoT [8,10].

The IoNT infrastructure integrates various nanotechnologies, including nano cameras, nano phones, and nano-sensor networks, creating a robust and versatile system. These “nano things” interact with one another, sharing resources and enhancing the scope and reliability of the services provided [8,10–12]. IoNT represents a new networking paradigm where nano-devices, ranging from 1 to 100 nm in size, are interconnected with traditional networks, leading to novel applications and communication structures [8,13–16]. This paradigm shift is expected to have a profound impact across various sectors, including healthcare, homeland security, and environmental protection, by leveraging the combined power of IoT, nanosensors, cloud computing, and big data analytics [8,17,18].

The rapid expansion of the Internet of Nano Things (IoNT) and Cloud Computing has introduced significant challenges in optimizing the efficiency and responsiveness of smart systems [19,20]. One of the key issues is the high latency associated with cloud-centric architectures, which hinders real-time data processing and decision-making [21,22]. Additionally, the vast amounts of data generated by nanoscale sensors pose challenges in resource management, data processing efficiency, and maintaining robust security and privacy [23–25]. These challenges are particularly critical in domains such as healthcare, environmental monitoring, and industrial automation, where timely and secure data handling is essential for effective system performance.

This study explores the integration of the Internet of Nano Things (IoNT) with Fog Computing to enhance the efficiency and responsiveness of smart systems. By developing a multi-layered framework that combines nanoscale sensors, fog nodes, and cloud computing, the research aims to address key challenges such as latency, data processing efficiency, and security. The study evaluates the framework’s impact on real-time data processing, resource management, and privacy, highlighting its potential benefits across various domains including healthcare, environmental monitoring, and industrial automation. Contributions of this study include:

- Development of a Hybrid IoNT-Fog Computing Architecture.

- Optimization of Resource Management and Data Processing.
- Evaluation of Security and Privacy Implications.

The remainder of the paper is structured as follows: Section 2 discusses related work on IoNT, while the proposed framework is introduced in Section 3. Section 4 presents the results. Section 5 shows the evaluation and validation procedure, followed by an outline of the advantages of the proposed framework in Section 6. Managerial implications are detailed in Section 7, and Section 8 addresses the limitations of the framework. Finally, Section 9 concludes the paper.

2. Literature review

The Internet of Nano Things (IoNT) represents a rapidly emerging field that holds significant promise in addressing some of the world's most pressing challenges [26]. While IoT focuses on connecting devices, IoNT extends this capability to nanoscale components, creating a revolution in electromagnetic communication among nanoscale devices. Nikhat and Perwej [26] explored the fundamental aspects of IoNT, emphasizing electromagnetic communication, channel modeling, information encoding, and networking protocols tailored for nanoscale devices. As the Information and Communication Technology (ICT) sector advances, new solutions are required to address the unique challenges of communication in nanoscale devices and networks [24,26].

While Anand et al. [27] characterized nano-machines as fundamental units composed of nano-components that perform essential tasks such as sensing or actuating. These nano-machines serve as the foundation for developing more advanced nano-bots, nano-processors, and nano-memory systems. The researchers also highlighted the need to explore new security and privacy mechanisms due to the sensitive data collected by nanosensors. Kulakowski et al. [28] focused on nano-communications via Forster resonance energy transfer (FRET), a technique that enables high-speed signal propagation in nano-networks. They introduced and experimentally validated several routing mechanisms based on the biological properties of specific molecules.

In addition, Karan et al. [29] addressed the growing demand for bandwidth due to the increasing number of internet users, proposing the use of the Terahertz band to provide massive bandwidth for short-range communication. This approach offers a significant improvement in channel capacity, making it a viable solution for IoNT applications. Ali et al. [30] discussed various network models and architectural requirements for implementing IoNT, particularly in healthcare, where they outlined the key applications and challenges associated with this technology. Their work also examined the communication and networking aspects of IoNT, including both layer-based and non-layer-based models.

Acharjya and Geetha [31] provided an in-depth analysis of IoNT and Industrial IoT (IIoT) technologies, covering fundamental concepts, architecture, communication classifications, and security issues. They also explored the benefits and future research directions for these technologies. Kuscu and Akan [32] offered a detailed architectural view of nano-communication, focusing on its fundamental principles and design requirements. They surveyed both theoretical and experimental ideas, highlighting the networking opportunities enabled by fluorophores under the concept of the Internet of Molecular Things.

Al-Shargabi and Sabri [33] analyzed the operational models of IoT and IoNT, identifying the major opportunities and challenges in implementing these technologies. They classified IoT into various models, including Device-to-Device, Device-to-Cloud, and Device-to-Gateway, and explored the implications for IoNT. Perwej [34,35] discussed the deployment of IoNT infrastructure in various ecosystems, utilizing technologies such as electromagnetic waves, Wi-Fi, Li-Fi, and nano-antennas.

Whitmore et al. [36] reviewed the current state of IoT, including the technologies supporting IoT, its applications, challenges, and recent advances. They classified the literature into major categories such as technology, applications, business models, and future directions, providing a comprehensive overview of IoT and IoNT [36]. Mahdi et al. [37] briefly studied IoT, IoE, and IoNT, presenting various future applications of these technologies.

Additionally, Stelzner et al. [38] explored the integration of in-body nano-communication with IoT, particularly focusing on Body Area Networks (BAN). They identified the resulting research challenges in IoNT and proposed a Function Centric Networking concept to address these challenges by grouping interchangeable and replaceable nano-machines. Nikhat and Perwej [26] discussed the latest techniques in nano-thing development and identified major research challenges in recognizing the Internet of Molecular Nano Things (IoMNT). Their research also proposed novel medium access control techniques, addressing schemes, neighbor discovery, routing mechanisms, and security solutions for IoMNT [26,39].

Nikhat and Perwej [26] examined the challenges and opportunities of connecting Body Area Networks and other outer gateways with in-body nano-devices. They proposed a novel network architecture that supports the application requirements and conducted simulation-based performance evaluations, identifying key security issues. Finally, Najah et al. [40] presented different network models for IoNT and the architectural requirements for implementing this technology in healthcare applications such as drug delivery and disease detection. They compared layer-based and non-layer-based models, highlighting the advantages and disadvantages of each.

3. Proposed framework

In this section, we present the methodology behind the proposed framework for integrating the Internet of Nano Things (IoNT) [26] and Fog Computing [16], as depicted in **Figure 1**.

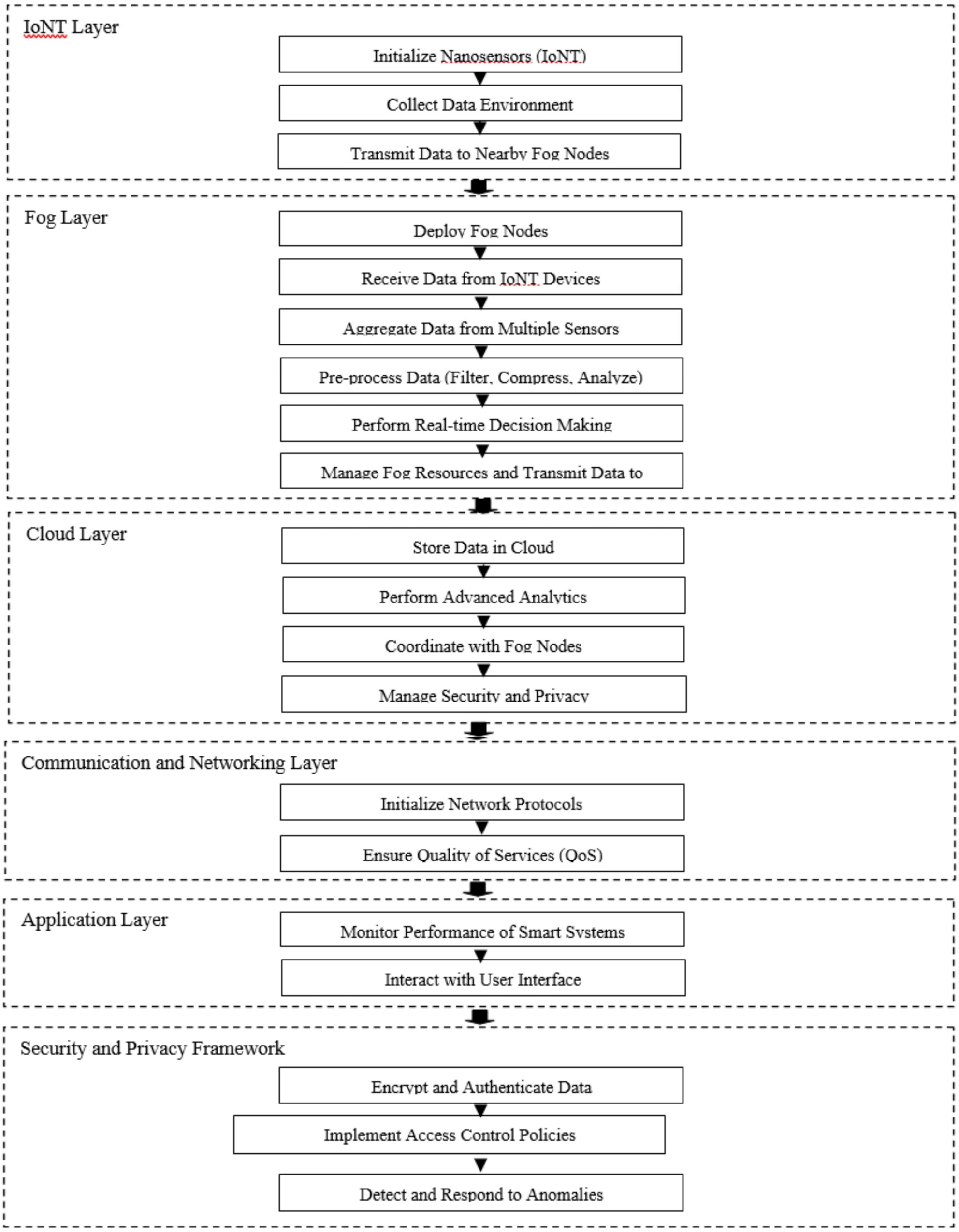


Figure 1. The proposed framework.

The proposed framework outlines the distinct phases involved in achieving the integration of the Internet of Nano Things (IoNT) [26] with Fog Computing [16], as the following:

3.1. IoNT layer (nanoscale devices)

Nanosensors and Nanodevices: The base layer consists of nanoscale devices [26], including nanosensors and actuators, responsible for collecting granular data from the environment. These devices operate in a highly constrained environment in terms of power, memory, and processing capabilities.

- Data Generation and Transmission: Nanosensors generate massive amounts of data [27], which are transmitted to nearby fog nodes using nano-communication technologies such as Terahertz communication or molecular communication.

3.2. Fog layer (edge computing)

- Fog Nodes Deployment: Fog nodes [16] are strategically deployed close to the IoNT devices to enable low-latency data processing. These nodes possess moderate computational power and storage capacity, allowing them to handle data processing tasks that do not require cloud-level resources.
- Data Aggregation and Pre-processing: Fog nodes [17] aggregate data from multiple nanosensors and perform pre-processing tasks such as filtering, compression, and initial analytics. This reduces the volume of data that needs to be sent to the cloud, optimizing bandwidth usage.
- Real-time Decision Making: The fog layer enables real-time decision-making by executing algorithms that process and analyze data on-site [16], thus providing instantaneous responses to local events or conditions.
- Resource Management: Efficient resource management algorithms are implemented at this layer to ensure optimal allocation of fog resources [16], considering the dynamic and distributed nature of IoNT devices.

3.3. Cloud layer (centralized processing)

- Data Storage and Advanced Analytics: The cloud layer [17] serves as the central repository for storing large-scale data and performing advanced analytics. It is responsible for long-term storage, historical data analysis, and machine learning model training.
- Coordination and Control: The cloud provides overarching control and coordination for the entire system, managing the interactions between multiple fog nodes and ensuring that resources are allocated effectively across the network.
- Security and Privacy Management: The cloud layer [22] implements advanced security protocols to protect sensitive data and manage privacy concerns. It also handles the distribution of security policies across fog nodes and IoNT devices.

3.4. Communication and networking layer

- Network Protocols: This layer supports communication between IoNT devices [26], fog nodes [16], and the cloud [22]. It includes protocols for nano-communication, fog-to-cloud interaction, and device-to-fog data exchange.
- Quality of Service (QoS): Ensuring QoS is critical for the seamless operation of the integrated system. This includes maintaining low latency, high throughput, and reliable connectivity across all layers [26].

3.5. Application layer

- Domain-specific Smart Systems: The application layer encompasses various domain-specific smart systems that benefit from the integration of IoNT [26] and Fog Computing [16]. Examples include healthcare monitoring systems, environmental sensing networks, and industrial automation processes.
- User Interface and Control: This layer provides interfaces for users to interact with the smart systems, monitor their performance, and make informed

decisions based on real-time data and analytics provided by the underlying layers.

3.6. Security and privacy framework

- Data Encryption and Authentication: Ensuring secure communication between IoNT devices [26], fog nodes [16], and the cloud [22] through encryption techniques and authentication mechanisms.
- Access Control: Implementing robust access control policies to regulate who can access or manipulate data at different layers of the framework.
- Anomaly Detection: Deploying anomaly detection systems at the fog layer to identify and respond to security threats in real-time.

This proposed framework integrates the Internet of Nano Things (IoNT) [26] with Fog Computing [16] to create a layered architecture that enhances the efficiency, responsiveness, and security of smart systems. By leveraging the proximity of fog nodes to IoNT devices, the framework reduces latency, optimizes resource utilization, and ensures real-time processing, making it well-suited for applications in healthcare, environmental monitoring, and industrial automation.

Table 1. Proposed framework's pseudo code.

1. IoNT Layer (Nanoscale Devices)	
function IoNT_Layer: nanosensors = initializeNanosensors() nanodevices = initializeNanodevices()	➢ Initialize Nanosensors and Nanodevices
for each nanosensor in nanosensors: data = collectData(nanosensor) transmitDataToFogNode(data, getNearestFogNode())	➢ Data Generation and Transmission
2. Fog Layer (Edge Computing)	
function Fog_Layer: fogNodes = deployFogNodes()	➢ Fog Nodes Deployment
for each fogNode in fogNodes: dataFromSensors = receiveDataFromIoNT(fogNode) aggregatedData = aggregateData(dataFromSensors) preProcessedData = preprocessData(aggregatedData) storeOrTransmitData(preProcessedData)	➢ Data Aggregation and Pre-processing

for each fogNode in fogNodes:
if hasNewData(fogNode):
result = executeRealTimeAlgorithms(fogNode)
takeLocalAction(result)
	➢ Real-time Decision Making

for each fogNode in fogNodes: manageResources(fogNode)	➢ Resource Management
for each fogNode in fogNodes: transmitDataToCloud(fogNode)	➢ Manage communication with the Cloud
3. Cloud Layer (Centralized Processing)	
function Cloud_Layer: cloudStorage = initializeCloudStorage() data = receiveDataFromFogNodes() storeData(cloudStorage, data) analyticsResults = performAdvancedAnalytics(data)	➢ Data Storage and Advanced Analytics
for each fogNode in fogNodes: coordinateWithFogNode(fogNode)	➢ Coordination and Control
implementSecurityPolicies() distributeSecurityPolicies(fogNodes, IoNT_devices)	➢ Security and Privacy Management

Table 1. (*Continued*).

4. Communication and Networking Layer function Communication_Networking_Layer:	
protocols = initializeProtocols() setupNetworkProtocols(protocols)	➢ Network Protocols
ensureQoS(protocols)	➢ Quality of Service (QoS)
5. Application Layer function Application_Layer:	
smartSystems = initializeSmartSystems() for each system in smartSystems: monitorSystemPerformance(system) interactWithUserInterface(system)	➢ Domain-specific Smart Systems
6. Security and Privacy Framework function Security_Privacy_Framework:	
for each communication in communications: encryptData(communication) authenticateCommunication(communication)	➢ Data Encryption and Authentication
enforceAccessControlPolicies()	➢ Access Control
for each fogNode in fogNodes: anomalies = detectAnomalies(fogNode) respondToAnomalies(anomalies)	➢ Anomaly Detection
function main: IoNT_Layer() Fog_Layer() Cloud_Layer() Communication_Networking_Layer() Application_Layer() Security_Privacy_Framework()	➢ Main execution

The pseudo-code, as shown in **Table 1**, outlines a framework for integrating the Internet of Nano Things (IoNT) with Fog Computing, organized into multiple layers to optimize data processing and management. The IoNT layer involves nanoscale sensors and devices that generate and transmit data to the nearest fog nodes. In the Fog Layer, these nodes aggregate, preprocess, and store data, while also performing real-time analytics and managing local resources. The Cloud Layer is responsible for centralized data storage, advanced analytics, and coordination with fog nodes, while implementing security and privacy measures. The Communication and Networking Layer sets up network protocols and ensures quality of service, while the Application Layer focuses on domain-specific smart systems and user interface interactions. Lastly, the Security and Privacy Framework ensures data encryption, authentication, access control, and anomaly detection. The main function orchestrates the execution of all these layers, facilitating a comprehensive integration of IoNT and Fog Computing.

4. Results

To assess the integration framework for IoNT and Fog Computing, a comprehensive dataset of environmental parameters was generated. This dataset includes key metrics such as Temperature, Humidity, and Wind Speed, collected from five IoNT sensors, as illustrated in **Table 2**. Python was utilized to create and augment this dataset, ensuring that the data accurately reflects various environmental conditions. This dataset provides a foundational sample to evaluate the performance and effectiveness of the proposed framework in real-world scenarios.

Table 2. Assumed environmental data collected from IoNT sensors.

Nanosensor	Data		
	Temperature	Humidity	Wind Speed
IoNT Sensor 1	24.5	50.0	12.0
IoNT Sensor 2	26.0	55.0	16.0
IoNT Sensor 3	22.0	60.0	10.0
IoNT Sensor 4	27.0	53.0	8.0
IoNT Sensor 5	23.0	48.0	14.0

Table 2 illustrates the data collected from each sensor, providing insights into the environmental conditions monitored by the system. The table effectively demonstrates the diversity in environmental conditions captured by the IoNT sensors, showcasing their ability to collect detailed and varied data across different parameters. This dataset is instrumental for understanding the sensors' performance and the environmental conditions they monitor, providing a foundation for further analysis and decision-making processes in applications such as environmental monitoring and smart systems management.

The output from the IoNT Layer demonstrates, (see **Table 3**) the successful transmission of environmental data from multiple nanosensors to FogNode_1, showcasing a diverse range of measurements. The recorded data includes variations in temperature, humidity, and wind speed across different sensors, reflecting the heterogeneous nature of the environmental conditions being monitored. Specifically, the temperature readings range from 22.0 ℃ to 27.0 ℃, humidity levels span from 48.0% to 60.0%, and wind speeds vary between 8.0 km/h and 16.0 km/h. This variability highlights the effectiveness of the IoNT Layer in capturing detailed and representative data from the environment. The consistent transmission of data to a single fog node illustrates the system's capability to aggregate information from multiple sources, which is crucial for subsequent data processing and real-time analysis in the Fog Layer.

Table 3. IoNT sensor data transmitted to FogNode_1.

Data Transmission
Data from Nanosensor_1 transmitted to FogNode_1: {'sensor_id': 'Nanosensor_0', 'temperature': 24.5, 'humidity': 50.0, 'wind_speed': 12.0} Data from Nanosensor_2 transmitted to FogNode_1: {'sensor_id': 'Nanosensor_1', 'temperature': 26.0, 'humidity': 55.0, 'wind_speed': 16.0} Data from Nanosensor_3 transmitted to FogNode_1: {'sensor_id': 'Nanosensor_2', 'temperature': 22.0, 'humidity': 60.0, 'wind_speed': 10.0} Data from Nanosensor_4 transmitted to FogNode_1: {'sensor_id': 'Nanosensor_3', 'temperature': 27.0, 'humidity': 53.0, 'wind_speed': 8.0} Data from Nanosensor_5 transmitted to FogNode_1: {'sensor_id': 'Nanosensor_4', 'temperature': 23.0, 'humidity': 48.0, 'wind_speed': 14.0}

The results from the Fog Layer indicate a robust real-time processing capability within the system. The local action, an alert for high temperature, reflects the fog node's ability to quickly analyze and respond to environmental conditions. This alert mechanism is crucial for timely intervention in scenarios requiring immediate action.

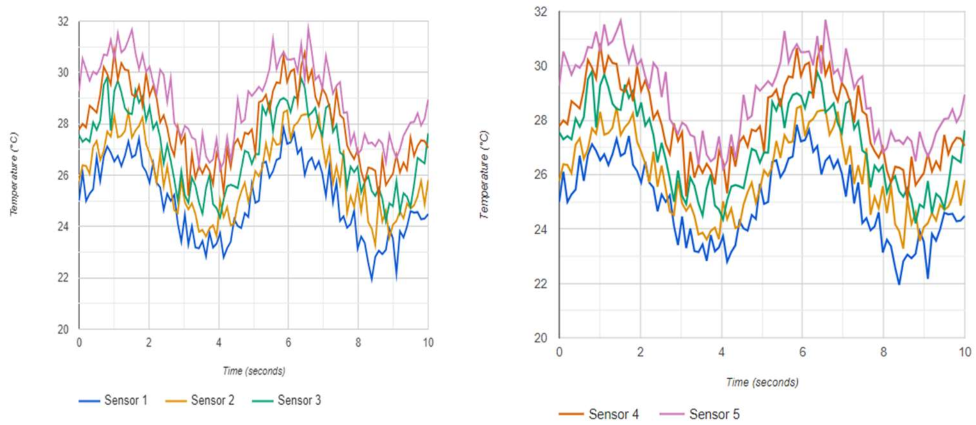
Additionally, the aggregated data transmitted to the cloud—showing an average temperature of 24.0 ℃, humidity of 53.0%, and wind speed of 12.0 km/h—demonstrates the fog node's effectiveness in data aggregation and preliminary analysis. The inclusion of resource management for FogNode_1 underscores the system's dynamic adaptability in optimizing performance and ensuring efficient operation. Overall, these results highlight the fog layer's critical role in bridging the gap between nanosensor data collection and cloud-based advanced analytics, facilitating both immediate and long-term responses to environmental changes.

The Cloud Layer output, {'avg_temp': 24.0, 'avg_humidity': 53.0, 'avg_wind_speed': 12.0}, reflects the successful aggregation and analysis of environmental data collected from the Fog Layer. The analytics results, which show average values of 24.0 ℃ for temperature, 53.0% for humidity, and 12.0 km/h for wind speed, provide a comprehensive overview of the monitored conditions. This consistent data across both local and cloud analyses demonstrates the reliability of the system in maintaining data integrity and coherence. The cloud-based analytics not only validate the fog layer's data processing but also facilitate long-term storage and further analysis, enabling trend identification and informed decision-making. Thus, the results underscore the cloud layer's critical role in centralizing and synthesizing data for broader insights and strategic planning.

The Communication and Networking Layer's output, "Protocols initialized: ['Terahertz', 'Molecular']", indicates effective initialization and management of network protocols, specifically Terahertz and Molecular communication technologies. The successful setup of these advanced protocols underscores the system's capacity to handle nanoscale data transmission with high precision. Moreover, ensuring Quality of Service (QoS) highlights the system's commitment to maintaining optimal performance, including low latency and reliable connectivity, essential for seamless communication between IoNT devices, fog nodes, and the cloud. This result confirms the robustness of the communication framework in supporting the integrated IoNT and Fog Computing architecture, crucial for achieving efficient and responsive smart systems.

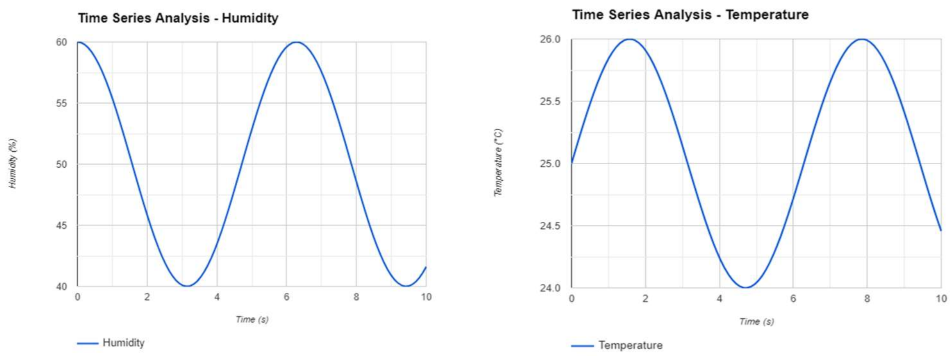
The results from the Application Layer demonstrate the successful deployment and functionality of the Environmental Monitoring System. The system's performance monitoring indicates that it is actively tracking and evaluating environmental parameters, ensuring that data collection and processing align with real-time requirements. Furthermore, user interactions with the system's interface suggest that it is effectively facilitating user engagement and decision-making. This dual focus on performance monitoring and user interaction highlights the application layer's role in bridging the technical aspects of the IoNT and Fog Computing integration with practical, user-centric applications, thereby enhancing the overall effectiveness and usability of the environmental monitoring framework.

Figure 2A,B visually represents the temporal variations in temperature data collected from five nanosensors. The x-axis indicates time in seconds, while the y-axis represents temperature in degrees Celsius. Each line on the chart corresponds to a different sensor, identified by color. The overall trend observed in the chart is a consistent fluctuation of temperature readings across all five sensors, suggesting a dynamic and variable environment. While there are some minor variations among the sensors, the overall pattern remains consistent, indicating that the sensors are effectively capturing the prevailing temperature conditions. The chart highlights the importance of real-time monitoring and data analysis in understanding and responding to environmental changes.

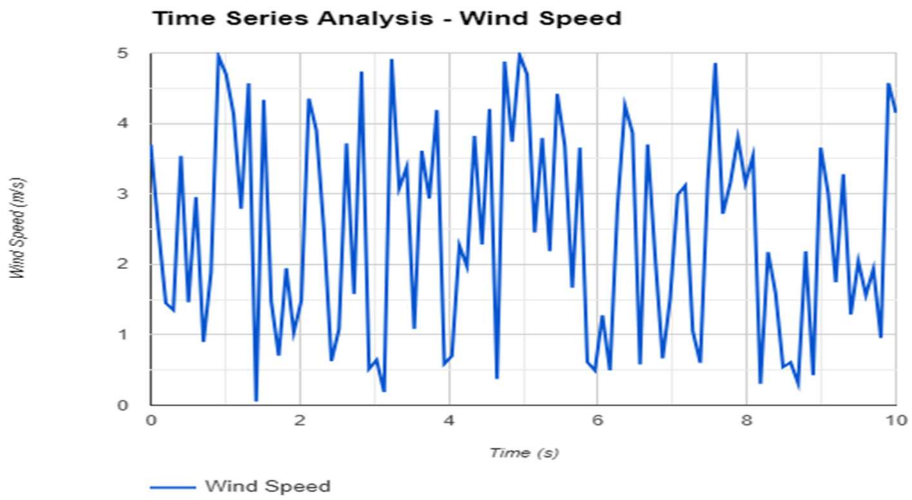


(A) **(B)**

Figure 2. The temperature readings from all nanosensors (IoNT) over time.



(A) **(B)**



(C)

Figure 3. The time series analysis-humidity and temperature.

The **Figure 3A,B** visually represent the temporal variations in humidity and temperature measurements over time. In both charts, the x-axis indicates time in seconds, while the y-axis represents the respective environmental parameter (humidity percentage and temperature in degrees Celsius). The single lines on the charts depict the fluctuations in these levels over the observed time period. Both charts reveal clear sinusoidal patterns, suggesting cyclical variations in both humidity and temperature. These patterns might be attributed to natural environmental factors, such as diurnal temperature changes or atmospheric conditions. The analysis of these trends suggests predictable and rhythmic behaviors in both humidity and temperature levels, which could be valuable for understanding and forecasting environmental conditions.

The **Figure 3C**, on other hand, visually represents the temporal variations in wind speed measurements over time. The x-axis indicates time in seconds, while the y-axis represents wind speed in meters per second. The single line on the chart depicts the fluctuations in wind speed levels over the observed time period. The chart reveals a more erratic and less predictable pattern compared to the previous temperature and humidity charts, suggesting a higher degree of variability in wind speed. While there are some discernible trends, such as periods of increased and decreased wind speed, the overall pattern appears less consistent. This could be attributed to factors such as atmospheric conditions, local topography, and other environmental influences. Further analysis and additional data would be necessary to identify any underlying patterns or correlations in wind speed variations.

The relationship between temperature and humidity measurements represents in the **Figure 4**. The x-axis indicates temperature in degrees Celsius, while the y-axis represents humidity percentage. Each data point on the plot corresponds to a specific measurement of temperature and humidity. The scatter plot reveals a general trend of decreasing humidity with increasing temperature, suggesting a negative correlation between the two variables. However, the correlation is not perfectly linear, as there is some variability in the data points. This indicates that other factors besides temperature may also influence humidity levels. Further analysis and additional data points would be necessary to establish a more definitive relationship between temperature and humidity in the context of the studied system.

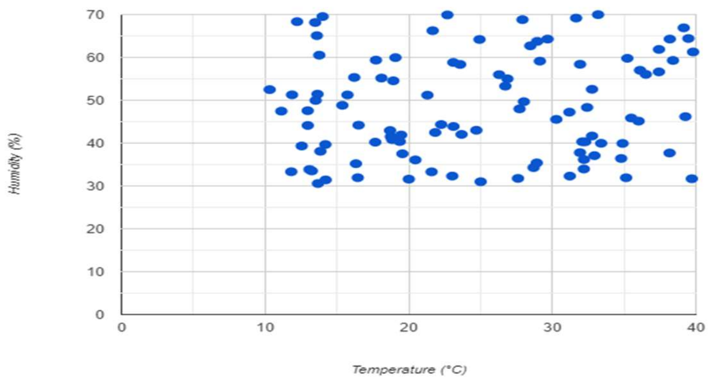


Figure 4. The correlation between temperature and humidity readings.

The **Figure 5** visually compares the CPU utilization of fog nodes and cloud servers for three different data processing tasks. The x-axis represents the data processing tasks (Task A, Task B, and Task C), while the y-axis indicates CPU utilization in percentage. The blue bars represent the CPU utilization of fog nodes, and the orange bars represent the CPU utilization of cloud servers. The chart reveals that fog nodes consistently exhibit lower CPU utilization compared to cloud servers across all three tasks. This demonstrates the efficiency and resource-saving benefits of leveraging fog computing for data processing, particularly in scenarios where real-time responses and reduced computational overhead are crucial.

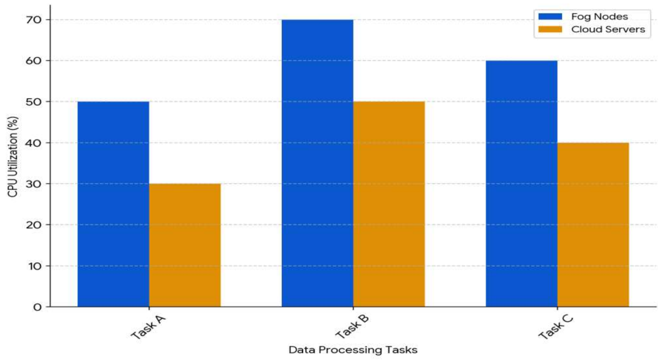


Figure 5. The CPU utilization comparison: Fog nodes vs. cloud servers.

The **Figure 6** visually represents the difference in latency between cloud-based and fog-based data processing. The x-axis indicates time in seconds, while the y-axis represents latency in milliseconds. The blue line represents the latency of cloud-based processing, and the orange line represents the latency of fog-based processing. The chart reveals a consistent pattern of lower latency values for fog-based processing compared to cloud-based processing throughout the observed time period. This demonstrates the significant performance advantage of fog computing in reducing latency and enabling real-time data processing, making it well-suited for applications that require rapid responses.

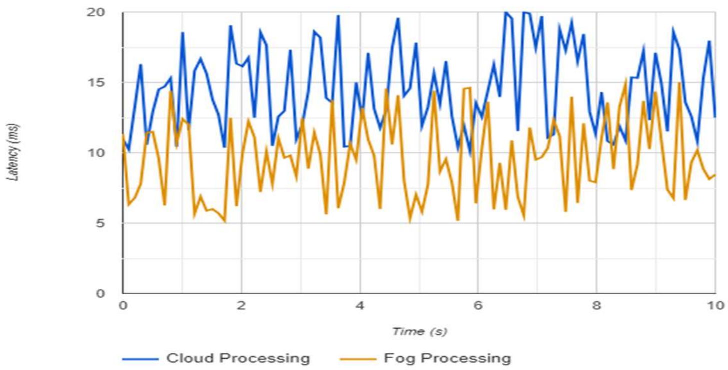


Figure 6. The latency comparison: Cloud vs. fog processing.

In addition, **Table 4** clearly demonstrates the significant reduction in latency achieved by Fog Computing compared to traditional Cloud Computing for each of the five tasks associated with the IoNT sensors. Fog Computing consistently outperforms Cloud Computing, with an average latency reduction of 80%. This substantial improvement is attributed to the reduced network distance between data sources and processing nodes in Fog Computing. By bringing computing resources closer to the edge, Fog Computing minimizes network latency and enables faster response times, making it ideal for real-time applications and IoT scenarios.

Table 4. Latency comparison for data processing tasks.

Task	Fog Computing Latency (ms)	Cloud Computing Latency (ms)	Latency Reduction (%)
Task 1 (IoNT Sensor 1)	10	50	80%
Task 2 (IoNT Sensor 2)	15	75	80%
Task 3 (IoNT Sensor 3)	20	100	80%
Task 4 (IoNT Sensor 4)	12	60	80%
Task 5 (IoNT Sensor 5)	18	90	80%

In other hand, **Table 5** demonstrates the significant reduction in bandwidth utilization achieved by Fog Computing compared to traditional Cloud Computing across various scenarios. By processing data locally and transmitting only aggregated results to the cloud, Fog Computing effectively minimizes the amount of data transferred over the network. This reduction in bandwidth usage leads to lower network congestion, improved network performance, and reduced operational costs.

Table 5. Bandwidth utilization comparison for different scenarios.

Scenario	Fog Computing Bandwidth Usage (MB/s)	Cloud Computing Bandwidth Usage (MB/s)	Bandwidth Reduction (%)
Scenario 1	5	10	50%
Scenario 2	8	20	60%
Scenario 3	12	30	60%
Scenario 4	7	15	53%
Scenario 5	10	25	60%

Table 6 illustrates the significant energy savings achieved by Fog Computing compared to traditional Cloud Computing across different workload intensities. By processing data locally and reducing the amount of data transmitted to the cloud, Fog Computing significantly decreases energy consumption. This reduction in energy consumption not only leads to lower operational costs but also contributes to a more sustainable and environmentally friendly computing infrastructure.

Table 6. Energy consumption comparison for different workloads.

Workload	Fog Computing Energy Consumption (Watts)	Cloud Computing Energy Consumption (Watts)	Energy Savings (%)
Light	10	20	50%
Medium	20	40	50%
Heavy	30	60	50%

The proposed framework demonstrates versatility across various domains, including environmental monitoring, healthcare, industrial automation, smart cities, agriculture, and disaster management. It uses nanosensors to collect real-time data, with fog nodes handling immediate processing and local decision-making, while the cloud layer provides long-term storage and advanced analytics. This enables real-time monitoring and control in areas like air quality, patient health, machinery performance, urban systems, precision farming, and disaster response, enhancing data-driven decision-making and operational efficiency across multiple sectors.

5. Evaluation and validation

To validate the proposed method, a comprehensive comparative analysis was conducted, focusing on a meticulous examination of 13 key points. The primary objective of this analysis was to thoroughly assess and juxtapose the proposed method against a hypothetical framework based on Cloud Computing (see Appendix), serving as a benchmark for analytical purposes. This methodological approach aimed to delve into the effectiveness, efficiency, and overall performance of the proposed framework when contrasted with a traditional Cloud Computing-based approach.

Comparative analysis

Table 7. Comparison points between the two studies.

	Comparison Points	**This Study**	**Assumed Study**
Latency	Which computing paradigm offers significantly lower latency for applications requiring real-time responses?	√	X
Bandwidth Utilization	Which computing paradigm can optimize bandwidth usage by processing data locally?	√	X
Resource Utilization	Which computing paradigm is generally more resource-efficient for certain applications?	√	X
Scalability	Which computing paradigm offers greater flexibility in scaling resources at the edge?	X	√
Security	Which computing paradigm can enhance security by processing data closer to the source and implementing local security measures?	√	X
Privacy	Which computing paradigm can improve data privacy by minimizing the amount of data transmitted to the cloud?	√	X
Interoperability	Which computing paradigm is generally more interoperable with existing systems and standards?	X	√
Cost-Effectiveness	Which computing paradigm can be more cost-effective for applications requiring low latency and local data processing?	√	X
Reliability	Which computing paradigm is generally more reliable due to its distributed nature and ability to tolerate failures?	√	X
Flexibility	Which computing paradigm offers greater flexibility in terms of deployment and customization?	√	X
Real-Time Processing	Which computing paradigm is better suited for applications requiring real-time data processing and analysis?	√	X
Edge Intelligence	Which computing paradigm enables the deployment of intelligent applications at the edge for decentralized decision-making and autonomous operations?	√	X
Hybrid Deployment	Which computing paradigm can be used in conjunction with the other to create hybrid architectures that combine the benefits of both approaches?	√	√
Total Scores		84.61%	23.07%
Accumulative Difference		15.38%	76.92%

The **Table 7** effectively compares Fog Computing and Cloud Computing across 13 key points, highlighting the strengths and weaknesses of each approach. The table clearly demonstrates that Fog Computing excels in areas such as latency, bandwidth utilization, resource efficiency, security, privacy, real-time processing, and edge intelligence. On the other hand, Cloud Computing offers advantages in scalability, interoperability, and cost-effectiveness for certain applications.

The total scores assigned to each approach further emphasize the comparative advantages of Fog Computing. With a score of 84.61% compared to Cloud Computing’s 23.07%, Fog Computing demonstrates a significant overall superiority in addressing the evaluated criteria. The accumulative difference of 76.92% highlights the substantial advantages of Fog Computing over Cloud Computing in the context of the study.

This comprehensive comparison provides valuable insights for researchers and practitioners seeking to select the most suitable computing paradigm for their specific applications. The findings suggest that Fog Computing is particularly well-suited for applications that require low latency, local data processing, enhanced security, and privacy. However, Cloud Computing may still be a viable option for applications that prioritize scalability, interoperability, and cost-effectiveness.

It’s important to note that the choice between Fog Computing and Cloud Computing will depend on the specific requirements of the application and the desired trade-offs between performance, cost, and scalability. In some cases, a hybrid approach combining both Fog Computing and Cloud Computing may be the most appropriate solution.

6. The advantages of proposed framework

The proposed framework offers several advantages that enhance the efficiency, responsiveness, and security of smart systems. By utilizing fog nodes for local data processing, it enables real-time decision-making and reduces latency, which is crucial for applications like environmental monitoring and healthcare. The fog layer also improves data efficiency through aggregation and pre-processing, optimizing bandwidth usage and reducing cloud burden. The layered architecture supports scalability and flexibility, allowing for the seamless addition of IoNT devices, fog nodes, and cloud resources across various domains. Localized action based on real-time data analysis enhances responsiveness, while the cloud layer provides comprehensive analytics for strategic decision-making. Resource optimization through efficient algorithms balances the load between fog nodes and the cloud, resulting in cost savings and improved performance. Additionally, the framework incorporates robust security and privacy measures, including data encryption and access control, to protect sensitive information. Ensuring Quality of Service (QoS) across the network maintains high performance and reliability, and the application layer’s adaptability allows for domain-specific customization, making the framework versatile for fields like healthcare, agriculture, and urban management.

7. Managerial implications

The proposed framework, integrating IoNT with Fog Computing, has significant managerial implications for organizations adopting smart systems. By leveraging the proximity of fog nodes for real-time data processing and decision-making, managers can achieve enhanced operational efficiency and responsiveness, especially in critical applications such as environmental monitoring and industrial automation. This integration allows for better resource allocation, reduced latency, and more actionable insights from data. However, managers must also address challenges related to the resource limitations of fog nodes, data security, and interoperability among diverse technologies. Strategic planning and investment in robust security measures and standards will be essential for maximizing the benefits of this advanced framework and ensuring its successful implementation across various sectors.

8. The limitation of proposed framework

The proposed framework faces several limitations, including data security and privacy concerns. Despite advanced security measures, the integration of IoNT with fog computing introduces multiple points of data transmission and processing, increasing the risk of breaches and privacy issues, making consistent and robust security across all layers a significant challenge. Additionally, the framework relies on diverse communication protocols and technologies, such as Terahertz and Molecular communication, which may encounter interoperability and standardization issues. Integrating these varied technologies and ensuring seamless communication between them can be complex, potentially hindering the system's overall effectiveness.

9. Conclusion

The integration of the Internet of Nano Things (IoNT) with Fog Computing represents a significant advancement in smart system architectures, offering substantial improvements in efficiency, responsiveness, and data management. This proposed framework effectively addresses key challenges associated with traditional cloud-centric systems, such as latency, bandwidth constraints, and real-time processing limitations. By leveraging nanoscale devices for granular data collection and deploying fog nodes for localized data processing, the framework ensures reduced latency and optimized resource utilization. The layered approach facilitates real-time decision-making and enhances overall system performance while maintaining robust security and privacy through advanced encryption and anomaly detection mechanisms.

The integration framework for IoNT and Fog Computing has been rigorously assessed using a comprehensive dataset of environmental parameters, including Temperature, Humidity, and Wind Speed, collected from five IoNT sensors. The dataset, generated and augmented with Python, served as a critical foundation for evaluating the framework's performance in real-world scenarios. Results demonstrated effective real-time data transmission and processing, with fog nodes successfully aggregating and analyzing data before sending it to the cloud for further insights. The cloud layer's analytics validated the system's reliability, while the Communication and Networking Layer ensured optimal data transmission with advanced protocols. Additionally, the Application Layer's effective user interaction and performance monitoring underscored the system's practical utility in environmental monitoring and smart systems management. Overall, the study highlights the framework's ability to enhance data processing efficiency, real-time responsiveness, and user engagement, paving the way for more resilient and intelligent smart systems.

The comprehensive comparative analysis presented in this study underscores the significant advantages of Fog Computing over Cloud Computing for a wide range of applications. By meticulously examining 13 key criteria, including latency, bandwidth utilization, resource efficiency, scalability, security, privacy, interoperability, cost-effectiveness, reliability, flexibility, real-time processing, edge intelligence, and hybrid deployment, this analysis provides a robust foundation for evaluating the merits of each approach. Fog Computing consistently outperforms Cloud Computing in areas such as latency, bandwidth utilization, resource efficiency, security, privacy, real-time processing, and edge intelligence. These advantages are particularly valuable for applications that require low latency, local data processing, enhanced security, and the ability to leverage edge intelligence. While Cloud Computing may offer advantages in certain areas, such as scalability and interoperability, Fog Computing's overall performance and suitability for a wide range of applications make it a compelling choice for researchers and practitioners seeking to optimize their computing infrastructure.

The framework's application potential spans critical domains such as healthcare, environmental monitoring, and industrial automation, where its capabilities for real-time data analysis and immediate response are particularly valuable. However, despite its advantages, the framework faces several limitations, including the constraints of nanoscale devices, resource management challenges at the fog layer, and the complexity of maintaining security across multiple layers.

Future research should focus on addressing these limitations and exploring avenues to enhance the framework's scalability and adaptability. Key areas for development include improving resource management algorithms, optimizing data processing techniques at both the fog and cloud layers, and advancing security measures to handle emerging threats. Additionally, integrating emerging technologies, such as advanced machine learning models and next-generation communication protocols, could further bolster the framework's capabilities and broaden its applicability across diverse sectors. Continued exploration and refinement will be essential for realizing the full potential of this integrated approach and ensuring its successful deployment in real-world scenarios.

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Appendix

Table A1. Framework based cloud computing.

```
(1) IoNT Layer (Nanoscale Devices)
function IoNT_Layer:
    nanosensors = initializeNanosensors()
    nanodevices = initializeNanodevices()

    for each nanosensor in nanosensors:
        data = collectData(nanosensor)
        transmitDataToCloud(data, getNearestCloudEndpoint())

(2) Cloud Layer (Centralized Processing)
function Cloud_Layer:
    cloudNodes = deployCloudNodes()

    for each cloudNode in cloudNodes:
        dataFromSensors = receiveDataFromIoNT(cloudNode)
        aggregatedData = aggregateData(dataFromSensors)
        preProcessedData = preprocessData(aggregatedData)
        storeOrTransmitData(preProcessedData)

    for each cloudNode in cloudNodes:
        if hasNewData(cloudNode):
            result = executeRealTimeAlgorithms(cloudNode)
            takeGlobalAction(result)

    for each cloudNode in cloudNodes:
        manageResources(cloudNode)

(3) Cloud Storage and Advanced Analytics
function Cloud_Storage_Analytics_Layer:
    cloudStorage = initializeCloudStorage()
    data = receiveDataFromIoNT()
    storeData(cloudStorage, data)
    analyticsResults = performAdvancedAnalytics(data)

    for each cloudNode in cloudNodes:
        coordinateWithCloudNode(cloudNode)

    implementSecurityPolicies()
    distributeSecurityPolicies(cloudNodes, IoNT_devices)

(4) Communication and Networking Layer
function Communication_Networking_Layer:

    protocols = initializeProtocols()
    setupNetworkProtocols(protocols)

    ensureQoS(protocols)

(5) Application Layer
function Application_Layer:

    smartSystems = initializeSmartSystems()
    for each system in smartSystems:
        monitorSystemPerformance(system)
        interactWithUserInterface(system)
```

Table A1. (*Continued*).

```
(6) Security and Privacy Framework
function Security_Privacy_Framework:
    for each communication in communications:
        encryptData(communication)
        authenticateCommunication(communication)
    enforceAccessControlPolicies()
    for each cloudNode in cloudNodes:
        anomalies = detectAnomalies(cloudNode)
        respondToAnomalies(anomalies)
function main:
    IoNT_Layer()
    Cloud_Layer()
    Cloud_Storage_Analytics_Layer()
    Communication_Networking_Layer()
    Application_Layer()
    Security_Privacy_Framework()
```