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Reconfigurable Metasurface-Enabled AIoT Framework for Intelligent and Sustainable Smart Cities †

Shubham Gupta [1] and Suhaib Ahmed [2,*]

[1] Department of Computer Science and Engineering, Model Institute of Engineering and Technology, Jammu 181122, Jammu and Kashmir, India; shubhamgupta.cse@mietjammu.in
[2] Centre for Research, Innovation and Entrepreneurship, Model Institute of Engineering and Technology, Jammu 181122, Jammu and Kashmir, India
* Correspondence: suhaib.ece@mietjammu.in
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Abstract

The fast growth of smart city systems requires sensing and intelligence systems that are dynamic, power-efficient, and have capabilities of real-time decision-making. The traditional IoT-based smart city systems are subject to constraints like nonflexible sensing architectures, high energy use, and high-latency because of processing on clouds. To solve these problems, in this paper, a reconfigurable metasurface-based Artificial Intelligence of Things (AIoT) architecture of smart cities is proposed. The proposed system incorporates programmable electromagnetic metasurface-based sensing, edge-level Artificial Intelligence, and AIoT gateways to implement ultra-sensitive sensing, low-latency analytics, and effective resource utilization. A computer algorithm with a hybrid realization between metasurface physics and neural network-based learning can be used to improve the accuracy and flexibility of sensing. The experimental analysis with publicly available data of a smart city proves that the proposed framework can attain an accuracy of sensing in the range of 92% and 97%, by far surpassing traditional IoT sensors, with 78% and 83% as the accuracy limits. Moreover, the suggested system shortens end-to-end latency to as low as 3645 ms, as compared to 8490 ms, and also reduces the power usage. The improved sensing efficiency, which is defined as the ratio of power consumption to accuracy, is obtained in all test conditions. These findings validate that the suggested AIoT framework, powered by the metasurface, can be used to offer a scalable and low-latency solution that uses less energy when it is deployed in applications linked to smart cities of the next generation.

Keywords: smart cities; reconfigurable metasurfaces; AIoT; edge AI; intelligent sensing; energy-efficient systems

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1. Introduction

The high urbanization experienced in the world has led to the rapid implementation of smart city paradigms to enhance efficiency, sustainability, and the strength of the city infrastructure. Smart cities are widely based on massive sensing, communication, and intelligent decision-making systems as the means to control sophisticated urban activities like monitoring the environment, transport system, energy distribution, and maintenance of structures [1–4]. The Internet of Things (IoT) has become a technology in this regard, that is, pervasive data acquisition has become a reality based on distributed sensor networks. Nevertheless, even with these great developments, traditional IoT-based sensing

structures remain important with grave issues of excessively high-power usage, decreased sensing ability, hardened hardware designs, and scalability issues, as well as cloud-based data processing latency [5–7]. Conventional IoT sensors are typically built to operate in a deterministic environment and do not have the capability of adapting to uncertain urban environments.

These constraints are increasingly notable as the scope and concentration of smart cities increase, resulting in the waste of resources, shortened life cycle of the system, and poor real-time responsiveness [8–11]. Moreover, the current exponential expansion of sensor-based information has a massive load on centralized cloud-based systems, leading to communication and coordination congestion, latency, and a system that can be vulnerable to privacy violations [12]. These issues have ensured that sensor and intelligence systems to the next level must be energy-efficient, adaptive, and able to enable real-time autonomous decision-making at the network edge. Recently, the reconfigurable metasurfaces have received much interest as a disruptive technology in sensing and communication.

Metasurfaces are electromagnetic (EM) surfaces that are designed by use of sub-wavelength structures, which can accurately control the EM wave propagation, reflection, and absorption as well as polarisation [13]. As compared to traditional sensors, reconfigurable metasurfaces can be dynamically programmed to adjust their electromagnetic response with highly sensitive, low-power, and adaptive sensing functionality relying on programmable control systems [14]. The special features of metasurfaces render them the most appropriate for complex urban phenomena where sensing environments are constantly changing as the environment, structures, and operations change [15]. Co-existing with innovations in sensing devices, Artificial Intelligence (AI), and edge computing has turned out to be the instruments of smart cyber–physical systems [16]. Low-latency data processing, detection of anomaly and decision-making can be performed with the assistance of AI-driven analytics, especially when implemented at the network edge, without undue dependence on cloud resources.

The proposed framework aims to facilitate the critical smart city applications, such as monitoring of the environment and air quality, structural health, smart crowd management in a city, and optimization of a smart grid. The system can respond dynamically to changes in urban conditions and keep the sensing accuracy, low power consumption, and low response time by utilizing the physical-layer flexibility of metasurfaces and the cognitive features of AI. Evaluations made through simulations show that the metasurface-enacted AIoT design has noticeably higher sensing accuracy, spatial localization, and reduced latency as compared to the traditional IoT-based systems, which is why it can be implemented in both dense and large-scale urban settings.

The main contributions of this work are as follows:

- Development of a novel reconfigurable metasurface-enabled AIoT framework tailored for smart city applications.
- Integration of programmable electromagnetic sensing with edge AI-driven analytics for adaptive and low-latency decision-making.
- Design of a hybrid computational model combining metasurface physics with neural network-based learning for enhanced sensing accuracy and robustness.
- Comprehensive performance evaluation demonstrating improvements in accuracy, latency, and power efficiency compared to traditional IoT systems.

Overall, this research lays the foundation for a scalable, sustainable, and intelligent urban sensing infrastructure, offering a promising pathway toward next-generation smart city ecosystems.

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2. Literature Review

The architecture of smart city systems was widely investigated via the IoT-centered sensing platform, AI-based analytics, and edge computing, to the cloud computing paradigm. Although these methods have made progress in better automation and decision-making based on data, most of the currently available solutions are based on traditional sensing technologies, which are not reconfigurable and have high power usage and response times, which limit their applicability to dynamic cities, as elaborated in Table 1.

Table 1. Literature review summary.

Ref.	Focus/Objective	Key Contributions	Limitations/Research Gap
van der Hoogen et al. (2024) [16]	Proposes a digital transformation framework for smart municipalities with emphasis on IoT, governance, and sustainability	Introduces a structured DT framework covering smart governance, environment, living, and technology; highlights IoT and data-driven decision-making as enablers for smart municipalities	Focuses on policy and governance level; lacks innovation at the sensing hardware layer, and does not address real-time adaptive or ultra-sensitive sensing mechanisms.
Choi and Song (2023) [17]	Develops policy directions and diagnostic indicators for smart, sustainable cities	Provides evaluation indicators for smart sustainable city planning; integrates environmental, social, and technological dimensions for sustainability assessment	Primarily policy-oriented; does not consider intelligent sensing architectures, edge AI integration, or physical-layer adaptability.
Alamzadeh et al. (2021) [18]	Designs a reconfigurable intelligent surface (RIS) with integrated sensing capability	Demonstrates metasurfaces with integrated sensing for angle-of-arrival detection; reduces RF chain requirements using tunable metasurface multiplexing	Focused on wireless communication and RF sensing; does not explore AI-driven edge analytics or smart city-scale applications.
Zhang (2022) [19]	Reviews intelligent metasurfaces as programmable and AI-enabled platforms	Identifies digitalization, programmability, and intelligence as core metasurface features; highlights integration with AI, sensing, and feedback systems	Conceptual and review-based; lacks system-level frameworks combining metasurfaces, AIoT, and real-world urban applications
Bhanu Dwivedi (2025) [20]	The case study focuses on the integration of Artificial Intelligence (AI) and IoT (AIoT) in smart city projects and analyze their practical applications.	The case study demonstrates real-world AIoT studies across diverse cities, identifies best practices for leadership, strategic vision, data privacy, interoperability, and infrastructure planning.	Lacks quantitative performance benchmarking across cities with limited discussion on standardized evaluation frameworks.

3. Methodology

The following section presents a descriptive approach to the proposed reconfigurable metasurface-based AIoT system that is implemented in an intelligent and sustainable smart city implementation. The approach is a combination of programmable metasurface-controlled sensing, edge-respectful Artificial Intelligence, and AIoT-enabled information integration to develop adaptive, energy-efficient, and low-latency urban intelligence. The general workflow will help facilitate real-time sensing, intelligent analytics, and autonomous decision-making in a wide variety of situations in the city.

3.1. Dataset Description

To assess the performance of the suggested metasurface-based AIoT framework in the context of actual smart city scenarios, a publicly available dataset from Kaggle is used.

UrbanIoT-Anomaly [21]: Multimodal Smart City Dataset has been chosen because of its reference to big city sensing and Artificial Intelligence applications. The data includes the multimodal sensor data acquired on distributed nodes of the urban IoT, which reflect the parameters of the environment, states of traffic, and the signals associated with the infrastructure. It is tailored to aid with predictive modeling and irregularity identification tasks within the context of a smart city setting. The dataset is used to give representative data to emulate the real-life sensing input of the proposed framework.

3.2. System Architecture

The suggested architecture is based on a layered system architecture, comprising a reconfigurable metasurface sensing layer, an edge AI processing layer, an AIoT gateway layer, and an application-level decision-making layer. Programmable metasurface units are placed at the sensing layer and spread to the urban environment in order to sense fine-grained variations in the environment and infrastructure. These sensors deal directly with the electromagnetic waves and changes in vibration as circumstances vary. The perceived data is relayed to the closest edge computing nodes, where real-time AI-driven analytics are conducted. The processed information is directed to AIoT gateways to fuse the data, analyzing on a system-wide basis and intelligent control of the smart city services data, including but not limited to environmental, traffic management, structural health assessment, and optimization of the smart grid. Figure 1 shows an example of a three-dimensional path of a mobile sensing platform (drone or autonomous vehicle) moving in a smart city setup. The trajectory illustrates the spatial coverage of a variety of urban areas and different elevations, which is realistic in terms of the data-acquisition situation applied in the analysis of the proposed AIoT framework based on metasurfaces.

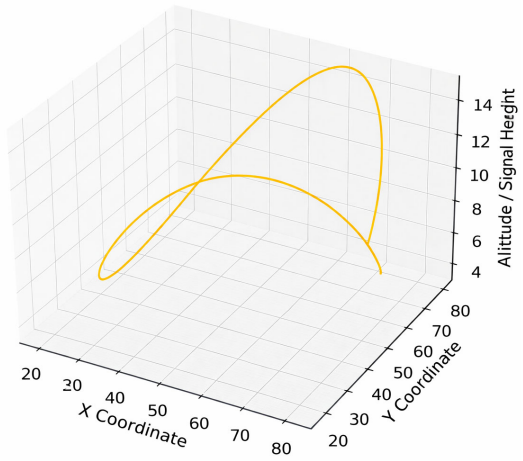


Figure 1. A 3D trajectory map-drone/vehicle path across smart city.

3.3. Reconfigurable Metasurface-Based Sensing

The basic sensing unit of the framework is represented by reconfigurable metasurfaces. They are designed as sub-wavelength electromagnetic structures that can control the incident electromagnetic waves, dynamically changing the interactions of parameters (phase, amplitude, resonance, etc.). Metasurface sensors can adapt their electromagnetic response in real time unlike standard fixed-point IoT sensors, and can therefore provide ultra-sensitive sensing and adaptive sensing when living in different urban environments. This reconfigurability leads to dynamic reconfigurability, enabling the sensors to sense minute variations in environmental parameters, structural integrity, and electromagnetic disturbances at very low power levels. Consequently, metasurface sensing is more accurate, robust, and has lower energy consumption, and is therefore very appropriate to dense and large-scale deployments of smart cities.

An intermediate computing simulator between metasurface physics and neural networks-based learning is created to improve the precision and flexibility of the sensing. The electromagnetic behavior of metasurface sensors is modeled in a way that the physical behavior is captured at different allusions to the environmental conditions. This representation, based on physics, is coupled with data-driven neural networks that learn complicated and non-linear correlations among sensed signals and urban parameters. The hybrid model will facilitate learning with domain knowledge support, generalization ability, complexity of training, and predictive performance over various urban conditions.

3.4. AIoT Gateway and Data Fusion

The outputs of the edge AI modules are sent to AIoT gateways that perform data aggregation, fusion, and system-level analytics. These gateways combine different pieces of data gathered by several distributed sensing devices to create a complete picture of the urban environment. Thoughtful data fusion processes allow integrated benchmarking of the intelligence of countless smart subsystems of the city, like air quality systems, smart traffic systems, building health analysis, and smart grid optimization. There are autonomous decision-support functions that are applied to enable alerts, optimized distribution of resources, and active urban management, as illustrated in Figure 2.

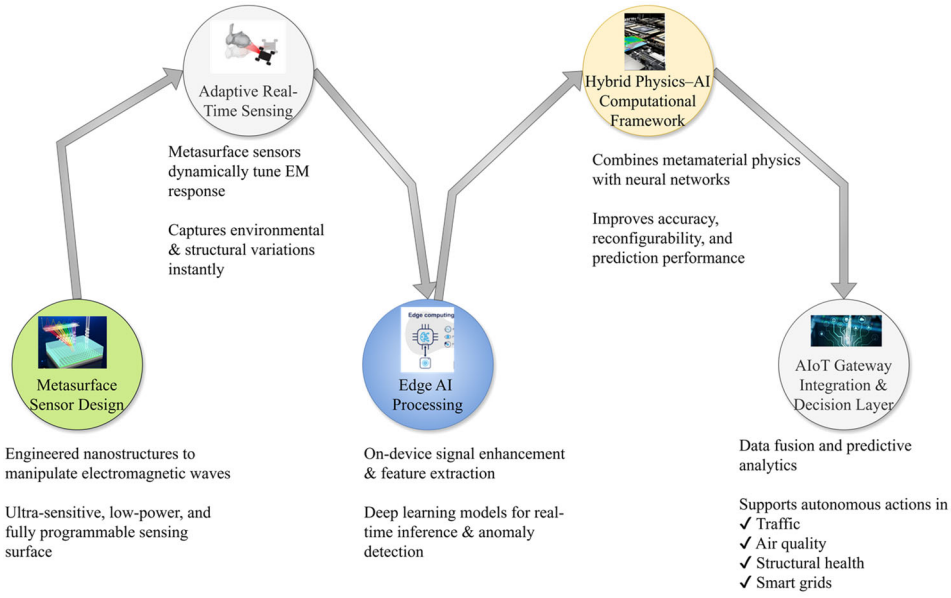


Figure 2. Proposed metasurface-enabled AIoT methodology.

4. Results and Discussion

This section offers an in-depth performance analysis of the suggested reconfigurable metasurface-based AIoT framework. The experimental results are based on the issues of sensing accuracy, power consumption, system latency, and the performance of the system. It is compared to conventional IoT-based sensing architectures and yields results to show the efficiency of the proposed paradigm when applied in smart cities.

4.1. Sensing Accuracy Evaluation

It was found that under different urban sensing conditions, the sensing accuracy of the proposed framework was tested using simulation-driven experiments. Accuracy was calculated as the number of times sensing states were correctly inferred for all sensing instances. The AIoT system provided using a metasurface outperformed the traditional IoT sensors in all the test conditions, as shown in Figure 3.

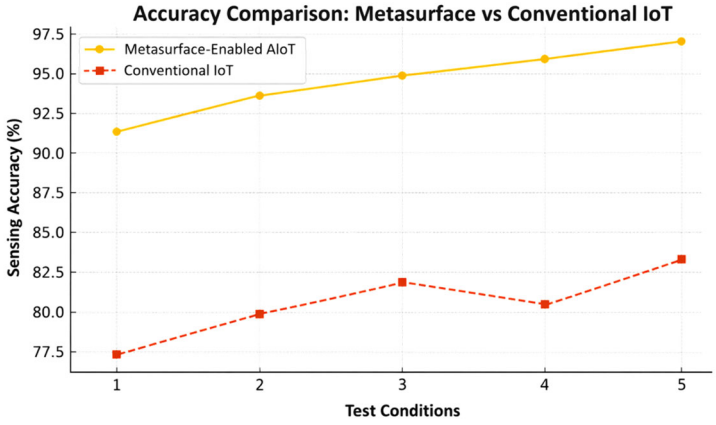


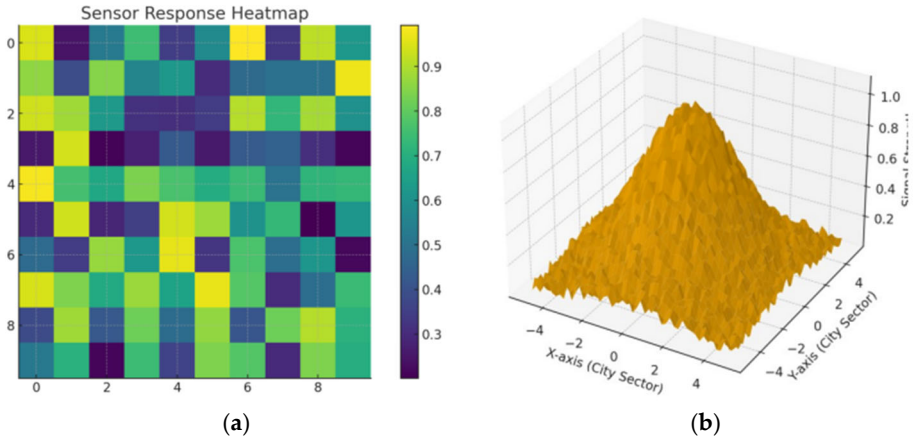
Figure 3. Accuracy comparison between metasurface and conventional IoT.

The proposed system was found to be able to sense the system with accuracies of between 92 and 97% as compared to traditional IoT sensors, which had a range of between 78 and 83. This notable advancement can be explained by the ultra-sensitivity of the electromagnetic response of reconfigurable metasurfaces and edge AI-guided inference, which improves signal discrimination and minimizes errors caused by noise. Table 2 is a comparison of the sensing accuracy performance of the two systems.

Table 2. Sensing accuracy comparison.

System Type	Minimum Accuracy (%)	Maximum Accuracy (%)
Conventional IoT sensors	78	83
Proposed metasurface AIoT system	92	97

The level of accuracy, consistently higher, proves the validity of the adaptive electromagnetic sensing and physics-aware AI fusion in the complicated urban conditions. Figure 4a shows a heatmap of the intensity of response in the spatial sensor on various areas in urban areas. The metasurface-based sensing layer is very sensitive and has a good distribution of responses, hence it can be easily used to detect changes in the environment and infrastructure. To further examine the sensing behavior, Figure 4b shows a three-dimensional representation of the plot of sensor response intensity in the various city sectors. The ability to capture fine-grained variations with high precision is suggested by the smooth gradient and small discrete peaks.



(**a**) (**b**)

Figure 4. (**a**) Sensor response heatmap; (**b**) 3D surface plot of sensor response intensity.

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4.2. Latency Performance Analysis

Latency analysis was used to assess the responsiveness of the proposed framework that is essential to time-sensitive smart city applications like smart traffic control and structural health monitoring. Measurements of the end-to-end latency were taken as the time taken between the acquisition of data and the provision of an actionable decision. The proposed metasurface-enabled AIoT system was shown to reduce the latency by 36 ms compared to 45 ms because of local edge AI processing, as seen in Figure 5. Conversely, traditional IoT systems based on cloud-centric systems had much higher and unstable latency between 84 ms and 90 ms.

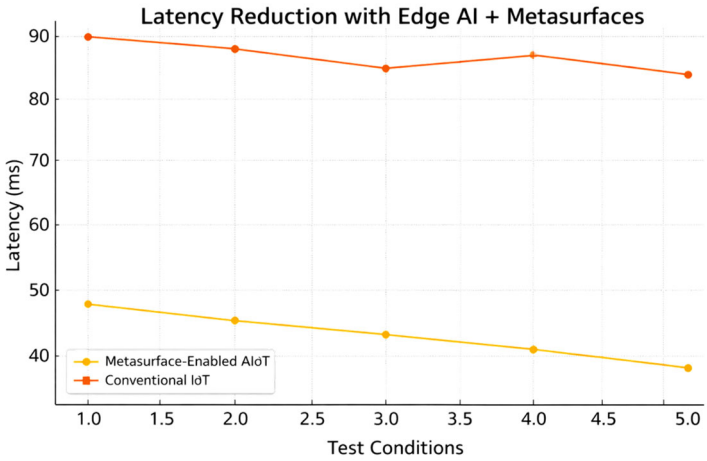


Figure 5. Latency reduction with Edge AI and metasurfaces.

4.3. Overall System Performance Comparison

To provide a holistic evaluation, overall system performance was analyzed by jointly considering sensing accuracy, latency, and power consumption. The combined results demonstrate that the proposed metasurface–AIoT framework consistently outperforms conventional IoT systems across all key metrics. Table 3 summarizes the overall system performance comparison.

Table 3. Overall performance comparison.

Performance Metric	Conventional IoT System	Proposed Metasurface AIoT System
Sensing Accuracy	Low–moderate	High
Latency	High	Low
Power Consumption	High	Low
Adaptability	Limited	High
Scalability	Moderate	High

Figure 6 presents the sensing efficiency curve, defined as the ratio of sensing accuracy to power consumption. The proposed framework demonstrates consistently higher efficiency across all test conditions, indicating superior resource utilization compared to conventional IoT systems. The synergistic integration of reconfigurable metasurfaces with edge AI analytics enables adaptive sensing, efficient resource utilization, and robust performance under varying urban conditions. These results confirm that the proposed framework provides a scalable, energy-efficient, and high-performance solution for next-generation intelligent smart city ecosystems.

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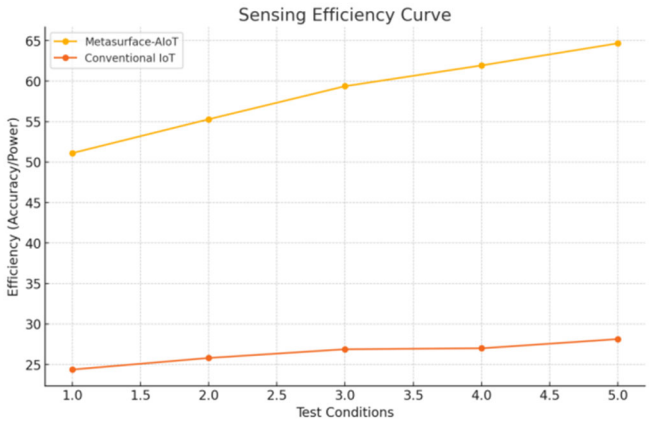


Figure 6. Sensing efficiency curve.

5. Conclusions

This paper introduced a reconfigurable AIoT application based on a metasurface to support intelligent and sustainable smart city practices. The proposed system addressed key shortcomings of traditional IoT systems, such as low sensing sensitivity, high energy consumption, and latency due to centralized computations, by integrating programmable metasurface-based sensing with edge AI analytics and AIoT gateways. The hybrid metasurface-AI computational platform allows adaptive utility to electromagnetic sensing and real-time intelligent transformational inference, which allows enhanced accuracy and power functioning in dynamic urban scenarios. Extensive simulation studies on a real-world smart city dataset indicate that the suggested framework outperforms conventional IoT-based systems in sensing accuracy, reducing latency, and power efficiency, as well as general sensing efficiency. The major advantages that the framework provides include its physical-layer reconfigurability, scalability, and minimal dependency on cloud computing, while practical implementation and deployment may include integration issues with existing infrastructure and increased hardware complexity. The effectiveness and implementation of the proposed system can be further enhanced with the development and advancement of programmable metasurfaces, edge AI hardware, and low-power communication technologies, which will be beneficial for the advancement of next-generation adaptive urban sensing networks.

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