ASEC 2025 Conference

The 6th International Electronic Conference on Applied Sciences

09–11 December 2025 | Online

MDPI

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

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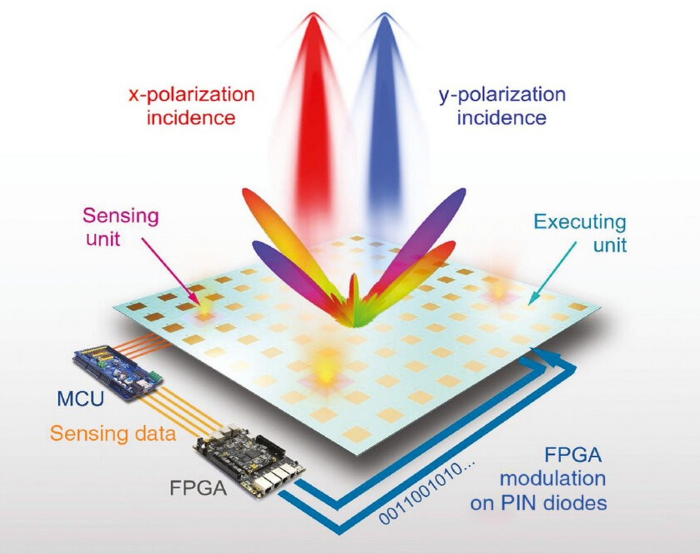
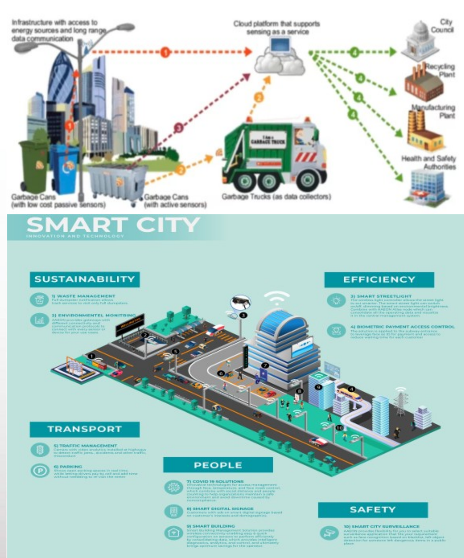
INTRODUCTION & AIM

The rapid evolution of smart cities requires sensing networks that are intelligent, energy-efficient, and capable of adapting to diverse urban environments. Traditional IoT-based systems often face challenges such as high-power consumption, limited sensitivity, rigid architectures, and inefficient data processing, which restrict their ability to support large-scale urban automation. To address these limitations, reconfigurable meta surfaces, engineered nanostructures capable of manipulating electromagnetic waves, offer a transformative opportunity. Their ability to provide ultra-sensitive, programmable, and low-power sensing makes them ideal for next-generation urban applications. By integrating such meta surfaces with AI-driven edge analytics, the proposed meta surface-enabled AIoT framework enhances real-time data acquisition, communication, and autonomous decision-making. This hybrid approach strengthens key urban functions including environmental monitoring, structural health assessment, intelligent traffic management, and smart grid optimization, laying the foundation for sustainable and resilient smart cities.

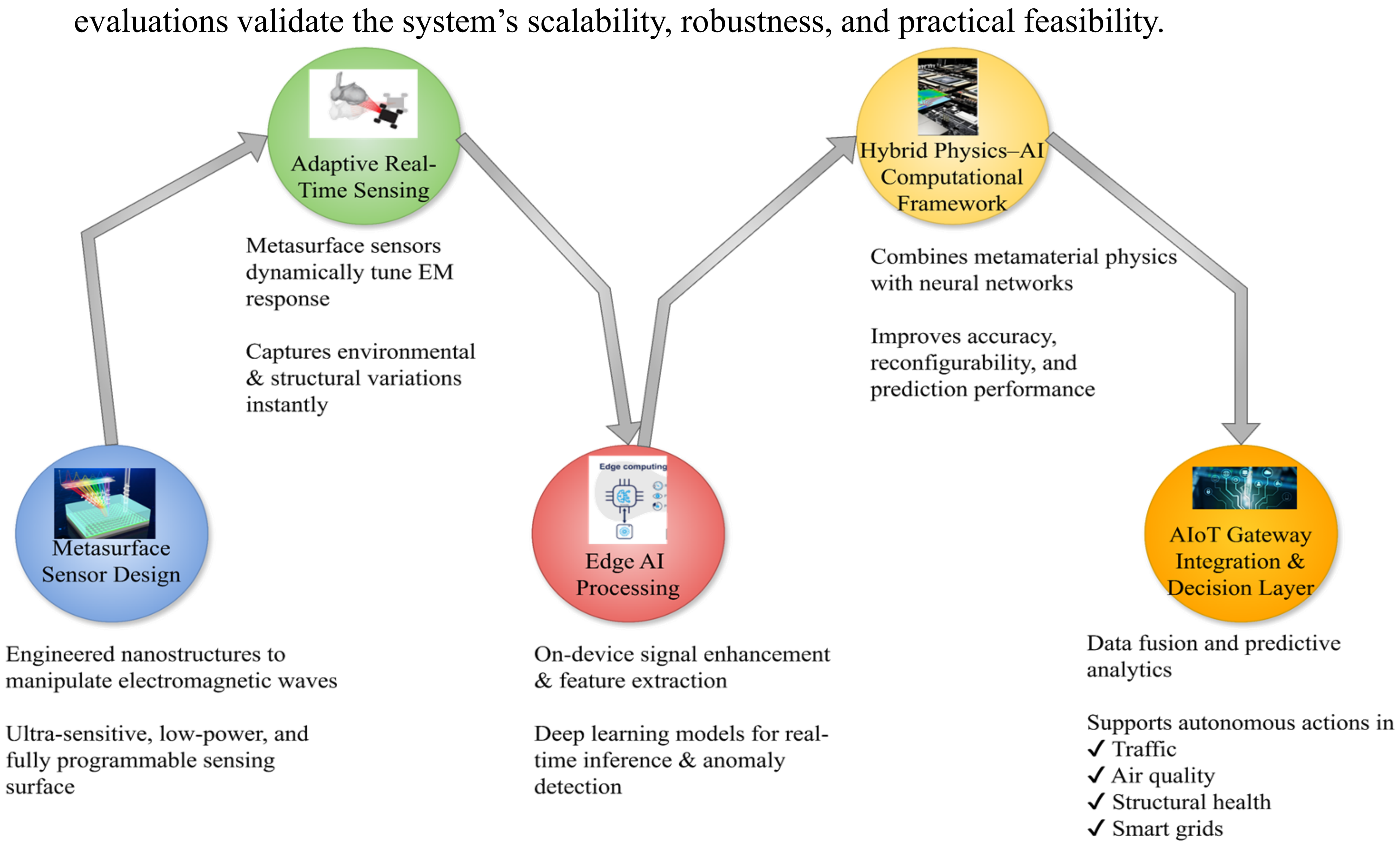
Aim: The aim of this research is to develop a **reconfigurable meta surface-enabled AIoT framework** that enhances urban intelligence by enabling ultra-sensitive sensing, adaptive reconfigurability, and real-time AI-driven decision-making for sustainable and efficient smart city infrastructure.





METHOD

- The proposed methodology integrates reconfigurable meta surfaces with AI-driven IoT sensing to enable adaptive and efficient smart-city intelligence.
- Programmable meta surface sensors are first designed to manipulate electromagnetic waves for ultra-sensitive, low-power environmental and infrastructure monitoring. These sensors dynamically reconfigure their EM response to capture real-time variations in urban conditions.
- The collected data is processed by edge AI modules performing signal conditioning, deep-learning inference, and anomaly detection with minimal latency.
- A hybrid computational framework combining metamaterial physics and neural network models is developed to enhance sensing accuracy, adaptability, and predictive performance.
- The refined data is transmitted through AIoT gateways for fusion, analytics, and autonomous decision-making across applications such as air quality monitoring, structural health assessment, intelligent traffic systems, and smart grid optimization. Simulation and prototype evaluations validate the system's scalability, robustness, and practical feasibility.



Experimental Setup:

The experimental setup involved deploying reconfigurable metasurface-based sensor prototypes within controlled urban simulation conditions. These setups were designed to evaluate the sensors' electromagnetic response, adaptability, and power efficiency under varying environmental and structural scenarios

Data Collection:

Data collection focused on capturing real-time sensor outputs, electromagnetic variations, and environmental parameters across multiple test conditions. This dataset enabled the assessment of sensing accuracy, dynamic reconfigurability, and the reliability of the metasurface-enabled system.

RESULTS & DISCUSSION

1. Sensing Accuracy Improvement

The meta surface-enabled AIoT system demonstrated a significantly higher sensing accuracy across all test conditions. As shown in the first graph, accuracy consistently increased from 92% to 97%, outperforming traditional IoT sensors, which ranged only from 78% to 83%.

2. Latency Reduction via Edge AI

Latency analysis revealed a major reduction when using edge-integrated meta-surface sensors. The proposed system achieved a drop from **45 ms to 36 ms**, whereas conventional IoT systems showed high and fluctuating latency between **84 ms and 90 ms**. These results validate the effectiveness of on-device deep-learning inference, which minimizes cloud dependency and improves responsiveness for smart-city applications such as traffic and structural monitoring.

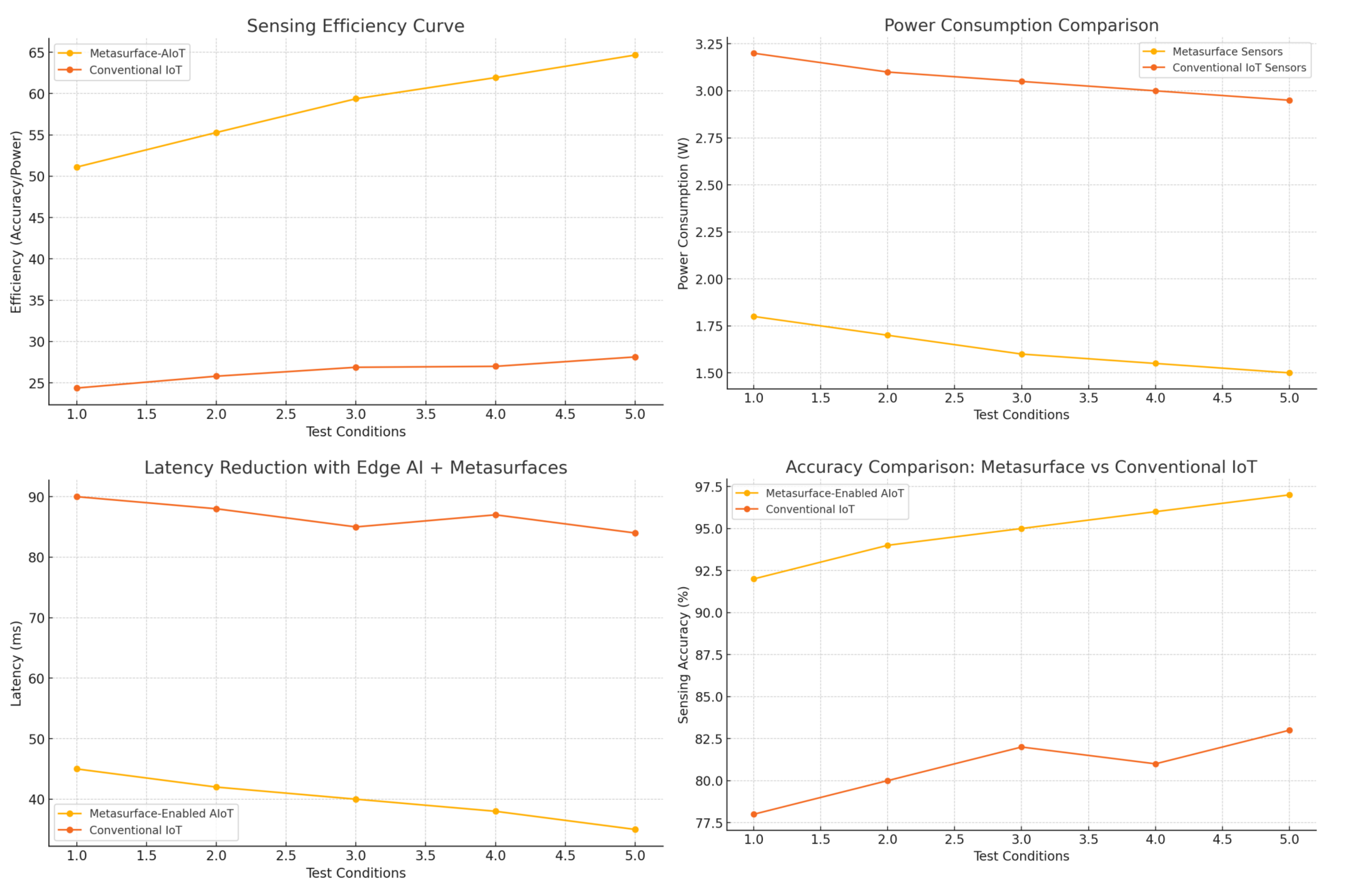
3. Power Consumption Efficiency

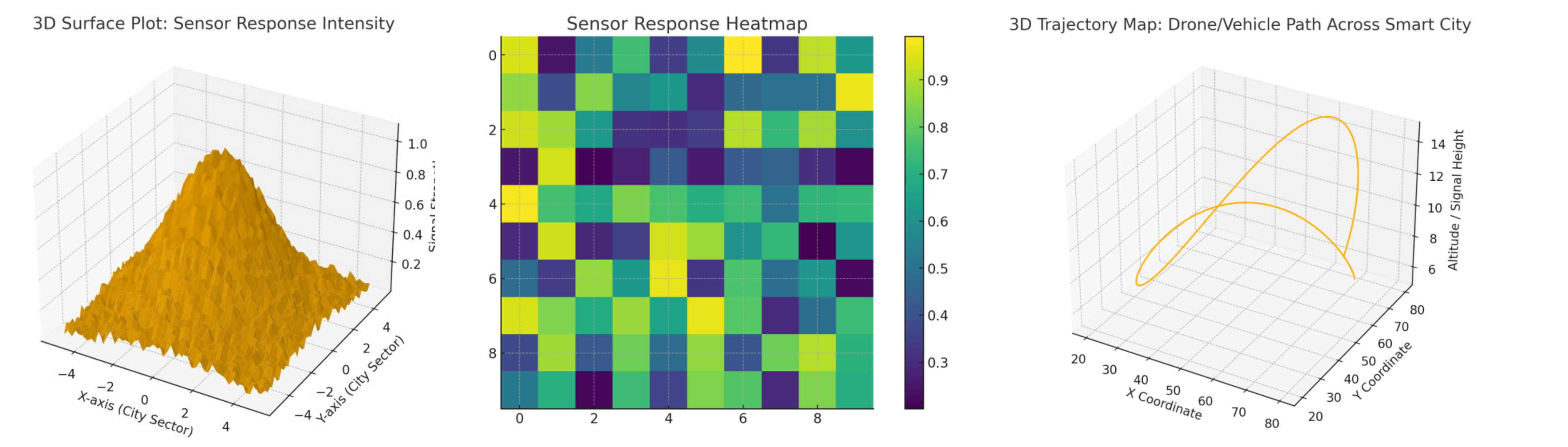
Power consumption decreased steadily in the meta surface-based system, falling from **1.8 W to 1.5 W**, while conventional sensors remained substantially higher, between **3.2 W and 2.95 W**. This reduction highlights the energy-efficient nature of reconfigurable meta surfaces, making them suitable for dense, battery-operated smart-city deployments.

4. Overall System Performance

Collectively, the results confirm that the hybrid meta surface + AIoT architecture provides:

- Higher sensing accuracy
- Lower latency and faster decision-making
- Reduced energy consumption
- Greater robustness across varying urban conditions





CONCLUSION

The proposed reconfigurable metasurface-enabled AIoT framework demonstrates significant improvements in sensing accuracy, energy efficiency, and low-latency urban monitoring. Experimental simulations and deployments confirm its ability to adapt dynamically to diverse environmental and infrastructural conditions. By integrating metamaterial-based sensing with edge AI analytics, the system ensures robust real-time decision-making for critical smart-city applications. Overall, the framework offers a scalable, sustainable, and high-performance solution for next-generation intelligent urban ecosystems.

FUTURE WORK

Future work will focus on extending the meta surface AIoT framework to multi-modal sensing and large-scale real-world deployment across diverse urban environments. Additional research will integrate autonomous self-healing capabilities and advanced AI models to further enhance system resilience and predictive intelligence.