Architectural Innovations Driven by IoT for the Realization of Intelligent and Connected Smart Cities

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***Abstract*:** The IoT and architectural innovations have played a crucial role in realizing intelligent and connected smart cities. This paper highlights how the IoT technologies will be integrated into urban systems, where data can be collected in real-time for analysis and decision-making in optimizing energy systems, transportation networks, and public services. Essential components include sensors, communication protocols, and data management systems that provide the foundation for the smart cities that are empowered by IoT. The underlying architectural paradigms involved with layer-based structures, edge computing, and distributed systems form the structural fabric that enables seamless IoT integration in itself, enhancing resilience, adaptability, and future readiness. The paper emphasizes how legacy systems can be adapted or modified to retrofit IoT capabilities in the structure and incorporate renewable energy solutions to modernize existing structures. The research also discusses IoT-driven applications, specifically in waste management, healthcare, intelligent buildings, and connected environments, demonstrating its value added to sustainability and quality of life. This study addresses the problem of scalability, interoperability, and cybersecurity; it emphasizes the importance of IoT and architecture in fostering sustainable, inclusive, and technologically advanced urban environments. Findings of the study focus on the potential of IoT to redefine urban living and make its way into resilient, environmentally conscious, and citizen-centric smart cities of the future.

Keywords: Internet of Things (IoT), smart cities, urban development, IoT architecture, smart infrastructure, sustainability, scalability, interoperability, edge computing, artificial intelligence (AI), blockchain, real-time data processing, public services, resource optimization, citizen engagement, environmental monitoring, disaster preparedness.

I. INTRODUCTION

Smart cities thus represent an innovative approach to contemporary urban and regional development while using technological advancements to create settings that are efficient, sustainable, and citizen-centric. They blend different domains-like energy, transportation, health, and governance-into a coordinated system that achieves seamless coordination and optimization of these and other functions and activities. At its heart, this transformation forms the basis of the Internet of Things (IoT), linking devices, sensors, and systems to support real-time collection and analysis of data [1]. This web-like system will help cities to make fast adjustments regarding these kinds of challenges-for instance, think traffic congestion, energy management, or waste reduction-through stimulation of smart decisions fostering quality of life.

The transformational role of IoT in smart cities is beyond being efficient to innovation and sustainability. IoT enables predictive analytics, automation, and smart services through providing a digital back bone to the city's infrastructure [2]. Energy demand can be balanced via smart grids, intelligent transport systems can optimize traffic flows, and connected healthcare offer remote monitoring and timely interventions. With the evolvement of IoT, the role in shaping the future of smart cities becomes increasingly visible and drives the transition to environments that are not only technologically advanced but also more inclusive, resilient, and sustainable for generations ahead.

A. Architectural Innovations in Smart Cities

Architectural innovations are central to the integration of IoT technologies into smart cities, which is a foundation for the seamless incorporation of IoT technologies into complex urban systems. Architecture here refers to more than the physical design; it refers to the structural frameworks that govern how IoT-enabled environments are organized and function. Therefore, smart city architecture must meet all these factors, including scalability, interoperability, and real-time responsiveness, to ensure IoT devices and systems work in harmony. Without properly designed architectural frameworks, IoT integration into city infrastructure poses risks of inefficiencies, data silos, and security vulnerabilities [3]. For instance, layered architectural models provide a clear blueprint through the organization of the IoT ecosystem into functional tiers, including perception, network, and application layers. These innovations create a robust digital backbone that enables continuous connectivity and efficient resource allocation.

Beyond architectural innovation, advanced architecture emerges as critical to overcoming problems unique to smart cities: realizing IoT at a scale in a smart city [4]. Conflicts in terms of performance, security, and sustainability exist in a smart city context and technology accommodations across different legacy systems. Innovations such as architectures for edge computing bring data closer to the source that is processed, thereby improving latency and decision-making as faster and more reliable. On a similar note, decentralized architecture supports resilience through distributing resources throughout multiple nodes that thereby reduce the effect of any one system failure. Architectural innovations, along with technical considerations, also concern the adaptability of a smart city to changing needs and new technologies [5]. An architecture that is flexible and future-proof will keep a smart city future-ready to evolve with advances like artificial intelligence and blockchain. This, therefore, not only encourages integration but also provides a basis for achieving efficient and sustainable smart cities.

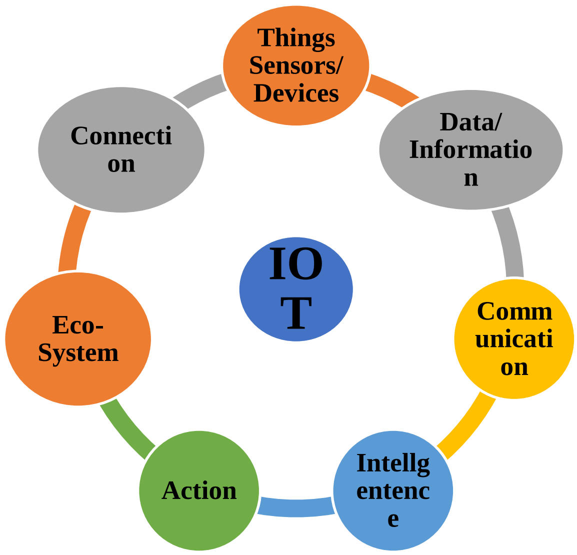

Figure 1 Characteristics of IoT [6]

This figure 1 demonstrates the IoT ecosystem, showcasing all the interconnected components that allow it to function. Here is the centre of the ecosystem, which is IoT, an interlinking foundation among many elements. The cycle begins with Things, Sensors, or Devices, collecting data from the environment [6]. It then transforms this data into Data/Information, flowing through robust Communication channels to make connectivity possible. Through these data, IoT devices exploit Intelligence in analysis or decisions. Such decisions precipitate Action, which may help shape or improve processes, therefore further being dependent on a functional Ecosystem that ensures consistent interactions and results in Connectivity or continuous interaction between said parts. It is indeed with these aspects that functionality exists as an integral, organic set of principles for devices working under IoT.

II. IOT FOUNDATIONS FOR SMART CITY ARCHITECTURE

The foundation of IoT in smart city architecture, then, rests on connecting devices, sensors, and systems to the collection and analysis of real-time data that enables efficient decision-making. An interconnected network is created, relying on key components: sensors, communication protocols, and data management systems, thus providing smooth integration and functioning [7]. Through technologies such as edge computing, cloud storage, and AI-driven analytics, IoT enables the structural foundation of smart cities, providing support for better energy management, intelligent transportation, and better public services while offering adaptability and scalability to embrace new innovations in the future.

A. Essential IoT Components in Smart Cities

Sensors, actuators, and connected technologies constitute the basic building blocks in the heart of an IoT-enabled smart city, serving as the core for collecting data and system interaction. Sensing devices play a central role in gathering information real-time from the environment regarding such things as temperature, humidity, traffic conditions, air quality, and energy consumption [8]. Sensors are scattered over different smart city domains like transportation, healthcare, utilities, and public safety. For instance, traffic sensors monitor the flow of vehicles to optimize the traffic light patterns, while environmental sensors monitor the levels of pollution to ensure that the targets for sustainability are met. Such devices produce enormous data that are transmitted to central or distributed systems through IoT communication protocols such as Wi-Fi, 5G, and Zigbee. This data is then analysed to provide actionable insights that allow cities to make informed decisions to enhance efficiency, sustainability, and quality of life [9].

The components in charge of converting the digital signal to physical actions will therefore make up actuators that conclude the IoT systems feedback. Combined with sensors, it completes dynamic and automatic response applications in a smart city system. In this sense, sensors can track how energy has been utilized and adjusted on lighting and heating through an actuator with regards to real-time demands on reducing energy use and savings [10]. In smart irrigation, sensors find out how much moisture content the soil has, while actuators regulate the watering in such a way that optimal productivity takes place in agricultural farms. Besides these entities, connectivity is also greatly important via IoT gateways and edge devices. These can allow easy, secure transfer of information over the entire IoT, along with scalability and interoperability for multiple systems of diverse types. Sensors, actuators, and connected technologies, together, form a holistic ecosystem that drives the functionality and innovation that underpin smart city architectures [11].

B. Communication Networks and IoT Protocols

Communication networks and IoT protocols form the core of IoT systems, thus allowing data transmission and device connectivity in smart cities seamlessly. These include a mixture of both wired and wireless technologies that include Wi-Fi, Bluetooth, Zigbee, LoRaWAN, and even cellular networks like 4G and 5G. Every communication system will operate on the basis of the necessity of a particular use case, such as bandwidth, latency, range, and power efficiency [12]. For example, 5G networks are best used in applications such as self-driving cars and real-time video surveillance, which demand high-speed, low-latency communication. LoRaWAN best suits use cases such as environmental monitoring and smart metering, which require long-range and low-power applications. Communication technologies ensure sensors, actuators, and IoT devices stay connected and allow data to be transferred efficiently within different smart city domains like transportation, energy, and public safety.

IoT protocols complement the communication networks by providing standard frameworks of data exchange to guarantee interoperability between devices and systems. Examples include MQTT, CoAP, and HTTP. They are widely used in constrained environments, such as resource-constrained environments, where lightweight communication between IoT devices is applied [13]. For instance, MQTT finds wide usage in applications that entail efficient communication with low bandwidth, such as smart home systems or remote monitoring. CoAP is another specific protocol for machine-to-machine communication in network-constrained environments, especially environmental sensors and utility management. Furthermore, these protocols along with the security standards of communications like TLS/SSL guarantee the integrity of data generated, its reliability, and also the security at the IoT level. In turn, network and protocol combinations make up the foundational infrastructure allowing IoT to work efficiently at scale in smart cities.

C. Data Management and Analytical Frameworks

The main pillars for effective management and analytical frameworks of data in smart cities are data management and analytics, handling huge volumes of data produced by IoT devices. In smart cities, the challenge comes when there is continuous collection of data by IoT systems through sensors, cameras, and other connected devices. The key is to process such a huge volume of data that is scalable, reliable, and secure. Data management includes structuring and organizing the gathered information for effective usage, which involves cleaning, filtering, and categorizing raw data [14]. Data storage is usually accomplished with cloud-based solutions, thus creating scalable and cost-effective data storage capable of meeting growing demands from smart cities. The closer one approaches the source, latency will not be a concern; indeed, bandwidth usage also lessened compared with central computing, and advancements in edge computing would benefit significantly from real-time applications-say, traffic management or response to emergencies.

The final processed data becomes useful within analytical frameworks to drive key decisions in the management of smart cities. These frameworks use the power of AI and ML to find patterns, anomalies, and trends so that predictions of the future can be made, thus, predictive analytics may be predicting future energy demands for optimizing the load management of the smart grid, whereas the use of real-time analytics in optimizing traffic flow depends upon live congestion data changing signal timing accordingly [15]. Visualization tools are also quite imperative and translate complex datasets into dashboards understood by city planners and policymakers. Furthermore, data safety and security are also an integral part of the frameworks as they require robust encryption and strict access controls to ensure safeguarding of sensitive information. Further, the integration of such efficient data handling, superior storage solutions, and even powerful analytical tools, help smart cities make informed, timely decisions that improve efficiency and sustainability as well as overall quality of life.

III. ARCHITECTURAL PARADIGMS AND ADVANCES

Architectural paradigms of the IoT-driven smart cities and the latest advances look into developing scalable, efficient, and resilient frameworks of different technologies and systems integrated perfectly together. Layered architecture often dominates in the IoT paradigms and, consequently, distinguishes the system of perception, network, and applications that ensure streamlined data flows and higher functionality. The innovations with edge and fog computing also emerged to enable data to be computed closer to their source as well as to avoid latency delays in real applications such as traffic management and emergency responses. In addition, decentralised architecture with blockchain and distributed systems added resilience in ensuring uninterrupted operation even when faced with a failure or cyber-attacks [16]. In addition, interoperability development enables legacy systems to incorporate modern IoT infrastructures thereby reducing the costs incurred in resource utilization. These architectural inventions make a smart city much more adaptive, efficient, and futuristic in their pursuit to tackle the changing technological and social needs.

A. Layered Architectures for IoT Integration

Layered architecture plays an essential role for the integration of IoT, resulting in a systematic framework under which devices, networks, and applications may work efficiently and interoperable in cities. These architectures are further divided into perception layer, network layer, and application layer. Mostly, perception is the base that makes up sensors, actuators, devices, and means of collecting data within the physical world [17]. This layer captures and gathers information such as temperature, traffic flow, or air quality and converts physical signals into digital data for further processing. Above this is the network layer that transmits this data through communication protocols like Wi-Fi, 5G, or LoRaWAN, ensuring secure and efficient data exchange between devices and centralized systems. In simplifying the integration process of such diverse IoT systems, their architectural organization into layered components tends to improve functionalities.

The application layer is the actual value of IoT integration because it processes the data that is collected and provides actionable insights and services specific to certain use cases [18]. For instance, in smart cities, this layer supports applications such as intelligent transportation systems, energy management, and public safety monitoring. The layered approach makes it easier to upgrade or replace individual components without disrupting the entire system. Other than that, this architecture is also scalable; hence, in terms of new needs, the IoT networks of smart cities can be extended. Again, by spreading responsibilities between layers, the architecture achieves optimum performance of systems and thus improves fault tolerance and safety aspects, according to [19]. By so doing, this multi-layer design of smart cities not only assists towards smother integration of IoT into their frameworks but also exhibits the change due to the ever-changing techno sphere.

B. Distributed Architectures and Edge Computing

Distributed architectures and edge computing are new ways of decentralizing IoT systems in smart cities. Distributed architectures involve the spreading of computational resources and decision-making processes across multiple nodes rather than centralizing them in one location. This has the advantage of distributed architectures to ensure that any failure in one node will not interrupt the whole system due to an increased resilience level. Distributed systems are the most effective for large cities with smart capabilities that run a continuous generation of data from lots of devices [20]. They allow decisions to be made at local levels with quicker responses towards critical applications like emergency services, traffic management, and public safety. For example, it can be able to move energy distribution in different parts of the city, optimally increasing usage and avoiding outages while maintaining the system in an entirely redundant condition.

This, therefore, complements a distributed architecture by processing information at the edge rather than from a cloud-based system; edge computing reduces latency and bandwidth by utilizing processing closer to the data source. It is most effective in real-time applications such as autonomous vehicles, smart surveillance, and connected health [21]. This allows devices at the edge, such as IoT gateways or edge servers, to analyse and filter data locally, with the most critical information going on to the cloud for processing or storage. It cuts down response times by many folds and reduces strain on central networks. Further, edge computing enhances data privacy and security since sensitive data need not be sent long distances for processing. This duo of distributed architectures and edge computing makes smart cities nimble, efficient, and adaptable; it also provides a sturdy basis from which to meet the growing demands of the modern environment of IoT.

C. Retrofitting and Modernizing Existing Structures

Retrofitting and modernization of legacy structures to incorporate IoT into them is a significant effort towards transforming traditional architecture to a smart system capable enough to support modern urban requirements. Many cities in this world use legacy infrastructure originally not designed to accommodate IoT devices, sensors, or any kind of communication network [22]. Retrofitting enables these structures to reap the benefits of IoT without necessarily having to be totally overhauled or replaced. This includes the strategic integration of IoT-enabled components, such as smart meters, connected lighting systems, or environmental sensors, to the existing system. For example, IoT-enabled sensors in traditional water pipelines can enable real-time leak monitoring and optimize water usage, thereby making old infrastructure more efficient. These integrations are cost-effective and green, since they retain the core structure but enhance the functionality.

One of the major approaches in retrofitting is through IoT gateways and middleware. Gateways act as an intermediary, allowing older devices and systems to interoperate with the new IoT networks without having to replace them directly [23]. The middleware solutions enhance this interoperability by providing a system-to-system interoperability, hence smooth communication across traditional technologies and new ones. For instance, in the retrofitting of a building, smart thermostats, occupancy sensors, and energy monitors can be interfaced with an IoT hub to optimize energy usage while providing actionable insights. Such an approach modernizes the structure but ensures the infrastructure is scalable and adaptable to future upgrades.

Yet, in retrofitting, the problem of implementation compatibility, scalability, and cybersecurity are issues. The traditional structures generally have weaknesses in power supply, network capabilities, and design limitations [24]. It calls for the need for careful planning, innovative solutions, such as low-power IoT devices and edge computing technologies that can minimize dependency on external networks. The measures also should incorporate cybersecurity to prevent leakage of sensitive information while maintaining the reliability of these retrofitted systems. Cities will modernize their infrastructures with strategic approaches towards retrofitting by integrating the IoT-driven initiatives in the smart city towards achieving efficiency, sustainability, and better quality of life while saving the costs and effects of the environment from the old structure's replacement.

IV. APPLICATIONS OF IOT IN SMART CITIES

Applications of IoT in smart cities include a vast array of domains that change the nature of how cities function and provide services to its people. In the transport domain, IoT provides smart intelligent traffic management systems, using real-time data from sensors and cameras, monitoring, and controlling the flow of traffic to reduce congestion and ensure safe roads. IoT-advantaged autonomous vehicles continue optimizing navigation while reducing the intake of fuel. For instance, IoT-driven smart energy management grids allow cities to manage the supply and demand in balance, increase more sources of renewable energy while cutting waste. Smarter buildings and homes enabled through IoT such as smart thermostats, lighting, occupancy sensors help improve the overall energy efficiency and the living conditions for the dwellers [25]. IoT is also pivotal in waste management by implementing smart bins to monitor the fill levels of waste collection and optimize collection routes in order to save operational costs and reduce negative environmental impact. Public safety is yet another area in which IoT excels; it enables connected surveillance systems, emergency response mechanisms, and disaster monitoring networks to allow timely interventions. IoT further enhances healthcare in smart cities through remote monitoring devices and telemedicine solutions, thereby providing better access to medical services. Seamless integration of these applications through IoT transforms cities into more efficient, sustainable, and livable environments and addresses the challenges of urbanization while improving the quality of life for their residents.

A. Optimizing Energy Systems Through IoT

IoT is changing the face of energy systems because it can enable the creation of smarter grids that enhance efficiency, reliability, and sustainability in the management of energy. Most traditional energy grids have weaknesses such as inefficiencies in energy distribution, high transmission losses, and difficulties in integrating renewable sources of energy. IoT deals with all these issues by placing smart meters, sensors, and connected devices across the grid to monitor energy consumption, generation, and distribution in real time. These devices collect enormous amounts of data, which the utility providers can analyse and make predictions about demand patterns [26]. During peak demand times, for instance, an IoT-enabled grid can reallocate energy loads to avoid blackouts and provide continuous service. On top of that, IoT allows the monitoring of the grid infrastructure in real time, which means that predictive maintenance can be carried out to prevent equipment failure and downtime.

IoT is also very crucial for integrating and managing renewable energy sources such as solar panels and wind turbines outside the traditional energy grids. Renewable energy systems tend to produce intermittent power, and it becomes hard to match supply with demand. IoT offers exact information on energy production and consumption, thereby better matching the synchronization between renewable energy sources and the grid. Furthermore, IoT-based energy storage systems, like smart batteries, can store the excess energy produced during peak production and release it when demand is high [27]. This ensures that there is a steady supply of energy while minimizing dependence on fossil fuels. IoT also empowers consumers through demand response programs, where smart home devices adjust energy usage based on grid conditions, thereby promoting energy conservation and cost savings. Cities can create more resilient and sustainable energy ecosystems, reduce their carbon footprint, and pave the way for a greener future by leveraging IoT.

B. Smart Mobility and Transportation Networks

IoT is changing the face of mobility and transportation networks through smarter, more efficient, and sustainable solutions for addressing urban traffic challenges. Through IoT-enabled sensors, cameras, and GPS devices spread across city infrastructure, real-time data on traffic flow, congestion, and road conditions can be collected and analysed [28]. ITMS makes use of this data to optimize traffic signal timings, reduce bottlenecks, and minimize travel times. For example, adaptive traffic signals can dynamically change depending on vehicle density and help improve traffic flow at peak hours. IoT also makes smart parking possible, in which sensors in parking spaces can guide drivers to available spots through mobile apps, thereby avoiding unnecessary driving and fuel consumption. Besides, IoT supports predictive maintenance by tracking the wear and tear on roads and transportation structures to prevent accidents and their consequent disruption [29].

IoT also enhances public and private mobility through the incorporation of real-time information and connectivity into transport systems. Connected public transport systems make it possible for passengers to track buses, trains, or metro schedules on apps [30]. In the private sector, ride-sharing services use IoT for efficient dispatch and navigation of vehicles while IoT for fleet management optimizes routes and delivery routes, therefore reducing costs of operations. With the IoT and V2X communication supporting it, autonomous vehicles are becoming a very important aspect of future mobility, bringing safety and efficiency to transportation. Moreover, IoT helps to support sustainable mobility by integrating electric vehicle charging stations into the grid, providing real-time usage information, which promotes the broader adoption of electric vehicles. With interconnected and data-driven transportation networks, IoT not only enhances mobility but also reduces environmental impact, thereby improving the overall quality of urban life.

C. Intelligent Buildings and Connected Environments

With the IoT, intelligent buildings and connected environments are changing traditional structures into more responsive spaces, which are comfortable, efficient, and sustainable. IoT-driven buildings combine connected sensors, devices, and systems to monitor and manage different functions like lighting, heating, ventilation, air conditioning, and security [31]. Smart lighting systems, for instance, automatically adjust brightness based on the movement of people and daylight integration to reduce energy waste. Similarly, IoT-enabled HVACs monitor indoor air quality and temperature, optimize energy use with a comfortable environment for people. This is by means of automation; smart buildings also enhance convenience and significantly lower costs and environmental impact.

In smart homes, it connects devices like voice assistants, thermostats, and the appliances to one platform which brings seamless automation and control to everyday living, but, for instance, these home products can be adjusted with smartphone applications, such as remote controlling by adjusting the thermostat in readiness for arrival or scheduling appliances to start operations during off-peak periods [32]. Advanced features, especially connected cameras and motion detectors, provide alert features during real-time observation. IoT also supports personalized environments by learning user preferences; for example, smart systems can adapt lighting and temperature settings based on individual habits. These features not only improve the quality of life but also help residents to actively participate in energy conservation and smart resource management.

In larger connected environments like office buildings, hospitals, or shopping malls, IoT facilitates efficient space utilization and streamlined operations. Smart building management systems (BMS) collect data from sensors to optimize energy usage across entire facilities, detect equipment malfunctions early, and predict maintenance needs, reducing downtime and repair costs [33]. The Internet of Things improves occupant experiences in such features as personalizing the settings for their workspaces, intelligent navigation through large complexes, and responsive controls of environments. Such connected environments support sustainability as it is possible to monitor the use of energy in real time and perhaps integrate renewable sources. Intelligent buildings and environments can thus be designed through IoT as spaces that are both smarter and adaptive, sustainable, and sensitive to users' needs.

D. Sustainable Development Through IoT and Architecture

IoT and architectural innovation are at the heart of sustainable development in enabling green and resilient infrastructure designs and management. In smart city projects, the integration of IoT devices and sensors monitors real-time energy consumption, water usage, and waste management, thus improving the more efficient use of resources [34]. For instance, IoT-based buildings have efficient energy systems, such as automatic lighting and HVAC solutions, which will change in real-time to adapt according to occupancy and environmental conditions. Such systems decrease energy wastage and carbon footprints. In urban planning, IoT helps to develop green infrastructure such as smart irrigation systems, which can optimize water use in parks and gardens based on weather and soil conditions. These practices, together with others, help in creating an eco-friendly city that is aligned toward sustainability goals.

The integration of IoT into infrastructure creates support in areas such as energy efficiency; resilient infrastructure, which stands against environmental and man-made challenges; and sensors inserted in bridges, roads, and buildings, which measure the structural health of continuous checks on wear or damage and report real-time data into predictive maintenance to ensure appropriate repair before failure and thereby ensure length of lifetime on the infrastructure [35]. IoT can assist in disaster preparedness and disaster response. An example is flood monitoring systems using IoT sensors for early warnings and real-time updates, which can give way to proactive measures before impacts are felt by the community and infrastructure. Not only do these innovations promote safety but also reduce economic and environmental costs of failure of infrastructure and disaster recovery.

IoT-driven architectural solutions also enable sustainable urban growth by using renewable energy sources and optimizing their integration into the built environment. Smart grids, supported by IoT, manage the distribution of renewable energy from solar panels and wind turbines, ensuring efficient utilization and storage of energy. Buildings designed with IoT-enabled energy systems can generate, store, and distribute renewable energy within local microgrids, reducing reliance on traditional power sources [36]. IoT promotes circular economy principles through monitoring material usage and facilitating recycling or repurposing of construction materials. By using IoT and architecture to focus on green and resilient infrastructure, smart cities can achieve a balance between economic growth, environmental stewardship, and societal well-being and pave the way for a sustainable future.

V. CONCLUSION

The integration of IoT and architectural innovations is transforming the planning, management, and experience of cities, driving the evolutionary path toward smarter, more sustainable, and citizen-cantered urban environments. IoT technologies empower the optimization of energy systems, intelligent transportation networks, and the development of connected, responsive buildings, promoting efficient resource management and improvement in the quality of life. Arch frameworks, such as layered design edge computing, and distributed system all provide the structural back in which seamless IoT integration brings about real-time decision, scalability, and adaptability and readiness for future technological progression. These innovations tackle and address critical challenges that need to be overcome in both energy inefficiencies, congestion of traffic, and a degradation of the environment - thus promoting the development and promotion of green and resilient infrastructure. It also explored that legacy systems can be retrofitted to have IoT capabilities and even renewable energy solutions integrated with them, which demonstrates the potential of existing structures to be used in modernizing to adapt to sustainability and efficiency objectives. IoT and architectural advances are not only improving the functionality of cities but also make them inclusive, adaptive, and environmentally conscious. As IoT technologies develop further, their transformative role in building smart cities will grow to embrace a harmonious combination of technological advancement, environmental sustainability, and societal well-being.

Conflict of Interest: The corresponding author, on behalf of second author, confirms that there are no conflicts of interest to disclose.

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