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Technologies and Challenges of IoT in Smart Cities: A Systematic Survey: A Review

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ABSTRACT: The Internet of Things (IoT) in smart cities is a network connecting various devices and technologies, reducing the need for human intervention. This framework is crucial in developing smarter cities worldwide, enhancing sustainable living and urban efficiency. The paper delves into the core elements of IoT in smart cities, including architectural frameworks, networking technologies, and AI algorithms. It also explores practical implementations in different urban sectors and discusses the challenges and solutions in deploying IoT infrastructure in these environments. The Internet of Things (IoT) is a transformative technology that has revolutionized the development and operation of smart cities. This survey provides an overview of the integration of IoT technologies within urban environments, focusing on the core technologies, practices, and challenges involved. The paper discusses the various IoT-based solutions that contribute to efficient city management, including smart traffic systems, energy management, waste management, and healthcare. Additionally, it explores the technological components such as sensors, communication protocols, cloud computing, and data analytics that enable these applications. Despite the promising potential, the adoption of IoT in smart cities faces numerous challenges, including security and privacy concerns, interoperability issues, and scalability limitations. Furthermore, this paper highlights the need for policy frameworks and collaboration between stakeholders to overcome these barriers. Finally, the paper offers insights into future trends and opportunities for the continued evolution of IoT in smart cities.

KEYWORDS: IoT in Smart Cities, IoT Architecture, Smart Infrastructure, Urban IoT Challenges, Smart City Components, Fog and Edge Computing.

1. INTRODUCTION

As the world population expands and urbanization increases, projected to rise by over 10% in the next 30 years, it's anticipated that by 2050, 70% of the population will reside in urban areas. This growth necessitates countries worldwide to prepare their cities for the surging influx of people and the subsequent pressures on existing urban systems[1]. In line with the UN Sustainable Development Goals for 2030, Smart Cities have emerged as key initiatives by governments worldwide. These projects aim to prepare cities for the anticipated population increase, enhancing the living experience for urban residents. Such initiatives are being pursued at both public and private levels, demonstrating a commitment to creating more navigable, welcoming urban environments[2]. This survey presents a comprehensive review of the Internet of Things (IoT) in Smart Cities and its role in supporting such initiatives. Due to the high interest in this subject among researchers, numerous related surveys were discovered during the literature search, indicating the topic's relevance and expanding body of knowledge[3]. In this survey, we offer a distinct perspective from the authors in [4],who discuss IoT deployment challenges in Smart Cities and rank them based on expert opinions. Our approach diverges by not relying solely on specific expert views, thus avoiding limitations to their application domains. We aim to provide a broader discussion on the critical elements IoT designers in Smart Cities should consider, addressing practices relevant to each of these aspects[4]. This survey provides a unique perspective compared to other studies. While[5] focuses on IoT architectures and applications in Smart Cities, and delve into application-oriented discussions with case studies, this survey offers a more comprehensive overview. It covers the core elements and technologies in smart city implementations and their current usage, differentiating from the specific angles of [5]. The survey's structure, as outlined in Figure 1, emphasizes a broader and more detailed exploration of these topics.

2. RESEARCH METHODOLOGY

2.1. Literature Selection Criteria

A systematic literature review was conducted to collect and analyze scholarly work on IoT in smart cities from academic databases such as IEEE Xplore, ScienceDirect, SpringerLink, and Google Scholar. The inclusion criteria for selected literature were:

- Peer-reviewed journal articles and conference proceedings (2014–2024)

- Focus on IoT technologies and architectures applied within smart city contexts
- Papers discussing real-world implementations, case studies, or experimental models
- Papers identifying technical or policy-level challenges in IoT deployment

2.2. Data Classification Approach

The selected literature was categorized into the following thematic areas aligned with the structure of the paper:

- Smart City Components (e.g., smart energy, health, transportation, etc.)
- IoT Architecture Models (Cloud, Fog, Edge Computing)
- Key Challenges in IoT Implementation (e.g., Security, Sensors, Networking, Big Data)
- Mitigation Strategies and Future Research Directions

This classification helped synthesize scattered findings into coherent subsections for in-depth analysis.

2.3 Analytical Framework

To critically examine the contributions, each selected work was analyzed based on:

- Technological scope (sensors, connectivity protocols, analytics)
- Application domain relevance (e.g., transport, health, governance)
- Scalability, interoperability, and energy efficiency
- Identified barriers (e.g., data privacy, standards, routing)
- Proposed mitigation techniques (e.g., decentralized computing, encryption, AI-based analytics)

A qualitative synthesis was employed to contrast findings across different studies and summarize technological convergence and divergence patterns.

2.4 Validation of Findings

To ensure reliability and coverage of current practices, the survey integrates:

- Comparative insights from recent meta-reviews and framework-based studies
- Industry case reports and whitepapers on pilot smart city projects
- Standards and regulatory reports to understand governance implications

2.5 Limitations

While the study covers a broad set of peer-reviewed papers and case studies, certain limitations persist:

- Rapidly evolving technologies may outpace literature cycles
- Some practical implementations are underrepresented due to confidentiality or lack of documentation
- Quantitative meta-analysis was not conducted, limiting numerical aggregation of effectiveness metrics

3. SMART CITY COMPONENTS

A smart city is an integrated city system that links a wide array of technological components with a vision to enhance efficiency, sustainability, and urban quality of life. Serving as the center of its functionality is a robust data lifecycle that includes data acquisition, transmission, storage, and smart processing. Data collection is highly application-specific and based on a massive network of sensors, cameras, GPS devices, smart meters, and cellular phones integrated into the city infrastructure. They are tailored to diverse industries such as transportation, health, energy, waste management, and environmental monitoring. As the domains of application grow, sensor technologies get more advanced with more emphasis on low power usage, high precision, and real-time capabilities. Once gathered, data is conveyed through secure and high-speed communications networks—i.e., city-wide Wi-Fi, 4G, 5G, and IoT-specific local area networks (LoRa, Zigbee) to central or decentralized cloud platforms[4].

Cloud storage is an essential determinant in organizing, aggregating, and preserving the vast quantities of urban data, which is then subjected to multi-layered analytics. Analysis ranges from simple statistical appraisals to extremely sophisticated computational models. Cloud computing infrastructure drives sophisticated analytics on data, driven by machine learning, deep learning, and other artificial intelligence (AI) techniques-based scalable and real-time processing. These help cities extract actionable insights, predict city behaviors, and automate services such as calibrating energy consumption, detecting traffic congestion, or predicting equipment failures in utilities. Lastly, by putting together such components, intelligent cities can make intelligent, evidence-based decisions that improve operational effectiveness, promote environmental sustainability, and improve the well-being of all the residents [6].

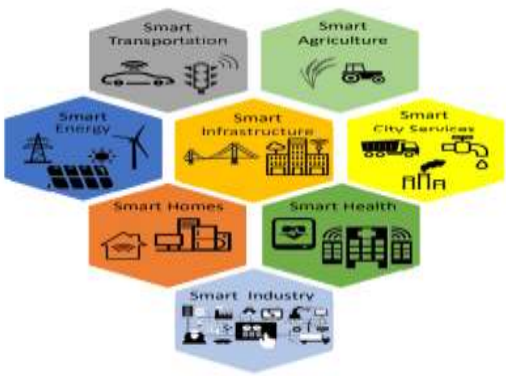

Figure 1. Smart City Components

3.1. Smart Agriculture

Smart agriculture plays a vital role in the achievement of the United Nations' 2030 Sustainable Development Goals (SDGs), particularly in ensuring food security in the midst of climate change and population growth. By employing technology such as IoT, sensors, and data analysis, smart agriculture provides real-time tracking of soil quality, weather, crop health, and water usage. Sensors in fields and crops collect useful data, which is subsequently analyzed to support precision farming practice-irrigation, fertilizer use, and pest control optimization. This not only boosts crop yields and efficiency in resource utilization but also resistance to environmental challenges, thereby making food production more sustainable and responsive to future demands.[7].

3.2. Smart City Services

Smart city operations encompass a wide array of primary urban activities towards the improvement of the quality of urban life, combined with resource use efficiency and sustainability. Primary municipal functions such as water supply, waste disposal, control of air quality, and environmental monitoring are increasingly being supplemented through the implementation of smart technology. Among the most critical areas is water resource management, and the utilization of advanced sensors has become a top priority [7]. IoT-based water quality sensors provide continuous and real-time monitoring of temperature, chemical content, turbidity, and pH levels. It enables quick detection of contamination, as well as detection of faults in infrastructure such as pipe leakage, and prevention of water loss. Additionally, the information collected is in support of predictive maintenance and evidence-based policy-making, and it guarantees that one of the most fundamental urban resources, water, is provided safely, sustainably, and efficiently. Such technologies allow smart cities to provide credible public services while keeping operational spending and environmental impact at a minimum.[8].

3.3. Smart Energy

Smart energy systems represent a transformative shift from traditional centralized power models toward more dynamic, decentralized, and data-driven approaches. Conventional electrical grids—often powered by hydroelectric or fossil fuel sources—operate on a unidirectional energy flow, where electricity is transmitted from a central generator to consumers. These systems rely primarily on feedback from substations, lacking real-time insight into actual consumer demand, which frequently results in inefficient overproduction and energy waste [9] With the growing adoption of cost-effective renewable energy sources such as solar and wind, consumers are increasingly becoming "prosumers" - both producing and consuming electricity. Smart Grids address the limitations of traditional systems by integrating Information and Communication Technologies (ICT) to create a responsive, adaptive energy infrastructure. These grids enable real-time monitoring and control of energy flows, allowing for two-way communication between utilities and consumers. They support distributed generation, facilitate the integration of diverse energy sources, and introduce self-healing capabilities that detect and respond to faults autonomously. By leveraging predictive analytics and big data, Smart Grids enhance energy efficiency, balance supply and demand dynamically, reduce environmental impact, and ensure a more stable and resilient power supply for modern cities [10].

3.4. Smart Health

Smart Health refers to the application of Information and Communication Technology (ICT) in health systems to improve the availability, effectiveness, and overall quality of health care services. It has gained prominence with increasing global populations, high costs of healthcare, and mounting pressure on traditional healthcare facilities. The majority of the existing systems are faced with high patient demand, limited resources, and geographical disparities in the supply of healthcare. Smart Health overcomes these hurdles by leveraging digital technologies such as telemedicine, health mobile apps, electronic health records, wearable monitoring systems, and AI-driven diagnostics. Telemedicine, in particular, plays a central role in extending medical services to remote or underserved areas with limited in-person encounters and maximum continuity of care. In addition, Smart Health enables real-time observation of patients and sharing of information that helps with early diagnosis, customized treatment, and prevention. By networking patients, medical professionals, and medical information through secure digital platforms, Smart Health enhances modern healthcare systems as well as makes them more responsive, accessible, and sustainable[10].

3.5. Smart Home

Smart Homes are a fundamental element of Smart Cities and are key to enhancing the quality of life of residents through the use of smart technologies. They incorporate a network of sensors and smart devices which collaborate to sense and manage aspects of the indoor environment. Sensors can monitor user activity, presence, indoor air quality, temperature, lighting, and energy consumption. This is real-time information that provides excellent insights into habits of daily living and enables the provision of automated adjustments to ensure maximum comfort, security, and energy efficiency. For example, smart thermostats can learn the habits of the user in order to deliver heat and cooling management, while motion detectors offer security and automation of lighting. Smart home systems also assist in sustainability by inhibiting wasteful energy usage and facilitating remote control and monitoring through mobile applications. As part of a larger smart city system, Smart Homes are not only convenient and improve living standards but also generate data that can be utilized to inform urban planning and resource management in the city[11].

3.6. Smart Transport

Urban centers often face traffic challenges like congestion, pollution, and issues with public transport efficiency and cost. The growth of Information and Communication Technologies has enabled the development of smart transportation systems, involving Vehicle-to-Vehicle (V2V), Vehicle-to-Infrastructure (V2I), Vehicle-to-Pedestrian (V2P), and Pedestrian-to-Infrastructure (P2I) communications. These technologies leverage GPS devices in cars and the ubiquity of cellphones to monitor traffic patterns and driver behavior, aiding in the design and implementation of more efficient urban transport systems[12].

4. IOT TECHNOLOGIES IN SMART CITIES

At the heart of modern smart city development, the Internet of Things (IoT) is a foundational technology that makes the easy integration of the physical and digital worlds possible. The Internet of Things refers to a broad network of intercommunicating devices-ranging from sensors, cameras, and meters to automobiles and home appliances—that communicate and exchange data via the internet. This connectivity makes urban systems more responsive, efficient, and adaptive to real-time conditions. In the context of smart cities, IoT enables a myriad of applications such as smart traffic control, environmental monitoring, smart lighting, energy efficiency, public safety, and waste management. These sensors continuously accumulate huge volumes of city data and submit it to centralized cloud-based infrastructure or edge computing platforms, which are analyzed using advanced algorithms for pattern recognition, anomaly detection, and forecasting. This data-driven approach enables evidence-based decision-making for city planners, policymakers, and service providers.[13].

It is estimated that over 75 billion active IoT devices would be in use globally by 2025, driving the next generation of urban development and digital infrastructure. The intersection of IoT with emerging technologies like AI, 5G, and blockchain takes the reliability, scalability, and security of smart city environments even further. For instance, AI-based IoT networks can dynamically adjust traffic lights based on congestion levels, and intelligent grids optimize electricity supply distribution to avoid waste and cost. Real-time IoT sensor data also increases urban resilience since it facilitates rapid response to disasters, natural disasters, or system failures. With increasing urbanisation, IoT technologies must be employed to make sustainable, habitable, and inclusive cities that are sensitive to emerging social and environmental challenges[11].

4.1. Core Components and Architectural Frameworks

The architecture of IoT systems in smart cities is generally conceptualized into three primary layers, each playing a critical role in the overall ecosystem:

a. **Perception Layer:** This foundational layer comprises heterogeneous sensors and actuators deployed across city infrastructures. These devices detect and measure various physical parameters such as temperature, humidity, air quality, noise levels, traffic density, and energy consumption. The diversity of sensors ranges from simple environmental monitors to complex biometric devices used in healthcare applications. The accuracy, reliability, and energy efficiency of these devices are paramount, given their widespread deployment and often constrained power resources.

b. **Network Layer:** Acting as the communication backbone, this layer facilitates data transmission between perception devices and upper-level processing units. It encompasses a variety of communication technologies, including cellular networks (notably 5G and emerging 5G-Advanced), Low Power Wide Area Networks (LPWAN) such as LoRaWAN and NB-IoT, Wi-Fi 6, and emerging protocols tailored for IoT requirements. The selection of communication technologies depends on factors such as data rate, range, energy consumption, latency, and cost.

c. **Application Layer**: This topmost layer handles data aggregation, processing, storage, and analytics. Cloud computing platforms provide scalable resources for big data processing, while edge and fog computing paradigms bring computation closer to data sources, reducing latency and bandwidth usage. Artificial intelligence (AI) and machine learning algorithms are extensively employed to extract actionable insights, perform predictive analytics, and enable autonomous decision-making.

Figure 2 depicts a typical three-layer IoT architecture for smart cities, illustrating the flow of data from physical sensors through communication networks to intelligent applications.

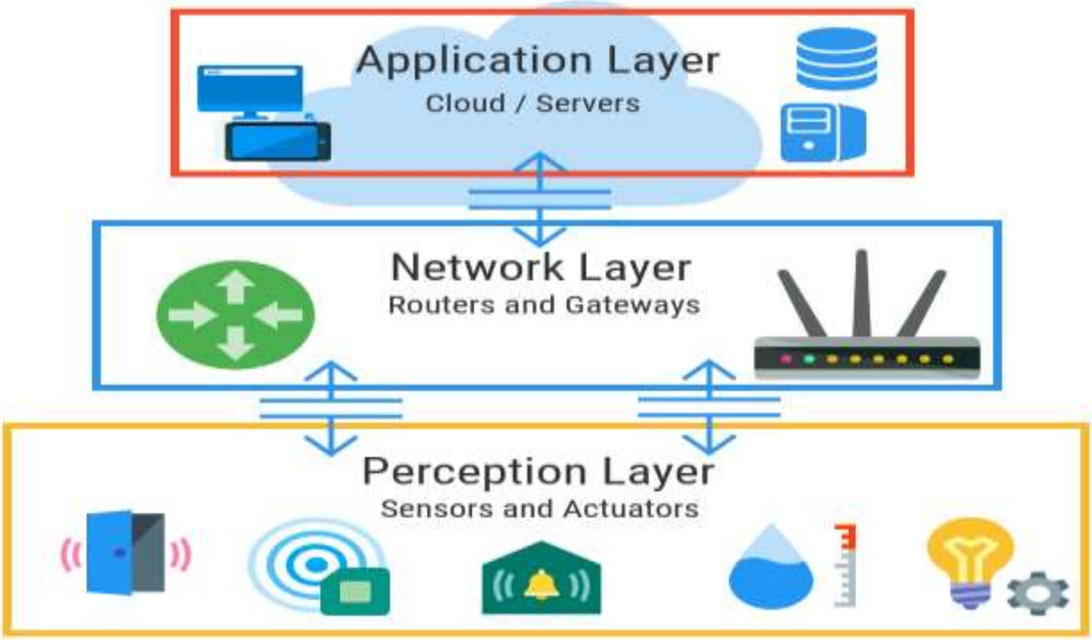

Figure 2: Typical IoT Architecture in Smart Cities

4.2. Communication Technologies: Detailed Analysis

It is the foundation of IoT-enabled smart cities. The following table (Table 1) is a comparison of the most prevalent communication technologies in terms of their technical characteristics, typical uses, advantages, and disadvantages.

Table 1: Comparison of IoT Communication Technologies in Smart Cities

Technology	Features	Use Cases	Advantages	Limitations	References
5G	Offers ultra-high bandwidth (up to 10 Gbps), ultra-low latency (<1 ms), and massive device connectivity	Autonomous vehicles, real-time video surveillance, emergency services	Supports massive IoT deployments, reliable and fast communication, enables mission-critical applications	High infrastructure costs, complex deployment, requires dense base station networks	[8],[11]
LPWAN (LoRa, NB-IoT)	Low data rate (~0.3-50 kbps), long-range (up to 15 km), low power consumption	Smart metering, environmental monitoring, waste management	Energy efficient, wide area coverage, low operational costs	Limited throughput, not suitable for real-time high-data applications	[5],[11]
Wi-Fi 6	High throughput (up to 9.6 Gbps), improved efficiency in dense environments	Public Wi-Fi hotspots, indoor sensor networks, smart buildings	High speed, backward compatible, easy deployment	Limited range (~100 meters), higher power consumption	[5],[8]

Selection of communications technology is generally a trade-off between power consumption, data rate, coverage, and cost. For example, 5G is specifically best for latency-sensitive applications such as autonomous cars and real-time public safety location tracking but is too costly for large-scale deployments of sensors. Conversely, LPWAN technologies are optimal for battery-operated sensors that infrequently need to send data across vast distances [8].

4.3. AI and Data Analytics in Smart Cities

The sheer volume and velocity of the data generated by IoT devices demand advanced analytics to transform raw data into actionable insights. AI and machine learning algorithms are now integral to smart city solutions, enabling [1][3][5]:

- **Predictive Maintenance:** Sensors on roads, bridges, and public transport feed data to AI models that predict failures before they happen, reducing downtime and maintenance costs.
- **Traffic Flow Optimization:** Machine learning algorithms run on real-time traffic flows to dynamically adjust traffic light timings, reduce congestion, and optimize bus/train schedules.
- **Energy Consumption Forecasting:** AI models run on real-time as well as past energy consumption to optimize the operation of the grid and promote energy conservation.
- **Anomaly Detection:** AI systems monitor environmental and security data to recognize atypical patterns that indicate mishaps, crimes, or system failures.

5. IOT DATA PROCESSING ARCHITECTURES

5.1. Cloud Computing Model

The first proposed architecture for IoT systems revolves around the concept of cloud-based data processing. Cloud computing offers uninterrupted access to shared resources like computing, storage, and services over a network. This system dynamically allocates resources without human intervention, accessible from various platforms. The cloud serves as a central management platform for IoT systems in smart cities, handling tasks like observation, control, command dissemination, and data mining. Its large computing and storage capacities enable complex tasks like pattern extraction and making inferences from sensor data, optimizing smart city operations[14].

5.2. Fog Computing Model

Fog Computing, proposed to address the limitations of cloud computing in IoT, shifts some data processing to local network devices. It occurs mainly at the 'edge' of the IoT system, where most data is generated. This approach utilizes routers and network devices for initial data operations, such as aggregation, collection, and simple processing. By performing these tasks locally, Fog Computing reduces the data load sent to the higher cloud layer, offering a more distributed processing structure in IoT networks. In the decision-making process within IoT systems, several key questions arise. These include determining the necessity of averaging certain data, the feasibility of extrapolating or using current measurements, and the potential of providing decision options based on historical data, which could enhance the efficiency of cloud resource utilization. Fog layers offer localized decision-making by accessing local data, facilitating distributed decision-making for specific applications. Additionally, they enable the creation of local networks using technologies like Zigbee, Bluetooth, and RFID, where data is transmitted to Fog nodes connected to the cloud[15].

5.3. Edge Computing Model

Fog Computing's aim was to move decision-making closer to the network's edge, leveraging increasingly capable devices at edge nodes for processing and simple decision-making. This helps further reduce costs and promotes deeper distributed decision-making. Edge computing processes data at the sensor or device level within the IoT system. It's also viewed as a middle layer between the Fog and sensors, focusing on data aggregation and decision-making on a smaller scale than Fog devices. Both Fog and Edge computing paradigms aim to decentralize the IoT system, reducing costs, enhancing scalability, and increasing robustness[16].

Table 2: summarizes the key characteristics of these computing models

Computing Model	Location of Processing	Latency	Scalability	Typical Applications	References
Cloud	Centralized data centers	High	Very high	Big data analytics, long-term storage	[14]
Fog	Network edge devices (routers, gateways)	Medium	High	Localized analytics, traffic control	[15]
Edge	Sensor/device level	Very low	Moderate	Real-time control, emergency response	[16]

6. IOT CHALLENGES FOR SMART CITIES

The Internet of Things (IoT) is set to digitize every aspect of our lives, particularly in smart cities where it involves widespread deployment of sensors across various city functions. Given the broad application range, implementing IoT systems in smart cities presents significant challenges. This paper discusses these challenges, focusing on the technological aspects that are crucial for IoT deployment in smart city contexts and have been a primary area of research interest.

In the context of Smart City IoT system deployment, Figure 3 identifies key challenges: Security and Privacy, Smart Sensors, Networking, and Big Data Analytics. Table 3 then summarizes these challenges, providing an overview of the complexities and considerations involved in deploying IoT systems within smart cities. This summary emphasizes the importance of addressing these areas to ensure effective and secure IoT integration in urban environments.

Figure 3. Challenges of IoT in Smart Cities.

6.1. Security and Privacy

In smart cities, security and privacy are paramount concerns. The online integration of crucial city infrastructures makes them vulnerable to disruptions, posing risks to both citizens and property. In an era where cybercrime is rampant, smart cities could become targets for malicious attacks. Encrypting data transmission is vital in this context. Citizen trust and participation are crucial for the success of smart city projects, yet the widespread use of sensors raises privacy concerns by potentially revealing personal activities. The paper suggests anonymizing data collection while maintaining its context for effective decision-making, addressing both security and privacy issues in depth.

6.2. Smart Sensors

Smart sensors in smart cities, produced by various vendors, differ in their sensing mechanisms, measurement standards, data formats, and connectivity protocols. Integrating these diverse devices in smart cities necessitates their ability to exchange data and aggregate it for making inferences. One solution is developing open protocols and data formats, enabling interoperability among devices from different manufacturers, thereby facilitating IoT system deployment. Another approach is creating standard access point nodes capable of communicating with devices using multiple protocols and interpreting the received data. Some manufacturers have already started making their products compatible with other protocols[17].

6.3. Networking

The Internet of Things (IoT) in smart cities hinges on the networking capabilities of various devices to communicate with each other and the Cloud. The challenge lies in providing these devices with reliable connectivity, as current networks are not fully optimized for smart city components. These devices often have specific mobility and data throughput needs for quality service. Solutions include defining new access points and local networks, and developing efficient, dynamic routing protocols that cater to both stationary and mobile devices, a feature not fully supported by many existing protocols[18].

6.4. Big Data Analytics

In 2018, IoT devices generated 13.6 Zetta Bytes of data, a figure expected to rise to 79.4 Zetta Bytes by 2025. To harness this data for improving smart city services, new data analytics algorithms must be developed. These algorithms should handle both structured and unstructured data, incorporating advanced data fusion techniques to draw meaningful inferences and recognize patterns. Deep learning, particularly effective with large data sets, is gaining attention in this field. It's crucial that these algorithms are scalable, ensuring their applicability across various applications within smart cities[19].

Table 3. Smart City IoT Challenges and Mitigation.

Challenge	Mitigation/Research Direction	Refrence
Security and Privacy	Encryption New authentication mechanisms New standards to anonymize data Prevent data leakage(paraphres)	[20]
Smart Sensors	Interoperability: Open Standards ability and Robustness: Decentralized and distributed architectures and decision making Power and Memory: Energy harvesting, Low power sensors, New database storage systems	[21]
Networking	Low power networks, Network schemes that ensure fluent mobility and routing	[22]
Big data analytics	ew algorithms which work with different natured data, Develop scalable and explainable AI	[23]

7. CONCLUSION

The integration of Internet of Things (IoT) technologies is effectively transforming urban environments into smarter, more sustainable, and citizen-centric cities through the enablement of real-time data collection, intelligent processing, and autonomous decision-making across major domains such as traffic management, energy, waste, healthcare, and public safety. Despite huge technological advancements in sensors, communication protocols, cloud, fog, and edge computing, as well as AI-driven analytics, there are numerous challenges that still persist, including security loopholes, privacy concerns, interoperability hurdles, scalability roadblocks, and the sheer need for energy-aware solutions. Addressing these challenges necessitates a holistic strategy involving the integration of technological innovation-including the uptake of open standards, the utilization of decentralized computing paradigms, and the incorporation of blockchain for secure data management-with strong policy structures and multistakeholder engagement between governments, industry, and citizens. Emerging trends like the integration of AI and IoT (AIoT), the use of digital twins for urban simulation, and a greater focus on energy-harvesting IoT devices for sustainable cities will further augment the potential and role of smart cities. Ultimately, the successful deployment of IoT in the urban ecosystem can enhance quality of life, optimize the utilization of resources, and develop resilient and adaptive cities. But turning this vision into a reality necessitates ongoing research, ethical consideration, along with collective resolve to surmount the complex technical and societal challenges in the pipeline, so that IoT remains an enabler of the sustainable, efficient, and inclusive city of the future.

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