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Review

Enabling Technologies for Next-Generation Smart Cities: A Comprehensive Review and Research Directions

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Abstract: The concept of smart cities, which aim to enhance the quality of urban life through innovative technologies and policies, has gained significant momentum in recent years. As we approach the era of next-generation smart cities, it becomes crucial to explore the key enabling technologies that will shape their development. This work reviews the leading technologies driving the future of smart cities. The work begins by introducing the main requirements of different smart city applications; then, the enabling technologies are presented. This work highlights the transformative potential of the Internet of things (IoT) to facilitate data collection and analysis to improve urban infrastructure and services. As a complementary technology, distributed edge computing brings computational power closer to devices, reducing the reliance on centralized data centers. Another key technology is virtualization, which optimizes resource utilization, enabling multiple virtual environments to run efficiently on shared hardware. Software-defined networking (SDN) emerges as a pivotal technology that brings flexibility and scalability to smart city networks, allowing for dynamic network management and resource allocation. Artificial intelligence (AI) is another approach for managing smart cities by enabling predictive analytics, automation, and smart decision making based on vast amounts of data. Lastly, the blockchain is introduced as a promising approach for smart cities to achieve the required security. The review concludes by identifying potential research directions to address the challenges and complexities brought about by integrating these key enabling technologies.

Keywords: smart city; blockchain; software-defined networking; IoT; edge computing; AI

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1. Introduction

The smart city concept is an evolving framework that introduces innovative services in transportation, energy management, and healthcare on a large scale, creating technologically advanced urban environments [1]. Smart cities depend on heterogeneous technologies and wireless devices, enabling real-time monitoring and control of various aspects of the city [2].

A smart city utilizes advanced technology and data-driven approaches to optimize its infrastructure and services to increase efficiency, sustainability, and usability [3]. By integrating people, devices, and systems seamlessly, smart cities create highly connected environments. Data are collected through sensors and analyzed using data analytics tools, enabling informed decision making in infrastructure management, transportation, energy consumption, public safety, and environmental protection [4].

Enhanced sustainability is a key advantage of smart cities, which is achieved through technologies that reduce the city's energy consumption, waste, and carbon footprint. For instance, smart illumination systems use sensors to detect human presence and automatically adjust the lighting to conserve energy [5]. Smart cities focus on providing personalized and responsive services to citizens, often through mobile apps, enabling access to information, payment for services, and feedback submission, leading to improvements in service quality and overall livability [6].

As an emerging urban planning and development paradigm, smart cities offer solutions to pressing urban challenges, particularly in the transportation sector [7]. By employing sophisticated technologies, smart cities can manage traffic flow efficiently, reduce congestion, and improve intermodal connectivity, thereby minimizing carbon emissions and air pollution [8].

Smart cities have garnered considerable attention from academic and industrial communities in recent years. Many proposals were presented to develop robust and reliable smart city networks or specific smart city applications [9].

There is no standardization of smart cities yet; nevertheless, the main features of smart cities can be viewed as six different axes. These axes can be defined as follows [10,11]:

1. Smart economy: This axis comprises economic competitiveness, such as tourism services and outdoor digital marketing. This includes innovation, entrepreneurial business, and digital currency.
2. Smart governance: this axis consists of the services that serve the citizens in a smart city, allowing for the participation of citizens in political opinions and authority performance.
3. Smart environment: this axis characterizes natural conditions and resources, e.g., weather, green areas, energy, and water, to reduce bad effects, better utilize resources, and meet nations' sustainability policies.
4. Smart living: this axis considers the quality of life, including many aspects such as culture, safety, security, health, and education.
5. Smart mobility: this axis considers transportation aspects, including safe transportation sustainability and infrastructure systems.
6. Smart people: this axis is related to human and social technology solutions. It is introduced to get people to be more creative, qualified, and engaged in life-long learning.

This work reviews the key technologies of smart cities, including the Internet of things (IoT), artificial intelligence (AI), distributed computing, network function virtualization (NFV), blockchain, and software-defined networking (SDN). Moreover, it shows the main features of each technology and the objectives of deploying it to enable smart cities.

2. Methodology

This study conducted an in-depth literature search to identify a wide range of scholarly articles within the field. The primary emphasis of the papers was on applications and solutions for smart cities, covering a time frame of the past five years. However, for this in-depth examination, the most relevant works were shortlisted. The selected papers were categorized according to their themes: smart city applications and features, key solutions, and technology integration. We considered the PRISMA protocol during this work [12]. The workflow started with introducing various smart city applications and their key features. Then, benchmark technologies and diverse integration approaches for smart cities were identified. Subsequently, 15 papers presenting relevant solutions based on the mentioned technologies were carefully selected among fifty articles and thoroughly analyzed. The articles were filtered based on the application category, publication year, journal, or conference rank. The selection was carried out in a way that provided relevant articles that covered different smart city applications. Finally, research directions were identified. Figure 1 presents the number of articles considered and excluded at each stage of the proposed work. We considered three main phases of the work development: review of smart city background and applications, key technologies of future smart cities, and applied research.

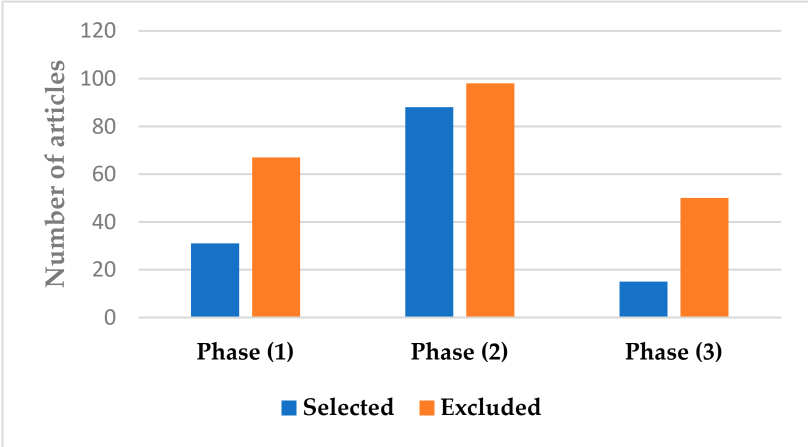

Figure 1. Number of the selected and excluded articles during the main three phases of the work.

2.1. Eligibility Criteria

All included articles in this literature were selected based on the following aspects:

- The degree of relevance to the context of communication networking for smart city applications: The selected articles are research and survey works that consider communication networks for smart cities. This included physical, network, and application layers protocol design and algorithms.
- The data of the publications: All included articles were published over the past five years. More than 80% of the considered works were published in the past two years.
- The rank of the journal or conference: All selected articles are conference or journal articles. Also, technical papers of well-known organizations in the field of ICT, including 3GPP and ITU, were considered. The selected conference papers are of ranked conferences in the Scopus database, and the included journal articles are of high-ranked journals in both Scopus and Web of Science (WoS) databases. Most of the selected journal articles were published in a first- or second-quartile (Q1 or Q2) journal, as indexed by the WoS 2023 report.
- The articles should cover all the topics of the survey: Mainly, the articles cover the topics of smart city applications, specifications of communication networks of smart cities, and challenges in designing communications networks for smart city applications. Moreover, the articles covered the considered key enabling technologies of smart cities, including 5G, AI, IoT, blockchain, edge computing, AI, virtualization, and SDN. Figure 2 summarizes the main topics of the considered articles.

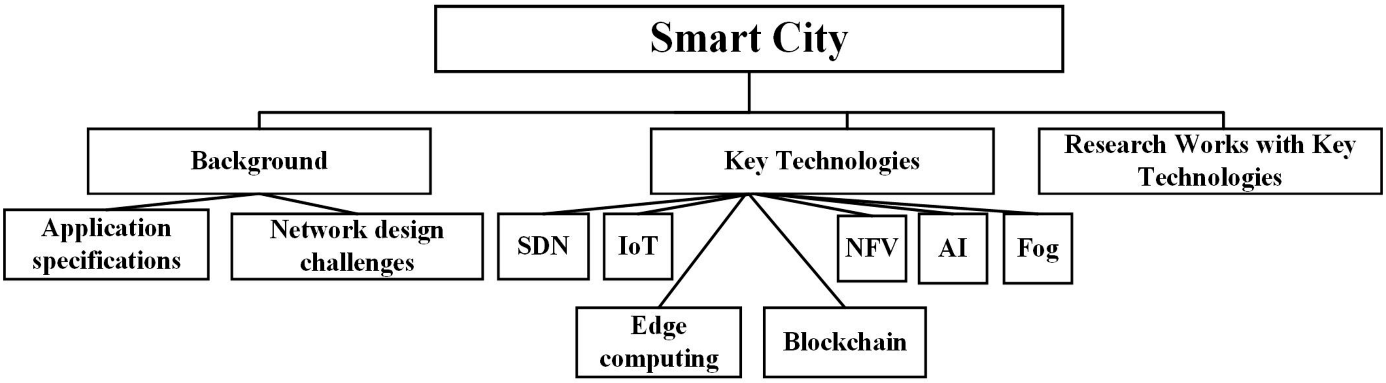

Figure 2. Main topics covered in this work.

During the search process, we used different filters of the search engines of the mentioned databases with certain keywords and strings. Also, Boolean operators were considered to include or exclude some terms to refine the search process. Table 1 highlights the keywords and index terms considered for the Internet paper searches. These terms were grouped into three main categories: smart city, key technologies, and applied research. The first group contained the index terms for gathering data related to smart city background, features, applications, specifications, and challenges. The second group considered the key terms used for gathering data related to key enabling technologies of smart cities that were considered in the work. The third group contained the keywords used to collect data about existing smart city proposals and studies.

Table 1. Main categories of keywords and index terms.

Category	Area	Keywords/Strings
A	Smart city	A1—Smart city A2—Smart city applications A3—Smart city challenges A4—5G use cases A5—Sustainable development
B	Key technologies	B1—Key technologies of future smart cities B2—SDN for smart city networks B3—Benefits of deploying SDN for smart city networks B4—Challenges with SDN-based smart cities B5—NFV for smart cities B6—Challenges with NFV B7—Mobile edge computing for smart city applications B8—Challenges with MEC B9—Internet of things-based smart cities B10—Internet of things connectivity B11—Challenges with IoT-based smart cities B12—Fog computing for smart cities B13—Challenges with fog-based smart cities B14—Blockchain for smart city applications B15—AI-based smart cities B16—Benefits of deploying AI for different smart cities B17—Challenges of implementing AI for smart cities B18—Smart city datasets
C	Applied research	C1—Smart healthcare C2—Smart parking C3—Smart city networking C4—MEC-enabled smart city C5—Fog-enabled smart city C6—Smart grid C7—Smart homes C8—Smart city networking

2.2. Problem Statement

The creation and evolution of smart city applications have encountered significant hurdles attributed to the extensive set of devices involved. Several design challenges face the evolution and development of smart cities; Figure 3 presents the main categories of these challenges.

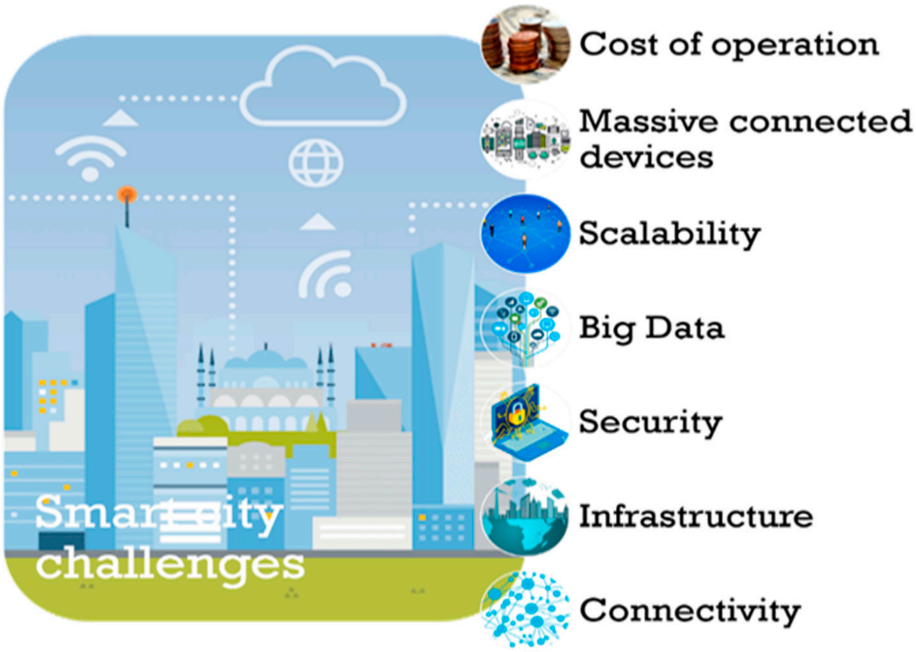

Figure 3. Main categories of smart city challenges.

These groups of challenges are summarized as follows [13–16]:

a. Cost of operation: All organizations depend on innovations for managing data, such as cloud storage and virtualization, but these innovations provide higher costs because of the rapidly rising amount of data. New technologies and high-level software and hardware tools are needed to develop efficient solutions; therefore, smart city operators strive to create effective solutions through cost-effective strategies.

b. Numerous devices: Smart cities require numerous sensors to collect data from various aspects of urban life. These sensors play a crucial role in transforming cities into intelligent, data-driven ecosystems. The proliferation of numerous devices in smart city development poses significant issues that should be handled to ensure smart cities' effective and sustainable implementation. Communication networks of smart cities are anticipated to support dense deployment, which introduces many constraints on the design and development of such networks. These constraints include data management, ensuring coverage requirements, achieving network availability, and managing the communication overhead. Ensuring seamless communication and integration among numerous and heterogeneous smart city devices requires standardized interfaces and protocols.

c. Scalability: Network scalability refers less to the quality of the network than to its efficiency and capacity to accommodate growth with little impact on performance. The scalability of a network is measured by its ability to accommodate the growing number of users, devices, or services without degrading overall performance. For a network to expand effectively, it must maintain its efficiency, even as its capacity or resources increase. As the network grows to meet rising demand, it is important that its performance stays steady or even improves. Large businesses, data centers, cloud infrastructure, and telecommunications networks are just a few examples of settings where expansion is expected, making scalability a crucial factor in network design.

d. Big data (sources, characteristics, and quality): Developers must utilize big data tools to manage, categorize, and maintain heterogeneous data formats, including audio, photos, video, and text, into structured data formats. The complexity and size of data generated by smart city applications and the diversity of end devices pose challenges for software tools in effectively managing and processing such data. It is difficult to handle issues such as data assessment, data management, data development, system architecture, distributed big data mining, data visualization, data compression, and data secrecy. Maintaining some part of the generated data would not be productive if it is irrelevant or redundant. Various resources are essential for data retention and storage. Quality data should only be stored in distributed databases to provide effective data maintenance. The issue for developers is to preserve a higher level of consistency, heterogeneity, and data integrity.

e. Security: Smart city sensors are deployed for surveillance, monitoring, and other critical purposes. Thus, protecting smart city data from malicious attacks is critical. The large-scale deployment of devices in a smart city creates an extensive attack surface for potential cyber threats and privacy breaches. Moreover, smart cities integrate various systems through multiple networks, which increases the risk of potential attacks. Thus, it is essential to implement security approaches to save data, devices, and the entire smart city infrastructure from cyber-attacks.

f. Infrastructure: Smart cities face several infrastructure challenges that should be resolved for sustainable growth. It employs a wide range of sensors to monitor various aspects, including environmental parameters, traffic, waste management, and energy. Deploying and maintaining these sensors throughout the city's infrastructure requires careful planning, installation, and maintenance to ensure accurate and continuous data collection. Smart city initiatives often involve retrofitting existing infrastructure with technology-driven solutions. Integrating new technology with legacy infrastructure is challenging and needs coordination. Urban planning should focus on harmonizing physical infrastructure with digital systems to optimize resource utilization and improve overall city functioning. Smart city infrastructure should be designed to accommodate future growth and expansion. As the city evolves and new technologies emerge, the infrastructure must be scalable and adaptable. Integrating different systems and platforms to enable seamless communication and interoperability between various components is also challenging. Also, the infrastructure should be designed to minimize the environmental impact and improve resilience against natural disasters and other unforeseen events. Implementing eco-friendly solutions and disaster preparedness measures can address these challenges.

g. Connectivity: Smart cities should rely on robust and reliable connectivity to enable seamless data flow between devices, sensors, and infrastructure. Ensuring full coverage across the city can be a significant challenge, particularly in areas with limited infrastructure or remote locations. Moreover, ensuring connection availability over time with dense deployment requires special consideration while designing the communication networks of smart cities.

2.3. Aim and Objectives

Addressing the previously introduced challenges requires deploying novel technologies and solutions. This review investigated these technologies and solutions and deeply examined their benefits to future smart cities. The work's ultimate objective was to review the main key technologies of smart cities, providing the main features of each technology and the objectives of deploying it for enabling smart cities. The main contributions of this work are as follows:

A. Reviewing state-of-the-art smart city applications

Researchers and urban planners can identify successful implementations and best practices by studying existing smart city applications. Reviewing existing smart city applications provides a benchmark for assessing the effectiveness and performance of new approaches.

Studying modern applications allows researchers and developers to evolve their systems and solutions based on the applications' demands and features. Moreover, every city is unique regarding its infrastructure, demographics, and challenges. By studying state-of-the-art applications, city planners can adapt successful models to suit their specific local context, ensuring that smart city solutions are tailored and relevant.

B. Providing challenges of the evolution of smart cities

Cities can mitigate the risks associated with adopting smart city technologies by highlighting challenges. Understanding the potential challenges enables decision makers to take preventative measures, decreasing network drop and failure probabilities. Identifying and presenting challenges in the evolution of smart cities increases stakeholders' and policymakers' awareness of the potential difficulties and complexities of implementing smart city solutions. Awareness of challenges enables researchers to prepare and develop proactive strategies to address them adequately. By understanding the smart city challenges, researchers can develop sustainable and resilient solutions that consider potential environmental, social, and economic impacts.

C. Introducing key enabling technologies of future smart cities

Key enabling technologies, including the IoT, AI, distributed computing, blockchain, and SDN, enable smart cities to optimize resource utilization, reduce energy consumption, and promote sustainable practices. These paradigms have a significant role in achieving the goals of smart cities and overcoming the previously introduced limitations. Key enabling technologies provide powerful tools for addressing complex challenges and tackling these issues more efficiently and effectively. This enables researchers to recognize gaps and limitations in current solutions. By investigating the strengths and weaknesses of existing technologies, researchers can develop novel approaches to address these gaps and improve smart city implementations.

Understanding key enabling technologies helps researchers identify potential research areas and focus on topics that have not been extensively explored. It allows them to align their research with the most relevant and impactful technological trends. Moreover, smart city research often involves interdisciplinary collaboration between various fields, such as computer science, urban planning, engineering, and social sciences. Introducing key enabling technologies helps researchers from different domains communicate effectively and work together to tackle complex urban challenges.

3. Challenges with Smart City Applications

Smart city applications have grown rapidly with sensory manufacturing advances and wireless networking innovations [17]. Figure 4 presents the main smart city applications.

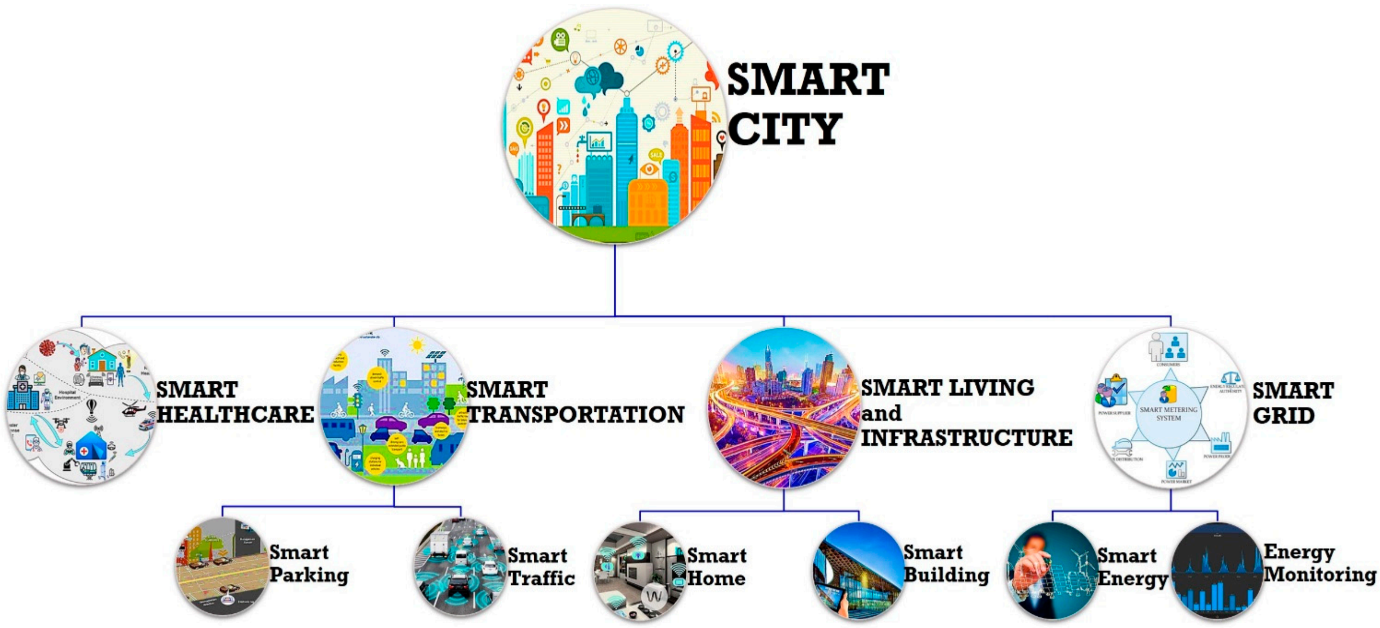

Figure 4. Main categories of smart city applications.

Smart grid: This comprises three main systems, namely, generation, transportation, and consumption [18]. The consumer system deploys sensing devices that control and monitor the machines on premises. One or more nodes act as a gateway and provide connectivity to the Internet. Cloud or edge computing platforms provide processing, analysis, and storage to the smart grid system. Also, a control unit can achieve real-time system management [19].

Buildings, homes, businesses, medical facilities, educational institutions, and other establishments depend on energy. Therefore, a sustainable smart city must have effective power management systems with environment-friendly energy sources, such as photovoltaic cells (PVCs), solar panels, and windmills [20].

Smart living and infrastructures: This domain provides public services in tourism, education, and cultural activities, as well as smart city infrastructure, including smart buildings and homes. Inside the home, everyday tasks are automated using smart technologies, including AI and the IoT [21].

Sensors, IoT gadgets, and network connections are the foundation of smart homes [22,23]. Modern smart homes incorporate solar energy. Additionally, residents must feel secure while they are at home. This necessitates the installation of a continuous monitoring and emergency system. The generated data must be processed and stored in a safe, trusted environment.

A smart home is essential to ensuring residents' quality of life. This infrastructure must, therefore, be upgraded over time in response to user demand [17]. Smart buildings and homes are the major applications of smart cities. Smart homes depend on the capabilities of the control systems to make an environment comfortable at home [24]. Smart buildings are integrated into two levels: physical and virtual levels. The physical level consists of the network capabilities through wired and wireless buildings that combine the power network and transportation system [25]. The virtual level consists of the information shared and operated between residents and used in buildings.

Smart transportation: The most recent advancement in intelligent and autonomous transportation is the development of vehicular ad hoc networks, which allows for inter- and intra-vehicular communications [26,27]. Vehicle connectivity makes real-time traffic analysis easier than the traditional transportation system. Traffic analysis assists in managing traffic congestion, responding to emergencies, and spotting illegal activity on the road [28]. Potential traffic monitoring for airlines makes smooth, secure, and adaptable air travel possible. Several sensors gather weather information, analyze it, and communicate their decision to the air traffic controllers. Onboard computers make intelligent decisions using the same data.

Smart healthcare: Humans have a basic need for healthcare. Measuring a patient's condition with sensor-enabled IoT devices is helpful [29]. Patients' heart rates, oxygen saturation levels, blood pressure, and other parameters can be measured by sensors. Historical patient information can aid in a precise diagnosis. The locations of doctors and nurses can be determined using sensors and paging devices, which can aid in the dispatch of emergency medical teams. Data generated by sophisticated medical and healthcare technologies will be substantial. Medical data are extremely sensitive and require improved privacy and security [30].

Table 2 summarizes the main networking features required for different smart city applications. The main design challenges associated with the evolution of the previously introduced applications are presented in Figure 5.

Table 2. Networking requirements for different smart city applications.

Smart City Application	Latency	Availability	Reliability	Mobility	Deployment Scenarios
Smart grid	Moderate–low	Ultra-high	High	Zero–low	Dense–ultra-dense deployment
Smart homes	Low–ultra-low	High–ultra-high	High–ultra-high	Zero–low	Indoor deployment, dense deployment
Smart building	Moderate–low	Ultra-high	High–ultra-high	Zero	Urban deployment
Smart parking	Moderate–low	High–ultra-high	Medium–high	Low–moderate	Dense deployment
Smart traffic	Low–ultra-low	High–ultra-high	High	Low–high	Dense deployment
Smart healthcare	Ultra-low	Ultra-high	Ultra-high	Low–high	Dense deployment
Industry automation	Ultra-low	Ultra-high	Ultra-high	Zero–low	Dense deployment

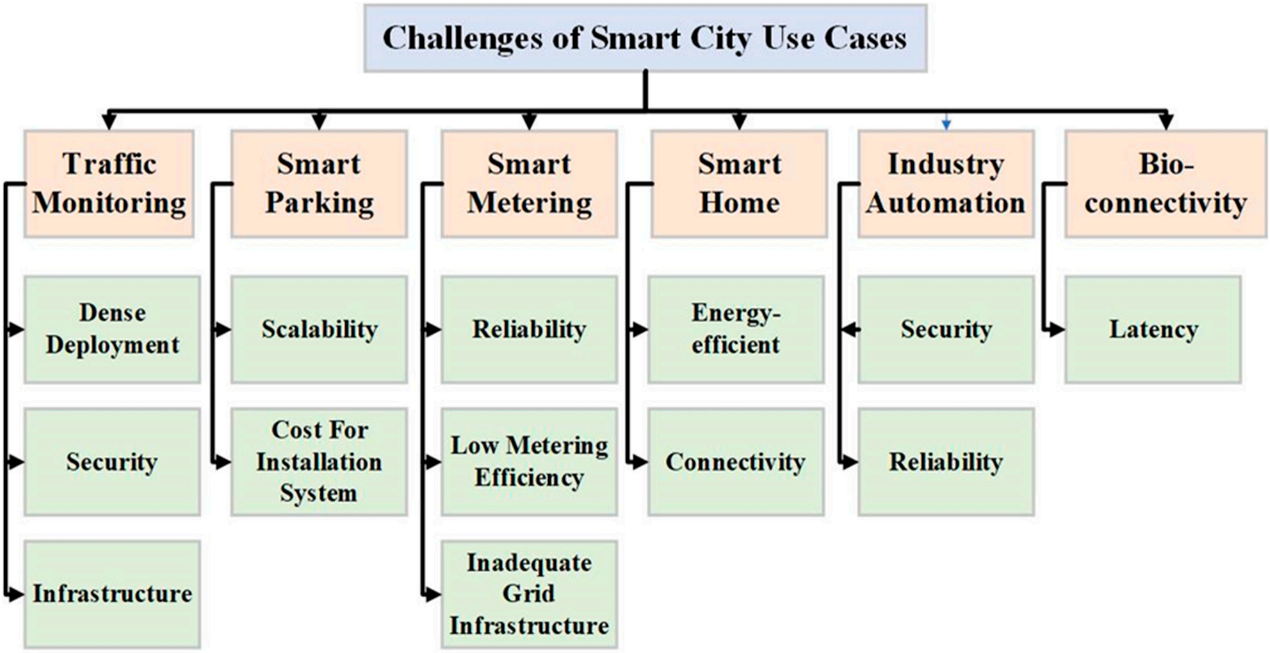

Figure 5. Challenges of smart city applications.

To address these challenges, we introduce different key technologies in the following sections. These challenges are summarized as follows [13–15,23,24]:

a. Dense deployment: The development of future smart city applications necessitates the provision of dense deployment, thus imposing numerous limits on network development. With a high density of devices and sensors, there is a high risk of network congestion. This can result in data transmission delays, increased latency, and decreased system efficacy overall. It is essential to ensure efficient network management and traffic prioritization. Dense deployments in IoT-based smart city networks can cause signal interference in regions with limited spectrum availability. This interference can reduce the quality of data transmission and compromise network dependability. Moreover, managing, processing, and analyzing the massive amount of data resulting from dense deployment is a challenging dilemma. For efficient network performance, efficient data storage, processing, and analytics are required. Accommodating rising demands through scalable dense deployments becomes vital as the city and its needs expand. Incorporating scaling considerations into the design of systems is crucial for ensuring their long-term sustainability.

b. Security and privacy: This is critical to secure the smart city's infrastructure against cyberattacks. As cyber dangers grow, it becomes more challenging to maintain an adequate level of protection. With a large number of networking points and devices distributed over smart cities, network security becomes a major problem. The protection of sensitive data and the prevention of unwanted access or cyberattacks are significant priorities. Concerns about privacy and security may be increased by collecting and processing massive volumes of data from various sources. It is a continual challenge to protect sensitive data while allowing users to access it.

c. Infrastructure: the infrastructure required to enable smart city applications, such as high-speed Internet access, sensor networks, and power sources, may be costly and time-consuming to build.
d. Scalability: Smart city systems must be scalable in terms of both user numbers and data volume. Designing systems that can grow effectively to assure long-term profitability is critical.
e. Cost of installation: the cost of installation of smart city applications can vary widely depending on various factors, including the size of the city, the scope of the project, the complexity of the applications, and the existing infrastructure.
f. Reliability: Most smart city applications require ultra-reliable transmission of less than 10^{-5}. This is challenging with the existing connections and interfaces. Thus, smart cities should introduce novel ways to ensure data reliability, including edge computing, AI, and SDN.
g. Energy efficiency: The growing use of smart city technologies may lead to substantial increases in energy demand. Thus, designing energy-efficient systems and including renewable energy sources is crucial. Moreover, many smart city applications involve deploying battery-operated devices that should be efficiently managed.
h. Latency: The delay of communicated data represents challenges with modern communication technologies. Many smart city applications are classified as ultra-reliable low-latency communications (uRLLC), which requires considerable work on network design to meet the latency demands.

These challenges necessitate introducing novel network structures and promising solutions to overcome such limitations and meet the demands of smart cities. The rest of the work considers introducing novel solutions and key technologies to face such challenges and meet these requirements. Figure 6 presents the leading key technologies that can assist the evolution of smart cities.

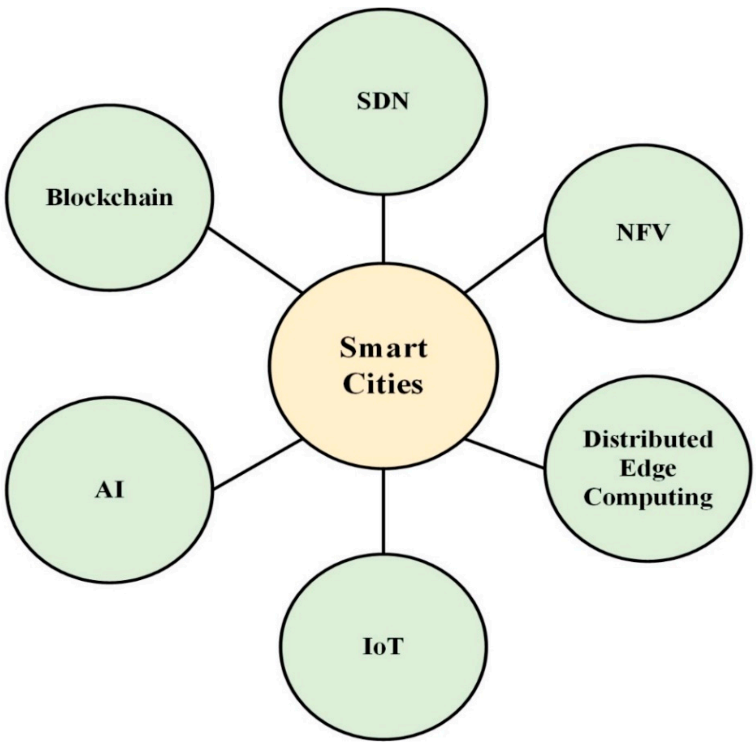

Figure 6. Key technologies of future smart cities.

4. Software-Defined Network (SDN)

An SDN moves the network from the traditional individual devices into a centralized control scheme. It identifies two separate planes: the control and data planes [31]. Separation enables the network controller to have a global view, facilitate the management at run time, reduce data traffic, and increase network flexibility. An SDN traditionally solves the issues of configuring routers and switches, leading to being error prone and not fully utilizing the network infrastructure capability [32]. It provides programmability for deploying network applications by breaking down the control and data planes through virtualization [33].

An SDN is an approach in the networking field where physical devices implement and maintain the network programmatically. Traditional networks cannot adapt to varying information technology (IT) requirements because of their limitations, which are expensive and change slowly [34]. An SDN has numerous benefits, such as automated load balancing, matching data and application needs to scale network resources, simple physical infrastructure, and on-demand provisioning [35]. It facilitates controlling and configuring network performance and troubleshooting using this software [36]. An SDN provides a centralized or distributed software application to control/manage the hardware decoupled from the hardware itself. It achieves programmability and flexibility and facilitates network innovation. The architecture layers of an SDN split the packet forwarding and decision making [37].

4.1. SDN Architecture

An SDN consists of the three-layer system presented in Figure 7.

1. Data plane: This contains packet-forwarding devices and is linked to the control plane via an appropriate interface. The interface is a communication channel that links the controller and application plane or the control and data planes. A southbound interface (SBI) is an interface to or from the controller and network devices, such as Open-Flow [38]. A northbound interface (NBI) is a channel to or from a controller and upstream SDN-aware applications. The east/westbound interface is the communication protocol used to connect the distributed SDN controllers [39].

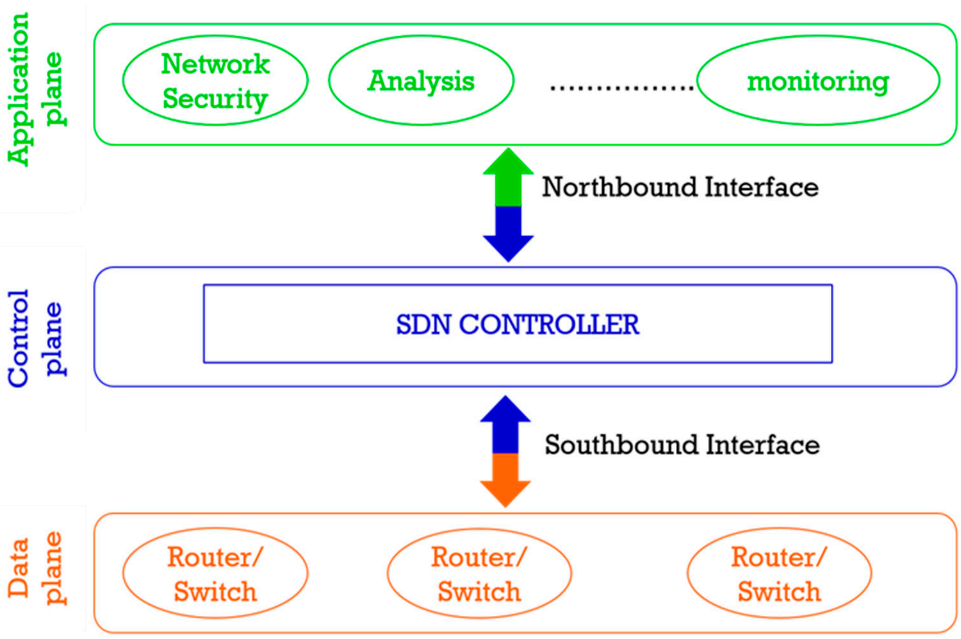

Figure 7. The general structure of SDN technology [40].

2. Control plane: This contains the network operating system (NOS), which orchestrates the operations and the computations. The SDN controller is the network brain, which

engages the network application and services, control plane containers, and database in which information is gathered. The SDN controller handles the routing, manages the interference, and allocates the security functions when finding weird attitudes [41]. It is the powerful plane of SDN network architecture, which manages and configures network traffic. The main requirement of the SDN controller is the flexibility to configure remotely [41]. It is responsible for getting useful information from devices and communicating with the network's abstracting view to SDN applications. Many routing schemes are commonly used with the control plane, including open shortest path first (OSPF), routing information protocol (RIP), and enhanced interior gateway routing protocol (EIGRP), which are managed with IPV4 and IPV6 using the control plane [35]. When the switch receives a packet and checks the matching on the entry table, it acts when there is a corresponding opening in the table. Otherwise, the switch forwards the packet to the SDN controller, which makes the forwarding decision and sends the switch the corresponding decision [41].

3. Application layer: This is above the control plane and is responsible for providing the admin with the network status, accessing the collected data, and offering many other SDN benefits. It is used in business platforms to manage network operations based on the business point of view [35].

4.2. SDN for Smart Cities

Traditionally, reconfiguring a network and adding features are exhaustive because of the fully distributed control. However, SDN is much simpler due to the centralization control, which allows the controller to overcome these complexities. Deploying an SDN for smart cities relieves the tasks of big data management, quality of service (QoS) guarantee, security and privacy concerns, heterogeneity, and communication resilience [35].

It implements the needs of IoT-based smart city networks by providing routing efficiency, managing the network, and optimizing resources by virtualizing IoT devices of the access network [42]. Deploying an SDN for smart cities solves many issues with traditional networks, including scalability, heterogeneity, interoperability between IoT devices, lack of dynamic services, bandwidth reduction, quality of services improvement, and adapting new services [43]. These achieved solutions can be classified into management, security, and architectural solutions. The management solution specifies how the management layer's applications should coordinate with the control layer. It also specifies the management procedure network administrators use in addition to SDN controllers.

Using an SDN, network service providers can easily configure and reprogram devices for smart cities [44]. Access to user equipment and network nodes is governed by several security parameters defined by the security solution. An SDN-based IoT architecture delineates distinct service layers in the control and data planes to better manage network traffic. The data plane illustrates a system for routing data to their intended destination [45].

By deploying SDN technology, smart cities can have a more adaptive, secure, and efficient network structure, enabling the efficient implementation of diverse smart city applications and services. Table 3 summarizes the benefits of implementing SDN for smart cities [42–44].

Table 3. Benefits of implementing SDN for smart cities.

Value Added	SDN for Smart Cities
Resources optimization	With an SDN, network resources can be dynamically allocated based on demand and usage patterns. This resource optimization ensures efficient bandwidth use and minimizes latency, allowing smart cities to operate smoothly and have real-time responses.
Enhancing network security	An SDN enables robust security policies and network segmentation. Segmented networks can isolate sensitive data and critical infrastructure from potential threats, preventing unauthorized access and mitigating security risks.

Table 3. *Cont.*

Value Added	SDN for Smart Cities
Flexibility and scalability	An SDN allows for centralized network management, making scaling and adapting smart city networks easier as the city's requirements evolve. Adding or removing network elements can be done quickly and efficiently, ensuring the network remains flexible to accommodate future growth and changing needs.
Ensuring QoS	In smart cities, various applications have different network demands, such as traffic management, surveillance, and healthcare. An SDN allows for implementing different QoS.
Ease of integration between distributed and centralized clouds	An SDN facilitates seamless integration between cloud and edge computing infrastructures. This integration enables the deployment of edge services closer to the end users, reducing the latency and enhancing the overall performance of smart city applications.
Centralized management	An SDN provides a centralized control plane, enabling operators to manage the entire smart city network. Centralized control enhances network visibility, simplifies management, and allows for dynamic and real-time adjustments to optimize the network performance.
Cost efficient	An SDN's simplified network management and resource optimization lead to cost savings regarding operational expenses (OPEXs) and capital expenditures (CAPEXs). Efficient network utilization reduces the need for additional hardware, optimizing infrastructure investments.
Rapid service deployment	Smart city services often need to be deployed and updated quickly. An SDN enables rapid service deployment through automated configuration and provisioning, reducing the time and effort required to roll out new applications and features.
Network innovation	An SDN allows developers and researchers to innovate and create custom applications and services for smart city systems. The programmability of an SDN fosters a culture of continuous improvement and drives innovation in urban services and applications.
Real-time monitoring and management of network traffic	An SDN enables real-time analytics and monitoring of network traffic and performance. These insights help administrators to make data-driven decisions, identify areas for improvement, and enhance the overall smart city system efficiency.

5. Network Function Virtualization (NFV)

NFV abstracts the hardware resources and embedded software of the network into a single logical entity, i.e., a virtual network [33]. It separates software functions from the hardware and enables the execution of network functions on a processing-based platform, e.g., signal processing in the network's core [46]. There are two common virtualization schemes: internal and external virtualization. Internal virtualization has an on-server single software container to present the functionality of a network. However, external virtualization presents multiple physical resources as a single virtual entity [47].

NFV is one of the greatest developments in the network evolution process that uses a platform of virtualization and commercial hardware to achieve the functionality of a mobile network. It does not depend on hardware devices but uses software modules [48]. The main benefits of NFV are reduced CAPEXs and OPEXs, reduced power consumption, greater flexibility to evolve, scale-up or scale-down services, and deployment of innovation services at minimum risks [49]. NFV does not rely on an SDN (i.e., it can be used alone); however, deploying an SDN with NFV provides wider benefits. It virtualizes and facilitates the dynamic mobility of SDN controllers to the required location [50]. Deploying NFV achieves various benefits, which are summarized as follows [51,52]:

- NFV reduces the cost of the network infrastructure by using virtual resources, i.e., virtual machines (VMs), and replacing the hardware boxes.

- NFV optimizes end users provisioning resources with high QoS and ensures the performance of virtual network functions (VNFs), e.g., low latency.
- NFV has higher flexibility than traditional networks because network operators use new services over the same hardware platform and can dynamically deliver services to customers based on their demands via NFV performance gradation. Software and hardware do various functions because of their separation.
- NFV decreases energy consumption by merging the network devices.
- NFV does not need additional hardware since the network operator can activate the software over virtual resources, e.g., VMs, and containers.
- NFV increases security since the main architecture components of NFV, e.g., virtual infrastructure manager (VIM), can be embedded with security methods.

The NFV infrastructure includes hardware and software resources that link VNFs via the virtualization layer. Examples of the virtualization layer are the hypervisor and the virtualization solutions of containers like Docker. NFV contains the following three main components [53,54]:

1. Virtual network function (VNF): VNF is responsible for the software's functionality to execute network operations specified by the infrastructure of the NFVI on one or multiple VMs.
2. Network function virtualization infrastructure (NFVI): The NFVI has software and hardware resources to manage and support carrier networks, processing, virtual storage, and VNFs.
3. NFV management and orchestration (NFV-MANO): NFV-MANO provides an architectural framework between services of interfaces of VNFs and NFVI and orchestrates their respective sub-components.

Deploying NFV technology in smart city networks offers significant benefits contributing to efficient operation, scalability, and adaptability of urban ecosystems. Table 4 provides some of the main benefits of this deployment [49–52].

Table 4. Benefits of implementing NFV for smart cities.

Value Added	NFV for Smart Cities
Ease of maintenance/migration	NFV facilitates the live migration of VMs. This is particularly valuable for maintaining continuous service availability and performing maintenance tasks.
Ease of recovery	NFV simplifies disaster recovery processes. VMs and their configurations can be easily backed up, replicated, and restored in case of hardware failures or other disruptions, ensuring business continuity for critical smart city services.
Efficient use of hardware	Multiple services and applications can share the same physical hardware without conflicts. This resource sharing increases the utilization of hardware components and reduces the need for dedicated resources for each service, leading to cost savings.
Resources optimization	NFV efficiently allocates computing resources between various smart city applications. This leads to reduced hardware requirements, energy consumption, and cost. Moreover, it achieves higher computing efficiency in terms of overhead.
Ease in integrating new services	NFV accelerates the deployment of new services and applications. VMs can be quickly provisioned, configured, and deployed, allowing smart cities to roll out innovative services faster and respond to emerging needs promptly.
Ease of testing new services	NFV offers a controlled environment for testing and development. New services or updates can be tested in isolated VMs, reducing the risk of disrupting the production environment.
Flexibility	NFV environments are highly adaptable. Smart cities can reconfigure and repurpose virtual resources as needed, enabling them to respond quickly to changing requirements and technological advancements.
Resource scaling	NFV enables the dynamic scaling of resources based on demand. As the usage of smart city services fluctuates, virtualized environments can scale up or down to accommodate changing workloads, ensuring optimal performance and responsiveness.

Table 4. *Cont.*

Value Added	NFV for Smart Cities
Enhanced security	NFV provides a strong separation between different applications and services running on the same physical infrastructure. This isolation enhances security by minimizing the potential for breaches and unauthorized access.
Resource partitioning	NFV allows resources to be partitioned and allocated based on specific requirements. This ensures that critical services receive the necessary resources while preventing resource contention that could lead to performance degradation.
Ease of integrating innovative technologies	As smart cities continue to evolve, NFV provides a foundation for incorporating emerging technologies. It allows for seamless integration of new applications and services, ensuring that the city's infrastructure remains adaptable and forward looking.

6. Edge Computing

6.1. Cloud Computing and Edge Computing

Cloud computing is a revolutionary technology that has revolutionized how individuals and businesses access, store, and process data. It is the practice of storing, managing, and processing data using a network of servers hosted on the Internet instead of local servers or personal devices. The concept of cloud computing has acquired immense popularity due to its numerous advantages, such as increased scalability, lower costs, and greater flexibility [55].

The activity of processing and analyzing data closer to the source of creation, often on or near the device or sensor that gathers the data, is referred to as edge computing. This method minimizes latency and bandwidth by allowing for real-time analysis and reaction and eliminating the need to transport all data to the cloud for processing. Edge computing is appropriate for applications requiring rapid decisions or minimal latency, such as driverless cars, industrial automation, and remote monitoring. Edge computing and cloud computing are two complementary technologies that work together to provide efficient and effective computing solutions [56].

On the other hand, cloud computing is a centralized strategy that incorporates the storage, administration, and processing of data on distant servers accessible over the Internet. The cloud provides enormous storage capacity, scalability, and computing power, making it ideal for large-scale data processing, analytics, and complicated computing activities. Without depending on local infrastructure, cloud computing enables enterprises to store and access data and applications from anywhere at any time.

Edge computing and cloud computing display constructive interaction. Edge computing offloads specific processing work from the cloud by analyzing data and making decisions on edge devices. It aids in the reduction in network congestion, the reduction in dependency on cloud services, and the improvement in reaction times and performance. Edge computing may filter and prioritize data before delivering it to the cloud, minimizing the quantity of raw data delivered while maximizing cloud resource use. Cloud computing, in exchange, offers a centralized infrastructure that supports edge devices, allowing them to use increased computational capabilities, machine learning techniques, and access to huge quantities of historical data saved in the cloud. Cloud computing simplifies edge device administration, monitoring, upgrades, and software deployment [57,58].

Distributed edge computing is a promising approach for next-generation networks (NGNs) to achieve the ultimate demands of such networks [56]. Multiple-access edge computing (MEC) represents a common form of the distributed edge paradigm, which provides computing services at the edge of the radio access network. The local servers at the edge contain the capabilities of the remote cloud at various scales. Fog computing is another model of distributed edge computing, which provides less capable servers than MEC but with closer distances to end users and higher deployment flexibility. The two edge computing models meet modern communication networks' latency, availability, reliability, and energy requirements, including smart city applications and ultra-reliable low-latency applications [57]. The limited capabilities of user equipment (UE) can be assisted by edge computing capabilities in terms of data processing and data saving. Furthermore, distributed computing enables processes, analyzes, and computes data locally in edge-cloud servers [58].

6.2. MEC for Smart Cities

Distributed edge computing can assist various smart city applications requiring high data rates, real-time interaction, high availability, and local processing. This includes healthcare, virtual reality, uRLL, entertainment and multimedia, tactile Internet, and intelligent transportation applications [59].

Edge computing provides services with the lowest transmission delay. It also handles large amounts of data pre-processing to ensure the fastest service and the required computing resources for the services [60]. Deploying MEC for smart city systems provides many benefits, including latency reduction, availability increase, reliability increase, energy saving, and network flexibility. Table 5 introduces the benefits of deploying MEC for smart cities [61–63].

Table 5. Benefits of implementing MEC for smart cities.

Value Added	MEC for Smart City	Applications
Real-time interaction	This is one motivation for using edge computing over cloud computing for smart cities. MEC improves the QoS and implements low latency for delay-sensitive services, including unmanned aerial vehicles (UAVs), tactile Internet, remote surgery, and vehicular accident prevention. Also, edge computing provides decision making and data analysis in real time.	• Surveillance applications • Traffic management • Autonomous vehicles • Smart homes • Smart metering • Healthcare
Local processing	MEC reduces traffic between cells and the core network and increases spectrum efficiency.	• Traffic management • Autonomous vehicles • Smart homes
Delay reduction	MEC pushes resources closer to the network's edge, lowering data transmission times. This low latency is critical for applications such as real-time traffic control, self-driving cars, and emergency response systems.	• Traffic management • Autonomous vehicles • Emergency response systems
Improved spectral efficiency	By performing data processing tasks in proximity to the source of the data, MEC mitigates the need to transmit substantial amounts of data to far data centers. Consequently, this approach optimizes the use of network capacity and alleviates congestion on the network. This is crucial for real-time and multimedia-based smart city applications.	• Surveillance applications • Traffic management • Autonomous vehicles
Improving the quality of service and experience (QoS and QoE)	MEC facilitates meeting various requirements of the QoS and QoE of heterogeneous smart city applications. Multimedia services need a high bandwidth and low latency, where the service providers do not control and distribute the contents. MEC facilitates implementing new applications and services that allow the service provider to specify certain QoS criteria. Service providers should be aware of customers and contextual information requirements, such as their interests and preferences. Then, the information can be allocated to attract customers and improve their QoE.	• Surveillance applications • Traffic management • Autonomous vehicles • Smart homes • Smart metering • Healthcare • Telesurgery

Table 5. *Cont.*

Value Added	MEC for Smart City	Applications
Predicting network demands	MEC provides the network with the required resources to supply the network or the user's demands. Accurately predicting a demanding network helps to improve network performance if the demand is executed locally at the edge. It also allocates resources effectively in an optimal way.	• Healthcare • Intelligent transportation • Smart homes • Smart metering • Surveillance applications
Improved security and privacy	Edge data processing can preserve user privacy by limiting the transmission of sensitive data to centralized cloud servers through the network core. This is especially important for applications involving personal or sensitive information.	• Healthcare • Smart homes • Intelligent transportation • Smart metering • Surveillance applications
Virtualization and service orchestration	MEC enables the implementation of various virtualization schemes at the edge of the network, which assist in introducing novel network services at the edge. MEC enables service orchestration, allowing for the efficient and dynamic allocation of computing resources based on the requirements of different applications and services in the smart city network.	• Intelligent transportation • Surveillance applications • Smart homes • Telesurgery • Autonomous vehicles
Energy efficiency	MEC reduces energy costs by providing energy resources near devices. This empowers the energy performance of smart city devices.	• IoT-based applications • Smart metering • Healthcare
Efficient data management	Data analysis and management techniques can be easily implemented over the MEC platform, reducing the load on the core network and providing data analysis results at the edge.	• Smart metering • Smart homes • Environmental monitoring
High data rate	Transferring the massive data of various smart city applications to edge clouds is important. Introducing remote servers at the edge gives a pass of data offloading, which achieves higher data rates.	• Telesurgery • Autonomous vehicles • Haptic communications
High availability	Incorporating MEC into the network architecture improves the overall availability of services, reduces the impact of network disruptions, and enhances the user experience. MEC guarantees the resources' availability, which encourages pushing data and applications to the edge. This increases network availability.	• Surveillance applications • Traffic management • Autonomous vehicles • Smart homes • Smart metering • Healthcare • Telesurgery
Customized services	MEC allows smart cities to tailor services and applications to local needs and preferences, resulting in a more responsive and citizen-centric urban environment.	• Remote monitoring • Autonomous vehicles • Smart metering

Data in smart cities are grouped into three types regarding time characteristics. These groups are presented in Table 6 with examples of applications that generate each data type [64]. Moreover, the benefits of introducing MEC for handling such data are introduced.

MEC deploys three roles to establish interactive and real-time smart city services. These roles are summarized as follows [65,66]:

A. Local storage: Edge computing offers the ability to offload massive amounts of data from entities to edge servers. The server provides local storage for these massive amounts of data. It offers various temporary storage approaches for different types of data.

B. Local computing: Edge computing helps to offload the process and computation from less complex devices, such as smartphones, to edge servers. MEC servers deploy intelligent computing methods and can implement artificial intelligence (AI) algorithms to facilitate computing processes.

C. Local data analysis: MEC provides real-time and critical data analysis of the massive amounts of collected data from different smart city applications. Various data analysis schemes can be deployed locally in a smart way. When edge computing undertakes local data analysis, it minimizes the delay in forwarding data to the remote cloud and waiting for the response.

Table 6. Data categories and characteristics of MEC-based smart cities.

No.	Data Group	Characteristics	MEC Benefit	Applications
I	Hard real-time data	This has a threshold latency; the edge servers handle services and applications with hard real-time requirements and provide efficient low latency because of their vicinity to UEs.	Achieving the ultra-low latency required	• Gaming • Video streaming • Healthcare services
II	Soft real-time data	This tolerates some predefined and bounded latency; the edge servers implement tasks for applications with soft real-time requirements. Data will be moved to the cloud when the response time exceeds this.	Achieving the low latency required	• Traffic control system
III	Non-real-time data	This can tolerate latency and is non-sensitive to time. Their tasks are moved to the cloud for load balancing with non-real-time issues.	Achieving load balancing	• Air quality analysis • Land use analysis • Cultural resource management

6.3. Challenges of Deploying MEC for Smart City

Edge computing has many advantages; however, it has limited resources compared with the centralized cloud. The combining of edge computing with cloud computing overcomes this challenge. Deploying edge computing for smart cities faces three main challenges associated with massive data and resource management. These issues are summarized as follows [67–69].

First, how tasks are deployed in the edge nodes. In cloud networks, the service is deployed in virtual machines; however, the VMs need to update the software, which is a time problem for delay-sensitive edge networks.

Second, the number of tasks deployed in edge networks. Deploying many services on a remote cloud can be easily managed due to the powerful computing resources; however, it may cause a problem for edge nodes with limited resources.

Third, how the edge nodes control their resources. The scalability of services in the edge networks is limited because of limited resources compared with the cloud network with infinite limitations. Providing a solution to overcome this issue is a priority.

7. Fog Computing

Fog computing is another way of implementing distributed computing. It reduces the overall time to transmit information to end users because of the vicinity of fog nodes [70]. It is a robust complement to cloud computing, putting the network's power and computation at the edge. Fog computing technology is a better solution for smart cities because it provides flexible platforms for meeting users' and operators' demands [71].

The fog computing structure makes the interaction between entities in the platform easily controlled [72]. The first part of the fog architecture is the physical layer, which establishes the connection between devices in a single platform and transfers information. This layer includes devices, sensors, and virtual sensors. Sensors sense data and transmit it faster to nearby locations, i.e., the upper layer of the architecture. The next part is the monitoring layer, which supervises the resource usage and manages the nodes. The following part is the pre-processing layer, which manages the data analysis by filtering the unwanted and reducing the worthless communication. The next is the storage layer, which stores information records in a summary style. The following part is the security layer, which maintains the information when sending it to oblique channels. The last layer is the transport layer, which passes the data to the cloud [72].

Fog computing decouples the software and hardware functions in multi-level architecture for the running applications. It can also reconfigure different applications dynamically when transmitted to intelligent computing or services [73]. Edge computing provides a transmission service for running applications directly in an enclosed location. It has a restricted number of devices; in contrast, fog computing is highly hierarchical and processes, controls, and stores accelerated data [74]. We can summarize the differences between fog and other computing approaches as follows [71–75]:

- Delay-sensitive and location awareness: Fog nodes communicate with each other since fog nodes are location aware. Thus, fog computing analyzes the information faster than other cloud paradigms and suggests the best path with the lowest delay.
- Real-time response: fog computing analyzes the data at the edge, and thus, applications' time and latency-sensitivity functions come closer.
- Fog node's agility and scalability: the network and data load changes when fog computing at groups and levels integrates resources.
- Heterogeneity: fog computing supports all data types as different data collections and processing.
- Geographical distribution: unlike the centralized cloud, fog nodes are distributed geographically.
- Mobility: Fog nodes can support a low level of mobility, which other paradigms cannot achieve. This is due to the small size and weight of fog servers that can be embedded in moving entities.

7.1. Fog Computing for Smart Cities

Fog computing offers several benefits when applied to smart cities. By bringing computation, storage, and processing closer to users, fog computing enhances smart city applications' efficiency, responsiveness, and functionality. Table 7 summarizes some of the key benefits of deploying fog computing in smart cities [76–78]. Also, examples of smart city applications that can benefit are introduced.

Table 7. Benefits of implementing fog computing for smart cities.

Value Added	Fog Computing for Smart City	Applications
Reduced delay	- Fog computing is a better way to reduce latency in time-sensitive and location-sensitive smart city applications. - Fog computing reduces data transfer times. - This is crucial for low-latency smart city applications.	• Traffic management • Autonomous vehicles • Emergency response systems
Improved spectral efficiency	- By processing data and filtering at the edge, fog computing minimizes the volumes of raw data passed to centralized cloud servers. - This optimizes the network bandwidth and reduces congestion, ensuring efficient data utilization. - This is crucial for real-time and multimedia-based smart city applications.	• Surveillance applications • Traffic management • Autonomous vehicles
Assisting scalability requirements	- Fog computing supports dynamic scalability by distributing the computational load across edge devices. - As smart city networks grow and demand increases, fog nodes can seamlessly accommodate additional devices and applications.	• Healthcare • Traffic monitoring • Energy monitoring • Smart homes

Table 7. *Cont.*

Value Added	Fog Computing for Smart City	Applications
Improved security and privacy	- Local data processing in fog nodes can preserve user privacy by limiting the transmission of sensitive data to centralized cloud servers. - This is especially important for applications involving personal or sensitive information.	• Healthcare • Smart homes • Intelligent transportation • Smart metering • Surveillance applications
Increased system availability and reliability	- Fog computing enhances system reliability and ensures continuous operation even if individual nodes experience failures. - Fog computing exists at various locations to directly provide cloud services. The solid distributed platform structure makes it easy to check and quickly addresses the huge amount of information.	• Healthcare • Intelligent transportation • Smart homes • Smart metering • Surveillance applications
Service orchestration	- Fog computing enables service orchestration, allowing for efficient and dynamic allocation of computing resources based on the requirements of different applications and services in the smart city network. - Fog nodes can autonomously manage their resources, adapting to changing conditions and workload demands. - This flexibility ensures optimal resource allocation and improved overall performance.	• Intelligent transportation • Surveillance applications • Smart homes • Telesurgery • Autonomous vehicles
Energy efficiency	- Local processing and reduced data transmission to the cloud result in lower energy consumption. - This is advantageous for smart city devices, which often run on limited power sources.	• IoT-based applications • Smart metering • Healthcare
Efficient data management	- The number of records explodes with the dramatic increase in devices. Fog computing provides an efficient way to manage massive records and check the information to get admission quickly.	• Smart metering • Smart homes • Environmental monitoring
Assists network resilience	- Fog nodes can continue to operate even if network connectivity to the central cloud is disrupted. - This enhances service availability and reduces the impact of network failures.	• Healthcare • Intelligent transportation • Lifeline communication
Improved user experience	- With reduced latency and faster response times, smart city applications deliver users a smoother and more engaging experience. - This is particularly important for applications that require instant feedback and interaction.	• Telesurgery • Autonomous vehicles • Haptic communications
Offline functionality	- Fog nodes can continue to operate even when disconnected from the central cloud. - This is critical for applications requiring continuous operation.	• Remote monitoring • Autonomous vehicles • Smart metering

Implementing fog computing for smart city networks involves many steps. In these steps, a combination of hardware, software, and network infrastructure works together to achieve distributed computing. Table 8 introduces the potential steps to implement fog computing for smart cities [78,79].

Table 8. Steps of implementing fog computing for smart cities.

No.	Step	Implementation Procedures
1	Use cases identification	- Determining specific smart city use cases and applications for the implementation. - These include real-time monitoring, video surveillance, traffic management, environmental sensing, and energy management.
2	Design the appropriate topology	- Identifying the suitable topology for implementing the identified use cases. - This includes identifying suitable locations within the smart city where fog nodes can be deployed. - Fog nodes can be existing infrastructure, e.g., lampposts, utility poles, or dedicated devices. - Defining a mobility model for each fog node.
3	Data processing and analytics	- Determine the data processing and analytics requirements for each use case. - Fog nodes can perform real-time data processing, filtering, aggregation, and analytics at the network edge.
4	Hardware selection	- Specifying the hardware requirements for fog nodes, considering processing power, memory, storage, and connectivity options. - Selecting appropriate hardware. - Fog nodes should be equipped with communication modules to collect and process data. - Ensuring reliable and high-bandwidth connectivity between fog nodes and the central cloud infrastructure.
5	Software setup	- Installing fog computing software on the fog nodes. - Several open-source platforms, e.g., OpenFog and EdgeX Foundry, facilitate fog computing deployments [80]. - These platforms provide middleware, application programming interfaces (APIs), and tools for data ingestion, processing, analytics, and communication between fog units and the cloud.
6	Offloading scheme	- Developing an efficient offloading approach for data management.
7	Network security	- Implementing robust security mechanisms to protect data and ensure privacy in the smart city network. - This includes secure communication protocols, encryption, access controls, and authentication mechanisms. - Considering data anonymization techniques to protect individual privacy when handling sensitive data.
8	Integration	- Establishing seamless integration between fog nodes and the central cloud infrastructure. - This enables data synchronization, synchronization, and coordination between fog nodes and cloud-based applications.
9	Monitoring	- Implementing monitoring and management tools to oversee the fog computing infrastructure. - This includes real-time monitoring of fog nodes, network connectivity, resource utilization, and application performance. - Using centralized management systems to configure, update, and maintain the fog computing environment.
10	Testing	- Conducting testing and optimization to investigate the effectiveness of the fog implementation. - Validating the fog nodes' performance, reliability, functionality, and overall smart city network.

7.2. Challenges of Deploying Fog Computing for Smart Cities

Many challenges face fog-based smart city systems. These challenges are summarized as follows [79,81]:

(1) Virtualization technology selection

Virtualization is the main factor in executing computing tasks at fog nodes. Fog nodes use lightweight containers for hyper-visioning as operating system (OS)-level virtualization. The defect of container-based virtualization is that it cannot adapt to other platforms.

(2) Privacy and security

Despite the security benefits of integrating fog computing into smart cities, fog computing faces many internal security issues that should be resolved. Privacy and security are among the greatest challenges facing fog computing. To overcome this, we should control and interrupt the location framework by supporting each layer of fog nodes. The sensors and computing nodes must be more secure when transferring information, especially critical data. Privacy is also a challenge in the smart city for protecting users' privacy and service providers' priorities to maintain it. Integrating different services in a smart city platform would result in mistakes for users and service providers, such as sending information to unauthorized people.

(3) System management

Managing distributed fog nodes is a challenge that can be solved by deploying SDN and NFV technologies. However, integrating SDN and NFV into fog computing systems is challenging. The problem comes from restructuring APIs of northbound, southbound, and east/westbound interfaces.

(4) Mobility model

Fog nodes always have a level of mobility that should be considered while designing communication models for such systems. Due to the massive number of devices in smart cities, devices with efficient resources can be deployed as fog nodes. The mobility in fog-based smart cities records a pattern of behavior and mobility. Applications that are data-sematic and context-aware need the capability of users' locations and equipment.

8. Internet of Things (IoT)

The IoT supports connecting devices, services, and systems using machine-to-machine (M2M) communications [82]. It consists of four layers: physical, gateway or network, transport, and application layers, as presented in Figure 8 [82]. It is a platform where any device can share and collect data without manual intervention over a network.

I. Physical and data link layer

Physical medium: The physical layer defines the physical medium used for IoT data transmission, which is mostly a wireless connection, e.g., Wi-Fi, Zigbee, and cellular. The choice of the physical medium depends on several factors, including range, power consumption, data rate, and application requirements [82].

The data link layer is responsible for framing IoT data into packets or frames for transmission. These frames often include headers and trailers for addressing, error checking, and synchronization [82].

II. Gateway and network layer

Data are transferred between IoT nodes and the cloud through hardware known as gateways. It provides connectivity for forwarding packets over LAN and WAN Internet protocol (IP) layers. It mitigates the volume of data via preprocessing and filtering. Also, it provides a high-performance and reliable infrastructure for IoT devices [83].

III. Transport layer

The data are continuously collected from sensory devices to establish efficient data analytics mechanisms that extract useful information from the collected data. This layer moves data between the network and application layers through the appropriate wireless interface [82].

IV. Application layer

This uses a graphical user interface (GUI) and an API for utilizing IoT applications.

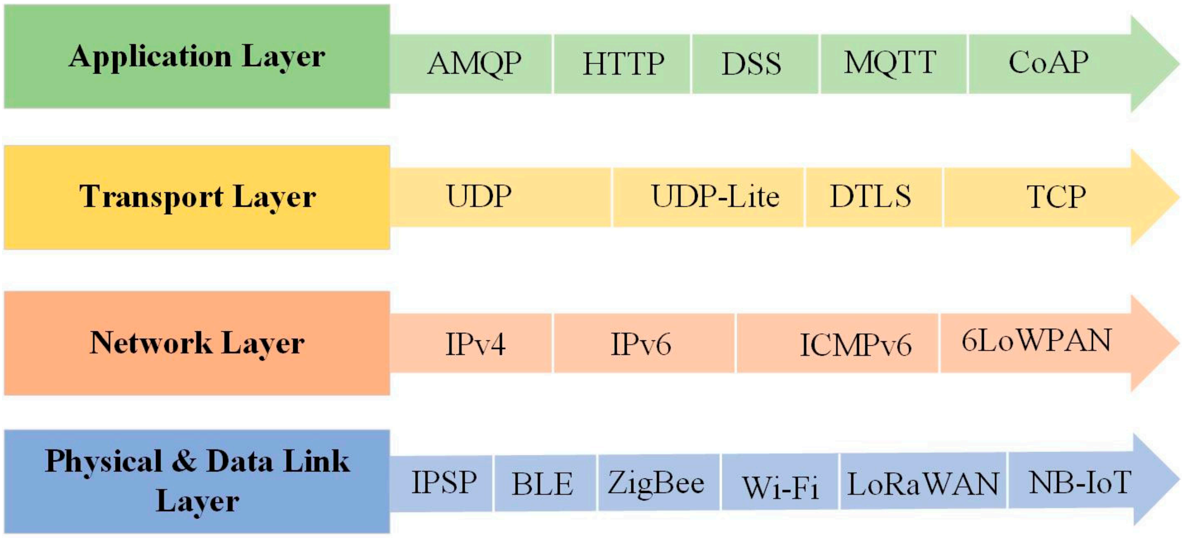

Figure 8. Structure of IoT networks.

8.1. IoT Connectivity

Connectivity is a crucial aspect of IoT networks. Relevant parties must determine the optimal connectivity to satisfy the demands of the applications. There are numerous market-available IoT connectivity solutions; however, each has characteristics that fit certain applications. Deploying various interfaces ensures full connectivity and empowers IoT networks [84].

The IoT should offer seamless connectivity and secure Internet access everywhere. Heterogeneous IoT networks support two main types of connectivity: short- or long-range communication technologies. Figure 9 illustrates the common long- and short-range communication technologies used in IoT networks [84,85]. Long-range technologies, including 5G and low power wide-area network (LPWAN), are intended for outdoor applications, while short-range technologies, on the other hand, such as Wi-Fi, Bluetooth, Zigbee, and near-field communication (NFC), are widely used for indoor IoT applications [85].

I. Short-range technologies Short-range communication interfaces provide coverage for a maximum of tens of meters. It is primarily suitable for indoor IoT applications. In the following, we consider the most common short-range interfaces [84–86].

1. Bluetooth
Bluetooth has long been recognized for its ability to stream enormous amounts of information. It is the optimal solution for personal IoT devices, such as activity trackers and wearables. Additionally, Bluetooth is made with low-power IoT gadgets. It is ideally suited for tools that offer small data values. These systems are configured to save power if data are not transmitted. Due to the narrow communication range and heavy battery consumption, it is used in a restricted number of industrial projects. However, these cons have been tackled in Bluetooth Low Energy (BLE).

2. ZigBee
   Zigbee is a wireless communication technology designed for low-power, short-range, and low-data-rate applications. It is based on the IEEE 802.15.4 standard, which defines the protocol's physical (PHY) and medium access control (MAC) layers. This standard operates in the 2.4 GHz band, although some regional variations use other frequencies. It fits well for many indoor IoT applications, including smart homes and smart lighting systems.
3. IEEE 802.11 (Wi-Fi)
   Wi-Fi is the optimal choice when transferring massive files, with a transfer rate 20 to 30 times higher than Bluetooth. Wi-Fi was not made for IoT networks; however, there are two currently improved IEEE standards, namely, 802.11ah and 802.11ax, for IoT applications. Sensors, which are critical components of IoT networks, run on batteries and send small quantities of data across vast areas. As a result, they require a different type of connection.
4. NFC
   NFC has a very short communication range, typically around a few centimeters. This close proximity requirement ensures that NFC communication is intentional and secure. It is a vital solution for secure and straightforward communication between electronic devices, e.g., smartphones. NFC operates at radio frequencies of 13.56 MHz, which is within the high-frequency (HF) band. This frequency band is unlicensed. NFC is commonly used for contactless payments, enabling users to make transactions by tapping their NFC-enabled payment cards, smartphones, or wearable devices on a compatible point-of-sale (POS) terminal.

II. Longe-range technologies

With the rapid growth of IoT technologies, numerous use cases in numerous sectors, such as security, asset monitoring, agriculture, smart metering, smart cities, and smart homes, have been identified [84]. Long range, low energy consumption, and cost effectiveness are all important characteristics of IoT applications. Popular short-range radio technologies, such as ZigBee and Bluetooth, are not intended for long-distance transmission. Thus, long-range radio technologies have evolved in response to the needs of current IoT applications [84,85]. Long-range technologies are divided into two categories: non-3GPP standards, i.e., unlicensed technologies, and 3GPP standards, i.e., licensed technologies [84,85,87].

A. Unlicensed technologies

(1) IEEE 802.11ah (Wi-Fi HaLow): IEEE 802.11ah technology enhances Wi-Fi by providing greater range and lower power connectivity. Wi-Fi HaLow satisfies the needs of the IoT to enable a range of use cases in commercial, industrial, residential, and public settings. Wi-Fi HaLow supports the low-power connectivity required for applications such as wearables and sensor networks. Its range is longer than many other IoT technology solutions in tough locations where the ability to pass through walls or other barriers is a key factor. It offers a more reliable connection.

(2) IEEE 802.11ax.: Wi-Fi 6 (IEEE 802.11ax) is the new generation of Wi-Fi technology focusing on efficiency and performance. Wi-Fi 6 technology is all about better and more efficient use of the existing radio frequency medium. It was introduced for video streaming, online gaming, and high-bandwidth applications.

(3) Low-power wide-area network (LPWAN): It is becoming increasingly well-liked in the industrial and research communities due to its low-power, long-range, and low-cost communication properties. Rural areas allow for long-distance communication up to 40 km, but in urban areas, it is only 1–5 km. Furthermore, it has a long battery life (over ten years) and is quite affordable. Therefore, IoT applications that send small amounts of data over large distances are ideal for LPWAN. LPWAN is in its infancy, and its maximum capabilities

and drawbacks will not be visible until the networks are established on a larger scale. Furthermore, the LPWAN currently supports no more than 20% of the people worldwide. This decreased adoption rate impedes LPWAN from being the optimal solution in the upcoming five years. Nevertheless, LPWAN accessibility is rapidly increasing, and by 2022, it is predicted that it will cover 100% of the world's population. Sigfox communication was introduced for the low-cost M2M application areas in which broad coverage is necessary. The Sigfox wireless interface permits any communications with a low power usage level. Therefore, it is optimal for remote devices requiring a power supply for prolonged periods without changing their batteries.

It provides a bidirectional capability and is utilized in IoT systems, including the following:

- Energy-associated communications, such as smart metering.
- Transportation, which may include automobile management.
- Home and consumer goods.

LoRaWAN is another long-range IoT network that is widely used. Lora is a long-range radio wide-area network delivering low-cost mobile security to the IoT, industrial applications, and smart cities. It is designed to save power and support a vast network of devices. Moreover, it is developed to save power and support a vast network of devices. For example, smart street lighting uses the LoRa gateway that employs the LoRaWAN protocol. It can identify signals below the noise level, besides having GPS-free positioning and built-in security.

B. Licensed technologies

(1) NB-IoT: NB-IoT is based on narrowband radio technology and is standardized by the third-generation partnership project (3GPP). Under permitted frequency bands, NB-IoT can coexist with the GSM (global system for mobile communications) and LTE (long-term evolution) (e.g., 700 MHz, 800 MHz, and 900 MHz). The frequency band NB-IoT has a span of 200 KHz [87]. With a high data rate and low latency, narrowband IoT (NB-IoT) is a long-range communication technology enabling several IoT devices and applications. In addition, NB-IoT is a price-efficient solution with a long battery life and better coverage [87].

(2) LTE CAT 1 and LTE CAT 4: Both are popular LTE IoT communication technologies. The key difference between LTE Cat 4 and LTE Cat 1 is their data transmission rate and prices. LTE Cat 4, with a maximum downlink rate of 150 Mbps and an uplink rate of 50 Mbps, has a better intel high data rate market by simultaneously communicating a greater volume of data, whereas the LTE Cat 1 IoT solution presents its advantages with its amazing cost performance in the medium-rate market [84]. The LTE Cat 1, along with the LTE Cat 4, also relies on the same existing 4G LTE network, which means adopting LTE Cat 1 communication technology will cost no extra deployment investment on the network operator's side. Moreover, taking advantage of the technological maturity and global coverage of the 4G network, LTE Cat 1 has a strong and reliable network foundation to empower various IoT applications and scenarios [84].

Tables 9 and 10 summarize the main features of the short- and long-range IoT technologies.

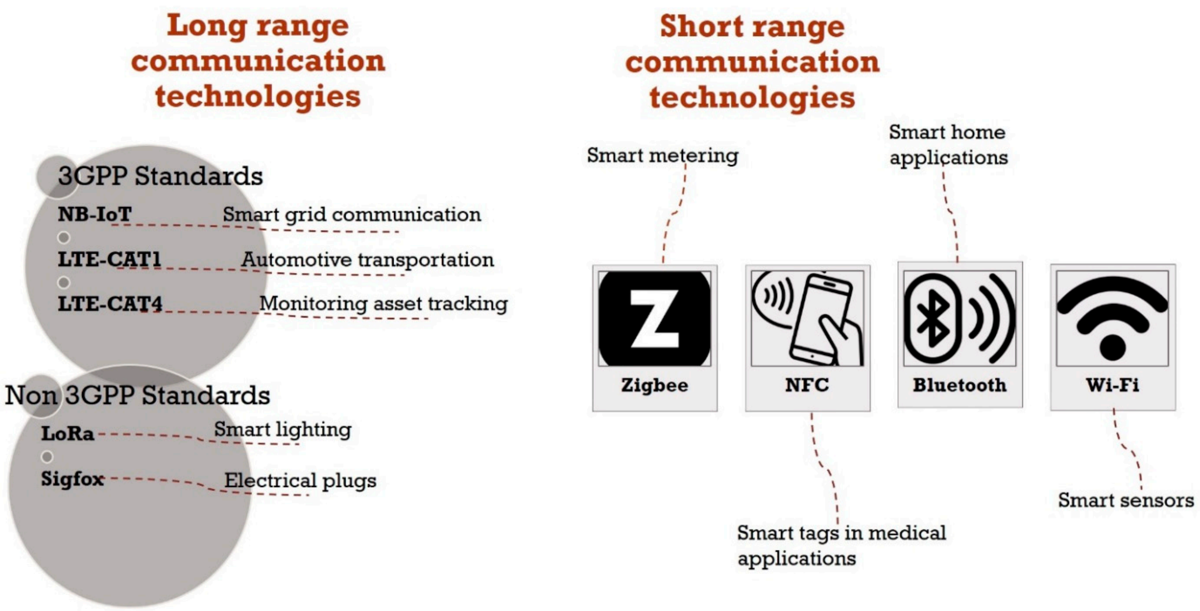

Figure 9. Main interfaces for IoT networks.

Table 9. Main characteristics of IoT short-range technologies [84–86].

RFID	NFC	Zigbee	Bluetooth	Characteristics
ISO/IEC 13157	802.15.4	802.15.1	IEEE 1451	IEEE specification
Varies	424 kbps	250 kbps	1 Mbps	Data rate
Varies	13.56 MHz	2.4 and 2.48 GHz	2.4 GHz	Frequency band
1 m	4 cm	10–100 m	10 m	Communication range
Low	Low	Low	Low	Cost
No battery (passive tags)	Intermediate	High	Ultra-high	Power usage (battery life)
Tracking items, E-passport	Smart tags for medical applications	Smart metering	Smart home application	IoT applications

Table 10. Main characteristics of IoT long-range technologies [84,85,87].

	LTE CAT-1	LTE CAT-4	NB-IoT	IEEE 802.11ah	IEEE 802.11ax	LoRaWAN	Sigfox
Frequency band	Licensed band			Unlicensed band			
Data rate	DL: 10 Mbps UL: 5 Mbps	DL: 150 Mbps UL: 50 Mbps	<150 kbps	433 to 6933 Mbps	600 to 9608 Mbps	<10 kbps	100 b/s
Range	Limited to cellular cell	Limited to cellular cell	Limited to cellular cell	Up to 1 km	2.4/5/6 GHz	Up to 15 km	Up to 50 km
Power consumption	High to ultra-high			Low	Low	Low to ultra-low	
Cost	High			Low			
Security	High to ultra-high			Low to ultra-low			
Application	Automotive transportation	Monitoring asset tracking	Smart grid communication	Smart sensors and meters	Smart metering	Smart building (smart lighting)	Smart building (electrical plugs)

8.2. IoT for Smart Cities

IoT applications establish the functionality of smart cities, such as healthcare systems, parking space utilization, transport management, and food supply chains. The IoT can assist smart cities in various aspects; Table 11 summarizes the benefits of deploying the IoT for smart cities [22,88,89].

Table 11. Benefits of deploying IoT for smart cities.

Benefit	IoT-Based Smart Cities
Improved network efficiency	The IoT enables the integration and automation of various city systems, which enables real-time monitoring, data analysis, and optimization, leading to more efficient resource utilization and cost savings. Moreover, IoT devices often use low-power communication protocols, which reduces the strain on network resources.
Increased scalability	The IoT paradigm supports a high level of scalability. This scalability allows smart cities to keep up with the increasing number of sensors, devices, and applications without compromising network performance.
Improved citizen engagement	The IoT empowers citizens to actively participate in city processes through real-time data access and feedback mechanisms. This fosters community and encourages collaboration between residents and city authorities.
Data-based decision making	The IoT generates a vast amount of data, which provides valuable insights for urban planning and policymaking. Data-based decision making helps city authorities to understand the needs and preferences of citizens, identify trends, and optimize resource allocation for effective governance.
Remote management	The IoT networks enable the remote management and configuration of devices. This feature reduces the need for physical intervention and allows administrators to optimize network settings without disrupting operations.
Support economic growth	Smart cities attract businesses, startups, and innovation hubs. IoT technologies create opportunities for new services, products, and industries, contributing to economic growth and job creation.
Dynamic allocation of resources	The IoT networks can dynamically allocate network resources based on the demands of different applications. This resource management ensures that critical applications receive the required bandwidth, enhancing the overall network performance.
Support of heterogeneous interfaces	IoT networks utilize various communication technologies, including cellular, Wi-Fi, and low-power wide-area networks (LPWANs). This diverse connectivity ecosystem ensures that devices can connect seamlessly, even in areas with varying coverage.

The IoT can be deployed for various smart city applications, achieving many benefits for each service. Table 12 introduces the main categories of smart city applications that can benefit from the IoT [88–91].

Table 12. Main categories of applications of IoT-based smart city.

Application Category	How Can It Benefit from IoT?
Infrastructure management	IoT sensors can monitor the condition of critical infrastructure in real time. These data enable proactive maintenance, early detection of faults, and efficient allocation of repair resources, enhancing public safety and reducing downtime.
Sustainability	The IoT can help cities become more sustainable by monitoring and controlling energy consumption, reducing waste production, and optimizing resource allocation. Smart grids, for example, can balance energy demand and supply, integrate renewable energy sources, and reduce carbon emissions.
Public safety	The IoT enables the implementation of smart surveillance systems, including video analytics, facial recognition, and sensor-based monitoring. These systems can enhance public safety by detecting and responding to incidents, managing crowd control, and providing timely emergency alerts.
Healthcare	IoT devices can remotely monitor patients' health conditions, leading to the early detection of health issues and timely interventions.

Table 12. *Cont.*

Application Category	How Can It Benefit from IoT?
Quality of life	The IoT can improve the life quality of citizens by introducing smart services. For example, smart lighting can adjust the brightness according to ambient light conditions, reducing energy consumption.
Traffic management	IoT devices are introduced to traffic applications, including intelligent traffic and connected vehicles. Real-time data on public transportation can provide accurate navigation information to commuters, reducing travel time and fuel consumption. The main benefit of the IoT here is the ease of deployment.
Environmental monitoring	IoT data can monitor environmental conditions, leading to better pollution control, efficient water usage, and preservation of natural resources.

9. Artificial Intelligence (AI)

9.1. AI for Smart Cities

The generated smart city data can be assisted, handled, and processed by AI with great efficiency and accuracy [92]. AI makes smart cities resourceful and sustainable by deriving inferences. The world is going for sustainability in terms of education, economic growth, climate control, health, and healthcare infrastructure that can be assisted by the recent advances in AI [93]. Many forms of AI are currently deployed for smart cities, including the following [94,95]:

(1) AI-optimized hardware

With significant advancements in graphics processing units (GPUs), central processing units (CPUs), and processing power units (PPUs), systems are being set up and organized specifically for industrial transformation to carry out and execute AI-oriented tasks. Today's hardware processors are multi-core devices that perform low-precision calculations, utilize dataflow architectures, or support in-memory computing.

(2) Speech recognition

This transforms human speech into a comprehensive format for computer applications to process and use. Devices and applications, e.g., Siri and Amazon Alexa, use speech recognition technology to perform tasks and actions.

(3) Deep learning

Deep learning technology could replace the human brain's dense and complex neural network to process the data and obtain patterns for decision making.

(4) Robotic process automation

Humans automate actions by using software programs and algorithms. A physical robot does the desired task like clicking, typing, or analyzing data in several applications using a software program. Currently, such technology is used to complete tasks in places where it is dangerous or not efficient for humans.

(5) Image/visual recognition

Image recognition detects or identifies a feature, face, or place in an image or a video file. It is used in reading and detecting vehicles' license plates, studying people and eminent personalities, and detecting variances in medical imaging.

AI plays a critical part in achieving the goals and meeting the demands of smart cities by providing real-time insights, automating processes, and optimizing resource allocation. AI can be deployed for massive smart city applications, including those presented in Table 13 [95–99].

Table 13. Main categories of AI-based smart city applications.

Application	AI Deployment
Smart grid	As the population grows, so does the need for electricity and other forms of energy. New infrastructures and various construction infrastructures require electricity, which we must supply. The need is for the intelligent management of energy resources. Energy resources must be used responsibly and effectively. AI can manage energy consumption more efficiently in buildings and public spaces.
Infrastructure maintenance	AI can predict maintenance needs; prioritize repairs; and prevent failures of infrastructure, including bridges, roads, and buildings.
E-health	The city's population grows as urbanization progresses, which raises the demand for amenities and healthcare facilities. Modern mobile devices and intelligent technology are combined with healthcare to create smart healthcare. Smart wearables like fitness bands, trackers, tools for assessing one's health, and apps are in use. These gadgets monitor the wearer's well-being and can offer solutions. Doctors, researchers, and other healthcare professionals can analyze the data generated by these devices to provide better, more individualized diagnoses and treatments. AI can monitor public health in cities by analyzing data from public health records. This data can be used to detect outbreaks of diseases and predict disease spread, allowing officials to take quick action to prevent the spread of infections.
Smart transportation	Smart transportation uses the Internet, sensors, and actuators to make travel faster, safer, and more convenient. AI can analyze these data and automate different processes inside intelligent transportation systems. AI-powered traffic management systems have optimized traffic, reduced congestion, and improved safety. AI can predict traffic patterns and adjust traffic signals.
Smart parking	Finding parking spaces and making the most of parking lots are essential due to the significant vehicle growth in the city. Cities can share parking information about available and occupied spots through a public portal or app. Users can access this information and quickly move to the designated spot.
Water management	AI can manage water resources more efficiently by analyzing data from sensors placed in reservoirs, pipes, and other infrastructure. It can predict water demand and optimize distribution.
Smart lighting	Energy conservation and increasing the efficiency and adaptability of lighting equipment were the main goals of implementing smart lighting in the smart city paradigm. An intelligent, wireless, decentralized local network includes a smart lighting system. It has seamless access to the Internet, a data center, and several other cloud-based management platforms.
Public safety	AI can assist public safety by identifying potential risks and responding quickly to emergencies.
Tourism	AI can enhance the city tourism experience by providing personalized recommendations to visitors based on their preferences and behavior. This can help visitors to discover new attractions and experiences while reducing overcrowding at popular tourist spots.
Systems for monitoring pollution	Pollution is at its highest point when urbanization accelerates, and people are moving to cities at previously unheard-of rates. To reduce pollution, the government must develop concepts and technologies. The state of the environment must be kept under observation. Installed and deployed smart devices are required to monitor the city's soil, water, and air quality. People and the government can take corrective actions that will help to improve environmental health based on the readings from these sensors.

9.2. Available Smart City Datasets

With the high demands of deploying AI for smart cities, many datasets have been generated for different smart city applications. Smart city datasets span a wide range of domains and applications. With AI, cities can gain actionable insights from this data to improve operations, plan infrastructure, and ultimately enhance the quality of life for citizens [99]. We can categorize the available datasets according to the smart city application [99,100].

I. Intelligent transportation applications

Transportation data comprise a critical common type of dataset of smart cities. Beyond traffic data, there are also datasets on public transit usage, parking availability, and bike sharing. These data can be used for the following:

- Traffic flow optimization.
- Demand forecasting for transit systems.
- Route planning and recommendations.
- Predicting congestion and traffic incidents.

II. Environmental monitoring applications.

Environmental data like pollution, noise, and weather are also crucial for smart cities. These data are introduced for the following:

- Air/water quality monitoring.
- Predict pollution levels.
- Issue warnings for extreme weather or hazardous conditions.

III. Smart grid applications

Utility data from sources, including water, electricity, and gas utilities, provide insight into consumption patterns and asset performance. This data can be used for the following:

- Detect leaks and outages.
- Optimize resource allocation.
- Implement demand-side management strategies.

IV. Public services

Citizen data from different sources, including call centers, social media, and surveys, provide insight into citizen needs and issues. This data can be used for the following:

- Improve city services.
- Respond more quickly to citizen requests.
- Assess citizen satisfaction.

V. Surveillance applications

Image and video data from closed-circuit television (CCTV) and traffic cameras provide visual information about the city. This data can be used for the following:

- Automated incident detection.
- Object tracking and recognition.
- Pedestrian flow analysis.

Table 14 provides a list of available datasets that are commonly used in smart city applications.

Table 14. Commonly used smart city datasets.

Dataset	Description
Smart cities index datasets [101]	- Collection of smart city datasets covering various domains, including transportation, utilities, environment, and citizen services. - Data were collected using IoT sensors.
Melbourne urban forest dataset [102]	- Melbourne's urban forest dataset includes information about trees in the city, including species, locations, and health status. - It is used for urban greenery management and biodiversity analysis.

Table 14. *Cont.*

Dataset	Description
Chicago traffic tracker dataset [103]	- This dataset provides real-time traffic information for various modes of transportation in Chicago. - It includes traffic speed, congestion, and travel times data, which can be used for traffic management and optimization.
Land and Transport Singapore (LTSG) datasets [104]	- Datasets on public transportation, road traffic, and vehicle ownership. These datasets are used for traffic management, urban planning, and public transport optimization. - It contains the following: • 8672 points of interest (with attributes: number of Google ratings, types, and street address). • 12,442 housing and development board buildings (with attributes: block number, street address, zip code, construction year, dwelling units, and functionality). • 5049 bus stations (with routing information). • 5018 bus stations (with passenger volume information). • 166 subway stations (with routing information).
Los Angeles GeoHub datasets [105]	- Datasets related to the city's infrastructure, environment, and services. - These datasets are used for urban planning, environmental monitoring, and public service optimization.
Los Angeles crime dataset [106]	- A comprehensive dataset of felony and misdemeanor crimes in Los Angeles from 2000 to 2018. - Useful for crime pattern analysis and predictive policing applications.
City of Chicago crime dataset [107]	- This dataset contains information about reported crimes in Chicago, including location, type of crime, and time of occurrence. - It is used for crime prediction, hotspot analysis, and law enforcement strategies.
Open traffic [108]	- Traffic data from several cities, including speed, traffic volume, and incident reports. - Useful for traffic prediction and management. - Linked to OpenStreetMap.
Citi bike trip dataset [109]	- It is a bike-sharing program in New York City, and its trip data include information about bike trips, locations, and timestamps. - It is used for studying urban mobility patterns and optimizing bike-sharing services.
London bike sharing dataset [110]	- Details about bike journeys from the Santander Cycles bike sharing scheme in London. - Includes trip duration, start/end stations, member types, and more. - Useful for bike infrastructure planning.
Beijing air quality dataset [111]	- This dataset contains historical air quality measurements in Beijing, including pollutants, e.g., PM2.5, PM10, and ozone levels. - It is used for analyzing air quality trends and predicting pollution levels.
Smart data hub [112]	- This dataset includes information from multiple domains for various cities, such as transportation, environment, energy, and demographics. - It is used for multidisciplinary smart city research and analysis.

9.3. Challenges of Deploying AI for Smart Cities

Due to several issues, implementing AI technology in smart cities is not an easy task. The main limitations of deploying AI for smart cities are summarized as follows [96–98]:

- Infrastructure and cost: AI systems need powerful hardware, databases, and energy to function, raising the overall cost.
- Privacy concerns: people might feel offended and worried about their privacy and personal space.
- Risk of socialization: When developing such cities, inclusive urbanization, which addresses the growing vulnerability of the slums and poor population, must be prioritized. No population should be left out of the big data collection for the AI systems; it must be ensured. Including members of all ages, genders, classes, and socioeconomic groups in society is crucial.

10. Blockchain

A blockchain operates on a peer-to-peer network and uses cryptographic algorithms to secure and validate transactions. It eliminates the need for intermediaries, as the transactions are verified by multiple participants in the network [113]. A blockchain is the underlying technology behind cryptocurrencies, e.g., Bitcoin, but its applications extend beyond just financial transactions, including supply chain management, healthcare, and voting systems [83].

A blockchain can support optimizing energy distribution and resource allocation in a smart city. By enabling peer-to-peer energy trading and data-driven resource management, a blockchain can minimize waste, improve energy efficiency, and foster sustainability within the city. A blockchain facilitates secure energy trading within a smart grid. It allows individuals and businesses to buy, sell, and exchange energy directly, optimizing energy usage [97,114].

A blockchain allows for the creation of a decentralized and tamper-proof ledger. By storing transactional data, contracts, and other information on a blockchain, smart cities ensure records' transparency and integrity. This transparency improves trust between stakeholders, including citizens, businesses, and government. Moreover, a blockchain can track and manage waste disposal and recycling processes. Creating an immutable record of waste generation, collection, and recycling enables transparency and accountability. This data can be utilized to optimize waste management systems, reduce waste, and promote recycling efforts [115]. Summing up, a blockchain can be deployed in smart cities to enhance their efficiency in several ways, as presented in Table 15 [114–116].

Table 15. Benefits of deploying blockchain for smart cities.

Benefit	Blockchain-Based Smart City
Transparency and trust	A blockchain provides an immutable and transparent ledger, ensuring that data cannot be tampered with or altered. This enhances trust and accountability within the city infrastructure, allowing citizens to trace how resources are allocated, ensuring transparency in decision-making processes, and minimizing corruption.
Efficiency and automation	Smart contracts on a blockchain can automate various processes, e.g., energy distribution, traffic management, and waste management, improving efficiency and reducing administrative costs. Smart contracts can automate and enforce agreements between different entities within a smart city ecosystem. It eliminates the need for intermediaries, reduces administrative costs, and ensures transparent and efficient transactions.
Supply chain management	A blockchain can enhance supply chain traceability in smart cities. By recording every transaction and movement of goods on a distributed ledger, stakeholders can have real-time visibility of the entire supply chain. This improves efficiency, prevents fraud, and promotes sustainable practices by monitoring the environmental impact of goods and services.
Enhanced security	A blockchain provides a decentralized and tamper-proof system, ensuring the integrity and security of data. This prevents cyber-attacks and unauthorized access to sensitive information, ensuring a safer environment for smart city residents.

Table 15. *Cont.*

Benefit	Blockchain-Based Smart City
Citizen engagement and governance	A blockchain can give citizens more control over their data, giving them transparency, privacy, and the ability to participate in decision-making. A blockchain can enable secure and transparent voting systems, ensuring integrity in the democratic processes within a smart city. It can also facilitate decentralized identity systems, allowing citizens to control their data while ensuring privacy and security.
Data sharing and interoperability	A blockchain facilitates secure and decentralized data sharing between various stakeholders within a smart city ecosystem. It can promote interoperability and collaboration between different service providers and government agencies.
Economic growth and innovation	Adopting blockchain technology can attract investments, foster entrepreneurship, and promote innovation within a smart city ecosystem. It can create new economic opportunities, attract tech startups, and enable the development of decentralized applications that cater to specific urban needs.

Security is among the benefits achieved by deploying a blockchain for smart cities. Blockchain-based solutions can have critical roles in improving the security of smart cities. The security benefits can be summarized as follows [117].

a. Transparency: A blockchain's decentralized nature ensures that all transactions within a smart city network are recorded in an immutable and transparent manner. This transparency helps identify unauthorized or fraudulent activities, improving security.
b. Data integrity and authentication: By leveraging a blockchain, smart cities can ensure the integrity and authenticity of their data. Through cryptographic techniques and consensus algorithms, a blockchain can verify the origin and validity of data, preventing tampering or unauthorized modification.
c. Secured identity management: Blockchain technology provides a robust framework for managing digital identities securely. Individuals and devices can verify and store their identities on a blockchain, ensuring that only authorized entities can access sensitive information or perform specific actions.
d. Enhanced IoT security: IoT devices, an integral part of smart cities, can introduce security vulnerabilities. A blockchain can establish a decentralized and secure network for IoT devices, eliminating the need for a central point of control and reducing the risk of cyberattacks.
e. Peer-to-peer transactions: A blockchain's inherent capabilities allow secure peer-to-peer transactions without intermediaries. This eliminates the need for trust in centralized authorities.
f. Data consent: Various stakeholders need access to specific data in a smart city ecosystem. Blockchain-based solutions can enable controlled data sharing with the use of smart contracts. Individuals or organizations can grant permission for data access, ensuring privacy while fostering collaboration.

When deploying blockchain technology in smart cities, several challenges may arise. Addressing these challenges requires collaboration between technology providers, city governments, regulatory bodies, and the community. Table 16 presents the main challenges of deploying a blockchain for smart cities [114–116].

Table 16. Challenges of deploying blockchain for smart cities.

Challenge	Discussion
Scalability	Blockchain networks often face scalability challenges when dealing with many transactions and data, which may pose difficulties when trying to handle the scale and complexity of a smart city.

Table 16. *Cont.*

Challenge	Discussion
Interoperability	Integrating different existing systems with a blockchain might be challenging due to compatibility issues and the need to establish common standards and protocols for seamless communication.
Regulatory	Smart cities must navigate complex legal and regulatory frameworks to ensure compliance with existing laws. Blockchain-specific regulations and standards are still evolving in many jurisdictions.
Privacy concerns	While a blockchain provides transparency, it may pose challenges in terms of privacy, as personal data on a blockchain might be accessible to all participants. Striking the right balance is crucial to protect personal information.
Energy consumption	Blockchain networks can be energy-intensive due to consensus mechanisms like proof-of-work. This can be a concern regarding energy consumption and environmental sustainability.
User adoption	Encouraging widespread adoption of blockchain technology may be challenging due to citizens' lack of awareness and understanding. Promoting digital literacy, conducting public awareness campaigns, and demonstrating the tangible benefits of a blockchain in areas like transparent governance and efficient services can aid in overcoming this challenge.

11. Current Studies and Future Directions

This section considers the current research in smart cities and the recent existing studies that consider key enabling technologies of smart cities. Moreover, this section provides future research directions for researchers dedicated to developing reliable communication networks for different smart city applications.

11.1. Current Research

There are many existing works and related frameworks for smart city applications. We present the recent relevant studies that consider the previously mentioned key technologies for enabling heterogeneous smart city applications. In [118], the authors developed a blockchain scheme for outdoor health applications in smart cities. The users' wearable sensors generated health data (HD). The work considered only healthcare applications among all smart city use cases. Also, the proposed approach used a blockchain and MEC as smart city enablers. In [119], the authors developed an offloading method on a fog computing system and formulated an optimization solution for energy consumption in the fog computing process. The authors proposed a fairness algorithm (FCA) to obtain fog nodes' optimal fairness cooperation policy. FCA was an effective solution that reduced energy consumption and overhead time. In [120], the authors used a machine learning (ML) approach to improve MEC performance. The results validated the proposed approach for large-scale networks with good stability but could not recognize fast algorithm convergence. The proposed algorithm for distributed coordination is close to the optimal MEC performance and could achieve fast convergence.

The authors of [121] studied the integration of MEC in automotive contexts by dividing the desired applications in the smart city into four main groups. They depended on three layers of MEC architecture to propose a data distribution mechanism. The results demonstrated that the performance of the suggested protocol could be greatly improved regarding data transmission, communication overhead, and latency. In [122], the authors proposed a hierarchical structure for smart city applications. The suggested design aimed to solve the drawbacks of previous methods. The suggested technique improved the scalability and dependability of user access. The data processing cost was reduced by spreading processing tasks over edge devices. The proposed model outperformed other models regarding delay and cost.

In [123], the authors offered a paradigm that enabled autonomous orchestration capabilities for smart cities. The work's contribution was integrating fog node orchestration with the application layer for transmitting service provisioning data between fog units. The developed approach reduced the bandwidth and latency. The authors of [124] created a basic gateway access node based on an adaptable and efficient NFVI. The results further demonstrated that the prototype offered security for IoT devices, recognizing fraudulent traffic with 99.8% accuracy.

In [125], the authors proposed a technical architecture that allows IoT architectures in military applications and demonstrates the challenges and mitigation methods. They discussed security issues when leveraging IoT for military purposes and presented mitigation methods to overcome these issues. The authors of [126] described the InterSCity platform's architecture and studied a set of experiments for their scalability. They experimentally evaluated the microservices architecture. The experimental strategy was based on an application scenario of smart parking and demonstrated the efficiency of the method employed to create artificial workloads.

In [127], the authors reduced the complexity of computations in fog computing for IoT devices by integrating SDN and NFV on the edge server. They used the EstiNet simulator and MATLAB to execute the proposed algorithm and evaluated performance parameters, satisfaction, reliability, and time delay. They compared the results of ASTP and software-defined unified virtual monitoring function (SuVMF). In contrast, the proposed framework achieved high satisfaction and reliability (up to 90%) and low delay (1800 s for 200 IoT devices). The authors of [128] offered a priority-based framework for transportation systems using fog computing. They reduced latency and increased QoS using MEC and fog servers. The latency decreased by 20% and the processing time by 35% compared with centralized computing architecture.

In [129], the authors introduce a conceptual framework and architectural design that effectively utilizes blockchain technology, big data analytics, and artificial intelligence (AI) to augment the cybersecurity measures used in smart cities. The suggested framework is comprehensively outlined, with a specific focus on its practical implementation. The simulation of the system was conducted using a dataset that was specifically tailored to a smart grid scenario. The results of these simulations clearly demonstrate the significant potential and effectiveness of the proposed framework in efficiently tackling the intricate cybersecurity concerns that are inherent in smart city environments. The findings not only demonstrate the theoretical robustness of the paradigm but also emphasize its practical relevance in real-life situations. The framework's efficacy, notably in the domain of smart grid cybersecurity, serves to validate its significance as a resilient solution capable of addressing cyber threats in the ever-evolving context of smart cities.

Table 17 summarizes the existing proposals that consider developing a reliable smart city network. The studies are compared, and the deployed enabling technology is mentioned.

Table 17. Comparison of the existing smart city framework and solutions.

Ref.	Key Enabling Technology						Distributed Edge Computing		KPI	Smart City Application
	IoT	Blockchain	SDN	NFV	UAV	AI	Fog	MEC		
[8]	√	×	×	×	×	×	×	×	• Pedestrian count • Power consumption	Ambient monitoring
[7]	√	×	√	×	×	√	√	×	• Latency • Scalability • Security • Privacy	Industrial application
[118]	√	√	×	×	√	×	×	√	• Security • Latency	Health monitoring
[119]	×	×	×	×	×	×	√	×	• Time overhead • QoE • Energy consumption	General
[120]	√	×	×	×		√	×	√	• Scalability • Stability	General

Table 17. *Cont.*

Ref.	Key Enabling Technology						Distributed Edge Computing		KPI	Smart City Application
	IoT	Blockchain	SDN	NFV	UAV	AI	Fog	MEC		
[121]	√	×	√	×	×	×	×	√	• Connectivity • Communication overhead • Resource utilization • Latency	Intelligent transportation systems (ITSs)
[122]	√	×	×	×	×	×	√	×	• Latency • Cost • Network usage • Reliability	Parking and monitoring system
[123]	√	×	×	√	×	×	√	×	• Bandwidth • Latency	Air monitoring
[124]	√	×	×	√	×	×	√	×	• Network congestion • Security	General
[55]	√	√	√	√	×	×	×	√	• Task delay • Bandwidth occupation • Energy consumption	General
[125]	√	×	×	×	×	×	×	×	• No evaluation	Military operations
[126]	√	×	×	√	×	×	×	×	• Scalability • Latency	Smart parking
[127]	√	√	√	√	×	×	√	√	• Latency • Reliability	General
[128]	√	×	√	×	×	×	√	√	• Latency • Processing delay	Smart transportation
[129]	√	√	×	√	×	√	×	×	• Security • Flexibility	Smart grid

11.2. Research Directions

Overall, the research directions of smart cities are diverse and require multidisciplinary collaboration. By prioritizing these research areas, cities can become smarter and more sustainable. We can summarize the research directions from the information and communication technology perspective as follows [130,131]:

A. Developing AI/ML algorithms to assist smart city applications

Creating advanced AI/ML algorithms is a top priority in the race to improve smart city applications. These algorithms are needed to overcome the typical difficulties of smart city technology implementation, including restricted hardware capacity and resource limits. The future directions of AI/ML for smart cities include the following two main categories:

1. Algorithms for overcoming resource and hardware limitations. In order for smart city applications to run smoothly on devices, mainly IoT devices, with limited processing power, it is crucial to build AI/ML algorithms that are both lightweight and efficient with resources. This involves optimizing algorithms for edge computing environments to save end nodes' resources. This includes deploying techniques, such as model quantization and pruning, to reduce the size and complexity of AI/ML models so they can be implemented for devices with limited resources. Another way to overcome resource limitations is to seek an efficient way of using them. AI/ML can play a major role in this direction by designing novel methods for dynamically allocating resources according to demand to optimize performance while reducing resource wastage. This includes using reinforcement learning to develop adaptive resource allocation schemes for IoT-based smart city applications.
2. Algorithms for enhancing communication network efficiency. AI/ML can significantly improve the network performance of different smart city applications, mainly to meet the demands of 5G. Algorithms for controlling and predicting network traffic are critical components, allowing for the intelligent distribution and allocation of network resources based on consumption patterns. Another critical aspect is the development of algorithms for assessing data reliability. AI/ML algorithms can analyze and verify

data integrity, identifying and mitigating potential issues, including data corruption and tampering. This increases the reliability of communications over smart cities in a way that meets the 5G demands. Another direction is the development of adaptive machine learning models that can change with smart city settings as they change. This means that the models should keep learning and adjusting based on new data to work in dynamic circumstances. In addition, this direction can include AI/ML algorithms that prioritize important data flow, guaranteeing that critical services receive the necessary bandwidth and resources during instances of heightened demand. Also, AI/ML algorithms can assist in developing QoS schemes that adaptively modify data prioritization according to the real-time demands of various applications. Furthermore, AI/ML can increase the network availability of smart city applications. AI/ML algorithms can be used for predicting potential network failures or disruptions, allowing for proactive measures to maintain network availability. This meets the novel demands of zero-touch networks that can assist many smart city applications.

B. Deploying distributed edge computing for smart city applications This includes novel structures of edge units and novel interfaces with other network parts. Moreover, the development of associated algorithms with the deployment of edge computing is an important direction. These algorithms should meet the demands of future smart cities. The main directions regarding distributed edge deployment for smart cities can be summarized as follows:

- Implementing a microservices-based architecture for edge nodes, breaking smart city applications into modular, independently deployable services. This enhances scalability, maintainability, and flexibility.
- Utilizing containerization technologies, e.g., docker, to encapsulate each microservice, ensuring consistency across edge units and easing deployment and scaling processes.
- Employing orchestration solutions, e.g., Kubernetes, to manage and scale the deployment of containers across distributed edge units seamlessly.
- Establishing standardized APIs for communication between edge units and other network components.
- Design edge computing infrastructure that can easily scale to accommodate the growing demands of smart city applications.
- Using 5G technologies to connect edge units and central data centers at high speeds and low latency.
- Implementing load-balancing algorithms to distribute computational workloads efficiently between edge units, preventing resource bottlenecks and optimizing overall system performance.
- Developing algorithms for intelligent data offloading between edge units and centralized cloud resources, optimizing data processing based on different parameters, including network congestion and application requirements.
- Introducing the paradigm of green edge computing by integrating energy-efficient computing practices into the design, utilizing low-power hardware, and implementing algorithms that optimize energy consumption.

C. Managing the massive network traffic via intelligent core This includes developing SDN networks efficiently for handling massive traffic of different smart city applications. Also, this direction includes developing associated network algorithms to facilitate the operation of SDN controllers. Moreover, developing API for network operators to facilitate managing smart city networks. An SDN has many remaining issues that can be considered for massive deployment networks. The research on this part of smart city networks can involve the following:

- Creating a distributed control plane architecture that enables effective resource management and coordination in response to the changing needs of different

applications for smart cities. A multi-controller scheme should be deployed for such core networks.
- Developing novel ways for communication between SDN controllers and avoiding communication overhead.
- Developing intelligent schemes, i.e., AI-based schemes, for load balancing between SDN controllers.
- Using network slicing to make virtualized, separate parts of the communication infrastructure. This will allow different smart city applications personalized and the best communication paths. This includes creating methods for dynamic network slicing, enabling the effective allocation and deallocation of resources according to the evolving demands of various applications over time.
- Developing adaptive routing protocols that dynamically adjust to network topology change and traffic patterns. This includes integrating machine learning algorithms for anomaly detection in network behavior, allowing the SDN infrastructure to adapt to emerging patterns.
- Developing intelligent algorithms for proactively detecting, predicting, and diagnosing network faults and failures to ensure ultra-high network availability.
- Developing novel reliable APIs for SDN networks using existing solutions, e.g., OpenAPI and Swagger.

D. Developing novel NFV approaches for future smart cities able to meet the required network scalability and cost efficiencies

Developing novel NFV approaches for future smart cities able to meet the required network scalability and cost efficiencies. This includes implementing continuous integration and deployment pipelines for automated testing, integration, and deployment of virtualized functions. The proposed NFV approaches should ensure compatibility with upcoming technologies and establish interoperability between various virtualized functions by referring to standardized interfaces and protocols. Also, this direction includes developing automated testing frameworks to ensure the reliability and robustness of virtualized functions.

E. Innovating novel frameworks for integrating all smart city applications over a single platform

Innovating novel frameworks for integrating all smart city applications over a single platform. This includes designing the integration framework with a plugin architecture, allowing easy integration of new applications and services.

F. Ways to assist dense deployment and ultra-reliable latency communications required by most smart city applications

This direction includes implementing small cell networks, including picocells and femtocells, to enhance capacity in densely populated areas. Thus, research in improving the performance of heterogeneous network (HetNet) architecture will assist the evolution of future smart cities. Furthermore, implementing advanced beamforming techniques to increase coverage and reduce interference in densely populated regions is recommended.

12. Conclusions

This work discusses future smart city main requirements and design challenges. The recent advancements in smart city systems and applications were investigated, and the limitations of these applications were introduced. The key enabling technologies that can be deployed to overcome these challenges are reviewed. This includes IoT, SDN, NFV, edge computing, blockchain, and AI. The main features and benefits of each considered technology are introduced. Also, the way each technology can assist smart city applications is discussed. Furthermore, the limitations and challenges of deploying such technologies are reviewed. This work also presents parts of the existing proposals that consider the discussed technologies to assist smart city applications. The considered studies discuss different smart city applications and deploy different technologies. Finally, this work provides research gaps for researchers dedicated to smart cities.

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