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Edge Computing for Smart Cities

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ABSTRACT

The rapid urbanization of the global population has necessitated the development of "smart cities," where interconnected systems optimize resources, enhance public safety, and improve the quality of life for residents. At the core of this transformation is the Internet of things (IoT), which generates vast amounts of data from connected sensors and devices. Traditional cloud computing models struggle to process this data efficiently due to latency, bandwidth constraints, and security concerns. Edge computing has emerged as a fundamental pillar to address the latency and bandwidth limitations of traditional cloud-centric architectures by decentralizing computation and moving it closer to the data sources. However, the integration of edge computing into smart city infrastructure presents a complex array of challenges. This paper examines the role of edge computing in smart cities.

KEYWORDS: *edge computing, cloud computing, smart cities, urban areas.*

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INTRODUCTION

The evolution of smart cities is intrinsically linked to advancements in computing paradigms that support real-time data processing, intelligent decision-making, and efficient resource utilization. As urban populations grow, cities are increasingly deploying Internet of things (IoT) sensors, cameras, and connected devices to manage infrastructure, public safety, and utilities. However, the traditional cloud-centric computing model, which relies on sending massive amounts of data to remote servers for processing, struggles to meet the real-time demands of these interconnected urban systems. Edge computing has emerged as a transformative solution, decentralizing data processing by bringing computation closer to the data source. It is the critical enabler of the modern smart city. By decentralizing data processing and bringing computational power closer to the source of data generation, edge computing offers transformative benefits for smart cities, including ultra-low latency, enhanced bandwidth efficiency, robust security, and increased resilience. Figure 1 shows the symbol of edge computing [1].

Edge computing is an indispensable enabler for the realization of smart cities, providing the localized processing power necessary for real-time, latency-sensitive urban applications. The most immediate and critical benefit of edge computing in a smart city context is the drastic reduction in latency. In applications where split-second decision-making is essential, the time it takes for data to travel to a centralized cloud server and back can be detrimental or even dangerous. Edge computing mitigates this by processing data locally at edge nodes, such as micro data centers or embedded hardware within the urban infrastructure itself [2].

CONCEPT OF EDGE COMPUTING

The history of edge computing traces back to the introduction of content delivery networks in the 1990s. The concept was straightforward: place servers close to end-user locations for faster cached image and video transmission. Edge computing was created jointly by Microsoft and their academic collaborators. Today, more and more services are pushed from the cloud to the edge of the network. Since data is increasingly being produced at the edge of the network, it would be efficient to process the data there. Keeping this data closer to its users (at the edge) eliminates many of the problems inherent with the public cloud model. Figure 2 shows how edge computing works [3]. Edge computing allows data from IoT devices to be analyzed at the edge before being sent to the cloud.

Edge computing (EC) or edge cloud is a computing paradigm where substantial compute and storage resources are placed at the edge of the Internet, in close physical proximity to mobile devices, sensors, end users, and IoT devices. It refers to bringing the flexibility and openness of cloud-native infrastructure to that local infrastructure. The idea of "edge" is to do processing near the data source. The terms "cloudlets," "micro data centers," and "fog" are used to refer to these small, edge-located computing nodes or data centers. A *cloudlet* is a cluster of computers well connected to the Internet and can be treated as "data center in a box." The main objective of a cloudlet is to extend the remote datacenter cloud services in close proximity to the end users. Physical proximity is the essence of edge computing since it improves latency, bandwidth, trust, and survivability. While the cloud has revolutionized the way we deal with data, the next wave of that revolution will happen at the edge [4].

A standard edge computing framework consists of three distinct levels [5]:

- The cloud: Which manages the overall data storage and processing.
- The edge: Tasked with near-instantaneous data handling.
- The device: Responsible for initial detection and basic data processing.

These three levels are related in the edge computing architecture shown in Figure 3 [6].

Edge computing covers a wide range of technologies such as wireless sensor networks, distributed data storage, and augmented reality. This has made its way to becoming the core of the data center. The term "edge" refers to the computing devices that sit closer to the sources of data, where the digital world meets the real world. These edge devices typically reside away from the centralized computing available in the cloud and are being created with increasingly compute capabilities. Typical edge devices are smartphones, tablets, sensors, wearables, routers, switches, integrated access devices, multiplexers, smart TV, modern cars, and a variety of MAN/WAN access devices. Edge computing enables analytics and data gathering to occur at the source of the data.

Edge computing covers a spectrum of technologies such as cloudlets, fog computing, and mobile edge computing. A combination of edge and cloud computing is referred to as *fog computing* because it combines centralized and distributed computing resources into a single architecture. (Edge computing is a relatively new concept that should not be confused with fog computing.) It is practically unsafe and unnecessary to send such a large amount of data to the cloud. A comparison between cloud computing, edge computing is illustrated in Figure 4 [7]. Compared to cloud computing, fog computing and edge computing have the following five advantages [8]: (1) greater data transmission speed, (2) less dependence on limited bandwidths, (3) greater privacy and security, (4) greater control over data generated in foreign countries where laws may limit use or permit unwanted governmental access, and (5) lower costs because more sensor-derived data are used locally, and less data are transmitted remotely. Figure 5 shows edge computing [9], while Figure 6 shows how edge data is processed [3].

WHAT IS A SMART CITY?

Cities around the world are being wrecked by the ever-increasing burden of traffic. Smart cities are a recent innovation perceived as a winning strategy to cope with some severe urban problems such as traffic, pollution, energy consumption, waste treatment. Governments can streamline the way cities are run, saving money and making them more efficient as a result. The notion of the smart city captured most people attention during the last decade as a blend of beliefs on how technology in general could be used to transform how cities around the world work, while improving their competitiveness, offering new ways of solving problems linked to poverty, social deprivation, pollution and poor environmental issues [10].

The concept of smart city emerges as a major response to the increasing global urbanization, global warming, sustainable growth, scarcity of resources, and socio-economic challenges faced by cities worldwide. IBM's Smarter Cities work began in late 2008 as part of the Smarter Planet initiative. The idea of "smart city" first appeared in the 1990s, with focus on the impact of ICT on modern infrastructures within cities. It is the merge of some other more familiar urban policies such as digital city, green city, knowledge city.

The word "smart" can be used to describe any device that can process information and can communicate with something. The term "smart cities" is a fuzzy concept and there is not a one-size-fits-all definition of the concept. The term has gained traction across sectors and has pervaded the fields of sustainability, urban planning, architecture, engineering, and computer science.

As typically shown in Figure 7 [11], a smart city is a high-tech urban area that connects people, information and technologies in order to increase life quality. It integrates ICT in a secure manner so as to manage the city's assets, increase operational efficiency, share information with the public, and improve citizen welfare. ICT is the key technology that weaves digital intelligence into cities' fabric. The main motivation for using ICT is the desire to eradicate human error. Smart cities are those communities that pursue sustainable economic development through investments in human and social capital and manage natural resources through participatory policies.

The main target for developing smart cities is to provide the following services [12]:

1. Convenience of the public services
2. Delicacy of city management
3. Liveable and sustainable living environment
4. Smartness of infrastructures
5. Effective integration of physical, digital and human systems in the built environment to deliver a sustainable, prosperous and inclusive future for its citizens.
6. Adequate water supply and electricity supply
7. Sanitation, including solid waste management
8. Efficient urban mobility and public transport
9. Affordable housing, especially for the poor
10. Good governance, especially e-Governance and citizen participation,
11. Safety and security of citizens, particularly women, children and the elderly
12. Health and education.

Figure 8 displays the six major characteristics of a smart city [13], while Figure 9 shows different elements of a smart city [14].

EDGE COMPUTING IN SMART CITIES

A city of one million people can produce approximately 180 petabytes of data daily. The sheer volume of data generated poses significant challenges for bandwidth and latency. Transmitting this data to centralized cloud servers causes delays that are unacceptable for time-sensitive applications, such as autonomous vehicles or emergency response systems. Edge computing addresses these bottlenecks by deploying micro data centers, edge servers, and intelligent nodes directly within the urban infrastructure—such as on traffic lights, utility poles, or buildings. By processing data locally, edge computing reduces network latency, improves bandwidth utilization, and enhances energy efficiency. By shifting data processing from the cloud to the edge of the network, cities can achieve the real-time responsiveness, efficiency, and scalability required to manage complex urban ecosystems. Figure 10 shows a representation of edge computing in a smart city [15], while Figure 11 shows edge-enabled smart city requirements [14].

As urbanization intensifies globally, nations are increasingly adopting the smart city approach to address the challenges of rising infrastructure demands and sustainability issues. Cities worldwide are already demonstrating the transformative potential of edge computing. Barcelona serves as a premier example of a city leveraging edge technology to modernize its ancient infrastructure. Partnering with technology providers like Lenovo and Cellnex, Barcelona has deployed a network of edge servers integrated seamlessly into the urban environment. Similarly, Singapore utilizes edge computing and IoT sensors for smart traffic control, successfully reducing travel times and managing congestion effectively [2].

APPLICATIONS OF EDGE COMPUTING IN SMART CITIES

The integration of edge computing into smart city infrastructure enables a wide array of intelligent services that improve urban efficiency and citizen well-being. Its transformative applications across key smart city domains include traffic management, public safety, energy optimization, and environmental monitoring. Common applications of edge computing in smart cities include the following [2,14,16]:

- *Intelligent Traffic Management*: Urban traffic congestion is a universal challenge. It is a persistent issue that leads to economic losses, increased emissions, and reduced quality of life. Traditional traffic systems operate on fixed timers or rely on data sent to a central server, causing delays in response times. With edge computing, cameras and sensors at intersections analyze traffic flow in real time. This allows the system to dynamically adjust signal timings, alter lane directions during peak hours, and alert drivers to hazards instantly.
- *Public Safety*: Ensuring public safety is a primary objective for smart cities. Video surveillance networks are extensive, but transmitting continuous high-definition video streams to central servers strains network bandwidth and

delays response times. Edge computing significantly enhances public safety by enabling real-time video analytics. High-resolution surveillance cameras equipped with edge AI can process video feeds locally to detect anomalies, unauthorized access, or accidents. These edge-enabled cameras can perform facial recognition, detect unauthorized access, identify abandoned objects, and monitor crowd behavior without sending raw video data to the cloud. Instead of streaming heavy video files to a central server, the edge device only sends alerts when a specific event is detected, ensuring swift emergency responses and reducing bandwidth congestion.

- *Smart Home:* A smart home offers enhanced security, smart meters, and smart control. Enabling smart homes with these features requires a multi-layer system with the ability to make a decision regarding home automation using real-time and historical data. Such types of multi-layer systems use different smart IoT devices along with AI techniques to provide various automatic operations at the home. However, performing smart home tasks based on AI requires instant computational resources at the edge. Therefore, edge computing can be one of the promising solutions to enable smart homes based on AI by offering on-demand computational resources with low-latency.
- *Smart Farming:* Smart farming is aimed to utilize advanced technologies for increasing productivity and reduce cost simultaneously. To enable efficient operation of smart farming, sensors layer require instant instructions and computational resource for processing of complex algorithms at the network edge. One way is to store frequently requested instructions at the remote cloud due its high storage capacity than edge computing servers. However, this will increase the delay and affects the system performance.
- *Smart Parking System:* Traditional parking systems suffer from challenges of inefficient parking space management and high computational time in finding empty parking slots. To cope with these limitations, one can use smart parking systems which offer instant computation of empty parking slots and efficient parking space management via different schemes based on machine learning. The smart parking can be enabled via existing surveillance cameras and image detection systems. Edge computing seems to be a promising solution for enabling the smart parking system through on-demand computation resources.
- *Smart Grids*: The modernization of energy infrastructures relies on edge–cloud architectures for intelligent grid management, decentralized energy trading, and predictive maintenance. Edge computing plays a vital role in stabilizing smart grids. It enables real-time load balancing by continuously monitoring power consumption, detecting fluctuations, and dynamically adjusting distribution. The transition toward renewable energy sources and the increasing demand for electricity—driven in part by electric vehicles—require a highly responsive and efficient energy grid. Smart buildings and utility grids benefit from edge computing by monitoring energy consumption in real time. Edge devices can instantly detect leaks, failures, or spikes in demand, allowing the grid to autonomously distribute power where it is most needed or integrate renewable energy sources efficiently.
- *Sustainable Infrastructure*: Beyond energy, edge computing supports various sustainability initiatives. Smart cities enable citizens to experience sustainable, secure, and reliable developments. For example, smart waste management systems utilize edge sensors in public bins to monitor fill levels and notify collection services only when necessary, optimizing routing and reducing fuel consumption. Similarly, edge nodes can monitor environmental factors like air quality and noise pollution, providing city planners with actionable data to improve public health outcomes.
- *Autonomous Vehicles:* Edge computing is foundational for the deployment of autonomous vehicles and intelligent public transit. The ultra-low latency provided by edge computing, particularly when combined with 5G networks, is crucial for autonomous vehicles and delivery robots. Autonomous vehicles generate terabytes of data daily, including LIDAR, radar, and high-resolution camera feeds. In Singapore, an urban community integrated edge AI systems into delivery robots to autonomously distribute parcels. The localized processing ensures the robots can navigate complex environments and avoid obstacles in real time without relying on a distant cloud connection.
- *Environmental Monitoring*: Smart cities strive to create healthier environments for their citizens. Edge sensors deployed throughout the city continuously collect data on air quality, noise pollution, temperature, and humidity. By analyzing this data at the edge, city authorities can receive immediate alerts regarding hazardous

pollution levels and take proactive measures, such as redirecting traffic away from heavily polluted areas or issuing public health advisories.

- *Resource Management:* Efficient resource management in multi-tier edge–cloud architectures is crucial to maintaining low latency, high availability, and optimal service performance in smart-city applications. Unlike traditional cloud-centric models, where resources are centrally managed, edge–cloud environments require decentralized, real-time coordination of computing, networking, and storage resources. The complexity of resource management arises from dynamic workloads, fluctuating network conditions, heterogeneous edge nodes, and mobility-induced service migrations.
- *Waste Management*: Waste management is a critical component of smart cities. Edge computing optimizes municipal services such as waste management. Smart bins equipped with edge sensors can monitor their fill levels and independently notify waste collection services when they are full. This allows cities to optimize garbage truck routes dynamically, reducing fuel consumption, lowering operational costs, and preventing overflowing bins.
- *Disaster Response:* Edge–cloud computing significantly enhances disaster response by providing real-time situational awareness, predictive analytics, and rapid resource deployment. Edge nodes facilitate immediate hazard detection by processing sensor data from surveillance cameras, unmanned aerial vehicles (UAVs), and environmental sensors. Instantaneous risk assessment enables authorities to make informed decisions and deploy emergency resources efficiently.

BENEFITS

The shift from cloud-centric to edge-centric architectures offers several distinct advantages for smart cities. The benefits are profound: intelligent traffic systems that adapt in milliseconds, robust public safety networks that protect citizen privacy, and resilient, sustainable utility grids that optimize resource consumption. Other benefits of edge computing in smart cities include the following [2,17]:

- *Low Latency*: Edge computing brings data processing and analytics closer to the data source, reducing the time it takes to transmit and process data. This low latency enables real-time decision-making and responsiveness, critical for applications such as autonomous vehicles, emergency response systems, and smart grid management. By processing data at the edge, smart cities can deliver faster and more immediate services to their citizens.
- *Bandwidth Optimization*: The proliferation of IoT devices in smart cities generates an unprecedented volume of data. Transmitting all this raw data to the cloud places an immense strain on network bandwidth and incurs substantial data transport costs. Edge computing addresses this bottleneck by filtering and processing data at the source. Instead of sending continuous, high-definition video feeds or constant sensor telemetry to the cloud, edge devices analyze the data locally and only transmit relevant insights, anomalies, or summarized reports.
- *Reliability and Resilience*: Edge computing enhances the reliability and resilience of smart city systems. By distributing computing resources across edge devices, even in the event of network disruptions or cloud outages, critical services can continue to operate locally. Edge devices can store and process data offline, ensuring uninterrupted service delivery and minimizing the impact of network failures. This is particularly important for applications like public safety, healthcare, and traffic management.
- *Enhancing Public Safety*: Public safety is a paramount concern for smart cities, and edge computing significantly enhances the capabilities of urban security systems. Video surveillance systems powered by edge AI can process high-resolution feeds locally to detect accidents, crimes, or suspicious behaviors in real time. By analyzing the video on the device itself, the system can trigger immediate alerts to law enforcement or emergency services without the delay of cloud processing.
- *Improving Data Privacy*: Edge computing inherently improves data privacy and security—a critical consideration when dealing with sensitive citizen data. The decentralized nature of edge computing means that raw, sensitive data (such as facial recognition data or personal movement patterns) does not need to be transmitted across vulnerable networks to a central server. Instead, the data is processed locally, and only anonymized metadata or specific alerts are shared. This approach aligns with privacy-by-design principles, helping municipalities comply with stringent data protection regulations like GDPR while maintaining public trust.

- *Building Resilient Infrastructure*: The resilience of a city's infrastructure is tested during natural disasters, extreme weather events, or network outages. Edge computing provides a decentralized architecture that ensures critical urban systems remain operational even if connectivity to the central cloud is severed. Because edge nodes process data locally, localized systems—such as smart grids, emergency response networks, and traffic controls—can continue to function autonomously during a crisis.
- *Urban Sustainability:* Sustainability is another area where edge computing will make a big impact. Edge computing plays a vital role in advancing urban sustainability. Smart grids integrated with edge analytics can monitor energy consumption patterns in real time, balancing supply and demand instantaneously. This localized intelligence allows for the seamless integration of variable renewable energy sources, such as solar and wind, by dynamically adjusting power distribution based on immediate local availability. By optimizing utility grids and detecting leaks or inefficiencies instantly, edge computing minimizes resource waste and supports the broader environmental goals of the smart city.

CHALLENGES

While edge computing offers immense benefits, its distributed nature introduces significant technical, operational, and governance challenges. Challenges of implementing edge computing in urban infrastructure include cybersecurity, data privacy, digital divide, system integration, and scalability. Other challenges of edge computing in smart cities include the following [2,16]:

- *Hardware Constraints*: One of the primary challenges in edge computing is the inherent limitation of computational resources at the edge. Unlike centralized cloud servers, which possess virtually unlimited processing power and storage, edge devices—ranging from smart sensors and traffic cameras to roadside units (RSUs) and micro data centers—operate with constrained CPU power, memory, and storage capacities. Overcoming the limitations of computational resources, securing a vastly expanded attack surface, ensuring seamless interoperability with legacy systems, and maintaining energy sustainability require concerted efforts from researchers, industry stakeholders, and urban planners.
- *Complex Algorithms*: Many smart city applications, such as real-time video surveillance analytics and autonomous vehicle coordination, rely on complex artificial intelligence (AI) and machine learning (ML) algorithms. Executing these resource-intensive models on constrained edge devices is a significant hurdle. As urban populations grow and the density of IoT devices increases, edge infrastructure must scale accordingly, which often conflicts with the physical and power limitations of the deployment sites.
- *Complex Integration:* Integrating modern edge computing solutions with legacy urban infrastructure—such as older utility grids or traditional traffic management systems—adds another layer of complexity. Many legacy systems were not designed to communicate with modern IoT protocols or handle real-time distributed processing.
- *Energy Consumption:* As the deployment of edge computing scales to support smart city initiatives, the cumulative energy consumption of thousands of distributed edge nodes and micro data centers becomes a critical concern. If not managed properly, the energy demands of edge infrastructure could undermine the sustainability goals of smart cities.
- *Security Vulnerabilities:* Decentralizing data processing significantly expands the attack surface of the city's digital infrastructure. Unlike centralized cloud data centers, which are heavily fortified, edge devices are distributed across public spaces, making them physically and digitally vulnerable. Many IoT devices have limited computing resources, restricting the implementation of robust security protocols. This expansive attack surface exposes edge networks to threats such as unauthorized access, data breaches, and distributed denial of service (DoS) attacks.
- *Privacy Concerns:* Smart cities inherently involve the continuous monitoring of public spaces and citizen activities. The collection and processing of this data at the edge raise critical privacy concerns. Edge systems continuously collect sensitive data from citizens, including video footage and location tracking. The lack of universally accepted privacy frameworks in edge computing can lead to fragmented implementations. To address this, cities must adopt "privacy-by-design" approaches. Techniques such as federated learning—where edge devices train AI models locally without sharing raw data—and differential privacy are

essential for protecting individual identities while still extracting valuable urban insights.

- *Interoperability:* Smart cities comprise a vast ecosystem of heterogeneous devices, platforms, and communication protocols developed by different vendors. Integrating thousands of edge devices from various manufacturers into existing legacy urban systems is complex. Ensuring interoperability between different hardware and software platforms requires standardized protocols and adaptable software solutions.
- *Lack of Standardization:* The absence of standardized protocols and interoperability frameworks poses a significant barrier to the widespread adoption of edge–cloud computing. The fragmented nature of current implementations results in compatibility issues across different platforms, leading to inefficiencies in system deployment and operational management. The lack of universal communication standards hinders seamless interaction between heterogeneous devices, making it difficult to achieve cohesive and scalable edge–cloud infrastructures.
- *Digital Divide:* As cities become "smarter," there is a risk of exacerbating the digital divide. The deployment of advanced edge infrastructure and 5G networks may be concentrated in affluent commercial districts, leaving lower-income neighborhoods underserved. This inequity in digital infrastructure can lead to disparities in access to improved public services, emergency response times, and economic opportunities. To build truly inclusive smart cities, municipal governments must prioritize digital equity, ensuring that edge computing deployments benefit all residents across the urban landscape.
- *Scalability:* Edge–cloud architectures rely on high-speed communication networks to facilitate real-time data exchange and deliver low-latency service. However, the scalability of these networks remains a fundamental challenge as the number of connected devices and data-intensive applications continues to rise. The proliferation of latency-sensitive services such as autonomous driving, industrial automation, and remote healthcare necessitates network architectures that can efficiently handle massive data volumes while maintaining ultra-reliable low-latency communications. Traditional cloud-centric networking models struggle to meet these stringent requirements, prompting the need for innovative approaches that leverage edge computing for localized data processing and hierarchical network management.

FUTURE OF EDGE COMPUTING IN SMART CITIES

By 2050, it is projected that more than two-thirds of the global population will reside in urban areas, placing unprecedented strain on city infrastructures. The future of smart cities is inextricably linked to the advancement of edge computing. It lies in the evolution from reactive systems to proactive, "cognitive cities." The future of smart cities is heavily dependent on the convergence of edge computing with artificial intelligence (Edge AI) and 5G wireless networks. This triad forms the backbone of next-generation urban infrastructure, providing the low latency, high bandwidth efficiency, and localized processing power required to manage intelligent traffic systems, optimize energy grids, and enhance public safety in real-time. The rollout of 5G networks provides ultra-low latency, high bandwidth, and the capacity to connect a massive density of devices simultaneously. 5G acts as the perfect conduit for edge computing, accelerating data transfer between edge nodes and enabling more complex real-time applications. Ultimately, edge computing will not only make cities smarter and more efficient but also more responsive, sustainable, and attuned to the needs of their citizens [2].

CONCLUSION

Edge computing is not merely an incremental technological upgrade; it is a foundational paradigm shift necessary for the realization of smart cities. By decentralizing data processing, edge computing overcomes the latency, bandwidth, and reliability limitations of traditional cloud architectures. As cities continue to grow, embracing edge computing will be imperative to creating environments that are efficient, sustainable, and responsive to the needs of their citizens.

Edge computing, which enables the processing and analysis of data closer to the source, has emerged as a promising solution to handle the data deluge in smart cities. It is a promising computing paradigm to enrich smart cities with instantaneous computing and storage resources. As smart cities continue to evolve, the integration of edge computing is no longer a luxury but a necessity. More information on edge computing in smart cities can be found in the book in [18-20] and a related journal: *Cities*.

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Figure 1 The symbol of edge computing [2].

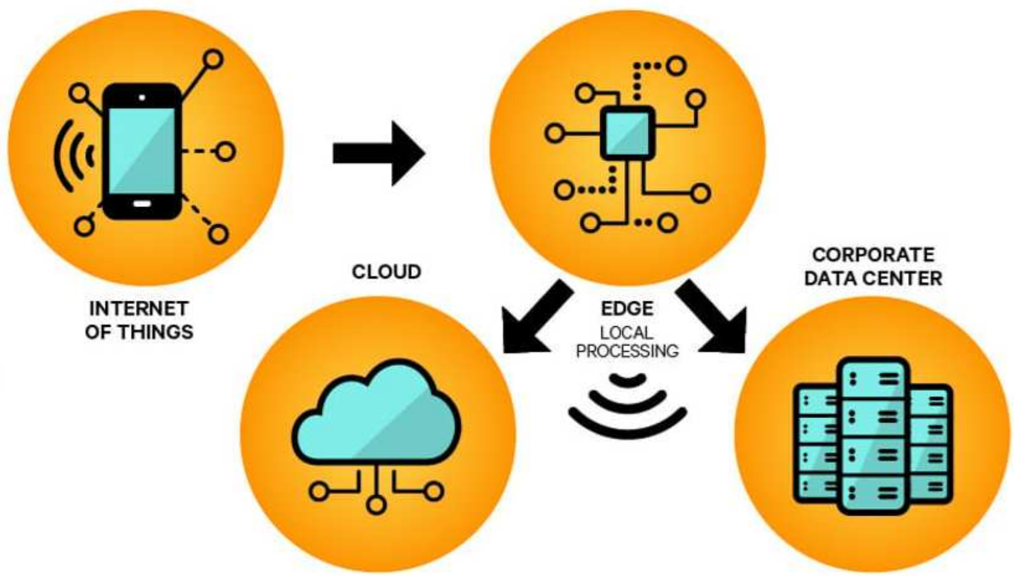

Figure 2 How edge computing works [3].

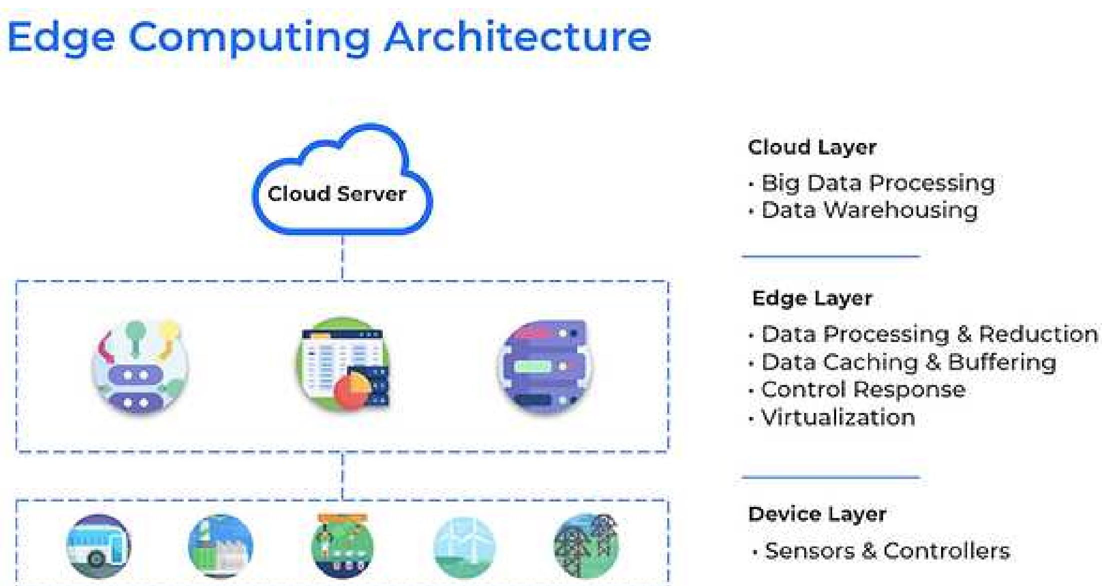

Figure 3 Edge computing architecture [6].

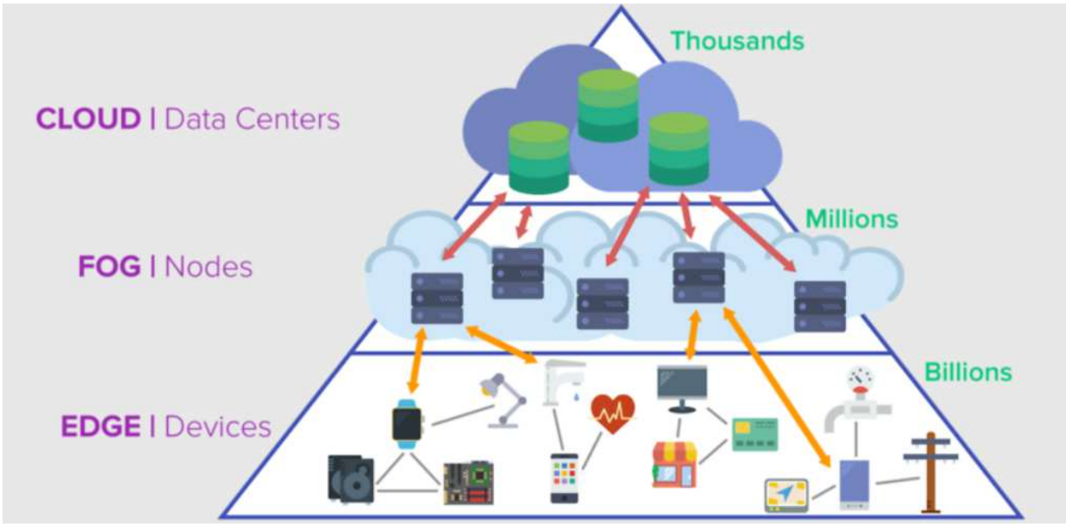

Figure 4 The relationship between cloud computing, edge computing, and fog computing [7].

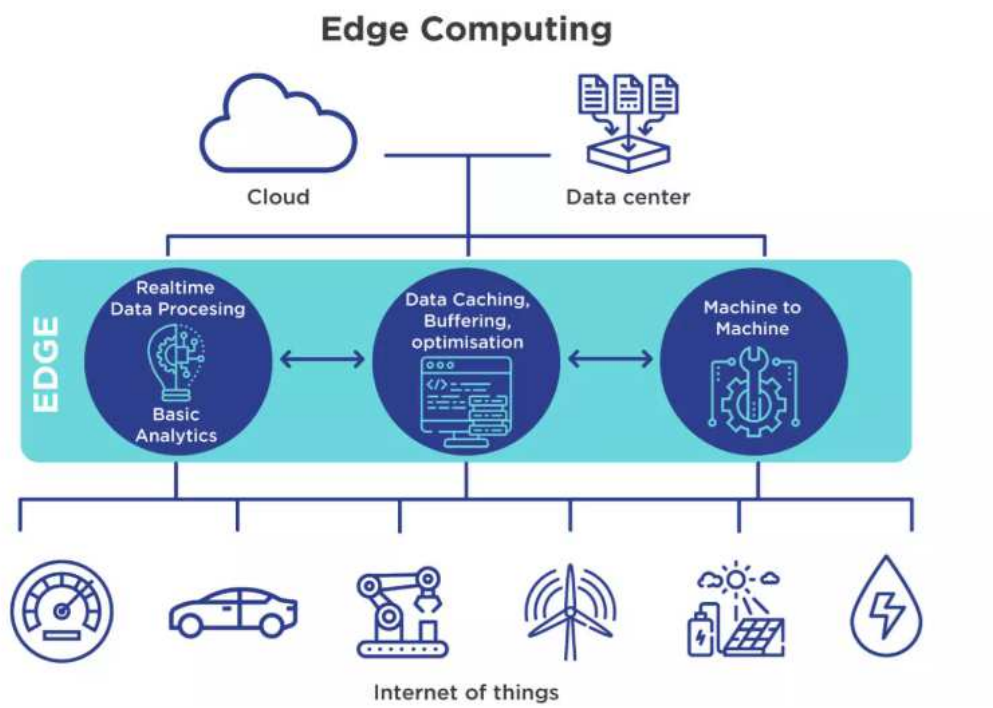

Figure 5 Edge computing [9].

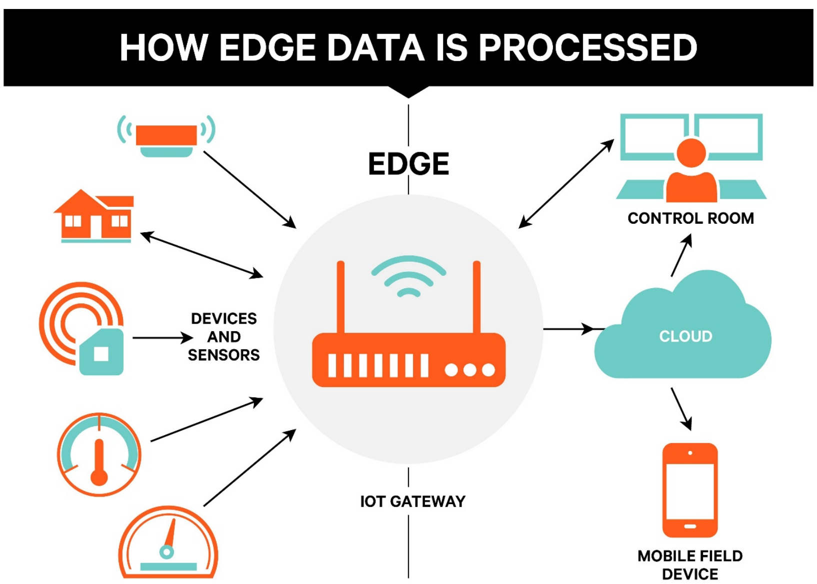

Figure 6 How edge data is processed [3].

Figure 7 A typical smart city [11].

Figure 8 The six major characteristics of a smart City [13].

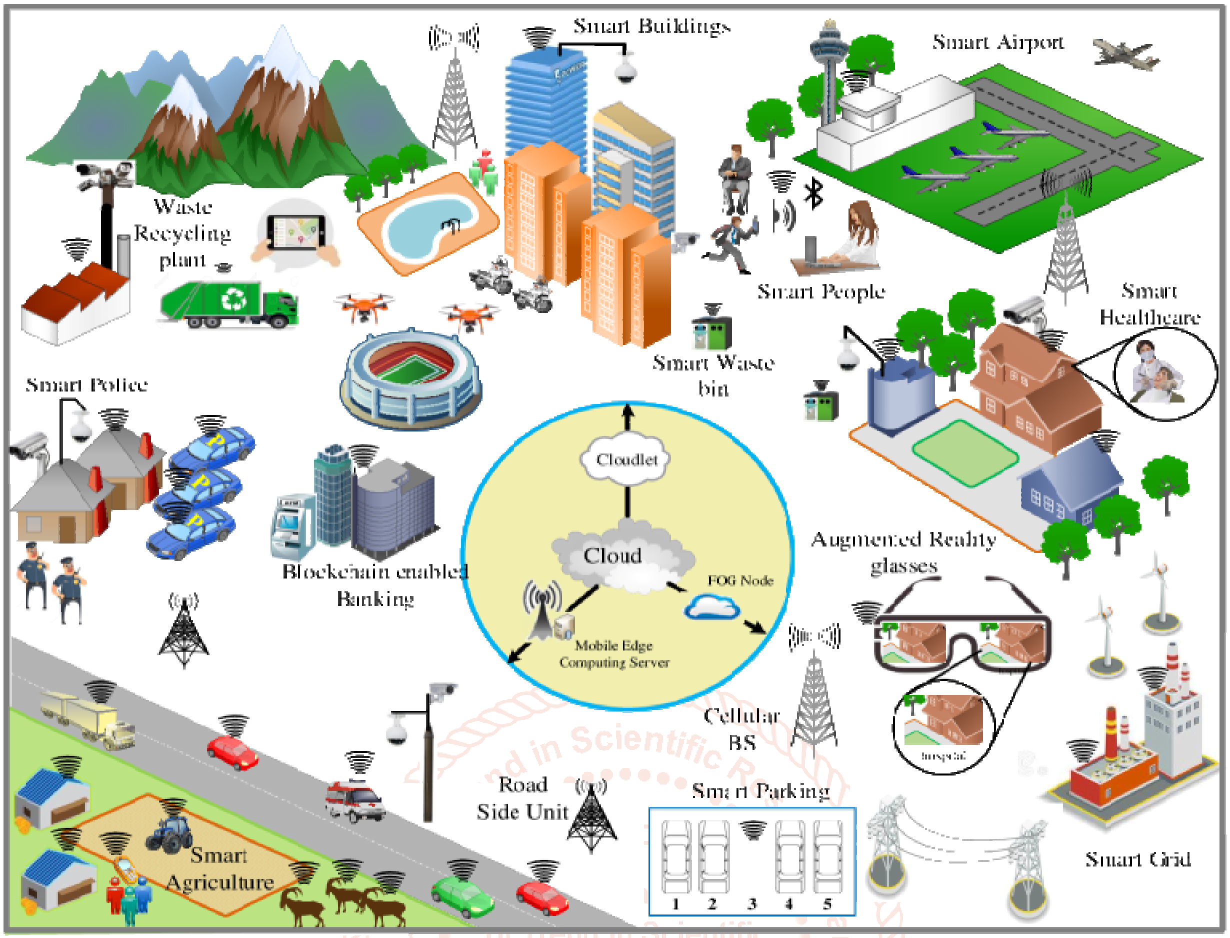

Figure 9 Different elements of a smart city [14].

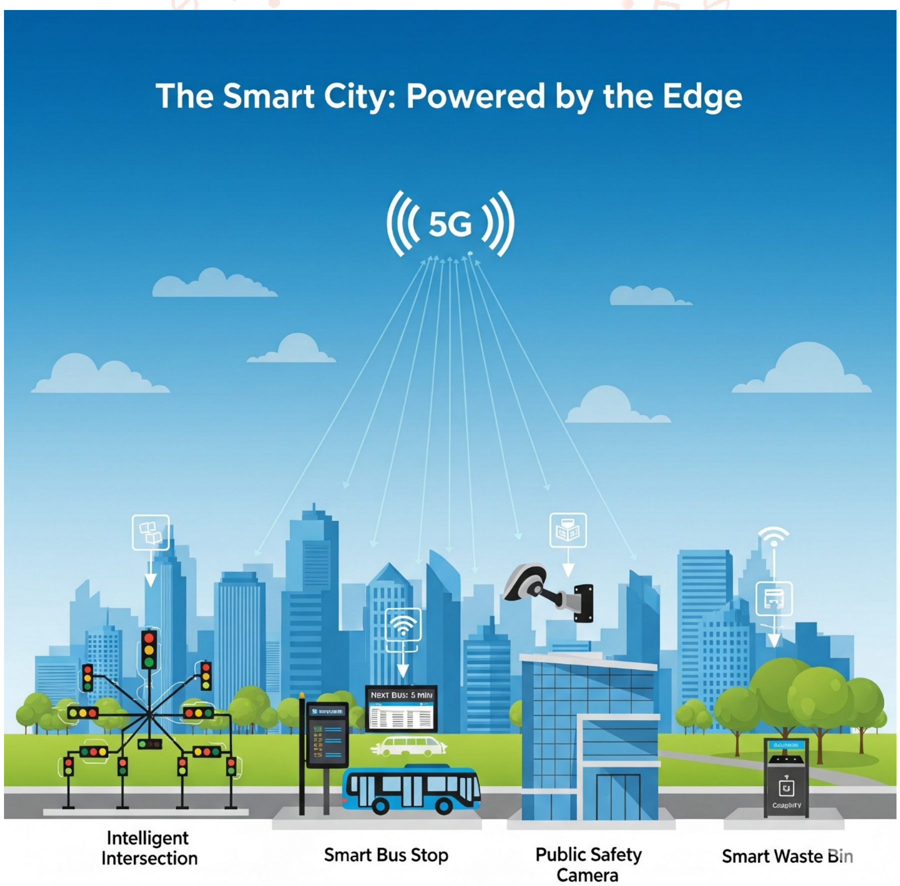

Figure 10 A representation of edge computing in a smart city [15].

Figure 11 Edge-enabled smart city requirements [14].