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Applications of Edge Computing

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ABSTRACT

The exponential growth of data generated by the Internet of things (IoT), autonomous systems, and mobile applications has exposed the limitations of traditional, centralized cloud computing architectures. In response, edge computing has emerged as a transformative paradigm that decentralizes data processing, moving computational resources closer to the data source. Edge computing is fundamentally altering the landscape of data processing by shifting computational resources away from centralized cloud data centers to the periphery of the network. This decentralized approach addresses the inherent constraints of centralized cloud systems, particularly concerning latency, bandwidth, and security. This paper explores the concept of edge computing and provides its transformative applications in various industries.

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KEYWORDS: *edge computing, cloud computing, applications.*

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INTRODUCTION

For over a decade, cloud computing has been the dominant model for enterprise IT infrastructure, centralizing data storage and processing in massive, remote data centers.

The proliferation of connected devices and the exponential growth of data have exposed the limitations of traditional cloud computing architectures. The centralized nature of cloud computing often introduces latency issues and bandwidth constraints that are incompatible with applications requiring instantaneous responses. In response to these challenges, edge computing has gained prominence as a distributed computing paradigm that brings computation and data storage closer to the sources of data generation. By processing data at the “edge” of the network-near or at the devices themselves-organizations can achieve significantly lower latency, improved reliability, and enhanced security. Figure 1 shows the symbol of edge computing [1].

The proliferation of Internet of things (IoT) devices and the demand for real-time processing have driven the evolution of edge computing-a decentralized paradigm that processes data closer to its source. Edge computing is not a replacement for cloud computing. Rather, it is a necessary evolution of the IT architecture designed to complement the cloud. By distributing computational resources to the periphery of the network, edge computing successfully addresses the critical challenges of latency, bandwidth constraints, and data security that plague centralized systems [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, and fog computing is made in Table 1 [7] and illustrated in Figure 4 [8]. Compared to cloud computing, fog computing and edge computing have the following five advantages [9]: (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 [10], while Figure 6 shows how edge data is processed [3].

APPLICATIONS OF EDGE COMPUTING

The edge computing use cases are mainly used to derive predictable business outcomes at a macro level by collecting and analyzing the data at the micro level. Applications of edge computing include autonomous vehicles, healthcare, manufacturing, retail, and smart cities, smart homes, and smart grid. Figure 7 shows some top applications of edge computing [11]. Common applications of edge computing include the following [2,12-15]:

1. *Autonomous Vehicles*: Autonomous vehicles (AVs) are self-driving cars and trucks that use edge computing to enhance navigation systems. Autonomous vehicles (AVs) represent one of the most demanding use cases for edge computing. These vehicles rely on a continuous stream of data from various sensors, including radar, LiDAR, and high-definition cameras, to navigate complex and rapidly changing environments. Self-driving cars generate terabytes of data daily from radar, LiDAR, and cameras. This sheer volume of data generated by these sensors-often terabytes per hour-makes it impractical and unsafe to rely on cloud processing for critical driving decisions. Edge computing will be one of the main enablers of autonomous vehicles, particularly in applications such as truck platooning. Edge computing enables AVs to process sensor data on board in real time. This allows the vehicle's navigation system to instantly detect obstacles, interpret traffic signals, and adjust speed or trajectory without waiting for a response from a distant data center.
2. *Healthcare*: Perhaps the most important usage of edge computing occurs in hospitals and other

medical facilities, where the speed of information can literally mean the difference between life and death. The edge computing can be quite useful in healthcare, for example, processing data from devices such as glucose monitoring or heart rate sensors right within the hospital. In the healthcare industry, edge computing is revolutionizing patient care by enabling continuous, real-time monitoring. Medical devices such as insulin pumps, pacemakers, and wearable health trackers generate vital data that requires immediate analysis. Transmitting this sensitive health information to a central cloud introduces latency and raises significant privacy and compliance concerns, particularly under regulations like the Health Insurance Portability and Accountability Act (HIPAA). By processing data locally on the device or a nearby edge server, healthcare providers can receive instantaneous alerts regarding critical changes in a patient's condition. For example, an edge-native application on a heart monitor can analyze cardiac rhythms locally and immediately notify medical personnel if an anomaly is detected, without exposing the raw data to the open Internet. This capability is also crucial for advanced medical procedures, such as robot-assisted surgeries, where latency must be virtually eliminated.

3. *Manufacturing*: Factories are rife with opportunities for using edge computing. Edge computing assists in coordinating automation efforts and in making sure that there is a sufficient supply of raw assets needed for manufacturing. The manufacturing sector is leveraging edge computing to drive the transition towards Industry 4.0. Modern factories are equipped with numerous operational technology (OT) systems and IoT sensors that monitor equipment health, track production metrics, and ensure quality control. Edge computing facilitates predictive maintenance by employing localized machine learning algorithms to analyze equipment data in real time. This allows manufacturers to detect anomalies and predict potential failures before they occur, thereby reducing costly downtime and extending the lifespan of machinery.

4. *Retail Industry:* In the pursuit of offering a pleasing customer experience, retailers are always looking for a competitive edge. Edge computing gives retail providers several ways to establish unforgettable user experiences. Retailers are increasingly adopting edge computing to enhance the customer experience and optimize supply chain operations. In physical stores, edge solutions can process data from point-of-sale systems, inventory sensors, and surveillance cameras to provide immediate insights. For example, edge computing enables dynamic inventory management by continuously analyzing purchasing patterns and real-time stock levels, allowing for automated restocking alerts. Furthermore, retailers are utilizing edge AI to analyze in-store video feeds for loss prevention and to gain insights into customer foot traffic and behavior, all while keeping the video data localized to protect consumer privacy.

5. *Smart Cities*: The development of smart cities relies heavily on the integration of edge computing to manage complex urban systems efficiently. As cities deploy extensive networks of sensors and IoT devices to monitor traffic, energy usage, and environmental conditions, centralized cloud processing becomes a bottleneck. Edge computing enables intelligent traffic management systems that process data from roadside cameras and sensors locally. This allows for real-time adjustments to traffic light timings based on current congestion levels, improving traffic flow and reducing emissions. Similarly, edge analytics in smart grids can monitor energy consumption patterns dynamically, optimizing power distribution and integrating renewable energy sources more effectively. Edge computing offers several advantages for smart cities, enabling them to overcome the limitations of traditional cloud-centric architectures. Figure 8 depicts edge computing in smart cities [16].

6. *Smart Homes:* Smart homes rely on a multitude of IoT devices, from thermostats to security cameras, that collect and process data to automate various functions. Traditionally, this data is sent to a centralized server for processing, which can lead to issues with latency, backhaul costs, and security. Edge computing addresses these challenges by processing and storing data closer to the smart home itself. This local processing reduces the time it takes for devices to respond to commands, such as a voice assistant like Amazon Alexa, and enhances privacy by keeping sensitive information within the home network. As smart homes become more prevalent, edge computing will be essential for improving performance and ensuring data security.

7. *Smart Grid:* Another highly significant usage of edge computing involves energy management. Edge computing will become very important in smart grid management since the consumption pattern gets complex with the integration of

renewable sources. Edge computing supports the use of smart grids, which can deliver energy more efficiently and help businesses leave a smaller carbon footprint.

8. *Oil and Gas Industry*: The oil and gas industry is normally operated in secluded areas with difficult climatic conditions, where dependable connectivity back to central data centers has been a challenge. Edge computing enables this by bringing data processing closer to assets, hence the capability of real-time monitoring and analytics. For example, sensors mounted on pipelines, rigs, or refineries could analyze immediately the data locally and detect issues such as pressure changes or equipment malfunction before they escalate into failures that may be dangerous or costly. This closeness reduces the need for high-quality internet connections, reduces latency, and ensures that life-critical decisions are done speedy and effectively, even from the remotest areas of the globe. Speaking of energy management, edge computing also supports the remote monitoring of oil and gas assets. This is no small feat, given some of the rugged locales where oil is drilled-for example, an ocean floor. Edge computing fosters the use of real-time analytics and does it closer to the specific asset, limiting the need for cloud connectivity.
9. *Telecommunications*: Telecommunications providers use edge computing to support 5G network automation and mobile edge computing deployments. A telecom operator deploys edge servers in stadiums to support AR-based fan experiences, reducing latency while freeing up core network bandwidth. By combining 5G and edge computing, telecoms deliver new services, reduce congestion, and create differentiated business opportunities. Operators, finding themselves burdened with the shift to 5G, are rapidly virtualizing their radio access networks (vRAN) as a lever to drive efficiency and lower costs. The processing required by virtualized infrastructure is complex and latency-intensive, meaning there can be very little ebbing or Dead Sea leftovers for edge computing. This is critical to support 5G demands for high-speed data transfer, massive IoT connectivity, and low latency of applications such as autonomous driving and augmented reality. Edge computing, in relation, avails more flexible and cost efficient ways of deploying 5G networks.
10. *Gaming*: A gaming provider deploys edge servers near players, cutting response times drastically. Gameplay feels seamless even with graphically demanding titles. Edge computing ensures smooth experiences in media and gaming, where milliseconds make the difference between success and frustration.
11. *Agriculture*: Some farms are located where high-speed internet and adequate resources are not available. This can be used to have intelligent and modern agriculture that can process generated data at the edge and help the farmer decide. Farms and environmental projects often operate in remote locations with limited connectivity, making edge computing highly valuable for real-time decision-making. Edge computing helps agriculture improve yields, reduce waste, and adopt sustainable practices even in bandwidth-constrained environments. Edge-enabled sensors monitor soil moisture, adjusting irrigation instantly.
12. *Entertainment*: Edge computing puts a new spin on content delivery networks, helping performers and their talents reach a broader spectrum of audience. It does this by using a cache to keep its web pages, music and streaming-video stream content at the edge. That is how edge computing can lower latency levels and ensure better-quality playback of video and audio when the consumer is streaming content.
13. *Finance:* Banks and financial institutions use edge computing to support real-time fraud detection, low-latency transactions and localized data processing that meets data sovereignty and compliance requirements across different regions.

Other applications include transportation, industrial IoT, logistics, marketing, utilities, and automobile industry.

BENEFITS

Edge computing represents a transformative shift in the IT landscape, offering unparalleled opportunities for real-time processing, reduced latency, and enhanced operational efficiency. It offers significant benefits such as reduced latency, improved bandwidth utilization, and enhanced scalability. This approach helps reduce latency, enhance security and increase efficiency. From enabling autonomous transportation to ensuring compliance with global privacy regulations, the benefits of edge computing are clear and far-reaching, cementing its role as a cornerstone of the future digital economy. Other benefits of edge computing include the following [2,12,17]:

- *Predictive Maintenance*: Predictive maintenance is a process that predicts failure before its occurrence so that maintenance can be conducted before a potential breakdown. Unexpected failures can execute comprehensive losses in time and profitability in a manufacturing or industrial setting. Edge computing enhances predictive maintenance by processing data from IoT sensors directly at the site, installed on machines. In such a configuration, continuous monitoring of equipment health is possible; real-time data analysis can be done for anomaly detection that might indicate wear or an impending failure. Thus, by identifying problems at an early stage, maintenance can be done in real time to avoid any downtime and enhance the life of equipment.

- *Latency Reduction*: Perhaps the most critical advantage of edge computing is the dramatic reduction in latency. In traditional cloud architectures, data must traverse long distances from the source to a centralized data center for processing, and the results must travel back. This round-trip journey introduces delays that, while often measured in milliseconds, are unacceptable for time-sensitive applications. Edge computing eliminates this geographical distance by processing data locally. This proximity ensures near-instantaneous data analysis and decision-making.
- *Decision-making:* As the volume of data generated by the Internet of things (IoT) and other connected devices continues to surge, edge computing has emerged as a critical enabler for real-time decision-making across various sectors.
- *Bandwidth Optimization:* The sheer volume of data generated by modern digital ecosystems makes transmitting all raw data to the cloud highly inefficient and prohibitively expensive. Bandwidth is a finite and costly resource, and network congestion can severely degrade system performance. Edge computing mitigates this issue by acting as a localized filter and processor. Instead of sending a continuous stream of raw data to the cloud, edge devices process the information locally, discarding irrelevant data and transmitting only essential insights, anomalies, or aggregated summaries to the central servers.
- *Enhanced Data Security*: As data privacy regulations become increasingly stringent globally, managing sensitive information has become a complex challenge for enterprises. Edge computing offers inherent advantages in both data security and regulatory compliance. Centralized cloud databases are lucrative targets for cybercriminals, as a single breach can expose massive amounts of aggregated data. Edge computing distributes data across numerous localized nodes, effectively decentralizing the risk.
- *Data Sovereignty*: Data sovereignty dictates that data is subject to the laws and governance structures of the nation in which it is collected or processed. In a centralized cloud model, organizations can often dictate where their data is stored. Global data privacy frameworks, such as the General Data Protection Regulation (GDPR) in Europe and the California Consumer Privacy Act (CCPA), place strict limitations on cross-border data transfers and mandate stringent controls over personal information. Edge computing simplifies compliance by enabling data to be processed and stored locally, within the jurisdiction where it was collected. Because the data does not need to cross international borders to reach a centralized cloud server, organizations can more easily adhere to data sovereignty laws and minimize the legal complexities associated with international data transfers.
- *Speed:* Edge computing brings analytical computational resources close to the end users and therefore can increase the responsiveness and throughput of applications. A well-designed edge platform would significantly outperform a traditional cloud-based system. Some applications rely on short response times, making edge computing a significantly more feasible option than cloud computing.
- *Efficiency:* Due to the nearness of the analytical resources to the end users, sophisticated analytical tools and artificial intelligence tools can run on the edge of the system. This placement at the edge helps to increase operational efficiency and is responsible for many advantages to the system. In distributed AI systems on the edge, data compression is increasingly recognized as a foundational design layer to mitigate bandwidth constraints caused by the exchange of large models and high-resolution sensor streams.
- *Increased Reliability*: Centralized cloud architectures are susceptible to single points of failure. If the central data center experiences an outage, or if the network connection to the cloud is severed, the dependent applications and devices are rendered inoperable. Edge computing enhances system resilience by enabling localized autonomy. Because edge devices possess local processing and storage capabilities, they can continue to function even if the connection to the central cloud is temporarily lost. This offline capability is crucial for remote locations, offshore platforms, or critical infrastructure where

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continuous operation is mandatory regardless of network stability. Once the connection is restored, the edge devices can synchronize their data with the central cloud. Other factors that may influence this aspect are the connection technologies in use, which may provide different levels of reliability, and the accuracy of the data produced at the edge that could be unreliable due to particular environment conditions. As an example, an edge computing device, such as a voice assistant, may continue to provide service to local users even during cloud service or Internet outages.

- *Sustainability:* Because it possesses so many potential benefits for businesses, it might be surprising to learn that edge computing can also assist the environment. One way is by using edge computing to monitor protected species of wildlife inhabiting remote places. Edge computing can help wildlife officials and park rangers identify and stop poaching activities, sometimes before these offenses can even occur.

CHALLENGES

While edge computing offers substantial benefits, it also introduces unique challenges. The transition from centralized cloud environments to distributed edge networks introduces new complexities. The fundamental architecture of edge computing, characterized by its distributed and heterogeneous nature, presents several technical and operational challenges. Other challenges of edge computing include the following [2,12]:

- *High Investment Costs*: Deploying an edge computing infrastructure requires substantial upfront investment in specialized, often industrial-grade hardware capable of withstanding harsh environments. Additionally, the cost of configuring, deploying, and maintaining a distributed network of edge nodes is significant. Organizations must also factor in the expenses associated with securing human resources possessing the niche skills required for distributed systems architecture and remote device management.
- *Intermittent Connectivity:* Edge devices often operate in environments with unreliable or intermittent network connectivity, such as remote industrial sites, offshore oil rigs, or connected vehicles. Cloud architects cannot assume continuous, fast network access for these devices. Consequently, edge systems must be designed to be fault-tolerant and capable of operating independently of the core network.
- *Hardware Failure:* The physical deployment of edge nodes often occurs in harsh or inaccessible environments, increasing the likelihood of hardware failures due to extreme temperatures, vibration, or moisture. Unlike centralized data centers equipped with redundant systems and dedicated IT personnel, edge locations may lack on-site technical support. A hardware failure at a remote wind farm or within a delivery fleet requires robust self-healing mechanisms to restart applications automatically, or necessitates costly and time-consuming physical service visits.
- *Complexity:* Managing a fleet of thousands of distributed edge nodes is significantly more complex than administering a centralized data center. Organizations must deploy software updates, security patches, and configuration changes across a vast, heterogeneous network, often dealing with intermittent connectivity. This requires specialized management tools and platforms designed specifically for distributed operations, adding layers of complexity to IT administration.
- *Cybersecurity Risks:* The distributed nature of edge architectures expands the attack surface, as data is processed across numerous remote devices rather than within a secure, centralized data center. Edge nodes, which may be resource-constrained IoT devices, are often more vulnerable to physical tampering and unauthorized access. Consequently, organizations must adopt decentralized security models, implementing robust encryption and zero-trust frameworks tailored for edge environments.
- *Resource Constraints:* Edge devices typically possess limited computational power, memory, and battery life. Implementing robust security protocols, such as complex encryption algorithms or intrusion detection systems, can overwhelm these resource-constrained devices. Consequently, designers face a delicate balancing act between maintaining adequate security and ensuring the device's operational efficiency.
- *Privacy Concerns:* The continuous collection and processing of sensitive data at the edge raise significant privacy concerns. IoT devices, such as surveillance cameras or health monitors, often gather personal information without the explicit awareness of the individuals being monitored. The lack of robust security measures on some consumer-grade edge devices-such as default passwords-can lead to unauthorized access and data breaches, instantly eroding the trust between users, manufacturers, and service providers.

- *Energy Consumption:* The environmental impact of edge computing is a subject of ongoing debate. On one hand, processing data locally reduces the energy required for massive data transmission to centralized cloud servers, potentially lowering the overall carbon footprint. On the other hand, the proliferation of thousands of edge nodes, each requiring power and cooling, contributes to increased energy consumption at the edge. Optimizing the energy efficiency of these distributed systems remains a critical challenge for sustainable edge computing deployments.
- *Data Governance:* Ensuring consistent data governance policies across a fragmented network of edge devices is challenging. Organizations must implement decentralized security policies, access controls, and data quality standards that apply uniformly across all nodes, regardless of their location. This requires sophisticated orchestration solutions and a fundamental shift in how data governance is approached.

FUTURE OF EDGE COMPUTING

The future of computing is not a binary choice between the edge and the cloud. Instead, the industry is moving toward an "edge-cloud continuum"-a seamless, hierarchical architecture where workloads are dynamically distributed across devices, edge nodes, and centralized cloud servers based on requirements for latency, bandwidth, privacy, and cost. The transition toward edge computing is accelerating.

Looking ahead, the edge computing market is poised for explosive growth. Industry analysts project that the market will expand significantly, driven by the escalating demands of AI workloads and the proliferation of IoT devices. The full potential of edge computing is being unlocked through its convergence with other transformative technologies, specifically 5G networks and artificial intelligence (edge AI). The rollout of 5G networks provides the high-speed, low-latency connectivity required to connect millions of edge devices efficiently. Edge AI involves deploying artificial intelligence and machine learning models directly on edge devices rather than relying on centralized cloud servers. This approach allows devices to perform complex tasks, such as image recognition and natural language processing, locally. By bringing AI to the edge, organizations can achieve faster decision-making, reduce bandwidth consumption, and operate in environments with intermittent connectivity [2].

CONCLUSION

Edge computing has evolved from a niche technological concept into a foundational pillar of modern digital infrastructure. By addressing the latency, bandwidth, and privacy limitations of centralized cloud computing, the edge paradigm enables a new generation of real-time applications across diverse industries. From powering the navigation systems of autonomous vehicles to optimizing energy usage in smart cities, edge computing is driving unprecedented levels of efficiency and innovation. The edge computing market is experiencing exponential growth, reflecting its critical role in the next phase of digital transformation. More information on edge computing can be found in the books in [18,19].

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Figure 1 The symbol of edge computing [2].

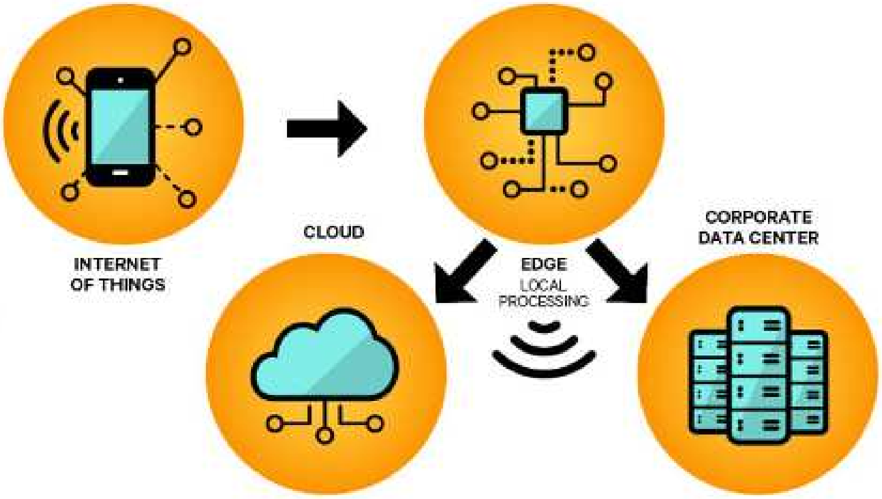

Figure 2 How edge computing works [3].

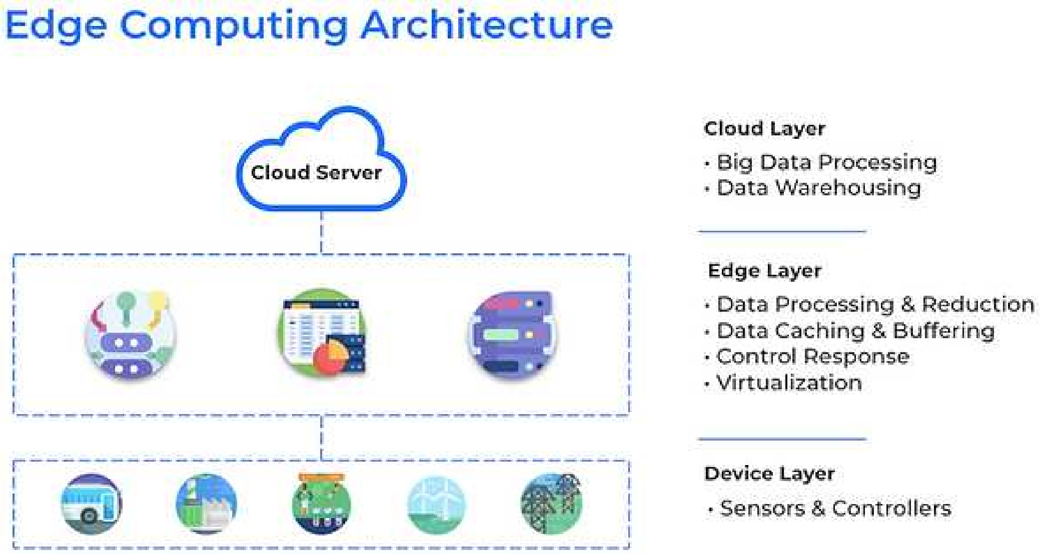

Figure 3 Edge computing architecture [6].

Table 1 A comparison of cloud, edge, and fog computing [7].

Characteristics	**Cloud**	**Fog**	**Multi-cloud**	**Edge**
Latency	High	Low	Very High	Low
Bandwidth Utilization	High	Low	Very High	Very Low
Response Time	High	Low	High	Low
Storage	High	Low	Very High	Low
Server Overhead	Very High	Low	High	Very Low
Energy Consumption	High	Low	High	Low
Network Congestion	Very High	Low	High	Low
Scalability	Medium	High	Medium	High
Quality of Service and Quality of Experience	Medium	High	Medium	High

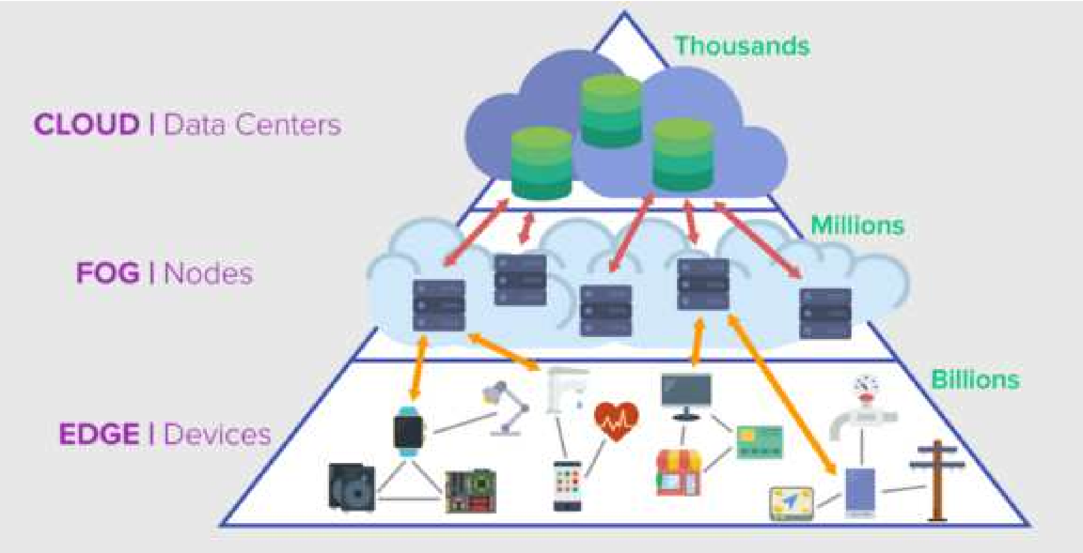

Figure 4 The relationship between cloud computing, edge computing, and fog computing [8].

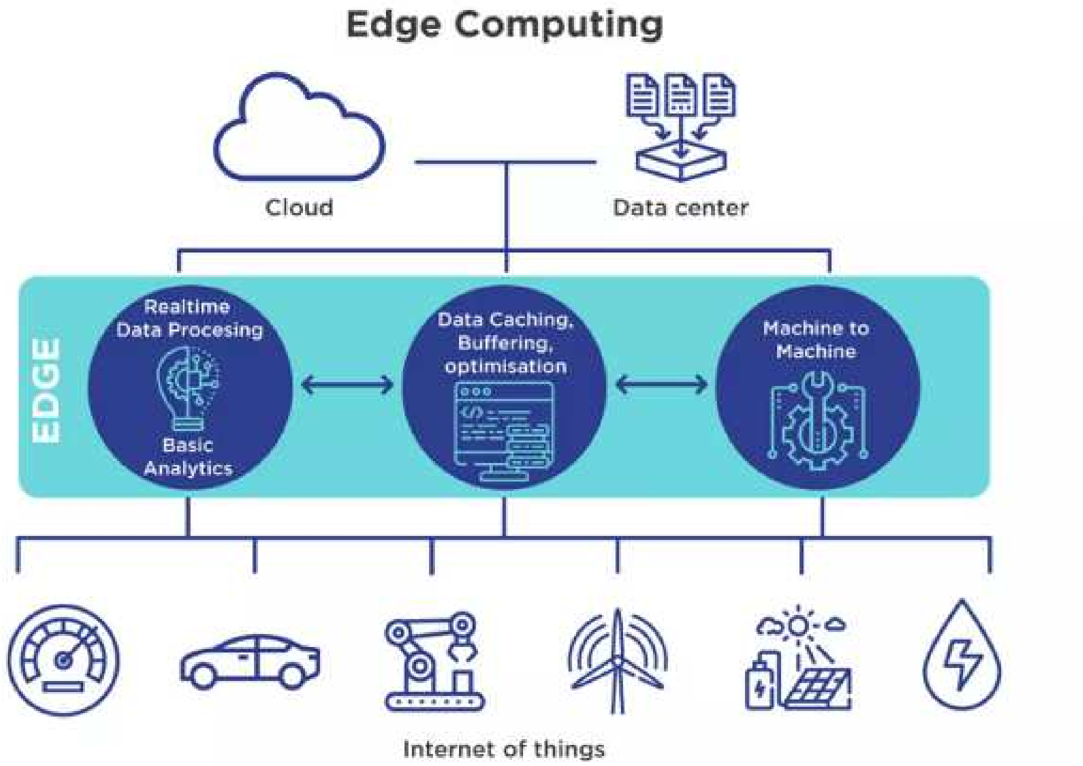

Figure 5 Edge computing [10].

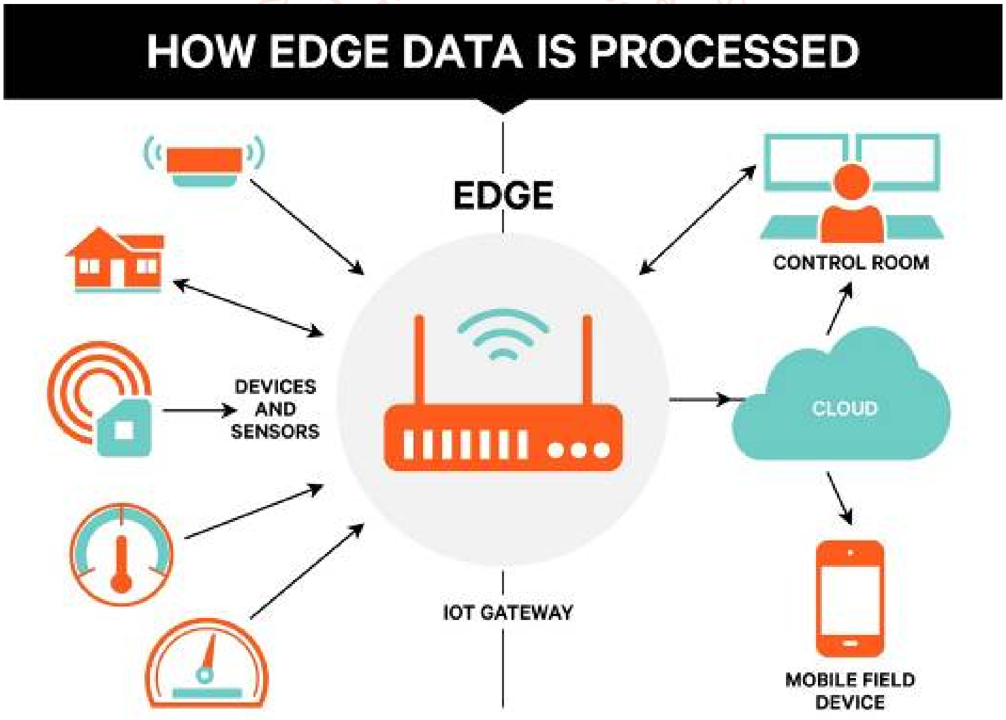

Figure 6 How edge data is processed [3].

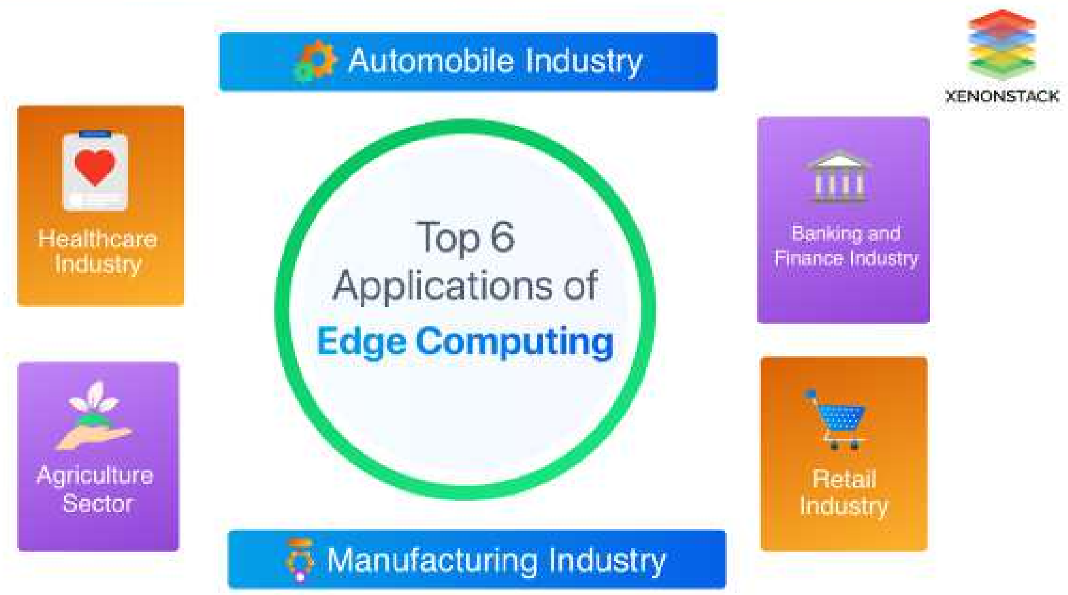

Figure 7 Some top applications of edge computing [11].

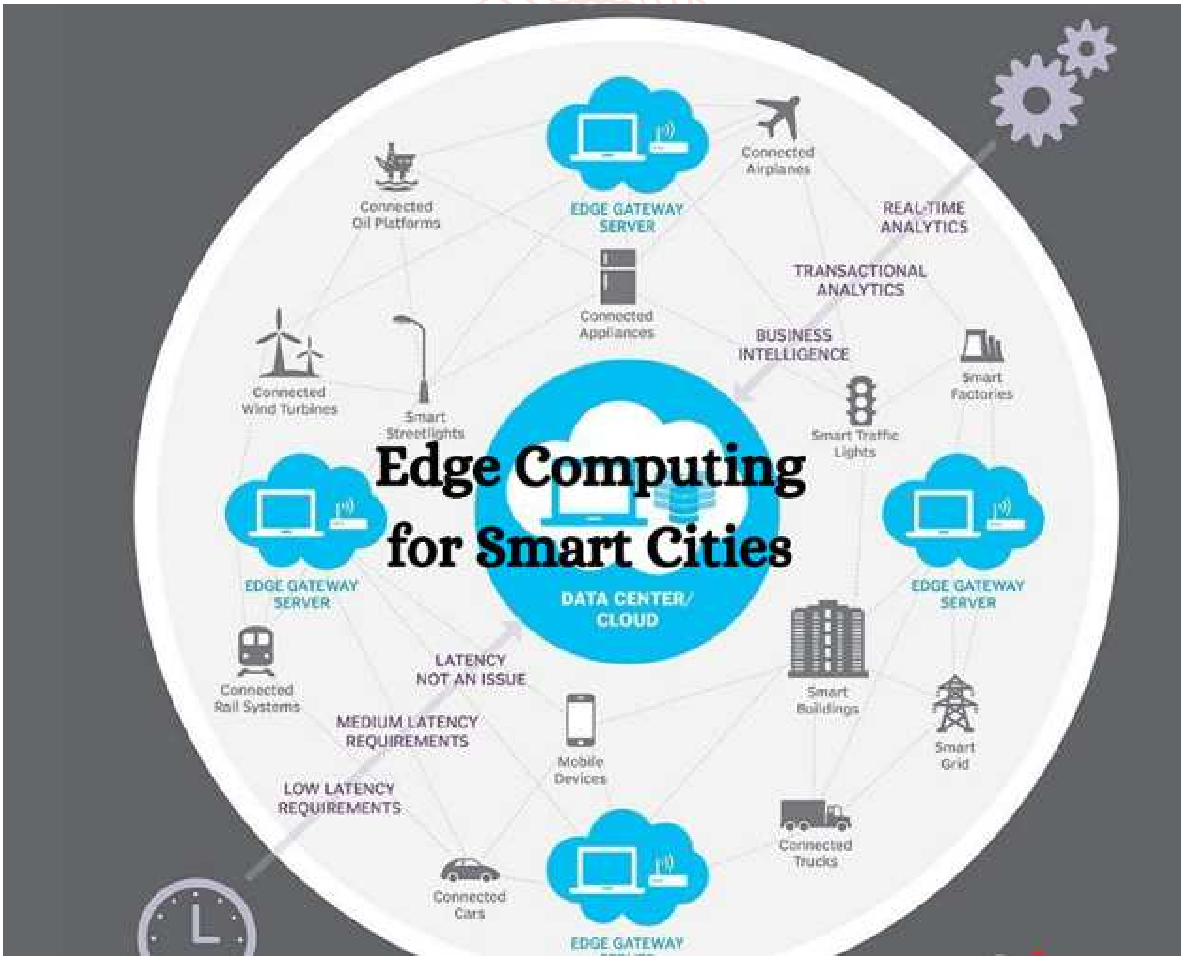

Figure 8 Edge computing in smart cities [16].