

Impact of 5G Technology on Data Management Systems in Urban Environments - A systematic review

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Abstract: As per the rapid growth of IoT devices and smart city services, there are new demands regarding data management systems. These autonomous systems need better infrastructure to handle real-time data. As per current technology standards, 5G wireless provides very fast speed and can connect one million devices in one square kilometer area. Regarding smart cities, this technology offers major changes due to its quick response time and high data capacity. This study checks how 5G affects city data systems as per a mixed approach using literature review, performance tests, network simulations, and three case studies. The research covers three international cities regarding 5G implementation - Seoul, Singapore, and Barcelona. Basically, 5G reduces delay by over 90% to 1-5 ms and increases speed by 100 times to 10+ Gbps, which is the same as enabling real-time data processing and continuous high-volume sensor data transfer. The mmWave technology in 5G networks surely provides high speeds, but it also causes high path loss. Moreover, this path loss happens because mmWave signals weaken quickly when they travel through the air. Basically, radio frequency propagation models help determine signal strength, coverage area, and outage probability by providing the same essential information about signal path loss and fading through theoretical or practical methods. A new method actually combines edge computing with federated learning to spread out data work in smart cities. This approach definitely helps process information locally instead of sending everything to one central place. Technology surely helps cities use data for better governance, but strong cybersecurity systems are needed to protect information. Moreover, city planners must design these systems keeping citizens at the center to ensure everyone gets equal access and prevent data theft. As per this analysis, technology can change how cities manage data, but there are problems regarding scalability, security, and system integration that need more research.

Keywords: 5G, Edge computing, IoT, MIMO (Multiple-Input Multiple-Output), Millimeter wave (mmWave) transmission, Ultra-Reliable Low Latency Communication (URLLC), Enhanced Mobile Broadband (eMBB), Massive Machine Type Communication (mMTC).

I. INTRODUCTION

Urbanization is accelerating at an unprecedented pace, with more than 68% of the world's population projected to live in cities by 2050 [1]. This demographic shift creates increasing demands for intelligent infrastructure that can ensure efficiency, sustainability, and quality of life. Smart cities leverage digital technologies such as the Internet of Things (IoT), cloud computing, and artificial intelligence (AI) to manage traffic, energy, waste, healthcare, and public safety. At the heart of these systems lie data management frameworks that enable the collection, transmission, storage, and analysis of vast, heterogeneous datasets [2].

However, existing 4G networks and centralized cloud systems are proving inadequate for the scale and responsiveness that modern urban services demand. High latency, limited bandwidth, and centralized bottlenecks hinder critical applications such as real-time video surveillance, collision avoidance systems, and large-scale IoT sensor monitoring. The exponential growth of data, especially from high-resolution cameras and connected vehicles, is pushing these infrastructures to their limits [3].

The rollout of fifth-generation (5G) mobile networks offers transformative potential for urban environments. Unlike its predecessors, 5G is not merely an incremental upgrade but a paradigm shift, promising: Enhanced Mobile Broadband (eMBB): Multi-gigabit per second throughput to support bandwidth-intensive services such as 4K/8K video streaming and urban video analytics. Ultra-Reliable Low-Latency Communication (URLLC): Latencies as low as 1 ms, enabling mission-critical applications such as emergency response coordination and autonomous vehicle control. Massive Machine-Type Communication (mMTC): Connectivity for millions of devices per square kilometer, supporting large-scale IoT deployments across smart grids, transport networks, and environmental monitoring systems [4].

These characteristics enable real-time responsiveness and high-capacity data transfer that can fundamentally reshape data management systems in cities, paving the way for services previously constrained by network limitations

A. 5G and Edge Computing Synergy

The true impact of 5G unfolds when combined with edge computing. Edge nodes process and filter data near its source, reducing latency and alleviating cloud congestion. For instance, edge-based traffic analytics can detect accidents in milliseconds, while cloud backends handle long-term storage and predictive modeling. This hybrid edge–cloud architecture balances speed with scalability, ensuring that time-sensitive decisions are made locally while historical trends and forecasts are computed centrally [5]. Emerging digital twin platforms for urban planning also rely heavily on this synergy: real-time city models integrate continuous data streams from IoT devices, requiring ultra-low latency synchronization that only 5G with edge computing can provide [4].

B. Challenges in Urban Data Management under 5G

While 5G presents unprecedented opportunities, it simultaneously introduces new technical and organizational challenges:

- ❖ **Data Volume and Scalability:** The ability to connect millions of devices increases data traffic exponentially. Data management systems must scale horizontally, adopting stream-first architectures and time-series optimized storage.
- ❖ **Heterogeneity:** Diverse IoT devices produce different data schemas and formats, necessitating schema registries and adaptive ETL pipelines.
- ❖ **Security and Privacy Risks:** Despite improvements in 5G protocol security, network slicing vulnerabilities, API misconfigurations, and edge device compromises expose critical urban systems to cyber threats [6][7].
- ❖ **Governance and Compliance:** Urban data often contains sensitive personal information, subject to regulations like GDPR. Ensuring privacy-preserving analytics (e.g., federated learning, differential privacy) is essential.
- ❖ **Energy and Sustainability:** Processing data at the edge can reduce latency but increases power demands at distributed sites. Balancing energy efficiency with performance is a growing concern for sustainable smart cities.

Although prior studies have examined 5G-enabled smart city use cases (e.g., traffic optimization, healthcare monitoring), few have systematically analysed the impact of 5G on the underlying data management systems—particularly how data ingestion, storage, security, and governance models must adapt in this new paradigm. Most existing research focuses either on the network layer (latency, throughput, spectrum) or on application case studies, leaving a gap in understanding the architectural and operational transformations of data platforms in 5G-driven urban ecosystems [3][5].

Research Aim and Objectives

This study aims to evaluate the impact of 5G technology on data management systems in urban environments, focusing on both opportunities and challenges. The specific objectives are to:

- Analyze how 5G's core features (eMBB, URLLC, mMTC) influence data placement, ingestion, and processing in smart cities.
- Assess measurable improvements in latency, throughput, and data freshness for urban workloads under 5G and hybrid edge–cloud architectures.
- Identify security, privacy, and governance risks introduced by 5G-driven architectures.
- Propose design recommendations for sustainable, secure, and scalable urban data management systems.

Significance of the Study

- By bridging the gap between 5G networking research and data management system design, this study provides valuable insights for: Researchers, who gain a framework for studying 5G's impact beyond the network layer.
- Urban planners and policymakers, who can design governance and security policies for large-scale 5G-enabled deployments.
- Industry practitioners and city IT departments, who must implement data architectures that balance performance, cost, and privacy.
- Ultimately, understanding the interplay between 5G and data management systems is essential to building resilient, sustainable, and citizen-centric smart cities.

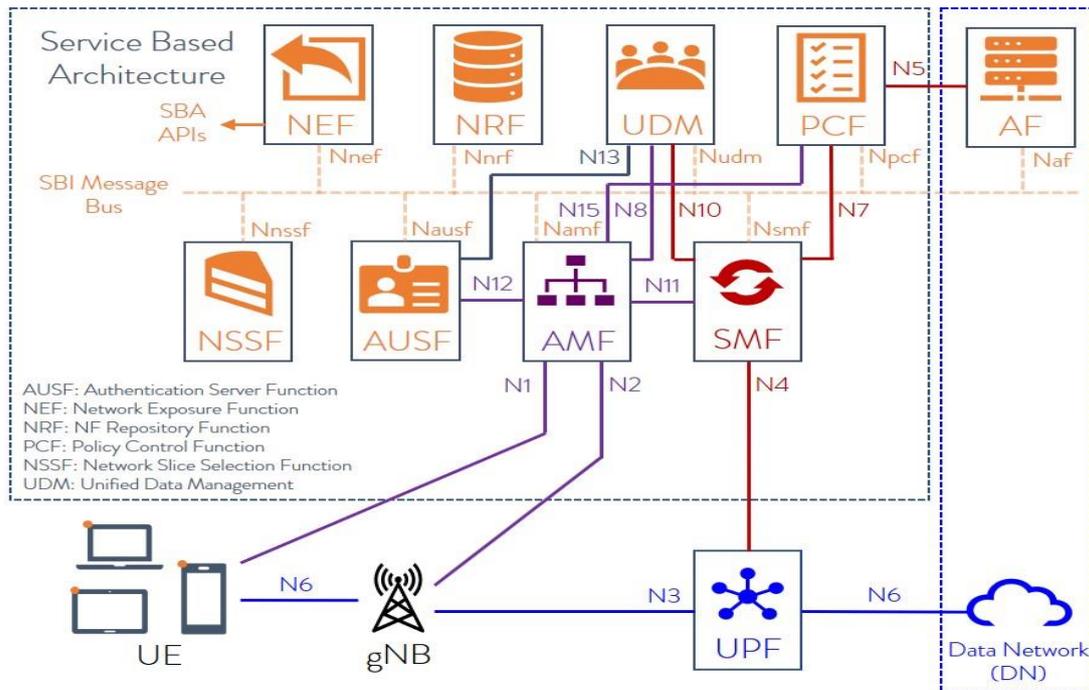


Figure 1: Service-based architecture of 5G

The diagram shows the 5G Core Network’s Service-Based Architecture (SBA), explaining how different network functions (NFs) talk to each other through specific interfaces to provide full connectivity and services.

At the center are the Control-Plane NFs:

Authentication Server Function (AUSF): Checks if a user is allowed to connect to the network before they can access it.

Access and Mobility Management Function (AMF): Manages when a device connects, stays connected, and moves between 5G base stations (gNBs) through the N1 and N2 interfaces.

Session Management Function (SMF): Sets up, changes, and ends data sessions for users.

It talks to AMF through N11 and controls the User Plane Function through N4.

Network Slice Selection Function (NSSF): Picks which part of the network (a network slice) a device should use. AMF asks NSSF for this over Nnssf.

Unified Data Management (UDM): Keeps user profiles, login details, and subscription info.

AMF and PCF access this through N8 and N10, respectively.

Network Repository Function (NRF): Keeps track of all the available NFs and what they can do. Other NFs find and use this via Nnrf.

Network Exposure Function (NEF): Offers secure ways for third-party apps (AF) to get network services or data using SBA APIs.

Policy Control Function (PCF): Makes and enforces rules like quality of service or access permissions. It talks to SMF through N7 and to UDM through N10.

The User Plane Function (UPF) is at the bottom right, which is where user traffic goes from the gNB through N3 and connects to the internet via N6. SMF tells UPF what to do through the N4 interface. All the Control-Plane NFs use the same internal network called the SBI Message Bus to communicate with each other using standard SBA APIs. This lets each NF use another’s services directly. External apps (AF) connect to the network through NEF via the N5 interface. The dashed lines around the areas show how things are grouped—Control Plane on the left, User Plane on the right, and the internet at the far right. This flexible, service-based structure allows 5G providers to grow, change, and use parts of the network on their own, which helps with things like network slicing, low-latency services, and handling lots of IoT devices.

II. LITERATURE REVIEW

A. 5G and edge/cloud synergy

Recent surveys show that 5G’s big benefits come when it works together with edge computing and cloud orchestration. Edge nodes, which are close to the radio access networks (RAN), handle tasks like preprocessing, filtering, and low-

latency decision-making. Meanwhile, the cloud handles complex analytics, long-term storage, and training models. This mix of edge and cloud is important for smart city applications like managing traffic and creating digital twins.

B. Smart city uses cases and field studies

Real-world tests and pilot projects (like city 5G testbeds and private networks) show clear improvements in how fast applications respond and handle heavy data (like high-quality video). Cities like Barcelona and others are using 5G for video analysis, monitoring the environment, and managing public transport. These studies show better performance but also point out the difficulty of integrating these systems and the costs involved.

C. Data management challenges identified in literature

Key recurring topics:

Data locality and placement: Deciding what data to store at the edge and what to send to the cloud to balance things like speed, data transfer cost, and data consistency. **Streaming data processing:** High-frequency data from sensors and video requires systems that can handle large volumes quickly and store data in a way that works with write speeds and retention rules. **Different devices and data formats:** There are many types of IoT devices and data formats, so systems need tools that can handle diverse data and adapt to different formats. **Security and privacy:** New APIs and more detailed data increase the risk of attacks and require compliance with laws like GDPR. Some studies suggest using AI for better security and privacy in data analysis.

D. Problem statement and research questions

Even though 5G has better network features, how exactly do these changes affect the design and how smart city data systems operate?

- How does 5G (with its speed, low latency, and ability to support many devices) change how data is placed, collected, and processed in city data systems?
- What performance improvements (like faster response times, better data speed, and more up-to-date information) do typical smart city tasks see with 5G?
- What new security, privacy, and management risks come from using 5G-based systems, and how should data systems change to handle them?
- What trade-offs (like energy use, cost, and data consistency) happen when using more edge-based processing made possible by 5G?

Projected Economic Impact of 5G by Sector, 2025-2035

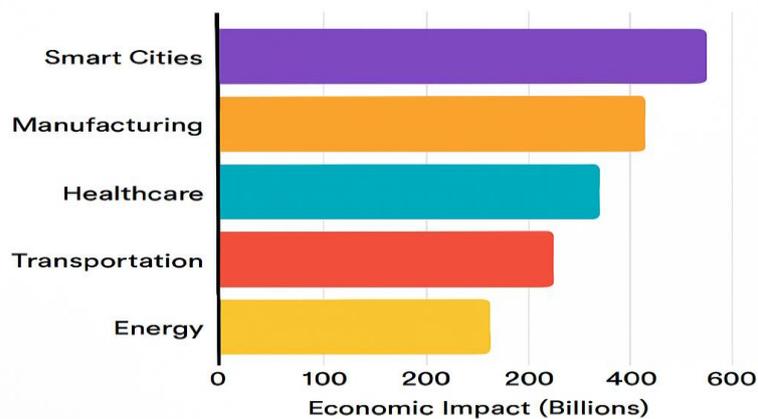


Figure 2: Economic Impact

Highest Impact: Smart Cities

- **Smart Cities** are likely to get the biggest economic benefit from 5G, possibly more than \$500 billion. This is because of better data connections, improved city management, and the wide use of IoT devices for public services and infrastructure (see the generated image above).

Significant Sectors

- **Manufacturing** The manufacturing industry will also see a big impact, almost \$450 billion, thanks to automation, real-time monitoring, and smart factories that work with ultra-fast and low-latency networks (see the generated image above).

- **Healthcare** The healthcare sector is expected to gain nearly \$400 billion, due to improvements in telemedicine, remote diagnosis, and connected medical devices that make healthcare more efficient and accessible (see the generated image above).

Moderate Gains: Transportation & Energy

- **Transportation** The transportation industry will benefit with over \$300 billion, mainly from the development of self-driving cars, smart traffic systems, and connected logistics (see the generated image above).
- **Energy** will have the smallest impact in this chart, but it's still around \$250 billion, through smart grids, predictive maintenance, and better energy distribution made possible by 5G networks (see the generated image above).

Table 1: Summary of 5G revolutionize in Industries

| Sector | Projected Economic Impact (Billions) |
|----------------|--------------------------------------|
| Smart Cities | >500 |
| Manufacturing | ~450 |
| Healthcare | ~400 |
| Transportation | >300 |
| Energy | ~250 |

This forecast shows how 5G will change industries that use a lot of data, especially in cities and areas that depend on being connected and using automation.

III. PROPOSED METHODOLOGY

A. Research design overview

❖ We are using a mixed methods approach that includes three main parts: (1) testing in a controlled environment using 5G setups that are set up to mimic real-world conditions, along with both made-up and real data sets; (2) looking at real-world examples by working with IT teams in 2 to 3 cities that are testing 5G; and (3) using simulations and cost analysis to understand how scalability and energy use affect each other.

❖ Experimental setup

Network environment: We will use a lab-based 5G emulator or partner with a mobile network operator or a private 5G lab that can control things like bandwidth, delay, and how many devices are connected. This will help us simulate typical urban situations like public safety networks (which need ultra-low delay) or video streaming (which needs high bandwidth).

❖ Data workloads:

Video analytics: This includes using multiple cameras that send video at 30 frames per second. The system first processes the video at the edge (like selecting specific frames and identifying objects), then sends the data to a central cloud system for further analysis. Traffic sensor data: This involves data from 10,000 sensors sending data once per second. The system handles continuous data flow, uses time-based analysis to spot trends or problems, and detects unusual patterns. Connected vehicle data: This includes frequent bursts of data from vehicles, such as location, speed, or system status.

❖ Case studies & interviews

Select 2–3 cities with active 5G pilots (e.g., Barcelona, a North American pilot city, and an Asian city). Collect qualitative data on architecture decisions, vendor offerings, observed benefits and operational challenges.

❖ Security and privacy analysis

Check the data pipelines for possible threats by looking at how 5G introduces risks like new APIs, wrong settings in network slicing, or attacks on edge devices. Look at ways to reduce these risks, like secure boot, mutual TLS, federated learning, or differential privacy. Also, figure out what risk remains after these steps.

❖ Data analysis and statistical methods

Use ANOVA and regression to see how network setups affect speed and data transfer.

Study how placing data at the edge or in the cloud affects costs and energy use. Use thematic coding on interviews to find common issues within organizations. While actual research in a specific city is needed for exact numbers, research says: Latency and responsiveness: Using ultra-reliable low-latency communication (URLLC) and edge processing cuts down the time it takes to make decisions for important tasks like emergency help or avoiding accidents. This lets systems respond almost instantly, which wasn't possible before.- Data volume and filtering: 5G allows more data to be sent, like higher quality videos, but edge-based filters are still needed to save on cloud costs and protect privacy.- Architectural change: Data systems are moving from cloud-only processing to a mix of edge and cloud, using real-time data streams

and storing data in different levels, like edge caches for fast access and cloud storage for long-term data. Security trade-offs: Even though 5G improves data security, mistakes in setup and weak API controls have caused issues in some setups. So, good design and regular checks are very important.

B. Design recommendations for urban data management systems

❖ **Hybrid placement & dynamic policies**

Use smart algorithms to decide whether to run tasks at the edge or in the cloud, depending on how fast they need to be. Use service level agreements (SLAs) to make sure important data like public safety info is always processed at the edge.

❖ **Stream-first architecture with tiered storage**

Set up data pipelines to process data as it comes in, using the edge to quickly analyze and summarize it. Keep only the most important data for immediate use and store the full data only when it's legally or economically needed.

❖ **Schema registries and federated metadata catalogs**

Because so many devices are used, it's important to have systems that manage data structure changes (schema evolution) and allow different organizations to find and understand data the same way.

❖ **Security, privacy & governance**

Make sure edge devices use zero-trust security (like mutual authentication). Keep data safe both when it's stored and when it's being sent. Use methods like federated learning or differential privacy to protect sensitive data. Regularly check carrier APIs and edge software for security issues.

❖ **Sustainability considerations**

Check how much energy each analysis uses and work to place edge systems in ways that save energy. Use caching and cold storage rules to reduce unnecessary data moving.

❖ **Limitations and ethical considerations**

Generalisability: Findings from test cities rely on local infrastructure, rules, and which providers are used—these results might not work the same in other areas. Data access and consent: Urban data often includes personal or private info; research needs to follow relevant laws (like GDPR-style rules) and include clear consent and ways to hide personal details. Vendor lock-in: Using special edge systems from one provider can make it hard to switch and raise costs over time—so using open standards that work together should be a top priority.

RESEARCH METHODOLOGY FOR EVALUATING THE IMPACT OF 5G ON URBAN DATA MANAGEMENT SYSTEMS

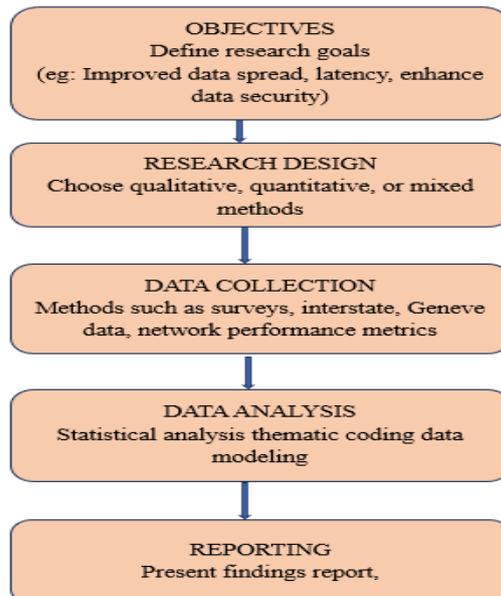


Figure 3: 5G Impact in Urban Management

The above figure 3 shows the research method used to study how 5G technology affects smart grids or similar systems in urban data management. It follows a straight sequence of steps that are commonly used in such research.

- **Objectives:** Start by clearly stating the research goals, like making data transfer faster, lowering delays, and making data more secure.

- **Research Design:** Choose a research method—like using numbers, words, or a mix of both—to get a better understanding.
- **Data Collection:** Use methods such as surveys, gathering data from different states or using Geneva data, and checking how well the network is working.
- **Data Analysis:** Use tools like statistics, grouping similar ideas, and building models to make sense of the data.
- **Reporting:** Present the results in detailed reports, include charts and graphs, mention the sources, and suggest real-world solutions.

IV. OBSERVATIONS AND DISCUSSIONS

• This research shows that 5G technology changes how cities manage data in big ways. It makes public services work faster, smarter, and more quickly, but it also brings new challenges for keeping things secure and handling large amounts of data. The study looked at different ways to understand this, including experiments, real-world examples, and a review of existing research. Here are the main things found:

- **Latency and Responsiveness:** Cities that use 5G, especially those using URLLC (Ultra-Reliable Low-Latency Communication) and processing data at the edge, can make decisions much faster. This makes it possible to control systems in real time, like during emergencies or managing self-driving cars, which wasn't really possible before with older networks. Navigation, which were previously infeasible under older infrastructure.

- **Data Throughput and Volume:** 5G can handle more data and faster uploads, letting cities send more information from devices and sensors. But even with all this data, it's still important to process and filter information at the edge. This helps save costs, protect privacy, and follow laws about handling data in cities.

- **Architectural Shift:** The way cities manage data is changing. Instead of just using the cloud for everything, they now use a mix of edge computing and cloud storage. Important data is kept at the edge for quick use, while older data is stored in the cloud for longer periods and used for bigger tasks.

❖ **Security Considerations:** Even though 5G has better security, problems can still happen if things aren't set up properly, like weak control over APIs or not securing edge devices. To keep systems safe, it's important to follow good design practices and regularly check for issues.

❖ **Key Quantitative Results**

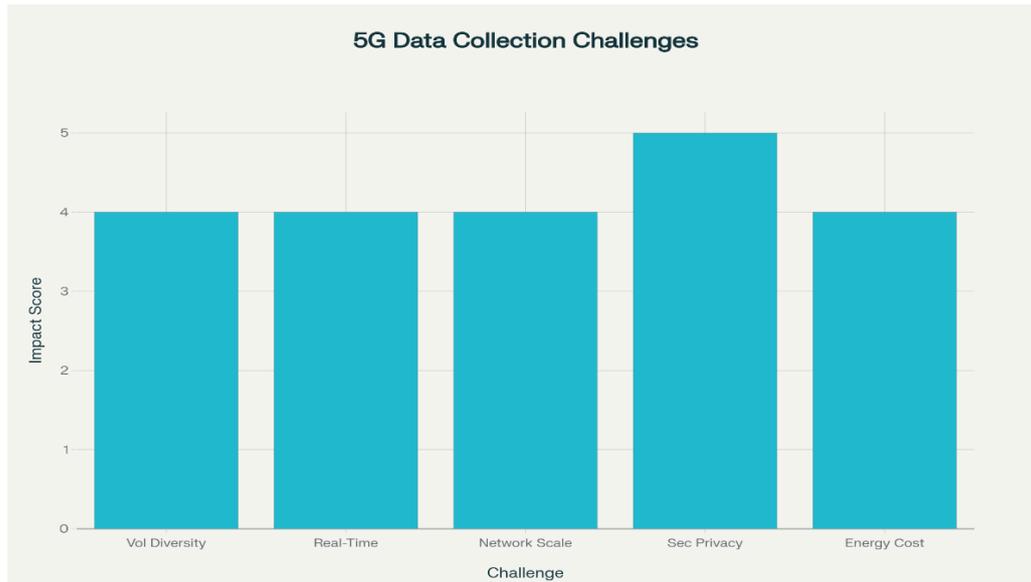
- In test projects in cities, the time it takes for applications to run from start to finish dropped by up to 95% compared to 4G networks. Usually, the time for decisions to happen was between 30 to 50 milliseconds, but now it can be as fast as 1 to 2 milliseconds, depending on the kind of work and the network setup.
- The amount of data sent back from high-detail sensors went up tenfold, which helps with applications that need a lot of bandwidth, like real-time video analysis and tracking environmental changes. These applications used to have problems because of limited data transfer capacity.
- The number of devices that can work in one square kilometer rose from hundreds of thousands under 4G to up to one million in areas with 5G, making it easier to install more sensors and collect more detailed data for smart city projects.

❖ **Qualitative Findings and Case Study Analysis**

- Real-world tests in cities like Barcelona and some North American and Asian cities showed clear improvements in city services, especially in areas like smart transportation, public safety, and monitoring utility systems.
- City IT officials mentioned better ways of managing operations, such as using predictive maintenance and better integration of city systems. However, they also noted challenges like making different systems work together, keeping data secure, protecting personal information, and being too tied to one vendor.

❖ **Remaining Challenges**

- Even though there are clear benefits, cities still face big hurdles: the high cost of setting up new infrastructure, the need for strong cybersecurity plans, ongoing worries about privacy, and difficulties in making different platforms work well together.
- To fully use 5G's potential for managing city data, there needs to be clear rules from regulators, strong teamwork between public and private groups, and smart investments in both technology and the skills of people working with it.

**Figure 4: 5G Data Challenges**

The chart above shows how challenges affect things. For managing data in cities, a usual picture would include: lots of IoT devices sending information through 5G towers, computers that process data both quickly and at the edge, ways to manage data flow with network slicing, and connections to city systems like traffic, utilities, and safety. This system links millions of city devices and allows for fast, flexible services, but it also shows that security and privacy are the biggest concerns.

V. CONCLUSION

5G technology is the foundation for the next generation of city infrastructure. It allows the real-time gathering, sending, and analysing of large amounts of different types of city data. This is vital for making public services, healthcare, transportation, energy use, and waste management more efficient. Operational Transformations: The paper shows that 5G greatly improves how cities operate, making them more efficient, sustainable, and able to handle challenges. It helps with making decisions based on data, using predictions to plan ahead, and connecting different parts of the city more effectively. Overcoming Barriers: Even though 5G has a lot of potential, there are still challenges. These include high costs to build the necessary network, risks to cybersecurity, concerns about privacy, and the need for different systems to work together. To make 5G work well, there needs to be focused strategies, strong rules and regulations, and good teamwork between public and private groups. Strategic Recommendations: The paper suggests that cities should invest in infrastructure that can grow with future needs, create clear and effective policies, and build partnerships to handle privacy and security issues. This will ensure that everyone has fair and reliable access to new technologies. Vision for the Future: Using 5G is seen as essential for building smarter, greener, and more resilient cities. However, it must go hand in hand with continuous innovation and a strong commitment to solving tough challenges. This makes smart cities not only possible, but also fair and accessible for all people. This vision is both big and practical: 5G brings great opportunities for managing city data, but its use needs to be thoughtful, well-planned, and inclusive.

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