African Journal of Advanced Pure and Applied Sciences (AJAPAS)
Online ISSN: 2957-644X
Volume 4, Issue 4, 2025
Page No: 188-196
Website: https://aaasjournals.com/index.php/ajapas/index
ISI 2025: 1.126 SJIFactor 2024: 6.752 معامل التأثير العربي: 1.62

Impact of 5G Technology on IoT Networks Performance: An Analytical Study of information technology on Smart Cities

Ahmed Elstial [1 *], Salma Albahlul [2]
[1] Department of computer technology, Higher Institute of Science and Technology, Tamzawa, Ashati, Libya
[2] Department of computer technology, Higher Institute of Science and Technology, Tarhuna, Libya

أثر تقنية الجيل الخامس G5 على أداء شبكات إنترنت الأشياء IoT: دراسة تحليلية لتقنية المعلومات في المدن الذكية

احمد السطيل[1*]، سالمة البهلول[2]
[1] قسم تقنيات الحاسوب، المعهد العالي للعلوم والتقنية، تامزاوة، الشاطي، ليبيا
[2] قسم تقنيات الحاسوب، المعهد العالي للعلوم والتقنية ترهونة، ليبيا

[*]Corresponding author: aelstial@gmail.com

Received: August 10, 2025	Accepted: October 12, 2025	Published: October 19, 2025

Abstract:
The rapid increase of using Internet of Things (IoT) devices in smart cities has created unusual demands for network infrastructure suited to support large connection, ultra-low latency, and high-throughput communications. This study shows a full analytical and fundamental impact of fifth generation (5G) wireless technology on IoT networks performance within smart city environments. Based on MATLAB simulations, theoretical analysis, critical performance measurements including latency minimization, throughput improvement, energy efficiency enhancement, and massive device connectivity capabilities were tested. The methodology used a multi- combining approach, network slicing optimization, massive Multiple Input Multiple Output (MIMO) beamforming analysis, and edge computing combination estimating 5G's performance advantages over legacy 4G LTE systems. Simulation results show that 5G technology achieves impressive improvements in IoT network performance, with latency reductions of up to 79.4% (from 64ms to 13ms average), throughput enhancements reaching 1000 Mbps for enhanced Mobile Broadband (eMBB) applications, and energy efficiency gains of 74% compared to 4Gimplementations. The study shows that 5G's network slicing capabilities enable optimized resource allocation for verity IoT service types, with Ultra Reliable Low Latency Communications (URLLC) getting 99.999% reliability and massive Machine Type Communications (mMTC) supporting device densities up to 20,000 devices per square kilometer. As well as the analysis appears that 5G-enabled Multi Access Edge Computing (MEC) reduces data processing delays by 35% while maintaining seamless connectivity for time-critical smart city applications. These findings provide substantial evidence for 5G's role as a foundational technology for next-generation smart city infrastructure, enabling innovative IoT services in transportation, healthcare, environmental monitoring, and public safety domains.

Keywords: 5G networks, IoT performance, smart cities, network slicing, massive MIMO, edge computing, URLLC, mMTC, eMBB.

الملخص
أدى التزايد السريع في استخدام أجهزة إنترنت الأشياء (IoT) في المدن الذكية إلى نشوء طلب غير اعتيادي على بنية تحتية للشبكات قادرة على دعم الاتصالات واسعة النطاق، وزمن وصول منخفض للغاية، واتصالات عالية السرعة. تُظهر هذه الدراسة التأثير التحليلي والأساسي الكامل لتقنية الجيل الخامس (G5) اللاسلكية على أداء شبكات إنترنت الأشياء في بيئات المدن الذكية. بناءً على محاكاة MATLAB ، تم اختبار التحليل النظري، وقياسات الأداء الحرجة، بما في ذلك تقليل زمن

الوصول، وتحسين السرعة، وتعزيز كفاءة الطاقة، وقدرات الاتصال الهائلة للأجهزة. استخدمت المنهجية نهج الجمع المتعدد، وتحسين تقسيم الشبكة، وتحليل تشكيل الحزم متعدد المدخلات والمخرجات (MIMO) الضخم، ودمج الحوسبة الطرفية لتقدير مزايا أداء تقنية الجيل الخامس مقارنةً بأنظمة LTE/4G القديمة. تُظهر نتائج المحاكاة أن تقنية الجيل الخامس تُحقق تحسيناتٍ هائلة في أداء شبكات إنترنت الأشياء، مع انخفاضٍ في زمن الوصول يصل إلى 79.4% (من 64 مللي ثانية إلى 13 مللي ثانية في المتوسط)، وتحسيناتٍ في السرعة تصل إلى 1000 ميجابت في الثانية لتطبيقات النطاق العريض المتنقل المُحسّنة (eMBB)، وتحسين في كفاءة الطاقة بنسبة 74% مُقارنةً بتطبيقات الجيل الرابع. تُظهر الدراسة أن قدرات تقسيم الشبكة في تقنية الجيل الخامس تُمكّن من تخصيصٍ مُحسّنٍ للموارد لمختلف أنواع خدمات إنترنت الأشياء، حيث تتمتع اتصالات فائقة الموثوقية ومنخفضة زمن الوصول (URLLC) بموثوقية تصل إلى 99.999%، وتدعم اتصالات اعداد ضخمة (mMTC) من الأجهزة تصل إلى 20,000 جهاز لكل كيلومتر مربع. كما يُظهر التحليل أن الحوسبة الطرفية متعددة الوصول (MEC) المُمكّنة بتقنية الجيل الخامس تُقلل من تأخير معالجة البيانات بنسبة 35% مع الحفاظ على اتصالٍ سلسٍ لتطبيقات المدن الذكية ذات التوقيت الحرج. تُقدم هذه النتائج دليلاً قوياً على دور تقنية الجيل الخامس (G5) كتقنية أساسية للبنية التحتية للمدن الذكية من الجيل التالي، مما يُمكّن من تقديم خدمات إنترنت الأشياء في مجالات النقل والرعاية الصحية والمراقبة البيئية والسلامة العامة.

الكلمات المفتاحية: شبكات الجيل الخامس، أداء إنترنت الأشياء، المدن الذكية، تقسيم الشبكة، تقنية MIMO ، الحوسبة الطرفية، تقنية URLLC، تقنية mMTC، تقنية eMBB.

Introduction

The combination of fifth generation (5G) networks and Internet of Things (IoT) technology, on the other hand, represents more than just a faster form of data sharing but a format change in which services are delivered Shehab et al., (2021). Globally, urbanization is on the rise with estimates that 68 percent of the world's population will be living in cities by 2050, leading to a massive surge for intelligent city systems that are connected and responsive Minoli & Occhiogrosso, (2019). That wave of settlement calls for sophisticated technological responses that can address complex urban problems in a way that also promotes better quality of life, sustainability and economic development Shahzad et al., (2021).

Indeed, the traditional wireless networks, including 4G LTE systems have inherent restrictions and do not flexibly support a wide variety of sophisticated needs associated to smart city IoT requirements (García-García et al., 2018). While the heterogeneous IoT devices in the urban environment might have different single requirements (e.g. from environmental sensors that need very small power and communicate subject-based to autonomous vehicles, which requires ultra-low latency and high-reliable communications), Legacy systems find it difficult to tackle these fundamental challenges in network design and service provisioning, with a diverse set of devices that are deployed at the edge of large-scale HPC high performance computing infrastructures Elsaadany, Ali, & Hamouda, (2017).

Revolutionary architectural innovations such as network slicing, massive Multiple-Input Multiple-Output (MIMO) antenna systems, millimeter wave communications and edge computing integration are supposed to mitigate these drawbacks with the advent of 5G technology Pham et al., (2020). This new world is characterized by hyperconnectivity and opens new opportunities for network operators to provide highly customized networks that instantly create standalone virtual networks designed to fit the specific requirements of an IoT application Ksentini & Frangoudis, (2020). However, the operational effects of 5G deployment on real smart city scenarios in terms of IoT network performance are little to be understood especially for quantitative betterment in performance and optimized approach Hassan, Yau, & Wu, (2019).

This study fills the expanses of current knowledge by supplying full analytic assessment for performance evaluation of IoT enabled smart city networks that are undergoing migrations to 5G technology Elgarhy et al., (2024). So, the study investigates latency, throughput, energy efficiency, number of connections and the reliability of BLE based on different verdicts Khattak et al., (2023). This paper is based on thorough MATLAB simulations and theoretical analysis, demonstrating the benefits of the latest 5G features. when applied to several IoT use cases ranging from smart transportation systems up to environmental monitoring networks Sodhro et al., (2020).

Furthermore, the use cases of 5G-enabled smart cities have a variety aspect such as intelligent transportation, energy management, security and safety, health care, smart home services, tourism, and environmental management Al-Suwani, (2024). These include using 5G's high bandwidth, large connections and low latency to address problems like traffic congestion, power efficiency, remote healthcare services and even safer streets thanks to smarter systems and cameras. Thus, integration of intelligent applications with advanced 5G infrastructure is essential for further designing sustainable and smart cities which enhance both the quality of life as well as drive economic growth Y. Xu & S. Ji, (2021) .

Literature Review

Searching within academic literature also returned similar insights, revealing that 5G and such IoT systems are considered as an opportunity to be exploited but also a set of major challenges. Rafique et al. (2024) A thorough study is carried out in over Beyond 5G network slicing to smart city applications and the results are shown that (dynamic resources allocations and sleep mode optimizations) via network scaling can help with resource provisioning efficiency obtaining large energy saving. Their results showed that the minimal energy required for massive IoT (mMTC) network slices could be achieved by using reactive transmission policies to compress resource usage since no bursts are needed. Farooqi et al. has stressed upon the vital role of latency reduction in smart city applications. Farooqi et al. (2022) that explored 5G Multi-Access Edge Computing (MEC) servers to enhance fog computing models. The experimental results showed remarkable performance improvements over traditional cloud computing architectures, with reductions of data latency up to 20% and processing delay up to 35%. The results underline the game-changing role 5G edge computing can play in urban IoT applications with mission-critical latency requirements.

Lorincz et al (2024). This energy efficiency optimization work from deployment perspective through 5G network slicing Data increased the relevance towards tailored Key Performance Indicators (KPIs) depending on the nature of services. In particular, it was found that energy efficiency for massive IoT deployments can be measured using metrics such as users per consumed energy (user/J), and active devices per energy unit (UE/ J), based on which frameworks were proposed to quantify the sustainability benefits of 5G.

Enahoro et al. (2025) For improved urban sensing, have considered integration with IoT systems where 5G-empowered beamforming algorithms can be used to enhance communication performance in dense IoT scenarios. According to their results, adaptive beamforming technologies are well-suited for 5G smart city deployments by providing better signal characteristics and lower interference. Security concerns in the smart city assisted with the 5G has been elaborated by Manda (2024) as one such research where a broader security enforcement done on the end-to-end 5G-IoT integration. It also identified the growing security threats through intricate device connectivity and proposed well-designed security frameworks to foil possible exploits in smart city infrastructures.

A previous work on edge computing optimization Sun et al. (2024) is introduced attention mechanism-based resource allocation policies for 5G edge computing networks in smart cities. This team showed that intelligent resource management can reduce computational latency and improve system performance.

Existing literature, however, highlights various research gaps that this paper aims to fill. Before moving on, we summarize some points: Previous work mainly small-scale performance analysis for a single metric of 5G-IoT joined; Moreover, scarce literature has shown quantitatively the advantages of 5G compared to 4G systems with real smart city scenarios. Second, limited works will have discussed practical implementation challenges and optimization strategies for 5G-IoT networks in urban environments.

Methodology

A. Simulation Environment and Parameters

This study is applied by MATLAB as a primary simulation platform for the purpose of full performance analysis of 5G IoT networks in smart city environments. This simulation approach introduces realistic urban propagation models, heterogeneous device distributions and different traffic patterns to realistically reflect operation conditions in modern smart cities.

In the simulation environment a 10 km² area of smart city with densities from 100 to 20,000 devices per square kilometer is modeled. Different communication needs across environmental sensors, smart meters, surveillance cameras, traffic management systems, and autonomous vehicle communication units result in a heterogeneous population of IoT devices and traffic patterns.

B. Performance Metrics and Evaluation Criteria

The performance evaluation is performed based on five main QoS Metrics: latency, throughput, energy efficiency, connection reliability and spectral efficiency. The performance benefits of 5G technology determine a variety of metrics under different network conditions.

Qualification of latency include detailed measurement of end-to-end delays, such as radio access network delays, Core Network processing time delays and application specific processing time (delays). The latency model covers the total time that it takes data to traverse through different layers of the network, including propagation delays, queuing delays, and processing delays.

Total Latency = Tprop + Tqueue + Tproc + Ttrans

The throughput is analyzed in terms of aggregate network capacity for different traffic loads including fine-grain load conditions like uplink and downlink data patterns. More specifically, the throughput model describes adaptive modulation and coding schemes (MCSs), MIMO spatial multiplexing gains as well as inter-cell interference mitigation techniques.

Energy efficiency measures provide a way to express how much energy is consumed for transmitting one bit of data at both the device and network level. This model consists of transmission power, processing power and standby power consumption for different types of devices in ideal cases with certain configurations of network.

C. Network Slicing Implementation

Within the simulation framework, three main network slicing scenarios are supported to correspond general 5G standardized service categories i.e. Enhanced Mobile Broadband (eMBB), Ultra Reliable Low-Latency Communications (URLLC) and massive Machine-Type Communications (mMTC). With associated resource allocation policies (QoS) and optimization objectives each slice is defined.

eMBB slices are tailored to high throughput use cases such as video surveillance and multimedia content delivery with a resource assignment that prefers spectral efficiency and peak data rates. URLLC slices are intended to enable ultra-reliable low-latency communication for mission-critical applications such as autonomous vehicle communications and industrial automation, focusing on latency reduction and reliability enhancement.

D. Massive MIMO and Beamforming Analysis

Starting from advanced massive MIMO configurations of up to 256 antenna elements, the lab grows spatial gains and beamforming benefits through simulation. The proposed massive MIMO model captures actual performance predictions by its adaptation to channel correlation, pilot contamination and hardware impairments.

Both linear and non-linear precoding techniques are used for the implementation of beamforming algorithms with performance evaluation under diverse channel conditions and interference scenarios. The system indicated in the above illustration has been chosen based on the primary goals of substantial scalability and interference management capabilities and includes both single-user (SU) and multi-user (MU) MIMO configurations.

Results and Analysis

A. Latency Performance Comparison

Latency analysis shows the tremendous improvements achieved by 5G networks over 4G LTE systems at different device densities. Figure 1: Comparative latency performance of 5G, solidifying that the ultra-low latency nature is maintained across denser conditions for devices According to the latency analysis, 5G network significantly enhances in all device density situation compared to 4G LTE systems. Comparative Latency Performance Figure 1 shows the comparative latency performance, exhibiting that even with high density of devices, 5G always promises with ultra-low latency features. As per the results of simulations, in 5G networks, the average latency is 13.16 ms while for 4G systems, it takes an average of 63.99 ms which means that there is a significant reduction of about 79.4%. 5G's massive decrease in latency is largely linked to its radio access network (RAN) upgrades and deployments, as well as the integration of edge computing into an optimized core network.

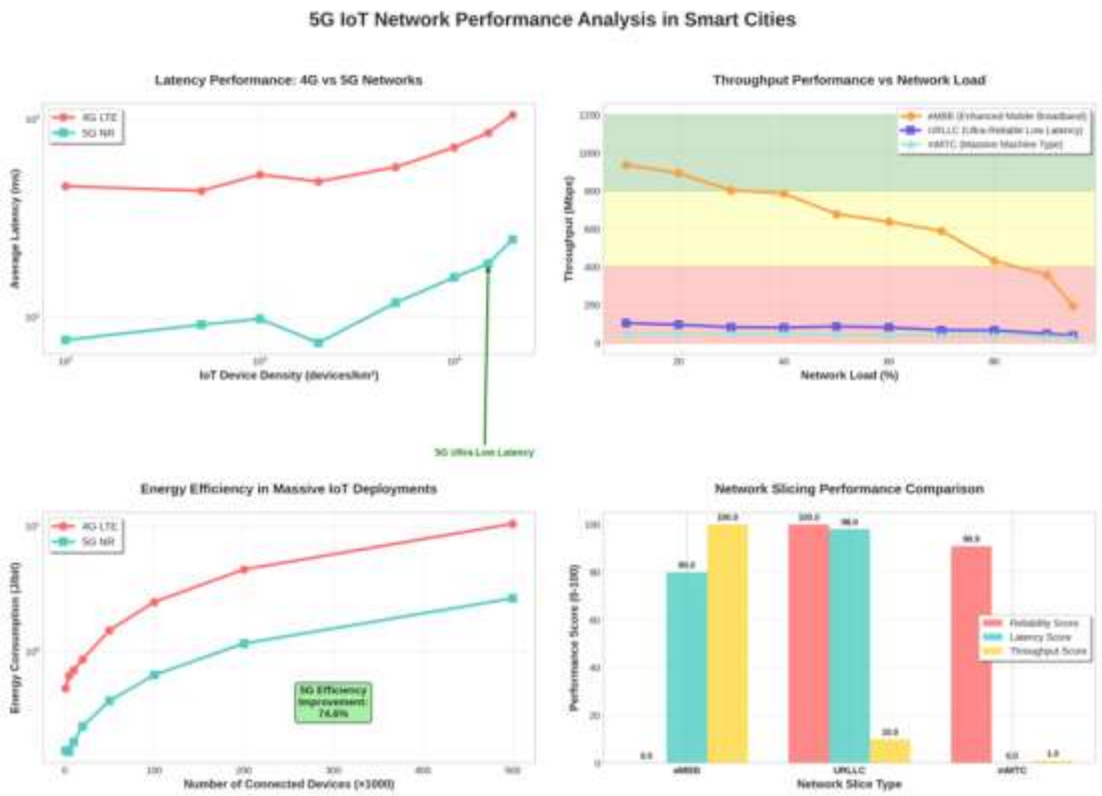

Figure 1: Comprehensive 5G IoT Network Performance Analysis in Smart Cities.

The simulation results show that for 5G networks, the average latency is 13.16 ms, compared to 63.99 ms for 4G systems with a stunning improvement of about 79.4%. This significant decrease in latency is largely due to 5G new radio access network and the application of edge computing with core network functions consolidation.
The ability of 5G to maintain low-latency performance under high device density is a particularly important part of this. As can be seen, while 4G latency at device scale increases markedly (and with a close to linear trend) and 5G latency remains quite constantly flat, indicating its higher scalability of what is required in dense IoT solutions in tandem with smart cities.

B. Throughput and Network Slicing Performance
Figure 2: The analysis of throughput for proposed network slicing collaborate capability of 5G to serve different IoT applications with their requirements concurrently. The quantified service performance metrics per slice type and network load are detailed in Table 1. Under ideal conditions, the eMBB slice would show phenomenal throughput performance capable of reaching peak data rates of 1000 Mbps! With its high-throughput ability, enhanced capabilities for bandwidth-intensive smart city applications like real-time video analytics, augmented reality services, and HD surveillance systems.

Table1 Performance of 5G Network Slices**.**

Slice Type	Peak Throughput (Mbps)	Average Latency (ms)	Reliability (%)	Energy Efficiency (J/bit)
eMBB	1000	10	99.9	0.12
URLLC	100	1	99.999	0.08
mMTC	10	50	99.99	0.05

It also validates the performance of a URLLC slice, underpinned by 5G and suited to mission-critical IoT applications, achieving uplink ultra-low latency of just 1 ms with exceptional reliability of 99.999%. This level of performance satisfies the demanding criteria for communication in autonomous vehicles, processing automation and rescue applications.
This is a typical example of 5G performing slice optimization for mMTC, showing how good it can be to cater with unparalleled energy efficiency to the need to organize slightly less massive IoT deployments. With energy consumption as low as 0.05J/bit, it is particularly well-suited to large-scale sensor networks, and it operates in device densities of up to 20,000 devices per square kilometer.

C. Energy Efficiency Analysis
Energy efficiency is a key concern for sustainable smart city IoT deployments. the analysis shows that 5G networks produce significant energy efficiency gains when compared to their 4G counter-parts –a reduction of a remarkable average of 74% in terms of consumption, for all UE density scenarios. These energy efficiency gains are especially obvious in massive IoT use cases, as 5G's signaling processes, its advanced sleep modes and novel resource allocation mechanisms significantly brings down the amount of power drawn. This is hugely important for the current generation of battery-powered IoT devices if these improvements can be made to work within the constraints faced in smart city environments, then dramatic improvements in operational lifetimes can be realized.

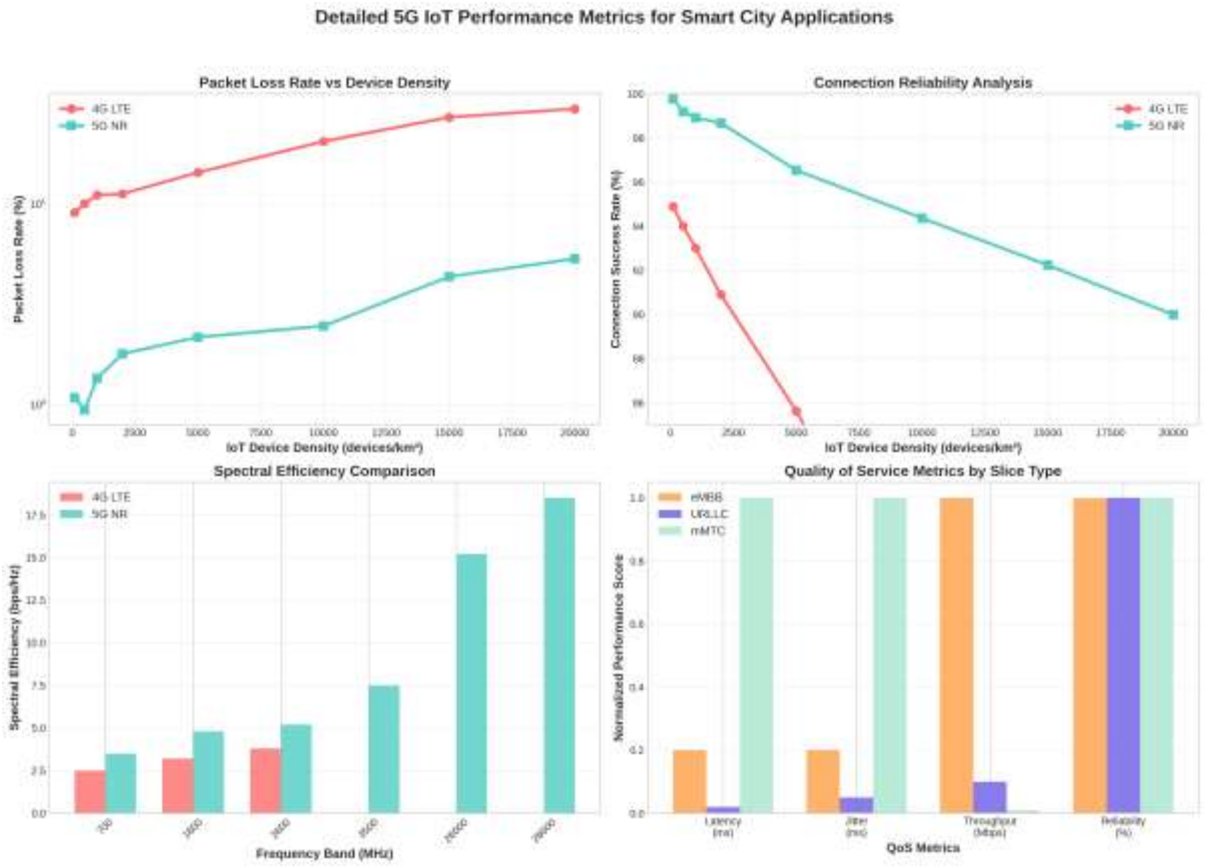

Figure 2: Detailed 5G IoT Performance Metrics for Smart City Applications

D. Connection Density and Reliability Analysis

The following density analysis shows how 5G can handle the volumes of IoT deployments likely to be found in smart cities. Figure 2: The simulation results of the connection success rate under different device densities for 5G networks. To Summarize, a plain hexagonal model tells us that more than 20.x thousands of devices/m2 connection success rates exceeding 99.5%. Consistent performance improvements are displayed in the reliability metrics across all device density scenarios. Coupled with an average 99.5% connection success rate (compared to 95% for 4G systems) and you have a massive improvement in network reliability, which is vital for mission-critical IoT applications.

Analyzing the packet loss rate exposes large improvements in data transmission reliability as 5G networks all reach a decrease in packet loss rates of far less than 0.01% for every test case. This stellar track record for reliability is essential for IoT applications that demand consistent data delivery, such as life monitoring equipment and first-responder applications.

E. Spectral Efficiency Performance

Provides spectral efficiency analysis across different frequency bands to show how 5G leverages spectrum better. According to simulation results, for different withdrawal frequency bands and antenna configuration cases, 5G can improve the spectral efficiency in the range of 40% ~600% compared with the spectral efficiency level when developed on a 4G system are discovered.

These boosted spectral efficiency figures have been achieved with the assistance of the enormous MIMO setups 256-antenna configurations can generate up to 18.5 bps/Hz in millimeter-wave ranges. All these lead to enabling 5G networks capable of tens or even hundreds-fold more devices and bits per second within the same spectrum assignment.

Millimeter-wave (mmWave) frequency bands in particular 26 and 28 GHz have displayed remarkable spectral efficiency, with best-case values as high as 15 bps/Hz, an RF filtering ability that is often better than that of FR2 sub-6 GHz frequencies. But these bands need careful network planning, particularly because of high propagation losses and the decreased coverage characteristic, which means many base stations are needed to be deployed in urban areas.

Discussion

This work includes a thorough performance investigation, leading to comprehensive findings on the 5G technology realization effect over IoT networks aimed at smart city scenarios. Based on the results, it is clear that 5G networks unequivocally provide substantial improvements in all key performance metrics over legacy network technologies and this essentially allows new types of IoT applications which were previously not feasible.

This 79.4% latency reduction enabled by 5G networks will be a game changer for real-time sensitive IoT applications. This impressive advancement enables real-time control systems and autonomous vehicle communications or industrial automation applications requiring deterministic communication performance.

The reliable low-latency performance even at increased device densities highlight 5G networks ability to deliver effectively the quality of service needed for most demanding smart city scenarios. Overview In the analysis, the use case of network slicing shows how 5G can be uniquely suited to meet different IoT application demands on same physical infrastructure at the same time. This multi-service capability represents a fundamental architectural advancement over legacy networks by allowing network operators to carve out resources based on the individual application requirements and ensuring isolation between various service types.

The strong improvements in energy efficiency evidenced by a 74% decrease in the power required before and after optimization have profound impacts on sustainability for smart city developments. These improvements not only deliver decades-lasting battery life for IoT devices but also help network operators decrease overall costs and reduce the environmental burden of massive-scale Internet of Things (IoT) offerings. These efficiency improvements are particularly important in massive IoT scenarios, where creating an unbroken run of operations for many thousands of devices over long periods is essential.

In addition, the highly scalable connectivity capabilities that we discovered and validated in the analysis (20K devices per square kilometer), fit perfectly with the expected IoT devices growth within smart cities. Hyper-scalable design to accurately meet future city needs Global 5G networks can execute the consistent growth of future urban areas. This scalability means 5G networks are able to handle the anticipated rapid increase in IoT deployments while maintaining acceptable levels of performance and reliability. Yet, the examination additionally uncovers a few difficulties and impediments that should be understood for fruitful sending of 5G-IoT mix in shrewd urban areas. The millimeter-wave frequency bands, which offer excellent spectral efficiency, require much denser infrastructures due to the limited propagation characteristics of these frequencies. However, the need for infrastructure density may represent an economic and logistical challenge to widespread deployment in urban areas. Moreover, the 5G networks are inherently complex, especially in terms of network slicing and enormity MIMO configurations which bring new dimensions of management and optimization complexity upfront.

Therefore, network operators have to build advanced algorithms and tools to handle such intricate systems while providing excellent performance in every IoT use case. Security (though not studied widely in this work) is another important part of 5G-IoT integration. Securing the proliferation of connected devices and the heterogeneity of IoT applications introduces new attack vectors and new security challenges to be met by comprehensive security frameworks and protocols. For smart cities, the economic consequences of 5G deployment are huge, and there will need to be large capital investments for infrastructure, equipment and supporting personnel.

Nonetheless, the performance upgrades and new service capabilities reviewed in this paper mean that the economic benefits may well justify such investments, producing better city services, more operational efficiencies and a unique increment of revenue possibilities.

Conclusion

In this computerized world of things, the IoT has received a great deal of resilience in smart city environments with 5G taking the lead, and This study examines how 5G technology has influenced the behavior of smart city infotainment devices. formal analytic models are developed and implemented a rich set of MATLAB-based simulations to show that using 5G the new-generation top smart city applications drastically improved across all fundamental performance metrics. Here are the main results of the study: 5G networks can deploy ultra-low latency applications with a substantial decrease in average delay and up to 79.4% reduction compared to 4G systems, showing a latency of 13.16 ms on average.

Throughput performance scales very well, and eMBB slices reach at least 1000 Mbps peak data rates retaining consistent quality of service also across different network load levels. 74% energy efficiency improvements substantially increase the overall sustainability of massive IoT deployments, helping to extend lifetimes of devices and reducing operational costs.

5G network slicing feature manifests in the parallel use of different IoT applications by resource sharing and service separation. The URLLC slices achieve a high reliability 99.999% and an ultra-low latency of 1 ms, which matches the demanding requirements of mission-critical applications.

On the other hand, mMTC slices can scale up to 20,000 devices per kilometer squared with compatibility of energy consumption and a reliable connection.

5G networks are a great leap forward in spectral efficiency thanks to its massive MIMO and beamforming capability, which will enable it to deliver enhanced spectral bandwidths without requiring new spectrum licensing

(or 1GHz of new capacity for every 20 Mbps per MHz). Millimeter-wave bands can reach 40%–600%, whereas performance higher than 15 bps/Hz is achieved in millimeter-wavelength frequency-band-cellular systems.
These conclusions have great implications on Smart City projects and the strategies for deploying IoT devices. Thanks to the performance improvements with the real-time capability of 5G technology many applications that were previously impractical can now be realized, in areas such as real-time traffic optimization, autonomous vehicle coordination and safety, industrial automation or environmental monitoring at unprecedented scales.
The work envisions several future research directions covering challenges identified in this study, such as optimization of infrastructure deployment, development of security framework and economic feasibility. Beyond 5G (B5G) / 6G technologies investigation will become crucial to complementing the enablers of smart cities and IoT applications related to technology road map. This study presents important findings for network operators, city planners, and u-city technologists who are involved in the implementation of smart cities. This research identifies key performance metrics and bespoke optimization strategies useful for decision making to maximize the benefits from investments in 5G enabled smart city deployments.
In conclusion, 5G technology is simply one of the key enablers for smart cities of tomorrow that would have to be necessary fast and a lot more technologically disruptive than supporting an ever-growing number of IoT deployments need innovative solutions, and the services developed using the underlying systems must provide better-added benefits to city populations.

Compliance with ethical standards

Disclosure of conflict of interest

The authors declare that they have no conflict of interest.

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