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GLOBAL ANALYSIS OF MOBILE BROADBAND NETWORK PERFORMANCE: INSIGHTS INTO 5G DEPLOYMENT AND FUTURE 6G CHALLENGES

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Abstract. This research is dedicated to a comprehensive analysis of the global experience in evaluating the performance of mobile broadband (MBB) networks, particularly in the context of 5G deployment and preparations for 6G technology. The study delves into crucial quality of service (QoS) and quality of experience (QoE) metrics that influence mobile network performance, including data download speeds, latency, connection stability, and network coverage. By assessing these factors, the study aims to identify how effectively mobile networks meet the growing demands of modern communication services. A significant portion of the research focuses on Kazakhstan, where the rollout of 5G technology is underway but is still limited to a few operators. The state of the current network infrastructure is evaluated, shedding light on the challenges and opportunities faced in this emerging market. Furthermore, the paper examines international practices from countries such as the USA, Malaysia, and Oman, offering insights into the global trends and challenges that accompany the development of next-generation

mobile networks. Advanced technologies such as millimeter waves, beamforming, and Massive MIMO are discussed in the context of their role in enhancing network reliability and efficiency in densely populated environments. Finally, the research proposes a mobile application architecture designed for real-time signal analysis in 5G networks. This application aims to evaluate mobility management and load balancing processes, which are essential for the smooth operation of next-generation networks.

Keywords: 5G technology, QoE, QoS, mobile broadband networks, mobile networks, next-generation, telecom operators.

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МОБИЛЬДІ КЕН ЖОЛАҚТЫ ЖЕЛІЛЕРДІҢ ТИІМДІЛІГІНІҢ ЖАҺАНДЫҚ ТАЛДАУ: 5G ЕНГІЗУ ЖӘНЕ 6G БОЛАШАҚ МӘСЕЛЕЛЕРІ

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Аннотация. Бұл зерттеу мобильді кеңжолақты желілердің (МВВ) тиімділігін бағалаудағы жаһандық тәжірибені зерттеуге және 5G технологиясын енгізу мен 6G-ге дайындықты қарастыруға арналған. Жұмыста қызмет көрсету сапасы (QoS) және пайдаланушы тәжірибесінің сапасы (QoE) сияқты негізгі көрсеткіштер қарастырылады, олар деректерді жүктеу жылдамдығы,

кідіріс, қосылымның тұрақтылығы және желінің таралу аймағын қамтиды. Бұл көрсеткіштерді талдай отырып, мобильді желілердің заманауи телекоммуникациялық қызметтерге деген өсіп келе жатқан сұраныстарды қаншалықты жақсы қанағаттандыратынын анықтауға бағытталған. Зерттеудің маңызды бөлігі Қазақстанға арналған, мұнда 5G технологиясының енгізілуі әлі де бірнеше операторлармен шектелген. Желінің қазіргі инфрақұрылымы бағаланып, дамушы нарықтың алдында тұрған қиындықтар мен мүмкіндіктер ашылады. Сонымен қатар, зерттеуде АҚШ, Малайзия және Оман сияқты елдердегі халықаралық тәжірибелер қарастырылып, мобильді желілердің келесі буынын дамытуға байланысты жаһандық үрдістер мен қиындықтар көрсетіледі. Жоғары тығыздығы бар ортада желінің сенімділігі мен тиімділігін қамтамасыз ету үшін миллиметрлік толқындар, сәулелендіру және Massive MIMO сияқты заманауи технологиялардың рөлі талқыланады. Зерттеу соңында 5G желілерінде сигналды нақты уақытта талдауға арналған мобильді қосымша архитектурасы ұсынылады. Бұл қосымша мобильділікті басқару және жүктеме теңгерімін бағалау процестерін зерттеуге бағытталған, олар келесі буын желілерінің тұрақты жұмыс істеуі үшін маңызды болып табылады.

Түйін сөздер: 5G технологиясы, QoE, QoS, мобильді кең жолақты қатынау желілері, жаңа буын мобильді желілер, байланыс операторлары.

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ГЛОБАЛЬНЫЙ АНАЛИЗ ЭФФЕКТИВНОСТИ МОБИЛЬНОЙ ШИРОКОПОЛОСНОЙ СЕТИ: ВНЕДРЕНИЕ 5G И БУДУЩИЕ ЗАДАЧИ 6G

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Аннотация. Данное исследование посвящено комплексному анализу мирового опыта оценки эффективности мобильных широкополосных сетей (MBB) в контексте развертывания 5G и подготовки к 6G. В работе рассматриваются ключевые метрики качества обслуживания (QoS) и качества восприятия (QoE), такие как скорость загрузки данных, задержка, стабильность соединения и покрытие сети. Анализ этих факторов направлен на выявление того, насколько эффективно мобильные сети удовлетворяют растущие требования современных телекоммуникационных услуг. Значительная часть исследования сосредоточена на Казахстане, где развертывание технологии 5G находится на начальной стадии и охватывает лишь несколько операторов. Оценивается текущее состояние инфраструктуры сети, что позволяет выявить вызовы и возможности, с которыми сталкивается этот развивающийся рынок. Кроме того, в работе рассматриваются международные практики из таких стран, как США, Малайзия и Оман, что дает представление о мировых тенденциях и вызовах, сопровождающих развитие мобильных сетей нового поколения. Обсуждаются также передовые технологии, такие как миллиметровые волны, фазированная антенна и Massive MIMO, и их роль в повышении надежности и эффективности сети в условиях высокой плотности пользователей. В завершение исследования предлагается архитектура мобильного приложения для анализа сигнала в реальном времени в сетях 5G. Это приложение направлено на оценку процессов управления мобильностью и балансировки нагрузки, которые являются важными для стабильной работы сетей нового поколения.

Ключевые слова: технология 5G, QoE, QoS, сети мобильного широкополосного доступа, мобильные сети нового поколения, операторы связи.

Introduction. 5G technology is the fifth generation of mobile network technology, designed to significantly improve the speed, capacity, and latency of wireless networks. It enables faster data transfer rates, reaching up to 10 Gbps, and supports more connected devices simultaneously, making it ideal for high-density environments like smart cities. Key features include ultra-low latency, enhanced mobile broadband, and massive machine-type communications, which enable innovations such as autonomous vehicles, the Internet of Things (IoT), and virtual reality. 5G also uses advanced technologies like millimeter waves, beamforming, and Massive MIMO to provide more reliable and efficient connectivity.

With the development of 5G and the preparation for the deployment of 6G networks, mobile broadband networks play a key role in ensuring high-speed data transmission and stable connectivity. The demand for mobile networks continues to grow, especially in urban areas with increasing connection density. This study presents an analysis of global experience in evaluating the performance of mobile broadband networks in various countries and regions. The performance assessment of such networks is becoming critically important for ensuring quality of service (QoS) and user satisfaction (QoE), particularly in densely populated areas with a growing number of connected devices.

Mobile broadband networks are one of the key tasks in 5G networks due to the ever-increasing demand for data transfer volumes. 5G networks are capable of providing significantly higher data transfer speeds and stable connections, which meets the requirements of modern users and contributes to the development of new digital services and technologies (ITU-T, 2017).

Methods and materials. Currently, only two telecom operators in Kazakhstan, Kcell and Tele2, provide communication services using 5G technology. Regarding the further development of 5G technology, Kcell and Tele2 operators will continue to work on expanding 5G coverage in the cities of Astana, Almaty, Shymkent and regional centers. To date, 1,144 base stations have been installed in 20 cities. According to information from the Kcell operator, 5G technology provides high-speed Internet, reaching 1600 Mbit/s, providing users with the ability to instantly download movies and stream video in 8K format, which significantly improves the quality of multimedia content consumption.

In turn, the coverage area in Astana of the 5G operator Tele2 is shown in Figure 1.

Figure 2 above displays a coverage map of the city of Astana, showing the 5G network coverage of the telecom operator Kcell. The purple areas represent regions within the city where Kcell provides 5G services. The coverage is concentrated around central areas of Astana, with some additional reach extending into suburban and outlying districts. The majority of the city center and key residential and commercial areas appear to have good 5G connectivity. However, there are still regions, particularly at the outskirts and in less densely populated areas, where 5G coverage is sparse or absent. This distribution indicates that Kcell has focused its 5G network expansion on densely populated and high-traffic zones, ensuring optimal service where demand is likely highest.

It is worth noting that in order to attract customers, many mobile operators do not display theoretical or declared speeds described in new standards (Lobo et al., 2020). In this regard, it is necessary to conduct independent research in terms of assessing the QoS and QoE indicators of existing 5G services of mobile operators.

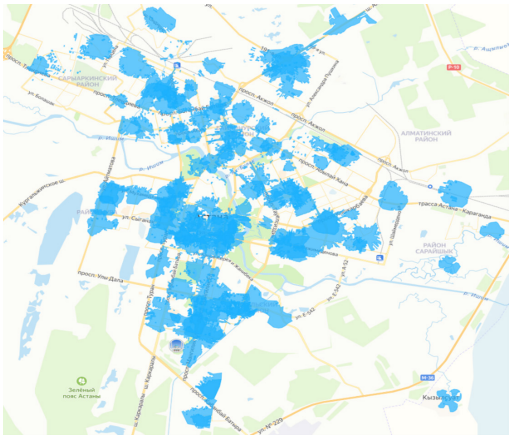

Fig.1. Tele2 coverage area in Astana

Also, the coverage area of Astana city provided by the 5G operator Kcell is shown in Figure 2.

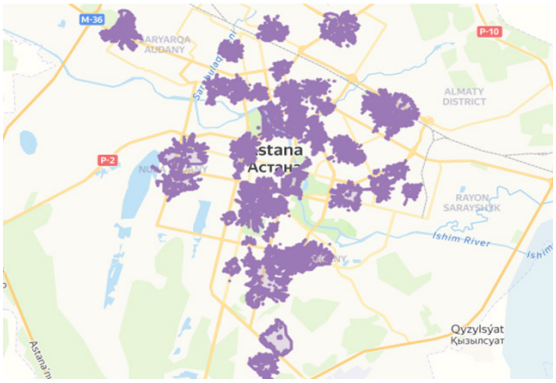

Fig.2. Kcell coverage area in Astana

Results and discussion

The study in the article (Shayea, et al., 2024) is devoted to the analysis of mobile broadband performance in Malaysia, Singapore and Thailand. The study evaluates the network quality of 3G and 4G based on metrics such as coverage, download speed, latency and user satisfaction. The results show that 4G networks perform significantly better than 3G networks, especially in dense urban areas. The study highlights the need to improve MBB services to successfully implement 5G and improve user satisfaction.

A study (El-Saleh, et al, 2022) conducted in Oman provided an analysis of the mobile broadband (MBB) networks of two national telecom operators. The evaluation was conducted based on drive tests in four urban and suburban areas, where metrics such as throughput, handovers, ping rate, signal strength and quality (RSRP, RSRQ and CQI) were analyzed. The results showed that the 4G network dominated in most of the tested areas, providing more stable coverage and high data speeds compared to the 3G network, especially in dense urban areas. The study (Busari, et al, 2018) shows that the introduction of 5G plays a key role in improving the quality of mobile communications due to the use of millimeter waves, which provide high data rates and minimal latency. However, such frequencies are subject to high path losses, which requires the support of small cells and dense placement of base stations. These features make 5G an ideal technology for improving the efficiency of networks in high-density user environments and creating new digital services such as autonomous vehicles and smart cities.

The work (Shayea, et al., 2021) assesses the performance of 3G and 4G networks in urban areas of Malaysia and their preparation for the introduction of 5G. The following metrics are considered for analyzing the performance of base stations of mobile operators:

• Content download speed;

• Coverage area;
• User satisfaction.

The authors of the study (Shayea, et al., 2020) analyze 3G and 4G networks in rural areas of Malaysia in order to optimize and improve MBB services for the introduction of 5G. The following metrics are considered for analyzing the performance of base stations of mobile operators:

• Latency;
• Coverage area;
• Content download speed

Due to the geographical features, the authors selected these metrics, which are essential in an infrastructure-limited environment. This study clearly shows the importance of planning and implementing 5G in rural areas and the need to adapt the network to geographical features.

It is worth noting that the studies in papers (Shayea, et al., 2021) and (Shayea, et al., 2020) are aimed at improving the efficiency of MBB network distribution in different regions of Malaysia. Paper (Shayea, et al., 2021) focuses on the development of urban networks taking into account the high user density, while paper (Shayea, et al., 2020) emphasizes the need to improve coverage and quality in rural areas where the infrastructure is more limited.

Paper (Shayea, et al., 2017) evaluates the performance of mobile broadband (MBB) networks in Malaysia based on the received signal strength (CSS). The study covers indoor testing of 3G and 4G networks of three national telecom operators in the Klang Valley, Selangor and Johor Bahru areas. The tests were conducted in real-world conditions using Galaxy S6 smartphones, which allowed us to evaluate the quality of web surfing and video streaming services at different resolutions. The results of the analysis provide insight into the coverage and performance of mobile networks and can help improve the quality of services for users. It is worth noting that this study was conducted in 2016. Therefore, an old model of smartphones was used. The article (Shayea, et al., 2017) evaluates the performance of mobile networks of five telecom operators in Malaysia in a smart city with a developed technological infrastructure. The current 4G networks were tested for metrics such as RSRP, RSRQ, SNR, throughput (download and download speed), latency, and handovers. The study shows that improvements in SNR and throughput are required for all operators to improve the quality of communication and prepare for the introduction of 5G. The article also discusses the possibilities of using similar methodologies and tools for analyzing 5G networks, which will help operators improve the operation of their networks and ensure high-speed data transmission with low latency.

The study (Malekzadeh, 2023). analyzes the impact of high connection density on the performance of 5G networks, especially in the millimeter wave (mmWave) bands. The authors note that the use of mmWave provides high data transmission speeds but also requires dense placement of base stations to maintain communication quality. This makes 5G particularly relevant for urban areas with a high density of users, where traditional methods may struggle with the load.

Article (Salahdine, et al., 2023) is a comprehensive review of recent achievements and future challenges in the field of mobile communications. The authors focus on the current development of 5G and the future possibilities of 6G, paying special attention to technical aspects such as improving bandwidth, reducing latency, and increasing connection density. Key achievements of 5G: Important achievements include enhanced bandwidth capabilities, ultra-low latency, and high connection density, allowing support for millions of devices in small areas. These improvements are already being implemented in the Internet of Things (IoT) industry, autonomous vehicles, and smart cities. 6G prospects: The development of 6G is aimed at using extremely high frequencies (terahertz range), which will provide even higher data transmission speeds. Artificial intelligence (AI) will play an important role in 6G, being used for network management, improving energy efficiency, and providing more reliable and low-latency connections. Main challenges: One of the key challenges for 6G is ensuring network security and addressing issues related to high connection density. Additionally, 6G requires significant infrastructure changes and new approaches to spectrum management.

In article (Salahdine, et al., 2023), the modeling of mobile traffic in a large metropolitan area based on measurements is explored. The authors emphasize that accurate traffic modeling is critical for improving the performance and reliability of 5G and 6G networks. The study uses big data analysis to examine traffic patterns in high-density connection conditions, including peak hours and holidays. Results show that adapting traffic models to dynamic usage conditions allows for more efficient network resource management. The authors also propose methods that can help predict load, which is particularly important for ensuring quality service in conditions of high user density. These approaches highlight the need to integrate traffic data into the planning and management processes of networks.

In work (Albaladejo, et al., 2016), Miguel Báguena Albaladejo and others discuss performance modeling of LTE in Dublin based on real measurements. The authors emphasize that understanding the current performance of LTE is critically important for planning and optimizing next-generation networks like 5G. The study finds that factors such as user density and interference level significantly affect communication quality in urban environments. Article (Oliveira, et al., 2015) is devoted to the development of a linear to circular polarization converter in the Ka-band. The authors highlight those converters play an important role in modern wireless communication systems, especially under high connection density conditions where high performance is required. This work underscores the importance of effective antennas and polarization technologies for achieving the necessary communication characteristics in 5G and 6G networks.

Article (Oliveira, et al., 2015) focuses on the development of a linear-to-circular polarization converter in the Ka-band. The authors emphasize that converters play an important role in modern wireless communication systems, especially under conditions of high connection density, where high performance is required. This work highlights the importance of effective antennas and polarization technologies for achieving the necessary communication characteristics in 5G and 6G networks.

Article (Albaladejo, et al., 2016) analyzes the compatibility of a cognitive broadband satellite system and mmWave networks. The authors find that the effective coexistence of these systems can significantly improve performance and expand network coverage. This study is important for understanding how different technologies can coexist and work together under conditions of high connection density, which is a key aspect for future mobile networks.

In article (Zhang, et al.,2017), high-performance and ultra-broadband metamaterials based on mixed absorption mechanisms are discussed. The authors emphasize that such technologies can be used to create more efficient antennas and devices, which is an important aspect for optimizing the performance of 5G and 6G networks in dense urban environments.

Article (Zhang, et al., 2020) analyzes the performance of mobile broadband networks considering 5G trends in urban areas of Malaysia. The authors emphasize that the introduction of 5G significantly changes traffic dynamics and service quality. The study confirms that the successful deployment of 5G requires adapting existing networks to new operating conditions, including connection density and performance requirements.

Article (Wang, et al., 2020) examines key technologies necessary for achieving ultra-low latency and high connectivity in 5G and 6G networks. The authors focus on solutions such as massive antennas (Massive MIMO), signal processing technologies, and distributed computing. These technologies help improve network performance under high connection density, which is particularly relevant for applications requiring rapid response times, such as autonomous vehicles and virtual reality.

Article (Shayea, et al., 2021) focuses on issues related to high connection density in 5G networks. The authors highlight several critical aspects, including spectrum management and resource allocation methods. They emphasize the need for new architectures, such as small cell networks and coordination technologies, to improve service quality in conditions of high user density.

Together, these studies underscore the importance of a comprehensive approach to addressing high connection density challenges and the necessity of developing innovative technologies. Effective use of massive antennas and distributed computing, alongside new architectural solutions, can significantly enhance the performance of 5G and 6G networks, ensuring the necessary reliability and service speed.

As a result of the literature review, the following metrics were identified for conducting web browsing measurements:

1) Cellular signal strength (dBm)
2) Total number of service attempts (number) and average success rate of page display
3) Average page download bandwidth (kbps)
4) Average page response delay (ms)
5) Average page display delay (ms)
6) Average RTT ping delay (ms)

For streaming video:

1) Cellular signal strength (dBm)

2) Total number of service attempts (number) and average success rate of initial buffering

3) Average Mobile vMOS (scale from 1 to 5; worst = 1; best = 5)

4) Average overall video download speed (kbps)

5) Average initial buffering delay (user-perceived delay) (ms)

6) Average RTT Ping Latency (ms)

7) Average Total Rebuffer Latency (ms)

Signal quality plays a key role in ensuring high performance and reliability of mobile networks. In LTE and 5G networks, parameters like SINR, RSRP, and RSRQ allow network operators to assess current network conditions and optimize its performance. SINR helps determine the ratio of useful signal to noise and interference, RSRP indicates the signal level from the base station, and RSRQ reflects the quality of the received signal.

The article shows that using these parameters allows for assessing current network conditions and taking necessary measures to improve coverage and performance, especially in conditions of high connection density. In 5G networks, the introduction of new technologies such as beamforming and massive MIMO has significantly improved signal quality metrics, allowing for high-level connectivity even in challenging conditions like dense urban areas and high user concentrations.

The first stage of the drive test requires the development of a mobile application for 5G/6G networks, which will serve as a platform for collecting and analyzing mobile data traffic in real time. The application will allow conducting research on mobility management processes (MRO), load balancing (LBO), and handover of communication sessions (HOD) in next-generation networks. In addition, the project is aimed at supporting the development of 5G and 6G infrastructure, as well as studying the technical requirements and challenges associated with the deployment of future cellular networks in smart cities of Kazakhstan. Based on the literature review, two types of testing scenarios are proposed for conducting real measurements based on the test drive, shown in Figure 3.

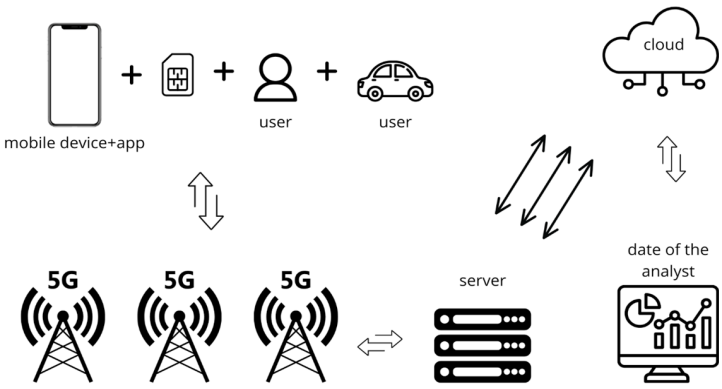

Fig.3. Work flow of mobile app

As shown above, Figure 3 represents the architecture of a mobile application designed for 5G networks. The architecture involves several key components:

• Mobile Device + App: The user operates a mobile device equipped with a SIM card and a specialized application that connects to the 5G network.

• User Interaction: The user interacts with the mobile application, either while stationary or in motion (e.g., in a car), showcasing the app's capability to handle mobile and dynamic environments.

• 5G Towers: The mobile device connects to multiple 5G base stations, which provide high-speed data transmission. These towers handle the data exchange between the user and the backend infrastructure.

• Server: The 5G towers relay data to a centralized server, where the data is processed and analyzed.

• Cloud: The server communicates with a cloud service to store and process large-scale data, ensuring scalability and reliability.

• Data Analysis: Data collected from the mobile device, the 5G network, and other components are analyzed and visualized to provide insights and reports for performance evaluation or other purposes.

The architecture is designed to support seamless data exchange, handle mobility, and provide real-time data analysis, leveraging the benefits of 5G technology for enhanced connectivity and performance.

Conclusion.

The study confirms that 5G technology is a crucial factor in improving the performance of mobile broadband networks, especially in high-density urban environments. By analyzing the global experience of 5G implementation and reviewing case studies from various countries, it becomes evident that 5G not only enhances network quality but also promotes the development of innovative digital services. In Kazakhstan, operators such as Kcell and Tele2 have made significant strides in expanding 5G coverage, particularly in metropolitan areas. However, gaps remain in less densely populated regions, emphasizing the need for continued infrastructure development. The proposed mobile application for real-time signal analysis offers a practical solution for monitoring and optimizing network performance, thereby supporting the ongoing development of 5G and the future deployment of 6G technologies.

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