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Advancements in Ultra-Reliable Low-Latency Communication (URLLC) and Integrated Sensing and Communication (ISAC) in the 6G Era

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Abstract. This paper discusses advancements in 6G communication technologies, focusing on Ultra-Reliable Low-Latency Communication (URLLC) and Integrated Sensing and Communication (ISAC). URLLC aims to achieve low latency (under 1 ms) and high reliability (down to 10^-6) crucial for applications such as autonomous driving, remote surgery, and industrial automation. ISAC integrates communication and sensing functions, improving efficiency and enabling new services in various industries, including healthcare, transportation, and manufacturing. This integration supports real-time operations and enhances the performance of smart systems. The paper highlights technological enablers, including ultra-dense networks, intelligent relaying, and advanced sensing techniques, necessary for implementing URLLC and ISAC in the 6G era. The discussion extends to the potential challenges and future research directions, emphasizing the need for resource optimization and security in 6G networks. The study suggests that combining AI with URLLC and ISAC can address latency and reliability requirements, proposing a unified approach for future communication systems.

Keywords: 6G communication, URLLC, 5G, ISAC.

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1. Introduction

The advent of 6G communication technology promises to revolutionize the landscape of wireless communication, addressing the limitations of its predecessors while unlocking unprecedented opportunities. As the fifth-generation (5G) technology gradually rolls out, its advancements are already paving the way for the sixth generation (6G), which is projected to introduce transformative features. Among these are ultra-reliable low-latency communication (URLLC) and the integration of sensing and communication (ISAC) technologies, which will necessitate a departure from existing wireless communication platforms [1].

6G technology is not merely an incremental upgrade but a breakthrough that will catalyze the evolution of various other concurrent technologies. This includes artificial intelligence (AI), the Internet of Things (IoT), the Internet of Everything (IoE), and the broader scope of the industrial revolution encompassing cloud manufacturing, cyber-physical networks, robotics, and renewable energy. The convergence of these technologies under the 6G umbrella heralds a new era of hyper-connectivity and intelligent automation, poised to reshape industries and daily life [2].

This paper explores the key features and innovations that 6G communication is expected to bring, highlighting its potential to overcome the limitations of 5G and its significant role in the future technological landscape. As we stand on the cusp of this new technological frontier, understanding the projected capabilities and implications of 6G becomes crucial for researchers, industry stakeholders, and policymakers alike.

2. Previous Studies

On Ultra-Reliable Low-Latency Communication (URLLC) and Integrated Sensing and Communication (ISAC) in the 6G era have underscored substantial advancements over 5G technologies. Researchers have investigated enhanced time and frequency synchronization, grant-free transmission design, and joint sensing and access mechanisms. For instance, Saad et al. (2020) [3] explored how URLLC in 6G can achieve sub-millisecond latencies, essential for applications like autonomous driving and industrial automation. Another study by Zhang et al. (2020) [4] emphasized the importance of integrated sensing and communication, highlighting its potential to improve both communication efficiency and reliability in 6G networks. Additionally, Chen and Zhao (2019) [5] discussed the transition from traditional relaying to two-way relaying with active eavesdropper management, which is crucial for secure and efficient communication in 6G. These studies collectively demonstrate that 6G networks are expected to deliver significantly higher data rates, improved spectral efficiency, and lower costs, paving the way for innovative applications and enhanced network performance.

Table 1. Previous studies

Ref	Study	Key Focus	Findings	Applications	Technological Enhancements
[3]	Saad et al. (2020)	URLLC in 6G	Achieves sub-millisecond latencies for real-time applications.	Autonomous driving, automation	Enhanced sync, grant-free transmission
[4]	Zhang et al. (2020)	Integrated Sensing in 6G	Improves communication efficiency and reliability.	Smart cities, IoT, healthcare	Joint sensing and access, better spectral efficiency
[5]	Chen and Zhao (2019)	Relaying Techniques	Shift to two-way relaying with eavesdropper management for secure and efficient communication.	Secure communication, data transmission	Two-way relaying, integrated sensing and interference management

3. Evolution from 1G to 6G

The most recent cell communications as the starting point, that is 5G. 5G is the fifth generation of wireless mobile telecommunications which started to roll out in 2019. It succeeds the 4G and offers in particular some extra characteristics indispensable for key vertical user groups – machine type communication, ultra-reliable and low-latency communication (URLLC). Machine type communications support a massive number of devices of various performance but mostly IoT [6]. It was conceived not only as an enhancement of the 4G technology but was seen as a support for the 'third industrial revolution' and the 'industry 4.0'. The 5G also laid the groundwork for the future sixth generation, whose primary target of enabling use cases is the fourth industrial revolution, the so-called digital transformation of the industry. On the other hand, the precise purpose of the so-called Tactile Internet is the ability to control and supervise remote systems as if they were local. This particular service offered by URLLC and integration with sensors could lead to novel Tactile Internet applications such as haptic communication and the control of robotic systems in critical environments, for example disaster recovery [7].

The 1G was the first generation of wireless telecom networks. It was analog and operated in a frequency range from 30 kHz to 3 MHz. These first generations of technology were used for voice telephony only. 1G was also called mobile ARP because it had a walking speed. The latency and reliability of 1G technology, although in pain, were nowhere as important as the data was primarily voice applications. 2G, that was digital technology (as the use of TDMA, FDMA, CDMA), compared to analog technology of 1G, enabled the use of short message service (SMS). In 3G era communication evolved into a wireless protocol for specialized access such as code division multiple access (CDMA), universal mobile telecommunications system (UMTS), time division synchronous code division multiple-access (TD-SCDMA), evolved universal terrestrial radio access (E-UTRA) [8]. 4G mobile communication standards commenced as a wireless access system commonly referred to as Long Term Evolution (LTE) but evolved to include variants such as Long Term Evolution Advanced (LTE-A). 4G networks offered the best support for mobile broadband and voice communication and opened the doors to multimedia services such as HD TV streaming, and reached speeds of about 1 Gbps [9].

4. Fundamentals of Ultra-Reliable Low-Latency Communication (URLLC)

In order to support these diversified communication, sensing, and control services and their related industrial applications, ultra-reliable and low-latency communication (URLLC) accounting for sensing and communication, such as integrated sensing and communication (ISAC), have become key interests for the research and development of the 6G era. These deal with low latency down to less than 1 ms and extremely high reliability down to 10^-6. We provide an insightful review on ULTRA, a URLLC and low-latency framework for integrated sensing and communication that aims to provide a hardware-software co-designed framework with both improved radio techniques and computational intelligence as a foundation for 6G applications [10]. This is because they can have the opportunity for efficiency improvements, due to not only new services adding to traffic but also due to providing tailored communication support [11].

Wireless communication has come a long way in supporting various phases of human life, from communication, sensing, navigation, imaging, and so on. It has evidently played a crucial role in many mobile communication standards, supporting the quality of service levels of relevance and interest in different generations. For example, voice and short message services in 2G, web browsing and short video streaming in 3G, high-resolution video and social media services in 4G, and ultra-broadband, ultra-reliable, and low-latency communication for industrial production enablers and mission-critical services that can save human lives in 5G. The upcoming 6G era is expected to not only support these old/new services with better capabilities but also to create new services, as well as to empower new industries with innovative efficiency [12].

4.1. Definition and Key Characteristics

Integrated Sensing and Communication (ISAC) is a new communication mode beyond URLLC, aiming to realize URLLC through physical layer processing as an external extension of advanced sensing technologies. Therefore, we advocate that the research community focus on the URLLC mode and its extension, ISAC, for the horizon of 6G. In this paper, we argue that the synergy of communication and sensing technologies and advances to provide URLLC and ISAC supports the vision of 6G [13]. The industrial IoT (IIoT) domain, the requirements for URLLC have specified ultra-robust reliability such as 10^-9, ultra-high availability, and ultra-insanely low end-to-end latency such as below 10 ms. If the requirements of URLLC services can't be met, the arrival of 6G will be a big question [14].

URLLC encompasses both ultra-low latency and ultra-high reliability requirements. It represents the culmination of efforts—the highest-quality data transmission capabilities. Such capabilities are especially critical for certain key applications in vertical industries and stand to benefit from 5G and 6G technologies, including the Internet of Vehicles, Industrial Internet, and Intelligent Transportation Systems. The URLLC towards 6G provides a means to value data transmission services by application sectors, enabling efficient and optimized network service delivery and trust [15].

In this article, we will propose a vision for the next-generation 6G era's communications and outline anticipated paths for its evolution. Specifically, we focus on ultrareliable low-latency communication (URLLC), including ultra-reliable communication and low-latency communication, and its extension, Integrated Sensing and Communication (ISAC) [16].

Ultra-reliable low-latency communication (URLLC), first proposed in 5G, envisions a communication system providing low-latency transmission with unmatched reliability. In URLLC, the average communication latency, along with latency tails, is expected to be well controlled to facilitate latency-sensitive applications, such as remote medical operations and factory automation. In URLLC, ultra-reliable (UR) communication features very low error rate, while low-latency (LL) communication targets a stringent latency requirement. It is expected that the traditional model-based design paradigm may not be able to fully meet the URLLC requirements due to the inherent uncertainty and unpredictability of diverse wireless environments [17].

4.2. Applications in Various Industries

Mining and retail, have similarly stringent communication requirements. By combining communication and sensing in the same spectrum and device, both requirements can be fulfilled using URLLC and ISAC. For the healthcare industry, URLLC and ISAC reinforce remote healthcare solutions, providing the real-time connection between patients and emergency medical care institutions or local wards. IIoT solutions in healthcare can also be achieved by integrating smart medical devices, including head-mounted intelligent equipment with wireless transmission functions, to conduct indoor navigation and positioning of medical devices via mesh networks [18].

In the transportation industry, URLLC and ISAC are essential for real-time vehicle-to-vehicle communication, highly accurate time and remedy coordination for large-scale, sophisticated schedule systems, and real-time operation of autopilots, especially in high-speed scenarios. In addition to vehicle-to-vehicle and vehicle-to-infrastructure communications, integrated sensing and communication technology allows the transportation industry to fully utilize the benefits of emerging intelligent transportation systems, which include highly precise offboard localization, traffic signal control, and cooperative perception of the driving environment [19].

For smart manufacturing, URLLC can be used as a key building block to implement many industrial IoT use cases, such as real-time control, real-time wireless data exchange for process feedback, wireless sensor monitoring and alarm, highly responsive remote expert system interaction, and augmented and virtual reality. URLLC can be combined with edge computing for low latency process decisions. Most of these applications need to ensure service continuity and network reliability for the critical and time-critical requirements of industrial process control and machine type communication (MTC) [20][21].

With many industries driven to implement automation technologies, URLLC and ISAC are seen as good platforms for various communication applications. Here, we present several URLLC and ISAC use cases within a few different industries.

5. Integrated Sensing and Communication (ISAC)

An architecture that can transmit and process physical quantities while considering SE and EE design metrics is the integrated sensing and communication (ISAC) paradigm. The key enablers needed to realize ISAC aim to achieve orders of magnitude better modulation schemes, concurrent physical layer operations, and order-of-magnitude improvements in the design of ultra-reliable and low-latency communication (URLLC) and physical layer algorithms. we provide recent results, ideas, and some directions on the advancement of ISAC theoretical insights and possible implementation schemes that fit the 6G poster child hardware targets [22].

To achieve high energy and frequency efficiency, society will move to an era of integrated sensing and communication (ISAC), where the same signal simultaneously drives both sensing and communication activities. Progress in key enabling technologies in the area of ISAC will alter the way electronics are manufactured, dissipate power, and propagate information in harsh environments, and will result in a ubiquitous communication interface that monitors and interacts with all aspects of the environment. The scarcity of integrated circuits in space- and power-constrained electronic systems has led the research community to develop and explore hardware that can simultaneously act as sensors and communication channels and use the same signal to convey information while interrogating the surrounding environment [23].

6. Concept and Importance

Key parameters to describe URLLC are latency and reliability, i.e., the time to deliver a packet from the transmitter to the receiver, measured in milliseconds, and the packet loss rate that can be tolerated by the application, respectively. In the current technologies, one particular radio resource (e.g., time, frequency, and code resources) alone cannot satisfy URLLC requirements or efficiently share between communication and sensing. Therefore, not only from the perspective of the deterministic capture detector, but also concerning other excellent detection and estimation technologies, this special issue focuses on URLLC technology and ISAC and its combination, and presents solutions for time-sensitive operations in either a standalone or a combined system [24][25].

This special issue "Advancements in Ultra-Reliable Low-Latency Communication (URLLC) and Integrated Sensing and Communication (ISAC) in the 6G Era" aims to enhance the performance of beyond the existing communication technology, both at the system level and at the physical layer, in part or as a whole. The issue scopes across several areas of integrated sensing and communication, ultra-reliable low-latency communication, and wireless sensing network theory , algorithms, and techniques to inform, stimulate, and assess 6G wireless communication technologies. In addition to the technologies, we are eager to foster discussions about various applications and target scenarios, such as wireless intelligence, synchronized electromagnetical systems, and mathematics [26].

Ultra-reliable low-latency communication (URLLC) has become one of the key technologies and an important performance aspect of beyond 5G (B5G) and 6G wireless communication technologies, serving diverse application scenarios such as Industrial Internet of Things (IIoT), autonomous vehicles, and tele-surgery. Integrated Sensing and Communication (ISAC) is considered by researchers as a possible approach to enhance the functionality and efficiency of wireless communication [27].

7. Technological Enablers for URLLC and ISAC

Sensing and communication play crucial roles for interchanging environment and service-related information in IoE. Since the 6G networks are expected to support a wide range of sensing and industry 4.0 applications, various Information-Centric Networking (ICN) approaches have been proposed to simplify the resource management and optimize the network architecture. For the future IoT and beyond-5G networks that maximize the utility of a massive number of devices in order to realize URLLC relevant applications and ISAC, several key technological enablers are being proposed or established, such as the Ultra-Dense Network (UDN) that increases the connectivity toward edge/fog areas through short-distance connections, the Intelligent Relaying and Transmission (IRT) approach that enables the networks to react differently toward various application requirements, and Integrated Sensing and Communication (ISAC) that allows a network to serve both sensor communication and service users with a sole communication system [28].

With the advent of the Internet of Everything (IoE) in the 6G era, short latency becomes more and more crucial. Ultra-Reliable Low-Latency Communication (URLLC) becomes a native component since good latency performance usually implies a small number of link hops and strong link quality, which benefits this type of service. Furthermore, Integrated Sensing and Communication (ISAC) has the potential to simplify network structures and facilitate flexible deployment of a large number of sensors for various applications (e.g., smart environment, robotics, and medical treatment). Many new technologies and approaches have been introduced to enable these applications with the desired performances. In this section, we will analyze key URLLC enhancers (e.g., ultra-dense network, intelligent relaying and transmission), and ISAC key enablers (i.e., in-band sensing, integrated transceiver design, and learning-based sensing) [29].

8. 5G vs 6G Technologies

The autonomous device communication time reference is less than 1 ms. Therefore, ULLC is an enabler of Industry 4.0. The end-to-end latency is expected to be less than 0.5 ms. To address this issue, we compare the existing non-Orthogonal synchronous random access (NORA) and the improvement of the time and frequency synchronization, in particular for downlink communication and random access, granted based grant-free transmission design, joint sensing and access, two-way relaying with active eavesdropper, integrated sensing and interference management, and Taylor series for massive MIMO, etc. 6G intelligent network anticipation consists of anticipatory content delivery and infrastructure prediction, including water monitoring, as shown in Figure 1 and Figure 2.

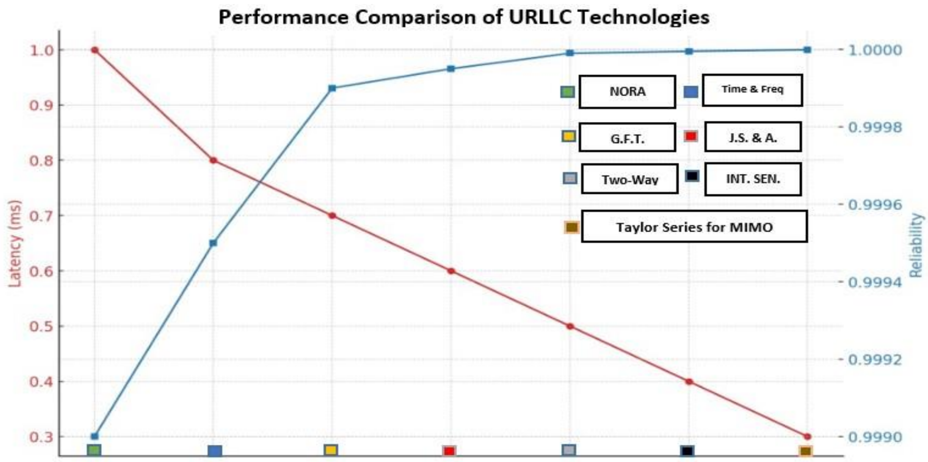

Fig.1. Performance Comparison of URLLC Technologies

The performance comparison of Ultra-Reliable Low-Latency Communication (URLLC) technologies includes several advancements. Non-Orthogonal Random Access (NORA) allows multiple devices to access the network simultaneously without strict orthogonality. Time and Frequency Synchronization ensures precise timing and frequency alignment for data transmission. Grant-Free Transmission eliminates the need for prior resource allocation, enabling immediate data transfer. Joint Sensing and Access integrates sensing capabilities with communication functions to enhance efficiency and reliability. Two-Way Relaying uses a relay station to improve signal strength and reliability by forwarding data in both directions. Integrated Sensing combines sensing and communication within the same signal, optimizing resource use. Advanced techniques, such as the Taylor Series for MIMO, improve the performance of multiple-input and multiple-output (MIMO) systems, highlighting the advancements in communication and network efficiency in the 6G era.

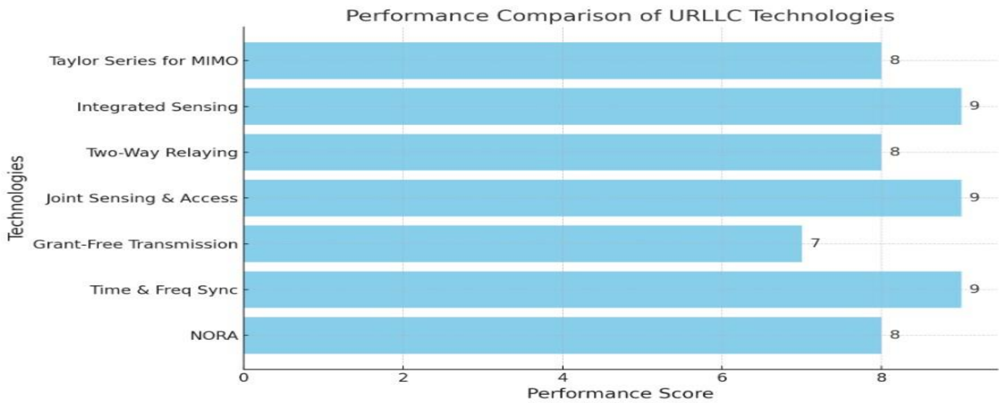

Fig.2. Achieving Ultra-Reliable Low-Latency Communication: A Look at Different Technologies

We compare the general design considerations, communication technologies, and networking concepts of 5G and 6G in Table 1. The data rate in 5G NR downlink peaks at 20 Gbps in the ideal scenario, and it falls to 70 Mbps at 0.1% achievable cell edge spectral efficiency. The 6G data rate is expected to be tens to hundreds of Gbps to satisfy consumer requirements. Three-dimensional (3D) underwater communication is still an open challenge for the existing technologies. We believe 3D communications in the 6G era are necessary due to the low propagation loss and less dense data path. 6G necessitates a reliable underwater backhaul, which can be accomplished using an integrated sensing and communication (ISAC) network. 6G is expected to be 10 times cheaper and 10 times more efficient than 5G.

Table 2. General design communication technologies, and networking concepts of 5G and 6G

Feature/Metric	5G	6G
Data Rate	Up to 20 Gbps (ideal scenario)	Tens to hundreds of Gbps
Latency	~1 ms	< 0.5 ms
Achievable Cell Edge Spectral Efficiency	0.1% achievable, 70 Mbps	Significantly improved
Communication Type	Orthogonal, synchronous random access	Non-Orthogonal, synchronous random access
Transmission Design	Grant-based	Grant-free
Synchronization	Time and frequency synchronization	Enhanced time and frequency synchronization
Sensing and Access	Limited	Joint sensing and access
Relaying	Standard relaying	Two-way relaying with active eavesdropper

Feature/Metric	5G	6G
Interference Management	Standard techniques	Integrated sensing and interference management
Massive MIMO	Basic Taylor series application	Advanced Taylor series application
Network Anticipation	Basic network anticipation	Intelligent network anticipation with anticipatory content delivery and infrastructure prediction, including water monitoring
3D Communication	Limited	3D underwater communication, reliable underwater backhaul using ISAC
Cost and Efficiency	-	10 times cheaper and 10 times more efficient

9. Challenges and Future Research Directions

In the 6G Era, when AI algorithms are widely used in the physical layer, as well as in positioning algorithms and channel modulation algorithms, using AI algorithms for integrated design and joint optimization of the two technologies to achieve the reuse of resources and low latency will become an important trend. We believe that it will be a very challenging but interesting future research direction to study the URLLC and ISAC technologies that unify the physical, data link, network, and intelligent layers toward a system [30].

Although these two technologies are different both in terms of modulation and coding techniques and in terms of application scenarios, they also have a commonality: A Higher Heterogeneity. URLLC needs to support a greater number of classes and a wider range of classes with less tolerance to the delay requirement degradation, while ISAC allows a new type of service to divide the time into short time slots, a system structure with fast access, and a low latency requirement [31].

For ISAC technologies, we believe the integration of positioning, IoT, and sensing applications in the future communication environment will be interesting research directions in the 6G Era.

For URLLC technologies, it is particularly challenging to address the requirements of a large number of practical applications. It is even more challenging to particularly support applications with unpredictable QoS in a complex wireless environment {Formatting Citation}. Researchers have to carefully balance the trade-off between complexity and performance to address these challenges [32].

Over the past decade, URLLC and ISAC technologies have been immensely popular in rapid iterations from the first three and a half generations of mobile communications. The 6G Era has presented these two technologies some new technical challenges and, in the meantime, provided them with great opportunities for future applications [33].

10. Security and Privacy Concerns

The future 6G networks are implemented not only to communicate and exchange data, e.g., images, videos, etc., but also to support various sensor (sensors are a subset of IoT devices) applications, e.g., sensing solutions for smart buildings, etc. These cross-domain interactions or, in other words, applications, have different requirements as far as time and energy are concerned from the point of view of sensing and the potential of XCI as an integrating method that will extend and combine futures like URLLC, with other commercial approachable services, i.e., asset protection, environmental monitoring, structural health monitoring, automotive control, etc., in under one 6G network [34].

The vehicular industry suffers from a variety of security and privacy risks. Apart from problems for protecting all vehicular-related information, i.e., requests of a driver, collision avoidance messages, etc., the major features of V2X communication, i.e., direct communication, receive safety warnings, etc., can also be abused by attackers resulting in different types of traffic breeding, road rage, updating life cycle, failure in advance, etc. Implementation of deep-learning and further the mobile edge of computing and blockchain to improve the immutability and transparency of the emitted and managed data are some of the most recent IoT-based methods in order to render vehicular infrastructure completely safe and secure [35][36].

11. Conclusion

6G communication technologies represent a significant leap forward, particularly through the integration of Ultra-Reliable Low-Latency Communication (URLLC) and Integrated Sensing and Communication (ISAC). These advancements promise to meet stringent latency and reliability requirements essential for critical applications such as autonomous driving, remote surgery, and industrial automation. URLLC aims to achieve latencies under 1 ms and reliability as high as 10^-6, while ISAC enhances system efficiency by merging communication and sensing functionalities. The key technological enablers for these advancements include ultra-dense networks, intelligent relaying, and advanced sensing techniques. However, the implementation of 6G technologies also presents challenges, particularly in resource optimization and security. Future research should focus on integrating AI with URLLC and ISAC to further enhance system capabilities and address these challenges. Overall, 6G technologies have the potential to revolutionize various industries by providing highly efficient, reliable, and low-latency communication systems, supporting a wide range of new and existing applications.

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مجلة كلية العراق الجامعة للهندسة والعلوم التطبيقية

التطورات في الاتصالات ذات زمن الاستجابة المنخفض فائقة الموثوقية (URLLC) والاستشعار والاتصالات المتكاملة (ISAC) في عصر الجيل السادس

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الملخص . تناقش هذه الورقة التطورات في تقنيات اتصالات الجيل السادس، مع التركيز على الاتصالات ذات زمن الاستجابة المنخفض فائقة الموثوقية (URLLC) والاستشعار والاتصالات المتكاملة (ISAC). يهدف URLLC إلى تحقيق زمن انتقال منخفض (أقل من 1 مللي ثانية) وموثوقية عالية (تصل إلى 10^-6) وهو أمر بالغ الأهمية لتطبيقات مثل القيادة الذاتية والجراحة عن بعد والأتمتة الصناعية. يقوم ISAC بدمج وظائف الاتصال والاستشعار، وتحسين الكفاءة وتمكين خدمات جديدة في مختلف الصناعات، بما في ذلك الرعاية الصحية والنقل والتصنيع. يدعم هذا التكامل العمليات في الوقت الفعلي ويعزز أداء الأنظمة الذكية. تسلط الورقة الضوء على عوامل التمكين التكنولوجية، بما في ذلك الشبكات فائقة الكثافة، والترحيل الذكي، وتقنيات الاستشعار المتقدمة، اللازمة لتنفيذ URLLC وISAC في عصر G6. وتمتد المناقشة إلى التحديات المحتملة واتجاهات البحث المستقبلية، مع التركيز على الحاجة إلى تحسين الموارد والأمن في شبكات الجيل السادس. تشير الدراسة إلى أن الجمع بين الذكاء الاصطناعي وURLLC وISAC يمكن أن يعالج متطلبات زمن الوصول والموثوقية، ويقترح نهجًا موحدًا لأنظمة الاتصالات المستقبلية.

الكلمات الرئيسية: اتصالات G6، URLLC، 5G، ISAC.