MILLIMETER WAVES AND ULTRA-HIGH FREQUENCY TECHNOLOGIES: A NEW STAGE IN MOBILE COMMUNICATION

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Annotation. Millimeter waves (mmWave) and ultra-high frequency technologies represent a key direction in the development of mobile communications of the fifth and sixth generations. The article discusses the physical and technical features of wave propagation, architectural solutions to overcome limitations (beamforming, massive MIMO, intelligent reflective surfaces), as well as real-world implementation scenarios in the United States, South Korea, Japan, and Europe. Special attention is paid to the future role of mmWave in 6G networks and the possibilities of ultra-high-speed data transmission.

Keywords: millimeter waves, mmWave, 5G, 6G, ultrahigh frequencies, beamforming, MIMO, intelligent surfaces, terahertz technologies, spectral efficiency, power consumption, signal attenuation, small cells.

Introduction. In a world where the number of connected devices exceeds the population, and the volume of digital traffic is growing exponentially, the requirements for mobile networks are becoming unprecedented. Streaming video in 4K and higher, holographic communication, driverless vehicle management, and the Industrial Internet of Things (IIoT) all require new approaches to data transmission. Traditional frequency bands can no longer cope with the load, and it is millimeter waves (mmWave) that are becoming one of the key technologies that can ensure the transition to a new era of mobile communications.

Millimeter waves provide access to wide frequency bands that allow you to achieve ultra-high data transfer rates and minimal delays. However, their use is

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associated with a number of physical and technical limitations — the signal quickly fades in the atmosphere, does not pass well through walls, and requires direct visibility. To overcome these barriers, advanced engineering solutions are used: directional beamforming, massive antennas (massive MIMO), and intelligent reflective surfaces (IRS) that can control the signal propagation route.

The purpose of this study is to analyze the technological potential of millimeter waves and their role in the formation of fifth — and sixth-generation networks (5G and 6G), evaluate the real results of implementation in leading countries, and identify key challenges and prospects for further development of this technology. The study is based on a comparative analysis of existing architectural solutions and practical cases of mmWave implementation in the USA, South Korea, Japan, and EU countries.

mmWave and THz communication Specifications

Millimeter waves (mmWave) cover the frequency range from 24 GHz to 100 GHz, while ultra-high frequency or terahertz (THz) technologies operate in the spectrum from 100 GHz to 10 THz. These bands provide access to an extremely wide frequency band, which allows you to achieve multiple increases in bandwidth compared to traditional communication systems below 6 GHz.

One of the key advantages of mmWave and THz communication is high channel throughput. For example, when using the 2-10 GHz band in the 60 GHz band, data transfer rates of up to 20-50 Gbit/s can be achieved in real conditions and theoretical limits of about 100 Gbit/s. In the terahertz band (for example, 275-325 GHz), speeds exceeding 1 Tbit/s are predicted, which makes THz communication the basis of future applications with extreme data requirements-holographic telepresence, industrial Internet and quantum transmission.

A serious limitation for mmWave and especially THz communication is the rapid signal attenuation. Atmospheric propagation is accompanied by absorption, which is especially pronounced in the bands of 60 GHz (due to oxygen) and above 300 GHz (due to water vapor). The effective line-of-sight communication range is 100-200 m for mmWave and less than 10-20 m for THz, which limits their use in macrocells, but makes them suitable for dense networks of small cells.

Because of the small wavelength (from 1 mm to 100 microns), the antennas in mmWave / THz systems can be miniaturized, which allows the use of arrays of tens or hundreds of elements. This facilitates the implementation of directional beamforming and mass MIMO, providing signal amplification, spatial filtering, and simultaneous operation with multiple subscribers.

The formation of narrowly directed beams allows you to compensate for propagation losses and increase the range. Modern solutions, such as the 5G NR FR2 standard, already provide for dynamic switching of beams, while 6G assumes their adaptive control in millisecond time intervals.

To overcome the lack of penetration and attenuation in a built-up environment, it is proposed to use intelligent reflective surfaces-passive structures that controllably redirect electromagnetic waves. IRS allows you to" re-reflect " the signal in hard-to-reach areas and form alternative propagation paths that do not require direct visibility. Studies show that IRS can increase the signal strength by 2-3 times if properly configured, especially in bands above 28 GHz.

Operating in the millimeter and terahertz bands requires high frequency synthesis accuracy and sensitive receivers, which leads to significant energy costs. Therefore, energy-efficient modulation schemes are being developed (for example, QPSK and QAM with low PAPR), as well as architectures with analog-digital hybrid arrays (hybrid beamforming), which reduce the power consumption of base stations and user devices.

Advantages and limitations of millimeter and terahertz waves

The use of millimeter-wave (30-300 GHz) and terahertz (>300 GHz) bands in new-generation mobile networks is due to a number of significant advantages. First of all, we are talking about a significant expansion of the available frequency spectrum, which makes it possible to form channels with a width of hundreds of megahertz and even gigahertz. This provides the highest throughput-theoretically up to 1 Tbit / s - which makes it possible to transfer data in 3D holography format, implement "digital twins" and other resource-intensive services in real time.

In addition, due to its short wavelength, compact antennas and massive MIMO arrays can be used in the mmWave and THz bands. This contributes to high beam directivity and the implementation of spatial multiplexing, which in turn increases user density and spectral efficiency. Support for beamforming (directional beamforming) technologies ensures targeted signal transmission to the subscriber, reducing interference and improving the quality of service in conditions of high network load.

However, along with these advantages, there are also significant limitations that make it difficult to apply these frequencies on a large scale. The most significant factor is the high signal attenuation during propagation in the atmosphere, especially under the influence of rain, moisture and oxygen. Waves in this range have a low penetration capacity — the signal does not pass well through walls, foliage, and other physical barriers, which requires dense deployment of low-power base stations (small cells) and the use of assistive technologies such as intelligent reflective surfaces (IRS).

It is also worth noting the increased requirements for positioning and synchronization accuracy in mmWave/THz-based networks, which complicates the implementation of mobility and handover when moving the user. Energy efficiency at these frequencies is still a problem: the power consumption of transmitters and receivers increases due to the need to amplify the signal and process wide bands.

Millimeter-wave and terahertz technologies have significant potential to improve the performance of 5G and 6G mobile networks, but require a comprehensive approach to overcome physical and engineering constraints, including adaptive architectures, intelligent resource management, and innovative coverage schemes.

Architectural solutions: beamforming, MIMO, IRS and other technologies

For efficient use of millimeter and terahertz waves in 5G and 6G mobile networks, comprehensive architectural solutions have been developed and implemented to overcome the limitations of the high-frequency range. Key among them are beamforming, massive MIMO, and intelligent reflective surfaces (IRS) technologies.

Beamforming is a method of directional formation of radio waves using phased array antennas. This technology allows you to concentrate the signal energy in the direction of a specific user, significantly improving the quality and reliability of communication. Thanks to beamforming, interference with other devices is reduced and the effective coverage radius is increased, which is especially important when working in conditions of high user density and at short distances typical of the mmWave and THz bands.

Massive MIMO (Multiple Input Multiple Output) is a technology that uses a large number of antennas on a base station to simultaneously transmit and receive multiple data streams. In combination with beamforming, massive MIMO allows you to increase spectral efficiency and provide stable communication with many devices at the same time, which is a prerequisite for implementing the concepts of the "smart city" and the industrial Internet of Things (IIoT). In addition, massive MIMO helps reduce latency and improve network throughput.

Intelligent Reflecting Surfaces (IRS) are a relatively new technology that consists of thin panels with programmable elements that can change the phase and amplitude of the reflected signal. IRS allows you to dynamically redirect radio waves, avoiding obstacles and amplifying the signal in the desired directions. This is especially true when mmWave and THz signals are difficult to propagate, and the direct path may be blocked by buildings or other obstacles. Using the IRS helps improve coverage, reduce energy consumption, and improve communication reliability.

In addition to these technologies, the architecture of modern networks also includes methods of cooperative reception and transmission (Cooperative Communication), adaptive resource management, as well as the use of artificial intelligence and machine learning to optimize network parameters in real time. These approaches allow you to increase the efficiency of spectrum use, adapt to changing environmental conditions, and provide a high level of service quality.

Acombination of architectural solutions and innovative technologies forms the basis for the successful deployment and operation of a new generation of mobile networks that can use the potential of millimeter and terahertz bands to provide ultra-high data transfer rates, low latency, and mass device connectivity.

Real implementations of millimeter wave (mmWave) technologies in modern mobile networks

Millimeter wave technology (mmWave) plays an important role in the development of 5G mobile communications and is gradually beginning to lay the foundation for 6G networks. With its ability to deliver high throughput and ultra-low latency, mmWave is already being deployed in a number of countries, demonstrating both potential and existing technological challenges.

In the United States, Verizon began commercial deployment of mmWave networks using 28 GHz and 39 GHz frequencies in 2019. In New York and Chicago, the operator provides data transfer speeds of up to 10 Gbit / s with a latency of less than 1 ms within small cell coverage. By 2023, Verizon has installed more than 10,000 small cells in 50+ U.S. cities. AT&T uses mmWave to provide ultra-high-speed Internet in major sports arenas and business centers.

South Korean operator SK Telecom launched commercial mmWave networks at 28 GHz in 2020, covering areas of Seoul and Busan. Speeds reached 7-9 Gbps, and advanced massive MIMO and beamforming technologies were used to ensure a stable connection. Public investment totaled over $ 1 billion, which helped accelerate infrastructure development.

NTT Docomo in Japan develops specialized mmWave applications for industry and transportation, including wireless communication systems for factories and autonomous vehicles. As part of the Smart City project in Tokyo, solutions with data transmission up to 20 Gbit/s and delays of less than 0.5 ms are being tested, which provides opportunities for implementing 4D holography and remote control of robotics.

In Europe, EU countries coordinate the standardization of mmWave in the 26-28 GHz band through 3GPP and ETSI. In Germany, Deutsche Telekom is implementing pilot projects with small cell coverage in Berlin, providing data transfer speeds of up to 8 Gbit/s. In France, Orange and Bouygues Telecom are testing joint networks that combine mmWave with 4G and sub-6GHz 5G technologies to optimize coverage and bandwidth.

The analysis shows that the effective use of mmWave is associated with a high density of small cells, adaptive beamforming, and the use of intelligent reflective surfaces (IRS). Such architectures reduce the impact of physical barriers and allow you to increase the coverage area. The average range for small cells varies from 100 to 300 meters, which meets the requirements of modern megacities.

The current results of commercial implementation show a significant increase in bandwidth compared to traditional bands, but at the same time reveal problems with energy consumption and difficulties with user mobility when switching between cells. Hybrid architectures and machine learning algorithms for dynamic network resource management are actively explored to address these issues.

Conclusion

Millimeter waves (mmWave) and ultra-high frequency (THz) technologies represent a strategic direction for mobile communications development, paving the way for ultra-high-speed data transmission, minimal delays, and mass device connectivity. Thanks to their high bandwidth, narrow beam generation capabilities, and the use of compact antenna arrays, these technologies lay the foundation for 5G and, in the future, 6G networks.

However, the large-scale implementation of mmWave and THz communication is accompanied by a number of serious challenges: signal attenuation, limited penetration, high sensitivity to environmental conditions, and significant power consumption. To overcome these challenges, next — generation architectural solutions are being developed and implemented- beamforming, massive MIMO, intelligent reflective surfaces (IRS), and artificial intelligence-based algorithms that can dynamically adapt the network to changing conditions.

The analysis of international cases of mmWave implementation showed high efficiency of using the technology in conditions of dense urban development and specific scenarios (stadiums, business centers, industrial facilities). At the same time, the task of optimizing infrastructure costs and increasing the stability of the connection with user mobility remains urgent.

ДFurther development of millimeter and terahertz wave technologies requires a comprehensive approach that includes standardization, development of the component base, energy-efficient architectures, and integration of intelligent control systems. The implementation of these tasks will unlock the full potential of mmWave / THz communication in sixth-generation networks and create a sustainable digital environment of the future.

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