Image and Video Transmission in 5G/6G Networks: A Comprehensive Survey of Enabling Technologies, Challenges, and Future Directions

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1. Abstract

The exponential growth of data traffic, predominantly driven by high-resolution image and video content, poses significant challenges to current communication networks. The advent of 5G networks has introduced groundbreaking capabilities, yet the insatiable demand for ultra-high-definition (UHD), augmented reality (AR), virtual reality (VR), and holographic content necessitate looking beyond 5G towards 6G. This paper provides a comprehensive survey of the key technologies enabling efficient and reliable image and video transmission in 5G and the visionary landscape of 6G. We examine the role of enhanced Mobile Broadband (eMBB), millimeter-wave (mmWave) spectrum, massive MIMO, and network slicing in 5G for media delivery. Furthermore, we explore the potential of 6G technologies, including terahertz (THz) communication, intelligent reflective surfaces (IRS), integrated sensing and communication (ISAC), and artificial intelligence (AI)-native air interface, in revolutionizing multimedia services. The paper also discusses persistent challenges such as latency, bandwidth constraints, energy efficiency, and security. Finally, we outline future research directions for achieving seamless, immersive, and semantic-aware multimedia communication in the 6G era.

Keywords: 5G, 6G, Video Transmission, Image Transmission, eMBB, mmWave, Network Slicing, Terahertz (THz), Artificial Intelligence, Holographic Communication.

نقل الصور والفيديو في شبكات الجيل الخامس والسادس: دراسة شاملة للتقنيات الممكنة، التحديات، والتوجهات المستقبلية

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2. الملخص:

يشكل النمو المتسارع لحركة البيانات في شبكات الاتصالات، مدفوعًا بصورة رئيسية بالاعتماد المتزايد على المحتوى المرئي عالي الدقة(High-Resolution Images & Video) . هذا التنامي يفرض تحديات تقنية معقّدة على البنى التحتية للشبكات التقليدية. لقد مكّنت شبكات الجيل الخامس 5G من إدخال قدرات رائدة، إلا أن الطلب المستمر على تطبيقات المحتوى فائق الدقة(UHD) ، والواقع المعزّز(AR) ، والواقع الافتراضي(VR) ، إضافة إلى الأنظمة الهولوغرافية (Holographic Systems) ، يبرز الحاجة الملحّة إلى استكشاف آفاق شبكات الجيل السادس (6G).

تقدّم هذه الورقة البحثية دراسة شاملة للتقنيات الأساسية التي تُمكّن من نقل للصور والفيديو بكفاءة وموثوقية في شبكات الجيل الخامس، بالإضافة الى استعراض افق الجيل السادس. نركز بشكل خاص على دور النطاق العريض المتنقل المعزّز(eMBB) ، وتقنيات الموجات المليمترية (mmWave) ، والأنظمة الضخمة متعددة المداخل والمخارج(Massive MIMO) ، وآلية تقسيم الشبكات (Network Slicing) في تمكين نقل الوسائط المتعددة عبر 5G، كما نستعرض الإمكانات المتقدمة لتقنيات 6G ، بما في ذلك الاتصالات في نطاق التيرا هيرتز(THz Communications) ، والأسطح العاكسة الذكية (Intelligent Reflecting Surfaces - IRS)، والتكامل بين الاستشعار والاتصالات (Integrated Sensing and Communication - ISAC)، والواجهات الهوائية المعتمدة على الذكاء الاصطناعي (AI-Native Air Interface)، ودورها المحوري في إحداث نقلة نوعية في خدمات الوسائط المتعددة.

إضافةً إلى ذلك، تناقش الورقة أبرز التحديات التقنية المستمرة، والتي تشمل قضايا (Latency)، والقيود المفروضة على النطاق الترددي(Bandwidth Constraints) ، وكفاءة الطاقة(Energy Efficiency) ، ومتطلبات الأمان .(Security) وأخيرًا، نسلط الضوء على الاتجاهات البحثية المستقبلية اللازمة لبلوغ اتصالات وسائط متعددة عالية الكفاءة، سلسة، غامرة، وواعية دلاليًا (Semantic-Aware) ضمن عصر شبكات الجيل السادس.

الكلمات المفتاحية: الجيل الخامس ، الجيل السادس ، نقل الصور، نقل الفيديو، النطاق العريض المتنقل المحسن، الموجات المليمترية، تقسيم الشبكات، تيرا هيرتز، الذكاء الاصطناعي، الاتصالات الهولوغرافية.

3. Introduction :

The proliferation of bandwidth-intensive applications, such as 4K/8K streaming, live broadcasting, cloud gaming, and immersive metaverse experiences, has made image and video traffic the dominant component of global internet traffic. Cisco's Visual Networking Index forecasts that by 2025, video will constitute over 82% of all internet traffic [1]. While 5G networks, with their enhanced Mobile Broadband (eMBB) pillar, have made significant strides in accommodating this demand, they are approaching their theoretical limits. The quest for truly immersive experiences like tactile internet, volumetric streaming, and real-time holography requires unprecedented performance metrics: terabits-per-second (Tbps) data rates, sub-millisecond latency, and near-perfect (99.99999%) reliability. This impending demand forms the catalyst for the development of 6G networks.

This paper aims to provide a comprehensive synthesis and analysis of the current state and future trajectory of image and video transmission technologies across 5G and 6G paradigms. The key contributions of this survey are:

1. A detailed analysis of 5G technologies (mmWave, massive MIMO, network slicing) specifically tailored for multimedia traffic.
2. An in-depth exploration of disruptive 6G technologies (THz, AI/ML, IRS, ISAC) and their transformative impact on video and image services.
3. A holistic discussion of cross-cutting challenges (latency, energy, security) and potential solutions.
4. Identification of promising future research directions for academia and industry.

The rest of the paper is organized as follows: Section 2 details 5G-enabling technologies. Section 3 explores the 6G vision. Section 4 discusses overarching challenges. Section 5 concludes the paper and outlines future research directions.

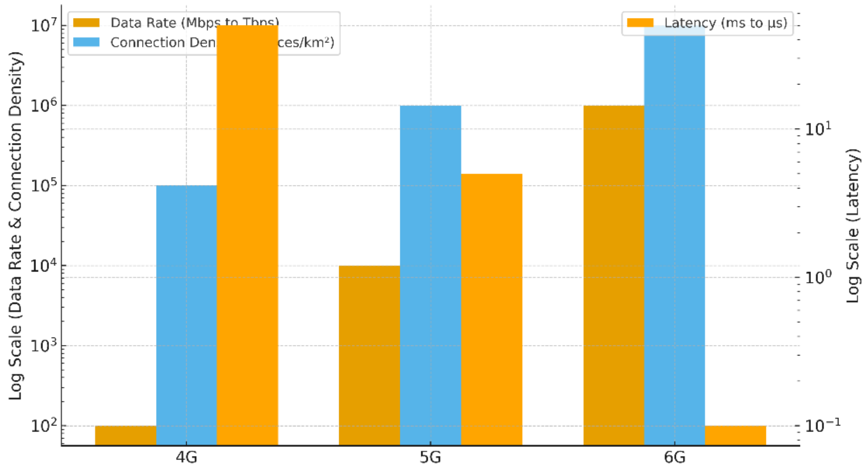

Figure 1 :Evolution of Network KPIs for Multimedia Applications (4G to 6G)

4. Transmission Technologies in 5G Networks:

5G has been a game-changer for multimedia services, primarily through several key technological advancements that work in concert to deliver high-quality, low-latency video experiences.

4.1. Enhanced Mobile Broadband (eMBB) and Millimeter-Wave (mmWave) Spectrum

The eMBB use case provides the foundational bandwidth boost for high-data-rate applications. It is fundamentally enabled by the exploitation of new spectrum bands, particularly the mmWave spectrum (24 GHz - 100 GHz). These high-frequency bands offer vast amounts of unused bandwidth, as shown in Table 1, which is crucial for achieving multi-gigabit-per-second data rates.

Table 1: Comparison of Spectrum Bands for Mobile Communication

Band Type	Frequency Range	Bandwidth Availability	Advantages	Disadvantages
Sub-6 GHz	< 6 GHz	Limited (e.g., 100s of MHz)	Good coverage, penetration	Lower data rates, congestion
mmWave	24 - 100 GHz	Very Wide (e.g., 100s of MHz - GHz)	Extremely high data rates	Short range, poor penetration

This allows 5G to practically support streaming of 4K (and potentially 8K) video content to mobile devices and fixed wireless access (FWA) customers, supporting bitrates often exceeding 100 Mbps per user [2].

4.2. Massive MIMO and Advanced Beamforming:

Multiple-Input Multiple-Output (MIMO) technology, scaled up to massive MIMO (with dozens or hundreds of antennas at the base station), significantly increases network capacity and spectral efficiency. By serving multiple users simultaneously on the same time-frequency resource (spatial multiplexing), massive MIMO drastically boosts the total throughput available for video traffic. Beamforming is the complementary technology that focuses radio signals directionally towards users instead of broadcasting indiscriminately. This results in stronger signal strength (higher Signal-to-Interference-Plus-Noise Ratio - SINR), higher throughput for video users, and better performance in crowded areas. Figure 2 illustrates the concept of beamforming versus traditional broadcasting.

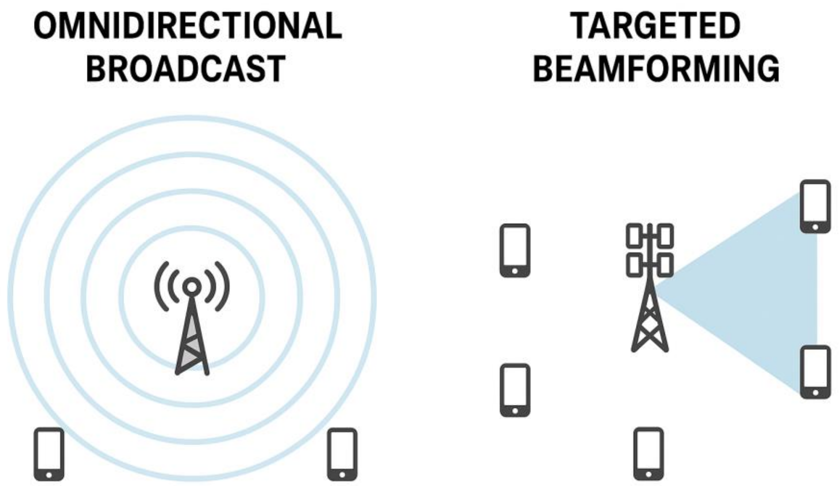

Figure 2: Omnidirectional Broadcast vs. Targeted Beamforming

4.3. Network Slicing for Quality of Experience (QoE) Network slicing is a transformative architectural paradigm that allows operators to create multiple virtual, end-to-end networks on a single physical infrastructure. Each slice is isolated and can be customized with specific performance characteristics. For multimedia transmission, this is a critical feature:

- A dedicated "Premium Video Slice" can be created for services like live sports broadcasting or cloud gaming (e.g., NVIDIA GeForce Now, Xbox Cloud Gaming). This slice would be configured to guarantee high bandwidth (>100 Mbps), ultra-low latency (<10 ms), and priority access, ensuring a consistent Quality of Experience (QoE) even during network congestion.
- A separate "Best-Effort Slice" could handle standard video streaming (e.g., YouTube, Netflix) where brief buffering is acceptable.

This ensures that critical, real-time video applications are never compromised by other network traffic [3].

5. Vision and Technologies in 6G Networks:

6G, expected to be standardized around 2030, is envisioned to bridge the physical and digital worlds seamlessly, creating a truly immersive "cyber-physical continuum." Its foundational technologies will fundamentally transform image and video transmission from a mere data pipe to an intelligent, context-aware service.

5.1. Terahertz (THz) Band Communication To support data rates required for holographic communication and volumetric video streaming (which can require tens of Tbps), 6G looks to the terahertz band (0.1-10 THz). This band offers orders of magnitude more spectrum than mmWave, as visualized in Figure 3.

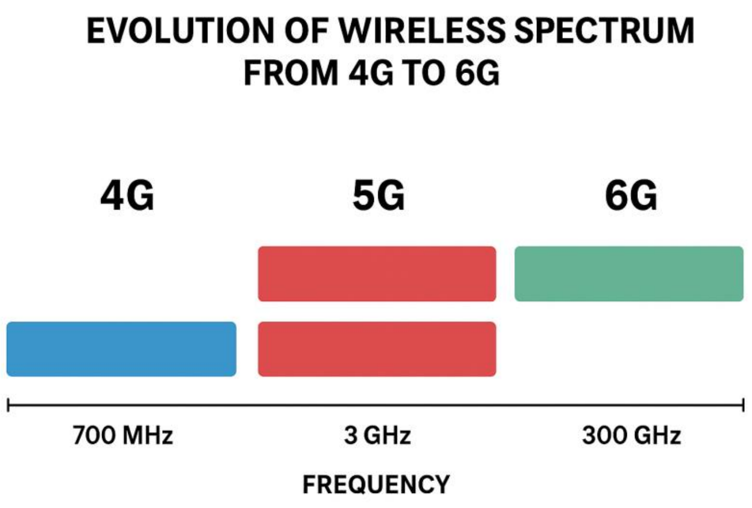

Figure 3: Evolution of Wireless Spectrum from 4G to 6G

The availability of such massive bandwidth could enable the transmission of uncompressed or lightly compressed raw video streams, effectively eliminating the need for lossy compression and its associated artifacts, thus delivering pristine visual quality [4]. However, THz communications face significant challenges, including high free-space path loss and molecular absorption, which limit their range to very short distances and require ultra-dense network deployments.

5.2. Artificial Intelligence and Machine Learning Deeply Embedded AI will be the central nervous system of 6G, moving beyond mere application-layer optimization to be deeply embedded in the core of the network architecture.

- AI-Native Air Interface: The physical layer itself will be adaptive and self-optimizing. AI algorithms will dynamically optimize modulation schemes, coding rates, and resource allocation in real-time based on predicted network conditions, traffic type, and QoE requirements. For instance, for a VR stream, the network could prioritize the ultra-low latency transmission of gyroscope and control signals over the slightly delayed transmission of a video frame to prevent motion sickness [5].
- Semantic and Goal-Oriented Communication: This represents a paradigm shift. Instead of transmitting every pixel of an image (syntactic communication), the network will be designed to understand the semantic meaning or the end-goal of the communication. For example, in a video surveillance application for autonomous driving, the goal might be "identify all pedestrians and vehicles within 100 meters." Instead of streaming the full HD video, the device would extract and transmit only this high-level semantic information (e.g., "pedestrian at coordinates x,y"), drastically reducing required bandwidth by several orders of magnitude [6].

5.3. Intelligent Reflecting Surfaces (IRS) IRS are artificial, programmable structures comprising thousands of passive metamaterial elements that can smartly reconfigure the propagation of incident electromagnetic waves. They can be deployed on building facades, walls, or indoors. For video transmission, an IRS can create highly efficient radio environments, effectively "steering" video data streams around obstacles and towards users, enhancing coverage and energy efficiency without the need for power-hungry signal processing, as illustrated in Figure 4 [7].

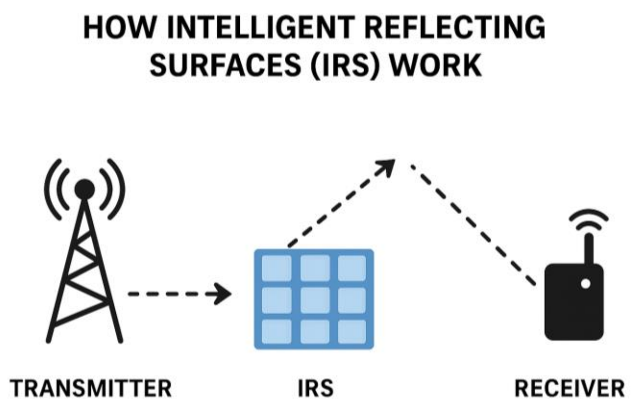

Figure 5: How Intelligent Reflecting Surfaces (IRS) Work

5.4. Integrated Sensing and Communication (ISAC) 6G infrastructure will likely perform sensing (like a radar) and communication simultaneously using the same hardware and spectral resources. For video transmission, this is a revolutionary concept. The network can sense the user's location, movement, orientation, and even the environment. This contextual information can be used to:

- Predictive Caching and Pre-fetching: The network can predict what video content a user will need next. In a 360° VR video, the network can sense which direction the user is looking and pre-load that specific video segment into a nearby edge server, drastically reducing perceived latency and stalling [8].
- Context-Aware Bitrate Adaptation: The system can adjust video quality based on sensed user activity. If the sensor detects the user is moving quickly on a train, it might temporarily switch to a more robust, lower-bitrate encoding to prevent buffering.

6. Challenges:

Despite the promising technologies, several critical and interconnected challenges persist across both 5G and 6G visions:

- Channel Characteristics: The high frequencies of mmWave and especially THz waves suffer from severe propagation loss, vulnerability to blockages (e.g., walls, rain, human hand), and atmospheric absorption. This limits their effective range and necessitates ultra-dense networks of small cells, raising deployment costs and complexity [4].

- Complexity and Energy Consumption: Processing signals for massive MIMO, running complex AI models for network optimization, and handling Tbps data streams require immense computational power. This poses a significant challenge for the energy efficiency and sustainability of future networks. Green communication designs are paramount [9].
- Security and Privacy: Semantic communication and pervasive sensing raise profound new privacy concerns. Transmitting extracted features or semantic meaning rather than raw data requires new encryption paradigms to prevent semantic-level eavesdropping and attacks. Furthermore, ISAC capabilities could be misused for unauthorized tracking and surveillance [10].
- Standardization and Interoperability: The convergence of communication, sensing, and AI necessitates global collaboration to develop new standards, protocols, and interfaces. Ensuring interoperability between equipment from different vendors and across different regions will be a monumental task.

- ***Table 2: Key Performance Indicators (KPIs) for 5G vs. 6G Multimedia Applications***

KPI	5G (eMBB)	6G (Immersive Multimedia)	Example Application
Peak Data Rate	20 Gbps	1 Tbps - 1 Pbps	Holographic Telepresence
User Experienced Data Rate	100 Mbps	1-10 Gbps	8K+ Streaming on Mobile
Latency	1-10 ms	< 0.1 ms (sub-millisecond)	Tactile VR/AR
Reliability	99.9%	99.99999%	Remote Surgery
Mobility Support	500 km/h	1000 km/h	HSI (High-Speed Internet) in Jets
Spectrum Efficiency	3x 4G	10-100x 5G	Overall Network Capacity
Energy Efficiency	10x 4G	100x 5G	Sustainable Network Operation

7. Conclusion and Future Directions:

The evolution from 5G to 6G represents a fundamental paradigm shift, moving beyond traditional communication to the seamless integration of communication, computation, and sensing. While 5G has established a robust foundation for high-quality video delivery, 6G is expected to enable truly immersive, context-aware, and highly efficient communication system.

This paper surveyed the key technologies driving this evolution. From the mmWave and network slicing of 5G to the THz, AI, and IRS technologies envisioned for 6G, the potential for revolutionizing image and video transmission is immense. However, significant challenges in hardware design, energy consumption, and security remain.

Future research must focus on several key directions to realize this vision:

1. Semantic Communication Theory: Developing new information theory frameworks and channel models for semantic and goal-oriented communication, moving beyond Shannon's classical paradigm.
2. Energy-Efficient Hardware: Designing novel, low-power transceivers and processors capable of operating at THz frequencies and handling massive AI workloads sustainably.
3. Integrated Sensing and Communication (ISAC) Co-Design: Creating advanced algorithms and protocols that allow sensing and communication functionalities to coexist and synergize efficiently without mutual interference.
4. Robust Security Protocols: Inventing new encryption and authentication mechanisms tailored for semantic data and pervasive sensing environments to ensure user privacy and trust.
5. Standardization and Collaboration: Fostering global, multi-disciplinary collaboration between industry and academia to drive early standardization efforts for 6G.

The realization of these research directions will be pivotal in unlocking the full potential of image and video transmission, ultimately paving the way for the immersive and intelligent applications of the next decade.

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