

Advancements in 360-Degree Virtual Reality Video Streaming: A Comprehensive Overview

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Abstract:- This paper presents a thorough examination of the recent advancements in 360-degree virtual reality (VR) video streaming technology, offering a comprehensive overview of its transformative impact on immersive digital experiences. The evolution of virtual reality is explored within the context of its rapid technological growth, setting the stage for an in-depth analysis of 360-degree video streaming. The underlying technologies, encompassing panoramic content capture, encoding, and efficient data transmission, are discussed in detail. Addressing challenges such as bandwidth constraints and latency issues, the paper highlights innovative solutions such as adaptive streaming techniques and compression algorithms. Applications across various industries, including entertainment, gaming, education, healthcare, and virtual tourism, are scrutinized, emphasizing the widespread influence of 360-degree VR video streaming. Ongoing research endeavors and potential future trends are also discussed, underlining the dynamic nature of this technology and its pivotal role in shaping the future of immersive digital content consumption. This comprehensive overview contributes to a deeper understanding of the current state and future prospects of 360-degree virtual reality video streaming.

Keywords:- 360-degree, virtual reality (VR), video streaming, panoramic content.

I. INTRODUCTION

The rapid evolution of virtual reality (VR) technology has transformed the way we perceive and interact with the digital world, ushering in a new era of immersive experiences. From its humble beginnings as a concept rooted in science fiction, VR has rapidly advanced, pushing the boundaries of technological innovation and human imagination.

In the early stages, VR was primarily associated with gaming and entertainment, offering users a simulated environment that transported them to fantastical realms. However, as technology progressed, the applications of VR expanded far beyond gaming, encompassing fields such as education, healthcare, architecture, and beyond.

The journey of VR technology can be traced through key milestones. The first wave saw rudimentary VR systems in the late 20th century, with basic headsets and limited graphics. These early attempts, while groundbreaking, were often clunky and lacked the sophistication needed for mainstream adoption.

The turning point came in the 2010s when major technological advancements, including improved graphics processing units (GPUs), motion-tracking sensors, and more sophisticated display technologies, propelled VR into the mainstream. Companies like Oculus, HTC, and Sony played pivotal roles in bringing consumer-grade VR headsets to the market, making immersive experiences more accessible.

As VR hardware became more refined, software developers capitalized on the technology's potential, creating a diverse range of applications. Educational institutions embraced VR as a tool for experiential learning, allowing students to explore historical events, scientific phenomena, and cultural landmarks in a virtual environment.

In healthcare, VR found applications in therapy, surgical training, and pain management. Architects and designers used VR to visualize and refine their creations before breaking ground, while industries such as automotive and aerospace utilized VR for prototyping and simulation.

The advent of standalone VR devices, untethered from external computers or consoles, further democratized access to immersive experiences. This development marked a significant step towards making VR an integral part of our daily lives, beyond specialized use cases.

Looking ahead, the rapid evolution of VR technology continues to be driven by advancements in artificial intelligence, haptic feedback, and the integration of augmented reality (AR) elements. The lines between the physical and virtual worlds blur as VR becomes more seamless, interactive, and integrated with our day-to-day activities.

In this dynamic landscape, the future of VR holds promises of even more captivating and inclusive experiences, shaping how we work, learn, socialize, and perceive the world around us. As VR technology evolves at an unprecedented pace, it not only redefines our digital interactions but also raises intriguing questions about the nature of reality itself.

In the realm of virtual reality (VR), the advent of 360-degree video streaming from traditional video streaming [11], [12], [13], [14], [15] has emerged as a transformative force, redefining the way we perceive and engage with digital content. This innovation goes beyond conventional forms of media consumption, offering a truly immersive experience that transcends traditional boundaries.

At its core, 360-degree virtual reality video streaming [1], [8], [34], [28] represents a groundbreaking fusion of technology and storytelling. Unlike traditional video formats that limit our perspective to a fixed frame, this evolution allows users to explore a complete panorama, enabling a sense of presence and agency within a virtual environment. As a result, the viewer is not merely a passive observer but an active participant, navigating through a seamless, all-encompassing visual narrative.

The significance of 360-degree VR video streaming extends across various domains, from entertainment and education to business and beyond. In the realm of entertainment, it has unlocked new dimensions for filmmakers and content creators, providing a tool to craft narratives that invite audiences to step into the heart of the story. Concerts, sports events, and travel documentaries, for instance, can now be experienced as if one were physically present, transcending the limitations of traditional flat screens.

In education, the potential of 360-degree VR video streaming is equally transformative. Students can embark on virtual field trips, exploring historical landmarks, natural wonders, or even microscopic realms with an unprecedented level of detail. This immersive approach enhances the learning process, making complex subjects more tangible and engaging.

Moreover, businesses are leveraging 360-degree VR video streaming for virtual tours, product demonstrations, and interactive presentations. Real estate professionals showcase properties in a more compelling manner, while companies use virtual reality to conduct remote meetings and training sessions, breaking down geographical barriers.

The technology behind 360-degree VR video streaming has matured rapidly, with advancements in camera technology, streaming capabilities, and VR headset design. These developments have made immersive experiences more accessible to a broader audience, contributing to the mainstream integration of VR technologies.

As we stand at the intersection of technology and storytelling, the significance of 360-degree virtual reality video streaming becomes clear – it has the power to redefine our digital experiences. By offering a more profound and participatory engagement with content, this technology not only transforms how we consume media but also lays the foundation for a new era in communication, education, and entertainment. In the unfolding narrative of virtual reality, 360-degree video streaming represents a pivotal chapter, promising a future where our digital encounters are not confined to screens but encompass the entirety of our perceptual reality.

This paper consists of seven sections. This comprehensive exploration begins by navigating the dynamic landscape of virtual reality (VR) technology, highlighting its rapid evolution. The introduction not only sets the stage for a deeper understanding of VR but also

underscores the paramount significance of 360-degree virtual reality video streaming in elevating immersive experiences. Delving into the fundamental concepts of virtual reality, the paper illuminates the basic principles and the profound impact that 360-degree video streaming has on reshaping the VR landscape. The subsequent section meticulously dissects the underlying technologies propelling 360-degree video streaming, from advanced camera systems facilitating panoramic content capture to intricate encoding and compression methods optimizing real-time data transmission. Addressing the challenges inherent in 360-degree VR video streaming, the paper identifies bandwidth constraints and latency issues, exploring viable solutions such as adaptive streaming techniques and compression algorithms. Venturing into diverse applications across industries, including entertainment, gaming, education, healthcare, and virtual tourism, the paper showcases the transformative influence of 360-degree VR video streaming on communication, training, and simulation. The exploration culminates in an analysis of ongoing innovations and research efforts dedicated to overcoming challenges and enhancing the overall user experience. The conclusion succinctly synthesizes key findings, emphasizing the transformative potential of 360-degree virtual reality video streaming and forecasting its continued evolution in reshaping the landscape of digital content consumption.

II. FUNDAMENTAL CONCEPTS OF VIRTUAL REALITY

A. *The basic principles and immersive qualities of virtual reality*

Virtual Reality (VR) [31] is a transformative technology that immerses users in computer-generated environments, creating a sensory-rich experience that can simulate real-world scenarios or transport individuals to entirely fictional realms. The immersive qualities of VR are rooted in fundamental concepts that shape its functionality and appeal.

➤ *Presence:*

At the heart of virtual reality is the concept of "presence" — the feeling of being physically present in a computer-generated environment. Achieving presence involves creating an illusion so convincing that users momentarily forget about the real world. This is often facilitated by high-quality graphics, responsive interactions, and an immersive audio-visual environment.

➤ *Immersive Environments:*

VR relies on the creation of immersive environments that engage multiple senses. This goes beyond traditional audio-visual experiences, extending to haptic feedback, spatial audio, and even olfactory sensations in some advanced setups. The goal is to replicate the richness of real-world perception.

➤ *Head Tracking:*

Head tracking is a fundamental aspect of VR interaction. As users move their heads, the VR system adjusts the perspective accordingly, allowing them to look

around and explore the virtual space. This real-time tracking enhances the sense of presence and contributes to a more natural and intuitive experience.

➤ *Stereoscopy and 3D Vision:*

Stereoscopy, or the presentation of slightly offset images to each eye, creates the illusion of depth perception. This mimics the way our eyes perceive the real world, contributing to a more realistic and immersive experience. 3D vision is crucial for creating a convincing sense of space and distance in virtual environments.

➤ *Interactivity:*

VR distinguishes itself by enabling user interactivity within the virtual space. Users can manipulate objects, navigate environments, and interact with virtual elements. This interaction is often facilitated through hand controllers, motion sensors, or other input devices, fostering a deeper sense of engagement.

➤ *Field of View (FOV):*

The field of view refers to the extent of the visual environment that a user can see at any given moment. A wider field of view contributes to a more immersive experience, reducing the perception of the edges of the virtual display and enhancing the feeling of being surrounded by the virtual world.

➤ *Latency:*

Low latency [5] is crucial in VR to maintain a seamless and responsive experience. Any delay between a user's movement and the corresponding adjustment in the virtual environment can lead to discomfort or motion sickness. Advanced VR systems strive to minimize latency to enhance the overall sense of presence.

➤ *Simulator Sickness Mitigation:*

Simulator sickness, akin to motion sickness, can occur in VR due to discrepancies between visual and vestibular (inner ear) cues. To mitigate this, VR systems often employ techniques like low-latency tracking, smooth locomotion, and providing reference points to help the brain reconcile conflicting signals.

Understanding these fundamental concepts provides insight into the mechanics of virtual reality and highlights the careful balance required to create truly immersive and comfortable experiences. As technology advances, these concepts continue to evolve, pushing the boundaries of what is possible in the realm of virtual reality.

B. The Transformative Impact of 360-Degree Video Streaming

Virtual Reality (VR) has undergone a paradigm shift with the advent of 360-degree video streaming, introducing a new dimension of immersion and interactivity to the virtual experience. This innovative approach fundamentally alters how users engage with digital content, offering a more encompassing and participatory form of storytelling. Here are key concepts that elucidate the transformative impact of 360-degree video streaming on the VR landscape:

➤ *Expanded Field of View (FOV):*

360-degree video streaming significantly expands the user's field of view, allowing them to explore an entire spherical panorama. Unlike traditional VR experiences confined to a fixed frame, users can look in any direction, fostering a heightened sense of presence and a more authentic feeling of being within the virtual environment.

➤ *User Agency and Interaction:*

The immersive quality of 360-degree video streaming lies in empowering users with agency. They are no longer passive observers but active participants in the unfolding narrative. Users can choose where to direct their attention, creating a personalized and interactive experience that aligns with the principles of presence and engagement central to VR.

➤ *Real-World Fidelity:*

360-degree video streaming strives for real-world fidelity, capturing scenes with a level of detail that mirrors our natural visual perception. This fidelity enhances the sense of immersion, making users feel as if they are truly present in the depicted environment. High-resolution imagery and seamless stitching contribute to a more convincing virtual experience.

➤ *Storytelling and Narrative Impact:*

The immersive nature of 360-degree video streaming redefines storytelling in the virtual realm. Creators can craft narratives that unfold all around the user, leveraging spatial audio and visual cues to guide attention. This dynamic storytelling approach enhances emotional engagement and makes narratives more compelling and memorable.

➤ *Accessibility and Mainstream Adoption:*

360-degree video streaming has played a pivotal role in making VR more accessible to a broader audience. Unlike traditional VR setups that require specialized equipment, 360-degree content can be experienced on a variety of devices, including smartphones and web browsers. This accessibility contributes to the mainstream adoption of VR technologies.

➤ *Applications Across Industries:*

The transformative impact of 360-degree video streaming extends beyond entertainment, permeating various industries. In fields such as journalism, education, tourism, and marketing, organizations leverage the immersive power of 360-degree content to offer unique and engaging experiences. This broad applicability showcases the versatility and impact of this VR concept.

➤ *Social VR Experiences:*

360-degree video streaming fosters social VR experiences [25], [16] by allowing users to share immersive content with others. Whether it's a virtual tour, live event, or interactive storytelling, the communal aspect adds a social layer to the VR experience, enhancing connectivity and shared exploration.

In conclusion, the integration of 360-degree video streaming into the VR landscape marks a transformative evolution. It aligns with the core principles of VR by enhancing presence, interactivity, and immersion, thereby reshaping how we consume and interact with digital content. As this technology continues to advance, it holds the promise of further blurring the lines between the virtual and real, offering users unparalleled levels of engagement and realism in their virtual experiences.

III. UNDERLYING TECHNOLOGIES

A. The Technological Backbone of 360-Degree Video Streaming

The immersive experience of 360-degree video streaming relies on a sophisticated interplay of technologies that work seamlessly to capture, process, and deliver panoramic content. Among the key components, camera systems play a pivotal role in enabling the creation of immersive environments. Let's delve into the underlying technologies that make 360-degree video streaming possible:

➤ 360-Degree Cameras:

At the forefront of 360-degree video streaming are specialized cameras designed to capture a complete spherical view [10]. These cameras feature multiple lenses strategically positioned to cover the entire field of view. Common configurations include dual fisheye lenses or multiple cameras arranged in an array. Notable examples include the Insta360, GoPro Fusion, and Ricoh Theta series.

➤ Fisheye Lenses:

Fisheye lenses [30] are a crucial optical component in 360-degree cameras. These lenses have an ultra-wide field of view, typically exceeding 180 degrees, allowing them to capture a broad panorama in a single frame. The distorted, hemispherical projection of fisheye lenses is later corrected during post-processing to produce a seamless and immersive spherical view.

➤ Image Stitching Software:

Capturing a 360-degree scene often involves stitching together images from multiple lenses or cameras to create a cohesive panorama. Image stitching software plays a vital role in this process, aligning and blending individual frames seamlessly. Advanced algorithms ensure that there are minimal artifacts, providing a smooth transition between different perspectives.

➤ Synchronization Mechanisms:

Achieving accurate synchronization among the lenses or cameras is critical for seamless stitching and a cohesive viewing experience. Synchronization mechanisms, such as precision timing circuits or software-based solutions, ensure that all components capture images at precisely the same moment, eliminating discrepancies that could disrupt the continuity of the panoramic view.

➤ High-Resolution Sensors:

To deliver immersive and detailed visuals, 360-degree cameras incorporate high-resolution sensors for each lens. The combined resolution of these sensors determines the overall clarity and sharpness of the final 360-degree video. Advancements in sensor technology contribute to improved image quality and a more realistic virtual experience.

➤ 360-Degree Livestreaming Technology:

Livestreaming in 360 degrees requires specialized technologies that enable real-time processing and delivery of panoramic content. This involves compression algorithms optimized for 360-degree video, adaptive streaming protocols, and efficient data transmission methods to ensure a smooth and low-latency experience for viewers.

➤ Ambisonic Audio Capture:

For a truly immersive experience, 360-degree video streaming often incorporates spatial audio, also known as ambisonic audio. Ambisonic microphones capture sound from all directions, allowing users to perceive audio cues that correspond to specific directions within the virtual environment. This enhances the sense of presence and realism.

➤ Playback Platforms and VR Headsets:

The delivery of 360-degree video to end-users requires compatible playback platforms. This includes dedicated VR platforms, web-based players, and apps that support 360-degree content. Users often experience this content using VR headsets, ranging from standalone devices to tethered systems connected to computers or gaming consoles.

The convergence of these technologies harmonizes to create the captivating and immersive experience of 360-degree video streaming. From the lens design and image capture to real-time processing and delivery, each component plays a crucial role in shaping the future of immersive storytelling and virtual exploration. As these technologies continue to evolve, the potential for richer, more lifelike 360-degree experiences is bound to expand, offering users unprecedented levels of engagement in the virtual realm.

B. Encoding and Compression for Efficient Real-Time Data Transmission

Efficient real-time data transmission is a critical aspect of delivering immersive experiences, particularly in the context of 360-degree video streaming in virtual reality (VR). The technologies that underpin this capability involve sophisticated encoding and compression methods. Let's explore the key components that enable seamless and efficient data transmission:

➤ Video Encoding Standards:

Video encoding [4] involves converting raw video data into a compressed format for efficient storage and transmission. Common video encoding standards include H.264 (AVC), H.265 (HEVC), and VP9. These standards employ advanced compression algorithms to reduce file sizes while preserving visual quality. H.265, in particular,

is known for its improved compression efficiency over its predecessor, H.264.

➤ *Adaptive Bitrate Streaming:*

Adaptive Bitrate Streaming (ABR) [11] is a technique that adjusts the quality of a video stream in real-time based on the viewer's internet connection and device capabilities. It involves encoding the video at multiple bitrates and resolutions, allowing the player to switch between them seamlessly during playback. This adaptive approach ensures a smooth viewing experience, even under varying network conditions.

➤ *Viewport-Adaptive Streaming:*

Viewport-Adaptive Streaming [7] is a refinement of ABR specifically designed for 360-degree video. Instead of adapting the entire video frame, this method focuses on adjusting the quality and resolution of the portion of the video that is currently in the viewer's line of sight. This approach optimizes bandwidth usage by prioritizing the visual elements relevant to the viewer's perspective.

➤ *Cube Mapping and Tiling:*

To efficiently encode 360-degree videos, cube mapping and tiling techniques [23] are employed. Cube mapping involves projecting the spherical video onto six faces of a cube, simplifying the representation of the video surface. Tiling divides the video into smaller regions, allowing for efficient encoding and streaming of only the visible portions of the video as the viewer navigates through the environment.

➤ *Spatial Video Compression:*

Spatial video compression techniques [6] focus on exploiting redundancies within a single frame. In the context of 360-degree video, where certain regions may be static or less detailed, spatial compression algorithms identify and represent these areas more efficiently. This reduces the overall data size without compromising visual quality.

➤ *Temporal Video Compression:*

Temporal compression [32] looks at redundancies across consecutive frames. Predictive coding and motion estimation are common techniques used in temporal compression. In scenarios where the environment changes gradually or exhibits repetitive patterns, temporal compression helps reduce the amount of data needed to represent the video sequence accurately.

➤ *Efficient Metadata Transmission:*

360-degree video often requires additional metadata to convey information about the spatial audio, camera orientation, and other interactive elements [27]. Efficient transmission of this metadata is crucial for a seamless VR experience. Compression algorithms are applied to metadata to ensure it is transmitted without significantly impacting the overall data stream.

➤ *Low-Latency Compression:*

In real-time applications, such as live streaming or interactive VR experiences, low-latency compression is essential [9], [21], [18][29]. Compression methods that

minimize encoding and decoding delays contribute to a more responsive and interactive user experience.

By leveraging these encoding and compression methods, content providers can deliver high-quality 360-degree video streaming experiences while optimizing bandwidth usage. These technologies play a crucial role in shaping the efficiency and feasibility of real-time data transmission, ensuring that users can enjoy immersive VR content without sacrificing visual fidelity or responsiveness. As advancements continue in this field, the potential for even more efficient and high-quality 360-degree video streaming experiences is on the horizon.

IV. CHALLENGES IN 360-DEGREE VR VIDEO STREAMING

A. *Challenges such as bandwidth constraints and latency issues*

While 360-degree virtual reality (VR) video streaming offers immersive experiences, several challenges persist, impacting the seamless delivery of content. Addressing these challenges is crucial for ensuring a high-quality and enjoyable VR viewing experience. Here are some key challenges in 360-degree VR video streaming:

➤ *Bandwidth Constraints:*

Streaming high-quality 360-degree videos demands substantial bandwidth due to the sheer volume of data required to transmit panoramic content. Users with slower internet connections may experience buffering, lower resolutions, or longer loading times. Optimizing compression techniques and employing adaptive bitrate streaming can mitigate bandwidth constraints to some extent.

➤ *Latency Issues:*

Latency, or the delay between user input and the corresponding action in the VR environment, poses a significant challenge. High latency can lead to motion sickness and a less immersive experience. Achieving low-latency streaming is essential, especially in interactive VR applications. This requires efficient encoding, fast data transmission, and responsive rendering on the user's device.

➤ *Device Compatibility:*

The wide array of VR devices available introduces compatibility challenges. Different VR headsets, smartphones, and web browsers may have varying capabilities and requirements for rendering 360-degree content. Content creators must optimize their videos for a diverse range of devices to ensure a consistent and high-quality experience across platforms.

➤ *Viewing Hardware Limitations:*

VR headsets [26] vary in terms of display resolution, refresh rates, and processing power. Designing 360-degree content that performs well on entry-level headsets while still leveraging the capabilities of high-end devices is a balancing act. Ensuring content remains visually engaging across a spectrum of VR hardware is a persistent challenge.

➤ *Heat and Battery Concerns:*

Extended VR sessions, particularly on mobile devices, can lead to increased heat generation and accelerated battery drain. Balancing immersive content with the need for energy efficiency poses a challenge for both content creators and hardware manufacturers. Optimizing content delivery to minimize resource-intensive processes can help mitigate these concerns.

➤ *Motion Sickness and VR Comfort:*

Some users may experience motion sickness or discomfort when viewing 360-degree content, especially during rapid movements or sudden transitions [24], [2]. Minimizing motion-to-photon latency, refining camera movements in content creation, and providing comfort settings for users can help reduce the likelihood of discomfort.

➤ *Content Creation Complexity:*

Producing high-quality 360-degree content requires specialized equipment, expertise, and often intricate post-production processes. Stitching together footage from multiple lenses and ensuring a seamless viewing experience demands a level of complexity beyond traditional video production. Streamlining workflows and improving accessibility to tools can address this challenge.

➤ *Interactive Elements and User Engagement:*

Enhancing user engagement in 360-degree VR experiences involves incorporating interactive elements within the content. However, integrating such features can be challenging due to limitations in current interactive technologies and the need for standardized frameworks. Developing user-friendly and universally applicable interactive features remains an ongoing challenge.

➤ *Metadata Handling:*

Efficient transmission and processing of metadata, including spatial audio cues, interactive elements, and additional contextual information, are vital for a comprehensive 360-degree VR experience. Challenges arise in standardizing metadata formats and ensuring compatibility across various platforms and devices.

As the field of 360-degree VR video streaming continues to evolve, overcoming these challenges requires collaborative efforts from content creators, hardware manufacturers, and streaming platform developers. Technological advancements, industry standards, and user feedback will play key roles in addressing these challenges and shaping the future of immersive virtual reality experiences.

B. Solutions to Challenges in 360-Degree VR Video Streaming

Addressing the challenges in 360-degree virtual reality (VR) video streaming requires a combination of innovative technologies and strategic approaches. Here are some solutions, including adaptive streaming techniques and compression algorithms, aimed at improving the overall VR viewing experience:

➤ *Adaptive Bitrate Streaming (ABR):*

- **Solution:** Implementing adaptive bitrate streaming allows the streaming platform to dynamically adjust the quality of the video based on the viewer's network conditions. This ensures a smooth viewing experience, mitigating the impact of bandwidth constraints. ABR enables users to enjoy content at the highest quality their network can support, reducing buffering and load times.

➤ *Viewport-Adaptive Streaming:*

- **Solution:** Viewport-adaptive streaming optimizes bandwidth usage by focusing on delivering the highest quality to the portion of the video currently in the viewer's line of sight. By dynamically adjusting the video quality based on the viewer's perspective, this technique conserves resources and enhances the overall efficiency of 360-degree VR video streaming.

➤ *Advanced Video Compression Standards:*

- **Solution:** Utilizing advanced video compression standards such as H.265 (HEVC) and VP9 can significantly reduce file sizes while maintaining visual quality. These standards offer improved compression efficiency over their predecessors, enabling more efficient data transmission for 360-degree content. The use of these standards aids in overcoming bandwidth constraints.

➤ *Cube Mapping and Tiling Techniques:*

- **Solution:** Cube mapping and tiling techniques optimize the encoding and streaming of 360-degree videos. By projecting the spherical video onto cube faces and dividing the content into smaller tiles, these methods enable more efficient data transmission. This approach minimizes the amount of redundant data transmitted, contributing to a smoother streaming experience.

➤ *Low-Latency Compression:*

- **Solution:** Employing low-latency compression algorithms is crucial for reducing the delay between user input and the corresponding action in the VR environment. Minimizing latency enhances the overall responsiveness and interactivity of 360-degree VR video streaming. This is particularly important for live events and interactive applications.

➤ *Efficient Metadata Transmission:*

- **Solution:** Efficient handling of metadata, including spatial audio cues and interactive elements, involves using compression algorithms specifically designed for metadata. Optimizing the transmission of metadata ensures that additional information is delivered seamlessly, enhancing the overall immersive experience without significantly increasing the data payload.

➤ *Device-Specific Optimization:*

- **Solution:** Tailoring 360-degree content for different VR devices involves optimizing resolution, frame rates, and encoding settings to match the capabilities of each device. This device-specific optimization ensures that users across a range of VR hardware experience

consistent and high-quality content without straining device resources.

➤ *Enhanced Content Creation Tools:*

- **Solution:** Simplifying and enhancing content creation tools for 360-degree VR videos can lower the barrier for creators. Streamlined workflows, intuitive stitching tools, and improved post-production processes contribute to the creation of high-quality content more efficiently, fostering a wider range of creators in the VR space.

➤ *Standardization of Metadata Formats:*

- **Solution:** Standardizing metadata formats facilitates interoperability across platforms and devices. Establishing industry-wide standards for metadata ensures that content creators can reliably include additional information in their 360-degree videos, leading to a more consistent and predictable user experience.

By integrating these solutions into the ecosystem of 360-degree VR video streaming, content providers, platform developers, and hardware manufacturers can collectively enhance the accessibility, quality, and overall user satisfaction with immersive virtual reality experiences. As technology continues to advance, these solutions will play a vital role in shaping the future of 360-degree VR content delivery.

V. APPLICATIONS IN VARIOUS INDUSTRIES

A. Diverse Applications Across Industries

The versatility of 360-degree virtual reality (VR) video streaming has propelled its adoption across various industries, transforming the way we experience and interact with digital content [22], [20], [19]. Here's an exploration of its diverse applications in entertainment, gaming, education, healthcare, and virtual tourism:

➤ *Entertainment:*

- **Immersive Films and Documentaries:** Filmmakers leverage 360-degree VR video streaming to create immersive films and documentaries, allowing viewers to explore narratives from every angle.
- **Live Events and Concerts:** Virtual attendance at live events and concerts becomes possible, providing an engaging and interactive experience for audiences globally.
- **Virtual Theme Park Rides:** Theme parks use 360-degree VR to recreate rides and attractions, offering a preview or simulation of the experience.

➤ *Gaming:*

- **Immersive Gameplay:** 360-degree VR enhances gaming by immersing players in virtual worlds, enabling them to explore environments in all directions and interact with in-game elements more naturally.
- **Virtual Arcades:** VR arcades leverage 360-degree video streaming to offer a wide range of immersive gaming experiences, from simulations to interactive storytelling.

➤ *Education:*

- **Virtual Field Trips:** Educational institutions use 360-degree VR to provide virtual field trips, enabling students to explore historical sites, natural wonders, and cultural landmarks.
- **Medical Training Simulations:** Healthcare education benefits from VR by offering realistic medical training simulations, allowing students to practice procedures in a virtual environment.

➤ *Healthcare:*

- **Therapy and Rehabilitation:** 360-degree VR video streaming supports therapeutic interventions and rehabilitation by creating immersive environments that aid in physical and psychological recovery.
- **Medical Training and Surgery Simulations:** Healthcare professionals use VR for realistic medical training, including surgical simulations and procedural rehearsals.

➤ *Virtual Tourism:*

- **Destination Previews:** Travel agencies and tourism boards leverage 360-degree VR to provide virtual previews of destinations, allowing potential travelers to explore and experience locations before making decisions.
- **Cultural and Historical Exploration:** Virtual tourism enables users to virtually visit museums, historical sites, and cultural landmarks, fostering a sense of exploration and discovery.

➤ *Real Estate:*

- **Virtual Property Tours:** Real estate professionals utilize 360-degree VR video streaming to create virtual property tours, allowing potential buyers or tenants to explore homes and commercial spaces remotely.
- **Architectural Visualization:** Architects and designers use VR to visualize and present architectural designs, providing clients with immersive walkthroughs of proposed structures.

➤ *Training and Simulation:*

- **Corporate Training:** Businesses use VR for employee training, creating realistic simulations for scenarios such as customer interactions, emergency procedures, and workplace safety.
- **Military and Defense Training:** The military employs VR for realistic training simulations, allowing personnel to practice in virtual environments before engaging in real-world situations.

➤ *Retail and Marketing:*

- **Virtual Shopping:** Retailers use 360-degree VR to create virtual shopping experiences, allowing customers to explore products and make informed purchasing decisions.
- **Branded Content and Advertising:** Marketers leverage immersive 360-degree videos for advertising campaigns and branded content, providing a more engaging and memorable experience for consumers.

The applications of 360-degree VR video streaming continue to evolve as technology advances and industries discover new ways to leverage immersive experiences. From entertainment and education to healthcare and beyond, the immersive and interactive nature of 360-degree VR is reshaping how we engage with digital content across diverse sectors.

B. Transformative Impact of 360-Degree VR Video Streaming on Communication, Training, and Simulation Across Industries

360-degree virtual reality (VR) video streaming has proven to be a game-changer in various industries, introducing transformative possibilities in communication, training, and simulation. Here's a closer look at its impact on these key aspects:

➤ *Communication:*

- **Virtual Meetings and Conferencing:** In the realm of business, 360-degree VR facilitates virtual meetings and conferences that transcend the limitations of traditional video calls. Participants can feel more present in a shared virtual space, fostering a sense of collaboration and connection.
- **Immersive Presentations:** Professionals use 360-degree VR to create immersive presentations, allowing them to showcase products, projects, or ideas in a more engaging and memorable manner. This technology adds a new dimension to storytelling and communication strategies.

➤ *Training and Development:*

- **Hands-On Skill Training:** Industries such as manufacturing, aviation, and maintenance benefit from 360-degree VR training modules. Employees can undergo hands-on skill training in a virtual environment, simulating real-world scenarios without the associated risks.
- **Emergency Response Training:** First responders, including firefighters and paramedics, use VR simulations for emergency response training. These simulations provide a realistic and controlled environment to practice crisis management and decision-making skills.
- **Soft Skills Training:** Beyond technical skills, 360-degree VR is employed for soft skills training. It allows individuals to practice communication, leadership, and interpersonal skills in simulated scenarios, enhancing their professional development.

➤ *Simulation:*

- **Medical Simulations:** Healthcare professionals engage in medical simulations using 360-degree VR to practice surgeries, medical procedures, and patient care. This technology provides a safe and controlled environment for honing skills and improving patient outcomes.
- **Military and Defense Simulations:** The military employs 360-degree VR for realistic training simulations, allowing personnel to simulate complex scenarios, mission planning, and tactical exercises. This enhances preparedness and decision-making in real-world situations.

- **Manufacturing and Engineering:** In manufacturing and engineering, VR simulations aid in product design, prototyping, and assembly line planning. Engineers and designers can visualize and interact with 3D models in a 360-degree space, improving the efficiency of the development process.

➤ *Remote Collaboration:*

- **Global Team Collaboration:** In a globalized workforce, 360-degree VR facilitates remote collaboration. Team members from different locations can feel as though they are working together in the same physical space, fostering a more connected and cohesive team dynamic.
- **Cross-Functional Collaboration:** Cross-functional teams benefit from 360-degree VR collaboration tools, allowing members from diverse disciplines to work together in a shared virtual environment. This is particularly valuable in fields such as architecture, design, and product development.

➤ *Crisis Management and Disaster Preparedness:*

- **Emergency Response Planning:** Governments and organizations use 360-degree VR for emergency response planning and disaster preparedness. Simulations of natural disasters or crises help train personnel, test protocols, and improve overall readiness.
- **Evacuation Drills:** In sectors such as education and hospitality, 360-degree VR enables realistic evacuation drills. Users can experience emergency scenarios, improving their understanding of evacuation procedures and response protocols.

The transformative impact of 360-degree VR video streaming on communication, training, and simulation is evident in its ability to create immersive and interactive experiences. By bridging geographical gaps, providing realistic training environments, and enhancing collaboration, this technology is reshaping the way industries approach communication, learning, and preparedness for various challenges.

VI. INNOVATIONS AND SOLUTIONS

A. Innovations and Solutions in 360-Degree VR Video Streaming:

Ongoing research and development efforts are continuously pushing the boundaries of 360-degree virtual reality (VR) video streaming, aiming to address existing challenges and enhance the overall user experience. Several innovations and solutions are being explored across different aspects of technology and content delivery. Here's a glimpse into these ongoing efforts:

B. Next-Generation Compression Algorithms:

- **Innovation:** Researchers are developing and refining compression algorithms that go beyond current standards, aiming to strike an optimal balance between high visual quality and reduced bandwidth requirements. Newer codecs are being explored to further improve the efficiency of 360-degree video

streaming, allowing for higher resolutions and smoother playback.

C. *Light Field Technology:*

- **Innovation:** Light field technology captures not only the intensity of light but also its direction, enabling more realistic and immersive experiences. This innovation has the potential to significantly enhance the sense of depth and realism in 360-degree VR content, providing users with a more natural viewing experience.

D. *Real-Time Content Adaptation:*

- **Innovation:** Advancements in real-time content adaptation algorithms are underway to dynamically adjust the streaming quality based on a user's changing viewing conditions. This includes factors such as network bandwidth fluctuations, device capabilities, and even user preferences, ensuring a consistently optimal viewing experience.

E. *6DoF (Six Degrees of Freedom) Experiences:*

- **Innovation:** Integrating 6DoF capabilities into 360-degree VR experiences allows users to move freely within the virtual environment, adding an extra layer of immersion. Ongoing efforts focus on developing more sophisticated tracking systems and responsive user interfaces to enable natural and intuitive interactions in 360-degree spaces.

F. *Interactive and Social VR Experiences:*

- **Innovation:** The evolution of interactive and social VR experiences involves creating more engaging and collaborative virtual spaces. Ongoing research explores ways to integrate interactive elements seamlessly, allowing users to interact with objects and other users in shared virtual environments, enhancing the social aspect of the VR experience.

G. *Haptic Feedback Integration:*

- **Innovation:** Integrating haptic feedback technologies into VR devices enhances the tactile experience, providing users with a sense of touch within the virtual environment. Ongoing efforts focus on developing more advanced haptic feedback systems that simulate different textures, pressures, and sensations, further blurring the line between the physical and virtual worlds.

H. *AI-Enhanced Content Creation:*

- **Innovation:** Artificial intelligence (AI) is being harnessed to streamline and enhance the content creation process for 360-degree VR videos. AI algorithms are used for automated stitching, object recognition, and even predictive analytics to optimize the overall production workflow and reduce the complexity of creating immersive content.

I. *Standardization and Interoperability:*

- **Solution:** Efforts to establish industry-wide standards and protocols for 360-degree VR video streaming aim to improve interoperability across devices and platforms. Standardization helps create a more

consistent user experience and facilitates the widespread adoption of VR technologies.

J. *Edge Computing for Low-Latency Streaming:*

- **Solution:** Leveraging edge computing infrastructure helps minimize latency in VR streaming by processing data closer to the end-user [8]. This approach reduces the time it takes for data to travel from the server to the VR headset, resulting in a more responsive and immersive experience, particularly crucial for real-time applications.

K. *Blockchain for Content Distribution:*

- **Solution:** Blockchain technology [17], [3] is being explored for secure and decentralized content distribution in VR ecosystems. By utilizing blockchain for content delivery and management, issues related to copyright protection, content ownership, and secure transactions can be addressed, ensuring a more transparent and equitable content distribution system.

These ongoing innovations and solutions in 360-degree VR video streaming signify a dynamic landscape where researchers and developers are committed to overcoming challenges and pushing the boundaries of what is possible in immersive content delivery. As these efforts progress, the future promises increasingly compelling and accessible virtual reality experiences.

The landscape of 360-degree virtual reality (VR) video streaming is continually evolving, driven by ongoing innovations and a pursuit of enhanced user experiences. Here are some innovative solutions and potential future trends that could shape the trajectory of 360-degree VR video streaming:

L. *Lightweight Compression for High-Quality Streaming:*

- **Innovation:** Researchers are focusing on developing lightweight compression algorithms that maintain high-quality visuals while minimizing the computational resources required for decoding. This can lead to more efficient streaming, reducing the burden on devices and networks.

M. *Holodeck-like Environments with Spatial Computing:*

- **Future Trend:** Advancements in spatial computing technologies, including improved sensors and gesture recognition, could contribute to the creation of holodeck-like environments. Users might interact with 360-degree VR content in more natural ways, using hand gestures and body movements for a fully immersive experience.

N. *AI-Driven Personalization and Adaptive Storytelling:*

- **Future Trend:** AI algorithms could play a significant role in personalizing 360-degree VR content based on individual preferences and interactions. Adaptive storytelling, where the narrative dynamically adjusts based on user choices and behaviors, could create highly engaging and customized experiences.

O. Photorealistic VR Environments:

- **Future Trend:** Continued advancements in graphics rendering, texture mapping, and lighting techniques may lead to the creation of photorealistic VR environments. The goal is to simulate the real world with such accuracy that users have difficulty distinguishing between virtual and reality.

P. Multi-Sensory Experiences with Haptic Feedback:

- **Innovation:** Haptic feedback technologies are evolving to provide users with a more immersive multi-sensory experience. Future trends may include the integration of advanced haptic feedback systems that simulate sensations such as texture, temperature, and resistance, enhancing the overall realism of VR interactions.

Q. Blockchain for Decentralized Content Distribution:

- **Innovation:** Leveraging blockchain for decentralized content distribution could address issues related to piracy, copyright, and ownership in VR ecosystems. Blockchain-based systems may provide a secure and transparent framework for managing and distributing 360-degree VR content.

R. 5G and Edge Computing for Low-Latency Streaming:

- **Future Trend:** The rollout of 5G networks and the widespread adoption of edge computing can significantly reduce latency in 360-degree VR streaming. This will enable more responsive and seamless experiences, particularly in applications requiring real-time interaction and low-latency responsiveness.

S. Enhanced Social VR Experiences:

- **Future Trend:** Social VR experiences are expected to become more sophisticated, allowing users to interact with friends, colleagues, or even strangers in shared virtual spaces. Enhanced avatars, realistic facial expressions, and natural communication cues could make social VR interactions more immersive and lifelike.

T. Extended Reality (XR) Integration:

- **Future Trend:** Integration with extended reality (XR) technologies [35], including augmented reality (AR), may offer a seamless blend of virtual and real-world elements. Users could switch between VR and AR modes, allowing for a more versatile and context-aware experience.

U. Cloud-Based VR Streaming Services:

- **Future Trend:** Cloud-based VR streaming services are anticipated to become more prevalent, enabling users to access high-quality 360-degree VR content without the need for powerful local hardware. This approach could democratize VR experiences, making them more accessible to a broader audience.

V. Biometric Feedback Integration:

- **Future Trend:** Integrating biometric feedback, such as heart rate and pupil dilation, into VR experiences could enable systems to adapt in real-time based on user

physiological responses. This personalized approach could enhance the emotional impact and immersion in 360-degree VR content.

W. AI-Enhanced Content Creation and Real-Time Rendering:

- **Innovation:** AI-driven content creation tools may evolve to assist creators in generating realistic 360-degree VR environments more efficiently. Real-time rendering powered by AI could contribute to on-the-fly adjustments, optimizing visual quality based on user interactions and hardware capabilities.

These innovative solutions and potential future trends reflect the dynamic nature of the 360-degree VR video streaming landscape. As technology continues to advance, the convergence of these trends is likely to shape a new era of immersive experiences, expanding the possibilities and accessibility of virtual reality content.

VII. CONCLUSION

The exploration of 360-degree virtual reality (VR) video streaming reveals a dynamic and rapidly evolving landscape that is reshaping how we consume and interact with digital content. Key findings and insights from this exploration include:

A. Immersive Experiences Across Industries:

360-degree VR video streaming has found diverse applications across industries, including entertainment, gaming, education, healthcare, virtual tourism, real estate, and training. The immersive nature of 360-degree content enhances storytelling, learning experiences, and user engagement.

B. Challenges and Solutions:

Challenges in 360-degree VR video streaming, such as bandwidth constraints, latency issues, and device compatibility, have prompted the development of innovative solutions. Adaptive streaming techniques, advanced compression algorithms, and real-time content adaptation are addressing these challenges, ensuring a smoother and more responsive user experience.

C. Transformative Impact on Communication and Training:

The technology has a transformative impact on communication, enabling virtual meetings, immersive presentations, and global collaboration. In the realm of training, 360-degree VR is revolutionizing skill development, emergency response training, and medical simulations, offering realistic and risk-free environments for hands-on learning.

D. Continuous Innovation:

Ongoing research and development efforts are driving continuous innovation in 360-degree VR video streaming. Lightweight compression algorithms, advancements in spatial computing, AI-driven personalization, and the integration of haptic feedback are among the innovations shaping the future of immersive content delivery.

E. Future Trends:

Anticipated future trends include the emergence of photorealistic VR environments, multi-sensory experiences with haptic feedback, decentralized content distribution through blockchain, and the integration of 5G and edge computing for low-latency streaming. Enhanced social VR experiences, extended reality (XR) integration, and cloud-based VR streaming services are also poised to play pivotal roles in the evolution of the technology.

F. Accessibility and Democratization:

Cloud-based streaming services and advancements in hardware are contributing to the accessibility and democratization of VR experiences. The potential for users to access high-quality content without requiring powerful local hardware aligns with a broader vision of making VR more inclusive.

In conclusion, 360-degree VR video streaming represents a transformative force in how we consume and interact with digital content. From entertainment to education, from training simulations to immersive communication, the technology's impact is far-reaching. As innovations continue to push boundaries, the future promises increasingly realistic, personalized, and accessible virtual reality experiences that will redefine the way we engage with the digital realm.

The exploration of 360-degree virtual reality (VR) video streaming underscores the transformative potential of this technology in reshaping the landscape of digital content consumption. The immersive and interactive nature of 360-degree VR experiences has propelled the technology into various industries, ushering in a new era of engagement and storytelling.

G. Key Takeaways:

➤ Immersive Evolution Across Industries:

360-degree VR video streaming has demonstrated its versatility and applicability across diverse industries, including entertainment, gaming, education, healthcare, real estate, and training. The technology is not only enhancing existing experiences but also creating entirely new possibilities for interaction and immersion.

➤ Challenges and Innovative Solutions:

The journey of 360-degree VR video streaming is marked by challenges such as bandwidth constraints, latency issues, and device compatibility. However, ongoing research and development efforts are yielding innovative solutions, including adaptive streaming techniques, advanced compression algorithms, and real-time content adaptation, ensuring a smoother and more responsive user experience.

➤ Revolutionizing Communication and Training:

The transformative impact of 360-degree VR extends to communication and training. Virtual meetings, immersive presentations, and realistic training simulations are reshaping how individuals collaborate, learn, and acquire new skills. The technology is facilitating global connections and providing realistic, risk-free environments for hands-on learning experiences.

➤ Continuous Innovation Driving the Future:

The landscape of 360-degree VR video streaming is characterized by continuous innovation. Emerging trends, such as lightweight compression algorithms, spatial computing advancements, AI-driven personalization, and haptic feedback integration, are indicative of a future where the technology becomes even more realistic, adaptive, and personalized.

➤ Democratization and Accessibility:

Cloud-based VR streaming services and advancements in hardware are contributing to the democratization and increased accessibility of VR experiences. The potential for users to access high-quality content without the need for powerful local hardware aligns with a vision of making VR more inclusive and available to a broader audience.

In conclusion, the journey of 360-degree VR video streaming is an exciting trajectory of transformation and evolution. As the technology continues to advance, it holds the promise of not only enhancing our current digital experiences but also opening doors to entirely new realms of creativity, communication, and exploration. The continued evolution of 360-degree VR video streaming signals a future where the boundaries between the physical and virtual worlds blur, offering users unparalleled opportunities for immersive and personalized digital content consumption.

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