



Edge Computing in Gaming

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Abstract

The game industry has transformed from localized, hardware-dependent experiences to vast, globally interconnected digital ecosystems. This transition has placed an unprecedented strain on network infrastructures. In competitive multiplayer environments, even a delay of a few milliseconds can determine the outcome of a match, making latency the primary challenge for modern gamers. Historically, cloud computing has provided the scalability needed to host massive multiplayer online games. However, centralized data centers are limited by the physical distance that data must travel to reach the user. As the demand for real-time responsiveness and high-quality graphics continues to grow, the industry is increasingly adopting edge computing. This distributed computing approach aims to bring computation and data storage closer to the data sources. Edge computing is a networking philosophy and a distributed IT architecture focused on positioning computing power as near to the source of data generation as possible. This paper explores the fundamentals of edge computing and its critical applications within the gaming industry.

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1. Introduction

Gaming has evolved from localized console and PC experiences into a massive, globally interconnected ecosystem. The gaming industry is undergoing a paradigm shift driven by the insatiable demand for high-fidelity, real-time interactive experiences. As cloud gaming become more prevalent, traditional centralized cloud computing architectures are exposing their limitations, primarily concerning latency, bandwidth consumption, and operational costs. Edge computing has emerged as the critical infrastructure solution to these challenges. By decentralizing data processing and bringing computational resources closer to the end-user, edge computing minimizes latency, enhances scalability, and enables the next generation of gaming technologies. Edge computing is a distributed computing paradigm that brings computation and data storage closer to the location where it is needed—the “edge” of the network—rather than relying on a central server thousands of miles away. Figure 1 shows the symbol of edge computing ^[1].



Fig 1: The symbol of edge computing ^[1].

Edge computing marks a pivotal evolution from traditional, centralized cloud computing by decentralizing data processing and bringing it closer to the data source—users and their devices. In the gaming industry, edge computing involves deploying micro-data centers, server outposts, or leveraging mobile network infrastructure (such as 5G towers) to process game data locally. By decentralizing computation and moving processing power to the periphery of the network, edge computing solves the persistent challenges of latency, bandwidth constraints, and server scalability. From enabling the widespread adoption of cloud gaming and immersive VR experiences to ensuring the competitive integrity of global esports titles like Valorant, the edge is where the future of play is being rendered ^[2]. Edge computing is pivotal for gaming and streaming services because it significantly enhances user experience by reducing latency, improving performance, and increasing scalability.

2. Methodology

The study employed a qualitative research method in conjunction with a systematic literature review. The literature reviewed and adopted a practical and foundational approach, thoroughly examining latency as a critical metric, particularly for latency-sensitive applications such as interactive gaming. The research provided valuable insights into the architecture of edge computing and its major components. Additionally,

the study compared edge computing with cloud computing, analyzing their implementations and the infrastructure costs. The methodology also enabled an examination of the technologies involved, including edge servers, design considerations, computational power, memory, storage, and cloud servers in the gaming industry. To collect data, the researchers referenced multiple sources, including peer-reviewed scholarly journals and other relevant materials. This approach allowed for a comprehensive evaluation of edge computing concepts, technologies, and applications, as well as the associated implementation challenges and benefits.

3. The Concept of Edge Computing

The history of edge computing dates back to the 1990s with the introduction of content delivery networks. The concept was simple: place servers closer to end-user locations to enable faster transmission of cached images and videos. Edge computing was developed jointly by Microsoft and its academic collaborators. Today, an increasing number of services are shifting from the cloud to the network edge. As data is generated closer to the edge, it becomes more efficient to process that data on-site. Keeping data closer to its users at the edge eliminates many issues associated with the public cloud model. Figure 2 illustrates how edge computing functions.

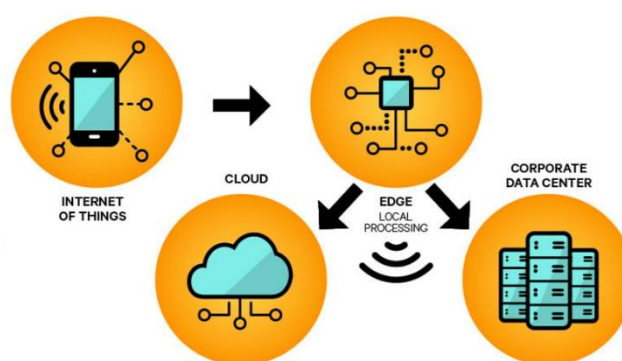


Fig 2: How edge computing works ^[3].

Edge computing allows data from Internet of Things (IoT) devices to be analyzed at the edge before being sent to the cloud. Edge computing, also known as edge cloud, is a computing paradigm that places significant computing and storage resources at the Internet's edge, in close physical proximity to mobile devices, sensors, end users, and IoT devices. This approach aims to bring the flexibility and openness of cloud-native infrastructure to local infrastructure. The key idea of "edge" is to process data near

its source. Terms such as "cloudlets," "micro data centers," and "fog" are used to describe these small, edge-located computing nodes or data centers. A cloudlet is a cluster of computers that is well connected to the Internet and can be viewed as a "data center in a box." The primary goal of a cloudlet is to extend remote data center cloud services close to end users. Physical proximity is central to edge computing, as it enhances latency, bandwidth, trust, and survivability. While the cloud has transformed how we handle data, the

next wave of this transformation will occur at the edge.^[4] A standard edge computing framework consists of three distinct levels^[5]:

- **The cloud:** Which manages the overall data storage and processing.
- **The edge:** Tasked with near-instantaneous data handling.
- **The device:** Responsible for initial detection and basic data processing.

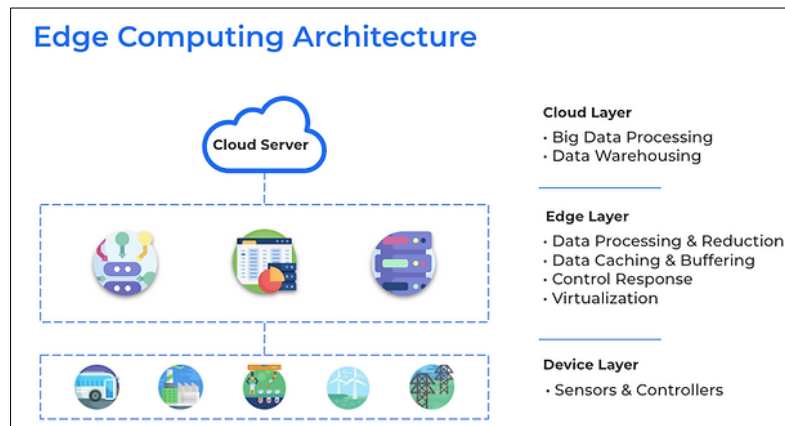


Fig 3: Edge computing architecture^[6].

These three levels are related in the edge computing architecture shown in Figure 3^[6]. Edge computing encompasses a wide range of technologies, including wireless sensor networks, distributed data storage, and augmented reality. This has become the core of the data center. The term “edge” refers to computing devices that sit closer to data sources, where the digital world meets the real world. These edge devices typically reside away from centralized cloud computing and are being built with increasing computing capabilities. Typical edge devices are smartphones, tablets, sensors, wearables, routers, switches, integrated access devices, multiplexers, smart TV, modern cars, and a variety of MAN/WAN access devices. Edge

computing enables analytics and data collection at the data source. Edge computing encompasses a spectrum of technologies, including cloudlets, fog computing, and mobile edge computing. A combination of edge and cloud computing is referred to as *fog computing* because it combines centralized and distributed computing resources into a single architecture. (Edge computing is a relatively new concept that should not be confused with fog computing.) It is practically unsafe and unnecessary to send such a large amount of data to the cloud. A comparison between cloud computing and edge computing is illustrated in Figure 4^[7].

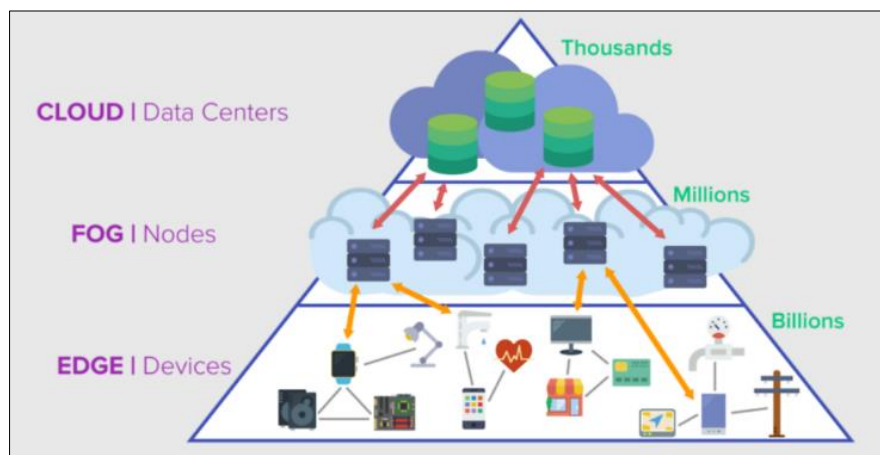
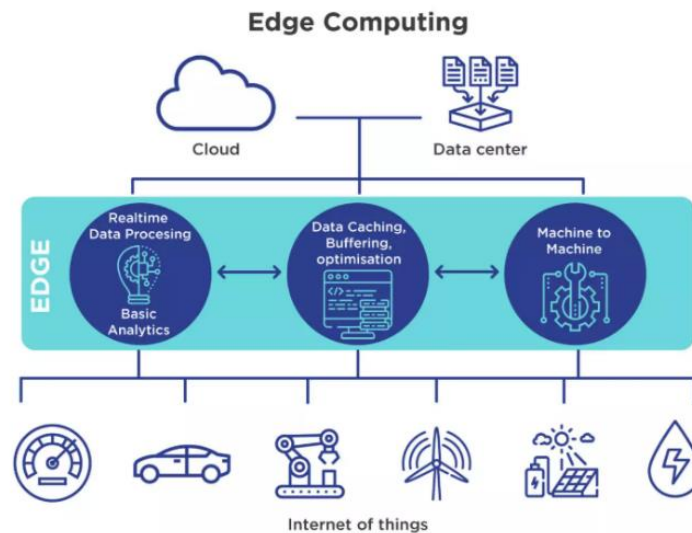
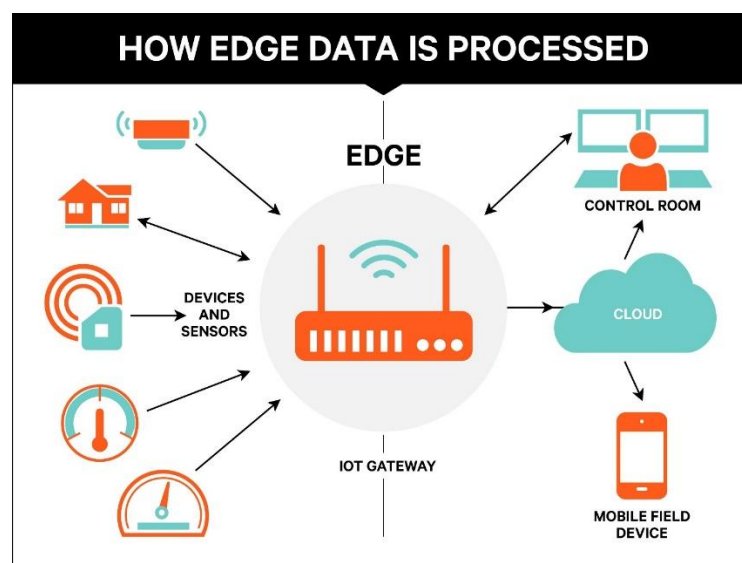


Fig 4: The relationship between cloud computing, edge computing, and fog computing^[7].

Compared to cloud computing, fog computing and edge computing have the following five advantages^[8]: (1) greater data transmission speed, (2) less dependence on limited bandwidths, (3) greater privacy and security, (4) greater control over data generated in foreign countries where laws

may limit use or permit unwanted governmental access, and (5) lower costs because more sensor-derived data are used locally, and less data are transmitted remotely. Figure 5 shows edge computing^[9], while Figure 6 shows how edge data is processed^[3].

Fig 5: Edge computing ^[9].Fig 6: How edge data is processed ^[3].

4. Edge Computing for Gaming

With over three billion gamers worldwide and an industry valuation exceeding \$200 billion, the demand for high-quality, immersive, and responsive gaming experiences has never been higher. The rapid evolution of the gaming industry, driven by the advent of multiplayer ecosystems, cloud gaming, and immersive technologies such as virtual reality (VR) and augmented reality (AR), has fundamentally altered the technical requirements of game delivery. Traditional cloud computing architectures, while scalable, often struggle to meet the ultra-low-latency and high-bandwidth demands of modern gaming. Edge computing has emerged as a transformative solution, decentralizing data processing by bringing it closer to end users ^[2]. It takes place at or near the physical location of either the user or the data source. By placing computing services closer to these locations (the “edge”), users benefit from faster, more reliable services while companies benefit from the flexibility of hybrid cloud computing. The “edge devices” process the

data at the point of use, sending only what is required to the hybrid cloud.

Gaming has come a long way since the first PC games and consoles like PlayStation and Super Nintendo in the 90s. The demands placed on games and live streams are increasing: players expect responses within seconds, smooth, pixel-free transmissions, and short loading times. Edge computing shifts processing closer to the user. This means that input is processed regionally rather than traveling long distances, even across continents. Especially in gaming, where every millisecond can mean the difference between winning and losing, edge computing is a valuable tool for significantly improving the gaming experience. This allows for stable, low-latency connections for live streams and interactive games, even when data traffic is routed through secure tunnels ^[10]. Figure 7 shows some game players ^[11], while Figure 8 represents how edge computing is revolutionizing gaming ^[12].



Fig 7: Some game players ^[11].

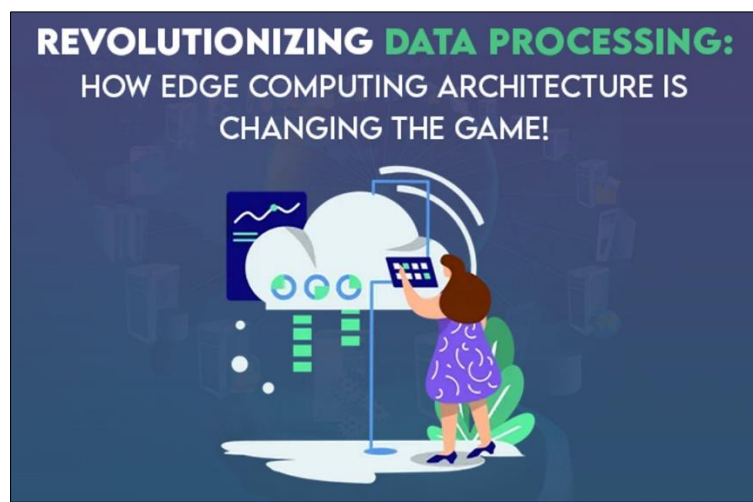


Fig 8: How edge computing is revolutionizing gaming ^[12].

5. Applications of Edge Computing in Gaming

Live streams benefit especially from the shorter loading times, fewer interruptions, and better coordinated transmissions enabled by edge computing. This applies to e-sports, gaming events, and live casino scenarios. Common applications of edge computing in gaming include the following ^[2,11]:

Cloud Gaming or gaming as a service (GaaS), allows users to stream high-end games to low-power devices, such as smartphones or smart TVs, by offloading the rendering process to remote servers. It allows users to play the newest-generation games requiring only an Internet connection and a screen (e.g., a TV screen, laptop, or mobile phone) by leveraging a cloud infrastructure. Games are located and processed in a cloud server, which streams the content to the end-user screen. Cloud gaming shifts the computational burden of rendering high-end graphics from the user's local hardware (e.g., a console or gaming PC) to remote servers. The game is then streamed to the user's device, much like a video on Netflix. However, unlike passive video streaming, cloud gaming requires real-time, bidirectional data transfer. Edge computing is the linchpin of viable cloud gaming. By rendering game environments on edge servers, the encoded video stream travels a much shorter distance to the user's screen, while the user's controller inputs are processed almost instantaneously. This allows players to experience AAA titles on low-powered devices, such as smartphones or smart TVs, democratizing access to high-fidelity gaming. Gaming edge computing is the solution for latency issues in cloud gaming.

Cloud networks must shift closer to users to ensure a flawless gaming experience.

Other applications include *Riot Games*. It is a premier example of edge computing in action is Riot Games' deployment infrastructure for its tactical shooter, *Valorant*. *Valorant* requires a very high-frequency simulation, with the server updating the game state up to 128 times per second. Riot Games, the developer behind massive eSports titles like *League of Legends* and *Valorant*, faced significant latency issues. For *Valorant*, a highly competitive tactical shooter, Riot aimed for a strict latency target of under 35 milliseconds. To achieve this, Riot partnered with Amazon Web Services (AWS) to deploy AWS Outposts—physical racks of AWS hardware installed in local data centers closer to the player base. This edge deployment allowed Riot to rapidly scale game servers and reduce latency by 10 to 20 milliseconds, effectively creating a level playing field.

Multiplayer Online Games, also known as multiplayer gaming, have evolved beyond traditional LAN setups and console duels. With billions of connected players globally, the demand for smoother, faster, and more immersive multiplayer experiences is skyrocketing. Multiplayer online games are a whole different story compared to single-player gaming experiences. With single-player cloud gaming, service providers must stream the game efficiently to a single user. On the other hand, multiplayer games require providers to effectively stream shared experiences to multiple users simultaneously. When gamers play a multiplayer FPS or co-op RPG, for example, they need to experience the same

content smoothly from a different perspective. Enhancing multiplayer online games with edge technology is now a realistic possibility. Gaming edge computing enables studios to introduce Web 3.0 features, such as blockchain-based microtransactions using cryptocurrency. The convergence of 5G and edge computing is now transforming the way multiplayer games are developed, hosted, and experienced.

However, in the e-sports industry, as in casual multiplayer online gaming, it can tremendously benefit from edge computing for gaming performance optimization. Games like League of Legends, Counterstrike, and Fortnite are just some of the leading e-sports titles. There are over 800 e-sports leagues around the globe. Latency issues during an e-sports event can create irreparable damage. An entire team can lose a vital tournament match due to a few milliseconds of lag. With centralized clouds, such issues are always a looming threat. Some countries, such as South Korea and the US, even recognize certain e-sports categories as official sports disciplines. E-sports are one of the most dynamic real-world applications of edge computing in game development. That is because edge computing can ensure super-low latency during massive e-sports competitions.

In edge computing, *immersive technologies* are widely used. Immersive technologies like augmented reality (AR) and virtual reality (VR) demand extremely high data streaming bandwidth and sub-20ms roundtrip latency to prevent “cybersickness”—a form of motion sickness caused by a disconnect between the user's physical movements and the visual feedback in the headset. Edge computing offloads the heavy rendering and AI processing from the AR/VR headset to nearby edge nodes. This not only ensures the ultra-low latency required for a comfortable experience but also allows headsets to become lighter, more mobile, and less expensive, as they require less built-in computing power.

6. Benefits and Challenges of Edge Computing in Gaming

The benefits of edge computing in the gaming industry include reduced latency, optimized bandwidth, enhanced multiplayer experiences, low response times, high bandwidth, lower data transmission costs, improved data protection, increased efficiency, enabling advanced technologies like AR/VR, and enhanced security and data privacy. Major players in the gaming industry are already realizing such benefits. Other benefits of edge computing in gaming include the following ^[2,10,13]:

Latency Reduction is an important factor in Cloud architectures, with metrics used to ensure efficiency and Quality of Service (QoS). Latency is the critical metric in online gaming. Unlike passive video streaming, gaming is inherently interactive and highly sensitive to time delays. The critical metric in online gaming is latency, often measured as “ping” or Time-to-First Token (TTFT) in AI contexts. Latency is the time it takes for a player's input (e.g., a button press or voice command) to travel to the server, be processed, and for the resulting action to be displayed on the screen. High latency results in “lag,” input delay, and desynchronization between players, leading to a frustrating user experience. Edge computing addresses this by processing data locally.

Immersive Experiences are also beneficial to gamers. Gamers value two things the most: top-quality immersive Gamer's and a smooth, enjoyable gameplay experience. One cannot work without the other. Edge has the potential to create technical conditions for more immersive live experiences: AR and VR

features, responsive games, and personalized streams. With lower latency, less buffering, and new interaction possibilities, edge brings better real-time experiences closer to the player, which gaming providers expect to result in higher player engagement.

Enhanced user experience is critical. The integration of edge computing into gaming and streaming services has led to a noticeable uplift in user experience, characterized by faster response times and enhanced content quality. For gamers, this means engaging in online multiplayer games with minimal lag, ensuring the playing field is as level as possible. The importance of this cannot be overstated, as the competitive integrity of online gaming hinges on the ability of all players to react and interact in real time without delay. Edge computing facilitates this by processing game data closer to the players, thereby reducing the time it takes for the game's server to receive and respond to player actions.

Security is a crucial consideration in edge computing, encompassing both devices and networks that must be adequately protected. Security and fair play are paramount in maintaining a healthy gaming community. Cheating ruins the experience for legitimate players and damages the game's reputation. Security in gaming encompasses not only responsible gaming and self-executing mechanisms but also data security. Despite the many advantages that edge computing offers, its decentralized nature increases the attack surface and makes devices potentially more vulnerable to security breaches, data theft, and disruptions. Distributed denial of service (DDoS) attacks are a persistent threat in the gaming industry, often used by malicious actors to disrupt servers or target specific players during competitive matches. Centralized servers are particularly vulnerable to being overwhelmed by massive traffic surges. Edge computing enhances security by distributing the attack surface. Edge nodes can act as localized scrubbing centers, filtering out malicious traffic before it reaches the core game servers. This distributed approach makes it significantly harder for attackers to bring down an entire game network.

Data Privacy is also a fundamental aspect of edge computing, which ensures confidentiality, integrity, availability, and lawful handling of data. Data privacy is another critical concern, especially with the implementation of strict global regulations like the GDPR. Edge computing allows for local data processing, meaning sensitive player data (such as biometric data from VR headsets or location data from mobile games) does not necessarily need to be transmitted across international borders to a central server. By keeping data localized, gaming companies can more easily comply with regional data sovereignty laws and reduce the risk of large-scale data breaches during transit. Ensuring data privacy across a vast network of edge servers requires robust encryption (both at rest and in transit) and sophisticated identity and access management protocols.

Bandwidth Efficiency for maximum data throughput is needed for gamers. Modern games, particularly AAA titles and cloud-streamed games, require immense amounts of data to be transmitted continuously. Streaming high-definition (4K or 8K) video feeds of gameplay consume significant bandwidth, which can lead to network congestion and buffering when routed through centralized cloud servers. Edge computing optimizes bandwidth utilization by processing and catching data locally. Instead of sending all game data back and forth to a central server, edge nodes handle the heavy lifting of rendering and state

synchronization. This local processing reduces the volume of data traversing the core network, alleviating congestion and lowering bandwidth costs for both service providers and end-users.

7. The Challenges of Edge Computing in Gaming

While the benefits are profound, the transition to edge computing in gaming is not without challenges. Challenges regarding infrastructure costs, security, interoperability, resource allocation, migration, and lack of standardization remain. Other challenges of edge computing in gaming include the following ^[2,10]:

Infrastructure costs were one of the constraints. The economic implications of edge computing in gaming are substantial. Deploying edge computing infrastructure necessitates substantial technical, logistical, and financial investment. Deploying thousands of edge nodes requires significant capital investment from telecom operators and cloud providers.

Resource Limitations are another challenge. Edge servers, by design, have less computational power, memory, and storage than centralized cloud servers. This limitation poses a significant challenge for gaming applications, particularly for rendering high-fidelity graphics or processing complex AI algorithms in real-time. It is expected that energy will become a crucial bottleneck for the deployment of this kind of system.

Other areas include computational constraints: Modern AAA titles and immersive AR/VR games require immense GPU processing power. While edge computing aims to offload this processing from the user's device, the edge servers themselves must be equipped with sufficient hardware. Balancing the cost of deploying high-end GPUs across thousands of edge locations against the performance benefits is a major economic hurdle for gaming companies. To mitigate these constraints, developers must optimize game code and employ lightweight algorithms that can run efficiently on edge hardware.

Synchronization is essential for edge computing. In multiplayer games, maintaining a consistent game state across all players is paramount. When players in the same match are connected to different edge servers, synchronizing the game state in real-time becomes highly complex. Any delay or discrepancy in synchronization can lead to "desync" issues, where players experience different versions of the game's reality, undermining the match's competitive integrity. Managing this distributed state requires sophisticated orchestration platforms and optimized networking protocols to ensure that all edge nodes remain perfectly synchronized.

One drawback of edge computing is a *lack of standardization*. A lack of standardization currently characterizes the edge computing ecosystem. A diverse landscape of hardware vendors, communication protocols, and software platforms complicates the seamless integration of edge devices. For gaming companies, this lack of interoperability means that deploying an edge infrastructure often involves navigating a fragmented market. Different edge providers may use proprietary technologies, making it difficult to create a unified, globally scalable gaming network. Without industry-wide standards, developers face the burden of creating custom solutions to ensure

compatibility across various edge environments, increasing development time and costs.

Interoperability is a critical issue in edge computing in gaming. The lack of standardized protocols between different edge providers, telecom operators, and game engines can lead to fragmented ecosystems, making it difficult for developers to build universally compatible games.

8. Future of Edge Computing in Gaming

The future of gaming is closely connected to advancements in edge computing, driven by the demand for instant, high-quality, and immersive content. As we move forward, we can expect highly immersive experiences powered by augmented reality (AR) and virtual reality (VR). These technologies require processing large amounts of spatial data and rendering high-resolution graphics in real-time. Edge computing provides the necessary computational power right at the edge of the network. The combination of edge computing and 5G networks, with their high throughput and low latency, is essential for the widespread adoption of mobile AR and VR gaming. As the global edge computing market continues to expand rapidly, its integration into gaming infrastructure will shape the interactive entertainment experiences of the coming decade. By reducing latency and allowing complex computational tasks to be offloaded, edge computing will enable high-fidelity immersive gaming to be accessible on any device, anywhere. Looking ahead, edge computing is poised to unlock incredible possibilities in the gaming and streaming landscapes. Innovations such as AR, VR, cloud gaming, and personalized streaming content are becoming more feasible and accessible due to edge computing's ability to process data at remarkable speeds. These advancements promise to create even more immersive and interactive entertainment experiences. By addressing issues related to latency, bandwidth, and processing capabilities, edge computing is not only improving the present but also shaping the future of digital entertainment.

9. Conclusion

Edge computing is no longer just a theoretical concept; it has become a crucial operational requirement for the modern gaming industry. This shift represents a fundamental change that tackles the inherent limitations of traditional centralized cloud computing. As player expectations for graphical quality, instant responsiveness, and AI-driven immersion continue to rise, the physical constraints of centralized cloud data centers have become a significant barrier. By relocating computation closer to the user, the industry is effectively reducing latency and enabling the seamless streaming of AAA games over 5G networks. However, realizing this vision presents substantial challenges. The financial and logistical difficulties of deploying distributed infrastructure, along with the increased security risks of a decentralized network, pose significant obstacles. It is essential to protect the distributed edge infrastructure against cyberattacks. For innovative game development companies, now is the time to invest in multiplayer gaming platforms designed for future networks. The future of real-time entertainment will be shaped by those who adopt these technologies today, crafting seamless environments where every millisecond and every interaction count ^[14].

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