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Gaming in the Cloud: 5G as the Pillar for Future Gaming Approaches

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The authors identify the critical factors in the cloud gaming user's experience and the impact of the network on it.

Abstract

One key element in the future of the video game industry is the adoption of the cloud gaming paradigm. This model allows high-quality and on-the-move gaming experiences in terminals with minimal capacity. However, such an approach establishes hugely challenging requirements on the network side to support the high amount of data exchanged with stringent latency demands. In this sense, 5G features are expected to achieve these requirements and become the main enablers for the pervasive adoption of cloud gaming. The present work identifies critical factors in the cloud gaming user's experience and the impact of the network on it. Along these lines, the most important aspects in 5G networks that will support the provision of cloud gaming are explained, offering a performance comparison with other network technologies through experiments in real-world network deployments. The outcome shows the potential of 5G networks in contrast with legacy technologies. From this, the 5G features destined to improve the delivery of the service are discussed, exposing the future challenges to address.

Introduction

The emergence of increasingly powerful access networks has led to drastic changes in the provisioning of data services and how users access media entertainment. Fast and reliable streaming multimedia services have made the use of specific-purpose physical data storage (e.g., DVDs) nearly obsolete. This migration to the cloud is also spreading to the general storage of data files, where the use of file hosting services is becoming widespread.

In this same trend, Cloud Gaming (CG) is a new emerging service approach for video gaming. CG allows playing a remote game hosted in the cloud without the requirement of having a powerful device. This also allows for new ways for video game commercialisation that, even after the discontinuation of Google's Stadia, has led to the increasing appearance of new CG platforms like Amazon Luna, Xbox Cloud Gaming and Nvidia's GeForceNow, which are competing for these new markets [1]. Such platforms are expected to eventually take on a wider share of video game delivery, putting current network deployments under additional pressure.

CG could be seen as a video streaming: the game-play elements are encoded and transmitted in the same way as video frames. However, due to its interactive nature, it has a low latency requirement, where maximum values are in the range of 60 to 100 ms to offer a reasonable gaming experience to a casual gamer[2].

Although there are several factors that affect CG latency, the most influential and unpredictable impact lies in the communications network. Beyond the technology or infrastructure used, network congestion and packet loss are major contributors to latency, delaying the delivery of the data stream. Several studies have been conducted on the impact of different network delay and loss conditions on CG Quality of Experience (QoE) [3, 4].

Where wired networks might be able to support CG requirements, wireless communications are essential to reach its full potential, considering the huge relevance of portable and mobile scenarios for gaming [5]. Here, works such as [6, 7] have discussed some of the characteristics that make 5G an enabling technology for wireless services. They mainly highlight higher bandwidth and edge computing as key factors for the provision of these services.

Whilst previous works have explored the intersection between CG and 5G technologies, this work goes beyond this by providing a holistic perspective of CG in next-generation cellular networks. In lieu of simply offering a superficial view, our research delves and explores the way this novel network technology will transform the gaming user experience, empirically demonstrating the inherent potential of this technology to deliver CG.

Here, the novelty of this article is threefold. Firstly, to specify three CG factors that facilitate the evaluation of network performance from different aspects of user service perception. Secondly, the deployment of CG services over a variety of real-world networks, including a 5G-SA deployment, which allows for more reliable information to be obtained about the delivery of CG than in simulated environments. This enables the assessment of CG against different network scenarios, which highlights the capabilities of 5G to support performance levels of service quality in comparison with other dominant wireless technologies (i.e., WiFi and LTE). Finally, the identification of the key features of 5G/B5G networks that can significantly enhance the CG provision, establishing future research and development lines for the future of CG over cellular networks.

Thus, this work is structured as follows: First, we provide an overview of the CG service and

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architecture in comparison to previous approaches. Then, different factors in the user's experience are identified and categorized. Following this, we expose the potential of 5G in the delivery of CG, providing a comparison with other technologies and identifying the 5G features which will boost the service's experience. Finally, we present the conclusions and outlook from this work as a stepping stone for future research in the field.

Cloud Gaming

A video game is an entertainment medium that recreates a virtual world in which the users, called players, interact with each other. Thus, players can control one or several characters by sending actions through an input device, such as a gamepad, keyboard or mouse, in order to reach some proposed goals defined by the game. Their execution has been extended to other devices (also called platforms) such as computers, consoles or smartphones. This available multiplatform has also eased the introduction of multiplayer modes.

The desire for full immersion in more realistic video games entails a large investment in handsets that can execute powerful graphic engines in their maximum configuration. Thus, the recreation of a very realistic virtual world, with high interactivity and very sharp scenes, leads to making these processes heavier, requiring powerful graphic cards for realistic representation. Furthermore, it also results in large setup files, which often reach up to 150 GB.

This environment is where the CG concept appears. Following the same philosophy as video streaming, this paradigm allows players to launch games in any place, at any time and on any device without requiring their installation. To do so, the game is hosted in the cloud, where the execution of all required tasks is supported with optimal performance. However, this architecture involves great changes in the gaming flow.

Figure 1 represents the game loop for local games (traditional gaming), online multiplayer and CG. This includes all the involved functions from an input action to its representation. As it can be seen, in traditional gaming, all elements are centralized in the user device. The actions, which are usually introduced through a peripheral device, are directly delivered to the game logic through the command interpreter. This latter process inputs signals according to the rules of the game. The game logic allows players to experience the full challenge of the game by updating the state of the virtual world and sending graphical instructions to the device. There, the updated environment is rendered by the graphic engine, which offers the scenes in a suitable format for their subsequent display on the screen.

Something similar happens with online multiplayer modes. In this case, both the command interpreter and the environment's representation are done on the user side. However, the game's state is located on an external server. This means that the server is in charge of managing the logic of the game and sharing with all the players the status of the virtual world. In this way, each player sends information to the server via periodic small packets over the network, allowing them to have a real-time interaction with other players.

Conversely, in CG the server performs much of these tasks: it receives user actions from the

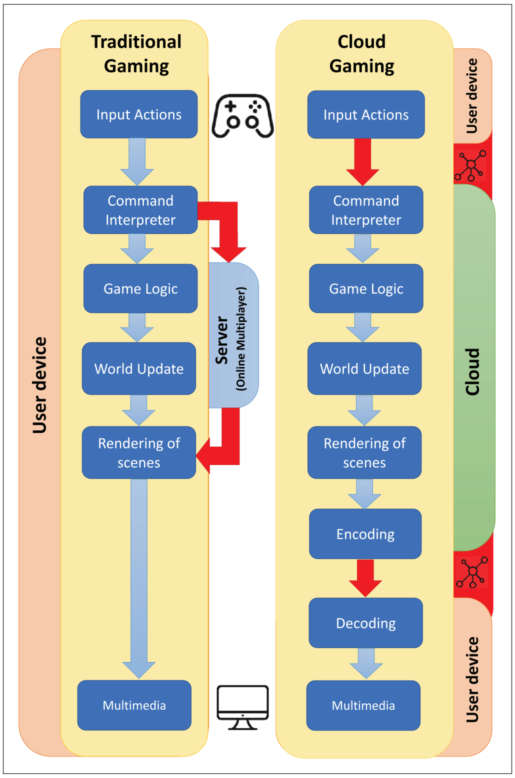

FIGURE 1. Gaming architectures.

network and interprets them, fulfilling the logic of the game and the virtual world state. In addition, it hosts the graphic engine of the game itself, rendering every 3D model for the game. The fact of allocating these heavy tasks to the cloud allows this paradigm to relieve user equipment and take advantage of the economies of scale of centralized servers. Unlike traditional gaming, this content then has to be delivered to players. Hence, a special codification is made to the multimedia content to enable the orderly delivery of the content with the lowest possible delay.

Despite all the benefits that CG presents, the challenge of this paradigm lies in offering a seamless gaming experience. At the expense of moving a large part of the computation to the cloud, huge pressure is put on the network. In this sense, it is necessary to identify the different impacting factors which should be considered in providing these services.

Performance Analytics

Evaluating network performance for service delivery is normally done by assessing QoE, which is commonly quantified by the Mean Opinion Score (MOS). However, due to the interactive nature of videogames, the CG QoE involves a number of interdependent variables that go beyond those present in services such as video streaming [8]. Collecting and combining all these factors therefore leads to a myriad of ways of assessing the performance of the network that supports the service.

In this sense, this section provides a high-level comprehensive categorization of three key factors related to the user's perception of the service, namely Key Quality Indicators (KQIs). This facilitates the evaluation of network performance for this type of service, based on the visualisation of and interaction with the game environment.

A video game is an entertainment medium that recreates a virtual world in which the users, called players, interact with each other. Thus, players can control one or several characters by sending actions through an input device, such as a gamepad, keyboard or mouse, in order to reach some proposed goals defined by the game.

Responsiveness arises as a key factor for the user's experience, defined as the time passing between player's action and the representation of its consequence on the screen.

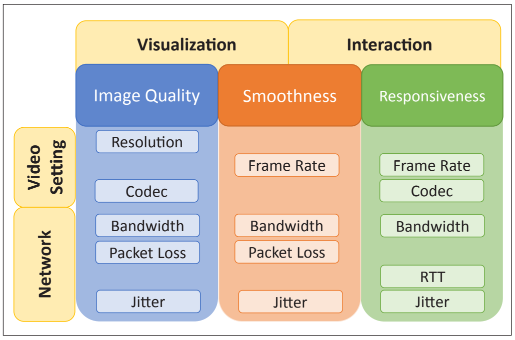

FIGURE 2. Key factors in the Cloud Gaming user's experience.

Figure 2 represents a hierarchical diagram of the network factors that impact game playing. Game visualization mainly depends on the *image quality* of the displayed game, as well as its *smoothness*. Interaction with the game is mainly affected by its *responsiveness*: the time the system needs to complete a loop between the execution of a game action and the visualisation of its effect. This is a key challenge for CG, as the actions of the user have to reach a remote server and then the response needs to be received back from the server after the necessary computations associated with the game mechanics and rendering.

Smoothness and interaction are not independent factors, as they are deeply interlinked. A smoother image will allow a more enjoyable interaction than the one experienced with a less fluid one. In this scope, the following subsections will focus on the parameters associated with these factors, identifying the relevance of video settings and network metrics in the service performance.

Image Quality

Image quality is related to the resolution. This implies the granularity measured in pixels with which the image is represented, where a pixel is the smallest homogeneous unit which makes up a digital image. Figure 3 presents a summary of the current most used resolutions, also indicating their number of horizontal and vertical pixels (width x height). Higher number of pixels generally leads to a finer image granularity, and therefore, better image quality.

An increase in resolution implies the use of more data. Encoders are applied to substantially reduce the amount of video information to be transmitted. This usually comes with information losses, which might downgrade the quality of the image, and/or increase delays in reconstructing the original images.

Here, the network capacity plays a key role in the image quality to be continuously transmitted from the server to the players. Like video streaming, radio bandwidth will restrict the quality of the content sent. Higher resolution images present larger data volumes to be sent than lower resolution ones. However, the latency requirements necessary in CG lead to avoiding the use of some compression techniques which introduce additional delay. This fact entails a bitrate increment of the final bitstream far beyond the rate of an on-demand video of the same quality. Figure 3 exposes the bitrate required from the network for each resolution and frame rate, which is recommended by Moonlight [9] for an adequate CG experience.

Image quality is impacted by packet loss and jitter. The former will cause a lack of information to regenerate the content sent from the server whereas the latter makes the arrival of this data temporarily variable, which sometimes also involves the loss of information. Packets are usually discarded if they do not arrive within a temporal threshold. Thus, as with codecs, this information loss will downgrade the service's perceived quality.

Smoothness

The visual perception of the user and interaction with the service is related to the smoothness attribute. A video is a set of digital images, whose successive presentation creates a movement sensation. This movement will be more or less seamless depending on the Time Between Frames (TBF), corresponding to the frame rate or the number of Frames Per Second (FPS).

Consequently, the smoothness of the image in CG also depends on the network, as seen in Fig. 2. Here, the throughput of the system acts as a limiting factor in terms of bitrate associated with higher frame rates. Figure 3 shows the bitrate suggested by Nvidia [9] to support different levels of smoothness under distinct resolutions. These values result from sending more frames in the same period, increasing the amount of exchanged data. Transmitting dataflows beyond the network capacity will lead to network saturation. In other words, the network will not be able to handle the required volume of data, leading to packet loss and jitter. As for image quality, both jitter and high packet losses can make the user device incapable of decoding the affected frames, leading to a decrease in the frame rate. Such sudden drops will result in frozen images, which have a very negative impact on the user's experience. Hence, to provide players with a proper gaming experience, avoiding freezes is strictly required. To do this, networks must support simultaneously high data rates, low loss ratio and delivery time fluctuation.

Responsiveness

Interaction is one of the paramount elements of CG services. In this scope, responsiveness arises as a key factor for the user's experience, defined as the time passing between a player's action (e.g., a keystroke) and the representation of its consequence (e.g., character movement) on the screen. This is associated with the delay introduced by the whole system, also known as input lag.

Here, the frame rate plays again an important role. A higher frame rate implies a higher image reproduction frequency. Figure 3 also shows the time difference between two consecutive frames (i.e., TBF) based on this parameter. Therefore, a 120 FPS frame rate could reduce responsiveness up to 4 times less than that achieved with 30 FPS. Moreover, the codec type also has an impact on the response time. These differences are based on the algorithms used, whose strategies might bring different execution times.

However, the most influential element in the responsiveness is the network, since the time taken to send the multimedia content will determine a large part of the input lag, so much so that the network is usually identified as the only cause of responsiveness. Network throughput will set the data delivery time, hence, a higher bitrate will allow shorter reception times. Likewise, geographical server location will be intrinsically related to the Round Trip Time (RTT) of the exchanged data. The greater the distance between the client and the server, the further the packets have to travel and the more intermediaries they have to pass through. This also means more delay due to data queuing or node processing.

Therefore, as identified in this section, the network acts as the cornerstone for the proper delivery of CG services. A network with insufficient capabilities could cause high input lag values, negatively affecting the quality of experience of these services, which has been the main bottleneck for their adoption.

Meeting Gaming Requirements in 5G

The arrival of 5G networks is expected to be a key factor in supporting and popularizing enabler for CG services.

To show their potential, different CG sessions were conducted with four resolutions (i.e., 720p, 1080p, 1400p and 4K) and three frame rates (i.e., 30, 60 and 120 FPS) over different network technologies using the testbed presented in [10]. This testbed allows the End-to-End (E2E) assessment of different multimedia services over real-world network deployments, especially two private 4G and 5G SA cellular infrastructure.

Furthermore, the service has been deployed by using Moonlight Gamestream [9], an open-source platform provided by Nvidia to empower CG service. On the top of this platform, it is instantiated the measuring framework presented in [11], which fetches information related to the KQIs introduced in previous section.

In this context, 4 network technologies (i.e., Ethernet, WiFi, LTE and 5G) were evaluated in terms of CG resolution, fluidity and responsiveness. Given cellular networks are mobility-enabled, two scenarios were simultaneously distinguished for 4G and 5G where the user is near the base station (referred to as cell center) or at the edge of the cell (cell edge). For these cases, the user location was selected based on UE Reference Signal Received Power (RSRP) and Signal to Interference Noise Ratio (SINR), ensuring equal conditions for both technologies.

Likewise, for each technology, a local and remote location of the CG server was evaluated. In the local configuration, the server was on the same local network as the client. For 4G and 5G technologies, the server was on the same subnet where the network core was instantiated, corresponding to a Mobile Edge Computing (MEC) scenario, described in later sections. In the external configuration (i.e., those cases labelled only with the name of the technology), the server was instantiated outside the client network, so that network traffic was routed through different nodes. To ensure the integrity of the results, the routing of the CG traffic was static, guaranteeing the same route for each of the cases. To simplify the assessment, the results were collected using a single static user who is playing *League of Legends*.

Figure 4 depicts in boxplots the smoothness and responsiveness values from the resulting 12 network scenarios. As expected, Ethernet technology allows smooth, low-responsiveness experiences, below 120 ms for each resolution. These values are considered the minimum that can be

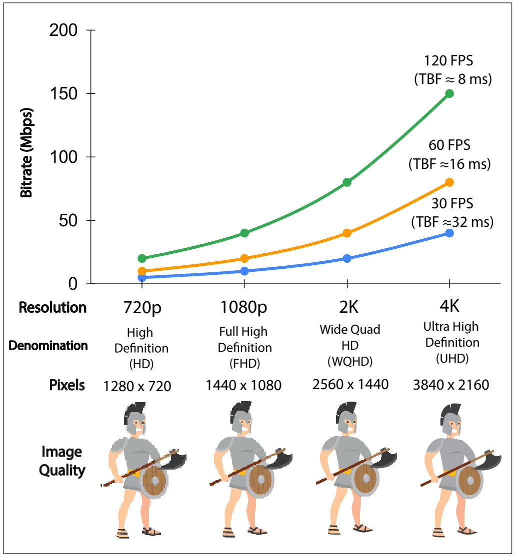

FIGURE 3. Frame rate impact on network bitrate.

> With WiFi, performance is similar to Ethernet, but with the advantage of a wireless connection. However, if the server is not close to the user, the service experience is degraded.

achieved in the CG deployment considered in this work, so they are used as a comparative reference for this analysis.

With WiFi, performance is similar to Ethernet, but with the advantage of a wireless connection. However, if the server is not close to the user (marked as WIFI), the service experience is degraded. In this case, freeze values are obtained for every resolution (especially for 4K), as well as a significant increase in system responsiveness with values up to 200 ms.

A similar behavior to WiFi is observed for LTE: the proximity of the server to the user allows an Ethernet-like service experience, whilst further away leads to a noticeable degradation of service experience. Additionally, there is a dramatic increase in the responsiveness and freezing rate of the service when the user moves away from the base station (i.e., LTE CELL EDGE). This indicates that although LTE has a greater coverage area, its use does not bring any advantage over WiFi as it is not able to provide a good service experience at the cell edge.

Finally, it can be seen that using 5G significantly improves CG service delivery. The results show values of smoothness and responsiveness of the system close to those experienced with Ethernet, offering a significant improvement in the wireless provision of this type of service. Simultaneously, it enables service provision at the cell edge (i.e., 5G CELL EDGE) with freezing and responsiveness thresholds below 15 percent and 150ms respectively.

Nonetheless, all these values are subject to improvement by the application of 5G novelty features. Here, 5G capabilities are analysed by looking at two main areas: the core and radio access network. Combining the features of both parts results in a CG scenario as shown in Fig. 5.

The following subsections provide a comprehensive description of the role of each of these characteristics in the provision of CG services.

Core Network

5G Core (5GC) is expected to highly strengthen the network performance provided to CG services. First, the 5G architecture will simplify the

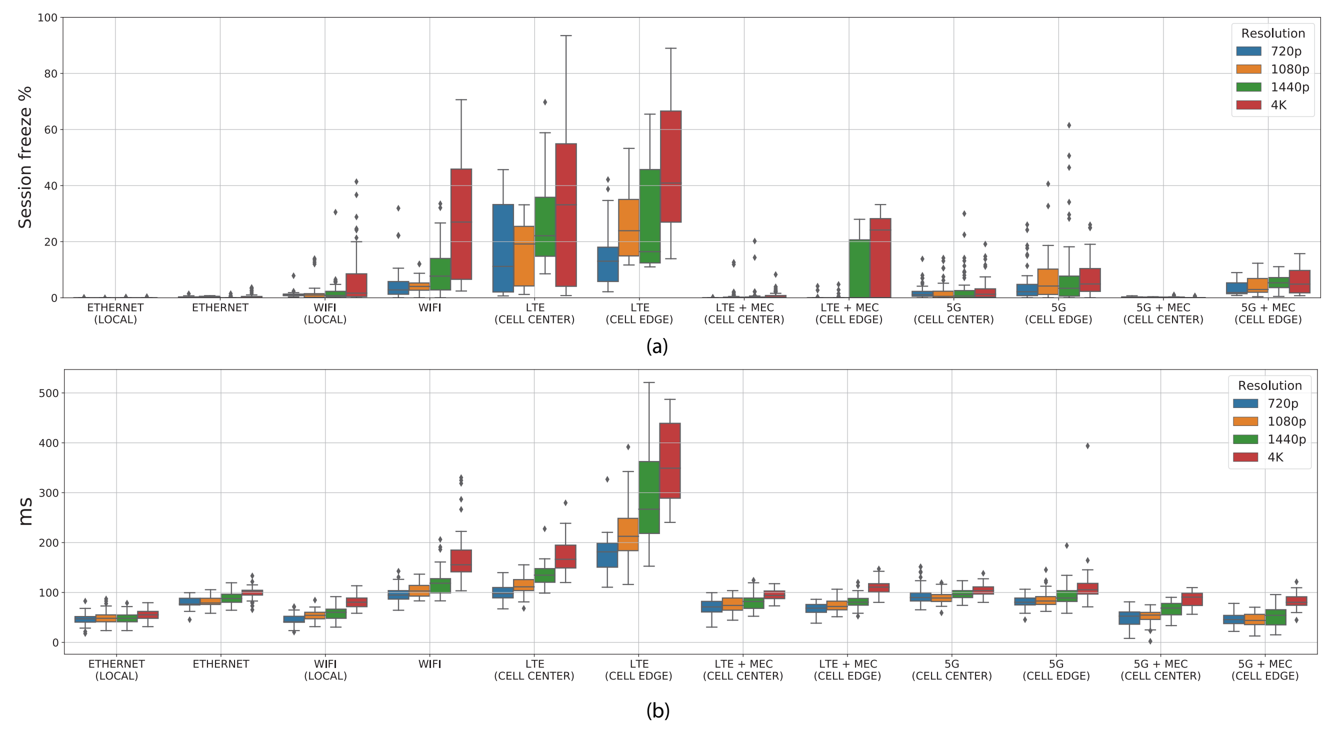

FIGURE 4. Network comparison over Cloud Gaming: a) Smoothness; b) Responsiveness.

provision of these services. Particularly, the Service-Based Architecture (SBA) introduced by 5G and supported by Network Function Virtualization (NFV) allows the full implementation of the MEC paradigm. This enables operators to implement and deploy services close to network elements, which will benefit CG due to its high sensitivity to server location. This paves the way for further reduction of system latency, as well as reducing the stress on centralized gaming servers and possible bottlenecks in the core network data links.

The impact of using MEC is clearly shown in Fig. 4, which shows significant improvements in service smoothness and responsiveness for each technology when the server is near to the user. Furthermore, using MEC in 5G offers service experiences close to those in wired scenarios.

5GC can also take advantage of Software Defined Networks (SDN) paradigm, being the key point of this concept the detachment of user and control plane. To accomplish this goal, SDN devices are composed by a software entity, known as a controller. This entity is in charge of setting routing policies through several rules. In this way, network operators can configure the network with specific conditions for each network segment, easing the management of the network performance based on specific E2E service requirements.

From the joint use of SDN and NFV, the concept of network slicing is defined as a key feature of 5G networks. Under this paradigm, 5G networks are able to create several network instances which provide specific resources and configuration. This enables the generation of dedicated latency/QoS-optimized pathways, fitted to the CG traffic requirements. Based on these, the 5GC will be able to assure latency restrictions using slices with routing and forwarding policies that treat gaming dataflows with a specific priority and that can be directed to the most suitable cloud servers. Network slices will also serve as a way to maintain QoS and appropriate network and radio configuration for the gaming service even on-the-move or based on variable shared infrastructure between different operators.

Radio Access Network

While 5GC features will greatly benefit the deployment of cloud services, including CG, the biggest improvements in 5G technology are expected to be in the radio part of the network. Here, 5G radio access network is defined by a set of new features commonly called New Radio (NR).

In 5G NR, link capacity is increased by using ultra-wide bandwidths. This would be supported by the use of higher frequencies reaching centimeter and millimeter-wave (mmWaves) ranges. Consequently, two newly accessible Frequency Ranges (FR) are defined: FR1, up to 7.1 GHz; and FR2, namely mmWaves, from 24.25 GHz to 52.6 GHz. This new radio spectrum enables allocating bandwidths up to 100 and 400 MHz in FR1 and FR2 respectively, which are values quite superior to the maximum 20 MHz available in LTE.

This increase in bandwidths leads to more radio resources available to allocate to each user. This also means that the achievable data rates for the user will be higher, enabling the proper delivery of videogames with high resolution and smoothness.

This is shown in Fig. 4, where it is observed how the higher bandwidth available in 5G compared to 4G (i.e., 90 MHz and 20 MHz respectively) allows not only to offer a smoother service, but also to reduce its responsiveness. Besides, having more radio resources allows services to be provided under similar quality at cell boundaries. In this case, a more significant improvement is observed in Fig. 4 for the 5G case compared to 4G.

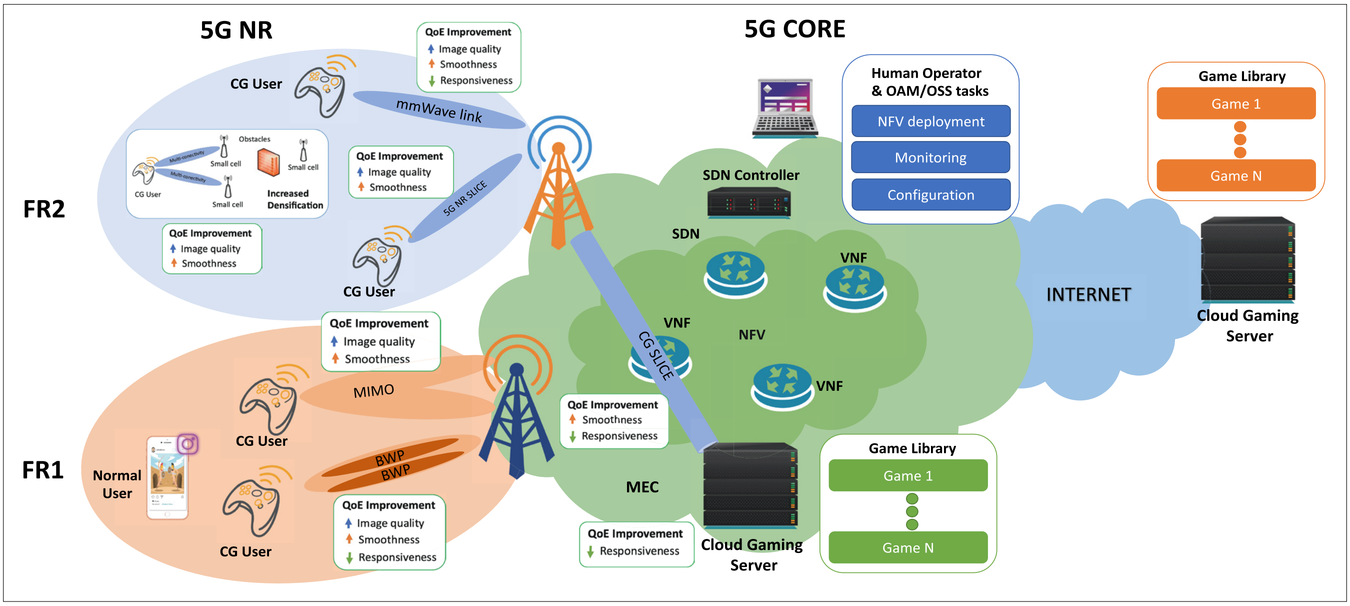

FIGURE 5. 5G Cloud Gaming scenario.

However, the use of high-frequency bands such as mmWaves brings propagation and attenuation constraints. These would negatively affect the user's perception, leading to sudden drops in frame rate and increased latency. A key tool in mitigating these negative effects is beamforming, which uses directional antennas and advanced signal processing techniques to focus signal energy in a specific direction. This improves the reliability and quality of wireless connections in environments prone to obstructions and signal loss.

In addition, the use of Multiple-Input-Multiple-Output (MIMO) schemes will improve the robustness of communications in such environments, where the creation of multiple channels allows the transmission of multiple simultaneous data streams (i.e., spatial multiplexing), which can be used to improve throughput or recover the original signal.

Increased densification in hotspots will also play an important role, allowing shrinking signal fades thanks to the reduced intersite distance (with 200 meters expected in urban and 20 meters in indoor scenarios) and boosting the application of the Multi-Connectivity (MC) paradigm. This approach improves data rates by enabling users to access radio resources of several nodes simultaneously. Thus, these key features would support the provision of highly performant CG service. However, the complex management behind these connections will be one of the most critical aspects to enable a consistent service.

In terms of latency, the use of mmWaves together with a flexible radio frame is also expected to highly improve the performance of the radio access. Here, 5G numerologies establish a set of predefined configurations which defines the frame structure in terms of slot time and subcarrier spacing. The general tendency is that the length of the scheduler time slot gets shorter as the subcarrier spacing gets wider. In other words, higher numerology will translate in lower latency at the cost of reducing slot time, affecting the user throughput negatively. This fact allows exchanging data with lesser delays in the transport segment. In this way, there is a trade-off between latency and throughput, being mandatory the selection of optimal numerology for CG. For example, a configuration that prioritises latency at the expense of throughput could degrade the smoothness of the session.

Nonetheless, this task is helped by the Bandwidth Part (BWP) feature of 5G: a BWP is defined as a subset of contiguous Physical Resource Blocks (PRBs) that can be assigned with different numerology to each carrier, giving a more flexible resource assignation. In this way, high numerology can be assigned in the uplink, reducing the latency of the user's actions. Simultaneously, high data rates can be reached in downlink thanks to lower numerology, enabling high image quality.

Thus, all aspects of core and radio depicted in Fig. 5 will endow 5G with features to enhance the above results, so providing wireless service experiences that are closer to the wired scenarios.

Conclusions and Outlook

This article has presented CG as one of the relevant applications in the near future of telecommunications, providing empirical evidence of the potential of 5G networks in its delivery. To this end, a comparative analysis of different network technologies has been offered, evaluating their performance in terms of three fundamental factors that influence the perception of the service: image quality, fluidity and responsiveness of the service.

The results demonstrate the ability of 5G to deliver such services wirelessly, providing experiences close to those in wired scenarios, and highlight the importance of game server location. Likewise, the aspects of the 5G core and radio that can be used to improve service delivery are discussed. Conversely, the combination of these features triggers many challenges for service delivery over 5G.

First, selecting a suitable location to deploy the servers and integrating them in MEC platforms will be extremely important to ensure certain latency levels. Apart from that, the use of intelligent agents for the network slices management will be essential to set the optimal path to the server, as well as ensure a constant service experience. The

The results demonstrate the ability of 5G to deliver such services wirelessly, providing experiences close to those in wired scenarios, and highlight the importance of game server location.

performance of slices may be degraded by hosting different VNFs on the same physical machine (a.k.a noisy neighbor). In this context, the location of VNF elements is primordial to prevent service outages as well as to reduce network latency.

Additionally, it is necessary to optimise the allocation of radio resources, assigning to each user the minimum required for each service to have a proper experience. This allocation must be handled in different base stations, thereby, enabling a constant service regardless of the user's mobility.

All these aspects are expected to be the focus of future research and commercial activities, oriented toward providing seamless and pervasive access to CG technologies.

Acknowledgments

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References

[1] A. Ojala *et al.*, "Developing Cloud Business Models: A Case Study on Cloud Gaming," *IEEE Software*, vol. 28, no. 4, 2011, pp. 42–47.

[2] Sabet *et al.*, "Towards the Impact of Gamers Strategy and User Inputs on the Delay Sensitivity of Cloud Games," May 2020.

[3] A. Wahab *et al.*, "Subjective Quality Assessment for Cloud Gaming," *J*, vol. 4, no. 3, 2021, pp. 404–19.

[4] N. Ahmad et al., "Significance of Cross-Correlated QoS Configurations for Validating the Subjective and Objective QoE of Cloud Gaming Applications," *Future Internet*, vol. 15, no. 2, 2023.

[5] S. Baek *et al.*, "Future Business Model for Mobile Cloud Gaming: the Case of South Korea and Implications," *IEEE Commun. Mag.*, vol. 61, no. 7, 2023, pp. 68–73.

[6] X. Zhang *et al.*, "Improving Cloud Gaming Experience through Mobile Edge Computing," *IEEE Wireless Commun.*, vol. 26, no. 4, 2019, pp. 178–83.

[7] Y. Zhang *et al.*, "Discussion on Key Technologies of Cloud Game Based on 5G and Edge Computing," *Proc. IEEE 20th Int'l. Conf. Commun. Technology*, 2020, pp. 524–27.

[8] ITU-T Study Group 12, " ITU-T Rec G.1032: Influence Factors on Gaming Quality of Experience," *ITU-T G-series Recommendations, International Telecommunication Union — Telecommunication Standardization Sector*, 2019.

[9] "Moonlight, An Open Source Nvidia Gamestream Client," Nvidia; accessed April 2023; available: https://moonlight-stream.org/.

[10] C. Baena *et al*, "Video Streaming and Cloud Gaming services over 4G and 5G: A Complete Network and Service Metrics Dataset," *IEEE Commun. Mag.*, 2023, pp. 1–7.

[11] C. Baena *et al.*, "Measuring and Estimating Key Quality Indicators in Cloud Gaming Services," *Computer Networks*, vol. 231, 2023, p. 109808.

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