Toward Hyper-realistic and Interactive Social VR Experiences in Live TV Scenarios

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Abstract— **Social Virtual Reality (VR) allows multiple distributed users getting together in shared virtual environments to socially interact and/or collaborate. This article explores the applicability and potential of Social VR in the broadcast sector, focusing on a live TV show use case. For such a purpose, a novel and lightweight Social VR platform is introduced. The platform provides three key outstanding features compared to state-of-the-art solutions. First, it allows a real-time integration of remote users in shared virtual environments, using realistic volumetric representations and affordable capturing systems, thus not relying on the use of synthetic avatars. Second, it supports a seamless and rich integration of heterogeneous media formats, including 3D scenarios, dynamic volumetric representation of users and (live/stored) stereoscopic 2D and 180º/360º videos. Third, it enables low-latency interaction between the volumetric users and a video-based presenter (Chroma keying), and a dynamic control of the media playout to adapt to the session's evolution. The production process of an immersive TV show to be able to evaluate the experience is also described. On the one hand, the results from objective tests show the satisfactory performance of the platform. On the other hand, the promising results from user tests support the potential impact of the presented platform, opening up new opportunities in the broadcast sector, among others.**

***Index Terms*—Broadband, Broadcast, Immersive Media, Immersive TV, Interactive Media, Social TV, Social VR, Virtual Reality, Volumetric Media, VR TV.**

I. Introduction

INTERACTING around media content has been traditionally a social habit. A relevant and widely common example is a group of users gathering at a common location for watching TV content (e.g. sports events, shows) together. In the last two decades, huge efforts have been devoted to achieving a seamless convergence between broadcast and broadband, opening the door to new interactive services thanks to the availability of IP-enabled consumption devices. In this context, two TV-related scenarios can be highlighted. The first one relates to the massive usage of companion screens (e.g. tablets, smartphones) while watching TV content (e.g. [1, 2]), which allows being provided with extra content or engaged with Social Media interactions, among other enriched features. The second one relates to the usage of technological solutions to allow the concurrent consumption of the same content by remote users, while being able to socially interact, e.g. via text and/or audiovisual chat channels (e.g. [3, 4]). These latest scenarios and related technology, combined with the former ones, are typically embraced within the Social TV concept [5]. Social TV scenarios have massively awakened the interest of consumers [5, 6], and currently many Video-on-Demand (VoD) platforms (e.g. Youtube), Social Networking platforms (e.g. Facebook), and even platforms by the research community (e.g. [4]), offer these kinds of services.

With the proliferation of immersive technologies in the last few years, this connected hybrid ecosystem can even go further. On the one hand, it is now possible to integrate Virtual Reality (VR) content, live VR360 videos, and consumption displays, like Head Mounted Displays (HMDs), in hybrid broadcast scenarios (e.g. [7], [8]). On the other hand, social interaction between remote users can now be enabled through shared immersive virtual environments, bringing up a new communication medium termed as Social VR [9]. Social VR rapidly attracted a high interest, magnified with the social distancing measures in the last months. Many Social VR platforms are currently available[1], being Facebook Horizon (formerly Facebook Spaces) and AltspaceVR (by Microsoft) two relevant examples. The existing Social VR platforms can be categorized based on the media formats used for the representation of the shared virtual environment (e.g. 360º scenes [10] or 3D environments [11]) and of the users (e.g. avatars [12, 13], video-based representations [10, 14] or 3D volumetric representations [15]). Likewise, although virtual meetings and gaming-like scenarios could be seen as the main Social VR use cases, this novel medium can also bring significant added value to the broadcast sector. A proof of evidence is Oculus Venues[2], a worldwide-adopted Social VR platform that aims at virtually bringing crowds to live broadcasted events, like concerts and sports. This is also the case for Fox Sports VR[3]. This paper focuses on this particular research challenge and opportunity, which is the applicability

[1] Comparison of Social VR platforms, https://ryanschultz.com/2019/11/12/an-updated-comparison-chart-of-sixteen-social-vr-platforms-first-draft-november-2019/ Last Access in April 2021.

[2] Oculus Venues https://www.oculus.com/experiences/go/1555304044520126/?locale=en _Last Access in April 2021.

[3] Fox Sports VR https://www.foxsports.com/virtual-reality Last Access in April 2021.

of Social VR in the broadcast arena, with a three-fold contribution.

Given the potential of Social VR in the broadcast sector, even for live events, the first and main contribution of this paper is an innovative and lightweight Social VR platform that enables interactive and hyper-realistic experiences, including a live ingest of (broadcasted) heterogeneous video content and a real-time volumetric capturing and integration of users in the virtual scenario, converting them from remote passive spectators to active audience members of the broadcasted event. There are five aspects that make the presented Social VR platform outstanding compared to the state-of-the-art ones. First, it enables photo-realistic volumetric user representations, unlike most of the existing solutions in which users are represented as avatars (e.g. AltspaceVR, Facebook Horizon, etc.), as reviewed in Section II. Second, it is lightweight, low-cost and uses off-the-shelf hardware, unlike other platforms that require high-end hardware and a fast Internet connection for achieving high quality real-time 3D reconstructions and providing realistic representation of users (e.g. [13, 15]). In particular, the presented platform enables real-time communication capabilities based on 3D volumetric representations, which are reconstructed from a number (from 1 to N, being N=4 a typical value) of affordable RGB-D cameras (e.g. Kinect or Intel RealSense sensors) surrounding the participants. Third, it supports a rich combination of media formats to compose the shared virtual environment, like 3D scenarios, 3D reconstructed users and 2D and 360º/180º videos. An adequate combination of media contents has been proved to enrich the user experience in previous studies (e.g. [16]). Fourth, it supports the live ingest of broadcast audiovisual content, including stereoscopic 180º/360º videos and video billboards from a Chroma key room with appropriate background removal features. Fifth, it not only enables a live interaction between the audience members, integrated as volumetric representations, but also between the audience members and the remote broadcasted show presenter, integrated as a stereoscopic video billboard. The Social VR platform additionally allows controlling the presentation of content (e.g. related videos, live connection with reporters…) based on the ongoing interactions. With respect to these last outstanding features, the other existing platforms (reviewed in Section II) are limited to enabling interaction between the users and with the virtual space (e.g. manipulating objects, controlling the playout of additional media).

To prove the potential of the presented platform, the second contribution of the paper is the production of a VR content piece in which a live TV show is recreated. This includes the TV set, a live presenter, the placeholders for the integration of audience members, and a set of content pieces (e.g. interviews with experts, connection with a remote reporter) and realistic animations. Fig. 1 shows an example of the created 3D Social VR scenario, and of users interacting with the Social VR experience in the lab.

As the third and final contribution, the paper reports on the objective and subjective evaluation of the presented Social VR experience. The results from the objective evaluation demonstrate the performance achieved and give an idea of the requirements to run these experiences. The results from the subjective tests (*N=40*) show that end-users rated positively towards the developed Social VR experience, which provides satisfactory quality of interaction, immersion and togetherness [17]. The insights from semi-structured interviews also confirm the potential of the presented contributions, the high interest they awake, and identify aspects to be improved and added in future releases.

In summary, the paper presents a full-fledged Social VR solution for live broadcast events and reports a holistic evaluation of the full workflow of Social VR, including, technological, production and user experience aspects.

The structure of the paper is as follows. Section II reviews the state-of-the-art, from Social TV contributions to more recent Social VR contributions. Section III presents the technological components and aspects of the innovative Social VR platform that has been developed, while Section IV reports on the production of a Social VR story and content to provide an outstanding Social VR experience using the developed platform. Section V reports on the objective and subjective evaluation of the Social VR platform and experience, respectively. Section VI provides a discussion about the obtained results and lessons learned. Finally, Section VII outlines our conclusions and suggests some ideas for future work.

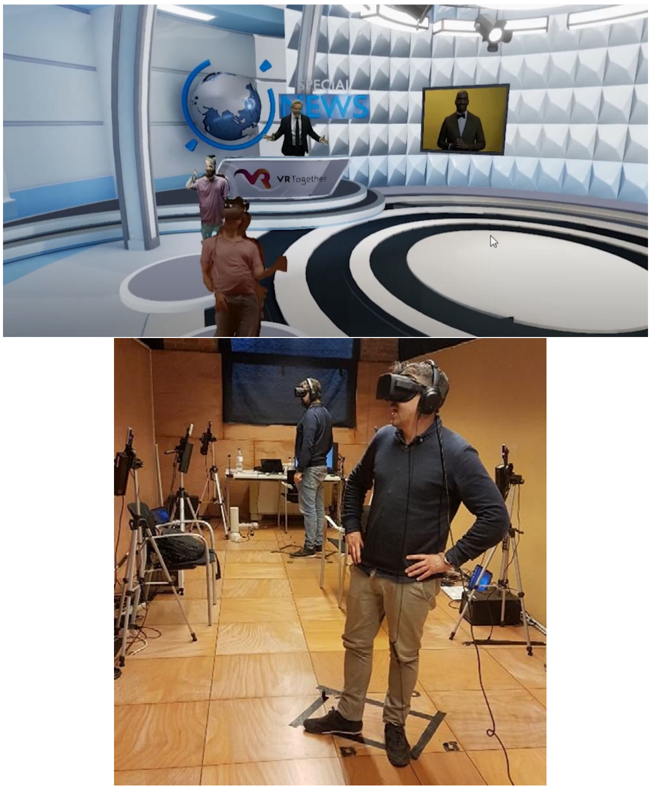

Fig. 1. Up) Two users and a live presenter integrated in the Social VR scenario presented in this work; Down) Two users experiencing the Social VR platform in the lab.

II. Related Work

This section reviews the state-of-the-art in this field, starting with an overview of relevant contributions focused on Social TV, and then continuing with technological solutions and studies toward or on Social VR, including open-source and commercial platforms. While the first sub-section motivates the relevance of the topic, reflects on lessons learned and potential benefits, as well as justifies the evolution toward Social VR, the second sub-section reviews related contributions in the Social VR field, showing the limitations of existing solutions and the advantages and benefits of the presented solution.

A. From Social TV to Social VR

Research on Social TV has attracted attention in the last decade. Some example works focused on: analyzing the advances in Social TV and categorizing the existing developments [5, 18]; studying the appropriateness of different chat modalities [19, 20, 4]; determining the impact of delays [20, 3]; and assessing the interest in these scenarios [6]. For instance, the survey in [6] reflected the high interest of consumers in enjoying Social TV like scenarios, but also the need for better technological solutions and interaction modalities to support them. Likewise, many lab-controlled [20, 4] and in-home [21] studies have shown the benefits provided by Social TV mainly in terms of engagement, togetherness, intimacy and improved relationships. In addition, recent works have revealed a high interest in Social TV (aka social viewing) platforms, not just in the entertainment sector, but also for training, education and collaboration [4].

B. Social VR: technology, user studies and market solutions

Given the benefits and high potential of Social TV, both the research community and industry started to explore how to support these scenarios through VR technology and formats with the goal of increasing the feeling of engagement, immersion and togetherness (i.e. feeling of being together, while apart). State-of-the-art contributions for these aspects are reviewed next.

1) Works from the research community

Many research works have provided valuable contributions and insights in the area of Social VR, with different application contexts, including broadcast environments as the key focus. These include Virtual/Augmented Reality (VR/AR) meeting systems, including Computer Generated Imagery (CGI) and 3D content for the shared environments, as reviewed in [22].

On the one hand, some relevant works have focused on enabling telepresence and social interaction for collaborative and training scenarios, which can are a relevant use case of Social VR. The work in [11] presents a multi-party telepresence system based on the use of color and depth sensors, like Kinects [23], for the end-users' reconstruction and their integration in 3D environments. The Social VR scenario in [11] was based on the use of projection-based displays, not HMDs, and was evaluated for the use case of virtual tourism. The work in [14] presents a similar telepresence system, but using virtual avatars and video-based reconstructions techniques, like free-view point video, for the end-users' representations. The target scenario in that case was collaborative training and exploration spaces. An evolved version of the system in [14] was then prepared in [24] for its application in Mixed Reality (MR) environments.

On the other hand, some other relevant works have focused on the supporting shared media consumption with Social VR platforms. The work in [21] showed that the adoption of HMDs in conjunction with RGB-D cameras for the end-users' capturing and representation can lead to an increased engagement, feeling of immersion and enjoyable embodied telepresence compared to traditional 2D social viewing tools. The work in [25] analyzed the requirement and challenges to efficiently support shared media consumption of 360º videos using HMDs, and proposed guiding and interaction strategies to contribute to this. The work in [10] presented a video-based Social VR platform mainly focused on shared media consumption of stored content. In that platform, users are photo-realistically captured by a single RGB-D camera (Kinect), and the shared VR scenario is represented as a 360º static image. Finally, the work in [17] proposed an experimental protocol and a questionnaire for evaluating Social VR experiences. By adopting a photo sharing use case, the experiment consisted of comparing the quality of interaction, social meaning and presence/immersion levels in three conditions: face-to-face, Skype, and Social VR (using the platform from [10]) scenarios. The results of the experiment not only proved that the proposed evaluation methodology was appropriate (i.e. the designed VR questionnaire was valid with high internal reliability), but also that Social VR provides an enhanced user experience compared to traditional conferencing tools, like Skype.

2) Works from industry: existing Social TV platforms

The industry is also devoting efforts to the development and deployment of Social VR, telepresence and collaborative virtual environments.

With regard to collaborative workspaces, IBM recently presented DataSpace [13], a re-configurable hybrid reality system supporting both AR/VR scenarios. Even though the key focus of DataSpace relies on the (re-)configuration and combination of physical and digital resources for supporting next-generation workspaces, including the interactive presentation of heterogeneous content, it also supports the interaction and collaboration between remote users, represented as 3D avatars.

With regard to realistic communication between remote users, two solutions from the industry can be highlighted. The first one is the Microsoft Holoportation system for HoloLens [15]. This system is however mostly focused on AR scenarios and requires a complex and expensive capturing setup, with eight custom (i.e. not off-the-shelf) camera pods. The second one is the solution by Mimesys (a Belgian startup acquired by

Magic Leap in 2019[4]) that developed an AR telepresence system based on holographic representations of end-users, by using Kinect and Intel RealSense sensors for the capture and Magic Leap headsets for the visualization.

In addition, many commercial and open-source Social VR platforms have appeared in the last few years, and even qualitative comparisons among them have been conducted, like the one by Ryan Schultz[5], which pays particular attention to high-level and commercial aspects. Table I provides a categorization of key Social VR platforms, including newer ones not considered in the previously mentioned comparison, and taking into account those platforms that are closer to support the use case explored in this paper (i.e. shared consumption of immersive video, including live and interactive content, through VR environments), as well as relevant aspects and features to support such a use case.

On the one hand, the availability of many platforms in the market is a proof of the high interest Social VR is awakening. On the other hand, the comparison serves to confirm and highlight the outstanding and enriched features provided by the platform presented in the paper, compared to other existing ones. The comparison in Table I confirms that almost every platform supports 3D environments, provides support for desktop and VR modes, allows for media sharing, and allows to live stream VR sessions to other 2D video platforms, like Youtube and Twitch. The presented Social VR platform also provides these widely supported features. Interestingly, all these platforms rely on the use of (either cartoon-like or human-like, even customizable) 3D avatars for the end-users' representations, and few of them (e.g. Mozilla Hubs and Spatial.io) also support the integration of live 2D windowed videos from the webcam. The presented Social VR platform not only also supports these features, but it is an outstanding platform with regard to the support of realistic volumetric end-users' representations as Time Varying Meshes (TVM).

In addition, the presented Social VR platform supports the integration of live broadcasted (stereo and mono) streams, with background removal (Chroma key), though a custom and low-latency standard-compliant pipeline. This provides higher control and minimizes delays than using third-party streaming platforms, like Youtube. Moreover, the presented Social VR platform enables the integration of live stereoscopic 180º/360º feeds, which is not supported in the other existing Social VR platforms.

TABLE I
COMPARISON OF STATE-OF-THE-ART SOCIAL VR PLATFORMS

Platform / Features	VR / Desktop Support	End-users' Representation	3D Environment	Integration of Live Broadcasted Video	Chroma Keying for Live Videos	Live 180º / 360º video	Broadcast Live Sessions
AltspaceVR[a]	Y / Y	Human-like avatars (customizable clothes, but no faces)	Y	Partially (integration of YouTube player)	N	N	Y (e.g. on Twitch)
BigScreen[b]	Y / N	Cartoon-like avatars (customizable)	Y	Yes (but integrating player of third-party platforms and TV channels)	N	N (only static 360º scenes for the environment)	Y (e.g. on Twitch)
Mozilla Hubs[c]	Y / Y	Cartoon-like avatars (customizable) and live 2D video from the webcam	Y	Partially (integration of YouTube and Twitch players)	N	N (only static 360º scenes for the environment)	Y (e.g. on Twitch)
NeosVR[d]	Y / Y	Cartoon-like avatars (customizable)	Y	Partially (integration of Twitch player)	N	N	Y (e.g. on Twitch)
Spatial.io[e]	Y / Y	Human-like avatars and 2D videos from the webcam	Y	Partially (integration of video players and screen sharing feature)	N	N	-
Virbela[f]	Y / Y	Human-like avatars (customizable)	Y	Partially (integration of YouTube player)	N	N	Y (e.g. on Twitch and YouTube)
Vive Sync[g]	Y / Y	Human-like avatars (customizable)	Y	-	N	-	Y (e.g. on YouTube)
Presented Social VR platform[h]	Y/ Y	Realistic volumetric representation (TVM), 3D avatars, live 2D video from the webcam, just audio communication, or no audio and video but just presence (i.e. ghost user)	Y	Y+ (Own live broadcasting pipeline)	Y	Y	Y (on YouTube)

[a] https://altvr.com/ [b] https://www.bigscreenvr.com/ [c] https://hubs.mozilla.com/ [d] https://neos.com/ [e] https://spatial.io/ [f] https://www.virbela.com/ [g] https://sync.vive.com/ [h] https://vrtogether.eu/

[4] Mimesys Joins The Magic Leap Family (May 2019) https://www.magicleap.com/en-us/news/press-release/mimesys-joins-magic-leap Last Access in April 2021.

[5] Comparison of Social VR platforms, https://ryanschultz.com/2019/11/12/an-updated-comparison-chart-of-sixteen-social-vr-platforms-first-draft-november-2019/ Last Access in April 2021.

A more complete comparative analysis and benchmarking for all these Social VR platforms can be found in [26].

III. Hyper-Realistic and Interactive Social VR Platform for Broadcast Content

Based on the insights from the review of existing Social VR solutions (Section II), it was decided to develop a new platform overcoming the limitations of existing ones in terms of support for: 1) ingest of low-latency live content; 2) photo-realistic volumetric representations of users, instead of avatars, captured in real-time, even including self-representations for each user; 3) blending of heterogeneous content in virtual immersive environments, including live 2D video, stereoscopic 180º/360º video, and 3D content; and 4) interactivity features, between the real-time integrated presenter and users and for the presentation of different media sources. In addition, the development of a new platform allows having higher control over the technological components and the experience.

This section presents an overview of the novel, lightweight and hyper-realistic Social VR platform that has been developed and used for evaluating the interactive Social VR experience, by describing its main parts and components, including technical and implementation details. A high-level architecture of the platform, depicting the streams and info exchanged among its components, is shown in Fig. 2.

A. Pipeline for Volumetric Media (TVMs)

1) Capturing & Reconstruction

To enable photo-realistic and fluid volumetric representations of users in the Social VR experience, a real-time video capturing and reconstruction sub-system has been integrated, based on the works in [27] and [28]. In that sub-system, the video capturing is performed by using multiple RGB-D sensors [29], like Kinect [23, 30] and Intel RealSense [31], which both capture the color and depth information.

Theoretically, there is no limitation with regard to the number of RGB-D sensors to be used in the capturing and reconstruction sub-system. However, limitations like the physical space, computational resources and interference between sensors need to be considered. To keep the costs and computational load low, the setup considered in this work is based on a capturing sub-system using four RGB-D sensors, concretely Intel RealSense D415 cameras[6] [31], placed, calibrated and synchronized according to the specifications described in [28].

The four RGB-D sensors are connected to four capturing stations, with no particular requirements beyond being able to receive the data from the sensors (e.g. mini PCs). These stations are connected via a Local Area Network (LAN) to a Reconstruction Station with a graphical board supporting Graphics Processing Unit (GPU) operations. In this work, PCs with an Intel Core i7 processor, 32 GB of RAM and a GeForce 1080 Ti board, have been used.

The effective capturing area is approximately a circle with a 3m radius. The RGB-D sensors are placed around the circle and are all pointing towards the action area in the center of the circle. The reconstruction is performed by merging the captured RGB-D frames from each sensor and extracting their 3D geometry. Then, the data from all sensors are synchronized to achieve a coherent volumetric capturing. Next, a background removal process is performed to isolate the geometry from the color information that is needed for the user's 3D representation. The sensors' color information is mapped into voxels and filtered to remove noise. A volumetric point cloud is then created and the voxels are projected onto meshes to be delivered as volumetric video.

2) Encoding & Transmission

The reconstructed volumetric sequences need be encoded and encapsulated for an appropriate real-time distribution via IP networks. Among the supported formats by the presented Social VR platform, this work is based on the use of dynamic meshes (i.e., TVMs) for which many compression methods have been proposed (e.g., [32, 33]), and open-source compression software solutions are available. In particular, the presented (version of the) platform has adopted the open-source Draco library[7] for the compression of TVMs, and the open-source RabbitMQ tool[8] for the delivery of the compressed TVMs data. Every node generating a TVM stream uploads that stream to a local RabbitMQ server, and the interested recipients retrieve the stream from that server, by getting the connection information from the Orchestrator (introduced in Section III.C).

Apart from the visual communication channel, the platform integrates an audio communication pipeline relying on the use of socket connections for the data exchange.

B. Pipeline for Traditional (Live) Media

In addition to the pipelines for volumetric media integration, pipelines for the integration of traditional audiovisual formats have been also integrated. This allows the interactive presentation of media assets stored on a (cloud) Media Server (see Fig. 2), but most importantly, the integration of live media sources for the interactive presentation of broadcasted content, like a remote presenter and video feeds (e.g. for interviews, scenes from a remote event or location, etc.).

The pipeline for live media sources includes the capturing from video cameras (including 180º/360º stereoscopic ones) and audio systems, the preferred encoding/transcoding settings, and the (multiplexed) transmission via Real-Time Messaging Protocol (RTMP), or alternatively its conversion into Dynamic Adaptive Streaming over HTTP (DASH). This allows a real-time bidirectional communication between remote people, like a presenter and the audience, augmenting the interaction possibilities, while enabling selection of the best suited delivery method based on the target requirements, like RTMP for low-latency and DASH for scalability.

[6] Intel RealSense D415 sensor: https://www.intelrealsense.com/depth-camera-d415/ Last Access in April 2021.

[7] Draco: https://google.github.io/draco/ Last Access in April 2021.

[8] RabbitMQ: https://www.rabbitmq.com/ Last Access in April 2021.

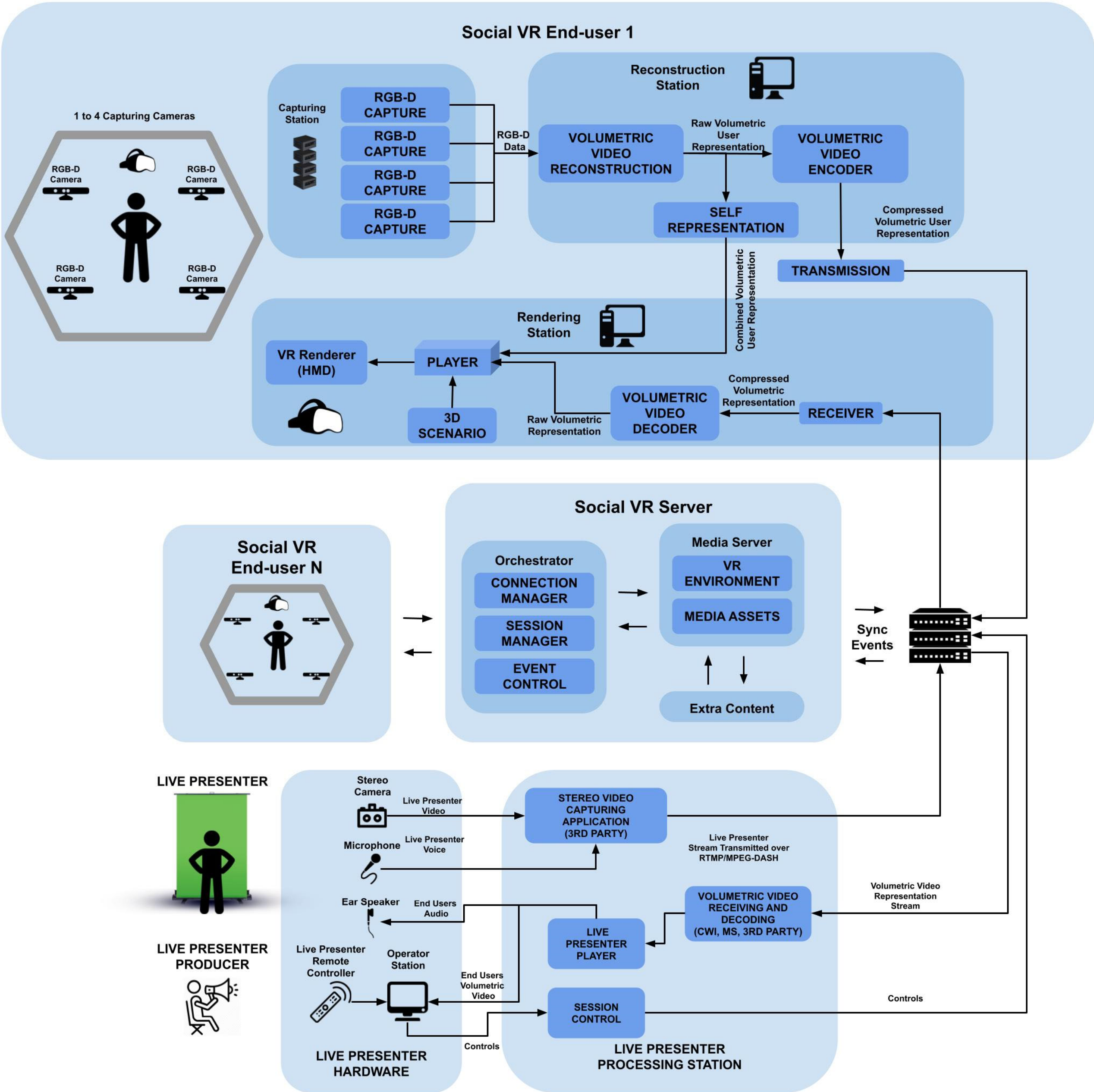

Fig. 2. High-level architecture and flow diagram of the presented Social VR platform.

C. Orchestration and Interactive Session Control

1) Orchestration

Orchestration components (i.e. Orchestrators) are commonly used in video conferencing systems to handle the set of audiovisual and control streams [35]. In the presented Social VR platform, an Orchestrator has been developed and integrated to deal with session and stream management tasks. The Orchestrator handles the remote networking information (e.g., IP addresses, ports, protocols), accommodates all remote users in a shared virtual environment, manages the real-time interaction channels, acts as a relay server for media streams, and ensures a consistent synchronized experience.

In addition, the Orchestrator informs about potential errors or unexpected behavior in the distributed shared sessions and can potentially perform a set of recovery actions in case of connection problems.

2) Interactive Session Control

The Social VR platform targets at enabling highly interactive sessions, in which remote audience members and presenter(s) can communicate and exchange impressions within the context of TV-related content consumption, and different media assets can be dynamically shown and hidden. Therefore, it becomes essential to be able to control the evolution of the session, including the interactive presentation of content. To enable this, a Unity app that runs on both mobile devices and PCs has been developed. The app includes a graphical interface that allows watching the representations of the end-users, a timeline, a panel with all available content assets, and controls to interactively control their presentation (Fig. 3). Thanks to the availability of this app, an operator / realizer, or even the same presenter (with the mobile version of the app), can trigger and control the presentation of different media content (e.g., related videos, live connections, etc.), according to the ongoing interactions and evolution of the session.

D. *Playout*

The final stage of the pipeline consists of the presentation of the media content at the client side, and the integration of all considered interaction modalities for the Social VR experience.

A Unity-based player has been developed to properly receive, integrate and present all available streams for the shared VR scenes, the end-users' representations (as TVMs), the traditional live media sources (i.e., presenter billboard, video feeds), and all other stored assets that will enrich the experience (e.g., recorded videos, graphics, visual effects, etc.).

The player includes different components and engines to provide the following features:

- Connection to, and interaction with, the Orchestrator. With regard to the communication with the Orchestrator, the user, through the player interface, needs first to log in, and then create and/or join a shared Social VR session, by selecting the desired VR scenario among the available ones. During the session, the necessary information will be exchanged to enable interactive and coherent experiences. Finally, at the end of the experience, the session will be terminated, by freeing all associated resources.
- Loading or receiving the 3D virtual scenario where the end-users will be teleported, placing initially each user in the appropriate position and orientation within the virtual scenario.
- Receiving the data streams for the self and others' representations, as TVMs.
- Receiving the data streams from the live and stored media sources, including traditional 2D and stereoscopic 180º/360º video. For such a purpose, an open-source software component[9] that connects the GStreamer multimedia framework[10] with Unity has been adopted. It is called Gstreamer Unity Bridge (GUB), and is able to transmit and play any media Uniform Resource Identifier (URI) provided by GStreamer pipelines into Unity 3D textures, with low latency.
- Eliminating in real-time the green background from the incoming live video stream captured in Chroma key rooms, thanks to an ad-hoc Unity shader. This is very useful to just display the (stereoscopic) silhouette of remote participants (i.e., presenter billboard) in the VR environment, thus increasing the perceived realism.
- Seamlessly blending all content formats and streams that constitute the Social VR experience.
- Ensuring intra-media, inter-media and inter-device synchronization [36], as well as a timely and synchronized presentation of events (e.g. launched through the "*Interactive Session Control*" app), in coordination with the Orchestrator.

The player can run on the Reconstruction Station, or on a different station with similar characteristics (see Fig. 2). The same station has been used in the setup of this work.

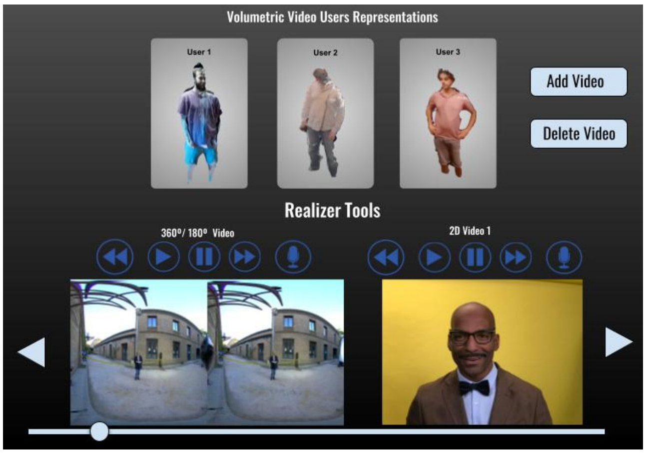

Fig. 3. Mockup of the developed interactive session control app.

IV. SOCIAL VR CONTENT PRODUCTION

In order to assess the potential of Social VR to provide satisfactory shared immersive experiences while apart, and to virtually participate in live TV shows, an innovative VR content piece has been produced.

An appropriate narrative was designed to balance the underlying immersive story, which tends to limit synchronous interaction [37], with one that facilitates and stimulates direct communication among participant users. It revolves around a last minute shocking piece of news announced in a live TV show, and includes immersive and interactive elements to ensure that the participants get the necessary insights while they have space to converse. Participant users are virtually placed in the TV studio and interact with the presenter (Fig. 1) who controls the production of the show, which media elements appear and when.

This sub-section provides details about the chosen scenario and the production process of the Social VR content and scenario to evaluate this new type of interactive and immersive experiences where VR and TV converge.

A. *Pre-Production*

The created content in this study belongs to the second episode of a three-episode thriller-like plot which theme is an investigation about the murder of a celebrity. In the first episode, two suspects are interrogated by a police officer in a 1970's look police station [16], and two users are tele-ported to

[9] Gtreamer Unity Bridge (GUB), GitHub repo: https://github.com/ua-i2cat/gst-unity-bridge Last Access in April 2021.

[10] GStreamer media framework, https://gstreamer.freedesktop.org/ Last Access in April 2021.

the virtual scenario to attend interrogation scenes behind one-way mirrors, playing the role of inspectors. Unlike traditional watching apart together scenarios, in which users watch the very same content, in that first episode it was decided to place the users in a shared observation room, but in front of two different one-way mirrors, each one of them connecting to separate interrogation rooms. In each of the rooms, different suspects are under interrogation. Therefore, although the users share a common virtual environment, and can see and talk to each other, they watch different interrogation scenes belonging to the same story. By adopting this strategy, the two users are both immersed and together while they are somehow pushed to: 1) discover that they have different information; and 2) interact to exchange information extracted from the interrogations. That first episode consisted of an offline content experience (i.e., all content pieces where preproduced, stored and linearly presented in the client application) and focused technically on enabling live interaction between users. The presented second episode contains live and interactive elements, and integrates heterogeneous video and 3D formats. On the one hand, the presented scenarios includes the integration of a remote presenter, who is live captured from a Chroma key room and inserted (i.e. somehow tele-ported) into the virtual TV set as a video billboard. The presenter is the one conducting the TV shown and informs about the last minute murder of the celebrity. Participating users (from 1 to 4) are also real time captured as volumetric 3D video and placed in different positions of the virtual environment. Unlike in the first episode, where the users experienced different parts of the connected story and could just interact between themselves, in this second episode up to 4 users experience the same story from different positions, and they are not only able to see and talk to each other, but also with the presenter of the show. During the episode, different interactive content pieces are presented and live connections with experts and protagonists at the crime location are made, aiming at increasing the feeling of realism and immediacy. With all these features, the users not just feel as passive and remote audience members, but as active participants inside the live show, even requiring their cooperation at some points to better understand what could happen between the murdered and the suspects.

1) Scripting and Casting

After the selection of the theme and scenario, the next steps consisted of writing the script and casting the actors. The story was further developed, revolving around the murder of Ms. Yelena Armova, a wealthy British celebrity at the peak of her career, in still unknown circumstances. Two persons are the main suspects: Mr. Ryan Zeller, the lover of the victim; and Ms. Christine Gérard, her assistant. In the first episode, the two suspects were interrogated by a police inspector, Sarge, revealing that both of them have a different version about what happened and have things to hide.

This second episode informs the audience about the murder and gives some information about what happened, the investigation procedure, involved people, and makes a live connection to the crime location where the investigations are in place. Therefore, a script for this second VR episode was written [38]. Likewise, a casting process was conducted to select the actors representing the roles of the presenter / host, experts to be interviewed, anchor / reporter and investigators. The actors playing the role of the inspector and the two suspects were already selected for the first episode, and thus are kept for a consistent evolution of the VR story being developed. In that sense, the participation of professional actors also contributes to make the experience more credible.

More details about the developed story, the pre-production analysis and tasks, and the casting processes are provided in [38].

B. Production and Post-Production

With respect to content production and consumption, the media formats to use can have direct implications on the required infrastructure, complexity, costs and on the user experience. The conducted tests in [16] showed that that a proper combination of 3D and video-based content does not just contribute to a reduction of production efforts and costs, but also provides the best Quality of Experience (QoE) in terms of feeling of realism, presence, and simulation sickness, as well as certain levels of motion parallax if the video planes are appropriately placed, when providing unlimited 6 Degrees of Freedom (6DoF) is not necessary. To leverage these insights and benefits, it was decided to place the users within specific sub-areas of the virtual environment delimited with circles, as in the *Still Standing* TV game show broadcasted in many countries (see Fig. 4). This gives a mixture between classical TV news and contest sets. The whole virtual TV set becomes then the shared VR environment for all participants, being the users located within circle sub-areas, all of them having an appropriate viewing perspective between themselves, with the host and with the projection spaces using a semi-sphere layout (see Figures 1 and 5).

Fig. 4. Typical distribution of *Still Standing* TV game shows (Spanish version, retrieved from https://www.antena3.com/).

Fig. 5. 3D distribution of the virtual TV set for the designed Social VR scenario, with the different media sources and viewing perspectives.

Key aspects about its production and post-production process are provided next, but readers can refer to [38, 39] for a detailed description and getting open access links to the created media assets.

With regard to the shared VR environment, the TV set was modelled and recreated in realistic 3D using with Autodesk Maya and then exported into FBX format and integrated in a Unity project (see Fig. 6). The 3D modelled environment adopted a cylindrical shape, and took into consideration the appropriate layout and distribution of elements and participants, with space for up to four users, the live presenter, and a semi-sphere projection space for projecting additional videos (e.g. stereoscopic 180º video connecting with the crime location and onsite reporter, or 2D videos for videoconferencing connections with experts), as shown in Fig. 5. The part where the users and presenters are located is static, but the part for the projection space is animated using fading effects when live connections are made/closed. When the connection is made, that part will display a stereoscopic 180º video (Fig. 5), opening a window to the crime location, giving the feeling of being tele-ported there. Once the action outdoors ends, this part comes back to its original state, and the story continues.

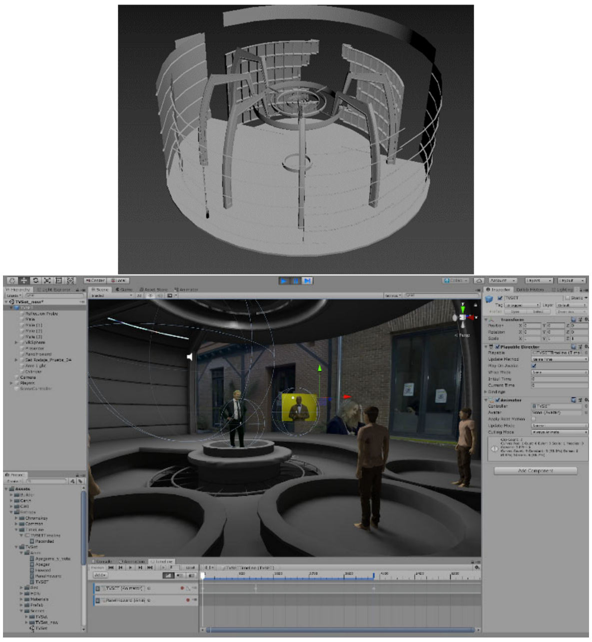

Fig. 6. 3D model of the virtual TV set (up) and Unity project for the designed Social VR scenario (down).

Fig. 7. Shooting to the presenter from a Chroma key room.

With regard to the dynamic video-based elements, they were shot using a Z CAM K1 Pro Camera (stereoscopic 180º video, 2880p30 resolution). All video scenes were recorded to be able of showcasing demos of the VR episode without requiring the participation of the actors. The scenes for the interventions of the presenter and a technology expert being interviewed were shot in a Chroma key room (see Fig. 7), while the ones for the connections with the reporter and investigators were shot in the exterior of a building where the crime was supposed to happen (see Fig. 8). This transition between a fully indoor environment and an outdoor stereoscopic 180º environment when the live connection with the reporter is media was targeted at achieving an appropriate omnidirectional scene blending, thus also potentially increasing the feeling of immersion, and even of teleportation.

Overall, the story was designed to be very dynamic, with a quickly changing environment with the presentation of different (interactive) content pieces, and moving the users' attention from one location to another. In particular, the story develops as follows:

- *Phase 1)* The TV show starts with some interactive visual effects and immersive music.
- *Phase 2)* The presenter welcomes the users, and quickly informs them about the last minute new about the murder.
- *Phase 3)* The presenter makes some questions to fake remotely connected users to give a higher feeling of realism and immersion. This allows increasing the attention of the real users and boosting interaction, but also adding credibility in case that a recorded version of the presented video is used in the experience (e.g. when an actor is not available for a demo). In the case of having a live (potentially broadcasted) connection with the presenter, he/she can directly talk to the captured users.
- *Phase 4)* A connection with a remote expert is made, who will describe a disrupting technology that will be used to help solving the crime.
- *Phase 5)* A connection with the crime location scene is made, where a reporter will interact with the presenter, who will also make questions to a police inspector to get further information about what happened and what is ongoing.
- *Phase 6)* After the connection is closed, further discussions between the users can happen, and in the case of having a live broadcasted connection with the presenter, he/she will further interact with the users, asking them about their impressions.

Fig. 8. Shooting in the exterior of the building to simulate the live connection with the crime scene location.

After the recording and modelling of all assets, post-production processes were conducted for all the raw material, including the required adjustment tasks for an appropriate compositing and seamless blending. Noise reduction and masking processes were conducted for the recorded video billboards. In addition, color adjustment processes were necessary for an effective removal of the green elements and the replacement with the appropriate color, together with the adjustments to achieve a seamless stereo view. Finally, realistic lighting conditions were recreated in order to provide a natural integration of the users and characters into the 3D virtual environment, dividing the Unity scene into a static and a dynamic part. While the static part makes use of lightmaps to bake all the light and optimize the scene, the dynamic part that unfolds makes use of dynamic lighting. A variety of post-processing effects have been also applied to increase the realism of the 3D environment. Some examples include: ambient occlusion, addition of dark corners, chromatic aberration, addition of vintage effects, correction and equalization of colors, etc. The final result for the 3D virtual TV set is shown in Fig. 9.

The overall VR episode with the recorded presenter and connections with the expert and the crime scene location, and all other interactive media elements, lasts around 6 minutes.

A demo video of the developed Social VR platform and the produced content experience for the live TV show can be watched at: https://www.youtube.com/watch?v=KfpTIyS5cA0

V. Evaluation

This section firstly describes the adopted evaluation methodology together with the evaluation setup and scenario. Then, it presents the obtained results, both from objective and subjective tests. In terms of objective data, we report the consumption of computational and network resources on the client side as well as end-to-end delays for the involved media pipelines. In terms of subjective data, we report on the perceived quality of interaction, togetherness, and immersion, as well as on the answers to conducted interviews.

A. Methodology

The Social VR experience was evaluated in sessions of two participants, plus a live presenter from a Chroma key room to increase the interaction possibilities. Although the VR scenario and the platform themselves support up to four participants, it was decided to proceed with sessions of two participants to first assess the user experience in simpler sessions, with a number that can actually boost interaction and with high applicability [6].

On the one hand, the evaluation included objective tests to gain insights about the computational and bandwidth requirements of the experience, as well as about the delays for the exchanged live streams.

On the other hand, the evaluation included user tests by making use of questionnaires and semi-structured interviews.

B. Evaluation Setup and Scenario

The experiments were conducted in a Social VR lab in Barcelona (Spain), which facilities are shown in Fig. 1. The lab room included the necessary equipment for the TVM-based - users' reconstruction, including four RGB-D cameras (Intel RealSense) and five PCs (one per camera plus one controller, Fig. 10). With regard to the TVM streams, they were set with a resolution of 12k vertices and a capturing frame rate of 22 fps, which was dropped to 14fps for an effective real time encoding and transmission. As parametrization, we adopted the outcome of the subjective study on mesh compression performance performed in [40]. For the reconstruction and rendering stations, a PC with an Intel Core i7 processor, 32 GB of RAM and a GeForce 1080 Ti board, has been used for each involved user. Although the two participants were in fact placed in the same physical room (see Fig. 1), they were interconnected through an Orchestrator deployed in Rennes (France), thus recreating an inter-country Social VR session.

The room had no background or surrounding noise. Each user was equipped with an Oculus Rift, with an integrated microphone for the audio interaction, and noise-cancelling headphones to isolate external noise and perceive better the spatial audio provided in the experience. Thus, the users were able to interact through (spatial) audio and (volumetric) visual channels. The users were standing at the center of the effective capturing region during the experience (see Fig. 1) and had limited 6DoF (although were instructed to not move too much during the experience, especially because of the cables). In addition, a laptop was used to record the audio and video from each participant via its integrated webcam and microphone.

The live presenter was captured from a Chroma key room located in an upper level of the same building (see Fig. 11). Its audiovisual stream was delivered through the Orchestrator by using RTMP, which is the output provided by the 180º camera (Z CAM K1 Pro Cinematic VR180 Camera). This allows minimizing the latency, avoiding the conversion into DASH. For a more pleasant experience, an experiment facilitator located at the same Chroma key room controlled the interactive session app for managing the presentation of content. That way, the participants see the presenter without any device on hand, and the presenter can actually focus on the play and interaction with the audience. The same PC used to run the interactive session app was also used to run the software that manages the live streaming session from the camera (Z Cam Wonderlive software that comes with the camera).

Fig. 9. Overview of the final 3D modelled Social VR scenario.

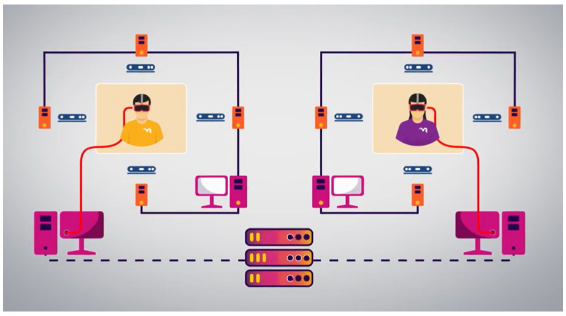

Fig. 10. Social VR lab setup.

Fig. 11. Live capture of the presenter and its integration in the virtual scenario.

With this setup, audiovisual communication channels were available between the two participants and the presenter. Apart from the Operator at the Chroma key room, an experiment facilitator was present in the Social VR lab room to assist the users and to control the test. Chat tools were used to enable communication between the experiment facilitators. The Orchestrator was used to synchronously launch the shared VR experience for each involved participant, by choosing the Social VR content presented in Section III as stimuli.

C. *Objective Evaluation*

This sub-section reports on objective performance metrics on the client application (i.e., the Unity-based player) measured when running the experience. In particular, it reports on:

- Computational Resources metrics: CPU load (%), GPU load (%) and RAM usage (MB), by using the tool from [41].
- Bandwidth consumption (Mbps), as reported by Wireshark[11].
- End-to-end delays, by comparing the capturing and rendering timestamps (explained later).

The metrics were measured on a PC with the following characteristics:

- CPU: Intel(R) Core(TM) i7-10750H @ 2.60GHz 2.59 GHz
- GPU: NVIDIA GeForce RTX 2070
- RAM: 16 GB.

The metrics were sampled along the duration of the whole session, and the reported values refer to the mean values from 5 repetitions for each assessed test condition.

1) Computational Resources Usage

The usage of computational resources was measured for different iterative test conditions with increased complexity to gain insights about the computation cost of adding the different visual elements and content formats in the Social VR experience. These test conditions along with the obtained values are summarized in Table II.

As expected, the iterative addition of extra visual elements in the session (live presenter, TVM streams) resulted in a higher consumption of CPU, GPU and RAM resources. The overall usage for the full evaluated experience was not that high, resulting in a smooth performance, and still providing some margin to add at least one extra TVM stream for a third user using the same (affordable) PC.

2) Bandwidth consumption

On the one hand, the used Z CAM K1 Pro camera used to capture the live presenter can provide an output stream of 4K resolution at 60fps (or alternatively 6K resolution at 30 fps), using H.264 video encoder, with input bitrates up to 30 Mbps, and Advanced Audio Coding (AAC). By setting a resolution of 4K@30fps, an input bitrate of 30 Mbps and an output bitrate (after encoding) of 5 Mbps, the average bandwidth consumption for the incoming RTMP stream at the client side was very close to that latter setting, as expected. On the other hand, the average bandwidth consumption for each TVM stream providing the end-users' representations (with the settings detailed in the previous sub-section) was 6.22 Mbps (stdv=5.3 Mbps).

3) End-to-End delays for the live streams

On the one hand, as a third-party software was used to broadcast the RTMP stream from the live presenter camera, the delays were measured by visually comparing timestamps captured by the camera (pointing at a visual clock counter) with the same ones being displayed at the player side, by placing the clock counter and the player screen side-by-side, and recording a video showing their evolution. That way, by pausing the video at some instants, the end-to-end delay (which in this case is actually the glass-to-glass delay) can be determined by calculating the differences between the timestamps. This method has been used in related works (e.g. [42]). The delays,

[11] Wireshark, https://www.wireshark.org/ Last Access in April 2021.

including the Orchestrator (deployed in another country) as a relay server, the connection between GStreamer and Unity and the background removal, were in the order of 1.5s, with very low variance.

On the one hand, the delays for the TVM streams were measured by inserting absolute timestamps for each captured frame at the origin side, extracting them prior rendering the frames at the destination side, and synchronizing the involved machines by using Network Time Protocol (NTP) to be able to accurately compute the difference between the rendering and capturing instants. By doing so, the average end-to-end delay for the TVM streams (in this case capture-to-render delay) was 751.57ms (stdv=140.45ms). Unlike for the delays for the live presenter stream, the delays for TVM streams do not include the acquisition and rendering delays (as it is very challenging to visually compare clock counters for this media format and resolution).

Although there was a delay difference between both types of streams (i.e. RTMP stream from the live presenter's representation and TVM stream for the end-users' representations), no inter-media synchronization mechanism was adopted, as it would had involved to delay the TVM streams, and providing highly interactive sessions between the participants was a key goal for the experience. In addition, these delay difference levels are within the tolerable limits to the human perception [36], as confirmed in the user tests.

D. *Subjective Evaluation: Protocol and Procedure*

The evaluation protocol and procedure for the user tests are summarized next.

First, the participants were recruited based on the following three criteria:

- They had to be older than 18 years old.
- They needed to have a good English level (to be able to understand the story).
- They had to know each other (to ensure a fluid and natural social interaction).

Second, the user tests underwent the next steps:

- *Step 1 (~10min)*. The facilitators welcome the participants, and briefly describe them the tests, with the necessary context and its procedure. The participants are also informed that their participation is totally voluntary, and that they can leave the experiment at any time, if they would like to do so for whatever reason.
- *Step 2 (~5min)*. The participants fill in a consent form, a demographic and background information form, and the Simulation Sickness Questionnaire (SSQ) [43].
- *Step 3 (~5min)*. The participants are brought to the lab room. Once arriving there, they are equipped with the HMD and audio headset, with the help of the facilitator(s) if needed.
- *Step 4 (~10min)*. When all the involved participants and the presenter are ready, the facilitators launch the experience via the interface with the Orchestrator. Although the experience's duration is about 6min, the participants were instructed to feel free to interact and talk to each other before, during and after the pilot experience, and even to explore the designed VR environment at the end of the TV show experience. Therefore, this step took a bit longer to be completed. The participants were standing during the experience (Fig. 1).
- *Step 5 (~3min)*. With the help of the facilitator(s), the participants step out of VR, and are brought to a meeting room with a round table.
- *Step 6 (~15min)*. The participants will fill in the SSQ questionnaire and the Experience questionnaire for Social VR designed in [17], slightly adapted by re-phrasing the question items according to the evaluated experience (see Tables III-VII).
- *Step 7 (~15min)*. The facilitators drive a semi-structured interview to discuss about the Social VR technology, the experience itself and other potential applicability scenarios with the participants of each session.
- *Step 8 (~2min)*. Participants are thanked, given a voucher of 30 euros, and said goodbye.

Overall, each test session took between 60 and 75 minutes.

E. *Subjective Evaluation: Sample of Participants*

Overall, 40 participants took part in the tests. Next, background information about them is provided:

- Aged between 18 and 60 years (average = 31, standard deviation = 11.61).
- 28 males and 12 females.
- 1 participant was left handed, 38 were right handed, and 1 was ambidextrous.
- None of the rest expressed to have audio-visual impairments.

The participants were also asked about their skills using computers and their previous experience in VR:

- 1 participant stated to be novice, 16 intermediate and 23 experts regarding the use of computers.
- 10 participants stated not having previous experience in VR, 25 affirmed to have some experience, and 5 of them expressed to be very experienced.

F. *Subjective Evaluation: Results from Questionnaires*

In this sub-section, the results from the used questionnaires are presented.

1) *SSQ Questionnaire*

With regard to the results from SSQ, no significant effects / symptoms were noticed to be caused by the VR experience.

2) *Social VR Experience Questionnaire*

The Social VR experience questionnaire includes question items categorized to assess four relevant aspects [17] (to be answered using a 5-level likert scale, with the potential answers detailed in Tables III-VI):

- <u>Quality of interaction</u> (Table III): including emotional experience, quality of the communication, and naturalness of the communication.

  From the results of Table III, it can be affirmed that the presented Social VR platform and experience provided a satisfactory quality of interaction to the participants. This is mainly supported by the highly positive scores for the items related to the naturalness and understanding of the conversations, and to the feeling of not being alone in the VR environment.

- Social connectedness (Table IV): including feeling of togetherness, emotional closeness, and enjoyment of the relationship.
  From the results of Table IV, it can be affirmed that the presented Social VR platform and experience provided a satisfactory social connectedness to the participants. This is mainly supported by the highly positive scores for the items related to the feeling of being together in the same space, low level of distraction by "real world" issues, high immersion, and having enjoyed the shared experience.

TABLE III
SOCIAL VR EXPERIENCE QUESTIONNAIRE – "QUALITY OF INTERACTION (QI)" PART

Question	Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
QI1. "I was able to feel the other users' emotions in the virtual shared experience."	0	1 (2.5%)	13 (32.5%)	**22 (55%)**	4 (10%)
QI2. "I was sure that the other users often felt my emotion."	0	1 (2.5%)	**23 (57.5%)**	11 (27.5%)	5 (12.5%)
QI3. "The virtual experience with the other users seemed natural."	0	3 (7.5%)	14 (35%)	**20 (50%)**	3 (7.5%)
QI4. "The actions used to interact with the other users were similar to the ones in the real world."	0	5 (12.5%)	10 (25%)	**18 (45%)**	7 (17.5%)
QI5. "It was easy for me to contribute to the conversation."	0	0	4 (10%)	16 (40%)	**20 (50%)**
QI6. "The conversation with the other users seemed highly interactive."	0	0	6 (15%)	**22 (55%)**	11 (27.5%)
QI7. "I could readily tell when the other users were listening to me."	16 (40%)	**18 (42.5%)**	3 (12.5%)	1 (2.5%)	0
QI8. "I found it difficult to keep track of the conversation."	16 (40%)	**18 (42.5%)**	3 (12.5%)	1 (2.5%)	0
QI9. "I felt completely absorbed in the conversation."	0	0	9 (22.5%)	**21 (52.5%)**	10 (25%)
QI10. "I could fully understand what the other users were talking about."	0	0	1 (2.5%)	**20 (50%)**	19 (47.5%)
QI11. "I was very sure that the other users understood what I was talking about."	0	0	3 (7.5%)	**24 (62.5%)**	12 (30%)
QI12. "I often felt as if I was all alone in the virtual shared experience."	17 (42.5%)	**22 (45%)**	1 (2.5 %)	0	0
QI13. "I think the other users often felt alone in the virtual shared experience."	17 (42.5%)	**20 (50 %)**	3 (7.5%)	0	0

TABLE IV
SOCIAL VR EXPERIENCE QUESTIONNAIRE – "SOCIAL CONNECTEDNESS (SC)" PART

Question	Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
SC1. "I often felt that the other users and I were together in the same space."	0	0	2 (5%)	**25 (62.5%)**	13 (32.5%)
SC2. "I paid close attention to the other users."	0	2 (5%)	12 (30%)	**19 (47.5%)**	7 (17.5%)
SC3. "The other user was easily distracted when other things were going on around us."	0	4 (10%)	11 (27.5%)	**19 (47.5%)**	6 (15%)
SC4. "I felt that the having the VR experience together enhanced our closeness."	0	2 (5%)	7 (17.5%)	**25 (62.5%)**	6 (15%)
SC5. "Having the VR experience together created a good shared memory between us."	0	1 (2.5%)	6 (15%)	**25 (62.5%)**	8 (20%)
SC6. "I derived little satisfaction from the virtual shared experience."	4 (10%)	16 (40%)	16 (40%)	4 (10%)	0
SC7. "The virtual shared experience with my partner felt superficial."	5 (12.5%)	**18 (45%)**	16 (40%)	1 (2.5%)	0
SC8. "I really enjoyed the time spent with the other users."	0	**0**	1 (2.5%)	**24 (60%)**	15 (37.5%)
SC9. "In the virtual world I had a sense of 'being there'."	0	0	5 (12.5%)	**24 (60%)**	11 (27.5%)
SC10. "Somehow I felt that the virtual world was surrounding me and my partner."	0	0	4 (10%)	**27 (67.5%)**	9 (22.5%)
SC11. "I had a sense of acting in the virtual space, rather than operating something from outside."	0	1 (2.5%)	11 (27.5%)	**22 (55%)**	7 (17.5%)
SC12 "My virtual shared experience seemed consistent with a real world experience."	0	0	15 (37.5%)	**20 (50%)**	5 (12.5%)
SC13. "I did not notice what was happening around me in the real world."	0	2 (5%)	10 (25%)	**16 (40%)**	12 (30%)

TABLE V
SOCIAL VR EXPERIENCE QUESTIONNAIRE – "PRESENCE / IMMERSION (PI)" PART

Question	Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
PI1. "I felt detached from the outside world while having the VR experience."	0	2 (5%)	9 (22.5%)	**19 (47.5%)**	10 (25%)
PI2. "At the time, the shared VR experience with the other users was my only concern."	0	3 (7.5%)	13 (32.5%)	**14 (35%)**	10 (25%)
PI3. "Everyday thoughts and concerns were still very much on my mind."	5 (12.5%)	11 (27.5%)	**17 (42.5%)**	6 (15%)	1 (2.5%)
PI4 "It felt like the VR shared experience took shorter time than it really was."	0	1 (2.5%)	4 (10%)	**22 (55%)**	13 (32.5%)
PI5. "When having the VR experience together, time appeared to go by very slowly."	10 (25%)	**17 (42.5%)**	11 (27.5%)	2 (5%)	0

TABLE VI
SOCIAL VR EXPERIENCE QUESTIONNAIRE – EXTRA AD-HOC QUESTIONS (AQ)

Question	Totally Disagree	Partially Disagree	Neutral	Partially Agree	Totally Agree
AQ1. "I liked the created VR content and scenario."	0	0	1 (2.5%)	17 (40%)	**23 (57.5%)**
AQ2. "The created VR content and scenario are realistic."					
AQ3. "The spatiality in the VR scenario (i.e. perceived distances and sizes of elements, including the participants' bodies) is consistent with a real-life scenario."	0	0	2 (5%)	**29 (72.5%)**	9 (22.5%)
AQ4. "Having more than 2 users in a shared virtual environment can provide added-value to the social VR experience"	0	0	8 (20%)	**22 (55%)**	10 (25%)
AQ5. "Having a remote presenter / actor in real-time provides added-value to the social VR experience"	0	0	8 (20%)	**22 (55%)**	10 (25%)

- Presence / Immersion (Table V): including mainly plausibility and place illusion.
  From the results of Table V, it can be affirmed that the presented Social VR platform and experience provided a satisfactory level of immersion / presence, with most of the participants stating to having felt detached from the real world, engaged with the VR story, and declaring to have had the feeling that the experience took shorter than its real duration.
- Additional ad-hoc aspects about the experience (Table VI): including level of realism, how much the content likes to the users, etc.
  From the results of Table VI, it can be affirmed that the participants liked the created content and the whole experience very much, and rated the experience as realistic and immersive. Interestingly, participants were especially surprised and satisfied with the ability to interact with elements of the VR environment (live presenter), which is one of the key innovations of the presented platform.

G. Subjective Evaluation: Results from Interviews

Finally, the pairs from each session participated in a semi-structured interview with the experiment facilitators. The audio recordings of the semi-structured interviews were transcribed and coded, following an open coding approach [44]. Since the interviews were conducted with the two participants for each pair together, their answers were transcribed and coded as a participant pair, not as individual participants. Therefore, the 20 participant pairs are hereafter labelled as P1-P20. From the coded transcripts, relevant aspects and insights were observed, which are further elaborated next.

1) Benefits and Potential of Social VR

All participants thought that the Social VR platform enabled them to experience *social presence*. First, they felt identified with the end-users' representations, both with their own and the other's representations. "*The quality is not great, but it is impressive to see yourself and your partner as part of the VR environment, in a volumetric representation*", P12 said. "*I could even see my watch / the pictures on my T-shirt*", participants from P3 and P11 stated. A few participants also pointed out that although the end-users' reconstructions provide natural interactions (50%), the facial expressions were partially blocked by the visual quality and the HMD occlusion (30%).

The participants generally felt *being together* with the other participant, which enriched the overall experience. P2 and P4 stated "*We felt together, sharing an experience, and this is really an added value to VR!*". P7 mentioned: "*We were aware of the activities and feelings of the other participant*". The fact of being standing and close to each other was well received by participants, as explicitly stated by P3 and P14. However, the short distance between participants also influenced the noticeability of the visual artefacts for the end-users' representations. This was pointed out by the majority of participants (70%). Three pairs (P5, P6, and P16) claimed: "*Having your colleague closer is great, but then you realize to a greater extend of the limitations in the visual quality of her/his representation*". P18 said: "*When your partner is closer, it also becomes clearer that the she/he is wearing the HMD, and thus* *that you cannot see her/his face*". Participants generally expressed that having eye contact is important, but that the lack of it – because of the HMD blocking – is not a major barrier for a rich interaction and enjoyable experience (50%).

The participants also found the VR environment and the created content immersive and realistic. P1, P3, P7, P19 said "*The TV set was realistic and consistent with the real world*". "*The high quality and realism of the VR environment help you to feel immersed in the experience, and part of the story*", P3 and P19 added. "*The presenter was talking to and pointing at you. This makes you feeling part of the story*", stated by many pairs. "*This is like being inside and being part of a TV program!*", P9 and P15 highlighted. "*The presenter and reporter looked very well integrated in the TV set. You felt like if you were where the news were actually happening*", stated by P3 and P13.

The participants in general felt comfortable in the virtual environment. "*As the experience is not too long, a standing posture gives the feeling of higher freedom and that you can move around*", P5 and P14 said. A few participants (10%) mentioned to had felt a bit tense at the first contact with the Social VR platform, because of the uncertainty, but then they rapidly felt more relaxed.

Besides the feeling of immersion and social presence, the quality of communication was found satisfactory in general. Even though the visual quality for the end-users' representation has room for improvement, being able to see themselves in VR was a fascinating feature for the participants. "*The quality of visual communication between us was not high, but it was a fascinating feature to see my full body and clothing, as well as my pair inside the virtual world*", P4, P9 and P20 stated. "*Despite of noticeable artefacts and not so fluent movements, we could fully recognize ourselves*", P8 and P10 mentioned. "*The quality of my partner's representation seemed better than mine*", stated by P2 and P10. "*The delays for the end-users' reconstruction was noticeable for some gestures, but it was not a barrier for an effective communication*", stated P3. The quality of the audio communication and the spatial audio effects were perceived as satisfactory by the participants, and good enough to feel immersed. "*You could perceive the spatial audio effects, especially when different speakers from different positions were active at different times*", P2 and P13 stated. In general, the interactions between the participants were perceived as natural. "*The interaction was natural, but it is not identical as in real life scenarios: you're wearing an HMD with cables, and you're experiencing a novel medium, not so common for us yet*", P15 stated. Around 90% of the participants stated that the audio-visual interactions enabled them to sense the emotions of their partners to a certain degree. "*We were able to feel the emotions and our excitement*", P6 stated. "*You don't have a full sensing of the emotions, but you can infer them from the audio communications and visual gestures*", stated by P9, P11 and P18. "*It is not always possible to tell the emotions from the expressions, especially when you cannot see the faces*", stated by P1 and P16.

All participants believed that the photo-realistic representations for the end users can help maintain, strength, and even create new, relationships in life. P3, P7 and P12 stated "*It is a very innovative and useful solution. We have friends and family members living apart. This would enable us to meet and share experiences, overcoming distance barriers, and saving time*". In general, participants believe that these systems can be applied to interact with both known people and new contacts, although the use of avatars was also considered convenient for the latter cases, especially when personal relationships are not so important, to overcome shyness, and/or to provide a higher privacy. Suggested applicability use cases for this Social VR technology are enumerated later.

Many participants (35%) affirmed it was an amazing experience for them, and that Social VR can be a powerful tool to evade from the real world in certain situations (20%).

2) Missing aspects / Weaknesses in Social VR

Most participants (90%) would like to be provided with an improved visual quality for the end-users' representations. Having more fluid movements (i.e. higher frame rates) was mentioned by 50%, and having faster reactions (i.e. lower delays) was mentioned by 35% of the participants, as aspects to be improved in the future. The limitations related to the visual quality of the end-users' representations have been already mentioned, so the lack of higher quality for this was also identified as a missing aspect. "*I felt identified with my self-representation, and also could easily recognize my partner. But I know him. This level of quality might not suffice when using the platform to meet with unknown people or for professional use cases*", as stated by P4. "*The quality of the end-users' representation should improve in the future*", declared by P5, P11, P13 and P18.

Integration of multi-sensory stimuli, like scents (10%) and especially haptic feedback (75%), was identified as a missing aspect. P4, P10 and P13 "*It would be great if you could touch things, and if the haptic interactions indeed have an effect on the VR environment or story*".

80% of participants would like to move freely in VR (e.g., 6DoF). "*It would be great if you could move around, get closer to other elements and participants in the shared environment*", stated by P2 and P11. "*If you can move close to each other, then the interactions could be richer; you could e.g. see more details of the emotions and gestures*", P18 stated.

With the combinations of haptic feedback and 6DoF features, participants mainly pursue enjoying more interactive and active experiences. "*If you can actively explore things and complete tasks together, as well as influence the VR environment, then you would be able to really enjoy an interactive and collaborative experience*", P3 remarked. "*The possibility to explore the environment and interact with it would largely increase the immersion*", mentioned P6 and P20.

3) Potential Use Cases

In general, the participants foresee a big impact of Social VR. They identified the following use cases as the most interesting for Social VR: dating (20%), shared video watching

(30%), co-creation spaces (30%), gaming (60%), training (65%), virtual meetings and consultation (85%) and virtual events (60%), like conferences, fairs and religious events. In the case of virtual events, 20% of participants remarked that Social VR can become a powerful tool and medium to plan these events, to experience with the organization and distribution of spaces, furniture, presentation rooms, etc. In these kinds of events, participants highlighted that Social VR can contribute to increase the audiences, because there is no need to travel, thus also contributing to accessibility, to reduce pollution, and to save time and costs. Some participants (15%) also identified Social VR as an ideal tool for migrants and to connect with known people living far away (30%), while others (15%) showed concerns about the duration of the Social VR experiences. "*If the experience is not too long, then Social VR can work. But for longer experiences, you may get tired and dizzy. HMDs should become more lightweight and comfortable*". In general, participants believed that Social VR is a powerful medium to meet with known users, but also to meet new contacts. Most of the participants (90%) declared their willingness to use Social VR in the future. "*I want this at home!*" stated by P8. "*This can be seen as the next generation Skype*", stated by P11. Many participants (25%) stated that the virtual interactions can be very intense and effective and that they are a good alternative especially for first contacts. A few participants (10%) thought that Social VR is more adequate in corporate environments, and not yet for domestic environments. Other ones (10%) shown concerns about Social VR contributing to sedentariness.

All participants agreed that being able to interact with elements of the VR environment, like the live presenter, provides added value. "*You can actually interact with a presenter, or alternatively an instructor, and your conversation influences the evolution of the session. It really provides added value, as you are not just a passive watcher*", stated by P7 and P12. Most of them (90%) also think that supporting more than 2 participants is beneficial and interesting. The rest affirmed that two-person meeting could be just enough in specific use cases, and provide richer interactions.

4) Next Generation of Social VR

The next generation of Social VR is envisioned by participants as environments where the boundaries between the real and the virtual worlds are blurred (P2, P4, P9, P12 and P17), under the umbrella of eXtended Reality (XR). P9 and P17 envisioned: "*A hybrid space where the real and virtual worlds are seamlessly mixed, with virtual elements augmenting the reality and detailed information about certain real elements, as well as multi-sensory stimuli, are provided*". P3 and P20 stated "*Virtual worlds where you can freely move around, and be tele-transported to the places of your choice or need*". P5 stated "*multi-user gatherings with real and virtual users, where you can hardly distinguish between the virtual and real ones, or that at least the quality of the virtual users does not impact the overall experience*". The application of Artificial Intelligence (AI) techniques was also identified as a key feature that can provide significant added value in next generation Social VR systems (10%).

VI. Discussion

This paper has presented an innovative Social VR platform that is able to seamlessly present and blend heterogeneous media formats and to integrate in real-time remote participants in shared virtual environments, both represented as volumetric TVMs and as video billboards (Chroma keying). The platform provides many outstanding and more complete features compared to state-of-the-art solutions, in terms of media and interaction capabilities. The paper has also described a professionally produced TV show-like VR story that has been used to demonstrate the platform's capabilities and to assess both its performance and user experience related aspects through an experiment involving 20 pairs of users.

The obtained results from objective tests reveal that the platform performs satisfactorily for sessions integrating various content modalities, a pair of participants and one live presenter, when using off-the-shelf hardware components. This is already valuable for use cases in which no more than 2-3 users are required (e.g., watching TV in VR together, one-to-one meetings, gaming, etc.). The obtained results from the user tests have proved that the Social VR experience (platform plus produced content) provides satisfactory quality of interaction, immersion and togetherness levels, and that these experiences awake high interest.

With regard to its applicability, the paper has conceptualized how certain future TV and broadcast services could look like, integrating immersive and traditional formats and enabling new forms of interactions, going a step beyond currently existing Social VR platforms and commercial experiences (e.g. Fox Sports). By using this novel technology and medium, the remote audience can become active participants inside TV events, being no more outside passive spectators. They can also feel together and interact with the usual participants of the TV event, like the presenter(s), who can also join the shared experience from remote locations. Thus, the proposed experience goes one-step beyond current watch-together TV scenarios, bringing new be-together-in TV scenarios where there is still an unlocked potential in terms of technological, creative and commercial levels. Besides, the demonstrated use case has awakened a high interest to the participants, anticipating a potential positive impact of this technology in the broadcast and media ecosystems. Even though the tests were conducted in February 2020, before the COVID-19 resulting in a lockdown in Spain, the others already foresaw many other user cases in which Social VR can provide valuable benefits, like training, virtual meetings and consultation, and virtual events. Although having obtained very satisfactory and promising results, it is firmly believed that the ratings related to user experience aspects, provided benefits and potential impact in other use cases would had been even more positive if the tests had been conducted after the COVID-19 out there, when the use of digital communication tools has been magnified, as well as their limitations for natural and realistic communication, interaction and collaboration.

Certainly, the current platform and the provided experience have limitations in terms of both technological and creative aspects. When it comes to technical aspects, additional work is necessary to scale up the number of live video feeds and volumetric users to recreate more massive TV show scenarios in a more realistic manner. Besides, the quality of the volumetric representations of users needs to improve (higher resolutions and frame rates) to provide commercially acceptable solutions. So far, the current bottleneck to scale up in terms of number of participants is on the computational needs to render each volumetric user representation on client side. Additionally, there are limitations regarding the server performance. Although the platform does include an orchestration and relay server, the paper does not provide performance indicators on the server side. This is partially due to the simplicity of its functionalities, limited to signaling direct communications among platform's components and session management.

When it comes to production and scenario-related aspects, the addition of extra interaction features would provide added value. This includes the availability of higher degrees of freedom (e.g. 6DoF), the change of manipulating the virtual environment and influence the storyline via user's actions and behaviors, and the integration of multi-sensory stimuli, like haptic feedback.

All these limitations are however an opportunity to perform further research in the field of Social VR, which has been proven to offer a new way of telling stories and to bring up distributed users together in an immersive and interactive manner. Among others, this can open new opportunities in the broadcast and Over-the-Top (OTT) sectors.

VII. Conclusions and Future Work

Social VR is expected to have a big impact in the near future. This work has presented an innovative and lightweight platform that provides key outstanding features. First, it allows a real-time integration of remote users in shared virtual environments, using (photo-)realistic volumetric representations and affordable capturing systems, and thus having the chance of avoiding the use of synthetic avatars. Second, it support a seamless integration of heterogeneous immersive media formats, including 3D scenarios, dynamic volumetric representation of users and (stored and live) stereoscopic 2D traditional and 180º/360º videos. Third, it provides two main types of interaction features, like a low-latency interaction between the users and presenter, and a dynamic control of the media playout to adapt to the session's evolution.

The Social VR platform has been evaluated for a live broadcast use case, by having recreated a TV show experience, and having obtained very satisfactory results, in terms of performance, user experience, and awakened interest. The evaluations have also shed some light on aspects to improve and on next steps to maximize the impact. In particular, future work will be focused on four key aspects. First, the system's performance, including the delays and the visual resolution of the volumetric user's representations, will be continuously improved. Second, it is planned to perform a comparison between: i) the presented platform and other existing ones; ii) different type of capturing sensors (e.g. RealSense vs Kinect) and setups (e.g. single-sensor vs multi-sensor); and iii) TVMs and other representation formats, like Point Clouds [34]. Third, it is planned to investigate the impact of the number of users in terms of performance and scalability issues, both also on the perceived experience. Finally, the platform will be evaluated for other use cases, including the ones suggested by the users in the interviews, like multi-user conferences/meetings and gaming.

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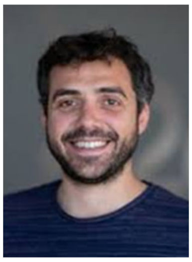

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