Deploying a Novel 5G-Enabled Architecture on City Infrastructure for Ultra-High Definition and Immersive Media Production and Broadcasting

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***Abstract*—With the massive growth of cutting-edge media services, such as ultra-high definition video and immersive media (i.e., virtual and augmented reality), demand for large investments in a scalable, ubiquitous, and robust communication infrastructure and services increases enormously. The H2020 5GCity project aims to provide a solution for such issues by designing, developing, and deploying a sliceable, distributed cloud/edge and radio platform with neutral hosting capability to support the sharing between information technology infrastructure owners and media service providers (i.e., vertical media actors). In this paper, we initially introduce the essential benefits of the 5GCity technology and neutral host model to facilitate the rise of highly demanding media use cases (UCs) and its implication on how service providers typically operate (in terms of business model). Then, we show how the 5GCity architecture and infrastructure, in light of certain key performance indicators, address this demand through three media UCs (namely related to "video acquisition and production at the edge," "immersive services," and "mobile production and transmission") and we explain how they are implemented and deployed in real city-wide pilots (in Bristol, Lucca, and Barcelona) to demonstrate the benefits for infrastructure owners and media service providers.**

***Index Terms*—5G, 5GCity, UHD, VR, NFV, neutral host.**

I. INTRODUCTION

AMONG others, the 5th Generation (5G) technology is targeting next generation of media services such as Ultra High Definition (UHD) and immersive media (such as Virtual and Augmented Reality - VR/AR) as mainstream services for end users. However, this will lead telecommunication providers to experience huge demands in terms of ubiquitous and adaptable coverage and performance requirements such as high throughput and low latency in the system [2], [3]. In addition, vertical media providers will engage in unmanageable amounts of transaction of data (produced and consumed) in the network.

5G technology is reaching more than 11 billion mobile users by 2020 [3] with new networking flexibility and higher data rates compared 4G and 3G [4]. As a result, the initiatives 5G Public Private Partnership (5G PPP) in Europe [5], the International Mobile Telecommunication 2020 (IMT2020) at International Telecommunication Union (ITU) [6], and 5G Americas [7] are promoting and supporting the realization of 5G networks by 2020 and beyond.

One of the key advantages of 5G enabled infrastructures is the evolution of the network sharing beyond the traditional infrastructure sharing models such as site, Radio Access Network (RAN) and core network sharing [8]. As a result, network sharing models will become one of the main pillars of the 5G networks by accelerating the trend towards network virtualization and cloudification. The flexibility offered by these technologies, mainly Software Defined Networking (SDN) and Network Function Virtualization (NFV) can be employed to develop virtual frameworks or network slices, including sets of logically segmented virtualized resources (such as compute, storage, and networks), share within the same physical infrastructure [8]–[11]. Such flexibility in the infrastructure enables customization of the network slices in terms of resource placement, alignment to specific verticals, and more. Moreover, decoupling of control plane from data plane - introduced by the SDN concept - can increase the flexibility and efficiency of the network. Finally, 5G enables migration of computing and storage resources closer to the users with the deployment of Multi-access Edge Computing (MEC) nodes in order to reduce the latency and traffic aggregation required by many digital services typically used by the vertical media industry [8], [9].

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Accordingly, 5G will not only provide higher transmission rates and lower latency compared to its predecessors, but also enable customizable, sliceable, and flexible solutions for the currently stagnated telecom and vertical sectors [10]–[13]. Relative Key Performance Indicators (KPIs), e.g., latency, bandwidth, mobility, etc., shall also be considered and carefully measured to ensure required network performance for successful delivery of media services.

H2020 5GCity technology and neutral host platform will enhance key advantages of 5G networks for next generation media service providers and consumers. It builds and deploys a flexible and intelligent 5G infrastructure sharing, in which network sharing will go beyond traditional infrastructure sharing model. For this, 5GCity will integrate Cloud, Edge computing and radio platform to perfectly align with 5G networks and neutral host model, to support the sharing between infrastructure owners and media service providers.

The rest of this work is organized as follows: Section II provides the required background in terms of projects related to media services, while Section III discusses important challenges in the current media technology. Building upon the understanding of these challenges, Section IV presents the 5GCity project and its architecture, while Section V describes the 5GCity media Use Cases (UCs) and how they are being developed and deployed on different 5G infrastructures in the three pilot cities, namely Bristol, Lucca, and Barcelona. Section VI provides an insight on certain technical KPIs considered by 5GCity project in its city pilots with an illustrative example. Finally, Section VII concludes this article.

II. BACKGROUND

Several researchers have already addressed the topic of media services in 5G systems. However, the focus was merely on facilitating the deployment of media services over 5G infrastructures, so that the benefit of neutral hosting, on-demand network slicing, and other emerging models, remain unexplored. In [14] a 5G-oriented system architecture for a next generation augmented reality tele-immersive two-player video game application is proposed. It considers packaging of Three Dimension (3D) media transcoders as Virtual Network Functions (VNFs) to be deployed on the 5G infrastructure. Reference [15] presents a network resource allocation system using machine learning, SDN, and NFV to enable Quality-of-Experience (QoE)-aware autonomous network management to reach the 5G vision in terms of high resource efficiency required by media streaming.

Tan *et al.* [16] proposed an Ultra-High Definition (UHD) slice design to separate video broadcast/multicast from mobile communication system, thus enabling UHD slices to adopt a new joint source channel coding scheme to approach network capacity. A new adaptive 5G UHD framework is presented in [17] aiming to achieve self-optimizing UHD video streaming in emerging 5G networks. Similarly, Wang *et al.* [18] proposed a cooperative architecture for live video transmission to reduce demand for network bandwidth. Their proposed framework combines a broadcasting network and a cellular network based on Cloud Radio Access Network (C-RAN) to improve the bandwidth efficiency of video broadcasting.

In [19] the SliceNet, a 5G PPP project is presented. It proposes an architecture composed by two architectural domains; i) Advanced managed domain, which slice SDN and NFV to provide a slicing-ready, softwarised infrastructure for 5G; ii) Management and orchestration domain, where the technological challenges envisioned by 5G will be addressed. SliceNet's architecture will be able to create slices with high QoE for video broadcasting UCs.

The architecture proposed in [20] is in the context of another 5G PPP project, 5G ESSENCE. As part of this project, the authors target to fully specify and define the underlying architecture and interfaces that will enable the development of a Software Defined Radio Access Network (SD-RAN) controller to manage all the Cloud-Enabled Small Cells. Moreover, they intend to further use virtualisation techniques to improve the resource usage, throughput, and delay at the service level. At the end, the project will demonstrate a novel cloud-integrated multitenant Small Cells network suitable for media services.

5G-MEDIA [21] is another 5G PPP project, which applies SDN and NFV technologies to media applications to build an integrated programmable service platform for facilitating, designing, and developing media services over 5G infrastructures. It aims to innovate media-related applications to be coupled with 5G networks, thus the applications ensure resource allocation for delivering high QoE, while preventing the overloading of media traffic. For this, 5G-MEDIA deploys the media application functions close to traffic sources, and 5G-MEDIA orchestration platform configures network paths to deliver required network traffic to the network edges.

5G-Xcast is also a 5G PPP project that demonstrates an architecture for broadcast and multicast communication over the 5G wireless networks [22]. It converges 5G infrastructure for fixed and mobile access network, including terrestrial broadcast, to audio-visual media content. 5G-Xcast targets innovative solutions for large-scale immersive media delivery to i) develop broadcast and multicast point-to-multipoint capabilities for media, IoT, public warning and automotive UCs and ii) design a novel adaptable 5G network architecture with layer-independent network interfaces to dynamically and seamlessly switch between unicast, multicast, and broadcast transmission (or use them in parallel).

Finally, FLAME is also a 5G PPP project [23], which develops a platform for large-scale experimentation of future media Internet services fully integrated with broadcasting supporting high mobility scenarios. This platform supports trials and experiments of media services on highly distributed software-defined infrastructures. FLAME platform provides fast access to media and services for users with low latency and high personalization of the experience through closer media processing. In addition, by enabling the broadcasting of contents to multiple users without the need for adopting clients and services to specific multicast protocols, FLAME claims to significantly reduce the costs of video delivery.

All 5G PPP projects including 5GCity are offering innovative services over 5G infrastructure to their customers with fast and seamless access to the media and services. However, 5GCity move one step further by empowering the city infrastructures and transforming them into a hyper-connected, distributed 5G-enabled edge infrastructure, where different media companies will utilize dynamically different slices in order to satisfy business requirements. This enables service providers, by using 5GCity platform, to offload capacity to the neutral host (real-time video acquisition and production in the Edge and the Cloud) in dense environments such as crowded districts and events in city wide 5G infrastructures.

III. CHALLENGES OF NEW CITY MEDIA SERVICES

The advent of UHD/4K and immersive reality services and the increasing demand of video production and distribution require higher flexibility and bandwidth [2], [13], [24], thus leading the broadcasting industry to adopt Internet Protocol (IP) as transport technology to provide flexible and agnostic video distribution. Therefore, the background of video over IP and network requirements for video production and distribution -related to our 5GCity media UCs - is discussed in the following paragraphs.

Video over IP allows convergence among video, metadata and general data by integrating the broadcasting industry into a larger IT industry. IP networks have been evolving its own architectures from traditional hierarchic ones to flatter ones, such as the leaf-and-spine, used in most of the big datacentre deployments nowadays facilitating horizontal data movement, useful for heavy load transactions between same level hosts.

A huge consumption of video over IP comes from the Hypertext Transfer Protocol (HTTP) protocol. Services like Netflix, Amazon Prime or even YouTube rely on this technology. Typically, this kind of services provides multiple versions of the same stream that adapt the quality of the video based on the available bandwidth and the capabilities of the device. The Adaptive Bitrate Streaming (ABS) happens when a single source video is encoded at multiple bit rates and followed by a manifest file. The streaming client loads the manifest to become aware of the available streams at different bit rates and the segment's locations in the streams. It works by detecting a user's bandwidth and CPU capacity in real time and selecting the streams that suite well for the bandwidth and decoding capabilities in specific time. Two well-known protocols for ABS are the HTTP Live Streaming (HLS) and the Moving Picture Experts Group - Dynamic Adaptive Streaming over HTTP (MPEG-DASH) [25], [26].

Furthermore, network layer, transport layer and application layer require some important functionalities to deal with video production and distribution challenges. The network layer can provide multicast routing (such as Distance Vector Multicast Routing Protocol (DVMRP); Protocol Independent Multicast (PIM), to name a few possibilities) and QoS functions as type-of-service/differentiated-services-code-point. The transport layer for video over IP uses User Data Protocol (UDP) for real-time video transport to avoid unnecessary retransmission for live streams. The Request for Comments (RFC) 3550 Real Time Protocol (RTP) was introduced to transport audio and media services using a timestamp field together with the RTP protocol for Control Purposes (RTCP). Recently, new extensions were introduced to support the adoption of services by broadcasters' workflows. Concretely, RTP1, RTP2, RTCP1 have been proposed to accommodate media-specific info over IP, responding to specific challenges.

On upper layers, new standards were created to encapsulate audio (Audio Engineering Society (AES) 67-2013) and video (Society of Motion Picture and Television Engineers (SMPTE) 2022-6) to support the transport of high-quality media signals over IP networks. On the video side, SMPTE 2022-6 is focused on mapping Serial Digital Interface (SDI) and High Definition Serial Digital Interface (HDSDI) (opposite to raw video, audio and metadata mapping - known as essence mapping) within IP packets and further specific solutions to manage packet loss recovery using Forward Error Correction (FEC) (SMPTE 2022-5) and a seamless protection switching system (SPSS)(SMPTE 2022-7).

In 2014, the Video Services Forum (VSF) formed a new group (SVIP) looking at new encapsulation mechanisms for audio, video and auxiliary data into IP without using SDI framing (raw data) to develop or recommend a standard for video over IP without SDI encapsulation. The work in VSF led to the creation of two recommendations or Technical Report (TRs), TR-03 and TR-04. TR-03 provided for video, audio and auxiliary data that can be managed independently as separate streams in the network. TR-04 was a recommendation on how to use the existing SMPTE 2022-6 to serve as an alternative video payload type within the VSF TR-03 structures, in a way that would allow for the audio and metadata streams as well as the SDI multiplex to be identified and routed in a video production network [27], [28]

The SMPTE developed the SMPTE ST 2110 suite of standards for Audio, Video, Metadata, and other elemental media types. The foundation for SMPTE ST 2110 [29] is VSF's TR-03 recommendation. Furthermore, SMPTE ST 2022-8 has been proposed to enable incorporation and coexistence in an ST 2110 system, of a rasterized video in RTP (SMPTE 2022-6), thus bringing to life the intentions of VSF TR-04. To tackle synchronization issues, SMPTE 2059-1 and SMPTE 2059-2 were created based on IEEE 1588-2008 Precision Time Protocol (PTPv2) [30]–[32].

Further to that, complementary industry specifications on registration and discovery, device connectivity and network control, are under discussion. Specifically, under the Networked Media Open Specification (NMOS): NMOS IS-04 for registration and discovery and NMOS IS-05 for device connection management have been developed by the Advanced Media Workflow Association (AMWA), while NMOS IS-06 network control is in progress. These processes simplify the building of IP production facilities and automate the pipeline of video production through automatic chaining of device connectivity configurations [33]–[35].

In the media plane, protocols such as Real-Time Streaming Protocol (RTSP) for end-to-end session control or Session Description Protocol (SDP) for service description provide capabilities for the stream management. SMPTE ST 2110-10 addresses the transport-layer protocols, synchronization and

TABLE I
VIDEO PRODUCTION REQUIREMENTS

Format/ Technology	Bandwidth (Uncompressed)	Bandwidth (Compressed) [30]
Mobile Camera	-	10/20 Mbps [37]
HD1080i	1.5 Gbps	110 Mbps
HDSDI 3G	3 Gbps	150 Mbps
4K @30fps	6 Gbps	600 Mbps
4K VR	6+ Gbps	600 Mbps

TABLE II
VIDEO DISTRIBUTION REQUIREMENTS [37]

Format/Technology	Live Event	Video on Demand
HD	6 Mbps	6 Mbps
VR 360 (4K)	20 Mbps	20 Mbps
4K UHD (HDR)	20 Mbps	20 Mbps

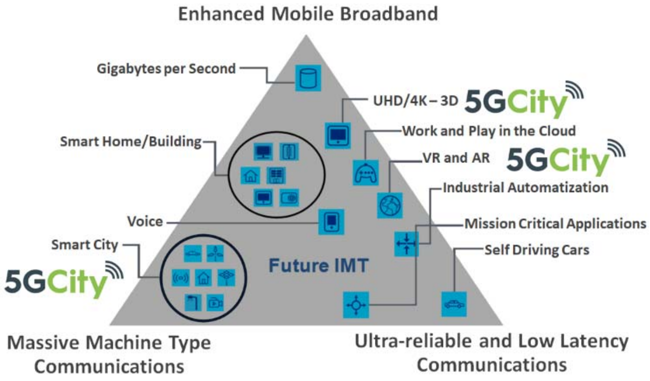

Fig. 1. 5GCity scenarios in the context of 5G media areas [6].

the requirements for SDP. SMPTE ST 2110-20 addresses the ways of transporting uncompressed video with the use of RFC 4175 and RFC 4566 (SDP) to provide a machine-readable layout of this information [29], [30].

Complementary, media wrappers aim to gather different types of media program and associated information, as well as generically identify this information. Currently, several wrapper formats are available, but few of them address characteristics like openness, extensibility, and performance for the media industry. Media Exchange Formal (MXF) (an SMPTE standard) is a "container" format, which supports several different streams of coded "essence". It is encoded in any of a variety of video and audio compression formats, together with a metadata wrapper, which describes the material contained within the MXF file and enables interoperability between different platforms. In addition, Data Distribution Service (DDS) (a machine-to-machine middleware standard from OMG) can be used to enable interoperable media exchange between actors. Meanwhile, the European Broadcasting Union (EBU) has launched a framework for interoperable media services, in order to answer to different interoperability issues between Service-Oriented Architecture (SOA) proprietary systems by defining an open, consensual framework with standardized interfaces.

As example of broadcasting requirement Table I summarizes compressed and uncompressed video production bandwidth requirements per connection and video format or technology [14], [36]. And Table II summarizes the bandwidth requirements per connection to be considered in the video distribution trials of the 5GCity UCs, for video compression formats MPEG-4 Advanced Video Coding (AVC) - H.264 or High Efficiency Video Coding (HEVC) - H.265.

IV. H2020 5GCITY PROJECT

A. Broadcasting-Related Technologies in the 5G Landscape

Network infrastructure sharing is an essential element to unlock commercial take-up of dense 5G wireless networks [9], since it will be unfeasible to deploy hundreds of vertically isolated access networks, especially in urban scenarios, where very dense deployments of small cells will be required. The neutral host model and network slicing will play a key role in the deployment of 5G networks that address the challenges faced by infrastructure providers [13] and vertical media actors, including video streaming and production in dense urban environments [5], [38]–[41].

One of the goals of 5G is to increase mobile broadband capacity to provide specific functionalities to users, industries, and the society in general. For this, as illustrated in Figure 1, 5G systems must support different areas and characteristics. Following this model, 5GCity addresses three different scenarios, namely video acquisition and production in live events, immersive video distribution, and UHD real-time wireless transmission, which are related to the 5G areas (enhanced mobile broadband, massive machine-type communications, and low-latency communications) as shown in Figure 1.

B. 5GCity Neutral Host

5GCity introduces "neutral hosting" functionalities in the design, deployment, and development of a distributed cloud and radio platform [5], [41]. To this end, the NFV, SDN and Multi-access Edge Computing (MEC) are integrated within a common distributed cloud and radio platform. This architecture allows infrastructure owners to monetize their investment and media service providers to deploy collaborative and innovative applications and improves the end user's quality of experience. One collaborative and innovative media deployment (Figure 2) with 5GCity architecture is the sharing of processing and caching capability into an integrated MEC with small cell radios to bring the network and video processing/production "closer" to the user while easing the deployment of dense small/macro cell deployments for urban environments.

C. Neutral Hosting and the Media Vertical

European mobile operators together with manufacturers and other vertical players have been working in recent years on various trials to validate 5G's new features. The European 5G Observatory demonstrates that European operators are heavily involved in 5G technology, testing with 114 trials reported in EU-28 countries [42]. As many mobile network equipment vendors are already engaged in pre-commercial trials and the

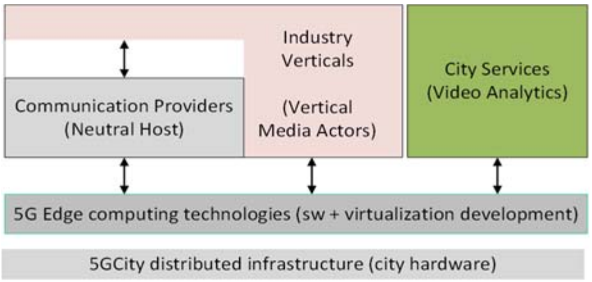

Fig. 2. H2020 5GCity project's architecture and actors.

two major chipset vendors have already announced to have their 5G modems by 2019 working alongside with cutting edge MNOs in concept tests, it is expected that soon European mobile operators yield up their route about 5G network deployment and the launch of commercial services [43]. According to 5G observatory it is also expected to see 5G deployments with tens of base stations in many cities across Europe by 2019.

The 5GCity project is deployed for validation of the different 5G infrastructure exploitation models, using NFV virtualization, network slicing and RAN sharing techniques. In 5G communication, where new demands are emerging in the world of wireless communication (availability of mobile broadband anywhere and at any time, capacity for massive connection of devices or support for critical communications such as remote control of devices), the 5GCity project was born with the intention of providing the basis to satisfy these needs. For that, a neutral operator or infrastructure provider (i.e., neutral host) can offer its infrastructure (access network, network core, management, etc.) to the third parties, and these (with the corresponding permits and licenses for the use of the radio spectrum) can create new instances of virtualized services in the neutral operator's equipment. This scenario will not only allow operators to practically eliminate Capital Expenditure or investments in goods (CAPEX) but also allow them to minimize Operational Expenditure or operational costs (OPEX), thus facilitating the introduction of new 5G technologies.

For the media industry, this means that the networks used for broadcasting and other services can be adapted or extended on demand via requests to the neutral host, without depending on "bigger" changes added by a telecom operator. Therefore, by offering a platform tailored to neutral hosting, 5GCity adds flexibility for the realization of dynamic and demanding media-related UCs.

D. 5GCity Platform and Infrastructure

The embodiment of all technical aspects described so far is materialized by the 5GCity platform [44]–[46], a software suite which allows complete lifecycle management of end-to-end network services dynamically created over heterogeneous city infrastructures. The 5GCity platform is composed of the following main elements.

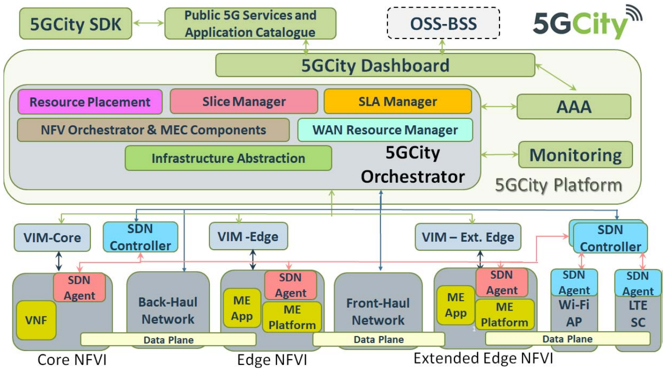

Fig. 3. H2020 5GCity architecture [44].

- **5GCity orchestrator** is the core entity of the platform, /which handles the complete life-cycle management of the network services, providing the suitable degree of abstraction between resources as exposed by hardware layer and services as intended by end-users.
- **5GCity dashboard** is the main operational interface allowing 5GCity users (vertical or service providers) to deploy network services over an owned set of network slices.
- **5GCity Virtual Interface Managements (VIMs)** are the entities which acts as intermediary between the orchestrator and the physical resources located at various levels (Core VIM for datacentre level, Edge VIM for network edge level, and Extended Edge for devices level).
- **5GCity NFVIs** are thin layers deployed over the pool of hardware resources and acting as agent for the configuration of the physical resource management (on the three levels, similarly to the VIMs).
- **SDN controllers** are the functional entities which provide suitable control plane operations.

Figure 3 presents the main vision of the 5GCity architecture and how the 5GCity platform will be integrated with VIMs, NFVIs, SDN controllers, networks, and radio elements to be deployed at the core, edge, and extremely edge of the city infrastructure.

To be able to successfully deploy the 5GCity platform, a city infrastructure should satisfy the following requirements:

- Central pool of hardware resources (computing/storage).
- One or more pool of hardware resources deployed at the edge of network borders.
- A high-speed communication network which can wire together different pool of resources.
- One or more radio access points (Wi-Fi Access Points (Wi-Fi AP) or Long-Term Evolution (LTE) Small Cells (LTE-SC)) which ensure 5G connectivity to the user.

Upon satisfying these requirements, the recommended deployment is depicted in Figure 4. Further, in Figure 5 we shown how Virtual Machines (VM) that contain implementation of Virtual Network Functions (VNF) are deployed upon this three-tier architecture to realize end-to-end (network) services. Concrete instances of this pattern are used in the next section to describe the deployment of the pilot media and broadcasting UCs.

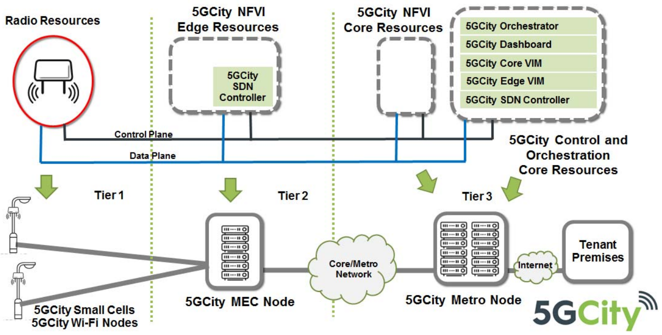

Fig. 4. Mapping of 5GCity architecture into a the three-tier candidate city infrastructure [46].

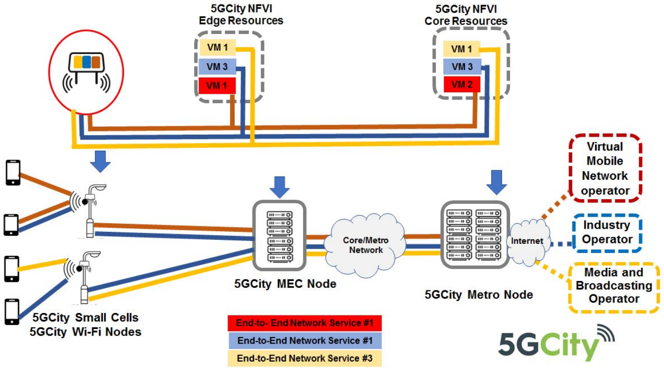

Fig. 5. Enablement of end-to-end network services by the 5GCity platform.

V. 5GCITY MEDIA USE CASES FOR SMART CITIES

To demonstrate the benefits of the 5GCity approach for infrastructure providers and UHD/4K and AR/VR media providers, the project designed three uses cases for deployment and test in three important European cities, namely Barcelona, Bristol and Lucca. Different aspects of the media and entertainment industry are integrated and tested within these 5GCity pilots, pivoting mainly around video acquisition, editing and delivery. The following subsections describe the three Use Cases (UC), as well as the way to deploy them by using the 5GCity system.

A. UC#1 Real-Time Video Acquisition & Production at the Edge

Description: Sports and music events are more and more filled with people using their smartphones to share the best moments [47], [48] of the show with their friends. Many of those applications not only exhibit very high business value for media companies and potential impact on society (e.g., increasing citizen participation) [50], but also have critical QoS/QoE constraints (e.g., latency, video resolution, number of users) and a need for dynamic adaptable infrastructure (i.e., dynamic scaling).

On a different page of the same UC, in July 2005, photographs and videos taken by ordinary citizens were the only illustration of what happened at locations affected by the London underground explosions and used by major television stations such as the British Broadcasting Corporation (BBC).

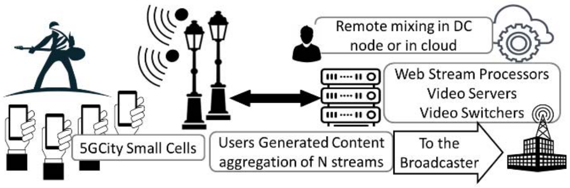

Fig. 6. UC#1 summary.

In November 2015, videos taken by spectators from the Eagles of Death Metal concert at the Bataclan show in Paris revealed in first-hand the beginning of the terrorist attack and the actions of the police forces. Enhancing the user experience of video acquisition and production for live event production and broadcasting can create chances for revenues. It can also promote user and community engagement experiences, such as the ones performed via Facebook or YouTube. With the wide deployment of smart objects and the increased numbers of connected mobile devices, many applications nowadays operate on a large scale and cooperative interactions among participants [45] via mass public engagement or as part of a persistent online community [46]. An illustrative summary of UC#1 is shown in Figure 6.

Implementation: The implementation of the referred concepts faces different challenges, such as:

- The need to guarantee a direct, efficient and effective means of communication between event organizers and citizens, using smartphones and available network infrastructure, regardless of the typology and format of the content that is intended to be created.
- The need to receive, select, and process in real time the different video streams in an elastic way [49], [50], to manage different types of crowds and to propagate the edit stream to the TV station so that it can be further distributed in the shortest time possible.

This UC showcases also how infrastructure owners (venue) can monetize their IT and connectivity investment by renting these edge resources to other third-party entities requiring dedicated connections with a set of specific networks KPIs during specific events [51]. The envisioned scenario is very well known to media service providers as added throughput capacity at the front-haul link is always required during such crowded events.

Deployment: Through 5GCity's platform, several dedicated network slices are being deployed in Bristol (See Section V) in an NFV fashion, offering dedicated 2-8 Mbps fronthaul links in a multiple Radio Access Technologies (multi-RAT) environment. With these access networks, end-users will be able to connect to different WiFi access points and even small cells LTE / 5G and leverage the low-latency communication link between edge applications and those running at 5GCity's core network. Crowdsourced video streams (e.g., from end-user's cell phones) will be pre-processed at the edge before being transmitted via a 1 Gbps link to the core or another edge datacentre or MEC node. This is shown in Figure 7, including the Virtual Network Functions (VNFs) used for this UC, while illustrating how their deployment is performed upon the three-tier 5GCity infrastructure.

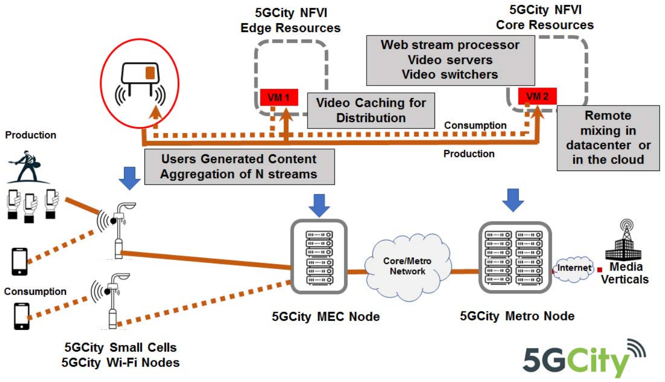

Fig. 7. Deploying the UC#1 service chain with 5GCity in Bristol.

B. UC#2 UHD Video Distribution and Immersive Services

Description: While previous generations of network technologies have been designed as general-purpose connectivity platforms with limited ability of adaptation to different UCs, the situation changes with the introduction of 5G networks. 5G creates a new ecosystem that allows the involvement of vertical markets in network service chain deployment, with media & broadcasting being one of those verticals.

Media companies are experimenting as vertical actors for evaluating the impact that the new generation of network will have on the overall TV production workflow. In this context, the 5GCity project proposes a technical solution for the creation of an end-to-end platform with the dual functionality of supporting TV production and provisioning of services for the end user.

This UC is designed to cover the needs of a media company both in production and in the field of the distribution of services by exploiting the potential of the 5G network in terms of data transfer rates, low latency, high number of connected devices, and intelligent orchestration of virtualized networks. In this regard, a key point of the technical solution is the interaction of the network with “smart objects” used daily in UHD video distribution. This includes the video acquisition devices along with new objects such as drones and 360-degree cameras.

Further, for the services and applications delivered to the end users, the broadcaster will be able to exploit a wide range of devices that are entering the consumer market, namely connected televisions but also new generation smartphones, and wearable devices of the viewers for virtual / augmented / mixed reality. All these devices will become part of the complex 5G ecosystem, which with our solution connecting them to the precious material that resides in archiving systems of the television world. An illustrative summary of UC#2 is shown in Figure 8.

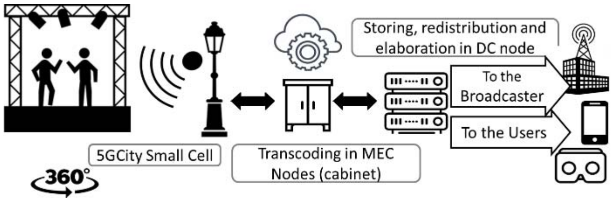

Fig. 8. UC#2 summary.

Implementation: To validate the network capabilities required to support this kind of devices and 5G network interconnection, the 5GCity project covers some big events in the City of Lucca with a set of services as UHD/4K video distribution and immersive experiences. The following test and promotional material have been specifically produced for the project: 5GCity video promo, Lucca Summer Festival backstage, Lucca Comics and Games and an immersive artistic tour of the “Casa Giacomo Puccini” museum.

This implementation is designed to allow the end-user to move in a city to obtain additional content related to the surrounding environment (monuments, objects, etc.) by using smartphones and/or VR/AR/MR-like devices [2], [36], [39], [52]. Further, the production of 360° video is improving the immersion of the user experience. At the same time, the visual search allows matching images or videos captured by the user, such as buildings, statues, and paintings, with contents present in databases. Additional content could be automatically retrieved, for example from television archives, in form of 2D video, panoramic video, and 3D models that will augment the reality in which the user is immersed.

The video 360 material is produced with specific camera systems which have a minimum of two sensors, and two lenses, to have a Field of View (FoV) as large as the whole spherical horizon around the camera. The different video contributions are processed in suitable applications, where the stitching of the different images, the colour correction, the projection – usually in the equirectangular format – and the coding, are performed. These systems require synchronization among the cameras. Recent products consist in a single system equipped with several sensors which are already synchronized. Some examples are the Nikon Key Mission 360 with two sensors, the Orah 4i with four, and the Nokia Ozo with eight sensors. To generate video 360 material to be used as VoD (Video on Demand), the Nikon system was selected both because of its ease of handling and because it is an “action cam” system, which is suitable for outdoor use. It records on an on-board micro-card from which the sequences can be transferred to an editing/processing machine for “makeup” and finally loaded on the video repository. To generate streaming material, the Orah 4i system is used because it has an embedded streaming server capable of providing “live” video. This system requires electric power supply and must be used indoors. Both systems generate 4K sequences at 24/30 Hz with equirectangular projection which are indistinguishable from traditional UHDTV signals. For 360° video streaming, the distribution of live or VOD 360° video services over IP can follow two possible approaches [37]–[40], namely either the “Viewport-Independent” approach or the “Viewport-Dependent” approach with tiled encoding. In both cases, it is assumed that an equirectangular projection is used for conversion of the 360° video into a two-dimensional rectangular video before the encoding stage.

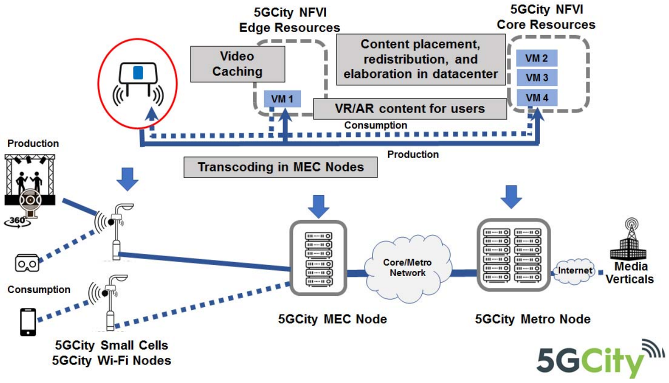

Fig. 9. Deploying the UC#2 service chain with 5GCity in Lucca.

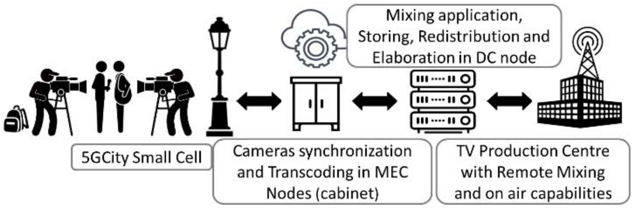

Fig. 10. UC3 summary.

Deployment: All in all, this UC requires high bandwidth to carry high quality UHD/4K video signals and a very low system latency, which should enable the implementation of interactive applications. The 5GCity architecture facilitates both with its distributed cloud & edge and radio 5G-platform via a service chain deployment such as the one shown in Figure 9, which is currently performed in the City of Lucca.

C. UC#3: Mobile Real-Time Transmission

Description: Almost all TV stations are currently using what in popular language is called "backpack unit" for video transmission in remote areas. The backpack unit bonds multiple 4G connections together to transmit the video signal back to the TV station for further processing. This kind of technology is already in use with the actual networks, but with big constrains, as it is not possible to use this system in very crowded areas, because network operators are not able to guarantee the connectivity or the required bandwidth. In such situations, TV broadcasters are using satellite technology, with all the constrains that this technology has, namely very low flexibility (the satellite segments must be booked in advance) and the high cost of the satellite time. An illustrative summary of UC#3 is shown in Figure 10.

Implementation: The mobile real-time transmission UC demonstrates how the 5GCity architecture can improve the available bandwidth of live connections (real-time transmission) leveraging on the capacity of 5G networks. The 5GCity system enables the increase of bandwidth used for live connections, provisioning specific slices with a guaranteed QoS, and enabling edge computing processing capabilities for production of video contents at the edge. This kind of edge computing reduces the high production cost of multi-camera events [36].

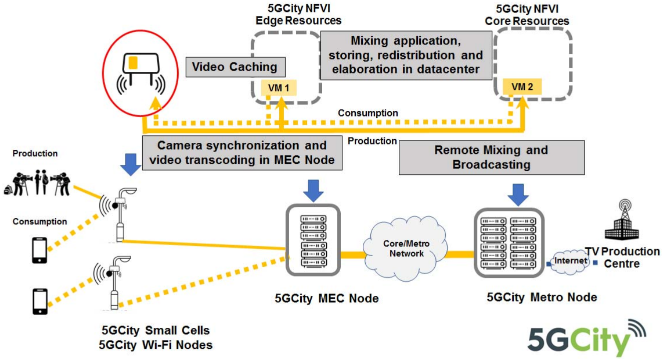

Fig. 11. Deploying the UC#3 service chain with 5GCity in Barcelona.

TABLE III
SOME REQUIREMENTS FOR UCS PRODUCTION

UC	Radio (Mbps)	Network (Gbps)	Edge (VM#)	Core (VM#)	Internet (Mbps)
#1	UL:2-8	~2	1	1	50
#2	UL:100 DL: 20	~1	1	3	100
#3	UL:10	~0.1	1	1	50

Description: The exact service chain and deployment upon the 5GCity three-tier architecture is under test in Barcelona and illustrated in Figure 11.

Table III summarizes the minimal computing and networking requirements for each media UC. First in terms of radio (wireless) bandwidth for video Uploading (UL) and/or Downloading (DL). Then, network bandwidth to transmit the video from the radio to the edge and core datacentres. Finally, we define the number VMs needed in the edge and core datacentres. And the Internet connection required for remote access and control.

VI. 5GCITY KPIS AND PILOTS

Key to the validation of the 5GCity architecture and its UCs is the measure of the performance of the various components and of the end-to-end system against a set of KPIs (Key Performance Indicator). In this section we present the set of main KPIs which will be measured during the execution of the various UC tests in the 5G infrastructure of the three cities. These general KPIs result from the synthesis of various technical metrics and performance indicators related to the virtualized infrastructure and the orchestration layer. An illustrative example of the planned trial and evaluation in the City of Bristol is also presented.

A. Targeted KPIs for 5GCity Pilots

A detailed analysis of the applicable KPIs to 5GCity pilots and UCs has been presented in [4]. Table IV below presents a summary set of the 5GCity performance indicators which have been elaborated starting from the general 5G PPP requirements [53] applied to the 5GCity context. Due to the

TABLE IV
5GCITY KEY PERFORMANCE INDICATORS

Projects KPI\UCs	**Crowded Venues**	**50+ Mbps everywhere**
1- Device Density	1000– 10000 devices per km2	**Rural:** 500 Mbps/km^2 **Urban:** 25 Gbps/km^2 **Rural/Urban:**5 Gbps/km^2
2- Mobility	0-6 Km/s	
3-Infrastructure	Medium (macro and small) cells	
4-User Data Rate	50 – 100Mbps.	DL: 50 Mbps (100 Mbps, ideal) UL: 25 Mbps
5- Latency	<= 10 ms	
6- Reliability	> 99 %	

nature of 5GCity UCs we decided to profile KPI for crowded venues and high throughput services per user (50+ Mbps).

To benchmark the level of performance in the various UCs executed in the three pilots, we have set up a measurement methodology which integrates performance metrics for:

- The various 5GCity NFVI platform components, in terms of time to boot and image footprint of the VNFs and extending to traffic isolation and VNF-to-VNF throughput
- The RAN slicing elements, to measure the switching throughput of the wireless virtualization solution for 802.11 radios and the number of devices that can be supported by the mesh wireless virtualization
- The virtual infrastructure management & orchestration, to profile the edge service instantiation time, orchestration responses, and streaming analytics for the monitoring component.
- Application-level metrics and Key Quality Indicators (KQI) to assess the responsiveness and scalability of the applications to be deployed in the various UCs in terms of measured end-to-end throughputs for media streaming, time to stream contents, number and type of applied transcoding's, frame losses/retransmissions, etc. These set of KQI allow to evaluate the end-to-end service performance and quality of the applications to be deployed in 5GCity pilots and can better reflect the customer experience with these services. In 5GCity we are in the process of defining a set of KQIs based on available standard references like those defined in 3GPP TR 32.862 V14.0.0 [54].

B. 5GCity Pilot in Bristol

As an example of environment for the execution and measure of the KPIs mentioned in the previous section, Figure 12 describes the 5GCity pilot under final deployment in the City of Bristol. Similar pilot strategy is also planned for the cities of Lucca and Barcelona. This infrastructure is composed by a 5GCity Metro Node hosted in the High-Performance Network Lab datacentre (HPN-DC) of the University of Bristol, two 5GCity MEC nodes hosted in We-The Curious (WTC) cabinets and 5G Room and Millennium Square (MS), and two clusters of radio resources of small cells and Wi-Fi nodes distributed between MS and Harborside. All components are interconnected by a core metro network formed by optical links. The bandwidth available of the optical links is 10 Gbps per wavelength. Each UC will use a slice of the infrastructure which is formed by VNFs or VMs in the computed nodes and network resources, like, wavelength and/or VLAN, virtual access points in Wi-Fi nodes and a channel in the small cells.

C. 5GCity Pilot's Illustrative Evaluation

The illustrative example introduced in Figure 12 shows the planned deployment and trial of media UCs #1 and #2 in the City of Bristol. The 5GCity dashboard is the front-end to 5GCity platform that enables the infrastructure slicing. Delay reduction required by the targeted KPI is made possible by deploying compute resources at the edge VIM rather than core VIM on the MEC nodes, closer to the media production and consumption area and 5G fronthaul. Intelligent resource scheduling algorithm will provide flexible and efficient slice ability for any of the tenants as per requirement.

The integration and collaboration between production and consumption is nurtured when the slice is customized to provide optimized content placement (or cached content) and resource elasticity (e.g., additional capacity for slice), not only to aggregate the production but also to improve the QoE of end users or consumers of the video. The Figure 12 shows two tenants sharing a 5G neutral infrastructure of Bristol. The first tenant is the UC#1 that deploys and connects the virtual machines (VMs) in edge VIM and core VIM to host an application for multiple users (e.g., 20-50 mobile phones with 2-8 Mbps UL) acting as producers or recorders of a live event. The VMs at the edge VIM and core

VIM will aggregate and synchronize the video contribution in the 5GCity MEC node and host a virtualized video server for processing, switching, and editing in the datacentre which is accessed and operated remotely by TV producers. This connection will demand some large network bandwidth during the event (i.e., $\sim$2 Gbps). Then, for immediate broadcasting or streaming for users or consumers, the producers will use the same slice with additional resources at the edge VIM in the 5GCity MEC node to host and cache video contents populated based on the demand. The flexibility and intelligence of 5GCity dashboard could allow the fast allocation of more resources (processing and bandwidth) for production in case of an increase in the demand (more users recording the event) or more users requesting to stream.

The tenant 2 is the UC#2 which consist of production and streaming of virtual reality or 360-degree video to users. Slice#2 will allocate resources for production in a VM at the edge VIM for transcoding, and VMs at core VIM for storing, redistribution and elaboration with the remote intervention of a broadcaster or a virtual reality company. Given that the delay and flexibility demand, the tenant 2 will also request for network resources at all lamp-posts, hooked up

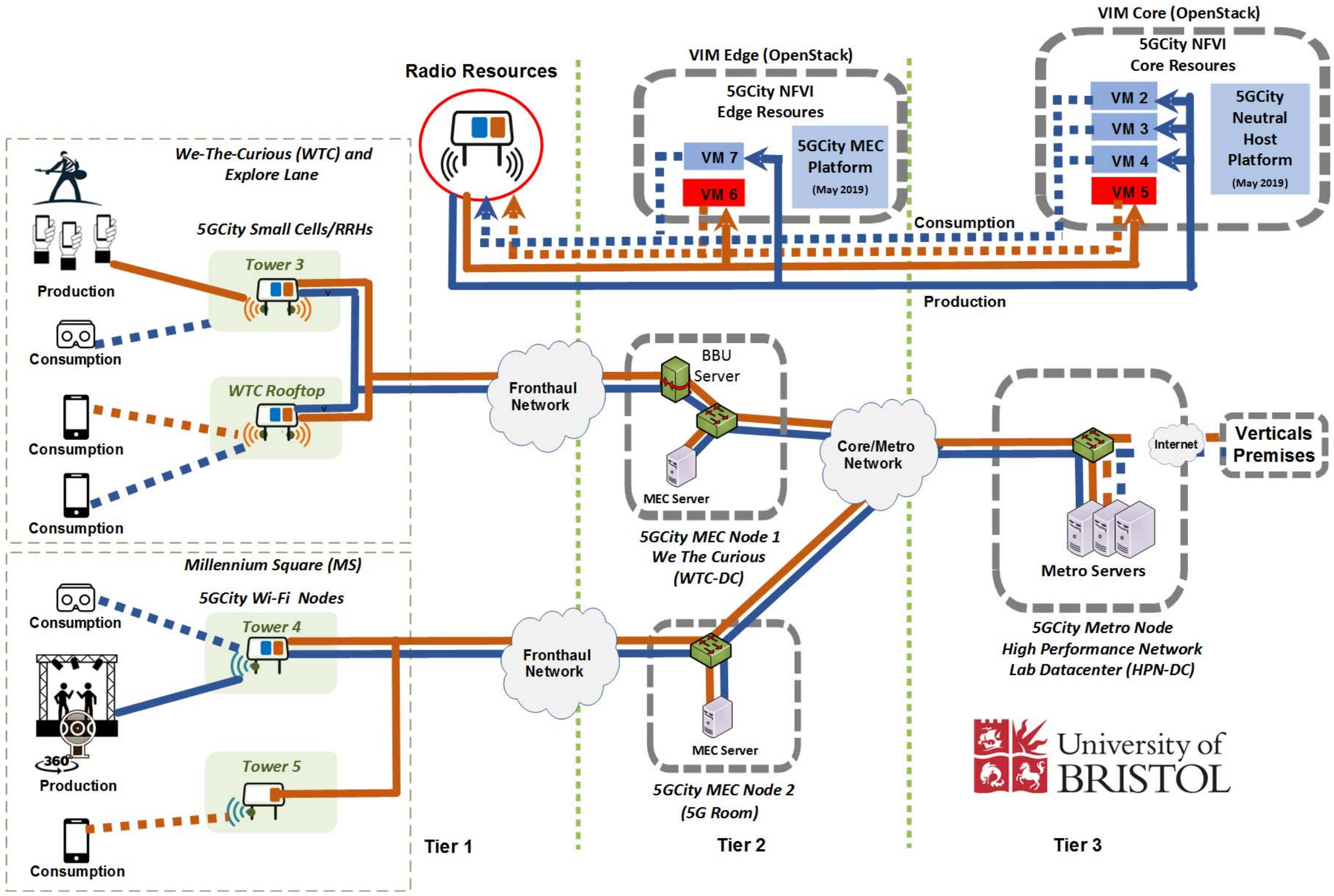

Fig. 12. Illustrative example of the planned pilots in the City of Bristol, where UC#1 and UC#2 are slices in the 5GCity testbed.

with Slice#2 computing resources at edge VIM, to make the processed 360-degree videos available for all the VR users.

Finally, the resulted video content will be placed in VMs on the edge VIM for consumers or local channels requesting the news or event coverage. The 5GCity dashboard will provide resource allocation and temporary schedule to handle the different demands and avoid collision or any capacity crunch of the shared infrastructure. As a result, 5GCity model will save time and money for small and large TV and media production and broadcasting companies and will also open many opportunities for new services [1].

D. 5GCity Pilot's Evaluation Methodology and Progress

To assess the performances of the 5GCity pilots and UC scenarios defined in the previous sections, we are defining for each city tested a standard suite of test and KPI measurements based on Table IV.

- *User Data Rate:* here we intend to measure the minimum data rate required to achieve an enough quality experience. For this we will monitor uplink bandwidth when a single UE generates traffic towards the application server. An early evaluation of this KPI with an early demonstration of UC#1 was successfully conducted in the partially deployed 5GCity testbed of the City of Bristol (Figure 12). The measurements confirm an average of 25 Mbps UL and 70 Mbps DL per UE, when 3 UEs where recording HD video and one UE was producing and broadcasting HD video to another 3 UEs. The UC#1 application was installed in a VM hosted in the VIM Core of the 5GCity Metro Node (HPN-DC). And the UEs where distributed between WTC and MS.
- *Latency:* here we intend to measure the time that takes to transfer a given piece of information from a source to a destination, either in data plane or in control plane. To measure this metric, we will execute repeated ping tests (divided by 2 to measure the one-way delay) between UE and the application server for data plane measures or between the 5GCity orchestrator and other components of the control plane.
- *Reliability:* here we will measure the percentage value of the amount packets successfully delivered to a given system entity within the time constraint required by the targeted service, divided by the total number of transmitted packets. To derive the reliability measure we will count the packets lost from UE and the system. In addition, we will perform reliability measurements by emulating different types of attacks or reliability treats targeting the 5GCity neutral host platform and the 5G control and data plane. The resulting measurement will help us to identify the vulnerabilities and some strategies

to reduce their negative impacts on 5G and neutral host model [55], [56]. However, any reliability study can only be performed after a full deployment and integration of the 5GCity platform on each testbed infrastructure.

In addition to what described above, we will also measure:

- *Service Creation Time:* this is the time needed to activate a Network Service that comprises multiple VNFs in a service chain. We will measure it as the difference between the time elapsed between when the Network Service instantiation is requested, and the time when all the QoS metrics defined for the service are met or exceeded.
- *Virtualised Resource Utilization of Network Slice Instance:* this metric measures the utilization of virtualised resource (e.g., processor, memory, disk) that are allocated to a network slice instance. It can be measured by counting the usage of virtualised resource (e.g., processor, memory, disk) in NFVI by dividing each value by the system capacity allocated to the network slice instance.

As a result, conclusive measurements are not available at the time of writing this article, because the 5GCity infrastructures are still under deployment. Our next study will report on the achieved performances.

VII. CONCLUSION

Ultra-high definition video services and immersive reality production and consumption in dense urban environments demand flexible, low-delay, and high-throughput wireless and IT infrastructure by leading to large investments for network operators and media producers. The H2020 project 5GCity is dealing with those issues by designing, developing, and deploying a neutral and sliceable Cloud & Radio platform, i.e., neutral host.

To demonstrate the benefits of our proposed 5GCity neutral host platform, we have designed three Use Cases (UCs) for ultra-high definition video and immersive reality production and distribution. A 5GCity neutral host platform can provide flexible infrastructure sharing to reduce the dense small-cell deployments and the necessity for large investment for network operators and media producers and broadcasters (media verticals). Finally, 5GCity project plans to demonstrate the ambitious UCs in real-life deployments in three different European cities to validate the proposed neutral host platform.

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Authors' photographs and biographies not available at the time of publication.