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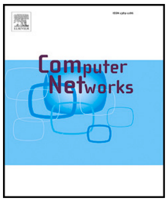

Survey paper

SDN and NFV for QoE-driven multimedia services delivery: The road towards 6G and beyond networks

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ABSTRACT

The concept for developing the future mobile communication systems has been explored in recent years with a vision towards 5G and 6G systems. Meeting performance targets such as higher data rate transmission, lower end-to-end latency, higher capacity, lower cost, and satisfied Quality of Experience (QoE) for delivered services is the key for the success of 5G and 6G networks. Within these performance targets and associated enabling technologies, QoE and the overall management of multimedia services is the one which has been less well addressed for 5G in the past. This paper provides a comprehensive and ground-breaking discussion regarding QoE management in the context of future softwarized 5G/6G networks. We introduce a generalized QoE provisioning ecosystem for emerging multimedia streaming services in softwarized 5G/6G and beyond networks. We explore potential network softwarization and communication technologies that will enable the end-user's QoE in 5G/6G. We further provide promising use case scenarios regarding (a) QoE-driven management of multimedia services over multi-access cloud/edge softwarized and virtualized 5G networks, (b) QoE monitoring for large traffic variations in business, residential and public areas in 5G networks, along with a Machine Learning (ML)-based softwarized controller for QoE provisioning over 5G/6G networks. We build on the achievements of 5G networks to provide the roadmap towards the development of 6G and beyond networks in terms of requirements, use case scenarios and service classes. We also present potential technologies that will be dominant through 2025–2030 in shaping the vision of 6G and beyond networks including (a) self-driving 3D network architecture, (b) network management, automation and orchestration, and (c) pervasive artificial intelligence. Moreover, we provide challenges and research directions in 6G and beyond wireless communication systems. The paper provides the first roadmap towards the management, orchestration and monitoring of multimedia 3D services in 6G and beyond networks. The comprehensive goal of this paper is to encourage researchers from the industry and academia to work together towards the realization of softwarized 6G and beyond networks while tackling the critical research challenges regarding the management of emerging 3D multimedia services and applications. The comments made by the authors in this paper are expectations on 6G, and the standardization of 6G where these aspects will be decided in 6G networks and beyond, will be started soon by different standardization bodies and fora.

1. Introduction

5G networks [1] are shifting from the traditional monolithic hardware-based networks to a new paradigm of agile virtualized and softwarized networks based on SDN, NFV, MEC and cloud/edge computing. The vast majority of the Internet services, ranging from computation and communication services to immersive content delivery, are shifting from the traditional centralized client–server model, to a more modular and distributed paradigm exploiting the potential of cloud/edge computing services. 5G networks bring higher data rates, minimal communication latency, increased connectivity densities, high velocity thresholds and accurate security levels to deliver next generation applications and services.

Network protocols (e.g., MPTCP [2] and a source-based routing technique using Segment Routing (SR) [3] and technologies (Software-Defined Networking (SDN) [4], Network Function Virtualization (NFV) [5], Multi-access Edge Computing (MEC) [6]) are being developed to facilitate the efficient operations of 5G and beyond networks. The development of the 5G New Radio [7] is key to enabling the 5G mobile communications system to meet the needs of high data rate

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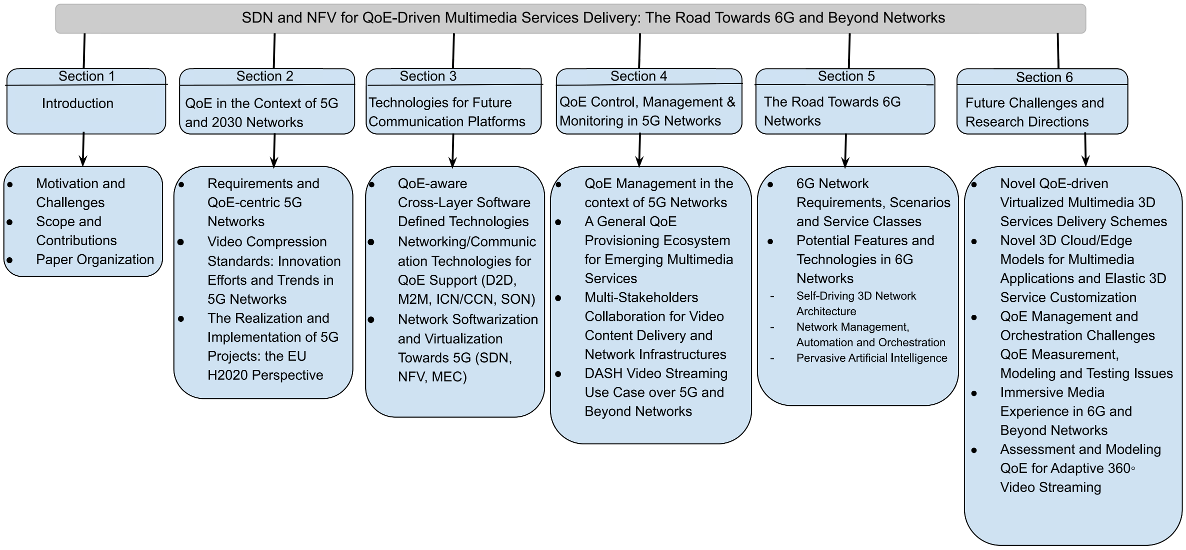

Fig. 1. Structure of the paper.

services when compared to 4G. The 5G New Radio provides communications for very high band with transmissions [8] like video streaming services and low latency communications for remote control vehicle communications and machine type communications. Emerging services and applications such as Immersive Video Gaming (IVG), Augmented and Virtual Reality (AR/VR), massive Internet of Things (mIoT), autonomous driving are projected to be the game changer in the 5G and beyond mobile/wireless networks. The exponential growth of multimedia streaming services (e.g., YouTube and Mobile TV) on smart devices has triggered and introduced new revenue potential for telecom operators and service providers. 5G can make the difference in supporting multimedia streaming services, which often serve millions of connections with high data rates and low latency [9].

1.1. Motivation and challenges

With the deployment of 5G networks, the media and entertainment industry will see new revolutions for streaming and broadcasting contents on a variety of platforms. While 5G is already seeing successful rollouts in different countries in the world, 5G and its successor (e.g., 6G) will enhance the accessibility and experience for consumers with content streaming platforms while generating new revenue opportunities for service providers [9].

However, maintaining and improving Quality of Experience (QoE) [9,10] for multimedia services delivery over the Internet is accepted to be a challenging task because of several factors including [9,11] (a) diverse changing network conditions, (b) limited network resources, unstable nature of wireless channels and the characteristics of fixed/mobile networks in heterogeneous environments, and (c) the emergence of new applications and services (e.g., VR/AR), immersive VR 360° video streaming services and video gaming), combined with the operational cost optimization by mobile and service providers. The fast growth and popularity of multimedia services over the Internet, as well as the heterogeneity of end-user devices with different capabilities such as computational power/resources, storage capabilities and screen size are also contributing to QoE management challenges. Moreover, it is a very challenging task when allocating resources to the end users with different QoE preferences [9].

Despite intensive efforts from content creators, service providers and network operators to enhance QoE for media streaming, there are two key technical challenges to achieve the overall management, monitoring and control of multimedia on 5G networks with QoE guarantee [9,12]. Firstly, creating a reliable, accurate, scalable and robust QoE prediction model for high definition streamed video (4 K/8 K) over 5G mobile and beyond networks is an ongoing active area of research [13] that is evolving in tandem with content delivery technologies. For example , the QoE models (e.g., ITU-T Rec. P.1203.3 [14] and ITU-T P. 1204.3 [15,16]) used today are those recommended by standardization bodies such as the International Telecommunication Union (ITU) [17]. The ITU-T Rec. P.1203.3 is a parametric bitstream-based quality assessment of progressive download and adaptive audiovisual streaming services over reliable transport. The ITU-T P.1203-series of Recommendations (ITU-T P.1203.1, ITU-T P.1203.2, ITU-T P.1203.3) addresses two application areas including: large-screen presentation as with fixed-network video streaming and mobile streaming on handheld devices such as smartphones. The P.1204.3 is a bitstream-based no-reference video quality model that can be applied to bitstreams encoded with H.264/AVC, HEVC and VP9. The ITU-T P.1204.3 can use different encoding options such as video resolution, framerate, bitrate, and video encoder settings including rate control variants, speed and number of passes [15]. The ITU-T Rec. P.1204.5 is a no-reference hybrid for video quality assessment of streaming services over reliable transport for resolutions up to 4 K with access to transport and received pixel information.

These models are designed for fixed-network video streaming and mobile streaming on handheld devices over networks where additional challenges exist such as softwarization, virtualisation, intelligentization, mobility, multi-tenancy and multi-domain requirements. Secondly, the popularity and fast growth of multimedia services over the Internet pose even more challenges when allocating limited resources among users with different QoE preferences. Preferences such as the heterogeneity of end-user devices with different capabilities (e.g., screen size, computational power/resources, storage capabilities etc.) need to be characterized by intelligent QoE-based streaming models in 5G and beyond networks such as 6G systems. The development of AR/VR technologies has brought new challenges in the network area in terms of supporting these applications [9].

The transmission of 360° video is rather challenging, especially over the current generation cellular networks because of the limited capacity and dynamic nature. While 5G can transport data at many gigabits per second at the air interface, it has yet to be proved to reliably handle high-throughput, low-delay 360° video streaming. Although there are several subjective studies [18–21] regarding 360° videos, the standardized methodologies for subjective metrics for 360° videos are still lacking [22]. This calls for efforts towards designing and developing quality assessment methods and QoE metrics for 360°

videos. The research community should develop novel strategies that introduce less noise by adding new stitching, projection, and packaging formats. Viewport-dependent streaming and tile-based streaming are the commonly used techniques for implementing adaptive streaming in a VR environment for 360° video content where a user can switch to neighbouring views randomly during 360° video playback as provided in a recent work [22]. The only challenge is the facilitation of smooth viewport switching where a certain level of resilience has to be provided in order to remove a smooth viewport switching. ML can overcome this 360° video streaming challenges through objective and subjective QoE assessments. In this aspect, deep reinforcement learning (DRL)-based approaches have to be developed for allocating video bitrates to the tiles in different regions of the 360° video frame [23].

These challenges yield three questions that urgently need to be addressed as we enter a new era of multimedia services provisioning over 5G and 6G networks: (i) how can a 5G/6G network become aware of the services that it provides such that the provision and management of resources can be adapted holistically based on the data content and the available network resources on an SDN/NFV-enabled platform? (ii) what is a generalized QoE provisioning ecosystem for emerging multimedia streaming services in softwarized and virtualized 5G/6G and beyond networks? (iii) what are the potential technologies and features of 6G and beyond networks that will contribute to network management, automation and orchestration of resources while optimizing the end-user's QoE? To adequately address the QoE-related open issues and challenges, extensive research is required while going towards 6G and 2030 networks.

Previous works regarding QoE management of multimedia streaming services have been explored over the past years [24–28] including our recent works [9,11,29,30]. However, the majority of the past publications in this domain are potentially focusing on hampering a comprehensive overview and extensive research in terms of QoE management components: QoE modelling; QoE monitoring and measurement, QoE optimization and control for multimedia OTT streaming services. However, the discussion concerning beyond 5G/6G systems such as (a) human-centric services and 3D volumetric video, (b) holographic and future media communications, (c) new video compression standards which are equally critical are missing from existing works. While the research on 6G networks and beyond systems continue to evolve and break new ground, existing works do not provide the description of potential technologies for enabling the end-user's QoE such as self-driving 3D network architectures, pervasive artificial intelligence, intelligentized architectures for network management, automation and orchestration. To this end, this paper explores the QoE management, monitoring and control of future multimedia streaming services over virtualized and softwarized 5G and 6G networks. The paper provides forecasts for 6G networks including potential technologies, infrastructure, applications and services from 2025 through 2030. This paper is among the first works to address how to quantify and ensure high QoE delivery for Ultra-High-Definition (UHD) 3D video to the end-users in 6G and beyond mobile/wireless networks.

1.2. Scope and contributions

In this paper, we provide an extensive discussion on the concept of QoE management in the context of future 5G and beyond networks. We introduce a generalized QoE provisioning ecosystem for emerging multimedia streaming services in softwarized and virtualized 5G/6G and beyond networks. We include the definition of QoE by encompassing the QoS, Grade of Services (GoS), Quality of Resilience (QoR), Quality of Design and Delivery (QoDD), Quality of Presentation and Perception (QoPP), Quality of Business (QoBiz) and Quality of Conformance (QoC). We also explore potential network softwarization and communication technologies that will enable the end-user's QoE in 5G/6G. We further provide different use case scenarios regarding (a) QoE-driven management of multimedia services over multi-access cloud/edge softwarized and virtualized 5G networks, (b) QoE monitoring for large traffic variations in business, residential and public areas in 5G networks, along with a Machine Learning (ML)-based softwarized controller for QoE provisioning over 5G and beyond networks.

While 5G networks are offering several advancements regarding the network softwarization and virtualization, the paper builds on the achievements of 5G networks to provide the first roadmap towards 6G and beyond networks in terms of requirements, use case scenarios and service classes (e.g., holographic and future media communications, human-centric services and 3D volumetric video streaming, new video compression standards such as H.266) as well as potential technologies that will be dominant through 2025–2030. Some of the features and 6G technologies explored in this article include: self-driving 3D network architecture, network management, automation and orchestration, and pervasive artificial intelligence. We provide challenges and research directions regarding QoE-driven virtualized multimedia 3D services delivery schemes over 6G architecture, 3D cloud/edge models for multimedia services and elastic 3D service customization via network intelligentization, QoE measurement, modelling and testing issues and QoE management and orchestration. The paper provides the first road map towards the management, orchestration and monitoring of multimedia 3D services in 6G networks. Our comprehensive goal is to encourage researchers from the industry and academia to work together towards the realization of softwarized 6G and beyond networks while tackling the critical research challenges regarding management of emerging 3D multimedia services and applications.

1.3. Organization

Section 2 presents the requirements and QoE-centric concepts as well as the realization and implementation of 5G research projects. Section 3 provides potential technologies that contribute to enable the end-user's QoE in the aspects of 5G and beyond networks. Section 4 presents the QoE control, management and monitoring architectures along with the QoE provisioning ecosystem for multimedia streaming services in softwarized 5G and beyond networks. Section 5 presents the road towards 6G and beyond networks by discussing the requirements, potential technologies, features and infrastructures, applications and services classes through 2025 to 2030. Section 6 provides future research challenges and the available opportunities towards enabling the QoE in 5G and 6G networks. Finally, Section 7 concludes our paper. Fig. 1 indicates the orgnaization of this paper.

2. QoE in the context of 5G and 2030 networks

The QoE [31], [32] concept was proposed in 2007 and complemented as a user-centric approach in current and future networks such as 5G. The QoE-centric concept is comprehensively defined in [31]. Different from traditional network factors that have been studied extensively on Quality of Service (QoS), QoE considers the user's subjectivity toward a specific service. In the context of 5G networks, QoE has been used as a metric centred on the apex of management in future multimedia streaming services. In line with the above argument, solutions for video quality management [33,34] or those about QoE-driven and energy-aware video adaptation in 5G networks have been recently proposed [35]. However, QoE covers all quality influencing factors (namely: system Influencing Factors (IFs), context IFs and human IFs [31]) in the end-to-end communication system (e.g., from service providers to clients). The system IFs as shown in Fig. 3 describe technical characteristics that produce the quality of an application or service in the traversed 5G networks. The system IFs are related to the *content, media, network or device*. The context IFs include any characteristics that may influence QoE. For instance, QoE can be influenced by temporal information (e.g., video playing time, video duration), physical location, movements or space where the service is being offered [36]. Human IFs describe factors that influence how the users

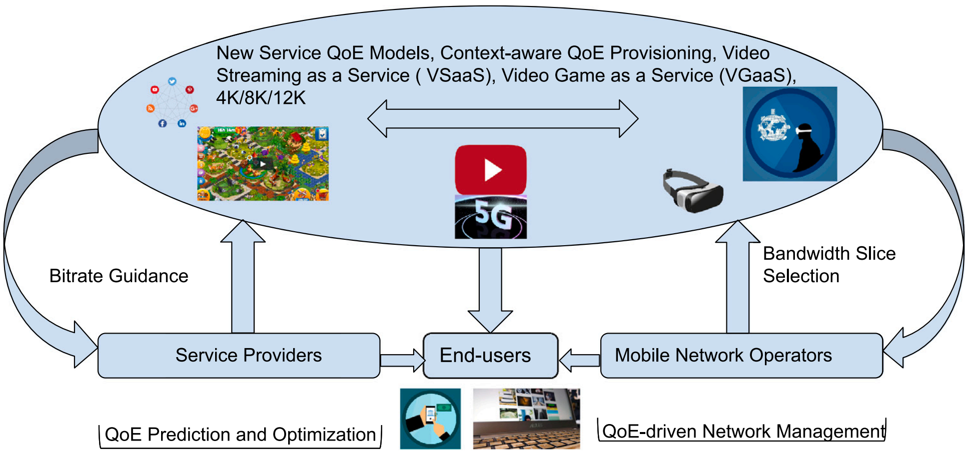

Fig. 2. QoE management from three perspectives: end-user, service provider, and network operator.

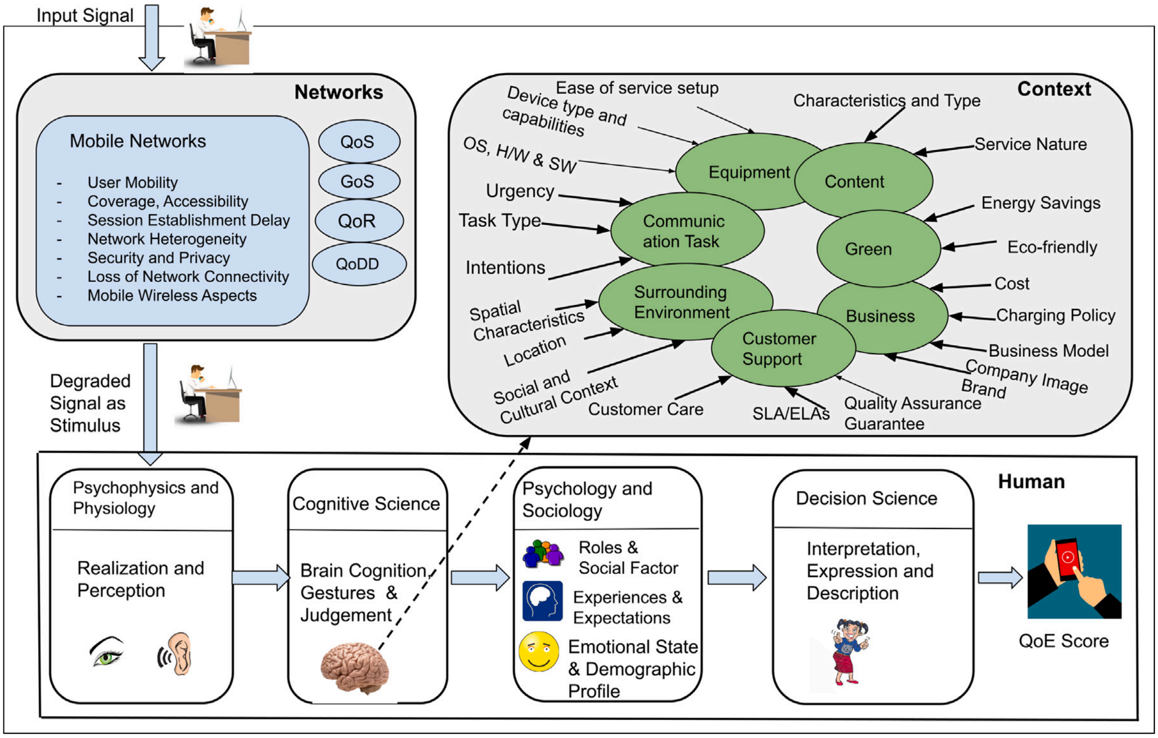

Fig. 3. The three QoE influence pillars [36].

perceive or feel the service quality delivered to them. It includes emotional and mental constitution of a human, demographic and social-economic background, the user's personal and cultural traits, user's gender, age, visual/auditory acuity, mood, attention etc. [37].

2.1. Requirements and QoE-centric 5G Networks

5G network is set to address the QoE concept from three broad perspectives (Fig. 2) that include the following stakeholders: the *End-user*, *Service providers* and *Mobile network operators* perspectives. From the end-user's side, 5G ensures that customers receive services with uninterrupted communication, 24 × 7 device connectivity and a good customer experience. From the service providers perspective, 5G is set to connect service providers to consumers through efficient QoE-control and management mechanisms equipped with intelligent transportation systems, mission critical monitoring services in the context of smart cities, smart homes and the Internet of Things (IoT). From the mobile network operators perspective, 5G is to provide a scalable, programmable, energy efficient and low cost, secure communications and a well-uniformly monitored infrastructure for network operators. Therefore, 5G is set to provide new enhanced user experiences through various specifications that contain requirements on performance targets and basic capabilities compared to 4G [1,11,33] as described below:

- 10–100× higher data rate with 1–10 Gbps connections [1].
- 1 ms end-to-end round trip delay-latency.
- 1000× higher mobile data volume per unit area [46].
- 10–100× number of connected devices with up to 10 years battery life for low power and machine-type devices [47].
- Transmission reliability of 99.999% and almost 100% services availability [1].
- 90% reduction in energy consumption and resource efficiency for 5G services ranging from low data IoT applications to high bitrate multimedia services.

Table 1
A summary of academia/industry 5G projects and implementations based on SDN and NFV.

Name	Focus Area		MEC/Cloud	Video Streaming	SDN/NFV-Related Work	Project Start Date
	SDN	NFV				
5G-NORMA [38]	Yes	Yes	No	No	Multi-service and context-aware adaptation of network functions to support a variety of services and corresponding QoE/QoS requirements.	1/7/2015 (30 months)
5G-MEDIA [39]	Yes	Yes	No	Yes	A flexible network architecture that provides dynamic and flexible UHD content distribution over 5G CDNs	1/6/2017 (33 months)
5G-MoNArch [40]	Yes	Yes	No	No	Employ network slicing to support the orchestration of both access and core network functions. The supported use cases in vertical industries include automotive, healthcare, and media.	1/7/2017 (24 months)
5GTANGO [41]	Yes	Yes	No	No	To develop a flexible 5G programmable networks with an NFV-enabled Service Development Kit (SDK) that support the creation and composition of VNFs and application elements as *“Network Services”*.	1/6/2017 (32 months)
5G-Transformer [42]	Yes	Yes	Yes	No	Develop an SDN/NFV-based 5G network architecture that meets specific vertical industries’ (e.g., eHealth, automotive, industry 4.0 and media) requirements.	1/6/2017 (30 months)
SLICENET [43]	Yes	Yes	No	No	Develop a cognitive network control, management and orchestration framework that supports infrastructure sharing across multiple operator domains in SDN/NFV-enabled 5G networks.	1/6/2017 (36 months)
5G Exchange [44]	Yes	Yes	No	No	Enabling cross-domain orchestration of services over multiple administrations or over multi-domain single administrations.	1/10/2015 (30 months)
5GmediaHUB [45]	Yes	Yes	Yes	Yes	To offer a DevOps environment for Testing as a Service (TaaS)) and a rich set of experimentation tools that are able to provide scheduling, validation, verification, analytics and QoS/QoE monitoring mechanisms. The project also will enable new business opportunities with the adaptation of the network to media application requirements and accelerate NFV-based service uptake in industry [45].	1/1/2021 (36 months)

Note: UHD = Ultra-High-Definition ; CDN = Content Delivery Network.

Table 2
A summary of technologies and services for future communication platforms.

Category	Technological example	Main Objectives	Limitations/Challenges
QoE-aware Cross-Layer Software Defined Technologies [49]	Massive MIMO on the physical layer, SDN on the network layer	To utilize network resources efficiently and optimize the end-users’ QoE through a joint cooperation between layers and coordination of their actions.	Efficient QoE-aware cross-layer software defined strategies have to be developed on 5G to provide the required QoE-fairness level among users. [50]
Networking/Communication Technologies for QoE Support	D2D/M2M, CDN [51] & SOQN	D2D/M2M aim to deliver data to neighbour devices through a low latency and reliable nodes/links while CDN proposes a shift from the traditional client–server approach to a user/network centric approach where contents are decoupled from location at the network level. SOQN aim to provide automation and dynamic configuration, optimization and self-healing capabilities in the 5G network.	QoE-driven management approaches for mobility support and management, radio resource allocation service and battery consumption optimization are of crucial in the 5G design.
Network Softwarization and Virtualization Technologies	MEC [6], Cloud/Fog Computing, SDN [33] & NFV [5]	MEC implements a content-oriented and embed intelligence at the mobile edge in 5G networks while SDN/NFV promise to enable the network control to be programmable, centrally or distributable managed, adaptive and cost effective [38].	An urgent need for QoE-based resource allocation algorithms that consider multi-domain and distributed VNFs, dynamic QoE-based resource management.

Note: M2M = Machine to Machine; SOQN = Self Organized Quality-enabled Network; MIMO = Massive Multiple-Input and Multiple-Output.

- ×5 reduction in network management operation expenses [9,48].

2.2. *The realization and implementation of 5G projects*

5G network is embracing precedence of emerging scenarios and use cases that not only include QoE-rich networking environment but also a seamless integration of the current wireless technologies.

There have been extensive efforts associated with future Internet, cloud computing and media/content convergence in 5G network from the recent and current EU projects including SLICENET, 5G-MEDIA, SELFNET, 5G-NORMA, 5GTANGO, 5GMediaHUB etc. (see in [11]). Projects such as 5G-Xhaul and SELFNET [52] have been initiated to realize self-healing, self-configuration and self-optimization capabilities for 5G networks. Recent 5G projects under the 5G Infrastructure Public Private Partnership (5GPPP) are focusing on developing novel architectures with a target on providing the needed flexibility and programmable 5G networks using SDN/NFV and cloud/edge Computing. The projects put efforts on developing novel solutions for multimedia services management with QoE-guarantees (along the delivery chain) over softwarized 5G network.

The 5GZORRO project uses distributed AI/ML to implement cognitive network orchestration and management using zero-touch automation. Distributed Ledger Technologies (DLT) [53] are employed to implement flexible and efficient distributed security, privacy and trust across the various parties involved in a 5G e2e service chain to allow SLA monitoring, spectrum sharing, intelligent and automated data-driven resource discovery and management in 5G and beyond networks.[54]. The 5GMediaHUB [45] provides a Cross-Domain Service Orchestrator (CDSO) that automates service and slice management to minimize service creation time in 5G and beyond networks. 5GMediaHUB also provides novel QoS/QoE adaptation and monitoring mechanisms of the network to multimedia application requirements and accelerate NFV-based service uptake in industry. The 5G-ERA [55] project develops an intent-based networking architecture that optimizes QoE to support enhanced robot autonomy in real-world applications. The developed architecture ensures robotic applications exploit the NFV/SDN infrastructures efficiently by integrating operational processes of essential autonomous robotic capabilities into Open Source MANO (OSM) [55].

5G-MEDIA applies the concepts of SDN and NFV to investigate how contents can be distributed over 5G Content Delivery Networks (CDNs). Three considered use cases in 5G MEDIA include: (a) immersive applications and VR, (b) remote and smart media production incorporating user-generated content, and (c) dynamic and flexible Ultra High Definition (UHD) content distribution over 5G CDNs.

The concept of 5G network slicing [11] is employed by different EU projects such as 5GTANGO, G-Crosshaul, SLICENET, 5G-NORMA to support the multi-service and multi-tenancy mechanisms in 5G and beyond systems. SLICENET project develops an architecture that provides cognitive network control, management and orchestration while supporting infrastructure sharing across various operator domains in QoE-softwarized and virtualized 5G networks. 5G-NORMA focuses on developing an architecture that supports multi-service and context-aware adaptation of network functions and their corresponding QoE/QoS requirements. Hamza [56] et al. use the network slicing concepts to propose a resource allocation and video quality management approach for vehicular networks while taking into account the reliability requirements of V2X communication. A sliced vehicular network in the downlink direction is considered which consists of a set of video streaming vehicles with multiple video qualities. The video quality selection and resource allocation tasks are optimized to enhance QoE by offloading the vehicles from weak Vehicle-to-Infrastructure (V2I) links to high quality Vehicle-to-Vehicle (V2V) links using a clustering algorithm. Faqir [57] et al. introduce a flexible 5G architecture for network slicing that revolves around flexible service-tailored mobility management, service-aware QoS/QoE control and network-wide orchestration. Key components in the architecture include a consistent QoS/QoE management framework and an enhanced mobility management algorithm that takes optimal decisions for User Equipment (UE) mobility on a per-slice basis. The end-user's QoE can be also improved using 5G network slicing by creating a CDN slice consisting of caches, transcoders, and streamers, in order to manage a number of videos based on a subscription category of customers for the service [58]. Montero [59] et al. provides a policy-based monitoring and actuation architecture that can maintain the desired QoS/QoE for the provisioned E2E network slice in multi-segment/multi-domain optical network environments. It is worth mentioning that, [58,59] are among the Proof of Concepts (PoC) which are validated using real slice deployments and traffic generation to demonstrate that network slicing is a key element for QoE/QoS provisioning guarantees to the end-users in 5G and beyond networks.

2.3. Video compression standards: Innovation efforts and trends in 5G networks

For video streaming services, dynamic adaptation of the video quality based on the current network conditions is achieved with technologies such as the HTTP Adaptive Streaming (HAS) paradigm. Current video compression/coding standards offer an integrated solution for seamless switching between (e.g., different video resolutions or frame rates) and quality scalabilities. However, it is difficult for these coding standards to compress 4 K/8 K and 360° video contents to small enough to facilitate video transmission over 5G systems and playback at the clients device [60]. This calls for new coding technologies and standards that provide higher compression efficiency.

The HEVC standard was released in 2013 by the ISO/IEC Moving Picture Expert Group (MPEG) and the ITU-T Video Coding Expert Group (VCEG) [61]. Compared to H.264, the video compression efficiency of HEVC increases by more than 50% under the same subjective visual quality. Extensions of AVC and HEVC have been recently developed to provide enhanced support for 3D video and spatial and quality scalability. As of today, the Joint Video Experts Team (JVET) between VCEG (Q6/16) and ISO/IEC JTC1 SC29's MPEG is developing a new video compression standard called a Versatile Video Coding (VVC) and the VVC Test Model (VTM) [62] with capabilities beyond H.265. The VVC standard provides advancement to the state of the art of video compression and the flexibility to enable emerging applications such as 360° omnidirectional immersive multimedia, remote screen sharing, cloud-based collaboration, cloud gaming, and region-based extraction and merging.

2.4. Summary and lesson learned

To summarize, Table 1 presents a comparison of recent and current projects by giving their SDN/NFV related work, their focus area and identifying whether the aspect of MEC/Cloud is supported in their implementations. For interested readers, a complete list of other 5GPPP Phase I, II and III Projects which are funded by the EU under H2020 can be found in [52,63,64]. Table 2 presents a summary of technologies and services for future communication platforms. We note that, extensive efforts have been made towards developing novel 5G network management architectures that can deliver multimedia streaming services to users with QoE guarantee. The new video codecs standard such as VVC have been designed to address all of the video needs including those with high resolution and high bitrates, HDR and 360° omnidirectional. In the next section, we present potential technologies for enabling the end-user's QoE in future communication platforms.

3. Technologies for future communication platforms

5G multimedia communications with enhanced QoE management capabilities will be enabled by cutting-edge technologies such as SDN, NFV, MEC, QoE-aware cross-layer software defined and networking/communication technologies for QoE support. We describe network softwarization/
virtualization technologies that provide different mechanisms for enhancing the delivery of multimedia streaming services in 5G networks.

3.1. QoE-aware cross-layer software defined technologies

QoE-aware 5G cross-layer software defined technologies are set to utilize network resources efficiently and optimize the end-users' QoE through a joint cooperation between layers and coordination of their actions. The QoE requirements can be defined and specified at the application layer and controlled at the network layer using SDN controllers [33]. For example, a cross-layer software defined 5G network approach is proposed [49] to provide the fine-grained control and flexible programmability of 5G network layers. Considering network-wide users' QoE maximization, QoE-based proportional fair scheduling and efficient QoE-aware cross-layer software defined strategies have to be developed on 5G and 6G networks to provide the required QoE-fairness level among users [9,11].

3.2. Networking/communication technologies for QoE support

3.2.1. D2D/M2M enabled communications

D2D communication is viewed as a promising and an exciting feature of 5G systems that can improve the network capacity and user experience. Using D2D, smart devices in the 5G era will be able to exchange information, deliver data to neighbour devices through low latency and reliable nodes/links and therefore enhancing transmission quality as well as reducing the communication delays [65]. With D2D for QoE support, the challenge for ensuring the impact of D2D/M2M on QoE is the need for smart and intelligent schemes for preventing congestion and managing traffic load distribution from a massive number of interacting devices that are expected when 5G will be fully deployed. Therefore, QoE-driven management approaches for mobility support and management, radio resource allocation service and battery consumption optimization are crucial in the 5G and 2030 networks design. However, recent proposals for QoE-aware D2D management presented in [66,67] and a D2D communication approach for enhancing the QoE of users in software defined multi-tier Long-Term Evolution Advanced (LTE-A) networks [65], [68] can be adopted in 5G/6G systems as the starting point for enabling the end-user's QoE.

3.2.2. Content Delivery Networks (CDN)

Content Delivery Network (CDN) operators have been relying on the widely distributed edge servers in handling the increasing demand of high-quality live videos to viewers. Using this technique, viewers can fetch and stream the requested video content from the cache server rather than the original video servers. Important CDN features include video content distribution among various servers, redirection of the user's video request, content retrieval, and management of the video content and servers [69]. It is worth noting that, caching in CDN plays a key role in reducing the response time and enhancing the multimedia service quality to the end-users. The cached content in CDN is replicated to different servers called surrogate servers or edge servers which are located at various locations [70].

3.2.3. Self Organized and Quality-enabled Networks (SOQN)

Realistic use case scenarios such as the tactile Internet [71], autonomous driving and the mounting pressure on QoE-based multimedia services from users, energy efficiency and increased capacity are triggering softwarized 5G and 2030 networks with self-healing, self-configuration and self-optimization capabilities [72–74] to be at the forefront of the architecture design. Optimizing the end users' QoE on 5G and 6G networks should be performed dynamically with capabilities for real-time measurement, decision, analytics and action within the network. We envision that through automation and dynamic configuration, optimization and self-healing of 5G networks, SOQN can achieve better QoE and aligning revenue to network operators.

3.3. Network softwarization and virtualization

3.3.1. Multi-Access Edge Computing (MEC): From Clouds to Edges

MEC provides cloud computing capabilities to satisfy the high-demanding requirements of 5G such as throughput and an improved QoE for the end-users [75]. MEC promises to provide environments in 5G networks which are characterized by high bandwidth, real-time insight, radio network information, location awareness and low latency. The MEC architecture consists of a MEC platform that forms a central point where servers are hosted. The MEC data plane consists of Traffic Offload Functions (TOFs) which provide interfaces with policy-based packet monitoring to both MEC Apps and MEC services. As shown in [76], SDN and NFV are to play a key role in the 5G MEC architecture to provide a virtual environment (e.g., vCompute, vStorage and networking resources) for MEC applications. The MEC server which is within the proximity of the users provides low-latency to bandwidth intensive applications such as video streaming.

3.3.2. Software Defined Networking (SDN)

SDN [33,77,78] is an approach that brings intelligence and flexible programmable 5G networks capable of orchestrating and controlling applications/services in a more fine-grained and a network-wide manner. SDN creates a virtualized control plane that is able to enforce intelligent management decisions in network functions. This bridges the gap between services provisioning and QoE management in 5G [79]. SDN can provide a context-aware QoE management and meet 5G Key Performance Indicators (KPIs) by maintaining network integrity, reliability as well as reducing latency for delay-sensitive multimedia applications. Intelligent strategies concerning major aspects of 5G networks such as QoE-aware context management [33], and context-aware adaptation of network functions [38] can be provided and supported in 5G SDN/NFV-enabled networks. Table 3 shows a summary of standardization efforts and open source projects that accelerate the adoption of SDN towards the development of 5G and beyond networks.

3.3.3. Network Function Virtualization (NFV)

NFV [5] promises to provide the needed flexibility by service providers and operators' networks that would enable them to meet changing customer demands, reduce their Capital Expenditures (CapEx) and Operational Expenditure (OpEx) through lower-cost agile software-based infrastructures. It also decreases the time of new network services to market through a new innovation cycle of software-based QoE-rich services deployment [80]. The MEC, SDN and NFV seek to drive a future software-based 5G networking solution that offers flexible and automated features for network connectivity and QoE provisioning to the end-users [11]. Chen [81] et al. propose a Deep Reinforcement Learning based QoS/QoE-aware Adaptive Online Orchestration (DRL-QOR) strategy that can adapt to the changing conditions in NFV-enabled networks. Martin [82] et al. propose an NFV-based resource allocator that enables QoE-aware dynamic network management by predicting the network resources demand to be allocated to the end-users. The Qos/QoE metrics are calculated on top of SDN/NFV-based networks and used for the end-to-end provisions of the network topology that can cope well with the end-users' traffic demand.

3.4. Summary and lesson learned

Table 3 provides a summary of standardization efforts and open source projects that accelerate the adoption of SDN towards the development of 5G and beyond networks. Table 4 shows a summary of standardization efforts and open source projects that accelerate the adoption of NFV. Fig. 4 shows a mapping of these technologies to QoE-centric service mechanisms for enhancing future communication platforms in 5G and beyond networks. It is worth mentioning that, MEC, SDN and NFV have been praised and lauded for the provisioning of value-added QoE-driven personalized management for multimedia streaming services over softwarized 5G networks [9]. To this end, a multi-service adaptive 5G network that is able to offer virtual resources at the mobile edge for supporting multiple tenants have to be developed. The developed architecture has to be equipped with adaptable intelligence as well as a tighter integration of SDN and NFV in 5G networks. Fig. 4 provides the QoE-centric service mechanisms which are mapped to technologies for future 5G communication platforms. Building on these technologies, we present in the next section, the QoE control, management and monitoring architectures in 5G networks.

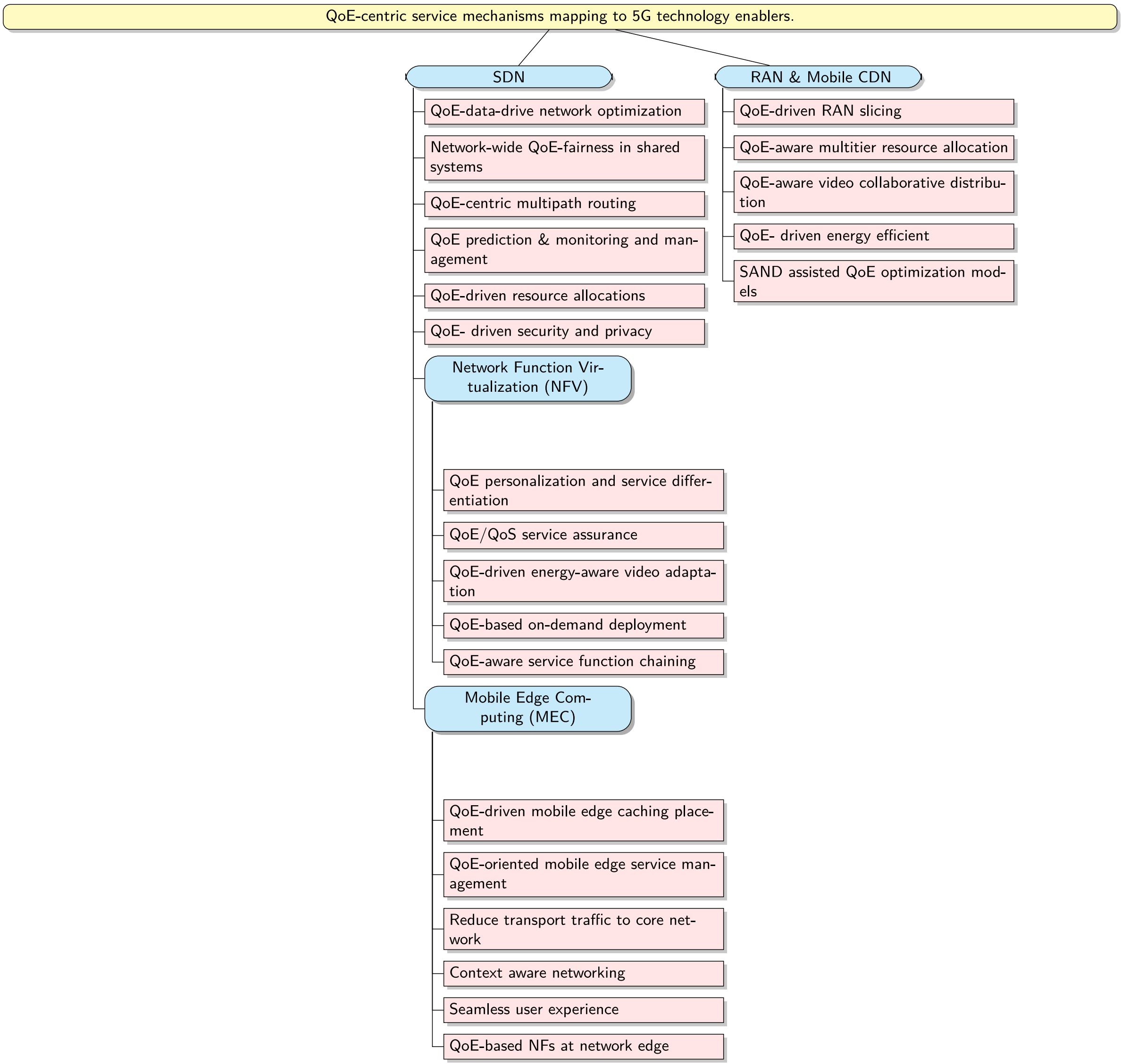

Fig. 4. QoE-centric service mechanisms and technologies for future communication platforms in 5G and beyond networks.

Table 3
A summary of SDN open source platforms, standardization efforts, projects and implementations.

Name	Description	Working group	Description of SDN-related work
ONF	Industry-led Consortia for OpenFlow Standardization	–	Analyse SDN requirements, OpenFlow Standard regarding to SDN concepts, frameworks, architecture, software, and certifications.
OpenDaylight	Industry-led Consortia	ETSI NFV	To accelerate the adoption and fostering new innovation for SDN applications and services.
ITU-T	International Organization	SG (11,13, 15 & 17)	Investigating the functional architecture, signalling requirements and protocols for SDN (e.g., security and unified intelligent programmable interface for IPv6).
IETF/IRTF	IRTF WG	SDN RG	To develop a customizable framework capable of orchestrating network services across heterogeneous NFV Infrastructures.

Note: WG = Working Group; RG = Research Group; SG = Study Group; ONF = Open Networking Foundation.

4. QoE control, management and monitoring in 5G networks

4.1. QoE management in the context of 5G networks

The QoE management context in 5G networks should go beyond the state-of-the-art as use cases expand drastically. As of today, a number of QoE issues of OTT services over 5G networks are still open [83]. For instance, challenges pertaining to QoE-rich multimedia services delivery especially, UHD videos in 5G mobile networks, need a context QoE-aware management that employs the control plane of SDN as proposed in [33]. With the emphasis of improving the users' QoE and the goal of meeting KPIs of 5G, Olatunde et al. [33] further provide an SDN-based approach that facilitates the management of localized congestions through a wider view of the entire 5G network. A data-driven architecture for QoE personalization in the context of 5G networks is presented in [27]. This approach can manage network resources based on the predicted user's preference/expectation and QoS status in order to maintain a satisfactory QoE.

Table 4
A summary of NFV open source platforms, projects and implementations.

Name	Technology	Company/Organization	Objective/Functionality
OpenMANO	SDN and NFV	Telefonica	To provide a practical implementation of the NFV MANO reference architecture.
OPNFV	NFV	Linux Foundation	To facilitate the development of NFV components across various open source ecosystems.
ECOMP	SDN, NFV & Cloud	AT & T	To provide an enhanced control, orchestration and life cycle management of VNFs and the cloud platform where the VFs reside on.
ZOOM	NFV	TM Forum	To develop a platform for monitoring and optimization of Network Functions-as-a-Service (NFaaS).

Note: ZOOM = Zero-time Orchestration, Operations and Management; ECOMP = Enhanced Control, Orchestration, Management and Policy; OSM = Open Source MANO.

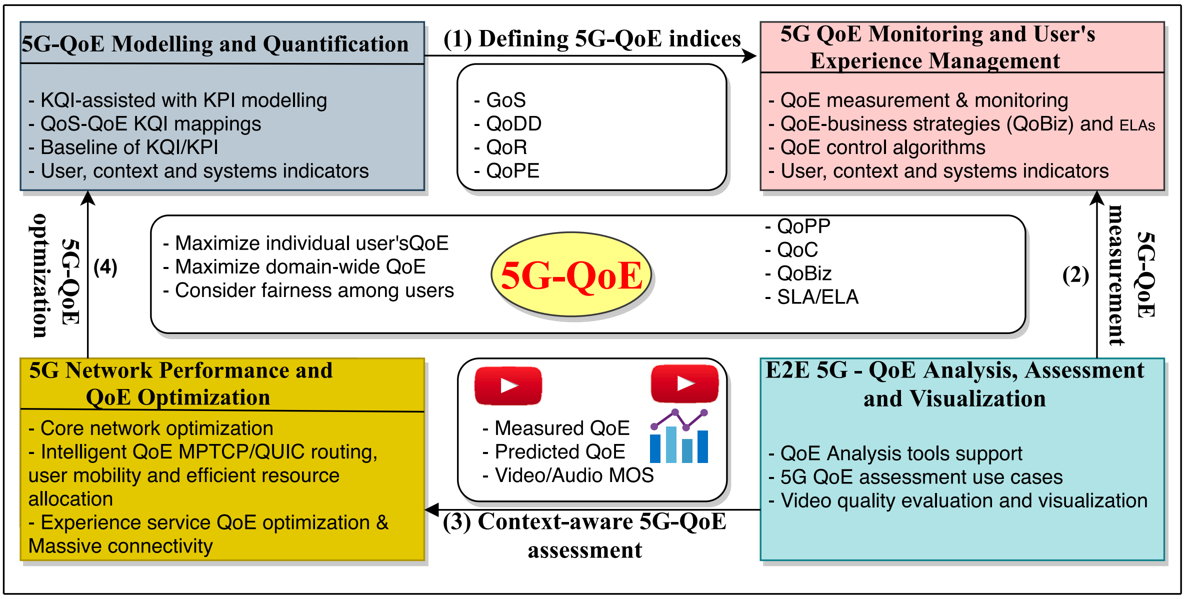

Fig. 5. The QoE ecosystem on 5G and beyond networks.

In an attempt to address the challenges of traffic heterogeneity in 5G networks, Trakas et al. [84] propose a QoE-aware user association heuristic strategies to maximize both QoE and MNO profit. 5G softwarized network should take into consideration the multimedia content control, management and awareness, user behaviour identification, network awareness, orchestration and sharing/slicing capabilities of virtual network functions. Tselios et al. [75] propose a QoE-awareness architecture for 5G networks equipped with advanced virtualization and data management capabilities to support the user-centric networking. Intelligent frameworks to manage 5G wireless/mobile broadband and meet the provision of diverse QoS/OoE have also been presented by Demestichas et al. [85]. In an attempt to support a variety of services and the corresponding QoS/QoE requirements, the modular architecture for multi-service and context-aware adaptation of network functions is presented in [38].

The goal is to allow multiple tenants to share network resources, support on-demand allocation of radio and core resources through flexible connectivity as well as QoS/QoE management for 5G networks. Recently, Barakabitze et al. [29] propose an autonomic QoE-aware resource management approach in virtualized 5G networks. Barakabitze et al. [9] further provide a high-level description of QoE management for multimedia services, that integrates QoE modelling, monitoring, and optimization. The novel contributions of this work include approaches for QoE-aware/driven strategies using SDN and/or NFV, b) QoE-aware/driven approaches for adaptive streaming over emerging architectures (MEC, CDN and cloud/fog computing), and c) extended QoE management strategies in new domains (video gaming, VR/AR, mulsemedia and video gaming applications). Ahmad et al. [24] propose the zero-rated QoE strategy for video quality and resource management in 5G networks that consider collaboration between MNOs and OTT providers. The contributions of this work is the introduction of novel components in the 3GPP architecture and the definition of the mechanisms for radio resources allocations to each user where significant improvements in terms of video quality fairness and the average provided quality at the same throughput were reported.

However, the introduction of QoE-aware 5G network management mechanisms need to be possibly transformed into a number of autonomic functions across a wide range of technology enablers that reside in the network infrastructure elements, the mobile terminals or in the application/service being delivered to the end-users. It further needs a self-healing, self-configurable and self-optimization capability with an enhanced QoE-monitoring mechanism able to identify network failures and redirect traffic towards the central network monitoring or control point to restore the end-users seamless connectivity. As described in Section 3, 5G multimedia communications with enhanced QoE management capabilities will be enabled through softwarization and virtualization technologies including SDN, NFV, MEC, QoE-aware software defined cross-layer and networking/communication technologies. However, this needs a tight cooperation between different players in the general QoE provisioning ecosystem as described in Section 4.2.

4.2. A general QoE provisioning ecosystem for emerging multimedia services in 5G and beyond networks

The 5G communication ecosystem that involves all stakeholders in the QoE delivery chain in future softwarized 5G and beyond networks is shown in Fig. 5. We envision that, video content providers should

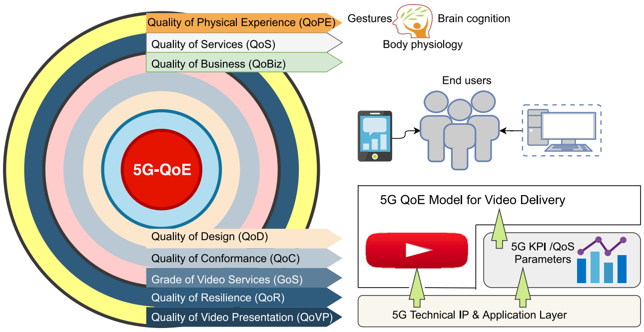

Fig. 6. An expanded definition of QoE over 5G and beyond networks.

prepare the actual video content as digital items by considering essential elements of high-quality content using streaming codecs such as H.266/Versatile Video Coding (VVC), High-Efficiency Video Coding (HEVC/H.265), VP9 or AV1. The Service Provider (SP) ensures that the multimedia content is delivered to customers based on the Experience Level Agreements (ELAs) [86] and Quality of Business (QoBiz) contracts [11]. Network providers have then to offer QoE-based connectivity services and reachability between network hosts. Finally, the customer should receive QoE-based services at anytime, anywhere to access services from service providers. The proposed 5G ecosystem for QoE provisioning consists of four parts namely, the *Customer QoE Quantification*, *Customer Experience and Service Quality Management*, *an E2E QoE Analysis, Assessment and Visualization* and *5G Network Performances and Optimization*. It is centred on QoE as the driving performance metric of 5G ecosystem. We include the definition of QoE with key concepts for quality improvement and important QoE defining features as shown in Fig. 6.

QoE encompasses the QoS, Grade of Services (GoS), Quality of Resilience (QoR), Quality of Design and Delivery (QoDD), Quality of Presentation and Perception (QoPP), Quality of Business (QoBiz) and Quality of Conformance (QoC). The GoS is used to categorize 5G data services that have high levels of requirements as defined in the QoE offered through well-defined SLAs/ELAs. For each 5G network data service category, a class of service has to be defined and established for users. The QoPP is mainly related to the spatial content problems as perceived by the end-users on the application level. The QoPP should be the main factor to be analysed in the QoE models since it is used to provide feedback to users at the application layer. The QoDD is related to the network design below the application level with efficient capabilities to deliver data in time and therefore meeting the reliability, scalability and flexibility which are among the strongest aspects of 5G softwarized and beyond networks.

During QoE cross-layer management design both, QoPP and QoDD should be taken into account to provide an acceptable and the best possible user's QoE level. These two factors have to be considered because the video quality have to be created (video codecs), delivered/transmitted (at less packet loss, minimal delay, low latency etc.), presented at the user's device (with minimum bitrate switching, low buffering events, no/less stalling events etc.) so that it can be perceived well by the end-users. The proposed ecosystem also integrates the QoC (what the quality that a customer needs) to ensure that the delivered services through the QoE provisioning chain and all involved stakeholders meet the design specifications of 5G and beyond networks. We provide a description of components in the QoE provisioning ecosystem in 5G networks as follows.

4.2.1. *Customer QoE quantification*

The customer QoE quantification defines the 5G service management guidelines and service quality design principles. It clarifies the customer perceptive and cognitive characteristics with respect to the service quality. It establishes a methodology for estimating QoE using quality-related information from the network, servers and end-user's terminals. This step identifies and defines the KPI/KQI relationships as well as QoS to QoE mappings useful for establishing the key customer QoE requirements. The KPIs are quantifiable measurements that provide reflection of critical successful or unsuccessful factors of multimedia streaming services. Examples of KPIs are packet loss rate, delay, jitter, handover success rate etc. The KQI defines the quality of a service perceived subjectively by the user. Examples of KQIs include service connect time, response time, availability, speech quality etc. The KQI provides an indicator for a specific performance aspect of the product and draws their data from a number of sources including KPIs [87]. It is worth mentioning that, the KPIs provide information related to the monitored resources while the KQIs are used for estimating the E2E QoE as perceived by the end users. The KPIs that are related to each of the KQIs are then defined and used to determine the service quality provided by network providers through the different measurement platforms and tools.

4.2.2. *Customer experience management and QoE monitoring*

Customer Experience Management (CEM) is an approach that focuses on methodologies and procedures to control and manage the end-user's QoE [88]. An efficient QoE monitoring and management system that retrieve information related to each QoE IFs over 5G softwarized networks is of great importance. The QoE monitoring architecture shown in Fig. 7 can monitor in real-time the E2E service KPIs and estimate the customer experience by using 5G network performance and monitoring tools. This can be designed to have different monitoring points and a realization between service providers and network operators to (i) provide in real-time, the QoE monitoring support for large variation traffic for 5G users in business, residential and public areas, (ii) have visibility and full access of E2E connectivity in all network segments such as transit ISPs, content server side networks, 5G core network, aggregation networks and customer's premises network, and (iii) controlling the QoE traffic flows dynamically based on changing network conditions.

The challenge of performing root cause analysis (e.g., from a network provider perspective) in determining the cause of measured QoE degradation is the lack of E2E visibility which is one of the requirements for QoE monitoring. Customer satisfaction is largely driven by QoE and not QoS. Given the dynamic nature of softwarized and virtualized networks, and the inability of current monitoring tools to assure virtualized-based services, network providers have less ability to monitor QoE or the service experience. That way, network providers have to perform per-application level quality assurance for different services and meet user's QoE requirements and the need for automated processes in softwarized and virtualized 5G and beyond networks.

The first monitoring point (MP1) shown in Fig. 7 indicates the data acquisition point and ensures that video streams for the end-users are generated without errors. Service providers at this measurement point also ensure that the agreed QoS/QoE policy (video bitrate, encoding rate, QoS parameters etc.) is met based on the subscription and QoE preferences of the end-users. The MP2 shows the data measurement point where service providers check for QoS/QoE policies and collect information on quality and performance parameters of video streaming services. MP3 indicates the measurement and monitoring point where IP network related parameters (packet delay variation, packet loss ratio etc.) are measured. MP4 shows the boundary between the access network and end-users premises where information regarding packet loss ratio, IP network parameters and reliability delivery of data can be measured and collected. The MP5 defines the QoE point at the end-user devices where the perceived video quality can be evaluated using application-specific information or the device characteristics.

QoE monitoring can be done using Crowdsourcing or virtualized probes (in SDN/NFV-based environments) by providing insights and real time data on the state of the network and the end-user's QoE.

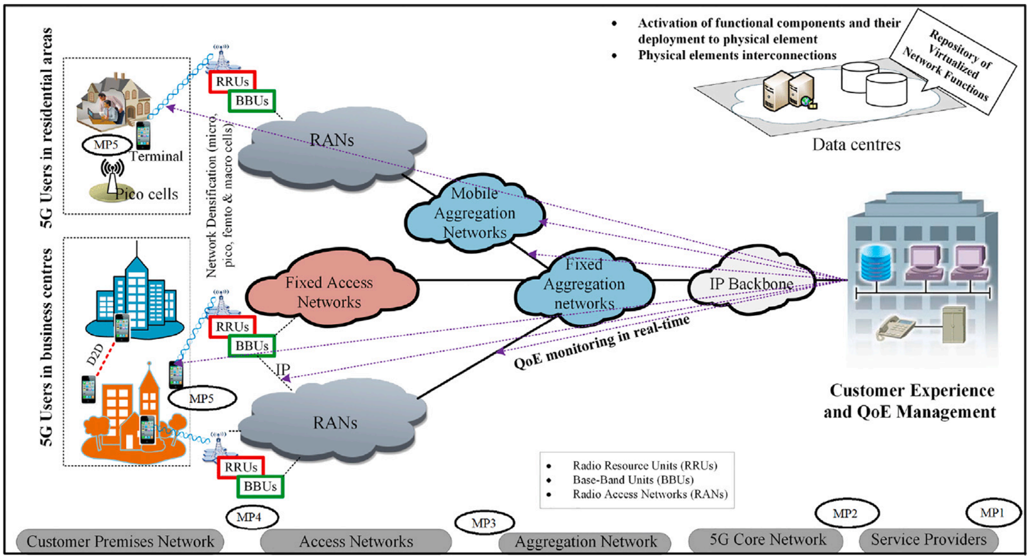

Fig. 7. QoE monitoring for large traffic variations in business, residential and public areas in 5G networks.

Crowdsourcing [89] is another approach that can be used to monitor QoE provisioning in 5G systems. This is done by collecting quality information of communication services on the 5G network and users' mobile terminals. Crowdsourcing can enable systematic verification of user's inputs and derives interval-scale scores that enable subsequent quantitative analysis and QoE provisioning to the end-users. In a virtualized network environment, virtualized passive probes (vProbes) [75] installed in the dedicated hardware can be used for monitoring traffic and testing of applications in 5G softwarized networks. Due to the increase in encrypted video traffic, QoE related metrics (Start-up delay and rebuffering (stalling) from encrypted traffic of video streaming is a topic of interest from the academia and industry [90,91]. Since 2016, a majority of YouTube traffic has been encrypted with a combination of QUIC and HTTPS. Since then, content providers have been increasingly adopting E2E encryption. Orsolic *et al.* [92] and Dimopoulos *et al.,DimopoulosqOeencriptioP*, use machine learning to classify Youtube QoE based on encrypted network traffic. Authors predict QoE metrics of stalls, and its variations using network traffic measurements (e.g., inter-arrival time, RTT, throughput and bandwidth delay product).

Wehner et al. [91] propose a web QoE-monitoring approach for encrypted network traffic through time series modelling while Khairi et al. [90] introduce a novel architecture for 5G networks that can enhance the end-user's QoE monitoring and management by integrating SDN and enhanced telecom operations map (eTOM). The proposed architecture can enable dynamic network monitoring for 5G networks by exploiting SDN functionalities and satisfy the ELA/SLA constraints by enforcing suitable strategies to adjust network parameters. Khokhar et al. [93] apply ML under realistic network conditions to build ML-based models (classification and regression) that estimate QoE (the stalling events, the startup delay, the quality switches, the spatial resolution of playout, and the MO) from encrypted video traces using network level measurements. Huet et al. [94] use ML to build data-driven models that estimate well-known application-level Web browsing QoS metrics (e.g., Page Load Time and SpeedIndex) from encrypted streams of network traffic. Authors measure both the application-level parameters (AppQoS metrics) and the network-level parameters (packet-level traces) after collecting a large data set of Web page load in a controlled experiment.

Authors in [95] develop Request, a Real-time QoE metric (buffer warning, video state, and video resolution) that identifies video and audio segments from the IP headers of encrypted network traffic. A large YouTube data set which consists of different video assets are collected and delivered through various WiFi changing network conditions. Request achieves prediction accuracy in terms of video state, buffer low warning and video resolution compared to the baseline approach [95]. Although the E2E encryption of the video streaming services provides challenges to ISPs to monitor and estimate video quality, efforts have been made to develop solutions regarding QoE monitoring and management in SDN platforms [90], methodology for detecting video streaming QoE issues from encrypted traffic [96], QoE estimation models and QoE inferring video streaming quality from encrypted traffic [97]. This development provides a significant capability for ISPs and MNOs to monitor and optimize the encrypted video traffic on 5G and beyond networks. It is worth mentioning that using the proposed approaches [93–97] MNOs and ISPs can optimize, balance and prioritize encrypted video/network traffic and maintain a satisfactory QoE for video streaming services [98].

4.2.3. QoE analysis, assessment, measurement and visualization

To help network operators and service providers to quickly solve the identified problems in 5G networks through monitoring, service developers and experts conduct an E2E QoE assessment, service quality detection and delimitation. At this point, network operators and service providers can perform network optimization tasks, 5G network performance measurements according to relevant service features from different network administrative domains. Based on recent advances in effective computing and sensing, Dudin et al. [99] propose an SDN/NFV-based resource allocation approach with automated QoE assessment in 5G/B5G wireless systems. Using a mobile Internet experience from end user perspective in Germany, Schwind et al. [100] propose a crowdsourced network measurements methodology that conducts more than 2.5 million throughput tests from Tutela Ltd, an independent crowdsourced data company with a global panel of over 300 million smartphone users. Recent work shows that crowdsourcing can support vendors, operators, and regulators to determine the end-users in new 5G networks architecture that enable various new applications and network services [101].

4.2.4. 5G network performance and QoE optimization

5G network performance and QoE optimization (arrow 4 in Fig. 5) should be able to handle various sessions of video services using intelligent QoE control algorithms (e.g., congestion control mechanisms) that redistribute the available network resources among the competing DASH clients. Altamimi and Shirmohammadi [102] propose a server-side QoE-fair rate adaptation approach that considers both efficiency and fairness of the end-user's QoE. The video bitrate for each user sharing the same bottleneck link to the server is selected using Reinforcement Learning (RL) to achieve fairness. Bentaleb et al. [103] propose an SDNHAS, an intelligent SDN-based streaming architecture that provides capabilities to assist competing HAS players to make better adaptation decisions. The novelty of this work is the reduction of communication overhead between the SDN core and HAS players and efficient allocation of the network resources in the presence of both short and long-term changes in the network.

Mehrabi et al. [104] maximize the end-users QoE of clients and proportional fairness of the bitrate allocation in mobile video streaming by proposing an integer nonlinear programming (INLP) QoE-optimization approach that exploits edge computing facilities. The novelty of this work is the scheduling algorithm that solve the clients to edge server mapping and video bitrate selection which includes self-tuning of the optimization parameters. Luo et al. [105] propose a strategy that consider adaptive bitrate (ABR) streaming, playout buffer dynamics, edge caching, video transcoding and transmission over MEC-enabled SDMN to improve the end-users QoE and energy efficiency. Nightingale et al. [106] leverages a realistic multi-tenanted 5G mobile edge network testbed to propose QoE prediction model that is sufficiently accurate and provides low complexity for real-time video applications in future 5G networks. The prediction model is validated using both empirical measurements in the 5G-QoE testbed and the subjective testing results.

QoE optimization can be performed at various points using different network and service optimization mechanisms, for example at the base stations within the access networks [107–110] by conducting multi-servers selection optimization [111], QoE policy management rules through a joint optimization of the core and access functions [38], intelligent mobility management and an optimized vertical handover decision [112]. It can also be on the end-user's device [113]. In addition, by considering various QoE influence factors and their correlations, the QoE optimization can be performed at different levels ranging from link to application-layer [114–116] or using promising QoE-aware cross-layer software defined 5G network mechanisms [33,49,117]. We envision that, through intelligent mechanisms for QoE control and management, QoE-centric routing, user mobility management, QoE optimization and new business strategies, the proposed ecosystem will help 5G networks and service providers to improve QoE and therefore reduce user complaints on the delivered services. We present next a multi-stakeholders collaboration aspects for video content delivery and network infrastructures followed by a DASH video streaming use case scenario over softwarized and virtualized 5G networks. Fig. 9 indicates the current contributions of QoE control, management and monitoring, modelling as well as challenges of multimedia streaming services in 5G networks.

4.3. Multi-stakeholders collaboration for video content delivery and network infrastructures

From the perspective of multi-stakeholders collaboration, the proposed QoE provisioning ecosystem shown in Fig. 5 can help content delivery systems to improve the efficiency of the video contents distribution and optimize the overall performance of 5G networks by using information provided by the network operators and the network characteristics [24]. The collaboration between ISP and CDN can provide them with triple-win benefits. For example, ISP can gain better QoE-traffic management and efficient network resources utilization leading to a reduced cost of operation and investment. The CDN can acquire the network information and use them to improve the performance of link load and user's experience based on location [118]. An SDN-based CDN–ISP collaboration solution can greatly improve the efficiency of content delivery and the end-users QoE. The CDN–ISP collaboration architectures in this direction are proposed in [119–121]. Akyildiz et al. [119] propose SoftAir, a software-defined architecture for 5G wireless networks that improves the efficiency of content delivery. The architecture adopts different approaches such as distributed and collaborative traffic classifiers and mobility-aware control traffic balancing to optimize the control of traffic control and network monitoring. Wichtlhuber *et al.* [121] propose an SDN-based architecture that provides a fine grained, integrated traffic engineering for CDN traffic in the ISPs network. The CDN provider is given an ability to decide on the selection of surrogate servers. Wang *et al.* [120] propose NetSoft, a software defined decentralized mobile network architecture for 5G to improve the efficiency of content delivery in 5G systems.

The QoE-aware OTT–ISP collaboration in service management has been investigated in recent years for improving QoE of users. Floris et al. [122] propose a QoE-aware service management reference architecture for a possible collaboration and information exchange among OTT and ISP in terms of technical and economic aspects. A joint venture, customer lifetime value and QoE-fairness mechanisms are proposed to maximize the revenue by providing better QoE to customers paying more. Authors in [123] propose a PPNet, a framework that enables isolation between the SP's web and video provider's interfaces. PPNet also allows CDN–ISP collaboration while preventing the ISP's access to the video request and availability information. Arslan *et al.* [124] propose a novel service delivery approach that is purely driven by the end-user's QoE while considering the collaboration between OTT and ISP. Recent developments of network slicing for multi-domain orchestration and management provides a realization of E2E management and orchestration of resources in 5G and beyond sliced networks [11]. It is worth mentioning that, the QoE provisioning ecosystem in Fig. 5 emphasizes on the collaboration between verticals (ISPs, CDNs, OTTs etc.) in 5G networks while ensuring that multimedia streaming service requests from different domains are mapped into multi-operator and multi-provider technology domains while matching each service ELA/SLA requirements [11]. The next subsection provides a multimedia streaming use case scenario for 5G networks and beyond networks.

4.4. DASH video streaming use case over 5G and beyond networks

Fig. 8 illustrates a DASH video streaming scenario over softwarized and virtualized 5G networks. The DASH server contains video contents that are encoded with H.265/HEVC or future H.266.[1] video codecs and segmented based on GPAC MP4Box [126] The video content on the server is made up of the Media Presentation Description (MPD) and segments. The MPD describes a manifest of the available video contents, their URL addresses, characteristics (e.g., video periods, adaptation sets and various representations) and other metadata that may be needed by the clients. The video segments contain the actual multimedia bitstreams that the DASH client plays in single or multiple files in the form of chunks [9]. The delivery of video segments, the client behaviour for fetching, adaptation heuristics, and playing content are based on the QoE prediction and segment-aware algorithms that consider the granularity of the video.

The DASH client runs the DASH.js [127] that is embedded with the QoE prediction, buffer filling strategy and bitrate guidance algorithms to perform QoE optimization. These algorithms enable a DASH client to learn about the media-content availability, their media types, video resolutions, minimum and maximum bandwidths as predicted, measured and monitored by using ML prediction, QoE measurement and real-time QoE monitoring entities as shown in Fig. 10. Using this information, the DASH client selects the appropriate encoded video and starts streaming the content by fetching the segments using HTTP/3 GET requests. Based on the predicted network throughput at the end-user's streaming client, the DASH client continues fetching the subsequent segments while monitoring in real-time the network bandwidth fluctuations using the

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[1] https://bitmovin.com/vvc-quality-comparison-hevc/.

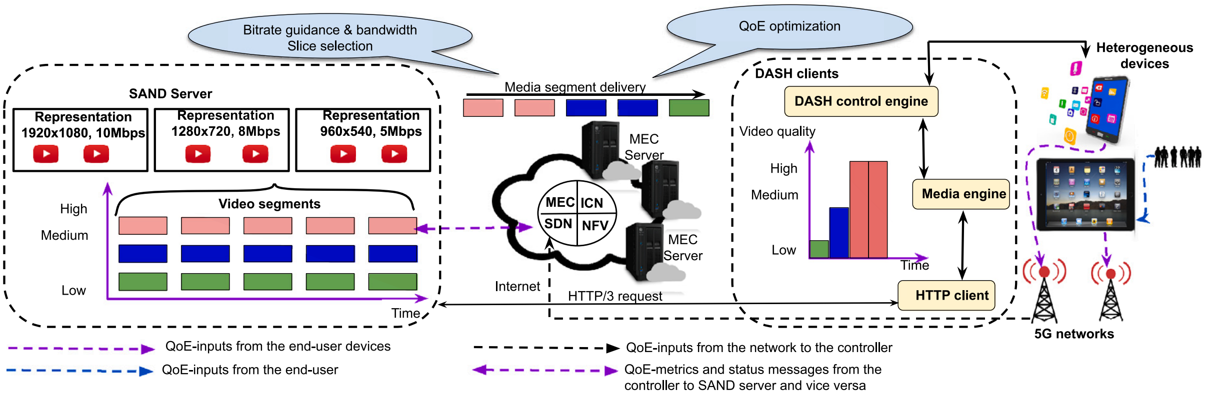

Fig. 8. QoE-driven management of video services over multi-access cloud/edge softwarized and virtualized 5G networks [9,125].

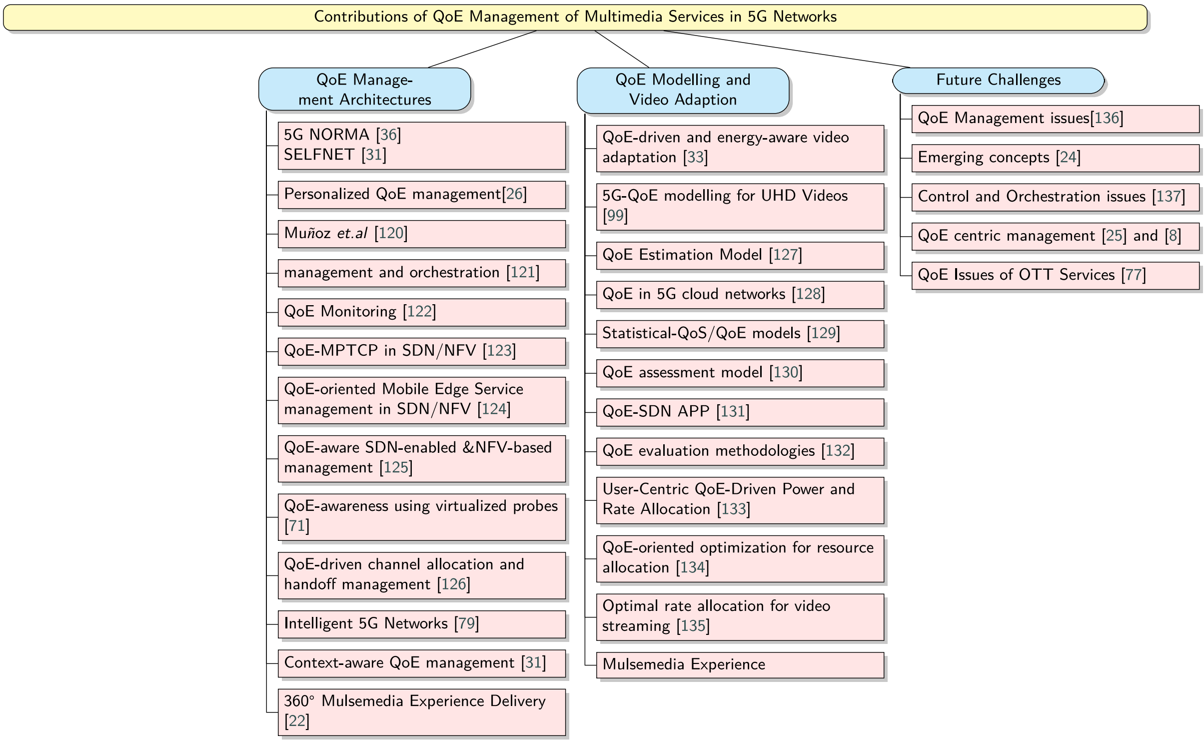

Fig. 9. Contributions of QoE management of multimedia services in 5G networks.

SDN controller shown in Fig. 10. The DASH client fetches video segments as guided by the maximum and the minimum boundary bitrate levels of the QoE prediction algorithm and the buffer filling strategy that maintains an adequate buffer for the client.

The use case shown in Fig. 8 employs the Server and Network Assisted DASH (SAND) technology to enable service providers and operators for enhancing the end-user's video streaming experience while maintaining an efficient utilization of network bandwidth. To improve the efficiency of video streaming services, SAND provides messages between various network elements and DASH clients. This is achieved by providing information about real-time operational characteristics of servers, caches, networks, proxies, and DASH client's streaming status and performance. It is worth noting that the MPEG SAND in the architecture enables better cooperation between the operations of media server and DASH client. It also provides the standardized interfaces toward realizing the (a) video streaming improvements using intelligent processing, caching and QoE-delivery optimizations mechanisms on the network and/or server side using feedback from the DASH clients on the requested segments and network bandwidth, (b) improved QoE adaptation on the DASH client side based on the server/network-side information (e.g., network throughputs, QoS/QoE, video segments) [125]. The use case shown in Fig. 8 is developed to support different MPEG-DASH standards such as MPEG-I [128] for immersive media and MPEG-V [129] information representations to enable interoperability between virtual worlds (e.g., digital content provider of a virtual world, gaming, simulation), and between real and virtual worlds (e.g., sensors, actuators, vision and rendering, robotics).

4.4.1. *Intelligent network policy agents*

Intelligent network policy agents can play a key role in the management of multimedia streaming services by determining the allocation of network resources (e.g., data storage, processing power, and memory), fault diagnosis, routing and communications among network components [130]. It is worth noting that SDN cares more about the created traffic flow, the purpose of the traffic flow and its outcome [29]. The concepts of network agents stem from the needs of packets and data that should be transferred from one application to another in the

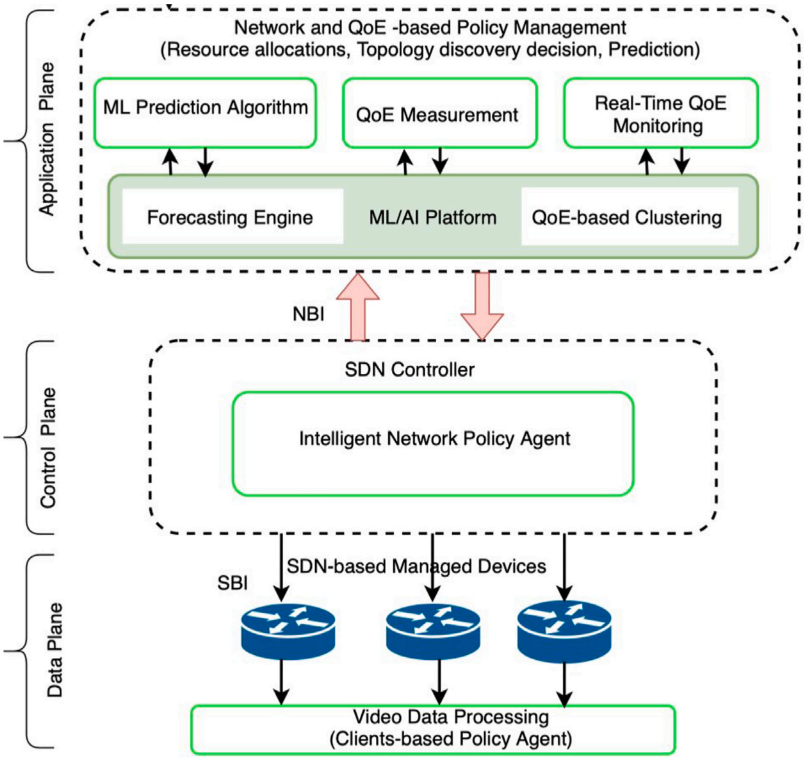

Fig. 10. SDN controller for QoE provisioning over 5G networks.

network [131,132]. The network agents are responsible to carry instructions or defined QoE policies from the control plane and translate those policies into a set of rules or actions on the data forwarding plane [133]. While keeping in mind that, network softwarization in future 5G networks integrates both SDN and NFV, the network agent can also help to implement virtual network functions (VNFs) on the network. That way, network agents residing in different network elements can activate workloads such as packet captures and traffic-forwarding features of video flows in SDN/NFV-based 5G networks. However, the descriptions regarding the implementation details of virtual network agents is out of scope of this paper.

4.4.2. *Artificial Intelligence (AI) platform*

AI/ML has been used to build efficient QoE traffic prediction or control mechanisms because of their ability to solve nonlinear problems [134,135]. The SDN controller integrates an intelligent machine learning platform that learns from the past experience (e.g., learns from the video streaming data available based on the current state). It uses the pre-defined knowledge to forecast the load of incoming DASH requests which in turn improve the overall performance of the system. To summarize, the chronological order of interactions is shown in Fig. 11 using a flow-chart style (from step 1 to step 6). The QoE-based problem formulation indicates the acquisition of system states, topology discovery and the corresponding calculations of QoE values specific to streaming DASH clients. Based on the collected data (step 2), the calculated QoE and all information regarding system states of a streaming session from all participating DASH clients are sent to the control plane (SDN controller). The controller thereafter invokes a function to analyse (step 3) data and performs QoE-based policy decisions related to resource allocation (bandwidth slicing/sharing) among video players. The QoE prediction function (step 4) is invoked to guide precisely the continuous QoE adaptation of the DASH clients to video quality (see Fig. 10). Step 5 signifies the function for evaluation, validation and error analysis of the enforced QoE-based policies, QoE prediction and video bitrate guidance/selection to DASH clients over 5G networks. If the QoE requirements of DASH clients are met, a continuous adaptation and provision of resources to those clients continues; otherwise, necessary actions can be taken by the SDN controller to satisfy the specific-needed QoE requirements of streaming DASH clients.

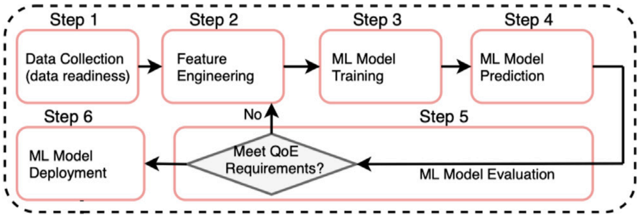

Fig. 11. End-to-end ML pipeline.

It is worth mentioning that, the use case scenario and the SDN controller shown in Figs. 8 and 10 respectively avoid buffer under-run that allows DASH clients to perform QoE-bitrate adaptation based on their buffer fullness level and estimates of short-term future throughput. To enhance streaming QoE, the use case also supports exchange of real time operational characteristics and messages between networks as well as DASH-Aware Network Elements (DANE). DANE consists of knowledge and minimum intelligence about DASH clients, servers, MEC caches and content delivery networks. As shown using coloured dotted arrows in Fig. 8, DASH clients could be allowed to announce information to DANE(s) regarding their required operating bandwidth, a set of segments and video quality. To provide QoE-fairness level, DANEs can send information to DASH clients about video segment and network throughput availability as well as caching status of the segment(s) in the DANE. For example, DANE can allow DASH clients sharing the same network information to use the available bandwidth based on their requirements to avoid overutilization or underutilization of resources. The DASH client can then use this information and preferably access the video content cached at the MEC server and hence reducing the download time. This is an important feature in 5G networks to reduce

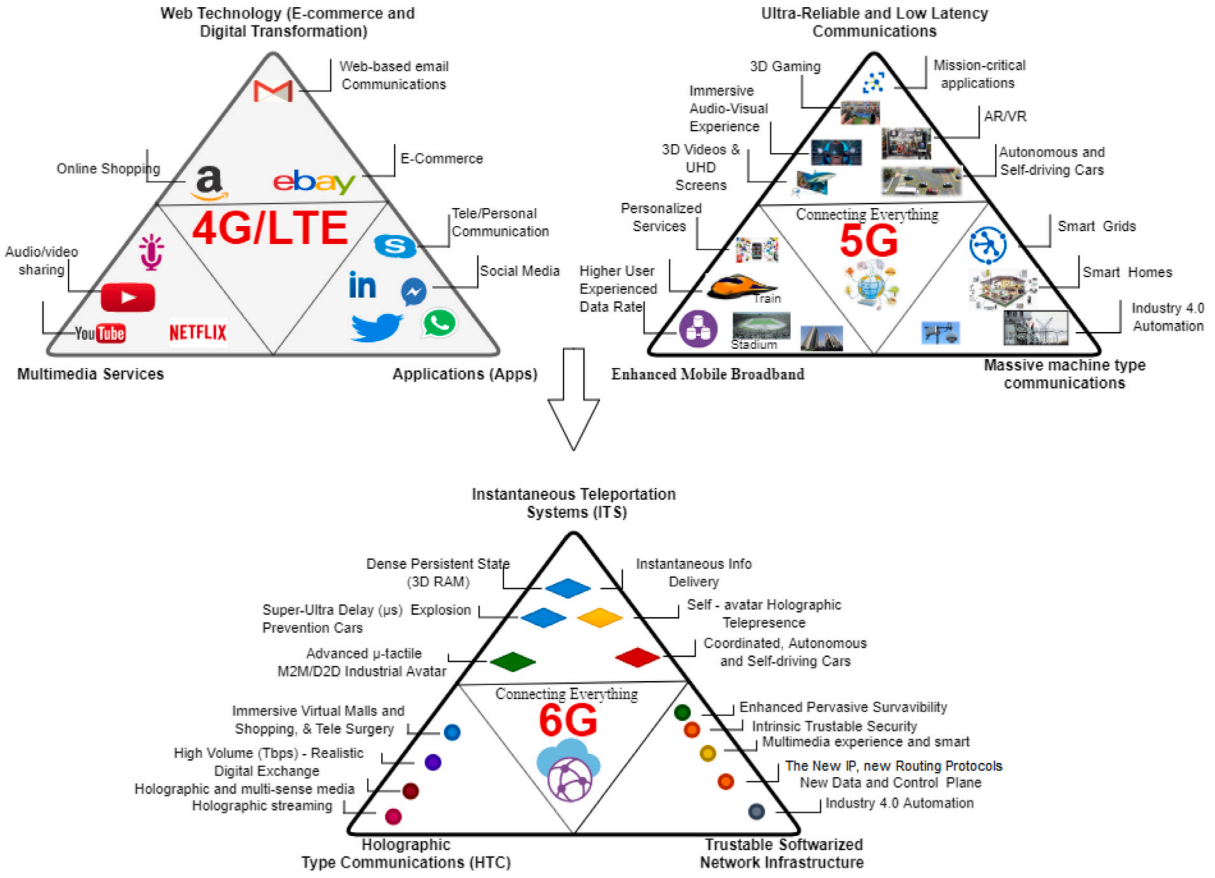

Fig. 12. Future 5G/6G communication services and applications.

latency for bandwidth-intensive applications such as video streaming. The DASH server may exchange QoE metrics to the SDN controller as inputs and apply bitrate guidance and bandwidth selection schemes, novel QoE prediction models and intelligent network/service management and orchestration schemes over softwarized 5G and beyond networks to enhance the user's QoE.

4.5. Summary and lesson learned

This section provides QoE control, management and monitoring aspects in 5G networks . It also presents a general QoE provisioning ecosystem for emerging multimedia services in 5G and beyond networks. We also provide multi-stakeholders collaboration for video content delivery and network infrastructures with a focus on the ISP and OTT collaboration for QoE-aware service management. We note that the use case for QoE-driven network assisted DASH over SDN/NFV (Fig. 8) can offer clients with better short term throughput prediction using AI/ML mechanisms. That way, DASH streaming sessions can adapt to changing 5G network conditions and end-users demands. However, the increasing societal needs, technological breakthroughs and advancement of new services and applications puts 5G to be challenged. For example, the emergence of volumetric video and 6 Degrees of Freedom (6DoF) will make 6G a significant technology that can offer capabilities to support these services/applications as discussed in the next section.

5. The road towards 6G networks

5G networks [1,46] are offering several advancements regarding the network softwarization and virtualization, new frequency bands, massive Multiple-Input Multiple-Output (MIMO), massive IoTs, ultra-densification etc. 5G use cases such as enhanced mobile broadband (eMBB), ultra-reliable low-latency communication (URLLC), and massive machine type communications (mMTC) support different applications and services including multimedia, VR/AR, M2M/D2D communications, eXtended Reality (XR), enhanced mobile broadband etc. However, 5G is always associated with trade-offs because of the increasing societal needs, technological breakthroughs and advancement of new services and applications towards 6G networks. The next generation of VAR (holographic teleportation) and XR experiences need microsecond-level latency and Terabytes Per Second (Tbps)-level data rates which cannot be sufficiently supported by 5G systems. The upcoming Industry X.0 paradigm also presents the next evolution of modern industrial and networked factories that will need reliable high-throughput connectivity across thousands of devices often with sub-millisecond response times [136]. 5G is not designed to serve this connection density that is beyond the 10^6 km^2 metric. 5G systems will not be able to support the evolution of 8 K/12 K VR, volumetric video and 6 Degrees of Freedom (6DoF). As of today, 360° 8 K and 360° 4 K video require 50–200 Mbps and 10–50 Mbps respectively which 5G can offer. However, the future of free viewpoint video or 6DoF technologies which are critical for full immersive experiences need 200 Mbps to 5 Gbps. This puts 5G in a position to be challenged. The rapid development of data-centric and automated processes makes 6G to play a key role towards opening the roadmap in a way that 5G is fundamentally not designed to do.

The development of 6G [136–138] networks has already started from different consortia, companies and Governments. The network 2030 builds upon the achievements of International Mobile Telecommunications 2020 (IMT2020) to define capabilities of 2030 networks, emerging technologies and corresponding communication services and applications. The IMT 2030 is investigating the needs to satisfy the requirements for the intelligent information society of 2030. The International Telecommunication Union (ITU) Telecommunication Standardization Sector (ITU-T) established the Focus Group Technologies for

Table 5
A summary of applications, usage scenarios and 6G networks characteristics.

Network category	Applications	Network characteristics	Usage scenarios
5G	VR/AR/360° Videos, UHD Videos, IoTs, Smart City/Industry/Factory/Home, Telemedicine, Wearable Devices.	Softwarization, Cloudization, Virtualization, Slicing.	enhanced Mobile BroadBand (eMBB); ultra-Reliable and Low-Latency Communications (uRLLC), massive Machine-Type Communications (mMTC).
6G	Tactile/Haptic Internet, Holographic Verticals and Society, Full-Sensory Digital Sensing and Reality, Industrial Internet, Fully Automated Driving, Space Travel, Deep-Sea Sightseeing, Internet of Bio-Nano-Things, Robotic Automation, Holographic Media, Multi-sensory Holographic Teleportation, Real-time Remote Healthcare, Autonomous Cyber–Physical Systems, Intelligent Industrial and Robotic Automation, High-Performance Precision Agriculture, Space Connectivity, Smart Infrastructure and Environments.	Intelligentization, Cloudization, Softwarization, Virtualization, Slicing.	extremely low-power communications (ELPC), Further-enhanced Mobile BroadBand (FeMBB), Long-Distance and High-Mobility Communications (LDHMC), Ultra-massive Machine-Type Communications (umMTC), Extremely Reliable and Low-Latency Communications (ERLLC).

Network 2030 (FG NET-2030) within the ITU Study 13. The FG NET-2030 investigates the future 2030 network architecture and requirements support different use cases such as holographic type communications (HTC) and high-precision communication demands of emerging market verticals. Several projects have been initiated in the European Commission's Horizon 2020 to investigate the network capabilities beyond 5G (B5G) and 6G networks. Projects such as TERRANOVA aim to provide optical network QoE in B5G systems using THz technologies.

TERAPOD investigates the feasibility of ultra-high bandwidth wireless access networks that operate in the terahertz band. The DEDICAT-6G [139] project develops mechanisms that can provide an intelligent placement of computation in mobile networks and maintain an efficient dynamic connectivity. The project also addresses security, privacy, and trust assurance challenges in 5G networks especially for mobile edge services. Moreover, the DEDICAT 6G designs and develops an architecture by transforming beyond 5G networks into a smart connectivity that is highly adaptive, ultra-fast, and resilient for supporting secured interaction between humans and digital systems through the exploitation of novel terminals and mobile client nodes such as robots, mart connected cars and drones [139]. 6G-BRAINS [140] proposes an AI-driven multi-agent Deep Reinforcement learning (DRL) architecture that performs resource allocation over and beyond massive machine-type communications with new spectrum links including THz and optical wireless communications (OWC). 6G-BRAINS is to enhance the performance of 6G and beyond systems with regard to reliability, capacity and latency for future industrial networks. The RISE-6G [141] project defines novel network architectures based on RISs to create a new generation of dynamically programmable wireless propagation environments. The aim is to support dynamic adaptation to future stringent and highly varying 6G and beyond service requirements in terms of localization accuracy, Electromagnetic Field (EMF) emissions and energy efficiency [141]. The key business drivers, applications and use cases pushing forward the development of 6G networks and beyond systems [137,142] are summarized in Table 5. The evolution of communication services and applications towards 6G and beyond networks is indicated in Fig. 12.

5.1. 6G network requirements, scenarios and service classes

6G wireless networks will envisage different Key Performance and quality Indicators including: user-experienced data rate, peak data rate of at least 1 Tb/s, which is 100 times that of 5G, an over-the-air latency of 10–100 μs and high mobility (≥1000 km/h), user-experienced data rate of 1 Gb/s, which is 10 times that of 5G, connectivity density which is 10 times that of 5G, a spectrum efficiency of 5–10 times and an energy efficiency of 10–100 times those of 5G [143]. The user-experienced data rate of up to 10 Gb/s for scenarios such as hotspots and an extremely low latency will provide an acceptable QoE for multimedia streaming services to the end-users. Table 6 shows a summary of KPI and KQI that are crucial in QoE provisioning to the end users in the era of 6G and beyond networks. The next section provides a description of three 6G use cases including (a) holographic and future media communications, (b) human-centric services and 3D volumetric video streaming, and (c) new video compression standards.

5.1.1. Holographic and future media communications

Holographic media [144] in 6G networks will need new form of communications over softwarized and virtualized systems such as holographic-type communications that are tolerant of quality degradation and characterized by very high throughput. Haptics and holograms will provide an immersive user experience even for multiple holographic streams. Hologram streaming in 6G networks will also support fast start-up and adapt to the changing network conditions in large bandwidth and low delay supported automated networks [142]. The 6G network will have new packetization models that support high precision for time-based and qualitative services to manage throughputs. Holographic and full-sensory immersive experiences will lead the applications in 6G networks and in a variety of market verticals. New network-friendly media formats will be characterized by mechanisms to disaggregate volumetric data sets to object centric approaches with lots of metadata support. New holographic applications are expected to emerge in 6G networks and provide fully immersive AR/VR/XR experience with holograms [145]. 6G networks will meet the requirements of extremely high data rates in the order of Gbps or Tbps and stimulate all human senses (vision, hearing, smell, taste, touch, and balance) that will be important for conveying real-time user experience. New distributed HTC techniques proposed in [146] that perform adaptive signalling and frame buffering can be a starting point towards designing efficient algorithms for managing and improving the user's QoE for teleportation streams.

5.1.2. Human-centric services and 3D volumetric video streaming

Human-centred service will be another class of services that needs intelligent, trusted, and inclusive quality models by considering physical factors from human physiology (brain cognition, body physiology, and gestures) [145]. The future of human-centric service in 6G and beyond networks will be supported by ML to provide meaningful one-to-one streaming experiences for users and allow them to receive great services via communication channels over Human-centric Intelligentized Multimedia Networking (HIMN). ML will enable utilizing communication, computing, and caching resources at different edge devices of 6G multimedia networks. The human's experience in HIMN in 6G systems will be put at the centre of mobile video streaming services. Optimization of video quality will be done in real-time based

Table 6
Key performance indicators for 5G and 6G wireless networks.

Key performance indicators	5G	6G
Experienced Data Rate	0.1 Gb/s	1000 Gb/s
Peak Data Rate	20 Gb/s	≥1 Tb/s
Experienced Spectral Efficiency	3× b/s/Hz	3× b/s/Hz
Peak Spectral Efficiency	30 b/s/Hz	60 b/s/Hz
Connection Density (Devices/km^2)	10^6 b/s/Hz	10^7
Area Traffic Capacity (Mbps/m^2)	10	1000
Maximum Channel Bandwidth (GHz)	1	100
End-to-end Latency	1 ms	10–100 μs
Mobility (km/h)	500	≥1000
Delay Jitter	NA	$10^{-}3$
Network Reliability (Packet Error Rate)	$10^{-}5$	$10^{-}9$
Energy Efficiency (Tb/J)	NA	1

on the human's content characteristics, context-awareness and human's perceptions.

The video evolution towards 8 K and beyond in 6G networks will rely on the strict requirements such as experienced data rate and low E2E latency for video delivery. However, with the development of new video coding standards (H.266)[2] for such services, a new set of QoPE metrics have to be defined and offered as mathematical function of traditional QoS and QoE metrics. The development of QoPE metrics models that learn human–brain can be achieved using AI/ML and multi-attribute utility theories from the operations research. A novel brain-aware learning and resource management approach proposed in [147] that explicitly factors in the brain state of human users during resource allocation in a cellular network can be a starting point in developing the QoPE models in 6G networks.

As we move towards 6G and beyond networks, multimedia content is not only gaining higher video resolutions but also higher degrees of immersion. Volumetric video streaming is an emerging key technology to offer user interactions and immersive representation of 3D spaces and objects in 6G and beyond networks [148]. Volumetric videos provide viewers a six Degree-of-Freedom (6DoF) and 3D rendering, making them highly immersive, interactive, and expressive. 6DoF means: three rotational dimensions (e.g., viewing direction in yaw, pitch, and roll) and three translational dimensions (e.g., viewpoint position in X, Y, and Z). Volumetric videos allow a viewer to freely change both the position in space and the orientation [149]. Streaming volumetric videos is highly bandwidth-demanding and requires lots of computational power because of their truly immersive nature.

Thanks to the experienced data rate and peak data rate (≥1 Tb/s) offered by 6G networks which will play a significant part in delivering enough data fast enough for applications like volumetric video. Zhang et al. [150] propose a viewport prediction and blockage mitigation approaches that are efficient for streaming high-quality volumetric videos to multiple users. Authors provides a viewport-similarity opportunity that the multimedia research community can employ for optimizing effectively the network resource utilization using efficient multicast, and mmWave-aware multi-user video rate adaptation. Feng et al. [149] introduce an efficient resource volumetric video streaming architecture that leverages edge computing over 5G/6G to reduce the computation burden on smartphone users while maintaining a high QoE. While the QoE metrics for regular videos have been well studied, but this remains to be an open problem for volumetric video streaming because the QoE of volumetric video streaming can be affected by factors such as viewing distance, visibility, point density, artifacts incurred by patches, motion-to-photon delay, and point density.

5.2. Potential features and technologies in 6G networks

Several technologies are being explored from both academia and industry to support the requirements summarized in Table 6 and meet the vision of 6G networks [136–138]. Fig. 14 indicates key features and technologies for 6G and beyond networks. The design principles of 6G and beyond networks aim to use higher and unlicensed frequency bands to provide richer spectrum resources as well as multiplex more parallel data streams to achieve high spectral efficiency. In the realm of 6G communications and signal processing, AI-driven design and optimization will be applied to computer vision, cognitive radios, remote sensing, and network management. Advanced ML-based algorithms at the 6G network layer will be used for traffic clustering and adapt the network resources based on users' QoE demands as well as various scenarios. On the other hand, deep learning will be applied in 6G networks to optimize resource allocations at the physical layer for power distributions, modulations and coding, channel estimation and multi-user detection.

Bolstered by the use of SDN and NFV, the IoST is envisaged to achieve a global connectivity at low costs and signifies a cyber–physical system that spans the air, ground and in-space backhauling as well as holistic data integration in 6G and beyond networks. The space segment of IoST consists of Unmanned Aerial Vehicle (UAV), CubeSats and near-Earth sensing devices while the ground segment is formed by ground station, on-Earth sensing devices and customer premises [136]. Different from mmWave communications [151] in 5G networks, THz communications in 6G and beyond promise to enable ultra-high bandwidth communication paradigms by providing Terabits/second (Tbps) links for various services and applications including high-definition videoconferencing among mobile devices in small cells environment. Large-scale SM-MIMO with huge multiplexing gain and beamforming capabilities will allow data/information collected from smart sensors to be transmitted with lower latency while offering higher data rates and reliable connectivity to the end-user's devices in 6G and beyond networks.

The SM-MIMO will significantly improve energy efficiency and achieve super-high spectrum efficiency by using spatial multiplexing techniques that transmit hundreds of parallel data streams on the same frequency channel [138]. Traditional wireless communications using electromagnetic-wave signals will not be enough to provide high-speed data transmissions in 6G networks that will encompass underwater networks and space/air networks with terrestrial networks. It is worth noting that Laser communications in 6G networks and beyond will provide ultrahigh bandwidth and achieve high-speed data transmission using laser beams, which are suitable for environments such as free space and under water. HBF is a new dynamic beamforming approach which employs a Software Defined Antenna (SDA) which will enable wireless service providers to reuse continuously abundant spectrum with higher intensity signals delivered to both stationary and mobile users using the lowest Cost, Size, Weight, and Power (C-SWaP) architecture. Unlike current cellular systems, HBF in 6G and beyond networks will allows for multiple concurrent transmissions using the same frequency without interference. The HBF will provide a more focused 6G network communications protocol between base station and user. RISs is a promising technology for enhancing the capacity and

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[2] https://jvet.hhi.fraunhofer.de/.

coverage of 6G wireless networks by smartly reconfiguring the wireless propagation environment.

The Amb-BackCom [152] is introduced in 6G networks to enable smart devices to communicate through the use of ambient radio frequency (RF) signals to address the energy efficiency issues for low-power communications systems such as sensor networks. Blockchain-based spectrum sharing [153] is a promising technology for 6G to provide secure, smarter, low-cost, and highly efficient decentralized spectrum sharing. Strong security in 6G and beyond networks will be provided through Quantum Communications by using quantum computing based on quantum superposition and entanglement. It is worth noting that, Quantum Communications in 6G and beyond networks will adhere to the no-cloning theorem where no copies can be made from an arbitrary quantum state [136]. Unlike conventional networks that are based on the store-and-forward paradigm, 6G and beyond-based quantum networks will apply the quantum teleportation process in transmitting unknown quantum states between remote quantum devices [154,155]. We provide the description of self-driving 3D network architecture, pervasive artificial intelligence, network management, automation and orchestration [156].

5.2.1. Self-driving 3D network architecture

Previous network generations including 5G networks were designed to provide better connectivity, increased link capacity, sufficient communication coverage and edge/cloud computing support [11]. The core design of 5G networks is to allow multiple isolated and self-contained logical networks to share the same physical network infrastructure. 5G network architecture provides support to different services in terms of low latency and operational costs and high reliability (URLLC)) in the two-dimensional (2D) space [1]. The emergence of new services and applications in 6G and beyond networks requires a three-dimensional (3D) architecture to provide ubiquitous 3D coverage, seamless and extremely service connectivity, pervasive connectivity, unmanned mobility, holographic telepresence support etc [136]. To improve radio access capability and unlock the support of on-demand edge cloud services in 3D space, the 6G heterogeneous architecture design should complement and integrate with terrestrial networks and non-terrestrial platforms such as low-orbit satellites, balloons and drones. To facilitate various 3D services and use cases in 3D space, future 6G 3D architecture should extend the concept of 5G network slicing and apply it across both terrestrial and non-terrestrial nodes. The 3D architecture in 6G networks should provide the management and orchestration of computing, communication and caching resources on demand basis, at any time and everywhere using AI/ML-based algorithms. Strinati et al. [157] propose a hierarchical 3D 6G network architecture shown in Fig. 13 that unify diverse 3D network nodes which are distributed over terrestrial and non-terrestrial platforms. The Low Attitude Platforms (LAPs), HAPs, aerial nodes (UAVs) and LEO/GEO satellites are placed at various layers in the architecture.

The LAPs and HAPs offer high flexibility, mobility and adaptive coverage capacity for ground mobile users at low cost. The Integrated Access and Backhaul (IAB) nodes form 3D base stations and 3D relay to provide efficiency and support additional use cases such as Time Sensitive Communications (TSC) and intelligent transportation systems. The IAB supports QoS/QoE prioritization of the traffic on the backhaul link, flexible resource usage between access and backhaul link and topology adaptability in case of link failure. The 3D connectivity services shown in the architecture provides the needed flexibility to accommodate various applications and services including 3D intelligent services, interactive 3D video, real-time 3D traffic monitoring, control and management [157]. The 3D 6G network architecture supports the network slicing concept to support different vertical use cases and services provisioned in 3D space across both terrestrial nodes and non-terrestrial nodes. The AI-based cognitive decision making and intent-based E2E service management will play a key role for network control and management by offering intelligent routing selection and load balancing approaches across 3D network layers. It should also provide 3D remote sensing mechanisms for pollution monitoring, land management and agricultural services as well as meteorological measurements. It is worth mentioning that the 3D network architecture and 3D multi-connectivity will allow the user equipment to establish multiple different traffic links with 3D network nodes. This improves the service performance of UEs through dynamic load balancing strategies and intelligent control and management AI/ML-based algorithms [158].

The development of 3D-based 6G network architecture is taking place within several projects. The H2020 VIrtualized hybrid satellite-TerrestriAl systems for resilient and fLexible future networks (VITAL) project addresses the integration of terrestrial and satellite networks through two key innovations [159]: (a) to bring NFV concept into the satellite domain, and (b) enable management of SDN-based federated resources in hybrid SatCom-terrestrial networks. The management of federated resources using SDN will pave the way for a unified control and management plane for future multimedia services. While this would allow mobile operators to optimize and efficiently manage the overall operations of the hybrid 3D network, enabling NFV into SatCom domain would enable them to offer virtualized satellite networks to third-party providers. The 5G-ALLSTAR project [160] leverages the outcomes of 5GCHAMPION project to design, develop and evaluate the multi-connectivity based on multiple access to integrate cellular and satellite networks to support seamless reliable and ubiquitous broadband services. The H2020 SANSA [161] project proposes an efficient self-organizing hybrid terrestrial–satellite backhaul architecture to provide: (a) capabilities of future terrestrial wireless networks to reconfigure automatically based on the changing traffic demands, (b) a shared spectrum between satellite and terrestrial segments, and (c) a seamless integration of the satellite segment into terrestrial backhaul networks [161].

5.2.2. Network management, automation and orchestration

Network automation using AI/ML will build upon the improvements offered by SDN and NFV and other technologies discussed in Section 3 to speed up the delivery of 6G network media services while guaranteeing experienced QoE to the users. ML will provide the needed functionality to guarantee automation of future 6G wireless communication networks [162].. The management and orchestration of 6G systems using ML-based will enable real-time analysis prediction and automated zero-touch operation, management and control in 6G and beyond networks [163]. The intelligence embedded in different communication nodes will rely on the availability of data timely streamed from wireless devices, especially in extreme services and applications such as XR, real-time video streaming and holographic media. Various categories of ML including supervised learning, unsupervised learning and supervised learning will enable several advanced services and QoS/QoE functionalities related to traffic prediction, and classification as well as predicting the QoE resource requirements associated with different network slice based on the anticipated traffic load. AI/ML will continue to be an indispensable tool in the network management domain, network security and the end user's QoE optimization in 6G and beyond networks [145].

The introduction of Management Data Analytics Service (MDAS) and the Network Data Analytics Function (NWDAF) within 3GPP Releases 15 and 16 which together form an important part of the 5G Service-Based Architecture (SBA). The 3GPP defines a SBA, whereby the common data repositories and control plane functionality of a 5G network are offered and delivered by way of a set of interconnected NFs, each with authorization to access each other's services. The SBA in the 5G/6G network and beyond will allow on demand deployment of each service while being updated independently with minimal impact to other services [136]. It will also allow automation and agile operational processes, vendor independence and reduction in services delivery and enhanced operational efficiencies of network 6G functions.

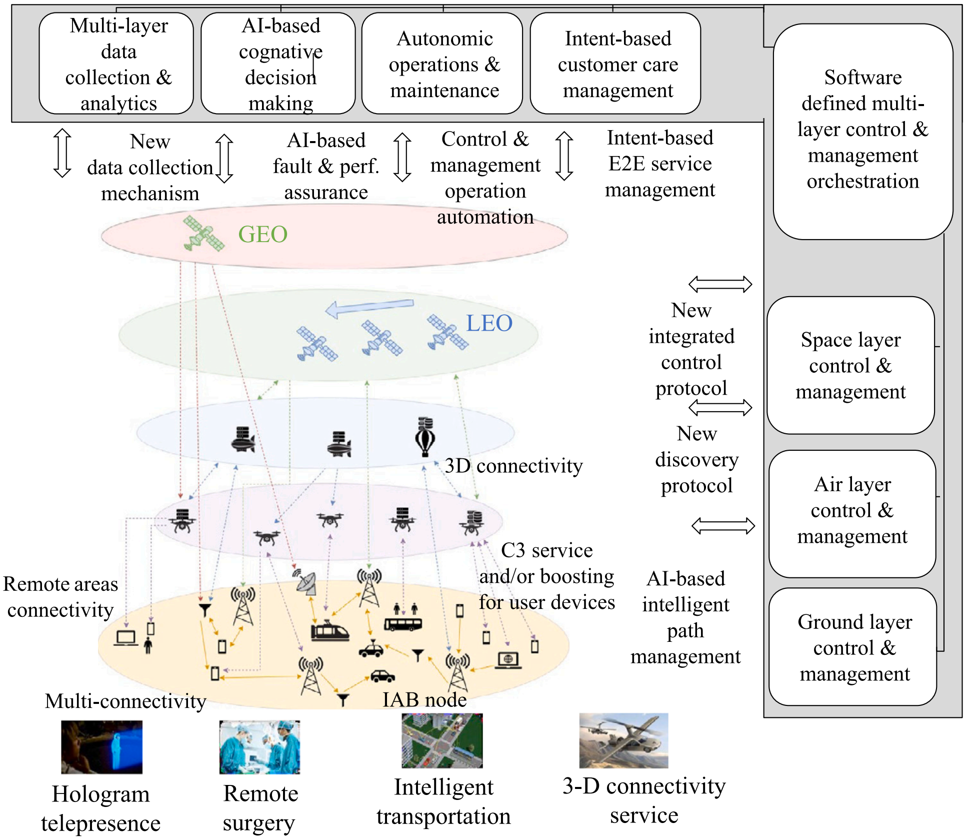

Fig. 13. Hierarchical 3D network system architecture [157].

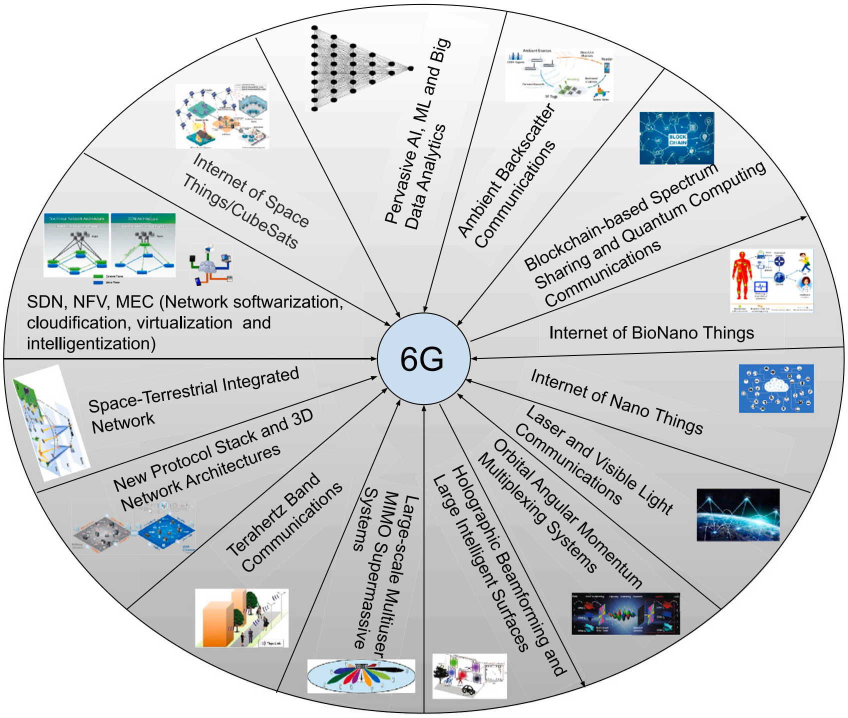

Fig. 14. Key features and technologies for 6G and beyond networks.

Network automation in 6G will transition from operator-driven network to self-driving networks and allow error-free operation, elastic management and utilization of resources, proactive rather than reactive service handling and quick responses to security incidents [136]. The O-RAN architecture [164] is one of the evolutionary steps from 5G to 6G networks where the different functions of the base station are split into the: centralized unit (CU), a distributed unit (DU), and a remote unit (RU) with open interfaces between them. The 3GPP also proposes a similar architecture like the O-RAN approach. The RAN intelligent controller (RIC) in the O-RAN architecture is extracted from the processing units and allows it to reach the management interfaces, like radio resource management (RRM) or self-organizing networks (SON) functions, which control the radio resources and network operation. The intelligence in the O-RAN concept lies is positioned in the RIC by the means of AI models for radio network automation.

5.2.3. Pervasive artificial intelligence

SDN and NFV are moving modern networks toward software-based automation by allocating resources on-demand basis using AI/ML [165]. SDN and NFV are also enabling the network slicing concept in 5G systems that allows multiple virtualized and independent logical networks to be created on the same physical network infrastructure [11]. While the networks towards 6G and beyond are becoming more heterogeneous, multi-layered and high complex, network softwarization concept might not be sufficient in supporting different application and services ranging from communications, computing, context networking, holographic, multi-informational holograms, Instantaneous Teleportation System (ITS), XR video gaming, immersive telepresence, industrial avatars, etc. The 6G network architecture should be intelligent and smart enough to provide fast learning and adaptation environments using AI techniques [136]. Intelligentization in 6G networks will allow dynamic network control, management and orchestration as well as QoS/QoE policy enforcement.

AI-empowered 6G will support several features including self-configuration and optimization, sophisticated learning, aggregation, opportunistic set-up, knowledge discovery and QoE-based context awareness to users [145]. AI-assisted brokering mechanism for RAN slicing and AI-empowered slice admission control, slice scheduling, handover management and mobility management will be prevalent in the era of 6G networks [163]. AI in RAN will help to optimize the network resources and enable real-time conversations amongst the 6G network entities. In terms of operation and management, AI-based 6G networks will enable intelligent measurement and monitoring as well as enhanced security. New AI-empowered data plane techniques have to be developed to support HTC and ITS in 6G networks that will be able to evolve and adapt dynamically to changing network conditions as well as user's service quality demands while transmitting holographic-payloads [145].

5.3. Summary and lesson learned

Table 5 provides a summary of applications, usage scenarios and 6G networks characteristics while Table 6 presents key performance indicators for 5G and 6G wireless networks. Fig. 14 summarizes the key features and technologies for 6G and beyond networks. It is worth noting that efforts are being made to develop 6G and beyond networks that will provide extremely low-latency communications and consistent multimedia streaming experiences even in emerging environments such as high-connected virtual shopping malls. New protocol stack and 3D network architectures, pervasive AI/ML and network softwarization, holographic beamforming and large intelligent surfaces, Internet of Nano Things, blockchain-based spectrum sharing and quantum computing communication as well as Terahertz Band Communication will be key technologies in 6G and beyond networks.

6. Future challenges and research directions in 6G networks

This section provides future challenges and research directions in 6G networks. We provide various opportunities that extensive research from the academia and industry regarding QoE-driven virtualized multimedia 3D services delivery schemes over 6G architecture, 3D cloud/edge models for multimedia services and elastic 3D service customization via network intelligentization, QoE measurement, modelling and testing issues and QoE management and orchestration challenges over 6G networks.

6.1. Novel QoE-driven virtualized multimedia 3D services delivery schemes over 6G networks

The perceived user experience today is mainly driven by service or application and management of networks [166]. The service and application management is within the control and power of content and service providers), while network management is within the control domain and power of ISPs and network operators [9]. These stakeholders are still isolated from each other. However, in the era of 6G and beyond networks, this isolation should be raised for mutual benefits especially in the provision of multimedia 3D services. This call for the development of innovative solutions that would enable the delivery of 3D services over 3D networks by looking at the service delivery chain as an ecosystem including end-users, ISPs, network operators, content/service providers. The developed schemes should holistically extract intelligence from the network, applications and servers and take smart decisions in improving the end-user's QoE of the delivered 3D services. Novel orchestration and software defined control 3D-based architectures, algorithms and interfaces have to be designed, developed and evaluated over 6G and beyond networks to meet the demands of critical multimedia 3D use case scenarios.

6.2. Novel 3D cloud/edge models for multimedia applications and elastic 3D service customization

The research community should develop innovative, abstraction 3D cloud/edge models suitable for multimedia 3D services and applications such as Video Game as a 3D Service (VGaa3DS) or Video Streaming as a 3D Service (VSaa3DS). They should also address the challenge of 3D service customization over 6G architecture by shaping the underlying network resources according to the performance requirements of incoming multimedia service requests. Similar to the approach used by the H2020 VITAL project, researchers should develop open interfaces to allow 3rd parties and vertical segments to control and manage the underlying 6G network infrastructure. This would facilitate the capability of 3D networking architecture to form VNFs and 3D services in a flexible manner while considering the requirements of the desired service. Network intelligentization via ML/AI will provide the means of composing novel virtual functions for 3D services on-demand using modular and sub-functions strategies to address a full service customization in 6G networks. Furthermore, an intelligent orchestration system based on SDN/NFV that will allocate flexible VNFs, create network slices and communicate with external entities in 6G networks has to be developed. To build an intelligent-driven 6G architecture, each external entity has to be equipped with sufficient computing, communication, and caching (3C) resources to support intelligent operations, control, management and monitoring of 3D media services.

6.3. QoE management and orchestration challenges over 6G networks

Network softwarization and intelligentization with technologies like SDN and NFV will continue to be the key in 2030 networks [136,143]. Several projects have been initiated to resolve the network automation issues in 5G and beyond networks including AT&T's ECOMP [167], OSM [168] and ONAP project [169] to provide emphasis on life-cycle management of multimedia services over softwarized networks. Open source platforms (OpenMANO) [170], RIFT.ware [171], and JUJU [172] have been implementing different architectures to support the functionalities for management and orchestration of resources in future networks. Mayoral et al. [173] propose an architecture that enables dynamic resource allocation for interconnected virtual instances in distributed cloud locations. Boutaba et al. [174] present comprehensive learning paradigms and ML techniques applied to fundamental problems in networking, including: resource and fault management, QoE-routing and classification, QoS and QoE management, traffic prediction, congestion control and network security. Despite these efforts, the fundamental challenge is developing QoE-driven multi-party, multi-domain, multi-tenant solutions which are crucial aspects in 6G and beyond networks for predicting demand and dynamically provisioning and reprovisioning resources to the end-users. This calls for novel QoE prediction models and intelligent network/service management and orchestration strategies over softwarized 6G networks [9]. Extensive research from the academia and industry is required to move from existing methods in use today for QoE delivery to the end users. The new QoE research in 6G and beyond networks should embrace the parameters from the user, context, system and content pillars for providing a better understanding of QoE in multimedia services [9].

6.4. QoE measurement, modelling and testing issues over 6G networks

Realistic and efficient measurements, modelling and testing models based on QoE for some 6G scenarios such as the new 3D massive MIMO channels [175] and high mobility channels for enhancing and reducing delays in 6G is still a challenge and an open area requiring investigations [176]. With the increase of network nodes in 6G through the network densification (e.g., dense deployment of small cells) [177], new requirements for channel measurement/modelling in the spatial domain for supporting user mobility with advanced receivers capable of interference cancellation are crucial and should be considered in the design of 6G networks. In addition, sub-path amplitude modulation, spherical wave modelling and non-line-of-sight (NLOS) path-loss in mmWaves which are currently unknown requires also major studies [178,179].

Furthermore, the development of 6G-BSs and UEs which have an impact on user's QoE poses design and testing challenges due to the requirements of extremely high data rates, zero latency (<1 ms), wide channel bandwidth, complex antenna configurations and the support for m-RATs. Some of the key challenges related to measurement and modelling of 6G propagation channels, testing of 6G and beyond systems such as drone base-stations (drone-BS) and cellular-connected drone users (drone-UEs) are summarized in [176,180].

6.5. Immersive media experience in 6G and beyond networks

A truly immersive experiences in 6G and beyond systems will consider extreme requirements on several dimensions of the three pillars of immersion: visual quality, sound quality, and intuitive interactions. For example, during a live sporting event, an exotic vacation or a concert performance, immersive experiences can stimulate a user's senses, vision, hearing, smell, taste and imagination [181]. However, due to the complexity and different constraints (performance, power, and cost) of devices in the era of 6G and beyond networks, achieving full immersion will be a very challenging task [182]. Tele-Immersive (TI) applications (e.g., tele-immersive participatory media and immersive interaction spectating) that enable real-time, multi-party interaction of users in a virtual world will be prevalent in the era of 6G and beyond networks [136]. For example, in a TI game scenario multiple players from around the globe enter a 3D area constructed in real time. For the game players to have a good playing experience in the virtual world, a new ultra-low latency-based TI architecture is needed that will utilize appropriate real-time 3D reconstruction methodologies and video compression standards in 6G and beyond networks [183].

To enhance and ensure smooth user experience, the QoS/QoE research should be the top priority in immersive media in 6G systems. The optimal approach of enhancing the key dimensions of sound quality, visual quality and intuitive interactions is to utilize heterogeneous computing (parallel and distributed processing), cognitive technologies (ML/AI) and a new immersive 3D media platform that can optimize QoE metrics and monitor parameters from the 6G infrastructure and application-level [181]. Cognitive technologies such as computer vision and ML/AI can make experiences more immersive. These technologies can enable devices to reason, perceive, and take intuitive actions. These devices can learn and personalize customer's preference as well as enable intuitive interactions. To achieve this, intelligent algorithms that will improve and personalize the QoE and make experiences more immersive for the users have to be investigated and developed.

6.6. Summary and lessons learned

We provide a summary of contributions for multimedia services in 5G networks as shown in Fig. 9. AI/ML architectures will likely represent a fundamental component of the 6G and beyond ecosystem. This will represent a shift towards a fully-human-centric architecture in 6G networks where end-user's terminals will be able to make autonomous network decisions by using intelligentized controllers. The increased role that AI/ML will play in 6G networks will lead into a more responsive network management that would provide high QoS/QoE guarantees, promote seamless mobility support and interruption-free communication during handovers [9]. For adaptive 360-degree video streaming, ML can bridge the gap between streaming by developing intelligent approaches for objective and subjective QoE assessments in 6G and beyond systems.

7. Conclusion

5G networks is offering several advancements regarding the network softwarization and virtualization. This paper provides a comprehensive discussion regarding QoE management in the context of future softwarized 5G and 6G networks. We introduce a generalized QoE provisioning ecosystem for emerging multimedia streaming services in softwarized 5G/6G and beyond networks. We explore potential network softwarization and communication technologies that will enable the end-user's QoE in 5G/6G.

The paper builds on the achievements of 5G networks to provide the first roadmap towards 6G and beyond networks in terms of requirements, use case scenarios and service classes (e.g., holographic and future media communications, human-centric services and 3D volumetric video streaming, new video compression standards). We also present potential technologies that will be dominant through 2025–2030 in shaping the vision of 6G and beyond networks. Furthermore, the paper provides various features and technologies as well as challenges and research directions in 6G and beyond networks. The comprehensive goal of this paper is to encourage researchers from the industry and academia to work together towards the realization of softwarized 6G and beyond networks while tackling the critical research challenges regarding management of emerging 3D multimedia services and applications.

CRediT authorship contribution statement

Alcardo Alex Barakabitze: Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing – original draft, Writing – review & editing. **Ray Walshe:** Conception and design of study, Acquisition of data, Analysis and/or interpretation of data, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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References

[1] M. Agiwal, A. Roy, N. Saxena, Next generation 5G wireless networks: A comprehensive survey, IEEE Commun. Surv. Tutor. 18 (3) (2016) 1617–1655.

[2] X. de Fo, M. Perras, U. Chunduri, K. Nguyen, M. Kibria, K. Ishizu, F. Kojima, Considerations for MPTCP operation in 5G, [Available at] https://tools.ietf.org/id/draft-defoy-mptcp-considerations-for-5g-01.html.

[3] M. Gramaglia, V. Sciancalepore, F.J. Fernandez-Maestro, R. Perez, P. Serrano, A. Banchs, Experimenting with SRv6: a tunneling protocol supporting network slicing in 5G and beyond, in: IEEE 25th International Workshop on Computer Aided Modeling and Design of Communication Links and Networks, CAMAD, Pisa, Italy, 2020.

[4] F.Z. Yousaf, M. Bredel, S. Schaller, F. Schneider, NFV And SDN-key technology enablers for 5G networks, IEEE J. Sel. Areas Commun. 35 (11) (2017) 2468–2478.

[5] R. Mijumbi, J. Serrat, J.-L. Gorricho, N. Bouten, F.D. Turck, S. Member, R. Boutaba, Network function virtualization: State-of-the-art and research challenges, IEEE Commun. Surv. Tutor. 18 (1) (2016) 236–262.

[6] T.X. Tran, A. Hajisami, P. Pandey, D. Pompili, Collaborative mobile edge computing in 5G networks: New paradigms, scenarios, and challenges, IEEE Commun. Mag. 55 (4) (2017) 54–61.

[7] P. Stefan, D. Erik, F. Anders, F. Mattias, NR: THe new 5G radio access technology, IEEE Commun. Stand. Mag. 1 (4) (2017) 24–30.

[8] M.A. Barakabitze, Behavior and techniques for improving performance of OFDM systems for wireless communications, International Journal of Advanced Research in Computer and Communication Engineering 4 (1) (2015) 237–245.

[9] A. Barakabitze, N. Barman, A. Ahmad, S. Zadtootaghaj, L. Sun, M. G.Martini, L. Atzori, QoE management of multimedia streaming services in future networks: A tutorial and survey, IEEE Commun. Surv. Tutor. 22 (1) (2019) 526–565.

[10] M. Seufert, et al., A survey on quality of experience of HTTP adaptive streaming, IEEE Commun. Surv. Tutor. 17 (1) (2015) 469–492.

[11] A. Barakabitze, A. Arslan, M. Rashid, A. Hines, 5G network slicing using SDN and NFV: A survey of taxonomy, architectures and future challenges, Comput. Netw. 167 (2020) 1–40.

[12] W. Robitza, et al., Challenges of future multimedia QoE monitoring for internet service providers, Multimedia Tools Appl. (2017) 22243–22266.

[13] C. Ge, N. Wang, G. Foster, M. Wilson, Toward QoE-assured 4K video-on-demand delivery through mobile edge virtualization with adaptive prefetching, IEEE Trans. Multimedia 19 (10) (2017) 2222–2237.

[14] W. Robitza, et al., HTTP Adaptive streaming QoE estimation with ITU-T rec. P. 1203: open databases and software, in: Proceedings of the 9th ACM Multimedia Systems Conference, 2018, pp. 466–471.

[15] R.R.R. Rao, et al., Bitstream-based model standard for 4K/UHD: ITU-T P.1204.3 — Model details, evaluation, analysis and open source implementation, in: Twelfth International Conference on Quality of Multimedia Experience, QoMEX, Athlone, Ireland, 2020.

[16] A. Raake, et al., Multi-model standard for bitstream-, pixel-based and hybrid video quality assessment of UHD/4K: ITU-T P.1204, Hum. Cent. Comput. Inf. Sci. 10 (53) (2020) 1–27.

[17] A. Takahashi, D. Hands, V. Barriac, Standardization activities in the ITU for a QoE assessment of IPTV, IEEE Commun. Mag. 46 (2) (2008) 78–84.

[18] H. Tran, et al., A subjective study on QoE of 360 video for VR communication, in: 19th International Workshop on Multimedia Signal Processing, MMSP, Luton, UK, 2017, pp. 1–6.

[19] R. Schatz, et al., Towards subjective quality of experience assessment for omnidirectional video streaming, in: Ninth International Conference on Quality of Multimedia Experience, QoMEX, Erfurt, Germany, 2017, pp. 1–6.

[20] A. Singla, et al., Comparison of subjective quality evaluation for HEVC encoded omnidirectional videos at different bit-rates for UHD and FHD resolution, in: Proceedings of the on Thematic Workshops of ACM Multimedia, Mountain View, Mountain View, CA, USA, 2017, pp. 511–519.

[21] A. Singla, et al., Subjective quality evaluation of tile-based streaming for omnidirectional videos, in: 10th ACM Multimedia Systems Conference, Amherst, MA, USA, 2019, pp. 232–242.

[22] R. Shafi, et al., 360-Degree video streaming: A survey of the state of the art, Symmetry 12 (9) (2020).

[23] I.-S. Comsa, R. Trestian, G. Ghinea, 360-Degrees mulsemedia experience over next generation wireless networks - a reinforcement learning approach, in: 10th International Conference on Quality of Multimedia Experience, QoMEX 2018, Sardinia, Italy, 2018.

[24] A. Ahmad, L. Atzor, MNO-OTT Collaborative video streaming in 5G: The zero-rated QoE approach for quality and resource management, IEEE Trans. Netw. Serv. Manag. 17 (1) (2020) 361–374.

[25] L. Skorin-Kapov, M. Varela, T. Hoßfeld, K.-T. Chen, A survey of emerging concepts and challenges for QoE management of multimedia services, ACM Trans. Multimedia Comput. Commun. Appl. (TOMM) 14 (2s) (2018) 2–28.

[26] S. Petrangeli, J.V.D. Hooft, T. Wauters, F.D. Turck, Quality of experience-centric management of adaptive video streaming services: Status and challenges, ACM Trans. Multimedia Comput. Commun. Appl. (TOMM) 14 (2s) (2018) 2–28.

[27] Y. Wang, P. Li, L. Jiao, Z. Su, N. Cheng, X.S. Shen, P. Zhang, A data-driven architecture for personalized QoE management in 5G wireless networks, IEEE Wirel. Commun. Mag. 24 (1) (2016) 102–110.

[28] T. Zhao, Q. Liu, C.W. Chen, QoE in video transmission: A user experience-driven strategy, IEEE Commun. Surv. Tutor. 19 (1) (2016) 285–302.

[29] A.A. Barakabitze, M. Liyanage, A. Hines, QoESoft: QoE Management architecture for softwarized 5G networks, in: IEEE International Conference on Communications Workshops, ICC Workshops, Dublin, Ireland, 2020.

[30] A.A. Barakabitze, I.-H. Mkwawa, A. Hines, L. Sun, E. Ifeacho, QoEMultiSDN: MAnagement of multimedia services using MPTCP/SR in softwarized and virtualized networks, IEEE ACCESS 8 (2020) 1.

[31] K. Brunnström, S.A. Beker, K. De Moor, A. Dooms, S. Egger, M.-N. Garcia, T. Hossfeld, S. Jumisko-Pyykkö, C. Keimel, M.-C. Larabi, et al., Qualinet white paper on definitions of quality of experience, 2013.

[32] G. Elisavet, A.A. Barakabitze, L. Atzori, L. Sun, V. Pilloni, An SDN-approach for QoE management of multimedia services using resource allocation, in: IEEE International Conference Communications (ICC), Paris, France, 2017, pp. 1–7.

[33] O. Awobuluyi, J. Nightingale, Q. Wang, J.M. Alcaraz-Calero, Ieee international conference on computer and information technology; ubiquitous computing and communications; dependable, autonomic and secure computing; pervasive intelligence and computing, 2015.

[34] I.-H. Mkwawa, A.B. Alcardo, L. Sun, Video quality management over the software defined networking, in: IEEE International Symposium on Multimedia, ISM, San Jose, CA, USA, 2017.

[35] A. Nightingale, Q. Wang, J.M.A. Calero, E. Chirivella-Perez, M. Ulbricht, J.A. Alonso-López, R. Preto, T. Batista, T. Teixeira, M.J. Barros, C. Reinsch., QoE-driven, energy-aware video adaptation in 5G networks: The SELFNET self-optimisation use case, Int. J. Distrib. Sens. Netw. (2016) 1–15.

[36] E. Liotou, D. Tsolkas, N. Passas, L. Merakos, Quality of experience management in mobile cellular networks: key issues and design challenges, IEEE Commun. Mag. 53 (7) (2015) 145–153.

[37] U. Reiter, K. Brunnström, K.D. Moor, M.-C. Larabi, M. Pereira, A. Pinheiro, J. You, A. Zgank., Factors Influencing Quality of Experience: in Quality of Experience: Advanced Concepts, Applications and Methods, Springer International Publishing, 2014, pp. 55–72.

[38] M. Gramaglia, I. Digon, V. Friderikos, D. von Hugo, C. Mannweiler, M. Puente, K. Samdanis, B. Sayadi, Flexible connectivity and QoE/QoS management for 5G networks: the 5G NORMA, in: IEEE International Conference on Communications Workshops, ICC, IEEE, Kuala Lumpur, Malaysia, 2016.

[39] 5G media: Programmable edge-to-cloud virtualization fabric for the 5G media industry, 2021, Online http://www.5gmedia.eu/. (Accessed 20 May 2021).

[40] 5G-MoNArch: 5G mobile network architecture for diverse services, use cases, and applications in 5G and beyond, 2021, Online https://5g-ppp.eu/5g-monarch/. (Accessed 20 May 2021).

[41] 5GTango: 5G development and validation platform for global industry – specific network services and apps, 2021, Online https://www.5gtango.eu/. (Accessed 20 May 2021).

[42] 5G-transformer: 5G mobile transport platform for verticals, 2021, Online http://5g-transformer.eu/. (Accessed 20 May 2021).

[43] SLICENET: ENd-to-end cognitive network slicing and slice management framework in virtualised multi-domain, multi-tenant 5G networks, 2021, Online https://slicenet.eu/. (Accessed 20 May 2021).

[44] A. Sgambelluri, et al., Orchestration of network services across multiple operators: The 5G exchange prototype, in: European Conference on Networks and Communications, EuCNC, Oulu, Finland, 2017.

[45] 5GMediaHUB: 5G experimentation environment for 3rd party media services, 2021, Online www.5gmediahub.eu/. (Accessed 22 May 2021).

[46] J.G. Andrews, S. Buzzi, W. Choi, S.V. Hanly, A. Lozano, A.C.K. Soong, J.C. Zhang, What will 5G be? IEEE J. Sel. Areas Commun. 32 (6) (2014) 1065–1082.

[47] S. Chen, J. Zhao, The requirements, challenges, and technologies for 5G of terrestrial mobile telecommunication, IEEE Commun. Mag. 52 (5) (2014) 36–43.

[48] 4GAmericans, 4G Americans' Recommendations on 5G requirements and Solutions. http://www.5gamericas.org/files/2714/1471/2645/4G_Americas_Recommendations_on_5G_Requirements_and_Solutions_10_14_2014-FINALx.pdf.

[49] M. Yang, Y. Li, L. Hu, B. Li, D. Jin, S. Chen, Z. Yan, Cross-layer software-defined 5G network, Mob. Netw. Appl. 20 (2015) 400–409.

[50] T. Hoßfeld, et al., Definition of QoE fairness in shared systems, IEEE Commun. Lett. 21 (2017) 184–187.

[51] A.A. Barakabitze, T. Xiaoheng, Caching and data routing in information centric networking (ICN): The future internet perspective, Int. J. Adv. Res. Comput. Sci. Softw. Eng. 4 (11) (2014) 26–36.

[52] 5G PPP PHASE 1 PROJECTS. https://5g-ppp.eu/5g-ppp-phase-1-projects/.

[53] M.J.M. Chowdhury, et al., A comparative analysis of distributed ledger technology platforms, IEEE ACCESS 7 (2020) 167930–167943.

[54] 5G ZORRO- zero-touch security and trust for ubiquitous computing and connectivity in 5G networks, 2021, Online https://5g-ppp.eu/5gzorro/. (Accessed 22 May 2021).

[55] 5G-era: 5G enhanced robot autonomy, 2021, Online https://5g-ppp.eu/5g-era/. (Accessed 22 May 2021).

[56] H. Khan, et al., Enhancing video streaming in vehicular networks via resource slicing, 2020, pp. 1–10, arXiv:2002.06928.

[57] F.Z. Yousaf, et al., Network slicing with flexible mobility andqos/qoe support for 5G networks, in: IEEE International Conference on Communications Workshops, ICC Workshops, Paris, France, 2017.

[58] S. Reta, et al., Content delivery network slicing: QoE and cost awareness, in: IEEE ICC 2017 Next Generation Networking and Internet Symposium, Paris, France, 2017.

[59] R. Montero, et al., Content delivery network slicing: QoE and cost awareness, in: Proc. SPIE 10946, Metro and Data Center Optical Networks and Short-Reach Links II, 10946, 2019.

[60] M. Georgios, et al., QoE assessment of video codecs for video streaming over 5G networks, in: 3rd World Symposium on Communication Engineering, WSCE, Thessaloniki, Greece, 2020.

[61] G. Esakki, et al., Adaptive video encoding for different video codecs, IEEE ACCESS 9 (2021) 68720–68736.

[62] J. Chen, Y. Ye, S. Kim, Algorithm description for versatile video coding and test model 7 (VTM 7), document: JVET-P2002-v1 ITU-T SG 16 WP 3 ISO/IEC JTC1/SC 29/WG, 2019.

[63] 5G PPP PHASE 2 PROJECTS. https://5g-ppp.eu/5g-ppp-phase-2-projects/.

[64] 5G PPP PHASE 3 PROJECTS. https://5g-ppp.eu/5g-ppp-phase-3-projects/.

[65] J. Liu, S. Zhang, N. Kato, H. Ujikawa, K. Suzuki, Device-to-device communications for enhancing quality of experience in software defined multi-tier LTE-A networks, IEEE Netw. 29 (4) (2015) 46–52.

[66] E. Liotou, E. Papadomichelakis, N. Passas, L. Merakos, Quality of experience-centric management in LTE-a mobile networks: the device-to-device communication paradigm, in: 2014 Sixth International Workshop on Quality of Multimedia Experience, QoMEX, Singapore, Singapore, 2014, pp. 135–140.

[67] N.-S. VoTrung, Q.D. HoangTuan, H. Kortun, Optimal video streaming in dense 5G networks with D2D communications, IEEE Access 6 (2017) 209–223.

[68] A. Md Abbas, A.B. Alcardo, Evolution of LTE and related technologies towards IMT-Advanced, International Journal of Advanced Research in Computer Science and Software Engineering 5 (1) (2015) 16–22.

[69] A.A. Barakabitze, T. Xiaoheng, G. Tan, A survey on naming, name resolution and data routing in Information Centric Networking (ICN), Int. J. Adv. Res. Comput. Commun. Eng 3 (10) (2014) 8322–8330.

[70] M.H.B. Waheed, et al., A new efficient architecture for adaptive bit-rate video streaming, Sustainability 13 (8) (2021) 1–20.

[71] G.P. Fettweis, The tactile internet: Applications and challenges, IEEE Veh. Technol. Mag. (ISSN: 1556-6072) 9 (1) (2014) 64–70.

[72] J. Sanchezl, I.G.B. Yahia1, N. Crespi2, T. Rasheed, D. Siracusa, Softwarized 5G networks resiliency with self-healing, in: 2014 1st International Conference on 5G for Ubiquitous Connectivity, 5GU, Akaslompolo, Finland, 2014, pp. 229–233.

[73] F. Ahmed, J. Deng, O. Tirkkonen, Self-organizing networks for 5G: Directional cell search in mmW networks, in: 2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC): Workshop: 6th International Workshop on Self-Organizing Networks, IWSON, Valencia, Spain, 2016, pp. 1–5.

[74] A. Imran, A. Zoha, Challenges in 5G: How to empower SON with big data for enabling 5G, IEEE Netw. 28 (6) (2014) 27–33.

[75] C. Tselios, G. Tsolis, On QoE-awareness through virtualized probes in 5G networks, in: 2016 IEEE 21st International Workshop on Computer Aided Modelling and Design of Communication Links and Networks, CAMAD, IEEE, Toronto, Canada, 2016, pp. 159–164.

[76] Q.-V. Pham, F. Fang, V.N. H, M.J. Pira, M. Le, L.B. Le, W.-J. Hwang, Z. Ding, A survey of multi-access edge computing in 5G and beyond: fundamentals, technology integration, and state-of-the-art, IEEE Access 8 (2020) 116974–117017.

[77] A.A. Barakabitze, L. Sun, I.-H. Mkwawa, E. Ifeachor, QualitySDN: Improving video quality using MPTCP and segment routing in SDN/NFV, in: IEEE Conference on Network Softwarization, Montreal, Canada, 2018, (Submitted).

[78] A.A. Barakabitze, L. Sun, I.-H. Mkwawa, E. Ifeachor, A novel QoE-centric SDN-based multipath routing approach of mutimedia services over 5G networks, in: IEEE International Conference on Communications, Kansas City, MO, USA, 2018, (Accepted).

[79] A.A. Barakabitze, L. Sun, I.-H. Mkwawa, E. Ifeachor, A novel QoE-Centric SDN-based multipath routing approach of mutimedia services over 5G networks, IEEE International Conference on Communications (2018).

[80] A.A. Barakabitze, L. Sun, I.-H. Mkwawa, E. Ifeachor, A novel QoE-Aware SDN-enabled, NFV-based management architecture for future multimedia applications on 5G systems, in: 2016 Eighth International Conference on Quality of Multimedia Experience (QoMEX), 2016.

[81] J. Chen, et al., DRL-QOR: DEep reinforcement learning based QoS/QoE-aware adaptive online orchestration in NFV-enabled networks, IEEE Trans. Netw. Serv. Manag. (2021) 1.

[82] A. Martin, et al., Network resource allocation system for QoE-aware delivery of media services in 5G networks, IEEE Trans. Broadcast. 64 (2) (2018) 561–574.

[83] H. Feng-Hui, Z. Wen-An, D. Yu, QoE issues of OTT services over 5G network, in: 2014 Ninth International Conference on Broadband and Wireless Computing, Communication and Applications, BWCCA, IEEE, 2014, pp. 267–273.

[84] P. Trakas, F. Adelantado, N. Zorba, C. Verikoukis, A quality of experience-aware association algorithm for 5G heterogeneous networks, in: IEEE ICC Communications QoS, Reliability, and Modeling Symposium, 2017.

[85] P. Demestichas, A. Georgakopoulos, K. Tsagkaris, S. Kotrotsos, Intelligent 5G networks:Managing 5G wireless/mobile broadband, IEEE Veh. Technol. Maga Zine 10 (3) (2015) 41–50.

[86] M. Varela, P. Zwickl, P. Reichl, M. Xie, H. Schulzrinne, From service level agreements (SLA) to experience level agreements (ELA): The challenges of selling QoE to the user, in: Proceedings of IEEE ICC QoE-FI, London, 2015.

[87] M. Vaser, S. Forconi, QoS KPI and QoE KQI relationship for LTE video streaming and VoLTE services, in: 9th International Conference on Next Generation Mobile Applications, Services and Technologies. Vol. 7, Cambridge, UK, 2016, pp. 318–323.

[88] M. Anderson, C. Ana, A.T. Hai, M. Abdelhamid, A. Brice, H. Said, C.-S. Antonio, B. Kjell, A. Andreas, Managing customer experience through service quality monitoring, in: Future Network & Mobile Summit 2012 Conference Proceedings, Berlin, 2012, pp. 1–9.

[89] T. Hossfeld, M. Hirth, J. Redi, F. Mazza, P. Korshunov, B. Naderi, Best practices and recommendations for crowdsourced QoE - lessons learned from the qualinet task force crowdsourcing, in: European Network on Quality of Experience in Multimedia Systems and Services, COST Action IC 1003 Qualinet, 2014, pp. 1–27.

[90] S. Khairi, B. Raouyane, M. Bellafkih, Novel QoE monitoring and management architecture with eTOM for SDN-based 5G networks, Cluster Comput. 23 (2020) 1–12.

[91] N. Wehner, M. Seufert, J. Schuler, S. Wassermann, P. Casas, T. Hossfeld, Improving web QoE monitoring for encrypted network traffic through time series modeling, in: Conference: 2nd Workshop on AI in Networks and Distributed Systems, 2020.

[92] I. Orsolic, et al., A machine learning approach to classifying youtube QoE based on encrypted network traffic, Multimedia Tools Appl. 76 (2017) 22267–22301.

[93] M. Khokhar, et al., From network traffic measurements to QoE for internet video, in: IFIP Networking Conference, Varsovie, Poland, 2019.

[94] A. Huet, et al., Revealing QoE of web users from encrypted network traffic, in: IFIP Networking Conference, Networking, Paris, France, 2020.

[95] C. Gutterman, et al., Requet: Real-time QoE metric detection for encrypted YouTube traffic, ACM Trans. Multimedia Comput. Commun. Appl. 16 (2s) (2020) 1–28.

[96] G. Dimopoulos, et al., Measuring video QoE from encrypted traffic, in: Proceedings of the 2016 Internet Measurement Conference, 2016, pp. 513–526.

[97] F. Bronzino, P. Schmitt, S. Ayoubi, G. Martins, R. Teixeira, N. Feamster, Inferring streaming video quality from encrypted traffic: Practical models and deployment experience, Proc. ACM Meas. Anal. Comput. Syst. 3 (2019) (2019) 1–25.

[98] A.A. Barakabitze, L. Sun, I.-H. Mkwawa, E. Ifeachor, Multipath protections and dynamic link recovery in softwarized 5G networks using segment routing, in: IEEE GLOBECOM Workshop on Future Internet Architecture, Technologies and Services for 2030 and Beyond, IEEE, 2019.

[99] B. Dudin, N.A. Ali, A. Radwan, A.-E.M. Taha, Resource allocation with automated QoE assessment in 5G/B5G wireless systems, IEEE Netw. 33 (4) (2019).

[100] A. Schwind, F. Wamser, T. Hoßfeld, S. Wunderer, E. Tarnvik, A. Hall, Crowd-sourced network measurements in Germany: Mobile internet experience from end user perspective, 2020, https://arxiv.org/abs/2003.11903.

[101] T. H., et al., White paper on crowdsourced network and QoE measurements – definitions, use cases and challenges, in: Seminar on Crowdsourced Network and QoE Measurements, 2020, pp. 1–24, http://dx.doi.org/10.25972/OPUS-20232.

[102] S. Altamimi, S. Shirmohammadi, QoE-fair DASH video streaming using server-side reinforcement learning, ACM Trans. Multimed. Comput. Commun. Appl. 16 (2s) (2020) 1–21, http://dx.doi.org/10.1145/3397227.

[103] A. Bentaleb, et al., SDNHAS: AN SDN-enabled architecture to optimize QoE in HTTP adaptive streaming, IEEE Trans. Multimed. 19 (10) (2018) 2136–2151.

[104] A. Mehrabi, et al., Edge computing assisted adaptive mobile video streaming, IEEE Trans. Mob. Comput. 18 (4) (2018) 787–800.

[105] J. Luo, et al., Adaptive video streaming with edge caching and video transcoding over software-defined mobile networks: A deep reinforcement learning approach, IEEE Trans. Wireless Commun. 19 (3) (2020) 1577–1592.

[106] J. Nightingale, P. Salva-Garcia, J.M.A. Calero, Q. Wang, 5G-QoE: QoE modelling for ultra-HD video streaming in 5G networks, IEEE Trans. Broadcast. 64 (2) (2018) 621–634.

[107] M. Hasan, E. Hossain, Distributed resource allocation in 5G cellular networks, in: Book Chapter in, Towards 5G: Applications, Requirements and Candidate Technologies, Wiley, 2015, pp. 129–161.

[108] T.O. Olwal, K. Djouani, A.M. Kurien, Wireless backhauling of 5G small cells: challenges and solution approaches, IEEE Commun. Surv. Tutor. 18 (3) (2016) 1656–1686.

[109] B. Maaz, Radio resource allocation in 5G wireless networks, in: Micro and Nanotechnologies/Microelectronics, Vol. 10, University Paris-Saclay, 2017, pp. 1–128.

[110] S. He, W. Wang, User-centric QoE-driven power and rate allocation for multimedia rebroadcasting in 5G wireless systems, in: 83rd IEEEVehicular Technology Conference, VTC Spring, Nanjing, China, 2016.

[111] B. Eugen, A. Tudor, D.N. Joachim, Optimization of multi-server video content streaming in 5G environment, in: The Eighth International Conference on Evolving Internet, Barcelona, Spain, 2016, pp. 48–54.

[112] I. Demydov, M. Seliuchenko, M. Beshley, Mobility management and vertical handover decision in an always best connected heterogeneous network, in: The Experience of Designing and Application of CAD Systems in Microelectronics (CADSM), 13th International Conference, Lviv, Ukraine, 2015, pp. 103–105.

[113] N. Kien, I. Kentaro, K. Fumihide, USD: A user-centric software defined platform for 5G mobile devices, in: International Internet of Things Summit, Rome, Italy, 2016, pp. 530–538.

[114] U. Oruthota, F. Ahmed, O. Tirkkonen, Ultra-reliable link adaptation for downlink MISO transmission in 5G cellular networks, Information 7 (1) (2016) 1–14.

[115] J. Sterle, M. Volk, U. Sedlar, J. Bester, A. Kos, Application based NGN QoE controller, IEEE Commun. Mag. 1 (49) (2011) 92—101.

[116] S. Bikramjit, L. Zexian, T. Olav, A.U. Mikko, M. Preben, Ultra-reliable communication in a factory environment for 5G wireless networks: Link level and deployment study, in: 2016 IEEE 27th Annual International Symposium on Personal, Indoor, and Mobile Radio Communications (PIMRC) - Workshop: From M2M Communications To Internet of Things, Valencia, Spain, 2016, pp. 19–24.

[117] R. Miha, S. Urban, V. Mojca, Novel cross-layer QoE-aware radio resource allocation algorithms in multiuser OFDMA systems, IEEE Trans. Commun. 62 (9) (2014) 3196–3208.

[118] J. Qingmin, et al., The collaboration for content delivery and network infrastructures: A survey, IEEE ACCESS 5 (2017) 18088–18106.

[119] I. Akyildiz, et al., SoftAir:A Software defined networking architecture for 5G wireless systems, IEEE Netw. 85 (2015) 1–18.

[120] H. Wang, et al., SoftNet: A Software defined decentralized mobile network architecture toward 5G, IEEE Netw. 29 (2) (2015) 16–22.

[121] M. Wichtlhuber, et al., An SDN-based CDN/ISP collaboration architecture for managing high-volume flows, IEEE Trans. Netw. Serv. Manag. 12 (1) (2015) 48–60.

[122] F. Alessandro, et al., QoE-aware OTT-ISP collaboration in service management: Architecture and approaches, ACM Trans. Multimed. Comput. Commun. Appl. 14 (2) (2018) 1–24.

[123] K. Akpina, K.A. Hua, PPNet: Privacy protected CDN-ISP collaboration for QoS-aware Multi-CDN adaptive video streaming, ACM Trans. Multimed. Comput. Commun. Appl. 16 (2) (2020) 1–23.

[124] A. Ahmad, et al., QoE-centric service delivery: A collaborative approach among OTTs and ISPs, Comput. Netw. 110 (2018) 168–179.

[125] Guidelines for implementation: DASH-IF SAND interoperability, 2018, Online https://dashif.org/docs/DASH-IF-SAND-IOP-v1.0.pdf/. (Accessed 22 June 2021).

[126] GPAC:Multimedia Open Source Project, [Available at] https://gpac.wp.imt.fr/mp4box/.

[127] Dash-Industry-Forum, dash.js, [Available at]. https://github.com/Dash-Industry-Forum/dash.js/wiki.

[128] MPEG-I: ISO/IEC 23090- Coded representation of immersive media, 2021, Online https://mpeg.chiariglione.org/standards/mpeg-i/. (Accessed 22 June 2021).

[129] MPEG-V: ISO/IEC 23005 - Media context and control, 2021, Online https://mpeg.chiariglione.org/standards/mpeg-v/. (Accessed 22 June 2021).

[130] M. Beacken, et al., The provision of intelligent agent-based enhanced multimedia network services, AT T Tech. J. 4 (1995) 1–35.

[131] M.M. Cheikhrouhou, P.O. Conti, R.T. Oliveira, J. Labetoulle, Intelligent agents in network management a state-of-the-art, 1997, 2022, Online https://www.eurecom.fr/diana/publications/september97/soa-toc.html. (Accessed 12 May 2022).

[132] R. Weihmayer, H. Velthuijsen, Intelligent agents in telecommunications, in: N. Jennings, M. Wooldridge (Eds.), Agent Technology, Springer, Berlin, Heidelberg, 2022, Online https://doi.org/10.1007/978-3-662-03678-5_11. (Accessed 12 May 2022).

[133] O. Aouedi, et al., Intelligent traffic management in next-generation networks, Future Internet, MDPI 4 (2022) 1–35.

[134] E. Danish, M. Alreshoodi, A. Fernando, B. Alzahrani, S. Alharthi, Cross-layer QoE prediction for mobile video based on random neural networks, in: 2016 IEEE International Conference on Consumer Electronics, ICCE, Las Vegas, USA, 2016, pp. 227–228.

[135] P. Charonyktakis, M. Plakia, I. Tsamardinos, M. Papadopouli, On user-centric modular QoE prediction for VoIP based on machine-learning algorithms, IEEE Trans. Mob. Comput. 15 (6) (2016) 1443–1456.

[136] I.F. AKYILDIZ, A. KAK, S. NIE, 6G and beyond: The future of wireless communications systems, IEEE ACCESS 8 (2020) 13399–134030.

[137] W. Saad, M. Bennis, M. Chen, A vision of 6G wireless systems: Applications, trends, technologies, and open research problems, IEEE Netw. 34 (3) (2020) 134–142.

[138] Z. Zhang, Y. Xiao, Z. Ma, M. Xiao, Z. Ding, X. Lei, G.K. Karagiannidis, P. Fan, 6G wireless networks: Vision, requirements, architecture, and key technologies, IEEE Veh. Technol. Mag. 14 (3) (2019) 28–41.

[139] DEDICAT 6G: Dynamic coverage extension and distributed intelligence for human centric applications with assured security, privacy, and trust: from 5G to 6G, 2021, Online https://5g-ppp.eu/dedicat-6g/. (Accessed 22 May 2021).

[140] 6G BRAINS: Bringing reinforcement learning into radio light network for massive connections, 2021, Online https://5g-ppp.eu/6g-brains/. (Accessed 22 May 2021).

[141] RISE-6G: Reconfigurable intelligent sustainable environments for 6G wireless networks, 2021, Online https://5g-ppp.eu/rise-6g/. (Accessed 22 May 2021).

[142] Network 2030: A Blueprint of Technology, Applications and Market Drivers Towards the Year 2030 and Beyond. [Available at] https://www.itu.int/en/ITU-T/focusgroups/net2030/Documents/White_Paper.pdf.

[143] T. Nakamura, 5G evolution and 6G, in: International Symposium on VLSI Design, Automation and Test, VLSI-DAT, Hsinchu, Taiwan, 2020.

[144] A. Clemm, et al., Toward truly immersive holographic-type communication: Challenges and solutions, IEEE Commun. Mag. 58 (1) (2015) 93–99.

[145] K.B. Letaief, W. Chen, Y. Shi, J. Zhang, Ying-Jun, A. Zhang, The roadmap to 6G: AI empowered wireless networks, IEEE Commun. Mag. 57 (8) (2019) 84–90.

[146] I. Selinis, N. Wang1, B. Da, D. Yu, R. Tafazolli, On the internet-scale streaming of holographic-type content with assured user quality of experiences, in: IFIP Networking Conference, Networking, Paris, France, 2020.

[147] A.T.Z. Kasgari, W. Saad, M. Debbah, Human-in-the-loop wireless communications: Machine learning and brain-aware resource management, IEEE Trans. Commun. 43 (11) (2019) 7727–7743.

[148] S. G, D. Podborski, T. Buchholz, T. Schierl, C. Hellge, Low-latency cloud-based volumetric video streaming using head motion prediction, in: Proceedings of the 30th ACM Workshop on Network and Operating Systems Support for Digital Audio and Video, 2020, pp. 27–33.

[149] F. Qian, B. Han, J. Pair, V. Gopalakrishnan, Toward practical volumetric video streaming on commodity smartphones, in: Proceedings of the 20th International Workshop on Mobile Computing Systems and Applications, 2019, pp. 135–140.

[150] A. Zhang, et al., Mobile volumetric video streaming enhanced by super resolution, in: Proceedings of the Twentieth ACM Workshop on Hot Topics in Networks, 2021, pp. 16–22.

[151] Y. Niu, et al., A survey of millimeter wave communications (mmWave) for 5G: opportunities and challenges, Wirel. Netw. 21 (2017) 2657–2676.

[152] N.V. Huynh, et al., Ambient backscatter communications: A contemporary survey, IEEE Commun. Surv. Tutor. 20 (4) (2018) 2889–2922.

[153] K. Kotobi, et al., Secure blockchains for dynamic spec- trum access: A decentralized database in moving cognitive radio networks enhances security and user access, IEEE Veh. Technol. Mag. 13 (1) (2018) 32–39.

[154] M. Caleffi, et al., Quantum internet:From communication to distributed computing, in: Proc. 5th ACM Int. Conf. Nanoscale Comput. Commun., NANOCOM, 2018, pp. 1–4.

[155] S.J. Nawaz, et al., Quantum machine learning for 6G communication networks: state-of-the-art and vision for the future, IEEE ACCESS 7 (2019) 46317–46350.

[156] M.W. Akhtar, S.A. Hassan, R. Ghaffar, H. Jung, S. Garg, M.S. Hossain, The shift to 6G communications: vision and requirements, Hum. Cent. Comput. Inf. Sci. 10 (53) (2020) 1–27.

[157] S. Emilio Calvanese, B. Sergio, A.P. Taesang Choi, G. Alessandro, D.S. Emanuele, V. Josep, B. Zdenek, H. Thomas, C.F. Nicolas, K. Costanzo, I. Kim, 6G in the sky: On-demand intelligence at the edge of 3D networks (invited paper), Wiley ETRI J. (2020) 1–15.

[158] J. Kim, G. Casati, A. Pietrabissa, A. Giuseppi, E.C. Strinati, N. Cassiau, G. Noh, H. Chung, I. Kim, M. Thary, J.-M. Houssin, F. Pigni, S. Colombero, P.D. Zotto, L. Raschkowski, S. Jaecke, 5G-ALLSTAR: An integrated satellite-cellular system for 5G and beyond, in: IEEE Wireless Communications and Networking Conference Workshops, WCNCW, 2020, pp. 1–6.

[159] F. Mendoza, R. Ferrus, O. Sallent, Experimental proof of concept of an SDN-based traffic engineering solution for hybrid satellite-terrestrial mobile backhauling, Int. J. Satell. Commun. Netw. 37 (3) (2014) 1–18.

[160] J. Kim, G. Casati, A. Pietrabissa, A. Giuseppi, E.C. Strinati, N. Cassiau, G. Noh, H. Chung, I. Kim, M. Thary, J.-M. Houssin, F. Pigni, S. Colombero, P.D. Zotto, L. Raschkowski, S. Jaeckel, 5G-ALLSTAR: An integrated satellite-cellular system for 5G and beyond, in: IEEE Wireless Communications and Networking Conference Workshops, WCNCW, 2020, pp. 1–6.

[161] A.I.P.-N. Shaat, G. Agapiou, S. Chatzinotas, M. Landmann, I. Moreno, K. Ntougias, C.T. J. Nunez-Martinez, M.C. Vigano, R. Zetik, G. Ziaragkas, SANSA: HYbrid terrestrial-satellite backhaul network for the 5th generation, in: ETSI WORKSHOP on FUTURE RADIO TECHNOLOGIES – AIR INTERFACES, 2016, pp. 1–6.

[162] C. Zhang, P. Patras, H. Haddadi, Deep learning in mobile and wireless networking: A survey, IEEE Commun. Surv. Tutor. 21 (3) (2019) 2224–2287.

[163] H. Yang, A. Alphones, Z. Xiong, D. Niyato, J. Zhao, K. Wu, Artificial-intelligence-enabled intelligent 6G networks, IEEE Netw. 34 (6) (2020) 272–280.

[164] O-RAN architecture overview, 2021, Online https://docs.o-ran-sc.org/en/latest/architecture/architecture.html. (Accessed 22 June 2021).

[165] A. Ali, B. Abdelhak, A.A. Barakabitze, V.G. Bogdan, Z. Thomas, Bandwidth prediction schemes for defining bitrate levels in SDN-enabled adaptive streaming, in: International Conference on Network and Service Management (CNSM), 2019.

[166] S. Schwarzmann, et al., Estimating video streaming QoE in the 5G architecture using machine learning, 2019, pp. 7–12.

[167] AT & T. Enhanced Control, orchestration, management, and policy (ECOMP) architecture, 2018, Online https://about.att.com/content/dam/snrdocs/ecomp.pdf. (Accessed 27 February 2018).

[168] OSM ESTI NFV, 2018, Online https://osm.etsi.org/. (Accessed 27 February 2018).

[169] ONAP:LInux foundation project, 2018, Online https://www.open-o.org/. (Accessed 27 February 2018).

[170] Telefonica research institute, 2018, Online https://github.com/nfvlabs/openmano. (Accessed 27 February 2018).

[171] RIFT.io, 2018, Online https://riftio.com/tag/rift-ware/. (Accessed 27 February 2018).

[172] Canonical, 2018, Online http://www.ubuntu.com/cloud/juju. (Accessed 27 February 2018).

[173] A. Mayoral, R.C.R.M. Raul Muñoz, Ricard Vilalta, V. López, Need for a transport API in 5G for global orchestration of cloud and networks through a virtualized infrastructure manager and planner, J. Opt. Commun. Netw. 9 (1) (2017) A55–A62.

[174] R. Boutaba, M.A. Salahuddin1, N. Limam, S. Ayoubi, N. Shahriar, F. Estrada-Solano1, O.M. Caicedo, A comprehensive survey on machine learning for networking: evolution, applications and research opportunities, J. Internet Serv. Appl. 9 (16) (2018) 1–99.

[175] A. Fjolla, T. Martin, R. Markus, 3GPP 3D MIMO channel model: a holistic implementation guideline for open source simulation tools, EURASIP J. Wireless Commun. Networking (2016) 1–14.

[176] J. Medbo, K. Borner, K. Haneda, V. Hovinen, T. Imai, J. Jarvelainen, T. Jamsa, A. Karttunen, K. Kusume, J. Kyrolainen, P. Kyosti, J. Meinila, V. Nurmela, L. Raschkowski, A. Roivainen, J. Ylitalo, Beyond 5G with UAVs: Foundations of a 3D wireless cellular network, IEEE Trans. Wireless Commun. 18 (1) (2019) 357–372.

[177] B. Naga, L. Junyi, M. Durga, R. Gilmore, B. Dean, D. Aleksandar, T.S. Ravi, P. Chirag, G. Stefan, Network densification: the dominant theme for wireless evolution into 5g, IEEE Commun. Mag. 52 (2) (2014) 82–89.

[178] M.K. Samimi, S. Shu, T.S. Rappaport, MIMO Channel modeling and capacity analysis for 5G millimeter-wave wireless systems, in: European Conference on Antennas and Propagation, EuCAP'2016, Taipei, Taiwan, 2016, pp. 1–5.

[179] Z.M. Fadlullah, N. Kato, HCP: HEterogeneous computing platform for federated learning based collaborative content caching towards 6G networks, IEEE Access (2020) 1.

[180] E. Hossain, M. Hasan, 5G cellular: Key enabling technologies and research challenges, IEEE Instrum. Meas. Mag. 18 (3) (2015) 64–68.

[181] Driving the new era of immersive experiences. [Available at] https://www.qualcomm.com/media/documents/files/whitepaper-driving-the-new-era-of-immersive-experiences-qualcomm.pdf.

[182] S. Gul, D. Podborski, J. Son, Cloud rendering-based volumetric video streaming system for mixed reality services, 2020, pp. 1–4, https://arxiv.org/abs/2003.02526.

[183] G. Caruso, F.S. Nucci, S. Rizou, J. Magen, G. Agapiou, P. Trakadas, O.P. Gordo, Embedding 5G solutions enabling new business scenarios in media and entertainment industry, in: IEEE 2nd 5G World Forum, 5GWF, Dresden, Germany, 2020.

Further reading

[1] A.A. Barakabitze, L. Sun, I.-H. Mkwawa, E. Ifeachor, A novel QoE-centric SDN-based multipath routing approach of mutimedia services over 5G networks, in: IEEE International Conference on Communications, Kansas City, MO, USA, 2018.

[2] A.A. Barakabitze, L. Sun, I.-H. Mkwawa, E. Ifeachor, A novel QoE-aware SDN-enabled, NFV-based management architecture for future multimedia applications on 5G systems, in: 8th International Conference on Quality of Multimedia Experience, QoMEX, Lisbon, Portugal, 2016.

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