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5G TECHNOLOGY FOR MUSIC EDUCATION: A FEASIBILITY STUDY

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ABSTRACT

The goal of this paper is to analyze and show, also through practical examples, how the emerging 5G technology can improve music education. First, the key characteristics of 5G networks, i.e. improved bandwidth, reliability, and density of devices in an area, will be presented. From such a discussion, it will emerge the possibility to design and implement innovative educational services that are rich in multimedia content, support two-way multimodal interaction, and are highly customizable to respond to users' requirements and special needs. A number of case studies in the domain of music education will be presented and commented.

KEYWORDS

Education, e-learning, interactive media system, music teaching, 5G.

1. INTRODUCTION

The latest generation of cellular mobile communications known as 5G is expected to change our everyday lives in the near future. As discussed below, 5G will introduce relevant improvements with respect to current network technologies in terms of a larger bandwidth, a more reliable service, and a higher density of devices. These features, if profitably exploited, will be able to influence or even revolutionize many aspects of human activities, from business to entertainment, thanks to the enhancement of already available services and to the introduction of brand-new ones.

Consequently, 5G is expected to have a potential impact on pedagogical experiences, too. More specifically, in this work, we will focus on music education, namely a field where the availability of a large bandwidth is particularly relevant to exchange high-quality multimedia streams, and latency in bidirectional communication should be reduced to an acceptable value, in the millisecond range.

The research questions we want to address in this paper are: Can 5G be profitably applied to music education, which is still a very traditional and conservative context? What services, currently hard or impossible to implement, will become potentially available to music learners? Finally, how will 5G affect the way we learn music and practice an instrument?

In order to answer these questions, the paper will provide details about the technical specifications and the expected performance of 5G networks (Section 2), will shed some light on brand new or enhanced educational services (Section 3), will present some music-related scenarios where 5G is expected to show its potential (Section 4), and will investigate the feasibility of implementing such services in 5G infrastructures (Section 5). Finally, Section 6 will draw conclusions.

This work is the extension of a paper previously presented at the 13th International Conference on e-Learning held in Porto, Portugal on 17 – 19 July 2019 (Baratè et al, 2019b).

2. KEY FEATURES OF 5G TECHNOLOGY

The standard document for 5G technology (3GPP, 2019) has been published in March 2018 by 3GPP and officially approved in the Plenary Meeting in June 2018.

For the goals of this paper, we are interested in investigating 5G functionalities and performance that may facilitate the implementation of advanced e-learning services in the music field. In particular, we analyze the support that 5G may give to audio and video data exchange, and its capabilities of facilitating data sharing through the formation of extemporary classrooms anywhere using just users' devices.

As a first step, an analysis is conducted of the typical requirements of multimedia applications, regardless of 5G networks. Table 1 summarizes the bandwidth, latency, and reliability requested by different applications and data traffics. As far as latency is concerned, while streaming applications tolerate delays of a few seconds, two-way conferencing applications have a more stringent requirement in the order of around 100 ms in order to supply high Quality of Experience (QoE) to the users (Cisco, 2017). Applications involving Augmented Reality (AR) and Virtual Reality (VR) significantly push forward these requirements (Mangiante et al., 2017; Qualcomm Technologies Inc., 2018; Mushroom Networks, 2017): in order to supply a realistic and immersive experience to users, ultra-low latencies of less than 10 ms are needed; for retina-experience video, the requested bandwidth may increase up to some Gbps.

As far as services are concerned, 5G includes both an ultra-reliable low-latency communications (URLLC) service, and an enhanced mobile broadband (eMBB) service (3GPP, 2019). Deliverable D1.1 of the 5G-EVE consortium (5G EVE, 2018), published in Oct. 2018, defines the characteristics of these services. URLLC aims at providing latencies no greater than 50 ms and reliability of more than 99.9% (Li et al., 2018); it is intended for use mainly with industrial and vehicular applications in order to guarantee prompt delivery of emergency notifications. Under these points of view, it also fits the requirements of AR and VR applications; though, it will be able to provide a data rate of up to 10 Mbps only. By contrast, eMBB aims at providing ultra-high throughput so as to address the needs of users accessing multimedia content, ranging from real-time video streaming to online gaming with 3D 4K video;

in particular, it should provide a peak data rate of up to 20 Gbps for the base station, with a minimum guaranteed to users of 100 Mbps. This service seems best suitable for e-learning applications. In the same document, the goal for Media & Entertainment applications is TV service for mobile users with throughput of 100-200 Mbps (with peaks of up to 250 Mbps in downlink) and latency lower than 100 ms. An aspect that is still under investigation is how the different services will coexist; their combination seems impossible since different mechanisms are adopted to implement each of them (Ji et al., 2018). Coexistence of URLLC and eMBB might delay network access for eMBB traffic, thus affecting its performance; this will depend on the mix of different traffics in real infrastructures.

Table 1. Summary of needed network performance for multimedia applications

Application	**Bandwidth**	**Latency**	**Reliability**
standard A/V streaming	≤ 3 Mbps	4-5 s	≥ 95%
HD video streaming	4-8 Mbps	4-5 s	≥ 95%
3D HD video streaming	9 Mbps	4-5 s	≥ 95%
4K video streaming	25 Mbps	4-5 s	≥ 95%
interactive real-time conferencing	≥ 2 Mbps	~ 100 ms	99.0% - 99.5%
AR	100 Mbps - 5 Gbps	1 ms	99.0% - 99.5%
VR (interactive)	100 Mbps - 2.35 Gbps	10-30 ms	99.0% - 99.5%

An interesting characteristic of 5G is its multi-RAT (multi-Radio Access Technology) nature. This means that 5G will be able to cooperate with different technologies such as 4G cellular telephony, but also with Bluetooth or WiFi. Both Bluetooth and WiFi are license-free technologies, which however might provide limited bandwidths: Bluetooth 5 supplies a bitrate around 2 Mbps, while WiFi – in version 802.11ac – can reach, in real deployments, up to ~200 Mbps. An alternative incoming possibility is that of using LTE Direct: it is an addition to 4G LTE technology, standardized on March 2015 in 3GPP Release 12 (3GPP, 2015), that allows to offload base stations by supporting direct device-to-device communications between devices in the same cell. In 2015, Deutsche Telekom deployed a first trial of LTE Direct, validating the feasibility of the technology (Qualcomm Technologies Inc., 2015). LTE Direct supplies a higher radio range than WiFi also in urban areas, it supports quite high mobility (up to 30 Km/h) but provides throughputs of the order of 3.5 Mbps uplink and 13 Mbps downlink only.

With these premises, a number of scenarios currently not implementable will be achievable in the future, through an accurate combination of radio technologies and services. Figure 1 outlines some possible applications, by arranging them along the axes that link the peculiar features of 5G systems: capacity enhancement, ultra-high reliability and low latency, and a third type of service, namely, the ability of connecting an ultra-high number of devices.

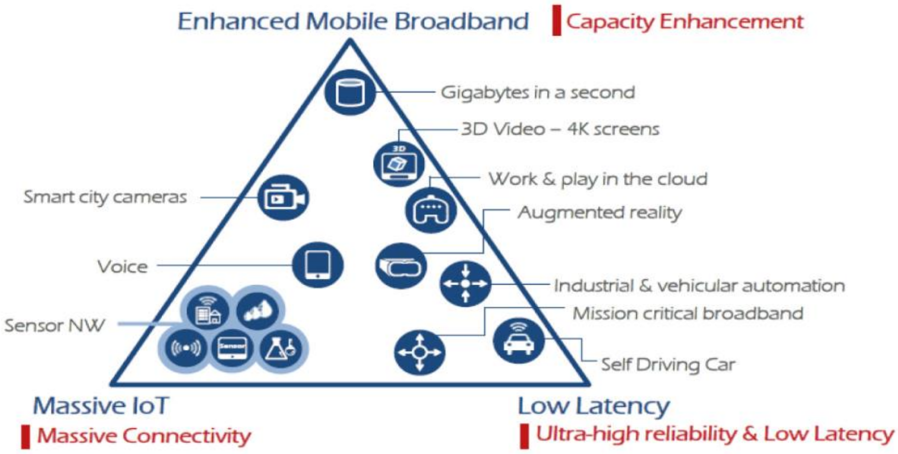

Figure 1. The triangle of 5G applications (source: ETRI graphic, ITU-R IMT 2020 requirements)

2.1 5G State-of-the-Art and Trials

In order to assess the characteristics of 5G networks in real or realistic environments, a number of experiments are ongoing. On December 2018, the Italian Inter-University Consortium for Telecommunications (CNIT) promoted a conference involving information technology companies, telecommunication companies and representatives of the European Commission (CNIT, 2018). The talk by Enrico Salvatori of Qualcomm supplied a measure of bandwidth of 1.4 Gbps in a testbed in San Francisco. According to Peter Stuckmann of the European Commission, the 26 GHz frequency band will be reserved for fixed wireless access with a throughput of up to 10 Gbps, while the 3.6 GHz frequency band will be used for urban mobile access guaranteeing users a data rate of 1-3 Gbps.

For the Bari-Matera installation in Italy, the 5G-PPP consortium (The 5G Infrastructure Public Private Partnership, 2018) reports an obtained throughput of around 3 Gbps with a latency of about 2 ms (Fastweb, 2018). In this case – as mentioned above – 5G is mixed with the LTE technology (TIM et al., 2018); the migration towards pure 5G was scheduled for mid-2019.

The 5G-EVE consortium (5G-EVE 2018) was founded in June 2018 with the goal of coordinating and tracing the experiences conducted in European trials. According to Deliverable 3.1 published in December 2018, two trials are planned for Media & Entertainment applications: the former in Spain with the goal of achieving 200 Mbps throughput with around 100 ms of latency; the latter in France with comparable latency and a lower throughput of 80-200 Mbps.

The European 5G Observatory (European 5G Observatory, 2019) provides data from more than 190 trials and experiments. Data are contradictory, as noticed in the site, with bitrates largely variable; this depends both on the frequency band used for the channel, and on whether measurements are taken in a real urban infrastructure or rather are conducted in a laboratory.

Indeed, in European trials, a few, most used, radio frequency bands are adopted with very different characteristics. In Table 2, the characteristics of those bands are summarized, as taken mainly from (GSMA, 2019; Nokia, 2017; Nguyen, 2017; HKT et al., 2018; Halvarsson et al., 2018; Sulyman et al., 2014). It is worth to notice that specific bands may belong to different band classes in the classifications of different standardization institutions. In the following of this work, we adopt the EU names that have a higher granularity.

As far as the radio range is concerned, the 5G infrastructure will involve both *macro-cells*, and several kinds of small cells (Nguyen, 2017). The latter ones are further classified in:

- *micro-cells that are less than 1 Km radius (urban area)*
- *pico-cells that are less than 100 m radius*
- *femto-cells that are in the order of 10 m radius.*

In the last column of the Table the expected bitrate is reported, and – in bold – the measured bitrate, when available, averaged over all the trials adopting the corresponding band. A few remarks about the different bands:

- **700 MHz:** Europe has prioritized this band for wide area services (including mobile broadband coverage across urban, suburban and rural areas, IoT, and telecom TV) (GSMA, 2019). This band allows the construction of 5G *macro-cells*; in order to increase throughput, MIMO antennas with more than 100 elements will be deployed. Alternative frequencies used to this purpose are 600 MHz in the USA, and 850/900 MHz. These frequencies are indicated as the *sub-1 GHz* bands (Nokia, 2017).
- **3.4-3.8 GHz:** *prime* 5G mid-bands and mobile bands, available globally. For dense 5G small cell networks in urban hotspots, but also macrocells for wider area coverage, including fixed wireless access. This band can provide the same coverage, and use the same cell sites, as the current 2.6 GHz and 1800 MHz mobile bands (GSMA, 2019). Together with the 2.3 GHz and 4.5 GHz bands, they are indicated as the *sub-6 GHz* band (Nokia, 2017). The 4.5 GHz band should be an alternative to the 3.4-3-8 GHz band for several countries included China and Japan (GSMA, 2019).
- **15 GHz:** adopted in Ericsson testbeds in Europe (Turkey, Hungary and Russia) and in Hong Kong.
- **26-28 GHz** and **70-80 GHz:** these bands fall within the *mmWaves* frequency bands. They are envisaged for ultra-high-speed mobile broadband (GSMA, 2019). The latter one is used by standards IEEE 802.15.3c and 802.11ad, and can be adopted to build *femto-cells*. It is worth to notice that mmWaves are unable to penetrate obstructions.

Table 2. 5G radio channels

ITU band name and number	*IEEE band name*	*EU band name*	*Frequency*	*Cell radius*	*Bitrate*
Ultra High Frequency (UHF, 9)	UHF	C	700 MHz	tens of Km	>= 200 Mbps
	Short wave (S)	E	2.3 GHz	<= 1 Km	<= 2 Gbps
Super high frequency (SHF, 10)		F	3.4-3.8 GHz		<= 2 Gbps (400-800 Mbps in cell [Nokia 2017]) **3.87 Gbps**

	C	G	4.5 GHz		<= 2 Gbps **10 Gbps**
	Kurz-under (Ku)	J	15 GHz		**23.9 Gbps**
	Kurz / Kurz-above (K / Ka)	K	26-28 GHz	~ 500 m	<= 20 Gbps **9.3 Gbps**
Extremely high frequency (EHF, 11)	V / W	M	70-80 GHz	10 m.	<= 20 Gbps **52 Gbps**

From an in-depth data analysis, it seems that the most realistic measures have achieved 700 Mbps to 1 Gbps data rate in download; this test was conducted in Finland in urban area, hence possibly with a reasonable user density. Over all experiments, peak data rates have been achieved of 70 Gbps in the M-band. It is worth noticing, however, that the peak data rates have been obtained in small testbeds (e.g., involving just a small number of users and one antenna) possibly in laboratory, and their applicability is thus limited. In general, latencies are lower than 5 ms.

Summarizing the above considerations, we may say that the existing realistic trials in the prime sub-6 GHz bands are able to provide a 700 Mbps to 1 Gbps (or more) of throughput on user's devices, with low latencies of the order of a few milliseconds. According to Table 1, this performance may satisfactorily fulfill the requirements of all applications including AR/VR with medium-quality, thus making 5G the elective technology to support the deployment of innovative e-learning services such as those discussed later in this paper.

However, a few remarks should be discussed. The analyzed trials results have been obtained with currently existing infrastructures, which represent the first prototype implementations of the 5G standard, possibly built from existing 4G infrastructures of providers that are gradually trying to commute to 5G; better results will be likely obtained in future years with the improvement of both the hardware and software components. Moreover, in specific situations, where very high performance is needed, custom deployments of 5G infrastructures resorting to the mmWave band may further enhance throughput. Finally, the performance really observed by users will strongly depend on the mix of traffics (asking different services) that will be injected into the network, and on how both users and traffic flows will compete for the network resources. Part of these aspects will be investigated in Section 5 by means of simulations.

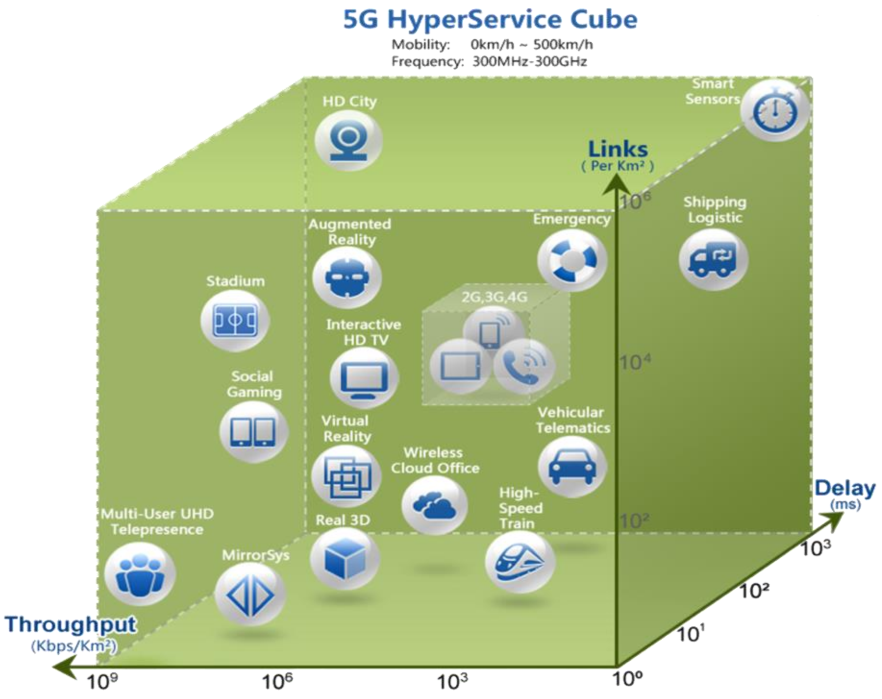

Figure 2. The 5G HyperService Cube (source: Huawei, “5G: A Technology Vision”)

3. 5G TECHNOLOGY FOR EDUCATION

The technical features of 5G and the state of the art about trials in real or artificial environments let us predict a number of new applications in the field of education, as well as significant improvements in already available ones.

An alternative way to represent the triangle of 5G applications shown in Figure 1 is the so-called 5G HyperService Cube by Huawei (Figure 2). In this representation, 3 dimensions clearly emerge: throughput, latency, and density of connections. The goal of this section is to highlight which kind of didactic experiences can be placed at both ends of these axes, in the knowledge that the space of applications is continuous.

Concerning the first dimension, namely *throughput*, at the low end of the axis we can place the distribution of pure text, images, and, in general, all those multimedia objects requiring a low bitrate (such as low-resolution or highly compressed video footage); conversely, at the high end of the axis we find demanding applications such as augmented reality and virtual reality for educational goals.

Referring to *connection density*, at the low end of the axis we can identify standard educational environments, characterized by a relatively low density of students and a sporadic use of network-attached technological devices. Please note that in some schools the usage of smartphones and tablets during lessons is even prohibited. At the high end of the axis, on the contrary, we find educational activities occurring in very crowded places (e.g., stadiums, arenas, theatres, etc.), where many independent user devices are concentrated in a small area and concur for network resources.

Finally, regarding *delay*, a high value of latency can be tolerated for asynchronous didactic activities (e.g., educational videos) or situations with relaxed constraints about interaction (e.g., a teleconference lesson with a final session for student questions); conversely, at the other end there are synchronous activities with 2-way interaction and strict latency requirements (e.g., a remote lesson of surgery or a distributed music performance).

After analysing the different dimensions separately, it is worth exploring the space as a whole. The features introduced by 5G may support the simulation of in-presence learning (*remote synchronous*), wherever learners actually are, thanks to high-bandwidth and low-latency services. In the space shown in Figure 2, this kind of experience can be placed near "multi-user UHD telepresence". *Remote synchronous* learning is one of the hardest in terms of quality of service (QoS), since it requires seamless interactivity with little bidirectional delay. Even if time constraints are not as strict as for self-driving cars or other critical real-time applications, the interaction should be perceived as fluid, so the suffered delay should be in the order of 100 ms or less.

A case study requiring a moderate throughput, a barely perceivable delay and, above all, the availability of high link density, is the real-time replication of a lesson in another classroom or congested place. Its position in the cube shown in Figure 2 could be near "wireless cloud office" applications. Whenever no interaction or customization is required by "distant" students, technologies supporting this reduced form of participation are already available. For example, crowded university courses can be easily replicated in other classrooms through projections. Conversely, if we want to provide students with the possibility to interact with the professor (e.g., if blackboard notes are too small) or to customize their experience (e.g., focusing on the professor's face as well as on his/her multimedia presentation), 5G features are required. Moreover, 5G gives the possibility to attend live lessons in mobility, still providing an interactive and customizable learning environment, and this new modality can represent a paradigm shift for non-attending and off-site students.

Student groups can be formed dynamically using participants' devices, in a BYOD (*bring your own device*) context, exploiting higher connectivity support. Thanks to the 5G multi-RAT feature, it is possible to constitute impromptu ad hoc groups formed by the devices of both teachers and learners, wherever they are. For instance, this is made possible by the LTE Direct technology. In case no fixed infrastructure exists, users may leverage the ad-hoc networking capabilities of WiFi and Bluetooth. From the point of view of required network features, such a scenario resembles the "social gaming" application shown in Figure 2.

For *remote asynchronous* learning, the 5G architecture assumes to involve cloud or fog computing. Students may take tests and exercises offline and then upload their results on the cloud, where statistical processing of their data may either bring into evidence topics that are unclear to a majority of students (and must thus be discussed in more depth during lessons) or highlight students with a significantly low rate of success in assessment (thus needing special tutoring). The position of such a scenario in the cube of Figure 2 could be close to the one of "interactive HD TV".

Finally, let us remark that 5G networks foster applications with highly-demanding transfer rates, such as the enrichment of educational activities through augmented reality (AR). An example in the field of music education will be discussed in the next section. Similarly, 5G supports the virtualization of lab experiences through virtual reality (VR), exploiting both high bitrates for ultrahigh-definition video streams (4K is not very defined when applied to a spherical video), and low latency coupled with cloud/fog/edge computing for the real time calculation in response to user actions, gestures and movements. The space shown in Figure 2 exemplifies the possible positions of "AR/VR applications".

4. CASE STUDIES IN MUSIC EDUCATION

In this section, we will discuss some relevant case studies covering heterogeneous educational goals and investigating different aspects of 5G technologies. This analysis takes the move from and improves our preliminary investigation in (Baratè et al., 2018) carried on before the stabilization of the 5G standard.

4.1 Exploitation and Enhancement of Music Archives

Before the Internet era, the access to intangible heritage archives was very limited for laypersons. Recently, digitization campaigns on one side and web technologies on the other have provided Internet users with the possibility to unveil many hidden treasures in a digital form. In this way, cultural heritage has been brought to a new life and somehow democratized. In the field of music, relevant examples are the online historical archives of opera houses (e.g., La Scala,[1] Metropolitan Opera,[2] New York Philharmonic[3]), and score digitization initiatives (e.g., Bach Digital,[4] Petrucci Music Library,[5] the music collections of the Bibliothèque nationale de France[6]).

Digital availability and technologically-augmented sharing of cultural heritage has an impact on education, too. First, providing new generations with the access to cultural heritage has an intrinsic value: in the case of music, this implies, e.g., the possibility to listen to historical performance, view high-resolution scans of scores and enjoy related iconographic materials. Moreover, getting in touch with relevant cultural heritage has a valence that goes beyond a passive knowledge of the past: it implies the possibility to learn from the past, e.g., discovering (or re-discovering) how a great singer performed a given operatic aria, analysing the handwritten notation of a composer and comparing it to printed versions, and so on.

In an initial phase, the online availability of previously inaccessible information was considered an outstanding advancement in itself. In general, applications like the ones described above tolerate non-negligible delays and rarely need to support a high density of devices, but they can benefit from the expected improved bandwidth of 5G, allowing to send high-resolution and low-compressed images to mobile devices or to share full HD videos over a mobile network.

But, nowadays, content providers are more interested in innovative services aiming at rediscovering the past through novel approaches, so as to raise the interest of new categories of users and to open new markets by extending the potential audience. Improvements of already existing services may include, for instance, cultural enrichment through engagement and edutainment applications and highly customized user experiences.

Let us consider an application for mobile devices capable of giving new value to archive materials by offering advanced features, such as score and libretto synchronization, links to additional contents, and so on. The interface, as the one shown in Figure 3, can be customized in many of its aspects (language, font size, panels, etc.). An archive or institution that wants to exploit its archives and fund preservation or dissemination initiatives could sell this innovative service, made available on demand to online users. The QoS guaranteed by 5G would offer a bandwidth sufficient to stream high quality media objects and an uninterrupted and fluid fruition on personal devices, even in mobility.

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[1] http://www.teatroallascala.org/en/archive/the-historical-archive.html
[2] http://archives.metoperafamily.org/
[3] https://archives.nyphil.org/
[4] https://www.bach-digital.de/
[5] https://imslp.org/
[6] https://gallica.bnf.fr/

Figure 3. A mobile application to revive archive materials and let users enjoy them in an innovative way

4.2 AR/VR Applications for Music Education

Many applications of augmented and virtual reality can be figured out in the field of music education, taking benefit from the 5G technology.

An example is to apply AR to live music experience with didactic purposes. For instance, while watching and listening to a symphonic orchestra, additional information could be delivered to mobile devices in a customized environment, where users can enjoy score following while music is playing, obtain on-screen labelling of musical instruments and performers, read related textual material (also synchronized with music, as for librettos), and so on. Moreover, customization could take into account previous knowledge of music, pedagogical goals, possible student impairments, etc. In this way, attending a concert would be far from a passive fruition, and technological augmentation could result in a more involving and effective didactic experience.

This kind of applications requires the ability to bidirectionally interact with user devices, presumably in a crowded place like a concert hall or an opera house; besides, latency must be almost imperceptible. Conversely, a high bandwidth, in general, is not required.

An example describing an augmented reality application for interactive opera experience has been discussed in (Baratè and Ludovico, 2016). The interface, shown in Figure 4, presents a number of advanced features, such as the dynamic identification of characters, score following, synchronized libretto with a custom translation, etc. The experience must be designed to enhance user experience rather than produce information overload, a typical risk of augmented-reality initiatives, above all in an educational environment.

Figure 4. An example of augmented reality application for interactive opera experience (Baratè and Ludovico, 2016).

Concerning VR approaches for music education, we can figure out applications such as the immersive visualization of music parameters in real time, the interactive experience of a remote live event, the virtual participation to a music lesson. These examples can pave the way to new commercial products, such as the extension of physically available seats for a concert or the virtual attendance of a class with a great performer or the rehearsal of a renowned conductor, also with some interaction features. These examples could occur, e.g., during the hour of Music and without moving from the school, taking benefit from a BYOD approach that supports user-tailored experience.

4.3 Multi-Layer Music Education

The possibility to deliver simultaneous and synchronized high-quality data streams in applications for music education enables a demanding application in terms of bandwidth, namely multi-layer music learning and teaching. With the locution *multi-layer* we denote an approach to the description of an information entity from multiple points of view, possibly making their heterogeneous relationships emerge.

In the field of music education, this implies the possibility to describe a music piece in a multi-layer framework. Let us consider a typical music lesson or individual-study session for young learners: they can imply theoretical activities such as the analysis (or multiple analyses) of music notation (potentially, many different forms of notation), physical and motor activities for instrumental practice, listening activities to draw inspiration from historical performance, etc.

A publicly available example is represented by a web-based interface realized by the Laboratory of Music Informatics, University of Milan for an educational book by Pearson, whose interface is shown in Figure 5 (Ludovico and Mangione, 2014). Such a multi-layer approach embraces different kinds of representation: a logic description of music events, one or many graphical representations for notation, one or many audio/video tracks of human or computer-based performance, a structural description of the piece to foster analytical activities, etc.

The first educational advantage of a multi-layer approach is the possibility to offer a more articulated set of organized information to students. For example, a young learner can listen to an already available audio track and watch the corresponding score so as to get inspired, and an application able to support synchronization can ease the task.

Another advantage of a multi-layer approach is user-tailored customization, which, in this context, implies:

- the possibility to choose alternative forms of notation (e.g., colored notation for children affected by dyslexia or Braille notation for blind people);
- on-the-fly selection of the most suitable video content (e.g., a timed animation of the keys to play or a close-up footage over the hands of an experienced pianist);
- the comparison of already available performances to improve expressiveness;
- the use of learning aids, such as the possibility to reduce the beats per minutes during playback or to (visually or aurally) emphasize a part within an orchestra score.

Adopting a multi-layer pedagogical approach within a remote learning framework (e.g., a Web portal or an ad-hoc mobile application) presents a drawback: the need to exchange a number of simultaneous high-quality materials over the network.

In the context of remote didactic activities, supporting a high density of devices is required only in very particular cases, such as the attendance of a lesson in a crowded place.

The aspect concerning low latency could seem secondary, above all for asynchronous didactic activities, but this enables, e.g., client-server requests to send a different data stream on the fly, with no significant delay perceived in multimedia experience. In this way, it is no more necessary for the client to receive a number of media streams simultaneously, ready to be switched. Consequently, the band available to single users can be exploited in more efficient ways.

In any case, 5G is expected to unveil its potential above all in terms of bandwidth. Let us analyse the different kinds of materials to embed in a multi-layer environment. Needless to say, symbolic content (text, logic representations of score, etc.) is very lightweight information. Also images whose quality is sufficiently high to be enjoyed via Web or on small screens do not pose technological challenges. Concerning audio streams, sending multiple simultaneous uncompressed or losslessly compressed stereo streams can be a little tricky, while 5G reveals its full potential in delivering high-quality video material. In the next section we explore this aspect through simulations.

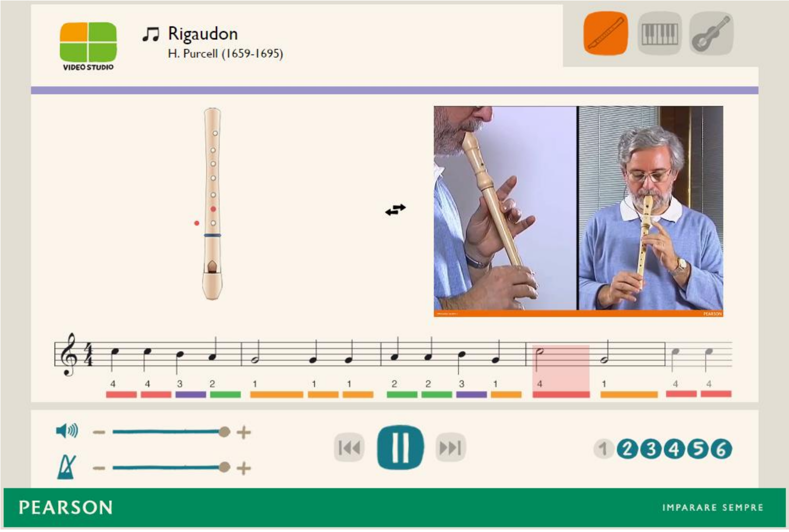

Figure 5. An example of multi-layer application for music education

5. 5G FOR EDUCATION: FEASIBILITY ANALYSIS

In this section, a performance measure and comparison of the 5G and LTE techniques is presented for different scenarios. The analysis is conducted through simulation techniques. Various applicative scenarios are considered among those described in Section 4. For the 5G infrastructure, different cell sizes, number of connected clients, and channel characteristics are studied. In Section 5.1, an overview is provided on network requirements for some popular audio/video encodings. In Section 5.2, the simulation results are presented.

5.1 Multimedia Network Requirements

When projecting video-streaming applications on a network, an aspect to be considered is the transport protocol to use. The most recently proposed protocol is VSF TR-03 [VSF 2015], standardized in 2018 as SMPTE ST 2110-20. This protocol minimizes the control information added to the video data, and it asks to use UDP messages not larger than 1440 byte and a clock rate of 90 KHz. According to this standard, the source settings in terms of both bitrate and packet rate are determined depending on the video format. The *Kush Gauge* rule of thumb to compute the bitrate is:

$$Bitrate = frame\ width \times frame\ height \times frame\ rate \times motion\ factor \times 0.07$$

where the motion factor accounts for the amount of movements in the video.

Yet, this is not the global generated traffic. Three addressing modes exist to diffuse information in Internet, namely unicast, multicast, and broadcast. *Broadcast* implies that a data is contemporarily diffused to all devices in a certain network, which in the case of wireless networks comes at no cost since the radio media is intrinsically broadcast. Yet, in e-learning scenarios, not all devices in a certain wireless cell necessarily belong to learners involved in the same class; hence, broadcasting is not applicable. *Multicast* means that a group of users is identified with a particular network address, and multicast protocols are used in the network in order to limit the message replication to the different destinations. Unfortunately, multicast is seldom supplied by Internet Service Providers, and only on demand of clients. It requires an a-priori setup of both the network and the involved devices, thus it is not suitable to form an extemporary classroom where learners dynamically request access to the content stored in a remote server. Hence, unicast is the only viable solution, but it imposes that *one copy of data* is replicated for each destination. As a consequence, both *(i)* the available network bitrate must be shared among the replicas of a certain content addressed to different destinations; *(ii)* queues may form on the network devices, and consequently the reception of data is slowed down. For many recipients, there is the risk that some data are dropped due to memory exhaustion. Finally, it is worth considering that not the whole available bandwidth can be used for data. In fact, part of it must be used either for control messages needed for the proper network operations, or for control information added to data for proper management.

Table 3. Required bitrate for different number of users

	360p	**720p**	**1080p**	**4K**
Bitrate	387.07 Kbps	1.55 Mbps	3.48 Mbps	13.93 Mbps
Packet interval	29.76 ms	7.44 ms	3.31 ms	826.7 µs

Table 3 shows the *minimum* bitrate that a network is asked to provide as a function of different video formats, according to the Kush gauge with low motion factor (equal to 1) and the minimum frame rate of 24 FPS.[7] The inter-packet interval corresponding to these bitrates is also supplied; we marginally notice that, in (Nokia, 2017), the authors specify that the minimum transmission time in 5G is 0.125 ms: the packet interval times supplied in Table 3 satisfy this constraint. These parameters are adopted for the simulations discussed in Section 5.2. It is worth noticing that YouTube requires higher bitrates considering higher motion factor and safety margins for an optimal fruition (cfr. Table 4).

Table 4. Video bitrates recommended by YouTube for standard-dynamic-range (SDR) uploads. Values for high-dynamic-range (HDR) videos are similar

Type	**Video Bit Rate Standard Frame Rate (24, 25, 30)**	**Video Bit Rate High Frame Rate (48, 50, 60)**
2160p (4K)	35-45 Mbps	53-68 Mbps
1440p (2K)	16 Mpbs	24 Mpbs
1080p	8 Mpbs	12 Mpbs
720p	5 Mpbs	7.5 Mpbs
480p	2.5 Mpbs	4 Mpbs
360p	1 Mpbs	1.5 Mpbs

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[7] FPS = frames per second.

5.2 Measurement Results

In this section, an estimation is presented of the expected 5G performance for video streaming in comparison with 4G LTE cellular telephony technology, basing on performance measurements using simulation techniques. As a simulator, the OMNET++ Discrete Event Simulator version 5.1.1 has been used;[8] in order to measure the performance of LTE, the INET and SimuLTE frameworks were used. For both technologies, different cardinalities of the set of destinations are considered; destinations are all located inside the same cell thus sharing the available bandwidth.

5.2.1 Performance of LTE Networks

At the time of writing, LTE is the best available wireless technology, and – according to the standard specification – it should provide gross bitrates (transporting both data and control information) of the order of 150 Mbps downlink and 75 Mbps uplink.

LTE simulations were conducted in a network formed by a server in Internet that transfers a video of variable format to a number of users ranging from 1 to 100, all in the cell of a LTE antenna. Internet characteristics do not represent a network bottleneck. According to the VSF TR-03 standard, frames are broken in packets of 1440 bytes at most.

The plots in Figure 6 show *(a)* the performance in terms of average bitrate at the destinations, and *(b)* the latency for the transfer of 1 MB file. The bitrate is represented as a percentage of the expected bitrate according to Table 3, averaged over all destinations. In the 720p case with 100 users, the bitrate refers to just the users who received at least 1 packet, which are 83. Similarly, with 1080p and 4K, some destinations did not receive any data, while others observed bitrates lower than expected. These results emphasize the queuing problem described in Section 5.1: the data to the missing destinations were dropped. As far as latency is concerned, some bars in Figure 6 are not visible in the plot as they refer to values around 5 ms. While with a 360p video the observed latency is always less than 5 ms, with a 720p video it grows to 5.2 ms with 50 users, and with 100 users the average latency is 2.22 s, which is inadequate for two-way interactive conferences and AR/VR applications according to Table 1.

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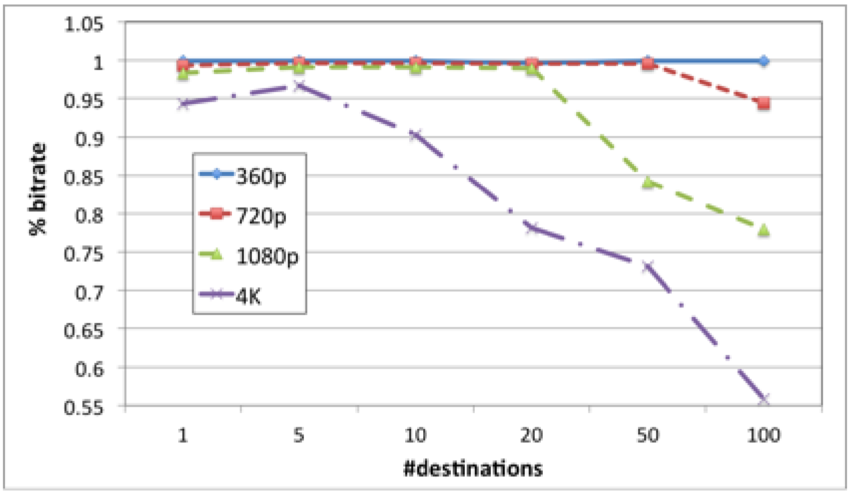
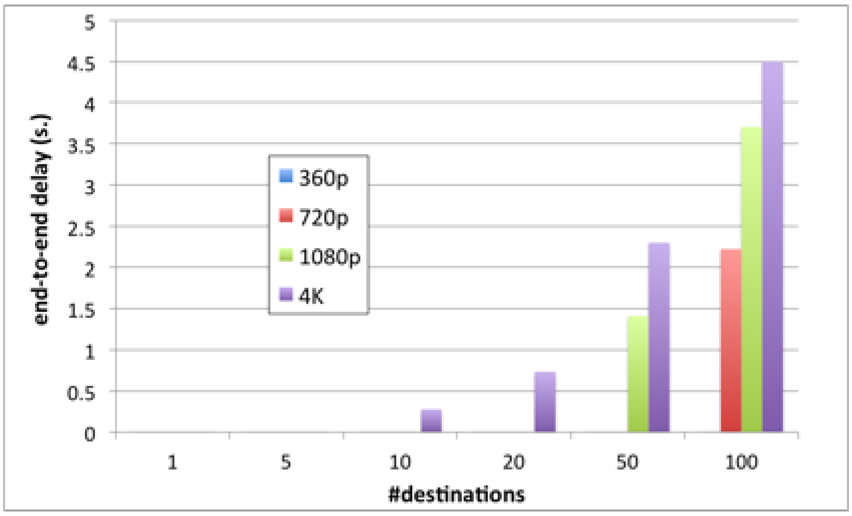
[8] OMNET++ can be retrieved from https://omnetpp.org



(a)



(b)

Figure 6. (a) Percentage of expected bitrate and (b) latency results for LTE.

5.2.2 Performance of 5G Infrastructures

The 5G network topology reproduced in the simulations is constituted by a server connected to the fixed Internet, which can send data to users in a 5G cell via an antenna. The server communicates with the antenna through a 10 Gbps channel with no packet loss; the unique latency source on this link is the transmission delay, which depends on the packet size. Thus, the fixed link does not represent a bottleneck in the considered network. The antenna can either broadcast a packet to all users in its cell, or send a packet to a subset (possibly of cardinality 1) of users in the cell. In the latter case, a FIFO queue of infinite length is used to store the packet replicas for different users; hence, replicas are never dropped due to buffer exhaustion. The bitrate of the wireless channel between the antenna and the users varies according to the specifications supplied in Section 2.1; in any case, the channel does not lose any packet and retransmissions are not needed. Also in this case, the unique source of latency is the packet transmission time depending on the packet size. Users simply measure the quality of received traffic, and then drop the received packets.

Additional performance indexes measured are: the number of packets received at the destinations – which is a measure of reliability – and the queue size in the antenna, which might highlight potential overload or buffer overflow events in the antenna. It is worth to notice that, in the following results, the case of just one destination supplies the same performance achievable by the broadcasting case (Section 5.1).

The first set of simulations is conducted in the same application conditions as for LTE (Section 5.2.1): a 1 MB file is transferred according to the bitrate for the considered encoding as reported in Table 3, in packets of 1440B. The F-band – which is the primary 5G band – is considered, with a bitrate of 2 Gbps (Table 2). In these conditions, for all considered encodings, 5G guarantees the reception of all packets at all the destinations (reliability 100%); the measured throughput equals the bitrate injected by the source into the network. The antenna queue experiments a maximum length of 1 packet; this means that all the replicas of a certain packet succeed to be transmitted to their destinations before a new packet arrives from the source. As a consequence, the latency between the generation of a packet at the source and its reception at a destination *D* only depends on the number of destinations to which the packet was sent before the transmission to *D*. As an example, in the case of 5 destinations, the packet latency measured by the first destination is 6.9 µs, while the last destination measures a latency of 30 µs. Figure 7 shows the packet latency averaged over all destinations, which is a measure of the capability of the infrastructure in delivering real time data; this figure is the same for all simulations in this set, due the lack of congestion. In the absence of congestion, the latency for receiving the whole file depends only on the file size and the source bitrate; due to the round robin policy to send each packet to all destinations, all the users experiment the same latency. E.g., in the case of a 1080p video, each user completes the reception of the 1MB file after 2.30 s, which is the ratio between the file size and the source bitrate.[9]

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[9] Yet, it is worth noticing that, the higher the video quality, the higher the amount of bits spent to represent one frame, and the shorter the video duration for the same file length.

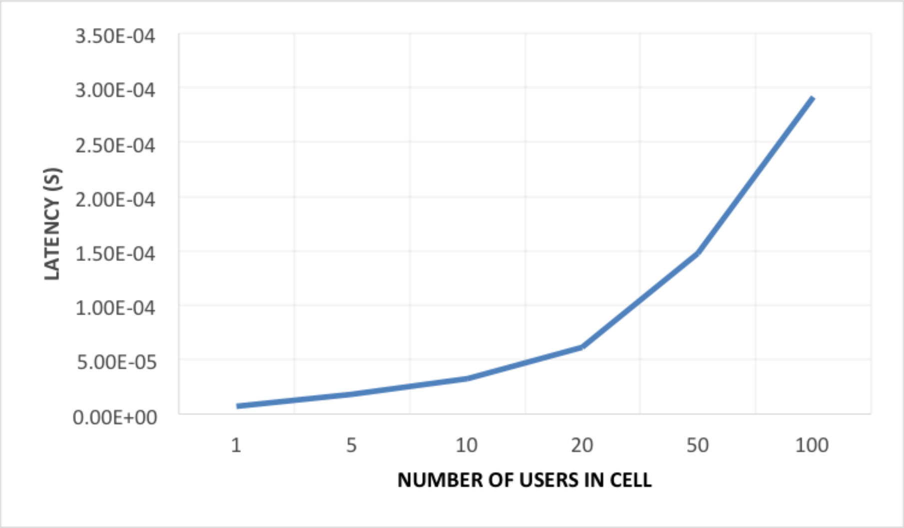

Figure 7. Mean latency experimented by a data packet, averaged over all destinations

In conclusion: 5G succeeds in guaranteeing the latency and reliability parameters (provided in Table 1) for minimum quality video streams with the characteristics reported in Table 3, whereas LTE fails for a number of destinations >=20 (or before, in the case of 4K). Moreover, the considered F-band spans a cell radius of up to 1 Km and – according to the 5G HyperService Cube (see Figure 2) – the forecasted users' density per square kilometer and for services useful for e-learning (such as VR, realistic 3D videos and wireless cloud co-working) is in the order of 10^2 as in our measures. Hence, these measures are promising in terms of the 5G capability of satisfying minimal applications requirements.

We stressed the 5G infrastructure by simulating higher quality video streams. The bitrates recommended by YouTube and supplied in last column of Table 4 are obtained considering high motion factors, in between 1.35 and 2 for the case of 60 FPS. We repeated the measures above with the source generating traffic at those rates, and recomputing the inter-packet interval time accordingly. The lowest inter-packet interval obtained for 4K video equals 169.4 µs, thus still fulfilling the constraint in (Nokia, 2017).

A high quality 1080p video with a bitrate of 12 Mbps still achieves the desired delivery quality: 100 destinations receive the whole 1MB file (reliability 100%) with a throughput that is 100% of the transmission rate and a latency equal to 0.29 ms; the maximum length of the antenna queue is 1. By contrast, for higher quality video users start experimenting a service degradation. The 2K encoding with 60 FPS requires a maximum bitrate of 24 Mbps. With 2K encoding and 100 users, the 5G bandwidth is not enough to accommodate all the replicated data packets to be sent to the destinations. As a consequence, data accumulate in the antenna queue and their disposal takes time: Figure 8*(a)* plots the queue length sampled at every change; the simulation time is shown on the *x*-axis. When the source ends transmitting the file at time 1MB/24 Mbps = 0.333 s, the queue stops growing and the waiting packets are pushed to the destinations. This also affects the time spent by a destination to receive the whole file, which increases from 333.12 ms for 50 destinations to 395.75 ms for 100 destinations, and the throughput observed by users, which amounts to 84.3% of the source bitrate. In Figure 8*(b)*, the red dashed line shows the delay experimented by packets, which – for 100 users – increases of two orders of magnitude in comparison with the usual behavior for non-congested situations: the continuous blue line is the same as in Figure 7. The effects of channel congestion could be a bad quality fruition by users, who would observe discontinuities in the video playing.

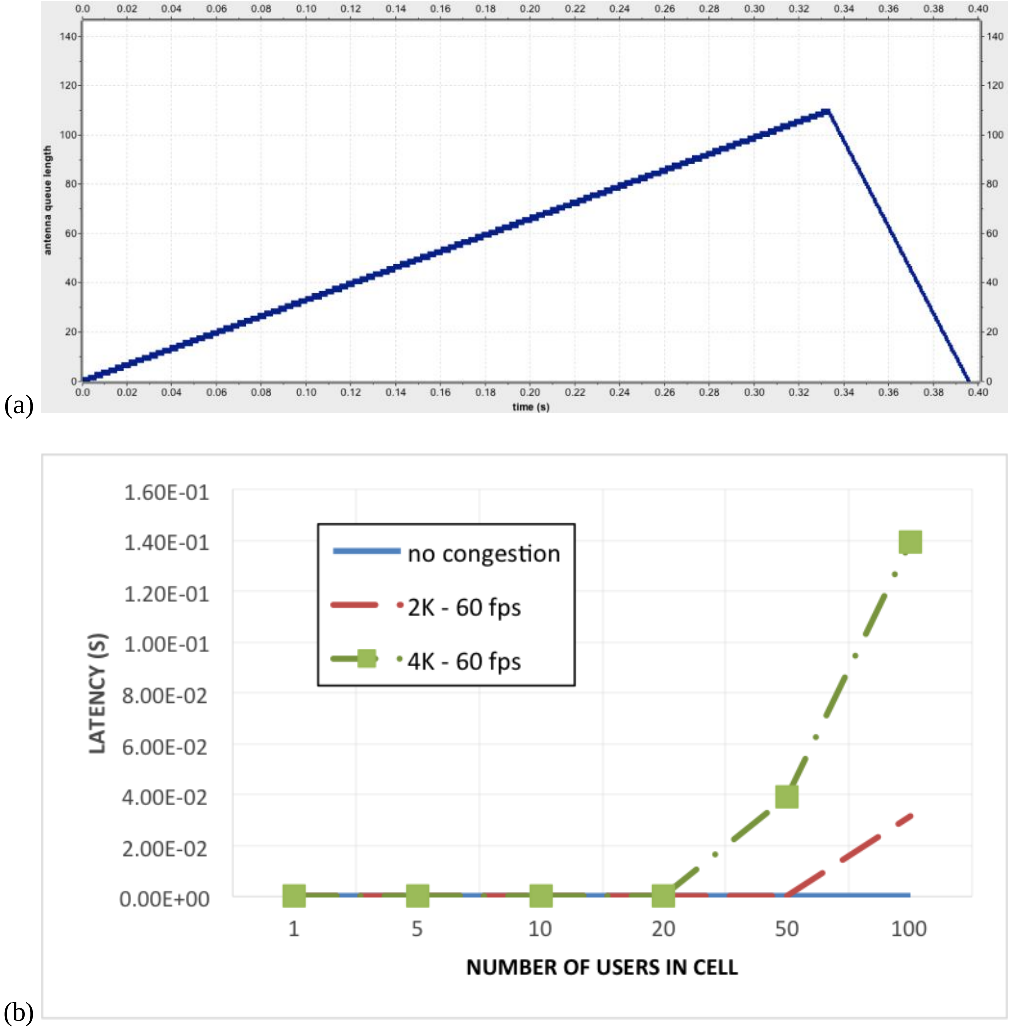

Figure 8. (a) Queue length vs. time, and (b) mean latency experimented by a data packet averaged over all destinations, for a 2K - 60 FPS video and 100 destinations

Things are even worse with 4K encoding using a bitrate of 68 Mbps. The packet delay is shown in Figure 8*(b)* (green dashed-dotted line): although these latencies still fulfill the requirements of applications such as interactive real-time conferencing (Table 1), a potential violation of AR/VR requirements is revealed. Throughput is 60.11% of the source bitrate for 50 users, and just 29.75% with 100 users; the time spent to receive the whole file - which is around 118 ms for 20 users - grows to 196 ms for 50 users and 396 ms for 100 users. The maximum queue length observed with 4K encoding and 100 users is 488; in real systems, such a queue overload might lead to buffer overflow and discarded packet due to memory exhaustion and, as a consequence, to a reduced reliability (and reduced quality of experience).

The measures above do not indicate that 5G fails in supporting sophisticated services; rather, they indicate that not all available 5G bands may be adequate for providing any service. In the last set of measures, we leverage the multi-RAT capability of 5G infrastructure by switching from the F-band to the M-band, in order to improve the performance for high quality applications. The modeled bandwidth in this case is 70 Gbps, which is the peak rate measured by some trials in the considered band (European 5G Observatory, 2019). As shown in Table 2, this band covers cells of 10 m radius, that is, roughly 300 m^2; this may model densely populated locations such as university classrooms, theaters, etc. By repeating the previous measures for the M-band, both 2K and 4K videos succeed in achieving optimal performance (100% throughput and reliability, maximum queue length equal to 1, and packet latencies in the order of microseconds) for up to 100 users.

As a final test, we measured the performance achievable in the M-band by AR/VR applications. To this purpose, just the lowest quality was considered, corresponding to a 100 Mbps source rate (Table 1): this bitrate requires a packet interval time of 115 µs, compatible to the minimum allowed in 5G according to (Nokia, 2017),[10] and a packet size of 1440B according to the attitude of implementing this sort of applications as high quality videos (see, e.g., Braud, 2017). In this setting, up to 100 users achieved a 100% throughput with packet latency of at most 10 µs, and the whole 1MB file was received within 80 ms from the reception of the first data packet.

A fallback of the simulations is that they show that – by appropriately choosing the radio technology and channel characteristics – 5G infrastructures are actually able to supply the performance envisaged by stakeholders for media and entertainment applications (Section 2.1).

6. CONCLUSIONS

This paper focused on the applicability of 5G technology to novel educational scenarios, proposing a number of advanced didactic services and applications in the field of music. Due to the tight connections with multimedia and to low-latency requirements, music education is a good testbed to design demanding environments and stress their performance.

Among other advantages, it is worth citing the possibility to organize synchronous interactive sessions with a student population mainly constituted by already employed people, having difficulties in connecting through a PC during working hours. In this context, the availability of 5G technology can offer an interesting option for overcoming the above limit, allowing students to interact with teachers/tutors with full access to visual materials.

The simulations show that – by appropriately selecting the frequency band to be used depending on specific application requirements – 5G infrastructures in fact show a very promising capability of providing high quality services also to a high number of users contemporarily. Yet, in some cases, this might require the pre-deployment of antennas in places

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[10] Higher bitrates are incompatible with this constraint, thus requiring larger packet sizes, and their implementation characteristics have not been investigated in this work.

where those applications might be requested, as is the case for M-band antennas forming femtocells.

In conclusion, 5G technology can open innovative e-learning scenarios, like the one dealing with music education described in this paper, also in the context of augmented/virtual reality (Baratè et al, 2019c). Besides, 5G can significantly improve already available e-learning initiatives, such as on-line versions of university degrees (Baratè et al, 2019a). In the near future, we can expect that the mentioned experiences will constitute a testbed for advanced learning services, providing scholars and researchers from different domains with the possibility to assess 5G applicability and impact on students' performance in a real-world scenario.

As a future work, we plan to model and study specific e-learning scenarios such as: the deployment of a 5G infrastructure in a realistic location (e.g., Teatro alla Scala) so as to achieve the desired quality of service; the distribution of e-learning content to learners located in different cells for remote synchronous learning; real-time interactive conferences with data produced by students and shared with other learners; lesson attendance in mobility.

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