5G TECHNOLOGY AND ITS APPLICATIONS TO MUSIC EDUCATION

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ABSTRACT

The goal of this paper is to discuss and provide some practical examples of how the emerging 5G technology can change current e-learning approaches. Thanks to the main characteristics of 5G networks, and specifically improved bandwidth, reliability, and density of devices in an area, it is possible to conceive and implement new educational services rich in multimedia content, supporting multimodal interaction, and highly customizable depending on users' requirements and special needs. In order to show the didactic efficacy, we will discuss an application to the field of music education that could benefit from this novel approach.

KEYWORDS

Education, e-Learning, Interactive Media System, Music Teaching, 5G

1. INTRODUCTION

Even if technological innovation in education is source of debates and controversies among scholars and experts, an aspect on which most of them agree is that technology-based didactic innovation should not be an end in itself, but, rather, a way to drastically improve the educational experience and to better meet the needs of teachers and learners.

A technology that, in the near future, is likely to change our lives is the latest generation of cellular mobile communications known as 5G, from "5th Generation". As discussed below, 5G introduces significant improvements with respect to current network technologies in terms of a larger bandwidth, a more reliable service, and a higher density of devices.

Narrowing the field to music education, the research questions we want to address in this paper are: Can 5G be profitably applied to such an educational context? What didactic 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 performances of 5G networks (Section 2), will shed some light on brand new or enhanced educational services (Section 3), and, finally, will present some music-related scenarios where 5G is expected to show its potential (Section 4). Section 5 concludes the work.

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. 5G technology promises to be able to support a number of both traditional and novel applications, such as device-to-device communication and Internet of Things (IoT).

For the goals of this paper, we are interested in investigating 5G functionalities and performances that may facilitate the implementation of advanced e-learning services. Since in this paper we focus on music education, we analyze in particular the support 5G may give to audio and video data exchange, and on its

ISBN: 978-989-8533-88-3 © 2019

capabilities of facilitating data sharing through the formation of extemporary classrooms anywhere using just users' devices. To this purpose, we carried out an analysis of existing – mainly European – 5G trials in order to assess the feasibility of e-learning platforms leveraging this technology.

Let us start from an analysis 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). 4G cellular telephony still meets the characteristics of high quality (4K) video streaming such as that supplied by some media-service providers (Gonzales 2018). By contrast, 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.

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%

Considering how recent the standardization of 5G is, it is not easy to determine to what extent 5G will be able to fulfill the requirements in Table 1. In the following, we summarize and discuss the characteristics of 5G services and of deployed 5G trials with respect to the expected needs of e-learning platforms.

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 msec. 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. 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 msec. 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. 2017). 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.

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.

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 & low latency, and a third type of service, namely, the ability of connecting an ultra-high number of devices.

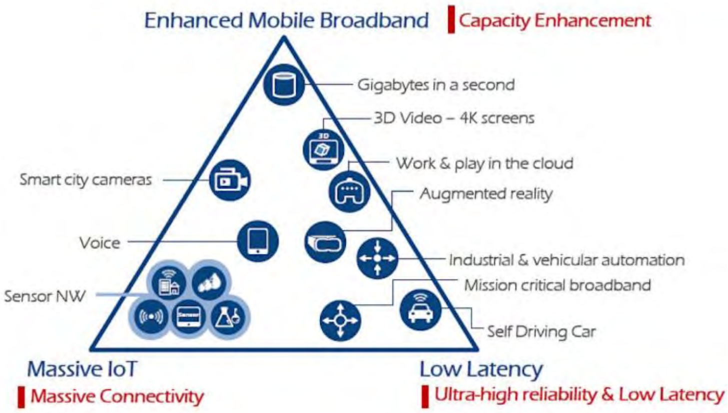

Figure 1. The triangle of 5G applications (source: ETRI graphic, from ITU-R IMT 2020 requirements)

In (Fallgren & Timus, 2013) these scenarios are described as follows:

- *Amazingly fast* – Users can obtain very high data rates with instantaneous connectivity and low latency. This is crucial for multi-layer applications based on multiple high-quality media streams;
- *Great service in a crowd* – Currently, connectivity is limited when many users share the same area (e.g., stadiums, concert halls, etc.), but in the future also crowded places will permit a satisfactory experience;
- *Ubiquitous things communicating* – The mix of IoT and human-centric communications tends to have different needs, and the 5G technology will efficiently handle these new requirements;
- *Best experience follows you* – Even when users are on the move (e.g., traveling by car or commuting), a high quality of service will be guaranteed;
- *Super real-time and reliable connections* – Future wireless systems will support new applications that take full advantage of very high reliability and low latency, thus allowing real-time fruition (e.g., augmented/virtual reality) as well as control (e.g., self-driving vehicles and industrial automation).

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, 5G Italy Global Meeting website 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, Fastweb and Huawei 2018); the migration towards pure 5G is scheduled for mid-2019. A laboratory testbed in Turin achieved a peak rate of 23 Gbps; however, this experiment does not seem to mimic realistic situations.

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 msec. of latency; the latter in France with comparable latency and a lower throughput of 80-200 Mbps.

The European 5G Observatory (European 5G Observatory 2018) provides data from around 180 trials and experiments. Data are contradictory, as noticed in the site, with bandwidths variable between 1.7 Gbps and 25 Gbps; this likely depends on whether measurements are taken in a real urban infrastructure, or rather are conducted in a laboratory. From the 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 between 250 Mbps and 70 Gbps, with an average of 1 to 4.5 Gbps for user devices, and latencies < 5 msec. 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.

Summarizing the above considerations, we may say that the existing realistic trials are able to provide a 700 Mbps to 1 Gbps (or more) of throughput on user's devices, with low latencies, also of the order of a few milliseconds. According to Table 1, this performance satisfactorily supports the requirements of all applications including AR/VR, 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 couple of remarks must 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, the performance really observed by users will strongly depend on the mix of traffics (asking different services) that will be injected into the networks, and on how they will compete for the network resources.

3. 5G-BASED APPLICATIONS FOR EDUCATION

After analyzing the technical features of 5G networks and the state of the art about trials in real or artificial environments, we can try to answer the research questions raised in the introduction, concerning new educational services based on 5G technology and their implications on teaching and learning.

First, network features introduced by 5G – as reported in Section 2 – may support the simulation of in-presence learning (*remote synchronous*), wherever learners actually are, thanks to high-bandwidth and low-latency services. As far as network applications are concerned, *remote synchronous* learning is one of the hardest in terms of quality of service (QoS). A strict requirement is seamless interactivity in distant education, which implies 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. Learners can experience a didactic session in a private as well as in a public and crowded place, thanks to the support of a high number of devices in a small area. In this sense, a very specific application could be the real-time replication of a lesson in another classroom. This situation is already common in case of, e.g., crowded university courses, but, differently from "on-site" students, "distant" colleagues are forced to watch the same big screen or projection, with no possibility to interact with the professor (e.g., if blackboard notes are too small) or customize the experience (e.g., focusing on the professor's face or on his/her multimedia presentation). Such an example can be easily extended to non-institutional places, such as a park, a bus, or a stadium. In this sense, for students there is also the possibility to attend live lessons in mobility, within an interactive and customizable learning environment, and this novel 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 massive 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. This is for instance possible by using the LTE Direct technology. In case no fixed infrastructure exists, users may leverage the ad-hoc networking capabilities of WiFi and Bluetooth. Another practical issue, especially in case of high transfer rates and consistent data volumes, could be the cost of data traffic for students. Once again, the expected features of 5G could solve the problem. In fact, through the use of free radio channels such as Bluetooth and WiFi, the educational experience could require no fees and imply no usage of Gb per month. Since an impromptu classroom is expected to cover a small geographical area, latencies should not be an issue.

As far as *remote asynchronous* learning is concerned: 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).

Finally, let us remark that 5G networks foster educational applications with highly-demanding transfer rates, such as the virtualization of lab experiences through virtual reality (VR). In this sense, an educational application can take benefit of high bitrates through ultrahigh-definition video streams (4K is not very defined when applied to a spherical video), and exploit low latency coupled with cloud/fog/edge computing for the real time calculation in response to user actions, gestures and movements.

4. CASE STUDY: MULTI LAYER MUSIC EDUCATION

In this section, we will propose a case study covering heterogeneous educational goals and investigating different aspects of 5G technologies. Specifically, we will discuss the possibility to deliver simultaneous and synchronized high-quality data streams in applications for music education.

A demanding application in terms of bandwidth is multi-layer 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 this sense, a relevant application field is music education, where the single music piece can represent the object to be described in a multi-layer framework. Let us consider a typical music lesson for young learners: a music tune can be studied in terms of music notation (actually, multiple forms of notation can be employed), gestures and movements used to play the musical instrument (or instruments), already available performances, 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 2 (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 performances, a structural description for analytical considerations, etc.

The first educational advantage of a multi-layer approach is the possibility to offer a more articulated set of organized information to students. A young learner, for example, can take benefit from an audio track corresponding to the score to study and showing the expected result, in particular if a computer-based application is able to support synchronized experience of graphical notation and an already available human performance. Another advantage is user-tailored customization, which implies, in our example:

- the possibility to choose alternative forms of notation (e.g., colored notation for children affected by dyslexia or Braille notation for blind people);
- the most suitable types of 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, e.g., the possibility to reduce the beats per minutes during playback, which requires materials with a high sampling rate.

Unfortunately, this approach presents a drawback: the need to send a number of simultaneous high-quality materials over the network.

In order to evaluate requirements, let us consider the bandwidth requested by digital media formats commonly in use, focusing on audio and video. Audio streams for Red Book audio CDs are two-channel signed 16-bit Linear PCM sampled at 44100 Hz, whose bit rate is 1411.2 kbps, or 176400 bytes per second. The DVD-Audio format presents a maximum permissible total bit rate of 9.6 Mbps. Concerning compressed audio, files typically present highly variable bit rates, depending on the encoding format, the expected

ISBN: 978-989-8533-88-3 © 2019

quality, and the characteristics of media content. FLAC files usually have a bit rate that ranges from 220 to 1184 kbps, whereas for MP3 files acceptable values for music applications usually span from 128 to 320 kbps. Also for video formats there are many standards and settings. At the moment of writing, YouTube adopts an MP4 container with AAC-LC as the audio codec and H.264 as the video codec. Audio playback bitrate is not related to video resolution. Recommended bitrates for audio are: 128 kbps for mono, 384 kbps for stereo, and 512 kbps for 5.1; values for video are shown in Table 2.

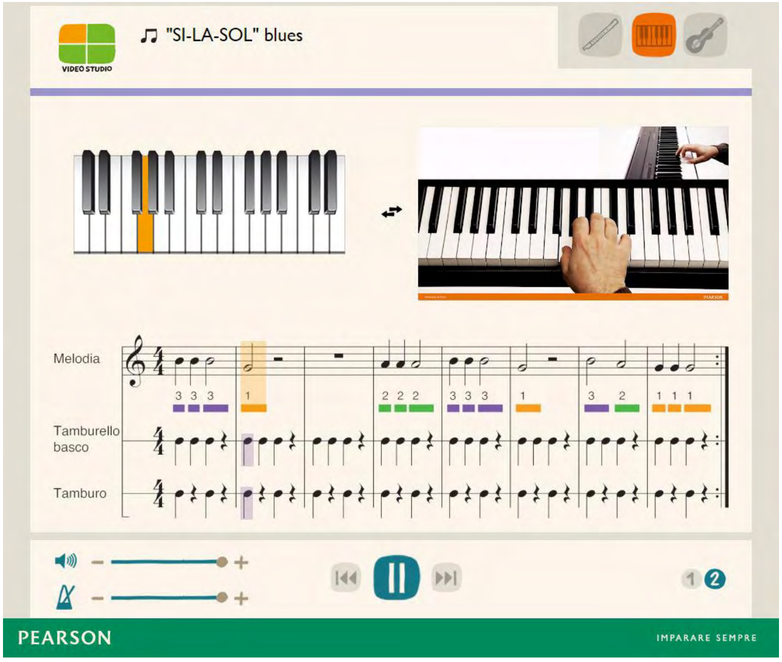

Figure 2. An example of multi-layer application for music education

Table 2. 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

Let us consider some cases of multi-layer applications dealing with music performances, particularly rich in multimedia materials and based on simultaneous delivery of audio and video streams. An example could be an educational product conceived to let learners practice their instrument alone or in group, playing over a previously recorded symphonic orchestra. Besides providing score following features, such an application should offer the possibility to suppress 1 to *n* audio tracks in a multi-track recording and choose one of many available video angles. Score events should be synchronized with multiple audio/video streams and mapped onto one or more scores (e.g., the full score and single parts). This kind of approach implies a high number of audio tracks, one per instrumental group and soloists, and as many different cameras as possible. Commercially available examples are Music Minus One music productions, meant to be accompanied by the listener on whichever instrument (or voice type) by excluding it from the recording. The technique is the same as the later development of karaoke for the voice. A computer-based generalization of the approach, allowing to subtract *n* sound sources, has been discussed in (Baratè, Haus and Ludovico 2018), and its graphical interface is shown in Figure 3. The latter case study, very close to the educational goals described in Section 4, could not be easily implemented as a web application with current network technologies.

Figure 3. An application presenting multi-track audio and multi-angle video

5G technology fosters this kind of applications, first providing the user with an improved bandwidth and guaranteeing a high QoS. Moreover, 5G networks present a very low latency, so the client-server request to send a new stream can occur on the fly, with no significant delay perceived in multimedia experience. In other words, it is no more necessary for the client to have a number of media streams simultaneously available and ready to be switched in real time, and the band available to single users can be exploited in better ways, e.g. delivering on demand an 8K HDR 60FPS (FUHD) spherical video that requires 100 Mbps approximatively.

The possibilities offered to music education by such a massive delivering of high-definition media streams are countless, ranging from a customizable multi-angle fruition of ad hoc materials for instrumental practice to the realistic virtualization of the experience occurring in a real performing context, such as a rehearsal room or an opera house.

5. 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 performances.

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.

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. 2019b). 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' performances in a real-world scenario.

REFERENCES

3GPP. «Overview of 3GPP Release 12 V0.2.0.» September 2015. http://www.3gpp.org/specifications/releases/68-release-12 (last accessed on February 28, 2019).

3GPP. «Release 15, TR 21.915 v0.6.0.» February 2019. http://www.3gpp.org/release-15 (last accessed on February 28, 2019).

5G EVE. *5G European Validation platform for Extensive trials.* 2018. https://www.5g-eve.eu/ (last accessed on February 28, 2019).

Baratè, Adriano, Goffredo Haus, and Luca Andrea Ludovico. «Advanced Experience of Music through 5G Technology.» *Florence Heri-Tech - The Future of Heritage Science and Technologies, 16–18 May 2018, Florence, Italy.* IOP Conference Series, 2018. 012021.1-012021.13.

Baratè, Adriano, Goffredo Haus, Luca Andrea Ludovico, Elena Pagani, and Nello Scarabottolo. «5G Technology and Its Application to E-Learning.» *Proceedings of the 11th annual International Conference on Education and New Learning Technologies*. 2019a. In press.

—. «5G Technology for Augmented and Virtual Reality in Education.» *Proceedings of the International Conference on Education and New Developments 2019 (END 2019)*. 2019b. In press.

Cisco. «Video Quality of Service (QOS) Tutorial.» September 2017. https://www.cisco.com/c/en/us/support/docs/quality-of-service-qos/qos-video/212134-Video-Quality-of-Service-QOS-Tutorial.html (last accessed on February 28, 2019).

CNIT. *5G Italy Global Meeting website.* 2018. https://www.5gitaly.eu/en/home2/ (last accessed on February 28, 2019).

European 5G Observatory. *Major European 5G trials and pilots.* 2018. http://5gobservatory.eu/5g-trial/major-european-5g-trials-and-pilots/ (last accessed on February 28, 2019).

Fallgren, Mikael, and Bogdan Timus. *Scenarios, requirements and KPIs for 5G mobile and wireless system.* Mobile and wireless communications Enablers for the Twenty-twenty Information Society (METIS), 2013.

Fastweb. *Rete 5G a Matera, accesa la prima antenna del progetto Bari-Matera 5G.* 5 March 2018. https://www.fastweb.it/internet/5g-matera-fastweb/ (last accessed on February 28, 2019).

Gonzales, Barb. «Internet Speed Requirements for Video Streaming.» *Lifewire.* October 2018. https://www.lifewire.com/internet-speed-requirements-for-movie-viewing-1847401 (last accessed on February 28, 2019).

Ji, Hyoungju, Sunho Park, Jeongho Yeo, Younsun Kim, Juho Lee, and Byonghyo Shim. «Introduction to ultra reliable and low latency communications in 5G.» *ArXiv*, 2017.

Li, Zexian, Mikko A. Uusitalo, Hamidreza Shariatmadari, and Bikramjit Singh. «5G URLLC: Design Challenges and System Concepts.» *Proc. 15th International Symposium on Wireless Communication Systems (ISWCS).* 2018. 1-6.

Ludovico, Luca Andrea, and Giuseppina Rita Mangione. «An Active E-book to Foster Self-regulation in Music Education.» *Interactive Technology and Smart Education 11.4*, 2014: 254-269.

Mangiante, Simone, Guenter Klas, Amit Navon, Zhuang GuanHua, Ju Ran, and Marco Dias Silva. «VR is on the Edge: How to Deliver 360° Videos in Mobile Networks.» *Proc. ACM Workshop on Virtual Reality and Augmented Reality Network (VR/AR Network).* 2017. 30-35.

Mushroom Networks. «Bandwidth requirements for Virtual Reality (VR) and Augmented Reality (AR).» 2017. https://www.mushroomnetworks.com/infographics/bandwidth-requirements-for-virtual-reality-vr-and-augmented-reality-ar-infographic/ (last accessed on February 28, 2019).

Qualcomm Technologies Inc. «LTE Direct trial - White Paper.» February 2015. https://www.qualcomm.com/media/documents/files/lte-direct-trial-whitepaper.pdf (last accessed on February 28, 2019).

—. «VR and AR pushing connectivity limits.» October 2018. https://www.qualcomm.com/media/documents/files/vr-and-ar-pushing-connectivity-limits.pdf (last accessed on February 28, 2019).

The 5G Infrastructure Public Private Partnership. *European 5G trials.* 2018. https://5g-ppp.eu/5g-trials-2/ (last accessed on February 28, 2019).

Tim, Fastweb, and Huawei. *Bari Matera 5G web site.* 2018. http://www.barimatera5g.it/ (last accessed on February 28, 2019).