Requirements and Enablers of Advanced Healthcare Services over Future Cellular Systems

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The authors aim at identifying the most representative healthcare scenarios that can benefit from 5G networks and synthesizing the communications requirements in these particular scenarios. The impact of three key 5G technologies, i.e., medical network slices, mobile edge computing, and the management of heterogeneous networks, will be discussed in the representative case study of the connected ambulance.

Abstract

The fifth generation (5G) of cellular networks has ambitious targets of data rate, end-to-end latency, and connection reliability. With the recent spreading of information and communication technology (ICT) into healthcare, leading to an Internet of medical things, new e-health services are being offered, in particular to the elderly population who needs daily assistance. This paper aims at identifying the most representative healthcare scenarios that can benefit from 5G networks and synthesizing the communications requirements in these particular scenarios. The impact of three key 5G technologies, i.e., medical network slices, mobile edge computing, and the management of heterogeneous networks, will be discussed in the representative case study of the connected ambulance.

Introduction

As life expectancy increases — projections report that 16 percent of the population will be aged over 65 in 2050 — the risk of severe age-related injuries and neurodegenerative diseases, as well as secondary pathologies and disorders (e.g., sleep disorders), is growing. Since mobility is typically affected, this reduces the independent accomplishment of daily life activities, and increases costs for caregivers and for the National Health Institutes. In order to mitigate these issues, the recent developments in information and communication technology (ICT) for healthcare, generally referred to as e-health and m-health (when wearables are employed), may be useful [1], [2]. Indeed, a novel healthcare paradigm arises, i.e., an Internet of medical things (IoMT) [3], [4], that promises ubiquitous, continuous, and personalized medical assistance, and is able to improve the individual quality of life and reduce healthcare costs. However, early trials of e-health services have highlighted, among others, the limitation of the current mobile communication infrastructure, a key element of any new-generation ICT-based healthcare. As an example, a tele-echography platform has been implemented over a long-term evolution (LTE) cellular link, providing rates of around 10 Mb/s, a latency of 60 ms, and a jitter of 8 ms, still far from the performance of a traditional wired network [5]. The new fifth generation (5G) of cellular networks promises to significantly improve over LTE, in particular on data rate, reliability, and latency. Even though e-health and m-health have been identified as relevant and challenging targets since the earliest phases of standardization in 2015 [1], the specific communication requirements for these kinds of applications have been investigated only sparsely [6]. This paper aims at filling this gap and, particularly, at (i) identifying the most representative healthcare scenarios that can benefit from 5G networks, (ii) defining their specific requirements (see similar collections in the 5G standard documentation [6]), and (iii) critically discussing the impact of three specific 5G technologies, i.e., medical network slices, mobile edge computing (MEC), and the management of heterogeneous networks, that will boost the use of cellular systems for advanced healthcare applications such as the connected ambulance.

Performance Indicators

We shall first describe the technical performance metrics used for standardizing 5G cellular communication systems by the services and system aspects group of the third generation partnership project (3GPP) [6]. They have already been specified for automation and control services, e.g., discrete automation motion control, electricity distribution, and remote control. We will then use these metrics to characterize new healthcare services. The considered metrics are the following (see [6] for more details):

End-to-End Latency: average latency at the application level. 5G targets an average latency down to 1 ms, specifically intended for highly interactive applications, while in LTE the average latency is well above 20 ms.

Jitter: measure of latency uncertainty, due to errors and non-idealities in communications. Jitter is quite significant in LTE networks, increasing the end-to-end latency in many cases to more than 100 ms.

Survival Time: maximum packet delay still tolerated by the application to operate properly.

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Scenario	Type	End-to-end latency ms	Jitter ms	Survival time ms	Commun. service availability	Reliability	User experienced data rate
Telepresence and robotic telesurgery	Telesurgery	5	2	0	$1 - 10^{-5}$	$1 - 10^{-7}$	2 Gb/s
	Wireless service robots	1	1				1 Gb/s
Remote pervasive monitoring	In hospital	250	25	10	$1 - 10^{-3}$	$1 - 10^{-3}$	300 Mb/s
	At home						1 Gb/s
Healthcare in rural areas	–	20	10	10	$1 - 10^{-3}$	$1 - 10^{-3}$	1 Gb/s
m-health[1]	Wearables	250	25	10	$1 - 10^{-3}$	$1 - 10^{-3}$	$0.1 \div 5$ Mb/s
	Connected ambulance	10	2	< 2	$1 - 10^{-5}$	$1 - 10^{-7}$	$50 \div 1{,}000$ Mb/s

[1] Performance requirements must be ensured for speeds up to 50 km/h (wearables) or 100 km/h (ambulance).

Table 1. Performance requirements for future healthcare applications — Part I.

Scenario	Type	Payload size	Traffic density Gb/s/km²	Connection density devices/km²	Service area dimension m × m × m	Distance [km]	Reference
Telepresence and robotic telesurgery	Telesurgery	Big	Low	Low	10 × 10 × 5	300	[1, 2, 7, 8]
	Wireless service robots	Medium	High	Medium	100 × 100 × 3	50	[2, 9]
Remote pervasive monitoring	In hospital	Medium	1	1,000	$10^3 \times 10^3 \times 50$	1	[7, 10]
	At home	Small	$< 10^{-3}$	20,000	$10^3 \times 10^3 \times 50$	20	[4, 7, 11, 12]
Healthcare in rural areas	–	Medium	Low	Low	$10^4 \times 10^4 \times 10$	100	[1, 13]
m-health[1]	Wearables	Small	50	10,000	1 × 1 × 2	50	[1, 7, 12, 13]
	Connected ambulance	Big	Low	Low	5 × 1.5 × 2.5	50	[14]

[1] Performance requirements must be ensured for speeds up to 50~km/h (wearables) or 100~km/h (ambulance).

Table 2. Performance requirements for future healthcare applications — Part II.

Communication Service Availability: percentage of the time in which the communication service is up. The service is considered in down state when a packet is not received within a given time constraint (larger than the sum of end-to-end latency, jitter, and survival time).

Reliability: degree of reliability, i.e., the probability of successfully delivering network-layer packets to a given system entity within the time constraint required by the targeted service.

User Experienced Data Rate: minimum acceptable data rate to satisfy the user experience of a specific service. 5G networks aim at improving over the LTE data rate by 10 to 100 times.

Payload Size: average size of the data packet. Addressing a wide variety of use cases, the 5G standard has broadened the range of packet sizes. Here, we will talk about a small payload when the packet is smaller than 256 b, medium when it is between 256 b and 10 kb, and big when it exceeds 10 kb.

Traffic Density: communication data rate per unit area, based on the assumption that all applications within the area require a given user experienced data rate. The 5G standard targets 1 000 times higher traffic density than LTE.

Connection Density: number of connected devices per unit area, under the assumption of full penetration of 5G networks.

Service Area Dimension: volume of the geographic area where the service is available.

Furthermore, when dealing with healthcare, the following additional metric could be useful.

Distance: distance between connected entities, e.g., between the surgeon and the patient in a telesurgery system. The distance can significantly impact on other important parameters, such as latency.

Reference Scenarios Definition

In line with the most recent scientific literature, we identify four major classes of scenarios, each requiring highly specific and challenging communication features, in terms of latency, massive access, support of mobility, or combinations of them, as summarized in Tables 1 and 2: a) telepresence and robotic telesurgery (including the telesurgery and wireless service robots scenarios); b) remote pervasive monitoring (including the hospital and home scenarios); c) healthcare for rural areas; d) m-health (including the wearables and connected ambulance scenarios). Each class is articulated into different scenarios that are described in detail in this section.

WSRs are expected to become more extensive in the near future, thus offering high traffic density at medium connection density. 5G networks should enable machine-type massive access to the network for robots to communicate with clinical centers and other robots within a range of up to 50 km.

Telesurgery

Rapidly expanding in use, telesurgery enables 1) visual guidance during surgeries, 2) augmented reality (AR), helpful for the surgery team, and 3) the assistance of robots that greatly reduce surgery invasiveness, thus making patient recovery faster. Data rates higher than 1 Gb/s [7], medium to short latency (from 200 ms to less than 5 ms) [1], [7], small jitters (from 30 ms to less than 2 ms) [7], and reliability higher than $(1 - 10^{-7})$ [2] are required to support a stable, real-time, haptic, and visual feedback from the surgical device and from the camera pointing at the anatomical target: thus, this provides the remote surgeon with a natural perception of the surgery [2], [7]. Despite the low traffic connection density, distance may reach 300 km, making the latency requirement quite challenging. Furthermore, in some recent attempts, the integration of holographic models of the target anatomical structure has been proposed. In this case, requirements become even more demanding: indeed, real-time holographic rendering requires an end-to-end latency below 5 ms [2], [8]. At the same time, the user data rate could easily jump to 2 Gb/s.

Wireless Service Robots

Telepresence defines a broad range of robotic services, where wireless service robots (WSRs) have a key role in providing assistance, support, monitoring, and even company to patients and the elderly, in a large variety of indoor and outdoor environments. If we include wellness in healthcare, WSRs are also increasingly being employed in advanced sport training setups. In this respect, seamless assistance is a key aspect which could facilitate user compliance, especially in the elderly, and could enable large-scale acceptance in the future.

In order to provide seamless and natural interaction with users, massive collections of images, videos, audio tracks, and environmental or motion sensor data have to be processed in real-time (often, in the cloud) and returned to the WSR to perform actions. In this scenario, data rates of the order of 1 Gb/s are needed, together with a latency of about 1 ms [9] and a reliability of $(1 - 10^{-7})$ [2].

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Remote Pervasive Monitoring in Hospitals

In a hospital, a large amount of data could be collected from a large number of patients for both routine (e.g., Holter's electro-cardiogram, ECG) and sophisticated (e.g., magnetic resonance imaging) monitoring devices. Such heterogeneous data can then be aggregated (eventually, in real-time) to continuously monitor patients' health and trigger alarms if needed. Other patient information can be extracted from their electronic health records (EHR), in order to reduce the false-alarm probability, while maintaining an acceptable mis-detection probability. As an example, pervasive monitoring in an intensive care unit generates traffic (including data on blood pressure, oxygenation, heartbeat rate and other vitals) with data rates up to 1 Mb/s/patient [7]. The high connection and traffic density given by a high number of monitored patients (expected to be 100 per unit in 2035, [10]) within the limited area of the hospital can challenge the communication network. The overall data rate could stably approach 300 Mb/s including imagery data [10], while moderate requirements on latency (250 ms), jitter (25 ms), survival time (10 ms), and service availability $(1 - 10^{-3})$ are expected.

Remote Pervasive Monitoring in the Home

Continuous health monitoring of chronic patients and fragile people, e.g., the elderly, can be implemented in the home using relatively cheap, yet reliable, biosensors [7], [11], and [12], forming a wireless body area network (WBAN) to monitor both physiological and vital parameters, e.g., glucose level and heart beat rate. Tiny and unobtrusive environmental sensors can also be installed for measuring temperature, humidity, and light exposure. Cameras are also helpful to monitor patients with balance and mobility disturbances. Furthermore, teleconsultation in the home with remote clinicians can reduce the burden of regularly reaching the hospital for therapies. Hence, houses become smart, providing real-time (within fractions of seconds) and continuous collection of heterogeneous health-related data and transmitting them to the medical network. Lastly, smart (edge or cloud) computing can generate alarms or give real-time feedback to the patient, i.e., during remote therapy. Here, latency together with massive data transmission, are the most relevant challenges for the network. Easily, 1 Gb/s traffic can be generated by monitoring a densely populated urban area (i.e., with over 2000 inhabitants/km^2) [4]. Interestingly, 5G networks will make it possible to assign different priorities to different e-health modalities, for example, video streaming or alarms, by using ad hoc network slices, offering a full range of quality of service (QoS) levels.

Healthcare in Rural Areas

Sparse points-of-care are intended to serve patients in rural, remote, or underdeveloped areas, where general physicians only are present and simple equipment is typically available. Here, remote specialized physicians can provide teleconsultation to the local physicians during patient visits. In this scenario, an advanced wireless communication network is required to provide seamless remote video interaction with both the local physician and the patient, and possibly collect data from biosensors and other examination equipment [1], [13]. Given a population density of a few tens of inhabitants/km^2, the user experienced data rate in rural areas ranges between 100 Mb/s (with no video consultation) and 1 Gb/s (with video streaming). Similarly, latency ranges between 150 ms and 20 ms (in the case of real-time multimedia stream). Lastly, the communication distances are in the order of 100 km, leading to a challenging network design to also ensure a reliability of at least $(1 - 10^{-3})$.

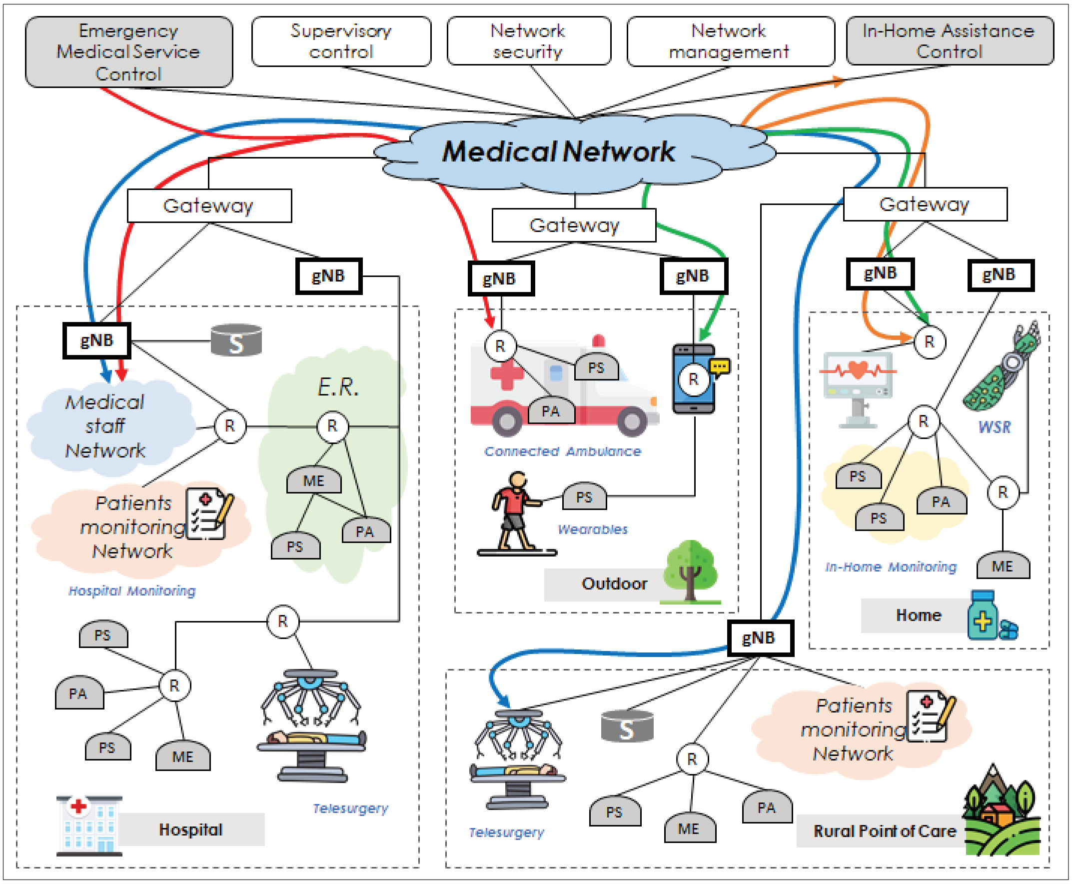

Figure 1. Network scenario and communication paths for service flows of the healthcare network. R: router; S: server; ME: medical equipment; PS: patient sensor; PA: patient actuator.

Smart computing and data mining are needed at the network edge, or in the Cloud, to reduce the amount of data traveling through it and to provide real-time feedback to users on their training level or health conditions. Therefore, the network is particularly challenged to ensure stable and reliable communication links, despite the high heterogeneity in the data traffic and user needs.

Wearables

Wearables, like smart clothing and accessories (e.g., watches and bracelets), can measure both vitals and physiological signals of individuals who are free to move in a variety of environments (indoor and outdoor, up to 50 km range), at different speeds (walking, cycling, driving a car up to 100 km/h) [12], [13]. They are increasingly employed in at-home healthcare, advanced sport training and even for fitness purposes, such as to improve training effectiveness or to ameliorate individual behavior (such as sleep quality). Implants are considered wearables, too; diabetic patients, for example, can continuously control, at home, their glucose level using an implanted glucose meter-insulin pump [1], [7]. Also, multiple wearables could be organized in a WBAN, with a smartphone or a tablet serving as the primary collector or gateway for the network. Wearables are expected to generate an increasingly big data traffic in the network: thus, smart computing and data mining are needed at the network edge, or in the Cloud, to reduce the amount of data traveling through it and to provide real-time feedback to users on their training level or health conditions. Therefore, the network is particularly challenged to ensure stable and reliable communication links, despite the high heterogeneity in the data traffic and user needs.

Connected Ambulance

Recent pioneering trials have been performed in Italy on an example of connected ambulance [14]. This scenario represents a relevant case study to show some of the major healthcare-related challenges for the 5G infrastructure in terms of latency, reliability, and mobility: thus, we shall describe it more thoroughly in one of the following sections.

5G Architecture for Healthcare

A pictorial description of the 5G architecture targeting the main healthcare scenarios, reported in Tables 1 and 2, is shown in Fig. 1 (matching Figs. D1-1 and D.2-1 of [6], corresponding to other 5G use cases). Here, the described scenarios are organized into four physical spaces: a rich and technologically advanced environment (e.g., a smart hospital); an indoor space, e.g., a smart home; an outdoor area; and a rural location. The medical network, possibly exploiting cloud computing, is expected to connect all healthcare-related services. It includes control entities for specific healthcare-related tasks (e.g., emergency management and home assistance), but also communication entities for network supervision, security, and management. Connection among devices is provided by the 5G network through data gateways and new-generation node-bases (gNBs). End devices may also be connected to the network via routers (R), creating WBANs in smart homes, rural-area point-of-cares, and dedicated emergency rooms (ERs) connected to ambulances. Devices include WSRs, generic medical equipments (MEs), patient sensors (PSs), patient actuators (PAs) for delivering drugs and regular medications, and telesurgery equipment. Servers (S) are available at local networks to store patient data

Heterogeneous network management can be particularly important in smart houses using low-rate short-range Bluetooth low energy (BLE) to transmit vital data, e.g., blood pressure, to the smartphone. At the same time, other devices may be connected to the cloud by long-range WiFi links. Both technologies operate on the unlicensed band, therefore inter-operability issues may currently arise.

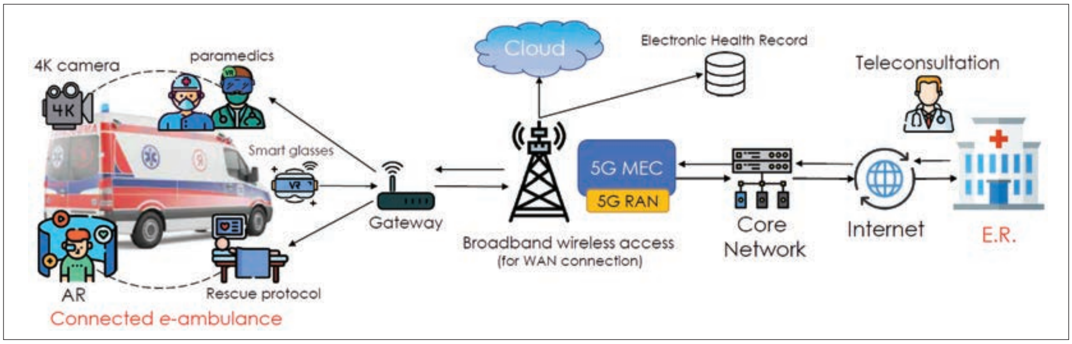

Figure 2. Connected ambulance.

and the software needed for medical network functioning and the smart edge-computing of big data. Various communication paths can be identified in the network: red lines represent communication flow associated to an emergency event managed by the emergency medical service control, operated via a connected ambulance, and solved by the medical staff at the hospital. The blue line refers to the communication flow of a telesurgery with the patient in a rural area and the specialized surgeon at a remote hospital. The orange line shows the communication path for monitoring patients in their smart home: the service is managed by the in-home assistance control unit and the end devices (i.e., biosensors and WSRs) collect data and send it, through the medical network, to the control unit, providing intervention if needed. Lastly, the green line connects the outdoor devices (possibly organized as a WBAN) to the smart home network through a smartphone, operating as a router, and the medical network, where cloud-computing is available. From the figure it becomes clear how the interplay among different network entities, the dynamically changing priorities of different healthcare services and the highly heterogeneous data traffic composes a truly complex picture that needs to be carefully and efficiently handled with the support of the future 5G cellular networks.

5G Enabling Technologies

Among others, flexible network slicing, network function virtualization, and mobile edge computing represent three key 5G technologies that will ease the implementation of innovative and efficient healthcare applications, as depicted in the previous sections.

Toward Medical Network Slices

To enhance the flexibility of the communication infrastructure, the international telecommunication union (ITU) defined three slice types for general 5G cellular networks: enhanced mobile broadband (eMBB), providing high data rate to mobile human users; ultra-reliable-low-latency communications (URLLC), typically targeting human-machine interactions; and massive machine-type communications (mMTC), for autonomous interaction among devices. However, many healthcare scenarios fall at the intersection between the above categories. For example, telesurgery needs both eMBB to support very high data rates (video-streaming) and URLLC to provide the remote surgeon with a highly precise haptic feedback of the local robotic device used for the surgery. Therefore, specific medical slice types for healthcare applications could be designed to more properly allocate resources both at the core and at the access networks. Moreover, privacy issues might arise, as the use of medical slices could disclose sensitive patient information to the network operators, such as heart attacks or severe neurological events. Thus, effective security/privacy solutions have to be embedded into the 5G architecture.

Mobile Edge Computing

MEC is a computing engine, located close to the sensors in the network, able to perform smart and fast, yet lightweight, data processing. It can be used to compensate for excessive end-to-end delays in the network, but also to aggregate and pre-process massive data coming from several sensors, e.g., in a smart house, before forwarding them to the cloud or to the medical network. Also, it acts as a suitable interface between heterogeneous devices, such as sub-5G sensors, and the 5G medical network, inserting/extracting data into the network slices. Among others, MEC can trigger early alarms whenever vital parameters of a patient in their home are abnormal, thus speeding up the emergency intervention.

Heterogeneous Network Management

Other than 5G wireless access technologies, including WiFi, Bluetooth, and Zigbee can co-exist in the same healthcare scenarios, thus leading to eventual inter-operability issues. However, the network exposure function (NEF) included in the new concept of network function virtualization (NFV), of 5G systems can be exploited as a control-plane interface between the cellular and other networks to map requirements of different kinds of networks. For example, slicing is being increasingly targeted by literature with the aim of mapping the same concept into WiFi technology. Heterogeneous network management can be particularly important in smart houses using low-rate short-range Bluetooth low energy (BLE) to transmit vital data, e.g., blood pressure, to the smartphone. At the same time, other devices may be connected to the cloud by long-range WiFi links. Both technologies operate on the unlicensed band, therefore inter-operability issues may currently arise.

Case Study

The connected ambulance [14] represents an emblematic example of communication challenge for future e-health services. The ambulance and the paramedics are equipped with advanced devices, both to improve the effectiveness of rescue operations and to speed up the emergency admission times (see Fig. 2). Paramedics wear smart glasses that display, in AR, the clinical protocol for the rescue and feed a facial recognition algorithm into the cloud to gather the patient's information from the EHR database, especially useful for chronic patients. A 4K camera and a teleconference system are used for an effective teleconsultation with specialists at the hospital, who can interact online with the paramedics while seeing the patient clearly. Specialists could also see echographic images of the patient, collected in real time by a wireless and portable echographer.

Moreover, a multiparametrical module is able to acquire several vital signs, e.g., ECG and blood pressure. Then, a MEC server performs edge-computing from the heterogeneous data being collected from the patient, to improve the preliminary diagnosis. Finally, a tablet can send the patient's information to the E.R. to significantly shorten the admission time.

The connected ambulance challenges the communication network greatly, requiring high data rates and low-latencies, very small survival times (e.g., 2 ms) and high connection reliability, in order to guarantee smooth and robust data streaming at moderately high speeds (up to 100 km/h).

Future Research Trends

Although 5G networks will offer a leap forward for the communication support of m-health and e-health services, paving the way for an IoMT, future e-health applications could require even more challenging network performance. For example, eXtended reality (XR) [15] may provide an even more immersive and natural experience that can be useful both in telesurgery and in remote first aid (even on connected ambulances). This pushes the requirements on latency and reliability further than those available with 5G systems. Therefore, early proposals for 6G networks have included healthcare scenarios, characterized for example by a massive deployment of sensors and wearables or the use of XR for telesurgery, in order to be ready to satisfy future healthcare needs.

Conclusions

In this paper we identify the most relevant healthcare scenarios and report the requirements of 5G networks to effectively support them in terms of, e.g., end-to-end latency, jitter, data rate, and reliability. Moreover, we have highlighted three enabling technologies (network slicing, MEC, and heterogeneous network management) that are specifically relevant for e-health and m-health applications over 5G networks. From our analysis, we can conclude that 5G systems will truly spur new e-health and m-health applications, offering personalized and ubiquitous medical care, while paving the way for even more advanced scenarios, which are being targeted by long-term future 6G networks.

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From our analysis, we can conclude that 5G systems will truly spur new e-health and m-health applications, offering personalized and ubiquitous medical care, while paving the way for even more advanced scenarios which are being targeted by long-term future 6G networks.