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A SURVEY ON HAPTIC DATA OVER 5G NETWORKS

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***Abstract*— Nowadays, the audio and visual modalities are totally defined in terms of communication, computation and data storage on the internet, but what is lacking so far is a methodology to involve the sense of touch. A fundamental part of this is to have the capacity to transmit touch in perceived real-time, which is empowered by suitable hardware, like robotic and haptic equipment at the edges, alongside with unprecedented communication networks. The majority of the unsolved aspects about haptic communication are expected to be covered by the introduction of the next generation mobile network, 5G. The specifications of the fifth generation networks promise such capabilities to allow uninterrupted data transmission of the demanding haptic information in every environment. The most challenging characteristic that need to be addressed is to minimize the latency up to 1 ms in order to achieve successful data delivery.**

***Keywords*— Cellular Networks, Fifth Generation, Haptic Data, Mulsemedia, Simulations, Tactile Internet, Trials**

1. INTRODUCTION

The term haptic is derived from the Greek word "aptiko" which signifies the sense of touch. Recently, this term comes to the foreground for technological aspects to refer to the science of manipulation and sensing of particular environments through touch. The tactile internet distinctively deals with the real-time transmission of this type of data, known as haptic information, which can considerably increase the degree of immersion for distant communications. Tactile internet will focus on human-to-machine (H2M) communications and will allow for a human-centric design approach towards creating innovative immersive experiences and enhancing the human capabilities through the internet. There are several requirements and constraints on designing, developing and realizing a tactile internet system, which mainly include the very high reliability and the ultra-low latency.

Tactile internet systems are required to attain ultra-high reliability, so that the packet loss will be less than 10^{-7} [1]. This is because higher packet loss probability, results in incorrect data at the slave side that leads to incorrect interaction with the remote side. Because of the required reliability and latency, present transmission

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protocols, like UDP and TCP, cannot be used for tactile internet applications and especially for haptic based applications. Thus, new protocols need to be developed.

Additionally, tactile internet systems require an end-to-end latency of 1 ms, which is not reachable by current applications and systems. Latest systems of present generation cellular networks handle a round trip latency of 15 ms [2], while the first release of 5G is expected to improve the latency performance and achieve an end-to-end latency of 5 ms [3].

At the moment, the major reason that limits the tactile internet from turning into a reality is its requirement for exceptional low latency. To avoid any noticeable delay, round-trip latency conditions for haptic response in the human body must be in the order of up to 1 ms, which means that all delays from the data transmission at the transmitter until the feedback reception at the transmitter should be at maximum of 1 ms to allow a satisfactory experience [4]. The network domain of the tactile internet systems should be designed in a proper manner to fulfill the requirements of the tactile internet and as the 1 ms latency is a main requirement, the communication network should deploy new technologies to achieve this. Thus, the next generation technologies have to face the so called “1 ms challenge”. Although, researchers and industry groups begin to take real steps and put road maps toward tactile internet system realization, 5G cellular systems are still far from 1 ms end-to-end latency. Consequently, intelligent 5G networks are envisioned to become enablers for advanced network architectures by supporting emerging applications, such as tactile internet, internet of skills and many more. Potentially, as the design of the future communication systems focuses on ultra-responsive connectivity, the convergence of both optical fiber and wireless (FiWi) technologies could, possibly, play an important role to unveil a completely new world, which the tactile internet has the ability to establish.

The structure of this survey is organized as follows. Section 2 presents a historical retrospective of present and previous technologies of cellular networks, with an in-depth analysis of their specifications. In Section 3 the latest developments on 5G mobile technologies are described. Furthermore, Section 4 discusses about haptic data transmission characteristics and data flow requirements. A general perspective of multiple sensorial media is given in Section 5. Section 6 gives an evaluation of haptic transport protocols and related work, while mentioning the requirements for haptic transport protocols. Next, Section 7 focuses on simulations regarding transport protocols in terms of delay and jitter and refers the results of some 5G field trials that have conducted globally. Finally, In Section 8 the conclusions are inferred.

2. EVOLUTION OF MOBILE NETWORKS

For over three decades, the International Telecommunication Union (ITU) develops the standards and spectrum arrangements to support International Mobile Telecommunications (IMT) for the implementation of next generation technologies.

2.1 FIRST GENERATION (1G)

Initially, analogue technologies were used by mobile telephony only for phone calls and they were comprised of several standards each used in different countries. Some of these standards are the Advanced Mobile Phone Service (AMPS), the Nordic Mobile Telephone (NMT) and the Total Access Communication System (TACS). All of them use frequency modulation techniques for telephone calls and all decisions for call tuning are taken from central stations. The frequency spectrum is divided into channels and for each call two channels are allocated. As it supports only phone calls its speed reaches up to 2.4 Kbps [5].

2.2 SECOND GENERATION (2G)

2G technology of mobile networks was originally introduced in 1991. Unlike first generation, it uses digital signals that are analogue, so it achieves more efficient compression and much more calls could be made using the same bandwidth. Its main purpose is phone calling as well as sending of small-sized data such as sending text messages (SMS), pictures and multimedia messages (MMS). The technologies of the second generation are divided into two categories depending on multiplexing, Time Division Multiple Access (TDMA) and Code Division Multiple Access (CDMA). Its popular standards are Global System for Mobile Communications (GSM), cdmaOne, Digital AMPS (D-AMPS) and Pacific Digital Cellular (PDC). Its speed reaches up to 64 Kbps [6].

The evolution of the second generation, known as 2.5G, is able to reach higher speeds up to 144 Kbps and its main difference is that network’s technology is packet switching instead of 2G circuit switching. New technologies such as High Speed Circuit Switched Data (HSCSD), General Packet Radio Service (GPRS) and Enhanced Data Rate for GSM Evolution (EDGE) had been introduced as, basically, GSM extensions. With the introduction of new technologies it is able to support sending and receiving of emails and surfing the web. HSCSD is using multiple time slots simultaneously to send and receive data, so it increases the data transmission rate to 14.4 Kbps from the 9.6 Kbps offered by GSM. GPRS is based on the packet switching function and thus, it could provide access to the internet. It uses 8 time slots and it has a theoretical data transmission rate of 144 Kbps. Some years later, EDGE was introduced to achieve theoretical data speeds of up to 473 Kbps using 8 time slots, as well [7].

2.3 THIRD GENERATION (3G)

3G mobile networks were introduced in 2000. These networks use a new architecture to deliver higher data rates and services that are more advanced. 3G supports the creation of video calls, mobile internet access, mobile TV and wired wireless data services. It includes two key technologies: Universal Mobile Telecommunications System (UMTS) for Europe based on Wideband Code Division Multiple Access (WCDMA) with theoretical rates of up to 11 Mbps and CDMS 2000 for North America with theoretical speeds up to 14.7 Mbps [8].

The development of 3G introduced High Speed Downlink Packet Access (HSDPA) technology, which is an upgrade of WCDMA networks. With this upgrade, there is an increase at the download rate with a theoretical download speed of 84 Mbps and a theoretical upload speed of 21 Mbps. It also achieves a reduction in delay of 100 ms from 180-200 ms of the inaugural version of 3G. In addition, it increases the data capacity of each base station up to 5 times more than previously, by importing a new High Speed Downlink Shared Channel (HSDSC) data channel. High Speed Uplink Packet Access (HSUPA) is a further development of HSDPA, which aim is to increase the data rate for uploading at speeds of up to 5.76 Mbps to create a more symmetric channel with reduced delay, something that makes it more efficient for real-time applications. By using lower order configuration systems, HSUPA can achieve energy saving on the user's device [9].

2.4 FOURTH GENERATION (4G)

4G networks are based on Long Term Evolution (LTE) technology, which increases network capacity and data rate and further reduces delay. Theoretical transmission rates reach 100 Mbps, which are about 10 times better than 3G networks and the maximum delay is estimated at 10 ms. In order to achieve full performance of LTE capabilities, it is necessary to transform existing hybrid networks, such as circuit or packet, into fully IP-based networks. For this purpose, 4G infrastructures consist of several networks that use IP as a common protocol so that users can choose any application and environment. This solution allows for the creation of new services with reuse of application software, while IP independence allows it to work on any access technology. This means that heterogeneous wireless networks will merge into a single network, thus making the majority of services independent of access technologies [10].

The International Telecommunications Union - Radio Communications Sector (ITU-R), defined an array of specifications for the International Mobile Telecommunications - Advanced (IMT-Advanced) back in 2008. ITU-R set a threshold for the maximum speed at 100 Mbps in a mobile environment and 1 Gbps in immobile environment. So, since LTE supports lower speeds, in the first place it was not considered as a fourth generation network. Subsequently, in 2010, ITU-R recognized that this technology, as well as others beyond the third generation, although not meeting the IMT-Advanced requirements, could still be considered as 4G, provided they are precursors for IMT-Advanced compatible versions. Thus, they have to show a significant performance and specifications improvement beyond the third generation systems. LTE-Advanced (LTE-A) is an IMT-Advanced compatible version and can be considered as an acceptable fourth generation technology [11].

Although, the abovementioned characteristics of the standards reveal the evolution of each generation regarding the previous one, it is noteworthy to mention that the real performance of every network will vary by numerous of other factors that affect wireless communications. Consequently, in real-world environments there are no guarantees for achieving the maximum theoretical data rates or the minimum latency values. An effortless but effective approach to estimate the performance expectations is to presume much closer to the lower bound for data throughput and toward the higher bound for packet latency for every generation, as shown in Table 1 [12].

Table I. Data Rates And Latency For An Active Mobile Connection

Generation	Data Rate (Kbps)	Latency (ms)
2G	100-400	300-1000
3G	500-5000	100-500
4G	1000-50000	< 100

3. FIFTH GENERATION (5G) NETWORKS

Nowadays, ITU and the whole community of 5G stakeholders collaborate in developing the standards for IMT-2020. Fifth generation networks are considered as the communication technology of the future and they will start to support their first services by 2020. 5G is designed to connect not only people, but also a massive number of devices. By doing so, 5G paves the way for the IoT. Cars, trains, heating systems, refrigerators and even the smallest device will become involved in the net, posing entirely distinctive challenges than regular network users. This emerging technology is going to play an important role for the evolution of today's applications that still need improvements.

3.1 REQUIREMENTS OF 5G SYSTEMS

The forthcoming technology of 5G cellular networks shall confront serious challenges faced with current networks, in terms of [13]:

- Volume: Both on the downlink and the uplink.
- Any Device: Data delivery solutions for fixed and mobile devices that also enable usage of multiple devices.
- Anytime: Ability to deliver data without signs of congestion, latency and delay, at sustainable cost and without the need for excessive spectrum and other network resources.
- Anywhere: Ability to deliver services anywhere, independently from the location or movement of the user, including the best network connectivity.
- Quality of Service (QoS): Ability to provide to both nomadic and stationary usages the required QoS.
- Security: For end-users as well as for service owners.

The emerging technology of 5G is expected to become a strategic priority for telecommunication operators. Almost every month, a telecommunication operator or vendor announces plans for a rollout or pilot launching regarding 5G. There is a constant collaboration between operators and miscellaneous industry players such as vehicle manufacturers, city administrative authorities, sport authorities and governing bodies to reveal their plans to improve technologies like smart mobility, smart city and many other innovative ones.

5G systems are anticipated to embrace and integrate existing or new innovative technologies, bringing small cells, MIMO, beam forming, true in-band full duplex (IBFD), edge computing together and extend spectrum support to both low band (600 MHz) and high band millimeter wavelength (26, 28, 38 and 60 GHz), in order to be able to support the abovementioned requirements. Moreover, it is estimated to foster the digitization of the economy like cloud based services, next generation transactions (e.g. block chain), big data, virtual reality (VR), augmented reality (AR), artificial intelligence (AI), internet of things (IoT) and tactile internet due to its ability to manage, in real-time, large amount of data with low latency.

ITU IMT-2020 standard outlines eight criteria for mobile networks, which should be fulfilled in order to qualify as 5G [14]:

- 10 Gbps maximum achievable data rate.
- 10 (Mbit/s)/m^2 traffic capacity across coverage area.
- 1 ms latency.
- 10^6/km^2 total number of connected devices.
- 3 times higher spectrum efficiency compared to 4G.
- Full (100%) network coverage.
- Mobility up to 500 km/h with acceptable Quality of Services.
- 10 times lower network energy usage compared to 4G.

3.2 TYPES OF SERVICES

The concept of very high performance 5G networks results from a combination of different factors. From the service and business perspective there is a distinction of three types of services [15]:

enhanced Mobile Broadband (eMBB): The eMBB services target applications with aggregated data rate more than 10 Gbps. The tension shows that in North America and Europe there is a noteworthy growth in mobile video streaming which will lead around 6 times higher the data transmission rate per device after 2020. The increasing use of cloud delivered Media and Social Media, in addition with the ever richer content, to smart mobile devices puts extra constraints on the intermediate communication links, which calls for considerable capacity increase. Virtual reality applications are anticipated to demand a few Gbps capabilities, whilst the generalization of 8K Ultra High Definition streaming should require capacity of higher than 100 Mbps for a single user.

massive Machine Type Communication (mMTC): The mMTC services target applications with millions of devices per square kilometer. The arrival of machine-to-machine (M2M) communication, with a large amount of connected devices or massive IoT used in industrial and professional applications or in smart cities deploying a huge number of sensors, requires highly efficient radio networks and very low energy consumption.

Ultra Reliable Low Latency Communication (URLLC): The URLLC services target applications with very low latency requirements. The existing technology cannot serve the novel time-demanding applications necessitating instant reaction, which means extremely low latency in the order of 1 ms, with the prerequisite guarantee of performance. Thus, the next generation networks should be designed not only to meet the end-to-end requirements but also to achieve an efficient system deployment. URLLC makes 5G qualitatively different from the previous mobile generations. Ultra-reliable communication will possibly become an enabler of a vast set of applications, some yet unknown. To put this in perspective, wireless connectivity and embedded processing have considerably transformed an amount of products and services by expanding functionality and transcending the traditional limitations.

Generally, the applications and the use cases of URLLC can be divided into cable replacement and native URLLC applications. Cable replacement use cases refers to the transformation of some of the existing applications that depend on cabled connections, but also add a new quality due to the flexibility of wireless connectivity. On the other hand, a native URLLC application is the one that has no precedent in wired communication, like vehicle-to-vehicle (V2V) communication.

URLLC will enable supporting the emerging applications and services. Typical URLLC applications include remote surgery, connected cars, smart factories and robotics or detection of faults in energy grids. In most cases, these time demanding applications will have to merge 5G connectivity with distributed (mobile) cloud technology so as to meet the needed end-to-end response times.

Taking into consideration the aforementioned services, each one of them should face different challenges, in order to provide acceptable QoS. The eMBB services have to cope mostly with network energy efficiency, area traffic capacity, peak data rate, user experienced data rate, spectrum efficiency and mobility. Connection density is of high importance for mMTC, while mobility and latency are the most crucial challenges for URLLC services.

From the technological perspective the following disruptive technologies are expected to act as game changers [15]:

Network Function Virtualization (NFV): NFV gives the opportunity of implementing specific network functions such as content delivery network and customer premises equipment management in software running on generic hardware, without the need for costly hardware specific devices. NFV is further expected to push for radical reduction in capital expenditure (capex) and operational expenditure (opex). Moreover, it is expected a sharing and reuse of the identical functionality between numerous customers and a higher innovation capability due to the simple implementation and introduction of new software functionalities and creation of a “network app” market place.

Software Defined Networking (SDN): SDN is a supplementary trend to NFV which opens the prospects to third parties to control network resources, with the possibility for them to manage their own physical or virtual resources individually, as they desire, with the required level of performance tailored to actual needs. The dawn of this service goes much beyond the management capabilities offered by the existing Mobile Virtual Network Operators (MVNO).

With regards to 5G advancements, SDN and NFV are viewed as key parts to empower these particular classifications of professional users to control their network capabilities dynamically as per their requirements and particularly in the perspective of supporting ad-hoc digital business models of industrial users. As network resources are potentially available to third parties through open interfaces, they additionally open the likelihood for smaller players to innovate through implementation of specific service offers building on network resources made approachable for third party access and programmability.

4. HAPTIC DATA

The advantages of 5G networks will drive future internet applications to be tactile, where users will be able to touch and manipulate objects remotely and moreover to exchange nonverbal communication cues like handshaking. Communication of haptic data entails physical interaction with remote items, objects or people. Information associated to the haptic perception handled by the human senses is called haptic. As illustrated in Figure 1, the procedure of data transferring can be divided into three domains. In the master domain every action or movement of the body produces haptic data via a Human System Interface (HSI), which then these data pass through the network domain to the controlled domain. In the controlled domain, the haptic data are used to control a teleoperator or in the case of a virtual environment a haptic rendering algorithm. In an ideal world, haptic communication systems in the form of telepresence and teleaction (TPTA) systems should be transparent to the user, where the remote system interaction feels exactly the same as if the remote system were substituted by the user [16].

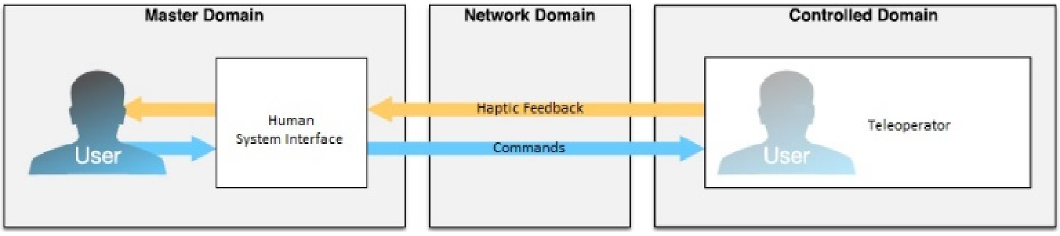

Fig. 1 Haptic data communication domains

4.1. TYPES OF HAPTIC INFORMATION

Haptic perception, handled by the human somatosensory system, comprises of two senses, the kinaesthetic and the tactile. Kinaesthetic information refers to the sensation of muscle movements and helps to determine joint positions. Tactile information refers to touch, pressure, temperature and pain and is a prerequisite for practically all neuromuscular activities like perception of objects and their position in case of limited visibility, identification of materials and other surface properties. Especially, in telepresence and teleaction systems the haptic modality plays a vital role [16].

4.2. HAPTIC DATA FLOW REQUIREMENTS

As every real-time multimedia streaming application, haptic ones are seriously affected when network disorders occur such as network delay, jitter, packet loss and out of order packet delivery. Haptic information transmission requires on time delivery of data and it should be capable to tolerate some packet loss to accomplish this goal. Furthermore, haptic applications are considered as vulnerable enough, which in some circumstances lead to instability. The Packet Delay Variation (PDV), widely known as jitter, usually triggers this instability. The amount of time it takes for a packet to travel across the network from one node or endpoint to another specifies the delay of a network. The maximum delay should be lower than 50 ms, the jitter lower than 10 ms and the packet loss lower than 10%. When delay and jitter reach values higher than the aforementioned ones, then several malfunctions could occur such as unpleasant sensation of handling, delayed response, oscillations and instability. Table 2 depicts the network conditions that should be satisfied in order to avoid such kind of malfunctions [17]. According to these elements, it could be said that haptic applications are more tolerant to data loss and low bandwidth but are sensitive to delay, jitter and update rate compared to the requirements that other multimedia applications have.

Table II. Network Requirements

QoS	Haptics	Video	Audio	Graphics
Jitter (ms)	≤ 2	≤ 30	≤ 30	≤ 30
Delay (ms)	≤ 50	≤ 400	≤ 150	$\leq$ 100-300
Data Rate (Kbps)	512-1024	2500-40000	64-128	45-1200
Packet Loss (%)	≤ 10	≤ 1	≤ 1	≤ 10
Update Rate (Hz)	≥ 1000	≥ 30	≥ 50	≥ 30

5. MULTIPLE SENSORIAL MEDIA

Figures In the last decade researchers have put a lot of weight on the improvement of multimedia applications which incorporate media components except from the typical audio and video. Such researches, beyond the sense of touch, include mostly olfaction (sense of smell), gustation (sense of taste) to a secondary degree and of course combination of them. These types of experiences are known as multiple sensorial media (mulsemedia) or multisensorial media. Therefore, as mulsemedia applications can be characterized those that involve three or more of human senses [18].

The senses of smell and taste are functionally related, so they are regularly considered together; it is practically impossible for people to taste something while pinching their nose, making the sensations of smell and taste difficult to distinct. Unlike other senses that interpret light or sound waveforms and convert these into electrical signals recognized in the brain, the senses of smell and taste are experiences triggered as an outcome of interaction with molecules being assimilated into the body.

5.1. MULSEMEDIA APPLICATIONS

Mulsemedia applications were initially designed in association with the film industry. The arts and the creative industries still continue to experiment mulsemedia in their content and delivery mechanisms. By this means, interactive digital experiences are no longer audio and visual creations but mulsemedia ones.

Another area that will possibly take advantage from the addition of humanity's sensory cues are computer games; thus, becoming mulsemedia games. It is anticipated that they will increase the sense of presence and reality and hence influence positively on user experience, making them more attractive.

Moreover, mulsemedia applications have great therapeutic potential. More and more people heal themselves using methods like aroma therapy, music therapy and massage, which all of them engage mainly one human sense. Creation of multisensory rooms can give mulsemedia experiences to people with special needs, ranging from learning difficulties to autism, Alzheimer and many others.

Mulsemedia authoring tools would play an assistant role for e-learning systems. For example, it would become feasible to combine an e-learning system with an olfaction-enhanced mulsemedia application. In so doing, the online learning of a specific topic can become much more interactive by adding the corresponding odors.

The constantly developing field of e-commerce has the opportunity to move a step forward by overcoming the touch, smell and taste barriers prior shopping products. The option to feel the texture of the clothes or to smell the fragrance of the perfumes before purchasing them, as well as to taste a dish of a restaurant prior booking a table, are some of the potential possibilities of integrating multiple sensorial media applications on e-commerce, enhancing the e-shopping experience [18], [19].

5.2. CHALLENGES FOR MULSEMEDIA APPLICATIONS

An extensive research is required to be conducted in order to confront the challenges of the emerging nature of multiple sensorial media, due to their complexity. These problems range from re-evaluation of aspects that were up to that time executed in the audiovisual domain, to deeper understanding of how humans perceive and consume mulsemedia content, to application domain certain research challenges for mulsemedia applications. The core challenges that have to be faced are integration, synchronization, standardization, sensor and display development, effects of intensity and duration and remote delivery of components [20].

6. TRANSPORT LAYER PROTOCOLS

A Transport layer is a central piece of the network architecture. It has the critical role of providing communication services directly to the application processes running on different hosts.

According to testbeds, haptic data are sensitive to network conditions such as jitter, delay, packet loss, out of order packet delivery and increased network congestion. Focusing on transmission protocol requirements many methods have been investigated to optimize telehaptic data transmission. Some of these techniques are multiplexing, perception-based data reduction, prediction-based data reduction, network prediction or network resource allocation, haptic visual aid decorators, wave variables and application-centric data transmission protocols. A real-time haptic transport system should work with minimal protocol overhead and ought to be optimized with respect to the required high signal update rates. Additionally, support for dejittering and stream synchronization would enable the haptic application to balance between disturbing additional latency and improved signal quality.

6.1. REVIEW OF TRANSPORT PROTOCOLS

The transport protocols that seem to have the potentials to deliver haptic data, especially in real-time conditions are [17], [21-23]:

Transmission Control Protocol (TCP): TCP is one of the most widespread transport layer protocols for internet services. It provides a reliable and connection-oriented service to internet applications. The TCP mechanism of packet retransmissions assists on packets reception. It also implements congestion control algorithms in order to adjust the transmission rate and offers a typical flow authentication mechanism by establishing a three-way handshake prior to data delivery. TCP protocol is not recommended for real-time services because its retransmission mechanism and congestion control algorithms drive the jitter values above the acceptable threshold, which make this protocol not suitable for real-time traffic.

User Datagram Protocol (UDP): UDP is a well-known transport protocol used for internet services. Unlike TCP, it offers an unreliable and connectionless mechanism that transmits interactive and real-time data and it is considered as a suitable candidate in applications, where the need of maximum available bandwidth is obligated for uninterrupted communication, like multimedia streaming, voice transmission over the internet protocol (VoIP), teleoperation and robotics. The UDP uses packet flows (datagrams) transmitted at constant rates without acknowledgments, loss or packet reorder provisions. In case of congestion it does not guarantee data packet delivery or rate adjustments. Using this protocol, data transferring can be accomplished without substantial time delay and variations. For the transmission of real-time insensitive data, without a guarantee of a reliable transmission, UDP is suggested, but if channel capacity is exceeded then it leads to data loss and real-time flow corruption. It can be characterized as the best effort protocol for the transmission of interactive services, even if it does not guarantee data reliability, since it manages to maintain a constant flow rate by minimizing jitter.

Real-Time Transport Protocol (RTP): RTP has been implemented some years after the introduction of UDP and it is considered as a successor of it as its aim is to carry interactive flow information between two end systems. RTP, in order to maintain real-time flow consistency, includes flow control and packet retransmission provisions. This protocol seems as a good option for real-time applications that include video and audio streaming services.

Real-Time Control Protocol (RTCP): RTCP is an enchanted version of RTP. It provides feedback to both communicating participants regarding data transmission such as the inter-arrival jitter estimate, information about the highest sequence number received, fraction of packets lost and cumulative number of packets lost.

Real-Time Network Protocol (RTNP): RTNP was developed for use on UNIX environments in order to eliminate time delay caused by the specific multitasking operating system; therefore, this protocol cannot be implemented on other platforms. The main subject that tries to confront the protocol is to reduce the time delay of the network, which may cause serious problems such as instability of the feedback system of a haptic application. To avoid such delay, timely execution of the protocol handler tasks with real- time interrupts allows for more immediate transmission of haptic data packets.

Interactive Real-Time Protocol (IRTP): IRTP has been designed for interactive internet based service in order to reduce the end-to-end delay. It uses the TCP 3-way handshake for flow connection establishment, as well as the RTP flow control and a retransmission mechanism for essential data. For real-time and interactive non crucial data, the IRTP uses TCP mechanism in contrast to UDP for critical data flow delivery.

Efficient Transport Protocol (ETP): ETP is an alternative protocol to IRTP and it is considered as a UDP based protocol. Like IRTP, it is designed for internet based interactive services. This protocol is based on a state machine that decides the best strategies for optimizing roundtrip time (RTT) and inter-packet gap (IPG). A time gap between two successive data packets is called IPG. Thus, ETP focuses on reducing the end-to-end delay by introducing IPG. This kind of control mechanism provides congestion control similar to the TCP window size based congestion control.

Synchronous Collaboration Transport Protocol (SCTP): SCTP adopts the concept of reliable packet delivery of key updates and unreliable delivery of normal updates. SCTP is encapsulated into UDP packets and assumes that the underlying physical network supports IP multicasting. By using IP multicast it becomes scalable and fast due to the utilization of the low overhead UDP packets. This reliability mechanism results in the increased overall latency in the communication system.

Smoothed Synchronous Collaboration Transport Protocol (Smoothed SCTP): Smoothed SCTP is built on UDP and is mostly used in haptic virtual environment applications as its predecessor SCTP and attempts to deal with jitter by employing a buffer at the receiver and handling packets according to a time stamp placed at the header of each packet. This method results in a fixed delay for all messages.

Network Adaptive Flow Control Algorithm for Haptic (NAFCAH): NAFCAH is a quit flexible algorithm, which combines the most known flow control algorithms, where the user can adjust its sensitivity to the network variations of the internet and the significant haptic events. When congestion is detected, NAFCAH decreases its transmission rate in stages and it monitors congestion based on roundtrip time measurements, but under asymmetric network conditions RTT may not provide an accurate estimate of the (one-way) delay on the forward channel.

Adaptive Medical Sensor Transmission Protocol (AMESETP): AMESETP is one of the newest network adaptive transmission protocols for real-time services. This protocol scans the network status in frequent intervals and depending on the noticed network conditions such as packet loss, jitter or inter-package delay time, it adapts the sending rate of the data packets and the quantization levels of the transmission in order to overcome congestion incidents.

Dynamic Packetization Module (DPM): DPM is a new transport layer congestion control protocol for telehaptic applications operating over shared networks. It is a lossless, network aware protocol, which adjusts the telehaptic packetization rate based on the level of congestion in the network. An innovative network feedback module is applied to observe the network congestion, which transmits the end-to-end delays confronted by the telehaptic packets to the corresponding transmitters with insignificant overhead. DPM responds to congestion with an aggressive rate reduction, which enables network buffers to get flushed quickly, minimizing the possibility of QoS violations. Furthermore, unlike NAFCAH, it estimates the delay on the forward and backward channels separately.

6.2 REQUIREMENTS OF TRANSPORT PROTOCOLS

Any incorrect data received by the user could result in an incorrect response given back to the remote environment. UDP provides fast transmissions and low delay variations, but is an unreliable connectionless service. TCP is connection-oriented and employs packet retransmission in case of packet loss. Unfortunately, its algorithms lead to delay and jitter, which is not desirable for transferring real-time data. To ensure haptic data are correctly transported, we require a highly reliable system with a maximum packet loss probability of 0.001%. So, it is obvious that using TCP as transport protocol for haptic systems is difficult to meet the requirements, in terms of delay and jitter. For haptic communication protocols should meet certain constrains and contain some qualitative features. The qualitative features that a protocol should fulfill in order to meet requirements, presented in a decreasing order of importance are prioritization, key updates, interaction stream, minimum overhead, error correction and data integrity, jitter control, congestion control, real-time flow control, synchronization, multicast, bandwidth estimation, multiplexing, scalability-adaptability, receiver buffer optimization and minimum TCP friendly capability [17].

7. SIMULATIONS AND TRIALS

There have been conducted numerous simulations of haptic information transmission in order to evaluate the efficiency of the several transport layer protocols in terms of latency, jitter and bandwidth.

7.1 COMPARING PROTOCOLS' PERFORMANCE

A comparison between TCP and UDP protocols about the control signal transmission, by sending real-time data from a master device to a slave one, shows the time difference of the arrival of the packets on the slave by these two protocols respectively. Every 100 ms the master controller sends packets to the slave manipulator, so it is expected that the packets should be delivered in every 100 ms. Nevertheless, a fluctuated time-delay was noted on the TCP connection, which in some cases it extends in the range of 600 ms. In contrast, on the UDP connection was not spotted any wide-ranging time-delay. The examination about the packet arrival on the slave device revealed that on UDP was caused some packet loss. However, due to the sporadically occurred packet loss, this situation did not affect the cooperation of master and slave. The simulations indicate that TCP protocol is not applicable to the critical real-time application due to the congestion control that occurs on the network connection. While using UDP, it is possible to carry out real-time applications, although the packet loss which observed during the simulations [24].

Another simulation compares the different behaviors of UDP and ETP protocols. The main aim of ETP is the reduction of RTT and IPG and it is, therefore, optimized for interactive applications which are based on processes that are repeatedly exchanging data. In this scenario the master sends the information to a PC (flow 1) and the PC returns the force values to the master (flow 2) using UDP and ETP respectively. It is observed that flow 1 has considerable variations because packet information is doing congestion. On the other hand, flow 2 has slight variations because the ACK packets are not enough to produce congestion. Thus, flow 2 has similar values (bandwidth, IPG, transmission time) in both protocols.

Table III. Comparison Between UDP And ETP

		IPG Time (ms)	Transmission Time (ms)	RTT (ms)
UDP	Flow 1	0.99	12.55	23
	Flow 2	0.99	10.36	
ETP	Flow 1	1.205	10.89	21
	Flow 2	0.99	10.36	

The most important problem of UDP is that it does not implement any algorithm to control the congestion and therefore its transmission rate is constantly the same. As shown in Table 3, it implies that IPG and required bandwidth almost reach the value programmed by the user (IPG close to 1 ms). Maintaining the same transmission rate might create congestion since transmission time could increase due to the rest data flows of the network (transmission time increase to 12.55 ms). In contrast, ETP protocol implements a congestion control so the transmission rate varies in accordance with the protocol algorithm. Thus, transmission rate will decrease when congestion is identified so the bandwidth decreases and the IPG increase (1.205 ms).

For the comparison of AMESETP against TCP and UDP, a source device was transmitting a single data packet of 2 byte/ms every 100 ms. As depicted in Table 4, the AMESETP protocol outperforms against the UDP transmission in the case of less packet drops due to the NACK periodic retransmission mechanism.

Table IV. Comparison Among AMESETP, UDP And TCP

	Min. Interpacket Delay (ms)	Max. Interpacket Delay (ms)	Packet Drop (%)
UDP	124	1214	8
AMESETP	114	998	2
TCP	448	1042	-

The simulations were conducted over 3G networks, where latency is introduced by the communication channel. The testing revealed that the 3G transmission can tolerate spurious or continuous latencies up to 890 ms before packet drop occurs. Moreover, similar inter-packet delays for AMESETP and UDP flows are sustained, because 3G communication channel is jitter tolerant, as well. The packet delivery delay time is less than 130 ms in a decent 3G signal reception, but in environments with low signal or increased contention the inter-packet delay time might extent up to 1200 ms. Moreover, remarkable jitter was noticed in a 3G network with increased mobility [22].

DPM adapts its transmission rate depending on the intensity of cross-traffic it experiences; thus, it responds to network congestion with an aggressive transmission rate reduction, allowing the network buffers to get flushed quickly, avoiding a QoS violation. Moreover, DPM results a roughly periodic delay evolution, against a steady cross-traffic. This is typical of congestion control algorithms. Even when the backward channel is highly congested, DPM manages to keep the telehaptic delays below the prescribed QoS limits.

Table V. DPM Performance

	Max. Delay (ms)	**Max. Jitter (ms)**
Haptic	29.738	3.628
Audio	27.952	5.372
Video	63.629	8.255

Table 5 summarizes the examined telehaptic delay and jitter for haptic, audio and video streams respectively. It can be noticed that DPM assists the telehaptic application to conform to the QoS limits even under heavy cross-traffic conditions. It should be noted that the measured 3.628 ms of haptic jitter are significantly below of the QoS jitter limit, which threshold is set up to 10 ms.

As already mentioned, DPM performs a prompt rate adaptation, maintaining end-to-end delays below the QoS deadline of 30 ms. On the contrary, RTP generates its first and the second congestion detection reports too slow to allow for timely rate-adaptation, so the haptic delays under such a protocol would keep growing, violating the QoS deadlines.

DPM accomplishes the QoS limitations, due to its aggressive step-increase mechanism for rate reduction and its precise end-to-end delay estimation mechanism. In contrast, NAFCAH cuts its transmission rate in stages, once congestion is detected. This outcomes in a comparatively sluggish congestion control. Additionally, NAFCAH uses roundtrip time measurements to estimate congestion on the forward channel. This drives to inaccurate delay estimations under asymmetric network conditions [23].

7.2 5G TRIALS

Recent years many telecommunication companies and vendors conduct trials, in order to test their potentials on the forthcoming 5G networks [25]:

In October 2016 The Swedish operator Telia and Ericsson conducted in Kista, Sweden a 5G field trial that achieved data speeds of 15 Gbps and a latency of less than 3 ms. The test was in the 15 GHz band and used 800 MHz of spectrum.

The Chinese vendor Huawei revealed in November 2016 the results of the first 5G large-scale field trial globally. The test was jointly conducted with NTT Docomo, which is the largest mobile communications carrier in Japan, in one of the most crowded commercial areas in Yokohama, Minato Mirai 21 District. The macro cell was constituted by a base station that worked in the 4.5 GHz band with 200 MHz bandwidth. In the trial were achieved total user throughput of 11.29 Gbps and latency lower than 0.5 ms.

Finnish operator Elisa Corporation conducted a 5G trial on the 3.5 GHz band in partnership with Nokia. The test took place in Rusko, Finland in April 2017 and attained speeds of 1.5 Gbps and extremely low latency of 1.5 ms.

In June 2017 Telekom Romania and Ericsson conducted in Bucharest the first 5G live demonstration in South East Europe. This inaugural trial of the Romanian telco comprised tests on speed, latency and beam forming. It achieved aggregate speeds of up to 24 Gbps, approximately 60 times more than the existing local highest commercial 4G speed, with an indicative latency of at least half of what is noticed in present mobile networks.

The Korean telco SK Telecom and Samsung announced in June 2017, that they successfully completed a trial to deliver a 5G end-to-end connection. Using the 3.5 GHz frequency, the test achieved speeds higher than 1 Gbps and latency as low as 1.2 ms. This ultra-low latency was made attainable by decreasing the transmission time interval down to 0.25 ms, which is one fourth the time of existing 4G networks. In addition to the latency improvements, a channel bandwidth of 80 MHz was used to make consistent gigabit performance feasible at the test, while 20 MHz is the maximum channel bandwidth for LTE.

In July 2017 the Chinese vendor ZTE published a number of strategic 5G scenario tests regarding eMBB at sub-6GHz frequencies, eMBB at millimeter wave (mmWave) frequencies, URLLC and mMTC, which took place in Huairou, Beijing. The most prominent scenario was the eMBB at sub-6GHz test. During it, ZTE was able to offer 28 streams to users through the 3.5 GHz pre-commercial base station, obtaining a peak cell throughput of more than 19 Gbps. Moving to mmWave frequencies, ZTE used the 26 GHz band and it achieved a four stream data rate of 13Gbps. The vendor achieved an ultra-low latency of 0.416 ms, while testing on the URLLC case, based on a unified test platform. Trialing mMTC, the Chinese technology solutions provider succeeded performance of 90 million connections/MHz/hour/km2, using the innovative multi-user shared access (MUSA) technology.

SK Telekom and Nokia reported in September 2017, that they have reduced the latency between a handset and the base station to 2 ms over its LTE network, while latency between handsets and base station in present LTE environment is about 25 ms.

The United Arab Emirates (UAE) telecommunications company Etisalat announced its trials of 5G technology in October 2017, during Gitex Technology Week in Dubai. It has in trials of 5G technology. Etisalat used 2 GHz of bandwidth, as well as massive MIMO, for its tests and it achieved the superior mobile data rates of 71 Gbps.

The German telco Deutsche Telekom (DT), which is the largest telecommunications provider in Europe, tested four 5G antennas in the capital city of Berlin in October 2017. It was the first time that this technology tested in a real world setting on the continent. DT reported speeds of higher than 2 Gbps and only 3 ms latency on some sites of the testing territory.

Vodafone Italia worked with Huawei in November 2017 on a demonstration, which took place in Milan. The trial involved massive MIMO technology using frequencies in the 3.7-3.8 GHz spectrum and achieved data speed of more than 2.7 Gbps with latency of just over 1 ms.

The member of BT Group, EE operator, in partnership with Huawei demonstrated an end-to-end 5G test network in its test lab in November 2017. EE linked the fully virtualized 5G core to the 64x64 Massive MIMO active antennas, in order to reach 2.8 Gbps downlink throughput and less than 5 ms latency, using 100 MHz spectrum of the 3.5 GHz band.

In November 2017 NTT Docomo with Samsung announced a 5G trial scenario with a mobile device that was in a vehicle traveling with 150 km/h. It achieved data rate higher than 2.5 Gbps, using the 28 GHz band.

Huawei and NTT Docomo conducted one more field trial in December 2017, which took place in downtown Tokyo. The base station was placed at a height of 340 m on Tokyo Skytree's viewing deck, while user equipment was located on the roof of a shopping facility at Asakusa Station. A high speed data transmission of more than 4.52 Gbps downlink and 1.55 Gbps uplink throughput within a distance of 1.2 km on the 28 GHz mmWave spectrum was succeeded.

Continental, a popular technology company, in collaboration with Huawei ran field trials to exam the efficiency of the Cellular Vehicle to Everything (C-V2X) communication standard in Shanghai during December 2017. At single event message were attained latencies as low as 8 ms, while the average latency was 11 ms. Worth noting that the packet reception rate was nearly 100% of the total amount of transmitted packets.

Vodafone Ireland, in partnership with Ericsson, announced in February 2018 the first successful live demonstration of 5G technology in Ireland. In an event at the Douglas Hyde Gallery at Trinity College, Vodafone Ireland and Ericsson achieved speeds of 15 Gbps and latency less than 5 ms.

5G wireless trials of AT&T in April 2018 produced speeds close to 1.2 Gbps and latencies between 9 and 12 ms from 28 GHz mmWave frequency, using a 400 MHz channel, even in bad weather or in some cases without a line-of-sight connection.

Proximus and Huawei performed a successful 5G field trial in Leuven, Belgium using the 3.5 GHz band in April 2018. At the test were reached transfer speeds of up to 2.94 Gbps and latency rate as low as 1.81 ms.

South African telecommunications group MTN and Huawei announced in May 2018 the results of the first live outdoor 5G trial in the African continent. The field trial demonstrated in a real-world environment at The Fields shopping center in Hatfield, Pretoria. The network allocated 100 MHz of the 28 GHz high frequency spectrum to conduct the test and MTN measured, in an online speed test, download speeds of 520 Mbps, upload speeds of 77 Mbps and latency of 7 ms.

Bouygues Telecom has opened, in July 2018, the first 5G pilot site in France, from two base station antennas of their network, providing coverage of up to ten kilometers. Bouygues Telecom chose the Bordeaux metropolitan area to conduct a public demonstration in order to present its inaugural 5G pilot network. During the throughput test, a downlink rate of 2.3 Gbps was observed with an upstream bandwidth of 260 Mbps and a latency of 7.5 ms.

The Greek dominant provider Cosmote in collaboration with Ericsson and Nokia launched the first 5G trial network in Greece, in December 2018, reaching speeds of over 12 Gbps. The trial took place at an outdoor space in the Municipality of Zografos, Athens, where the provider develops a 5G pilot network.

8. CONCLUSIONS

The English author and clergyman of the 17th century Thomas Fuller, once written "Seeing is believing, but feeling is the truth". Tactile internet is coming to transform this quote into reality through a digital perspective! The most imperative challenge that tactile internet systems have to face, is to provide latency values lower than 1 ms. Current technologies still lack from reaching such standards. The dawn of 5G networks will enable capabilities that will change the way people interact so far. This emerging technology will not only transform the human-to-machine communication, but also the machine-to-machine one.

Telecommunication providers and vendors work intensively to develop and introduce 5G services in the near future in order to provide applications which will improve humanity's everyday life to a better tomorrow. Still, researchers have to study on new protocols to deliver haptic data and mulsemedia in general, confronting the potential challenges of 5G communication.

REFERENCES

[1] Farhoudi, M., Palantas, P., Abrishamchi, B., Mihailovic, A., Aghvami, A.H. "A novel reliable routing scheme for Tactile-oriented Internet traffic", Proc. of the IEEE 2017 24th International Conference on Telecommunications (ICT), May 2017.

[2] Andrews, J. G., Buzzi, S., Choi, W., Hanly, S. V., Lozano, A., Soong, A. C. and Zhang, J. C. "What will 5G be?" IEEE Journal on Selected Areas in Communications, vol. 32, no. 6, pp. 1065-1082, June 2014.

[3] Ateya, A., Al-Bahri, M., Muthanna, A., Koucheryavy, A. "End-to-end system structure for latency sensitive applications of 5G", Электросвязь, vol. 6, pp. 56-61, January 2018.

[4] Schneider, O., MacLean, K., Swindells, C., Booth, K.. "Haptic experience design: What hapticians do and where they need help", International Journal of Human-Computer Studies, vol. 107, pp. 5-21, November 2017.

[5] Goleniewski, L. Telecommunications essentials: the complete global source for communications fundamentals, data networking and the internet, and next-generation networks. Addison-Wesley Professional, 2002.

[6] Dekleva, S., Shim, J. P., Varshney, U. and Knoerzer, G. "Evolution and emerging issues in mobile wireless networks," Communications of the ACM - Smart Business Networks, vol. 50, no. 6, pp. 38-43, June 2007.

[7] Mishra, A. R. Advanced cellular network planning and optimisation: 2G/2.5G/3G... evolution to 4G. John Wiley & Sons, 2007.

[8] Karjaluoto, H. "An investigation of third generation (3G) mobile technologies and services," Contemporary Management Research, vol. 2, no. 2, pp. 91-104, September 2006.

[9] Jaloun, M. and Guennoun, Z. "Wireless mobile evolution to 4G network," Wireless Sensor Network, vol. 2, no. 4, pp. 309-317, February 2010.

[10] Overview of 3GPP Release 8 V0.3.3, 3GPP, 2014

[11] Overview of 3GPP Release 10 V0.2.1, 3GPP, 2014.

[12] Grigorik, I. High Performance Browser Networking: What every web developer should know about networking and web performance. O'Reilly Media, 2013

[13] 5G and media & entertainment, New European Media (NEM), 5GPPP, January 2016

[14] ITU-R. "IMT Vision - Framework and overall objectives of the future development of IMT for 2020 and beyond," M Series, Recommendation ITU-R M.2083-0, September 2015.

[15] EU commission. Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions - 5G for Europe: An Action Plan. Brussels, September 2016.

[16] Steinbach, E., Hirche, S., Kammerl, J., Vittorias, I. and Chaudhari, R. "Haptic data compression and communication," IEEE Signal Processing Magazine, vol. 28, no. 1, pp. 87-96, January 2011.

[17] Kokkonis, G., Psannis, K. E., Roumeliotis, M., Kontogiannis, S. and Ishibashi, Y. "Evaluating transport and application layer protocols for haptic applications," Proc. of 2012 IEEE International Workshop on Haptic Audio Visual Environments and Games (HAVE), pp. 66-71, October 2012.

[18] Ghinea, G., Timmerer, C., Lin, W. and Gulliver, S. R. "Mulsemedia: State of the art, perspectives, and challenges," ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM), vol. 11, no. 1s, Art.no. 17, September 2014.

[19] Huang, P., Ishibashi, Y. and Psannis, K. E. "Fairness Assessment in Networked Games with Olfactory and Haptic Senses," International Journal of Communications, Network and System Sciences, vol. 10, no. 8, pp. 173-186, August 2017.

[20] Murray, N., Ademoye, O. A., Ghinea, G. and Muntean, G. M. "A tutorial for olfaction-based multisensorial media application design and evaluation," ACM Computing Surveys (CSUR), vol. 50, no. 5, Art. no. 67, November 2017.

[21] Kokkonis, G., Psannis, K. E. and Roumeliotis, M. "Network adaptive flow control algorithm for haptic data over the internet-NAFCAH," International Conference on Genetic and Evolutionary Computing, vol. 388, pp. 93-102, September 2015.

[22] Kokkonis, G., Kontogiannis, S. and Tomtsis, D. "An open source architecture of a wireless body area network in a medical environment," International Journal of Digital Information and Wireless Communications, vol. 6, no. 2, pp. 63-78, April 2016.

[23] Gokhale, V., Nair, J. and Chaudhuri, S. "Congestion control for network-aware telehaptic communication," ACM Transactions on Multimedia Computing, Communications, and Applications (TOMM), vol. 13, no. 2, pp. 1-26, March 2017, Art. no. 17.

[24] Arata, J., Takahashi, H., Pitakwatchara, P., Warisawa, S. I., Tanoue, K., Konishi, K., ... and Fujino, Y. "A remote surgery experiment between Japan and Thailand over internet using a low latency CODEC system," IEEE International Conference on Robotics and Automation, pp. 953-959, April 2007.

[25] 5GPPP https://5g-ppp.eu/

