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Procedia Computer Science 176 (2020) 3853–3862

Procedia Computer Science

www.elsevier.com/locate/procedia

24th International Conference on Knowledge-Based and Intelligent Information & Engineering Systems

On the Ultra-Reliable and Low-Latency Communications for Tactile Internet in 5G Era

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Abstract

New generations of mobile telephony succeed every decade, each bringing an evolution or even a revolution. Nowadays, the Internet of Things and the tactile Internet are starting to grow, and 5G technology is there to enable these services. 5G technology has introduced three types of services, namely eMBB (for services requiring very high bit rates), mMTC (for massive connection of user equipment), and uRLLC (for critical services requiring very high reliability and extremely reduced latency). In this paper, we have dealt with some issues encountered by uRLLC services for tactile Internet services. In this article, we have studied the transmission of very small packets as required by the 5G uRLLC services. We also examined the probability of transmission error and its variation concerning the transmission delay and the length of the packet transmitted. This study was conducted considering its application in the Tactile Internet.

Keywords: Tactile Internet; 5G technology; uRLLC;Shannon Capacity;Reliabilty; Latency.

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10.1016/j.procs.2020.09.003

1. Introduction

Almost every decade, we have witnessed periods of purely systems with no data capabilities for 1G, digital circuit-switched systems optimized for full-duplex communication and superb voice telephony for 2G, broadband and multimedia systems for 3G, cooperation between different systems and different existing technologies (in terms of speed, coverage, etc.). An intelligent system for integrating the current via a backbone network and a broadband radio access network based on the IP protocol, and provides support for packet-switched traffic with seamless mobility, quality of service (QoS) and minimal latency for 4G, and finally all-IP network revolution and massive and seamless end-to-end connectivity and mobility. However, the 4G specifications are designed for smartphones and not for critical network services.

The evolution from 1G to 5G has been all-encompassing involving significant changes at architecture level (core network, CN) and radio access network (RAN) from one generation to the next, and changes in user equipment. In all of these different generations, two principle parameters are fundamental, namely the throughput and the latency. The performance indicates how fast data is sent through a network. The latency indicates how long it takes data sent from a particular source to reach the target destination successfully. Table 1 shows the different values of the different generations concerning the theoretical bit rates (throughput) and the latency [1].

Table 1. Throughput and latency in 1G to 5G

Generation	Data rate/Troughput (Maximum)	Latency (Minimum)
1G	9.6 kbps	>1000 ms
2G	2 Mbps	600-750 ms
3G	100-300 Mbps (DL), 50-75 Mbps (UL)	<10 ms (UP) , <100 ms (CP) (typical values : 40-50 ms)
4G	1-3Gbps (DL), 0.5-1.5 Gbps (UL)	~5 ms (UP), <100 ms (CP) (typical values : 40-50 ms)
5G	1 Tbps (over 100 m) >20 Gbps (DL) , >10 Gbps (UL)	$\leq 1\ ms$

This paper is organized as follows: Section 2 presents 5G services and minimal technical performance requirements. Section 3 describes the concept of the Tactile Internet. Section 4 studies the performance of the 5G mobile network in terms of achievable rate and reliability for Tactile Internet. Section 5 presents some technologies used for ensuring low latency for Tactile Internet, and finally, Section 6 concludes the paper.

Nomenclature

uRLLC	ultra-Reliable Low-Latency Communications
eMBB	enhanced Mobile Broadband
mMTC	massive Machine Type Communications
CN	Core Network
RAN	Access Network
ITU	International Telecommunication Union
IoT	Internet of Things

2. 5G services and minimal technical performance requirements

2.1. 5G services

For 5G technology, International Telecommunication Union (ITU) defines in its IMT-2020 standard, three main types of service. These types of service are the following [2]-[3]:

- mMTC as massive Machine Type Communications is designed to help achieve the ultra-connectivity requirement (i.e., extensive area coverage for up to several thousands of devices per square kilometer of coverage.
- eMBB as enhanced Mobile Broadband primarily relates to the provision of ultra-high data rate and ultra-connectivity.
- uRLLC as ultra-Reliable Low-Latency Communication is essential to achieve the ultra-reliability requirement.

2.2. Technical performance requirements for uRLLC in 5G

ITU described in its recommendation critical conditions related to the minimum professional performance in terms of latency, reliability, and mobility and mobility interruption time as the following [4] – [5]:

- **Latency:** By definition, the latency refers to the transmission delay between a device to another device with an error-free reception. ITU distinguishes user part latency and controls part latencies. The user part latency is the contribution of the radio network to the time from when the source sends a packet to when the destination receives it (in ms). It is the additional time taken in delivering a packet (application layer message) as it traverses from a protocol layer 2/3 service data unit (SDU) ingress point to the protocol layer 2/3 egress point of the radio interface in either DL or UL. As defined by ITU, the minimum requirement for user plane latency is 1 ms for uRLLC, assuming unloaded conditions (i.e., single-user) for small IP packets (e.g., 0-byte payload + IP header), both downlink and uplink. In contrast, control plane latency refers to the transition time from a most “battery efficient” (e.g., in Idle state) to the start of continuous data transfer (e.g., Active state). The minimum requirement for control plane latency is 20 ms and is encouraged to be less than 10 ms.
- **Reliability**: Reliability relates to the capability of transmitting a given amount of traffic within a predetermined time duration with high success probability. The minimum required for the reliability is a good success probability of transmitting a layer 2 PDU (protocol data unit) of 32 bytes within 1 ms in channel quality of coverage edge for the Urban Macro-uRLLC test environment. Assuming small application data (e.g., 20 bytes application data + protocol overhead). The reliability performance indicator fails if :
  – Too many packets are lost
  – Too many packets arrive too late
  – The packets have errors
- **Mobility:** The mobility is defined as the maximum mobile station speed a defined QoS can achieve (in km/h). the following classes of mobility are defined: stationary (0 km/h), pedestrian (0 km/h to 10 km/h), vehicular (10 km/h to 120 km/h) and high speed vehicular (120 km/h to 500 km/h). Note that high speed vehicular up to 500 km/h is mainly envisioned for high-speed trains.
- **Mobility interruption time (MIT):** It’s defined par ITU as the shortest time duration supported by the system during which a user terminal cannot exchange user plane packets with any base station during transitions. The MIT includes the time required to execute any radio access network procedure, radio resource control, signaling protocol, or other message exchanges between the mobile station and the radio access network, as applicable to the candidate radio interface technologies.

Note that 5G architecture has redundant hardware, software, and network links with automated failover technologies consisting of switching to redundant systems in the event of failure of the central system. This guarantees that no system or network outage will interrupt network services. The low-packet error rate is helpful, but networks must be available 24 by 7, every day without fail. Customers require guaranteed service not only for latency and reliability but also for connectivity.

3. Tactile Internet

Today, wireless communications allow us to connect everything we can imagine (devices, sensors, collectors, cameras, people, etc.) to exchange multimedia content and all kinds of data. Data rates for wireless communications continue to grow exponentially, mainly due to innovation in electronics. In addition to very large capacity, massive connection density, and ultra-high reliability, 5G networks will have to support ultra-low latency. The latency of end-to-end communication systems is getting lower and lower, and reliability becoming more and more substantial, have started to change the way humans communicate in the world [6] – [9].

The Touch Internet will make people's lives even more comfortable in all areas, including healthcare, education, gaming, and industry. The tactile Internet will undoubtedly become an engine of economic growth and innovation and contribute to human development. There is also a new technology emerging that brings the cloud closer to the IoT device and reduces latency called Mobile Edge Computing (MEC) [10]. The Tactile Internet promises a significant paradigm shift in the way skills and labor are delivered digitally around the world; it converts existing content delivery networks into skills networks [11]-[14]. Tactile Internet is a concept that allows two human beings to interact with each other by touch or actuation [15]-[18].

In 2004, ITU has published a report where it defined the tactile Internet. ITU explains by an example of a chain between sensors and actuators how we can obtain 1-millisecond end-to-end latency of the Tactile Internet, and thus a system response of 1 millisecond. This chain is shown in Figure 1 below.

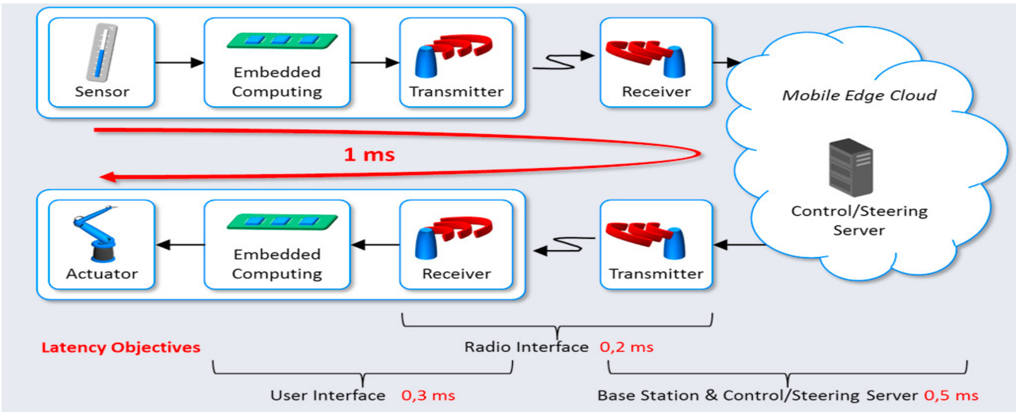

Fig. 1. Exemplary latency budget of a system of the Tactile Internet [9].

Note that latency and reliability alone are not sufficient to characterize industrial applications fully. Indeed it must also be essential to discuss the scalability requirements. For instance, for monitoring applications, many sensors in the range of 100–1000 may need to be connected.

4. 5G Mobile Network for Tactile Internet

The stochastic nature of the wireless channel is one of the main constraints in achieving stringent uRLLC service requirements. Ensuring high reliability requires overcoming variations in the received signal strength caused by the channel. Diversity is a well-proven technique in this regard.

4.1. Maximum Achievable Rate for Tactile Internet

For 5G uRLLC services, the strict requirement of ultra-reliability, and a very short latency for the Tactile Internet needs, Shannon's formula giving capacity must be modified to take account of these requirements. This capacity is given by [7]:

$$C(P_e) = W\left[\log_2(1+SINR) - \sqrt{\frac{V}{D_{tx}W}}\, Q^{-1}(P_e)\right] \quad (bit/s) \tag{1}$$

Where

$SINR = \frac{\alpha\, P_t\, g}{I + N_0 W}$ is the signal to noise and interference ratio, W is the bandwidth, P_t is the transmit power, α is the average channel gain that captures path loss and shadowing, g is the normalized instantaneous channel gain, N_0 is the single-side noise spectral density, I is the total interference, Q^{-1} is the inverse of Gaussian Q-function and V is the channel dispersion.

4.2. Maximum Reliability for Tactile Internet

According to ITU definition in Section 2, reliability, noted R, can be expressed as:

$$R = \left(1 - \sum_{k=1}^{n_{HO}} t_k\right)(1-P_e)\, P_{wd} \tag{2}$$

Where

n_{HO} is the number of Handover events, t_k is the MIT for the kth HO event, P_e is the error probability of transmitting a packet, P_{Wd} is the probability of receiving a packet within a certain delay.

After Handover failure, the retrieval of the connection of the user equipment is done via access stratum or non-access stratum protocols as shown in figure 2.

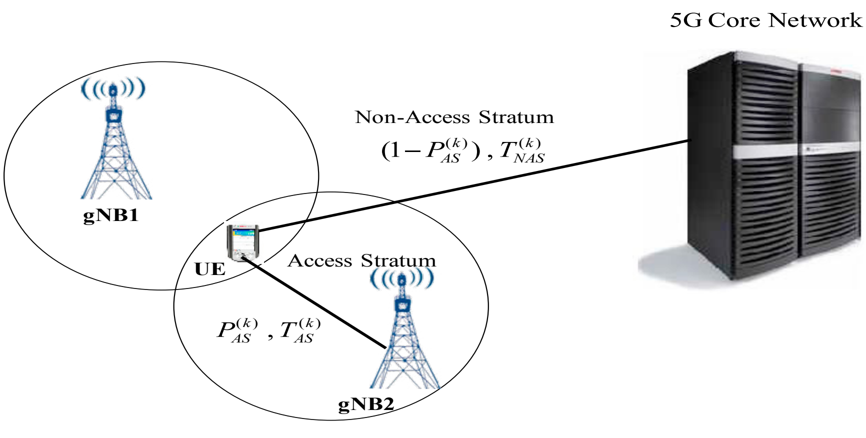

Fig. 2. AS and NAS retrieval after kth Handover failure.

We can obtain the MIT for the k*th* handover event as the following:

$$t_k = \left(1 - P_{HOF}^{(k)}\right) T_{SHO}^{(k)} + P_{HOF}^{(k)}\ T_{CR}^{(k)} \tag{3}$$

Where

$P^{(k)}_{HOF}$ is the probability of handover failure, $T^{(k)}_{SHO}$ is the MIT in a successful handover, and $T^{(k)}_{CR}$ is the time for the retrieval of the connection after a handover failure. In the Equation (3) $T^{(k)}_{CR}$ is calculated as follows:

$$T_{CR}^{(k)} = P_{AS}^{(k)}\ T_{AS}^{(k)} + (1 - P_{AS}^{(k)})\ T_{NAS}^{(k)} \tag{4}$$

Where

$T^{(k)}_{AS}$ is the MIT in an access stratum (AS) retrieval after kth handover failure, $P^{(k)}_{AS}$ is the success probability of access stratum retrieval after kth handover failure and $T^{(k)}_{NAS}$ is the MIT in a NAS retrieval after kth handover failure. Depending on the packet size, channel quality and scheduling strategy, the transmission duration D_{tx} can quite vary from one to multiple transmission time intervals (TTI).

For 4G systems, control signaling takes a large part of the transmission latency, which is generally between 0.3 ms and 0.4 ms. Thus, the design of a packet transmission system of short lengths and with a latency of 0.5 ms can result in a waste of more than 60% of the resources for the control overload.We suppose that the packet transmitted contains X bits, and the transmission delay is D_{tx}. Hence, by using the Equation (1) we have:

$$X = D_{tx}\ C(P_e) \quad (bits) \tag{5}$$

Hence,

$$\frac{X}{D_{tx}} = C(P_e) = W\left[\log_2(1+SINR) - \sqrt{\frac{V}{D_{tx}W}}\ Q^{-1}(P_e)\right] \quad (bit/s) \tag{6}$$

Then the error probability of transmitting a packet of X bits is calculated as:

$$P_e = Q\left[\sqrt{\frac{D_{tx}W}{V}}\left(\log_2(1+SINR) - \frac{X}{D_{tx}W}\right)\right] \tag{7}$$

We denote by $\rho = SINR$ and we suppose that we use Frequency Division Duplex mode (FDD), in this technique the transmitter and receiver operate at different carrier frequencies, so there is no interference between uRLLC users and we can suppose that I=0 in this case. Hence,

$$\rho = \frac{\alpha\ P_t\ g}{N_0 W} \tag{8}$$

We denote also,

$$W = \frac{\xi}{\rho} \quad \text{, where} \quad \xi = \frac{\alpha\ P_t\ g}{N_0} \tag{9}$$

The channel dispersion, V, is defined as:

$$V = 1 - \frac{1}{(1+\rho)^2} = \frac{\rho(\rho+2)}{(\rho+1)^2} \tag{10}$$

We note here that the transmission error probability (P_e) depends closely on ρ , X and D_{tx}. In this paper we will be interested in studying the variation of this transmission error probability as a function of the variation of the data packet length (X). This probability is given by:

$$P_e = Q\left[\frac{\rho+1}{\rho\sqrt{\rho+2}}\sqrt{D_{tx}\,\xi}\left(\log_2(1+\rho) - \frac{\rho}{D_{tx}\,\xi}X\right)\right] = Q\,(a - bX) \tag{11}$$

Where,

$$a = \frac{\rho+1}{\rho\sqrt{\rho+2}}\log_2(1+\rho)\sqrt{D_{tx}\,\xi} \quad and \quad b = \frac{\rho+1}{\sqrt{(\rho+2)\,D_{tx}\,\xi}} \tag{12}$$

And the derivative of Q with respect to X is given as following:

$$\frac{\partial P_e}{\partial X} = \frac{\rho+1}{\sqrt{2\pi(\rho+2)D_{tx}\xi}}\, e^{-\frac{1}{2}(a-bX)^2} > 0 \tag{13}$$

This derivative is positive, it is therefore deduced that the transmission error probability (*Pe*) is an increasing function in *X*. Consequently, for the transmission of data packets of very small sizes, this probability is also very low; and for larger packets, this probability also becomes greater. Consequently, in the case of the tactile Internet, which requires very high reliability and a very short latency time, and which therefore uses uRLLC services, very small packets respond perfectly to the reliability of the transmission required.

On the other hand, if we are interested in the variation of the transmission error probability (*Pe)* as a function of the transmission time D_{tx} of the short packet of length X bits, we have:

$$P_e = Q\left(A\sqrt{t} - \frac{B}{\sqrt{t}}\right) \tag{14}$$

Where

$$A = \frac{\rho+1}{\rho\sqrt{\rho+2}}\sqrt{\xi}\,\log_2(1+\rho) \quad , \quad B = \frac{\rho+1}{\sqrt{(\rho+2)\xi}}X \text{ and } \quad t = D_{tx} \tag{15}$$

According to approximation of error function [21] we have:

$$\frac{\partial P_e}{\partial t} = -\frac{1}{2\pi}\left(A^2 - \frac{B^2}{t^2}\right)\exp\left(-\frac{2}{\pi}\left(A\sqrt{t} - \frac{B}{\sqrt{t}}\right)^2\right)\left(1 - \exp\left(-\frac{2}{\pi}\left(A\sqrt{t} - \frac{B}{\sqrt{t}}\right)^2\right)\right)^{\frac{-1}{2}} \tag{16}$$

Thus,

$$\frac{\partial P_e}{\partial t} = 0 \quad \Leftrightarrow \quad t = t_m = \frac{B}{A} = \frac{\rho X}{\xi \log_2(1+\rho)} = \frac{X}{W \log_2(1+\rho)} \tag{17}$$

We also see that the error probability of transmitting a short packet X reaches its maximum value for $D_{tx} = t_m$, and this probability is increasing for the values of the transmission duration D_{tx} less than t_m and decreasing for the values of D_{tx} greater than t_m.

5. Some Technologies used for Ensuring Low Latency Tactile Internet

Some suitable technologies and communication protocols are used to reduce latency through different methods from an end-to-end network perspective. However, the low latency of the Tactile Internet presents many challenges. Those solutions are introduced in different 5G network segments, namely access network, core network, and customer premises equipment. In this section, we cite some solutions introduced in the different layers of the end-to-end network architecture to guarantee low latency. The Tactile Internet will add a new dimension to human-machine interaction by delivering a low latency enough to build real-time interactive systems. Besides, the Tactile Internet is described as a communication infrastructure combining low latency, very short transmission delay, very high availability, and ultra-reliability with a high level of security and quality of service [19].

5.1. Network Slicing

The 5G technology provides the ability for the mobile network operators to deploy a network slicing concept. As its name indicates, network slicing is a concept already done for 4G network that allows a virtual "cutting" of a telecommunications network into several slices. This makes it possible to provide different performances associated with each slice and, therefore, allocate dedicated resources by type of use or object, for example, in terms of reliability, bandwidth, latency, etc. Each network slice thus corresponds to use without infringing on the others. The network slice is a logical network that is deployed to serve a defined business purpose or customer. It contains all the necessary network resources that are configured as a set to serve that specific purpose and a particular quality of service.

The network slice can be considered as quite an enabler for the services. Indeed, the network slice can be created, modified, and deleted by means the network management functions. Thus, the network slice is a logical network that can be deployed technically in any fixed and mobile networks [20].

5.2. Network Function Virtualization (NFV)

The objective of NFV (Network Functions Virtualization) is to dissociate network functions from those of network equipment. This decoupling allows us to position the software executing the services of a device on a machine different from the device itself. NFV reduces capital expenditure and operating expenditure, increases management capacity, and optimizes network equipment and servers [21].

5.3. Software-Defined Networking (SDN)

Software-Defined Networking (SDN) is a network architecture designed to allow users to adapt to various applications' dynamic nature. This architecture separates network management from the underlying network infrastructure, allowing traffic to be dynamically adjusted across the network to meet changing needs. SDN's major goal is to reduce the complexity of statically defined networks further, automate network functions, accelerate deployment of applications and services, and simplify provisioning and managing network resources [22]- [23].

5.4. Multi-Access Edge Computing (MEC)

To meet the requirement for ultra-low latency, ultra-reliability, and high bandwidth, network functions, and content need to be even closer to the subscriber. Multi-Access Edge Computing (MEC) accelerates content, services, and applications, increasing responsiveness from the edge. The quality of experience of the mobile user can also be enriched by the network efficiency and service operations, based on an overview of radio and network conditions [24].

These applications are implemented as software entities only executed at the high level of the virtualization infrastructure. MEC offers application developers and content providers, cloud-computing capabilities, and information technology service environment at the edge of the network. There is a dedicated working group studying Multi-Access Edge computing within the European Telecommunications Standards Institute (ETSI). Still, MEC is often referred to as a general term for edge computing [25]-[28].

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