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A parametric quality model to evaluate the performance of Tele-operated Driving services over 5G networks

Pablo Pérez · Jaime Ruiz · Ignacio Benito · Raúl López

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Abstract We have developed a parametric model to quantify the Key Quality Indicators which affect video-based Tele-operated Driving (ToD) over a mobile network, as well as their relationship with the network Key Performance Indicators. This model can be easily used to specify Quality of Service policies (e.g. through network slicing) that guarantee the required conditions for remote driving on specific areas. We have used our model to validate the feasibility of deploying remote-assisted driving in different real networks, both from current 4G deployments and from pre-commercial and commercial 5G pilots. Our results show that some ToD services (supervision and, up to some point, parking) may be feasible with high-end existing 5G networks. However, full remote driving requires some improvements in the system, particularly to reduce end-to-end latency, increase uplink performance, and minimize service losses. Both the model and its results will be used in the framework of European Union H2020 project 5G-MOBIX to deploy a ToD proof-of-concept in the cross-border corridor between Spain and Portugal.

Keywords Tele-operated Driving · 5G · QoE planning model

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P. Pérez · J. Ruiz · I. Benito
Nokia Bell Labs
E-mail: pablo.perez—jaime_jesus.ruiz_alonso—ignacio.benito_frontelo@nokia-bell-labs.com

R. López
Nokia
E-mail: raul.lopez_lopez.ext@nokia.com

1 Introduction

The availability of 5G networks is becoming a reality, and it is brings the opportunity to support the deployment of new Cooperative Connected and Automated Mobility (CCAM) services. The scenario of combining CCAM and 5G has been under research in several funded and non funded projects recently [22,15,23], and specific test beds have been developed to validate such resarch efforts [9,27]. A particularly relevant scenario for CCAM services, especially in Europe, is that one where a car crosses the border between two different countries [39].

Formulating a comprehensive set of 5G technological requirements for advanced CCAM relevant for the automotive, telecommunication, IT and services industries, as well as public authorities, is a clear need in this topic. The European H2020 project 5G-MOBIX [1] will conceptualize the 5G reference framework tackling the overall lifecycle, from design to deployment of CCAM and 5G network services.

One of the use cases under consideration in 5G-MOBIX is Tele-operated Driving (ToD). ToD can be seen as a side effect of tackling with potential issues that autonomous driving cannot solve by itself, and therefore human intervention is required [20]. Such intervention can be feasible by making use of appropriate 5G infrastructure, a dedicated protocol, video data channels, and cockpit setup under the supervision of a control center. The 5G Automotive Association (5GAA) has estimated that ToD services would require dedicated bandwidth in the 5G network, going from 30 MHz in urban locations up to 100 MHz in rural areas [5]. However, even with dedicated networks and proper dimensioning, it could be challenging to actually achieve the required network QoS to provide these services safely [38]. Moreover, specific research and investigation is required when this ToD use case involves remotely driving a car which is crossing a border involving two 5G operators from different countries (roaming scenario) [2].

As a first step in this direction, in this paper we investigate the role of the evolving network and cloud architecture in Tele-operated Driving. We define a model which relates network performance (throughput, latency, loss rate) with perceived video quality in the context of driving (i.e. sufficient quality for driving at a specific speed). The model is fully parametrizable, so that it can be easily adapted to specific use cases (e.g. changes of video technology, camera placement, safety regulation, etc.). Then we use our model to analyze the performance of different network scenarios, using existing databases as well as our own field measurements, both in commercial LTE networks and in pre-commercial 5G pilots. This model will be used in the next steps of 5G-MOBIX project to plan and supervise the deployment of 5G infrastructure to support a ToD trial in the cross-border corridor between Spain and Portugal. In this paper we also extract conclusions from the analysis of the network scenarios, to suggest the main changes that need to be done in the network and ToD system infrastructure to be able to support the desired services.

The paper is structured as follows. In section 2 we summarize the state of the art in three different areas: Tele-operated Driving, QoE parametric models, and open 4G/5G trace datasets. In section 3 we describe the ToD use cases that we are considering in the article (*driving, parking, supervision*) as well as the reference architecture and requirements for them. In section 4 we propose the QoE parametric model and its parameters. In section 5 we use the model to analyze the performance of different networks. In section 6 we discuss the implication of our results, and how they translate into requirements or for future automotive communication networks. Finally, in section 7 we present our conclusions.

2 Related Work

2.1 Tele-operated Driving

From the perspective of the communication and automotive industry, 5GAA is leading the definition and characterization of Tele-operated Driving scenarios, where a remote ToD operator (either human or automatic) is able to exercise some level of control of the vehicle [4]. Depending on the level of engagement of the ToD operator, several ToD types are defined: from 0, where there is no remote operator at all, to 3, where the remote operator fully controls the vehicle. As of today, there are services which already use some level of ToD to supervise the operation of remote autonomous vehicles (e.g. Waymo, Zoox, Aptive) or even to complete manually override the vehicle driving (e.g. Roboauto or Designated Driver) [6].

The networking implications of ToD have also been studied by the research community. Gnatzig et al. performed end-to-end testing of a ToD prototype over HSDPA+ [14], managing to drive a vehicle at low speed with a multi-camera system, relatively low visual quality (640x480 pixels in the frontal camera, up to 2 Mpbs of bitrate), and around 600 ms of total delay. Liu et al. tested several subjects in a simulator with simulated LTE conditions (from network measurements) [25]. They found that a variable delay in image rendering has a stronger impact in QoE than a constant higher value. Neumeier et al. collected network traces, mostly from LTE, over 78 hours and 5200 km of driving over different areas of Germany, finding that, over 87% of the time, LTE networks can provide of what they consider enough quality for ToD: 3 Mbps of uplink and a RTT lower than 250 ms [31]. A relevant finding of this work is that network KPIs (e.g. throughput) are independent of the driving speed. Gaber et al. proposed multi-operator switching to improve LTE coverage. Under this scenario, they achieved consistent throughput values ($> 99\%$ of the time) higher than 3 Mpbs and latency measures ($> 91\%$) below 100 ms.

However, even though some of the aforementioned authors have performed limited remote driving trials or simulation, their measures are still far away from what could be considered enough quality for safe driving. For instance, uplink rates in the range of 3-4 Mbps are far from 5GAA requirements (32

Mpbs [4]), and latency measures, even within a reasonable range, are not including video coding or transport delay, which may account for several hundred additional milliseconds [7].

To mitigate the limitations of existing networks are systems, several actions can be taken, such as predicting the trajectory of other vehicles or pedestrians [16], projecting the predicted position of the vehicle in the future [11], or supporting the remote driver by controlling the maximum speed and smoothness of steering based on the network status [30].

2.2 QoE models

The works mentioned above normally take measurements on network KPIs (throughput, RTT) and establish hard service thresholds for the expected values of such KPIs. However, in the context of multimedia services, *QoS-QoE relationship models* [21] have been developed to map such KPIs into higher-level Key Quality Indicators (KQI), better related with the user QoE [37]. For the context of this article, we are mostly interested in *planning models* (also called *opinion models*) which can provide generic QoE assessment of a network, rather than instant monitoring values.

Planning models have been widely used for telephony, videoconference and IPTV [33], respectively leading into ITU-T recommendations G.107, G.1070 and G.1071. More recently, ITU-T has standardized G.1072 to model online gaming applications [26]. Even though none of these recommendations actually addresses ToD, they cover the main quality elements which appear in a ToD context: real-time video (G.1070/G.1071), voice (G.107), and remote control (G.1072), and therefore it is possible to build a plausible ToD planning model from them. A similar approach has been recently used by Krogfoss et al. to create a QoE model for VR/AR applications [24].

2.3 Datasets for mobile network KPIs in mobility

There are several publicly available databases of KPI traces, captured in different network scenarios. Bokani *et al.* provide geo-located throughput traces of 3G and 4G networks under vehicular driving conditions [8]. Raca *et al.* provide a richer dataset which includes throughput and ping RTT, together with geo-localization and network information (RSRQ, RSRP, RSSI, etc.), for 4G [35] and 5G [34] networks, in different capture conditions: stationary, walking, road (car/bus), and train. Narayanan *et al.* also provide throughput and latency measures in several 5G networks, including lower and millimetric bands [29].

All those databases are mostly focused on downlink-oriented use cases (e.g. file download) and performance measurements are done by exchanging data between the cellular User Equipment (UE) and a remote server (often in the cloud) over the standard internet. An additional property of the databases is

Table 1 Use case requirements based on 5GAA specification [6]

Use Case	Max. Latency (ms)	Max. Speed (km/h)	Vehicle Density (km^{-2})
Driving	120	50	10
Parking	200	10	100
Supervision	400	50	10

that, consistently with [31], all of them show similar performance in stationary, walking or driving conditions.

3 Scenario

3.1 Use cases

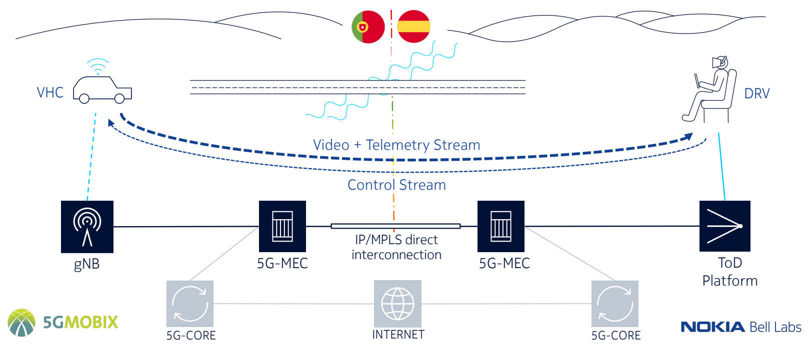
We are considering the following use cases, as defined by 5GAA [6]: Tele-Operated Driving (*Driving*), Tele Operated Driving for Automated Parking (*Parking*), and Tele-Operated Driving Support (*Supervision*)

Driving. The goal of this use case is to enable a ToD operator (human or machine) to remotely drive a vehicle. The vehicle provides the environmental information and data to enable remote driving functionality, and it receives and applies the driving instructions sent by the ToD operator. For instance, a temporary health issue (e.g. illness, headache) of a driver impairs their concentration, reactions and judgment and consequently affects their ability to drive safely. The driver of the vehicle (with some automated capabilities) asks a ToD operator to undertake the control of the vehicle and remotely drive it in an efficient and safe manner from the current location to the destination.

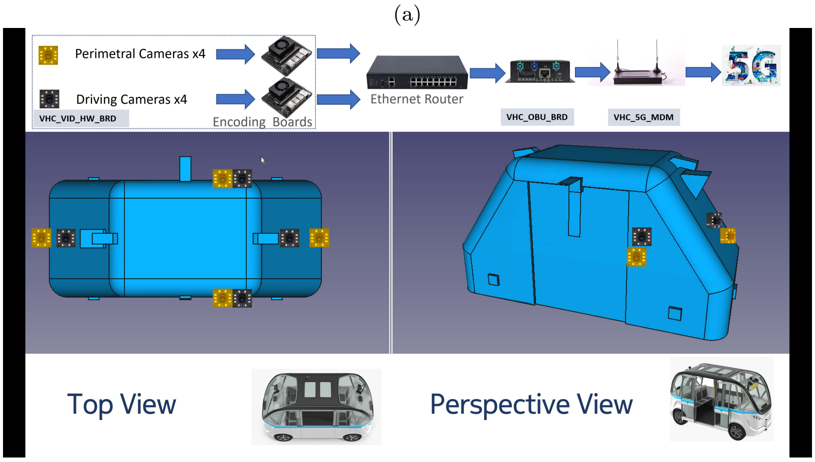
Parking. The goal of this use case is to execute automated parking of vehicles using ToD services. A remote entity, either human or machine, undertakes to park the vehicle, supported by real-time video and sensor information that is sent from the remotely driven vehicle. This use case can be extended to other maneuvering operations analogue to parking, such as controlling an automatic vehicle which has performed a safety stop operation and needs help to return to a safe path where it can resume its route.

Supervision. The goal of this use case, as defined by 5GAA, is to remotely support the tasks of a vehicle with automated capabilities (e.g. by providing a driving maneuver) for a short period of time, when the vehicle faces highly uncertain situations making decision-making difficult. In our case, we have focused on remotely support the tasks of a vehicle which is already controlled by a person, i.e. providing copilot services.

Table 1 provides some numeric requirements for these use cases. We have slightly modified the proposed values from 5GAA in order to have a wider range of available latencies and working vehicle speeds, and therefore have a better understanding of the capability of the network to support them.



(a)



(b)

Fig. 1 Reference ToD architecture from 5G-MOBIX project: (a) general end-to-end scenario, (b) vehicle elements and location of vehicular cameras.

3.2 Tele-operated Driving Architecture

The basic actors for the ToD architecture that need to be taken into consideration are the vehicle (VHC), the driver or ToD Operator (DRV), and the 5G Infrastructure (5GI).

A possible network architecture, defined by 5G-MOBIX, is shown in Figure 1(a) [3]. In this architecture, the vehicle is connected to the 5G RAN and the traffic received and routed by a Multi-access Edge Computing system (MEC). To support roaming and minimize latency, all MECs involved in the ToD service, which may potentially belong to different operators in different countries, must be directly interconnected. The ToD system is also connected to this specific network.

The vehicle includes three subsystems that are relevant for ToD architecture (Figure 1(b)) :

- The OBU/CAN Control Board (VHC_OBU_BRD).

- Video Cameras and Encoder Board (VHC_VID_HW-BRD).
- 5G Modem (VHC_5G_MDM).

In the technical solution that is being developed for 5G-MOBIX project, there will be two sets of 4 cameras (driving and perimeter), capable of capturing at a reference 1280x720 resolution and 60 frames per second. Driving cameras are used for *driving* and *supervision* use cases, while perimeter cameras are required for *parking*. Camera flows are injected into the hardware encoders for producing H.264/H.265 bitstreams which will be transmitted via RTP/UDP protocol to the network. A 5G modem, connected to the encoding boards using 1GB Ethernet connections, sends the video through the 5G-RAN uplink, together with any required telemetry data. This data stream is received by the driver application and presented in the driver screen or headset.

In the opposite direction, the driver generates real-time control commands (for speed and steering control) that must be sent downstream to the car VHC_OBU_BRD subsystem, to act to the physical throttle, break and steering systems.

5GAA estimates that each camera generates a constant flow of 8 Mbps, and the telemetry data may account for additional 4 Mbps, leading into a total of 32 or 36 Mbps of uplink data flow (depending on whether telemetry is needed or not). The downstream control flow is, on the other hand, much less demanding in terms of throughput: about 400 kbps [4].

Our preliminary tests suggest that these numbers may be overestimated for the use cases under consideration, and we will propose alternative values in section 4.2.

3.3 5G-MOBIX: Tests in the Spanish-Portuguese cross-border corridor

The first practical use for the model that we are presenting here is helping in the design of the network for the 5G-MOBIX project and, in particular, for the ToD trials to be performed in the Spanish-Portuguese cross-border corridor. In the targeted scenario (Use Case 2, Scenario 2 [2]) an autonomous vehicle is driving following a predefined route, and suddenly an obstacle appears in its path blocking the original route. In this situation, an operator is alarmed, and he/she is able to remotely take the control of the autonomous vehicle or issue a set of new navigation commands in order to handle a new route.

Depending on the context where this event happens, the scenario may be assimilated to a *driving* or a *parking* (maneuvering) situation. Additionally, a second operator may connect to the scene to monitor the situation, leading into a *supervision* use case.

The fact that the tests are being executed in the cross-border will add additional complexity to the scenario, such as keeping stream continuity when the car roams from one network to the other, as the car can only have direct connection to a MEC in the network of the operator to which it is connected. This hand-off event may result in some milliseconds of connectivity loss, which would lead into a loss burst in the RTP/UDP stream.

4 Quality Model

We propose a parametric QoE model based on independent Key Quality Indicators (KQIs), which describe different aspects of the remote driving experience. Following the common practices defined in all ITU-T planning models, for each KQI x we define its impairment level $I_x \in [0,1]$, where $I_x = 0$ means best quality (no impairment) and $I_x = 1$ means worst quality. Based on this, we propose:

$$R = I_V I_M I_D \tag{1}$$

where I_V, I_M, and I_D represent the *impairment levels* caused by video coding quality, *macroblocking* effect (due to packet loss), and end-to-end delay or responsiveness. As in ITU-T recommendations, global quality is described by a "rating factor" R in the same scale as the impairment levels. This rating factor can be used to estimate a subjective Mean Opinion Score (MOS) in the scale 1-5, by applying the equation $Q = \mathcal{F}(R)$ proposed by ITU-T:

$$Q = \mathcal{F}(R) = Q_{min} + (Q_{max} - Q_{min})\,(R + 2R(R-0.6)(1-R)) \tag{2}$$

where[1] $Q_{min} = 1$ and $Q_{max} = 4.5$.

It is also worth noting that our quality model is based on the multiplicative model (1), which provides better results, when handling unrelated heterogeneous impairments [18], than additive models traditionally used in ITU-T G.107x recommendations.

4.1 Individual quality components

For each individual quality component I_x, we will identify the main QoS KPIs which have influence on it and propose a QoS-to-QoE mapping function. Although standardized planning models tend to have complex mapping functions (see e.g. ITU-T G.1071), we will propose using a simple one, with as few parameters as possible, that captures the first-order QoS-to-QoE relationship. This is sufficient for our purposes, and it makes parametrization a much simpler task.

Video coding quality. It is well known that, for a given screen resolution, perceived video quality is mostly influcenced by the coding bit rate [10], and such relation is exponential in nature [17]. Therefore we will use:

$$I_V = 1 - e^{-v_0 \frac{B_v}{HWF}} \tag{3}$$

where B_v is the video coding bitrate, and $H \times W \times F$ is the product of height, width and frame rate, i.e., the number of pixels per second. Parameter

[1] These are the values proposed by ITU-T G.107. Other ITU-T recommendations provide slightly different ones.

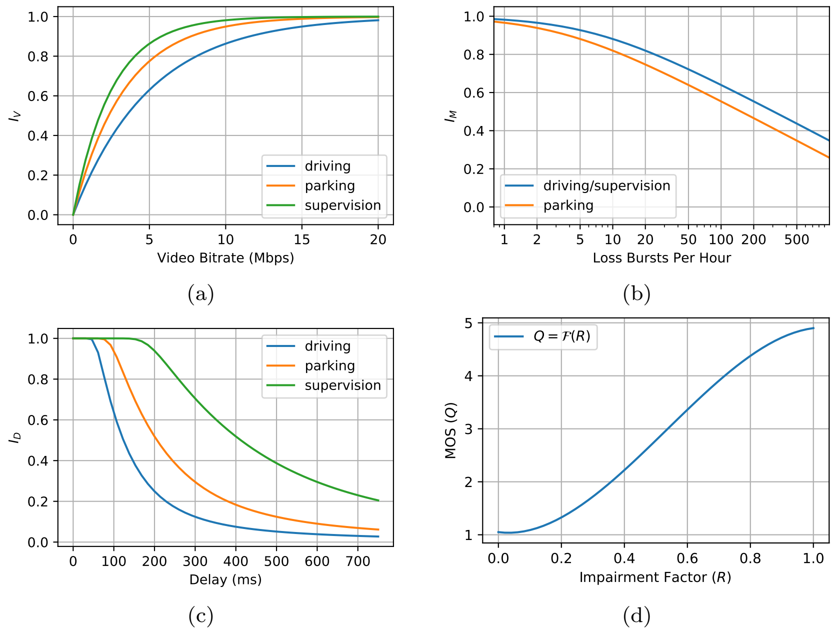


Fig. 2 (a-c) Impairment models for all the use cases and each of the quality components: (a) video coding quality, (b) macroblocking, (c) delay. (d) Mapping from R to MOS.

v_0 captures the dependency on the codec efficienct and the spatio-temporal content complexity [19].

Macroblocking. Packet losses cause that part of the information is lost and must be reconstructed with the data of previous frames, creating an effect of heavy "macroblocking" or "slicing" (big blocks in the image), until the next intra frame is received. It is well known that packet loss effect is directly related with packet loss rate [36]. In particular, in H.264 and later codecs, this effect is related to packet loss *burst* rate and the coding structure (intra frame refresh period) [32], which are the main components of the "Loss Magnitude" or "piXel Loss Rate" [12]:

$$I_M = 1 - m_0 \log\left(1 + m_b I_p L\right) \tag{4}$$

where m_0 and m_b are parameters of the model, I_p is the intra refresh period (in seconds) and L is the number of loss bursts per hour. The logarithmic relationship is derived from ITU-T G.1071.

Delay. Round-trip-time delay has been modeled for conversational and interactive applications, and it is typically characterized by a function with three steps: a first threshold where delay is not important, a fast and linear decay,

Table 2 Parameters of the different use cases

	Frontal	Side/Back	F	v_0	I_p	m_0	m_b
driving	1280x720	640x480	60	22	1	0.13	0.15
parking	1280x720	1280x720	30	33	2	0.13	0.15
supervision	1280x720	640x480	30	22	1	0.13	0.15
				T_m	N_{cod}	B_{vM}	T_{cod}
driving				30	2	15.1	33.3
parking		...		50	2	10.0	66.7
supervision				100	2	7.5	66.7

and a longer tail. The mathematical form of such function may be piecewise linear [40], logistic (ITU-T G.1072), log-logistic [24], or algebraic (ITU-T G.107). We have selected the latter:

$$I_D = \begin{cases} 1 - \frac{1}{2}\left\{(1+x^6)^{\frac{1}{6}} - 3\left(1+(x/3)^6\right)^{\frac{1}{6}} + 2\right\}, & \text{if } x \geq 0 \\ 1, & \text{otherwise} \end{cases} \tag{5}$$

$$x = \log_2\left(\frac{T}{T_m}\right) \tag{6}$$

Where T is the "interaction lag" (the application-level end-to-end delay), and T_m is a model parameter. A property of this function is that $I_D(T = 4T_m) = 0.5$. The value of T is computed from the ping round trip time (RTT) plus the (one-way) delay caused by coding and transmitting each video frame, which is:

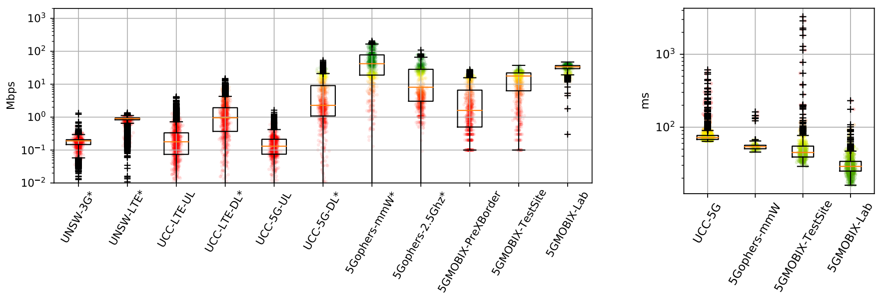
$$T = RTT + \left(N_{cod} + \frac{B_v}{B_T}\right)\frac{1}{F} \tag{7}$$

where N_{cod} is the coding delay (in frames), B_v is the video coding rate, B_T is the network transport throughput, and F is the frame rate.

4.2 Parametrization of the different use cases

We have used the use case requirements defined in section 3.1, mostly coming from 5GAA [4], to provide values for the parameters required in equations (3)-(7). They are shown in Table 2.

For the video resolution ($H \times W$), and based on informal preliminary tests, we consider that the *driving* and *parking* cases use a frontal high-definition camera (1280×720), while side and back cameras have lower resolution (640×480). Therefore we model $H \times W = 1280 \times 720 + 3 \times 640 \times 480$. Coding is done using H.264 with a short intra frame period ($I_p = 1$ second) to be more resilient to packet losses. We have used $v_0 = 22$ from ITU-T G.1071 (for H.264 high definition). Frame rate is higher in the *driving* mode ($F = 60$ fps vs. $F = 30$ fps for *supervision*).



(a) (b)

Fig. 3 (a) Distribution of throughput values of considered datasets. Datasets labeled with * contain downlink throughput, already scaled by 0.1 to transform it into *estimated uplink* throughput. (b) Distribution of RTT (ping) values of considered datasets.

The *parking* use case is performed with the perimetral cameras. We assume they are all high definition ($H \times W = 4 \times 1280 \times 720$) at $F = 30$ fps. A compression rate 50% higher is proposed, as images have less motion ($v_0 = 33$).

In all cases, we have computed a target video bitrate B_{vM} as the one where $I_V = 0.95$. We have also assumed that the video processing delay (capture, encoding, decoding, display...) is $N_{cod} = 2$ frames. This is probably in the edge of what can be achievable by specialized hardware. It leads to coding latencies of $T_{cod} = N_{cod}/F$.

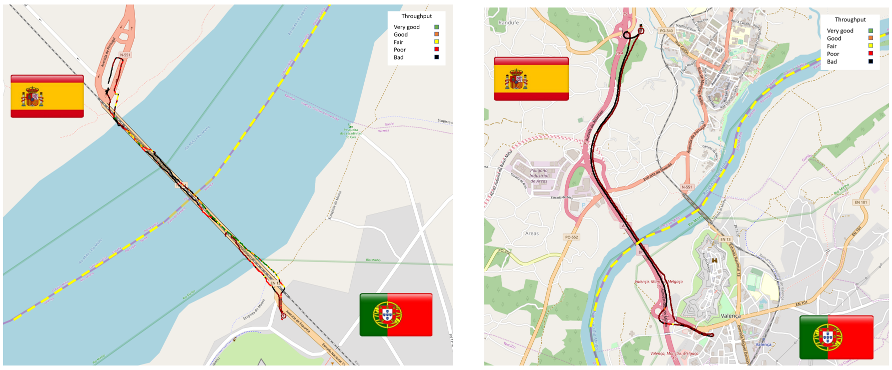
Parameters m_0 and m_1 for packet loss effect have been computed from [12]. Finally, the values for T_m that we have used are $T_m =$ "Max. Latency (ms)"/4 for the different recommended delay thresholds defined in Table 1. Figure 2 shows the resulting curves for each of the use cases.

5 Network performance evaluation

5.1 Datasets

To assess the feasibility of providing ToD services over the existing or the future network using our methodology, we would require to have a good distribution of measures for the KPIs that we are using as inputs: available uplink throughput (to ensure that enough B_v can be used), loss burst rate and network round-trip-time, all measured simultaneously. Unfortunately, in most cases, the only available measures are throughput (mostly downlink) and, in some cases, round trip time (typically computed using ICMP ping).

In all reported measures in the state of the art, the achieved throughput for uplink is always several orders of magnitude lower than the one achieved for downlink (see e.g. [35, 34, 28]). In some cases, it might be just because the test was not oriented to stress the uplink (e.g. download tests as [34]). Additionally, power limitations in the mobile phones used for testing may limit throughput as well. It is plausible that, with more powerful UEs, uplink performance



(a) (b)

Fig. 4 Paths for cross-border preliminary measures

will be closer to downlink performance. To model that uplink performance will be lower than downlik performance (but not much), as well as to be able to use existing datasets in our analysis, we have transformed downlink measures into *estimated uplink* ones by multiplying by 0.1 the throughput values. Additionally, we have taken our own measurements in three different locations: cross-border trial site, test site, and laboratory.

Measures at the cross-border (5GMOBIX-PreXBorder) were taken at the beginning of the project, to establish the baseline for the future developments. They were taken at the cross border corridor between Spanish city Tui and Portuguese city Valença, in two different trajectories: the old bridge (an urban location at low speed) and the new bridge (a motorway) upon river Miño, which is the natural border between Spain and Portugal at this location (see Figure 4). They were done using commercial NSA 5G in the 3.5 GHz band, with 40 MHz of bandwidth and 4/1 DL/UL TDD, and they include measures at both sides of the border (including hand-offs between operators).

Additionally, two extra measures were done in easier conditions: walking and driving in the neighborhood of a pre-commercial 5G base station (5GMOBIX-TestSite), and in a laboratory environment in a position where excellent coverage was guaranteed (5GMOBIX-Lab), to assess the performance of 5G infrastructure under "sunny day" conditions. It is worth noting that, even though the measurement conditions in those cases were controlled, the 5G infrastructure used the same configuration as in commercial deployments, which is also NSA 5G in the 3.5 GHz band, with 40 MHz of bandwidth and 4/1 DL/UL TDD.

All our tests measured uplink throughput (i.e. there is no *estimated throughput* here) using an instrumental cellular phone with professional measurement software. TestSite and Lab tests also include RTT measurements using ICMP ping (not simultaneous to the throughput measures).

Figure 3(a) shows the distribution of throughput for the considered datasets. We have evaluated UNSW dataset from 3G and LTE [8], which is the first comprehensive reference for vehicular measurements, UCC datasets for LTE [35] and 5G [34], as well as 5Gophers dataset [29], split between millimeter waves (mmW) and low band (2.5 Mhz) measurements. Most datasets only include downlink (DL) measures, that we have transformed into *estimated uplink*. UCC datasets also include uplink (UL) measurements. From the existing public datasets, it can be seen that only 5G measures of *estimated uplink* can achieve throuhgputs which allow ToD services (i.e. in the range of several Mpbs). Our 5G-MOBIX uplink measures are also usable.

Figure 3(b) shows the available RTT measures. All of them show latencies below 100 ms for the larger part of the distribution, which makes them valid, at least, for evaluation. It is also worth noting that there is a relevant number of outliers whose latencies expand from hundreds of milliseconds up to a few seconds.

5.2 KQIs estimations

As mentioned in the previous section, existing datasets are not enough, on their own, to feed our QoS-to-QoE models; they will need a previous processing. First of all, we will consider that throughput, RTT and loss rate are independent. With this assumption, for each dataset under consideration we will generate a sample of 10000 tuples to feed into equations (3)-(7):

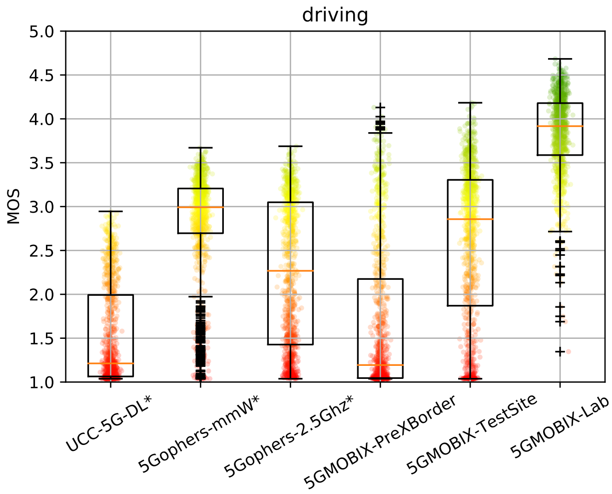
$$(B_T, B_v, L, RTT) \tag{8}$$

The values of B_T and RTT will be randomly sampled from the distributions of throughput and delay described in Figure 3. We will only consider UCC-5G-DL, 5Gophers and 5G-MOBIX datasets for our evaluation. 5Gophers-2.5GHz datasets will be assigned 5Gophers-mmW RTT distribution, and 5GMOBIX-PreXBorder will be assigned 5GMOBIX-TestSite RTT distribution, as neither of them included RTT measurements originally.

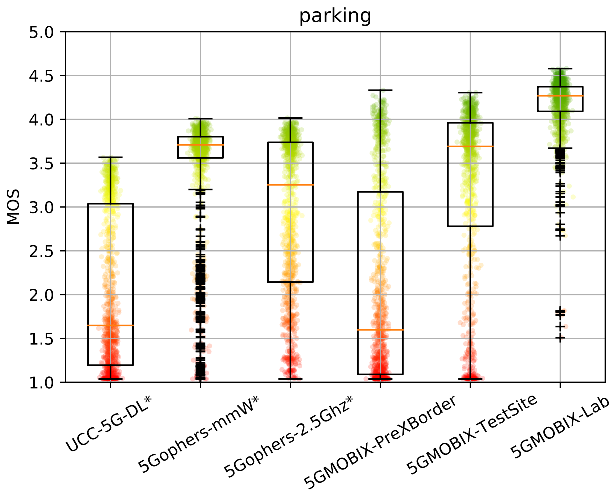
The value of B_v will be set to

$$B_v = \min(B_T, B_{vM}) \tag{9}$$

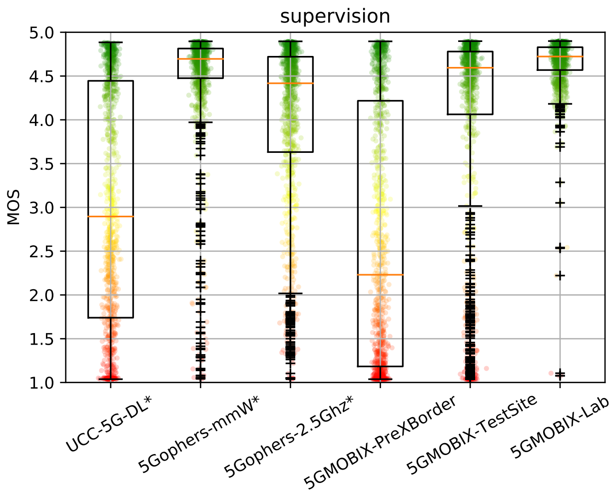
The frequency of packet loss bursts is difficult to estimate from the traces, as is it is a rare event (due to packet protection mechanisms in 5G RAN) and most datasets provide relatively short traces. We will therefore estimate an average rate $\bar{L} = 1$ loss per hour for stationary use cases (*parking*) and $\bar{L} = 10$ for dynamic use cases (*driving* and *supervision*). This is in the same order of magnitude of the predicted number of cell hand-offs according to 5GAA: for dynamic use cases, it is assumed a speed around 50 km/h and inter-node distances, in open areas, around 5 km. To generate the values for L, we will random sample an exponential distribution of decay rate $\lambda = 1/\bar{L}$ for each of the use cases.



(a)



(b)



(c)

Fig. 5 Distribution of QoE values for the considered datasets and the three use cases: (a) driving, (b) parking, (c) supervision.

Table 3 RTT values for several datasets

dataset	radio	min	max	mean	median
Gnatzig [14]	HSDPA+	65	1299	120.8	N/A
Liu [25]	LTE	56	358	97.7	N/A
Neumeier [31]	LTE	N/A	1000	N/A	54
Gaber [13]	LTE	50	850	N/A	90
UCC-5G [34]	5G	64	611	77	72
5Gophers [29]	5G-mmW	45.6	162	58	54
5GMOBIX-TestSite	5G	29	3200	55	47
5GMOBIX-Lab	5G	16	231	31.9	29

5.3 QoE results

Figure 5 shows the results of this process for the datasets and use cases under consideration. It can be seen that our model can smoothly combine the information of the datasets in a single view which allows a relatively simple interpretation of the data.

From a first view, it is clear that, with existing 5G networks and consumer UEs, deploying ToD services is challenging, especially for the most demanding services (*driving* and, to a lesser extent, *parking*). Regarding our particular scenario for 5G-MOBIX, it is also clear that the preliminary measures do not provide enough QoS to achieve any ToD use case; however, our test site and lab data show that, with the appropriate corrective actions (including improving coverage, UE characteristics, and RTT to a nearby MEC), it should be feasible to achieve even *driving* conditions with the existing 5G infrastructure.

It is somehow surprising that mmW datasets, which provide a sustained downlink throughput of several hundreds of Mbps (which translates into tens of Mbps of *estimated uplink*) are not good enough to support ToD. The reason beyond that is the strict latency requirements. It is worth noting that encoding and transmission is always taking 2 to 3 frames, which is 33 to 50 ms for *driving*. This needs to be added to RTT whose global minimum is 45 ms (see Table 3), which gives us already 80-100 ms of bare minimum. There is therefore very little margin to achieve the 120 ms of end-to-end delay defined by 5GAA for this use case.

The problem with latency is relevant and common for all public datasets. Table 3 shows RTT distribution values for several datasets and articles in the state of the art. It can be seen that achieving ping RTT values below 50 ms is extremely infrequent; however, it is critical to provide high-quality ToD services. Our measurements in TestSite and Lab, however, show that it should be feasible with the proper UE and network configuration.

An additional problem is the presence of outliers with low throughput or high delay (see Figure 3), which result in some very low MOS values even for the best-performing scenarios (e.g. *supervision* for 5Gophers-mmW or 5GMOBIX-Lab datasets). This problem of outliers has also been reported by other authors [31,13], and it definitely needs to be addressed in the future deployment of ToD services.

6 Discussion

6.1 Application of the parametric quality model

In this paper we have developed a parametric quality model for Tele-operated Driving. This model can be applied in three different levels: capacity planning, deployment assessment, and performance monitoring. The most relevant difference between them is how to obtain the model input parameters defined in equation (8).

- *Network capacity planning* is used to dimension the network deployment: cells, frequencies, etc. Input parameters are obtained by simulation.
- *Network deployment assessment* is used to assess the capacity of the network once it is deployed, but before actually running the ToD service. Input parameters are obtained by KPI measurement in different network locations, applying the same methodology described in section 5.
- *Network performance monitoring* is used for real-time assessment of the network conditions while the service is being provided. Input parameters are measured in real time from the systems involved.

6.2 Requirements for automotive 5G networks

We have observed that existing 4G/5G networks are not able, in general, to reach a minimum quality to guarantee the Tele-operated Diving use case (see Figure 5). We have also observed that, in controlled environments like laboratories and test sites, the quality improves. Therefore several relevant improvements are needed to enhance the quality of ToD Use in first deployments:

- 5G Automotive antennas are not yet ready but coming. The presented measures were taken with smartphones that have very limited coverage in mobility scenarios. New measurements with these antennas will improve drastically the performance.
- 5G Networks were not optimized for uplink contribution from UEs in deployed networks, most of the optimizations were focused in downlink performance.
- Mobile operators' antennas for the measurements are not located in roadside infrastructures or optimized for road users or vehicles speeds.
- Frequencies used on these measurements were very limited in baseband bandwidth (except one in mmW) or shared with other users. New higher frequencies will make possible the improvement of performance.
- Private mobile networks and/or dedicated network slicing will be recommended for some ToD scenarios that could guarantee the performance.
- 5G standalone (SA) networks will improve the latency and improve handovers over the 5G non-standalone (NSA) networks.
- New generation of 5G chipsets will support new features and with more efficiency, including new MIMO schemes and more carrier aggregation capabilities.

Nokia is working in the H2020 5G-MOBIX research project in collaboration with other automotive, telecommunications and research companies to develop a ToD use case crossing the border of two countries using the infrastructure of two different operators. During the project all these relevant improvements are evaluated and tested in one road and one highway crossing the border of Portugal and Spain.

We can conclude that ToD is one of the most challenging use cases that the new 5G networks will support. Current networks must be improved in different manners to make it feasible to deploy on the field, taking into account the particular requirements for different environments like the maximum vehicles speed, the level of autonomy of the ToD vehicle, the location or type of the remote driver or the required reliability and safety of the remote operation control.

7 Conclusions

In this paper we have analyzed the feasibility of the deployment of Tele-operated Driving services on top of existing or future mobile communication networks, particularly in 5G. For this purpose, we have created a parametric planning model, to estimate the global Quality of Experience offered to the remote driver, based on measures of Quality of Service KPIs. The model is based on a simplification of standard opinion models for multimedia services (ITU-T G.107x), and it considers the first-order effect of video coding quality, packet losses, and end-to-end delay, to provide a combined estimate for the system QoE. The parameters of the model have been selected to match the requirements defined by the 5G Automotive Association for Tele-operated Driving.

We have applied the model to several datasets of mobile network performance traces publicly available to the research community, as well as to field and laboratory measures that we have performed on our own. We have found that, with the existing networks and consumer-oriented UEs, it is not possible to safely implement *driving* use cases, and *parking* would only be achievable with difficulties, while *supervision* services are feasible for best-performing 5G networks. We have also found that these figures can be improved by taking some correcting actions in the system, such as enhancing coverage or using better UEs and user-side antennas.

As short term future steps, the results of this work will be used to plan and monitor the deployment and configuration of 5G infrastructure in the border between Spain and Portugal. This infrastructure will support the implementation and validation of a ToD proof of concept, which will be performed in the framework of H2020 5G-MOBIX project. Additionally, the experience gained in the development of such services will be used to refine this parametric model.

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