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RESEARCH ARTICLE

5G Performance Measurements in Mobility for the Bus Transportation System in an Urban Environment

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ABSTRACT 5G is a new technology that can provide more services, due to the improvement in performance, than the current mobile technologies. Because of that, it is selected as a possible technology for automotive transportation systems. Nevertheless, nowadays the 5G technology is in the deployment phase, which could present bugs requiring improvements in the network. Therefore, a tool capable of measuring some of the most relevant features of the 5G, as some of the requirements for the transportation system, is presented. The measurements with the specified tool were carried out in a specific line from the bus company in the San Sebastián city center with the aim of finding out the services that could be improved. Afterward, the results from the different measurements are shown, compared, and discussed. Finally, some conclusions about the obtained results and the services to use the target technology are presented.

INDEX TERMS 5G, performance, road, testing, wireless communication technology.

I. INTRODUCTION

Wireless communication technologies have evolved in the last years, especially cellular technologies. One of the last cellular technologies already tested and deployed is LTE. This technology is the best of the cellular in terms of performance and the most broadly deployed in terms of coverage. Nevertheless, another technology related to Public Mobiles Land Networks (PLMNs) emerged in the last years, 5G.

It is expected that 5G will accelerate economic growth and make a hyper-connected society possible, in which all people are connected to the network whenever needed, as well as a wide variety of devices and objects that are virtually connected to the network. Thus, the 5G network will enable new use cases such as smart cities, smart agriculture, logistics, and public safety agencies [1]. These improvements can be reached thanks to the better expected performance of 5G compared to LTE, making possible new applications and services.

Focusing on the specific knowledge of vehicular communications, nowadays the main current technologies envisaged are IEEE802.11p (short-range technology) and LTE (cellular technology), although they have some limitations. On the one hand, IEEE 802.11p provides a low communication range, and its throughput and delay performance degrade quickly as the network load increases. On the other hand, in LTE, the latency rises with higher numbers of users in the cell; every data packet (e.g., between two nearby vehicles) must traverse the infrastructure, and the coverage of the cellular technology would determine its availability [2].

Although LTE being as the most deployed technology, it does not provide the performance enough for certain applications such as remote driving. Covering this issue, the 5G is emerging as a new technology with advantageous features. Then, the focus of this paper is on this new technology and its benefits, which could bring new services and applications to

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society. Therefore, it has to be proved that this technology is capable of providing the needs for vehicular communications for correct functioning. For example, autonomous vehicles require strict latency with 99% reliability for critical packet transmission and high bandwidth for high video streaming applications. Consequently, 5G is a key technology for it as it is supposed to offer speed up to 10 Gbps and low latency of 1 ms [3]. In the literature, different works experiment with 5G network measurements as [4] and [5] do. Nevertheless, both [4] and [5] are focused on a local and private 5G network respectively, with no mobility that which transportation system needs. The first work [4] measures the latency value in a basic and static test environment up to 5G NSA while [5] focuses on private 5G networks for purposes other than transportation systems, in this case, industrial production plants. They often necessitate local (private) communication networks for an industrial campus without Internet connectivity [5]. In this case, they set a rigorous testbed focusing on the delays. Moreover, [6] study the possibility of using 5G for full communication from Intelligent Transportation System services by measuring some relevant features for the performance. Nevertheless, the resulting measurements are obtained from pre5G networks. Furthermore, [7] presents an exhaustive and fair evaluation of C-V2X and ITS-G5 technologies under identical conditions remaining the aim of autonomous driving. However, the results in the C-V2X perspective do not involve 5G results but 4G.

Then, there seems not to be any testing with the 5G network on the transportation system. Nevertheless, it is necessary to test the performance of different services and applications in this domain. The 5G technology is planned to be used in different domains and applications as it is expected to have better performance than its predecessors as 4G or 3G. Among all the transportation applications, the advanced driver assistance systems is one of the applications that could be directly benefit. In fact, it is supposed to reduce fatal accidents and support the driver in conducting routine tasks and managing complex traffic situations by sensing nearby vehicles, road conditions, and pedestrian activity [6]. Then, this application could have a positive impact on society being necessary to assert that its deployment and functioning would be possible with this new technology. Nevertheless, not only does the advanced driver assistance system bring positive aspects to the society but also other applications such as video maintenance or the Internet for passengers contribute for an improvement in the different services for the people.

Hence, this paper focuses on the transportation system use case, specifically on monitoring and analyzing the connectivity for specific applications on the road for the bus company in San Sebastián city center. In this case, the target technologies are 5G NSA (Non-Standalone) and SA (Standalone) using the n78 band, corresponding to 3.5 GHz.

This paper explains the current and future applications and the corresponding Key Performance Indicators (KPIs) in the bus transportation system (Section II), and the external factors affecting the communication technology (Section III). Moreover, the used tool for the analysis of the wireless communication technology in a vehicle in movement is introduced and explained (Section IV) to later on describe the different tests for the measurements (Section V) and the results from them (Section VI). Finally, some conclusions are drawn (Section VII).

II. CURRENT AND FUTURE APPLICATIONS IN BUSES

A. APPLICATIONS FOR THE BUS TRANSPORTATION SYSTEM

Different applications are currently used in the bus transportation system to improve the efficiency of the service in both academic and business perspectives. After a comprehensive review of the literature, the most common use cases in bus transportation systems are video surveillance and the use of Wi-Fi for free. Because of this reason, some examples of video surveillance adoption in public transport vehicles are explained below:

- Video surveillance is an application that the bus service of dBus company [8] in San Sebastián, is currently using since 2010. The services guarantee the safety of the passengers and drivers in any strange situation. This use case focuses on transmitting the HD images obtained from the different surveillance cameras installed inside the buses in real-time to the processing centre. Nevertheless, LTE technology, the current technology in use, does not provide sufficient performance for this service. In this particular case, the video application is affected by the quality of the bearer, sometimes not as good as it should be to work properly. Sometimes, because of the bad quality of the bearer, the application is stopped or even loses information. This effect could be caused by the low data rate or the high delay at some moments. This type of application needs a minimum data rate in the uplink to send the corresponding information for the video application from the bus to the control center.
- The academic literature also highlights the importance of video surveillance both in public transport hubs and in the vehicles themselves. In this regard, it is possible to find works that present heuristic architecture models on onboard video surveillance systems applying processing loads on edge nodes with the objective of minimizing the impact on network performance [9].

Below are several examples of the adoption of Wi-Fi for free in public transport vehicles:

- Internet for passengers [8] (improvement of the Wi-Fi connection inside the bus): dBus buses offer a Wi-Fi connection available to users. This connection was created over a 4G network, which limits its use when multiple users connect simultaneously. However, a 5G connection would improve the user experience.
- In this regard, the Korean government enables Gigabit Wi-Fi service onboard public transport using Flexible Access Common Spectrum technology [10].

TABLE 1. KPIs established for the correct applications functioning from dBus.

KPI	Value
RTT (ms)	80
Downlink data rate (Mbps)	100
Uplink data rate (Mbps)	15

TABLE 2. KPIs for advanced 5G-V2X use cases.

Use Case	Min-max range (m)	Max latency (ms)	Data rate (Mbps)	Packet reliability (%)
Vehicles platooning	80-350	10-500	50-65	90-99.99
Advanced/ autonomous driving	360-700	3-100	10-50	90-99.999

- The academic literature also refers to scenarios that include Gigabit Wi-Fi service in public transportation vehicles implemented through the Moving Network (MN) system for 5G vehicular communications [10].

Moreover, other more challenging applications need the supposed performance of 5G such as autonomous driving, in the transportation domain. The tradeoff is road safety, addressing road congestion, and decreased environmental impact due to less wasted fuel thanks to improved vehicle management [11].

B. KEY PERFORMANCE INDICATORS (KPIs)

The aforementioned applications need some minimum requirements related to the performance of the communication technology to reach the main purpose of working properly. In this case, these requirements should be established focusing on the dBus applications currently in operation, being video surveillance and Wi-Fi (Internet for passengers) applications. Consequently, Key Performance Indicators (KPIs) were established not only for uplink data rate but also for Round Trip Time (RTT) and downlink data rate as Table 1 shows.

The KPIs are the minimum values for the correct functioning of a given application. For example, the downlink data rate is related to some services for the passengers, such as the Internet for passengers directly related to the Quality of Experience (QoE). However, the uplink data rate is more related to video surveillance. Moreover, RTT affects both applications.

Moreover, other applications to be used in this transportation system are in development, such as self-driving. This applications is are more restrictive in terms of KPIs than the ones already mentioned. Its requirements for advanced 5G-V2X (Vehicle-to-Everything) use cases [12] are the ones exposed in Table 2.

III. EXTERNAL FACTORS AFFECTING THE 5G COMMUNICATION TECHNOLOGY

As already stated, this paper focuses on the 5G technology, in the n78 band (3.5 GHz). Therefore, a brief analysis of the different factors affecting the desired technology in the given frequency are exposed in the following list.

- The environment can affect the 5G technology in terms of attenuations and multipath effects. Some of the possible environments are urban, suburban, and rural, which contain obstacles such as buildings, forests, etc. In this case, the environment is an urban one.
  The propagation loss on a terrestrial line-of-sight path relative to the free-space loss [13] is the sum of different contributions as follows [14]:
  - Attenuation due to atmospheric gases (not in this frequency, above 10GHz).
  - Diffraction fading due to obstruction or partial obstruction of the path.
  - Fading due to multipath, beam spreading, and scintillation.
  - Attenuation due to variation of the angle-of-arrival/launch; especially for long paths, normally, the base stations (BSs) for 5G are close to the User Equipment (UE).
  - Attenuation due to precipitation (e.g. rain attenuation) which can be ignored at frequencies below about 5 GHz.
  - Attenuation due to sand and dust storms.
- Electromagnetic Interferences from unknown sources severely degrade system performance, for instance, through inter-cell interference on buses [15].
- For commercial LTE and 5G Non-Standalone (NSA) networks, if the users connected to the network are a high number of people, this would affect communication by having to connect to one more BS.
- Speed of the vehicle.

Therefore, the performance of the technology will depend not only on the technology itself but on the external factors at a given moment and position.

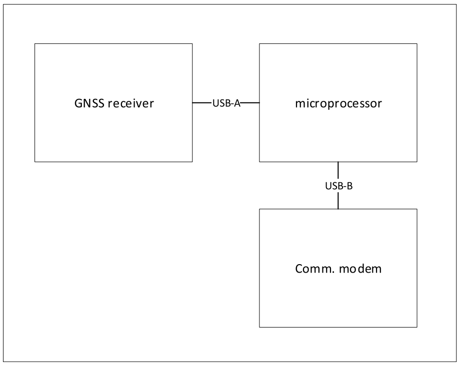


FIGURE 1. Block diagram for the CCT Agent.

IV. CHANNEL CHARACTERIZATION TOOL (CCT) SYSTEM MEASUREMENT

In order to measure the performance of the network, a tool, known as CCT, with the capability of doing it is needed. Therefore, in this section, the tool used to measure the

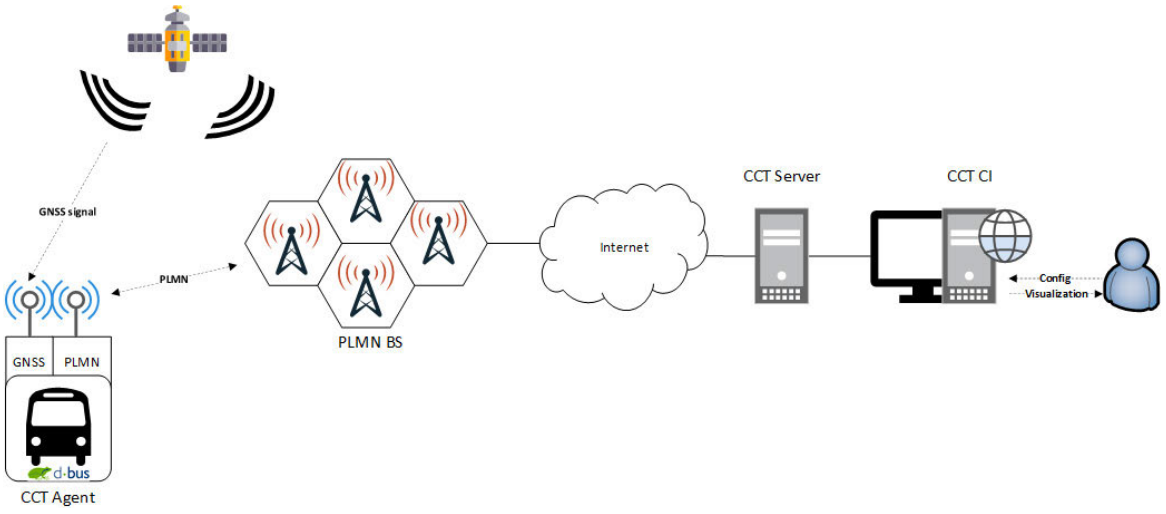


FIGURE 2. CCT architecture.

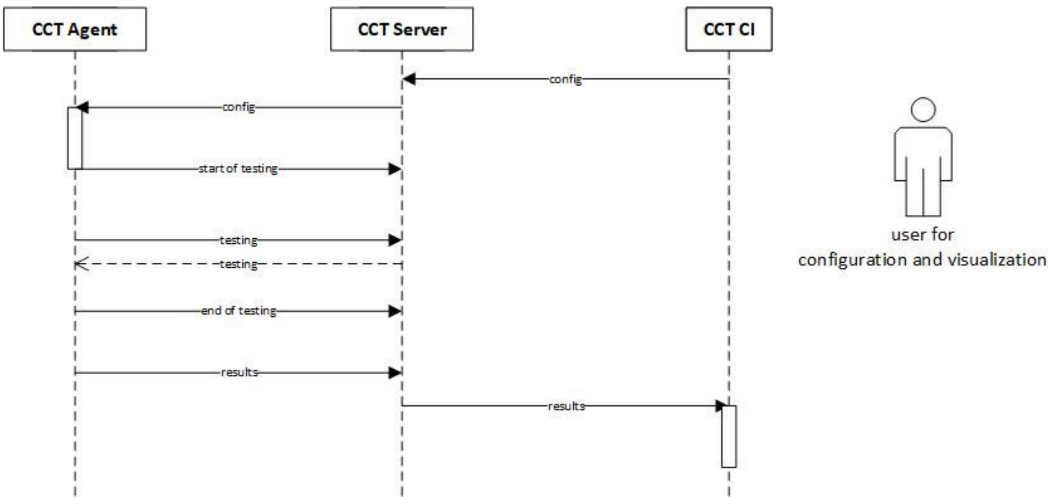


FIGURE 3. Sequence diagram for the interaction among each part of the CCT.

performance is presented, including a comparison with other tools in the market and its benefits.

A. DESCRIPTION OF THE TOOL

The CCT (Channel Characterization Tool) has as the primary goal the geolocation of different parameters of a given communication technology on the map [16]. Nevertheless, it is not the only service it provides; it gives other information such as the coverage of the different technologies, the statistics about the measured parameters, or the charts of the measured parameters along the test time.

Therefore, a brief description of the architecture of the tool is described in the following lines. This tool is based on the architecture and components shown in [16]. Nevertheless, some modifications must be implemented to adapt the tool to new technologies from both, software and hardware perspective. Firstly, regarding the software perspective, some modifications were needed to support the high data rates of 5G. Then, regarding the hardware perspective, some components, such as the communication module, needed to be replaced. Previously, it was a modem with connectivity with mobile networks up to LTE. Then, the modem was replaced with the Quectel RM 500Q release 15 [17], which supports 5G NR sub-6 bands and 5G NSA and SA modes and up to 2.5Gbps (DL) and 650 Mbps (UL). Then the block diagram respecting the hardware component is shown in Figure 1. Particularly, the interface for the communication between the microprocessor and the communication modem deserves special attention; this interface must theoretically support high data rates (up to 2.5 Gbps). In order to fulfill this requirement, the interface consists of a USB-A 3.0 (microprocessor) and USB-B 3.0 (communication modem) which allows rates of 4.8 Gbps.

Focusing on the CCT architecture, Figure 2 shows its architecture. It consists of three separate subsystems: CCT Agent, CCT Server, and CCT CI. The arrows presented within the

FIGURE 4. CCT agent.

figure shows the flow for three different stages of the CCT and their directions: configuration of the execution of the test, and sending of the results. Moreover, Figure 3 explains the messages exchanged among the different CCT parts related to the aforementioned flows.

1. CCT Agent, the onboard part. This module is placed on the bus; it contains a GNSS receiver antenna, allowing to know the position of the system at each moment, and the 5G communication antennas, for measuring the communication channel against the CCT Server. Figure 4 shows the physical device of the CCT Agent that is placed inside the bus. It is responsible for:
   - Receiving the configuration from the CCT Server.
   - Managing the initiation and ending of the test.
   - Executing the test against the CCT Server in order to obtain the performance of the communication channel.
   - Sending the results to the CCT Server so that they are post-processed before the final analysis.
2. The **CCT Server**, in this case, is placed in Amazon Web Services (AWS), more specifically in Ireland placed on the infrastructure. It is responsible for:
   - Sending the configured test to the CCT Agent;
   - Executing the test that will measure the performance of the communication channel.

   In this architecture, the CCT Server.
3. **CCT Control Interface** (**CI**) is responsible for the user's interaction with the tool. It allows:
   - the test configuration where the user can establish the target parameters to be tested along the trip;
   - the visualization of the results of each test.

To obtain the performance of a communication channel, which is a specific technology, a test must be configured in the CCT CI. Figure 5 shows the graphical interface that CCT uses in order to configure different types of tests. Within this interface, the user configures the test to be performed, the starting time and duration, and the CCT Agent that will perform the test.

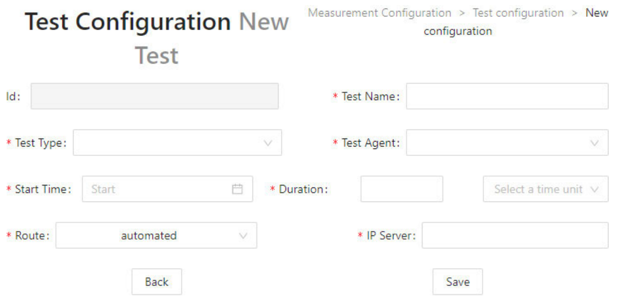


FIGURE 5. Test configuration interface for the CCT, in the CCT CI part.

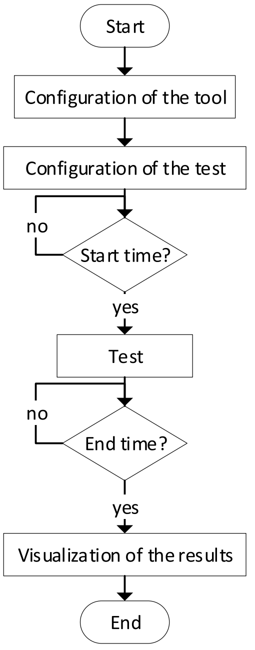


FIGURE 6. Flowchart for the functioning of the CCT.

In order to understand how the CCT works, Figure 6 shows the flow to be followed in each test. Firstly, the tool is configured, selecting both the CCT Server and the CCT Agent for the test. Note that the possibility of multiple CCT Servers and CCT Agents exists. Then, the configuration of the desired test should be done. Once the test is configured and sent, the system waits for the starting hour of the test to start its execution. During the test, the CCT Agent and CCT Server save the results obtained from the measurement of the technology and the position of the bus in these measurements. When the test finishes, the results are sent from the CCT Agent to the CCT Server and later on to the CCT CI to post-process the information, and to visualize the test results.

B. STATE-OF-ART

Currently, several tools are available for measuring the already mentioned parameters, which belong to a specific technology such as the RTT, the available data rate, or the RSSI to name a few. Each tool measures, in a different way, some common parameters such as data rate. However, each tool has a different implementation which could be crucial

TABLE 3. Comparison with other tools.

Features	5g android smart phone	Pilot Pioneer	CCT
	Using different applications such as G-Netrack		Proprietary tools for the goal of measuring
1	Integrated antenna	Integrated antenna as using integrated terminals (smartphones)	It has different SMA connectors where different antennas can be connected. This allows different emplacement for the antennas such as at the roof of the vehicle having no internal obstacles.
2	-	KPIs available	KPIs available
3	-	Using iperf to measure the data rate. The iperf is not robust against disconnections.	Measuring data rate in continuous mode
4	Predetermined servers, some applications allow to select the closest server that they have through a list but may not be enough close.	-	The CCT Server can be moved to another emplacement or have different servers along the word with the option to install it closer to the CCT Agent.
5	No possibility, integrated device	No possibility, integrated device	Possibility to update the same hardware up to a new technology (branching the new module for the technology and updating a software)
6	More applications than, in this case, the G-NetTrack are needed, for example, to record the location.		The CCT needs just a configuration to directly obtain the results in the graphical interface.

depending on the final application. Therefore, this paper exposes several aspects in which CCT differs from the other tools:

1. Possibility of changing antennas
2. % of values fulfilling the requirements
3. Measuring de data rate in continuous mode
4. Possibility of choosing the server which the onboard part will be measuring with.
5. Possible adoption of future technologies
6. All in one, the test is configured in the CCT CI and the user has no more responsibility for the performance of the test.

A comparison, based on the aforementioned listed features, with other tools is shown in the following table in order to demonstrate the benefits that this tool has.

In summary, the CCT carries more adaptability than other tools in terms of hardware (other technologies) and software (continuity in the measurements).

C. BENEFITS OF THE TOOL

The CCT brings some benefits to analyze the performance of the target technologies. These benefits are listed below:

1. The CCT allows comparing different technologies on the same road on a map.
2. The CCT allows discovering the coverage in the road of different technologies. That is, it allows for identifying a lack of coverage.
3. Different types of parameters related to the current technology communication can be analyzed: RTT, data rate in downlink, and uplink or coverage.
4. The CCT allows an analysis of how the environment can affect technology.

V. DESCRIPTION OF THE MEASUREMENT

A. DESCRIPTION OF THE ROAD AND ENVIRONMENT

The selected road for the measurements of the communication technology in transportation systems is a part of the line corresponding to the number 28 bus line in San Sebastian. This line passes through areas where the 5G technology (SA and NSA) are available. It is important to mention that the 5G network at the moment of the test campaign was in the first steps of deployment then, the 5G network can be unstable. Figure 7 shows the route of the bus with the bus stops that it owns marked in a circle.

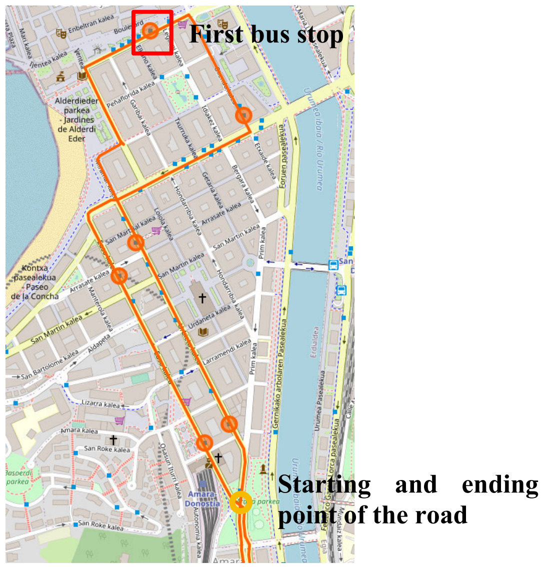


FIGURE 7. Route for the bus [18].

The first bus stop of the line is the one marked in a square in Figure 7. The bus starts the route at this point spending more time stopped there than at other bus stops. Furthermore, this road corresponds to an urban environment where the buildings and the number of users connected to the BSs can affect the performance of the technology as mentioned in Section III. Figure 8 shows two different environments corresponding to the urban area in the line.

Moreover, although the target technology is 5G, LTE is also measured to compare the different performances of the

FIGURE 8. Environments of the urban area in San Sebastián.

FIGURE 9. Set up of the CCT Agent in the bus.

FIGURE 10. Speed of the bus on the road.

technologies. Then, the available technologies for the CCT are:

1. LTE
2. 5G NSA
3. 5G SA

Additionally, the performance of the technology already mentioned in this paper is characterized by different measured parameters. These parameters are listed below:

1. RTT by using ping tool.
2. Bandwidth downlink sending TCP traffic and monitoring the received amount of data per second.
3. Bandwidth uplink sending TCP traffic and monitoring the received amount of data per second.

Consequently, the LTE, 5G NSA, and 5G SA measurements were carried out on the selected route. The measurements presented in this paper correspond to a period of time from December 2021 to March 2022.

In order to perform the different already mentioned tests for each parameter, the CCT, the device responsible for the measurements, has to be set up. As explained in Section IV, the CCT is split into different subsystems. The CCT CI and CCT Server are located in the AWS. However, the CCT Agent has to be installed in the desired vehicle. Then, the onboard subsystem is placed on a seat of the bus while the GNSS antenna is out of the bus, as Figure 9 shows.

Apart from the selected performance parameters, the speed of the bus is also monitored along the road while testing as the speed can affect the technology. The measured values go from a maximum speed of 42.54 km/h, an average speed of 8.67 km/h, and a minimum speed of 0 km/h when the bus stops (main bus stop or traffic lights).

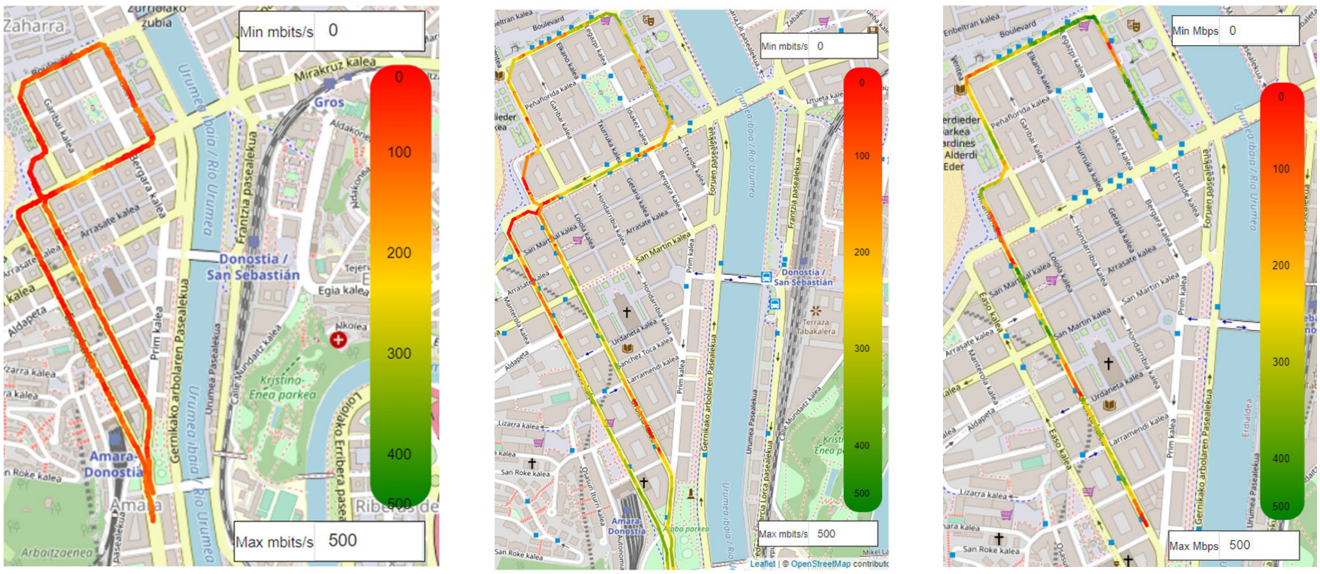
Figure 10 shows an example of the speed along the road. The values in the middle of the chart correspond to the main bus stop while the rest of the values being reduced to 0 correspond to different bus stops but shorter in time than in the main one.

B. DESCRIPTION OF THE TEST CAMPAIGN

The test campaign consists of different planned tests along the same road. The planned route for the test is defined as Figure 7 shows, the starting and ending points are the same location. Consequently, the bus passes through the same road to perform tests of different parameters at different moments during the planned days for the test campaign.

Each test measures only one parameter at the same time regarding the ones already aforementioned, that is to say, one test for RTT, another test for data rate downlink, and another one for data rate uplink [16]. Then, multiple tests are performed along the road to obtain results from different moments. This leads to multiple results for the same location.

It is remarkable that, for the aforementioned test campaign, the 5G SA network was not a commercial network, that is, exclusive for this work. In contrast, the 5G NSA and LTE are used for other purposes (commercial ones). However, exclusive APNs were given by the network operator for the test campaign within the project called 5G Euskadi [19].



(a) LTE (b) 5G NSA (c) 5G SA

FIGURE 11. **BW DL measurements for LTE, 5G NSA, and 5G SA.**

VI. RESULTS ON THE ROAD

In this section, the results from the on-site testing campaign on the road are exposed and detailed.

A. BANDWIDTH DOWNLINK

Regarding the bandwidth downlink (BW DL) and comparing the results from LTE and 5G, it can be stated that the values for 5G are higher than the ones measured in LTE. Figure 11 shows the values from the bandwidth downlink measurements on the map through the different target technologies. As Figure 11 shows, the values differ depending on the position of the bus within each technology. Moreover, Figure 12 shows the charts (values vs time) exposing the obtained values in more detail. It can be stated that there are some points at which the values are reduced in performance (lower data rate), no matter which the technology is, at the same position on the map. Besides, Figure 12 also shows how, in LTE, few values fulfill the established KPI as the majority of them are below the green line representing this KPI. In contrast, for 5G, the majority of the values are above the KPI line, although not every value is fulfilling the KPI.

Regarding the maximum obtained values, 5G reaches values close to 400 Mbps while LTE reaches values close to 100 Mbps, although the values are more stable than in 5G. Therefore, it can be stated that the data rate in terms of values in the downlink is better for 5G than for LTE.

Moreover, the possibility of analyzing the results through radiofrequency values is possible. As an example, the following charts show some RF parameters related to the 5G NSA measurements such as RSSI or RSRQ. It is clear how the LTE technology, as the control plane, has a continuous connectivity (no lack of values) shown in Figure 14 while in the RF values corresponding to 5G NSA shown in Figure 13 as the data plane, some gaps exist (no RF values) because of critical points of no coverage. Then, these charts allow knowing the quality of the signal and the critical points where no coverage exists.

B. BANDWIDTH UPLINK

As in the previous parameter, regarding the bandwidth uplink (BW UL) and comparing LTE and 5G, it can be stated that the obtained values for 5G are higher than the ones measured in LTE. Figure 15 shows the values from the bandwidth uplink measurements on the map through the different target technologies. In this case, the 5G network reaches data rates close to 100 Mbps, while LTE has maximum values of around 40 Mbps. Therefore, it can be stated that the data rate in 5G is better than the ones for LTE. Nevertheless, there are some positions where these values are reduced, and the performance is worse compared to other positions on the road.

C. RTT

Figure 16 shows the values from the RTT measurements on the map through the different target technologies. The RTT is totally stable in the LTE network, while in the 5G network, at certain points, the RTT increases, reaching a maximum value of 8.5s. In the case of the 5G NSA technology, RTT's high value can be caused by handovers from 5G NSA to LTE.

D. COVERAGE

The coverage from two of the three target technologies is analyzed. Focusing on this parameter, the fact of performing different tests along the road leads to the same conclusion: while LTE has total coverage along the road in every test that has been performed, the 5G NSA has some critical areas,

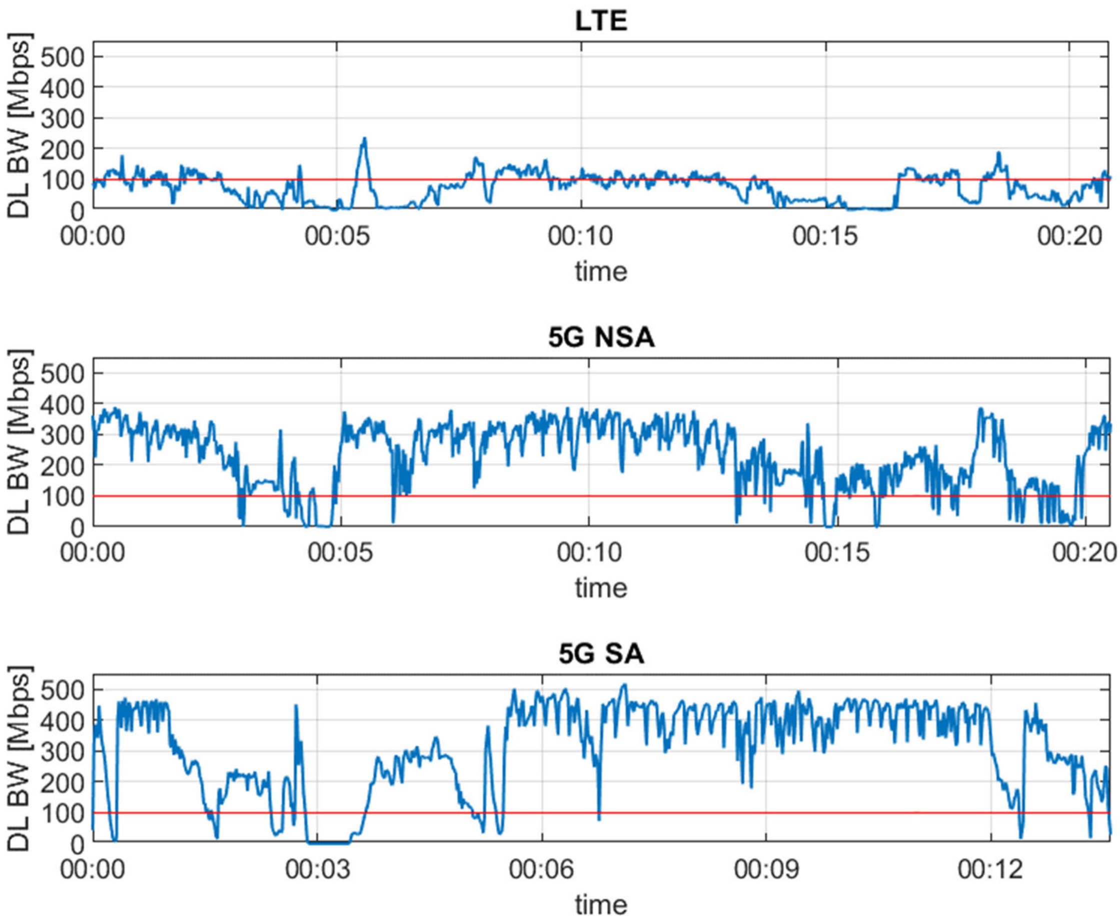


FIGURE 12. BW DL measurements for LTE, 5G NSA, and 5G SA.

FIGURE 13. RF values for 5G NSA data plane.

as Figure 17 shows. In these critical areas, there is no 5G coverage. Consequently, there is a vertical handover having communication through LTE instead of 5G. Then, the data rate is drastically reduced, and the RTT increases in these areas. However, in the 5G SA technology, no possibility to switch to another technology was enabled by the network operator during this test campaign. Then, when the CCT, equipped with 5G SA, was going through the critical areas mentioned before, the result was a loss of connection as there was no coverage.[1]

[1]Normally, when the CCT enters into a 5G SA-covered area, it should manage to connect again. Nevertheless, when performing the test, the network operator was not prepared for this; the reconnection takes a few minutes. Then, it is too late for the test as it finishes at the time of reconnection.

This specific tool, which provides the coverage map, can be helpful for the network operators as, e.g., the planned BSs are not enough to cover the whole road. Therefore, they can solve this issue by modifying or adding another BS.

E. KPIS VS. RESULTS FROM THE TEST CAMPAIGN DISCUSSION

The CCT allows the comparison of different parameters from different technologies.

Moreover, as the CCT can show the quantitative values from the tests, Table 5 shows the maximum, the average, and the minimum values from the different measurements of the different technologies.

It can be stated, based on the results, that LTE has worse performance in terms of the results values than 5G. For

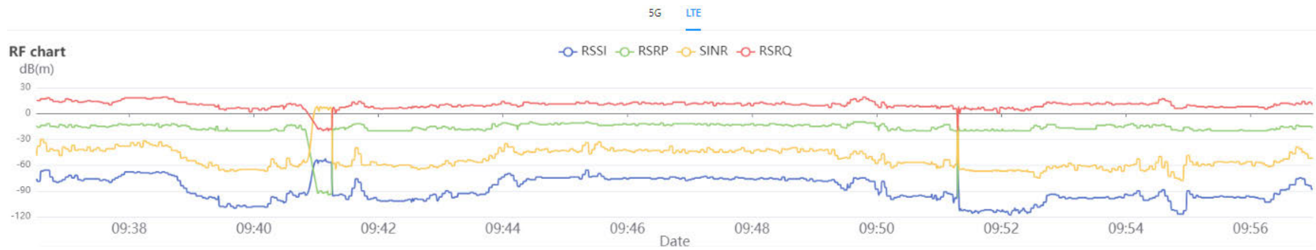
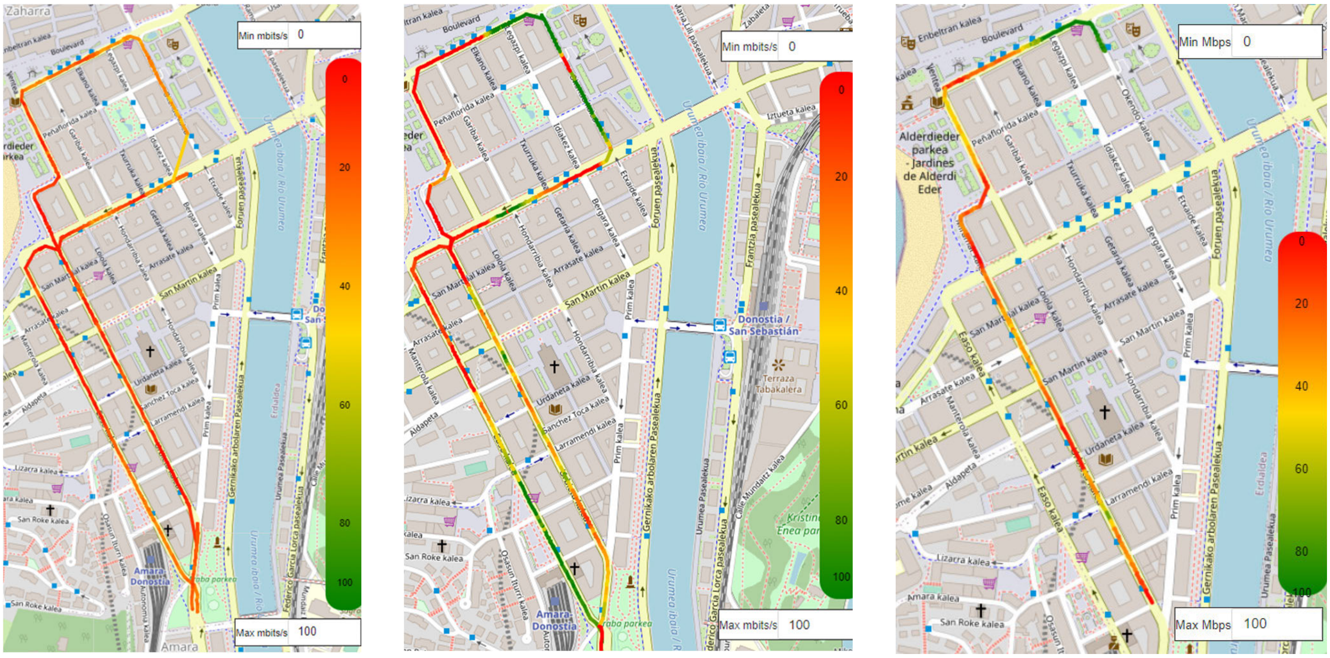


FIGURE 14. RF values for LTE control plane.



(a) LTE (b) 5G NSA (c) 5G SA

FIGURE 15. BW UL measurements for LTE, 5G NSA, and 5G SA.

example, focusing on the average value, in the downlink data rate, the 5G NSA value is three times the LTE one, and the 5G SA value is four times the LTE one. Moreover, in the uplink data rate, the 5G is three times the LTE value.

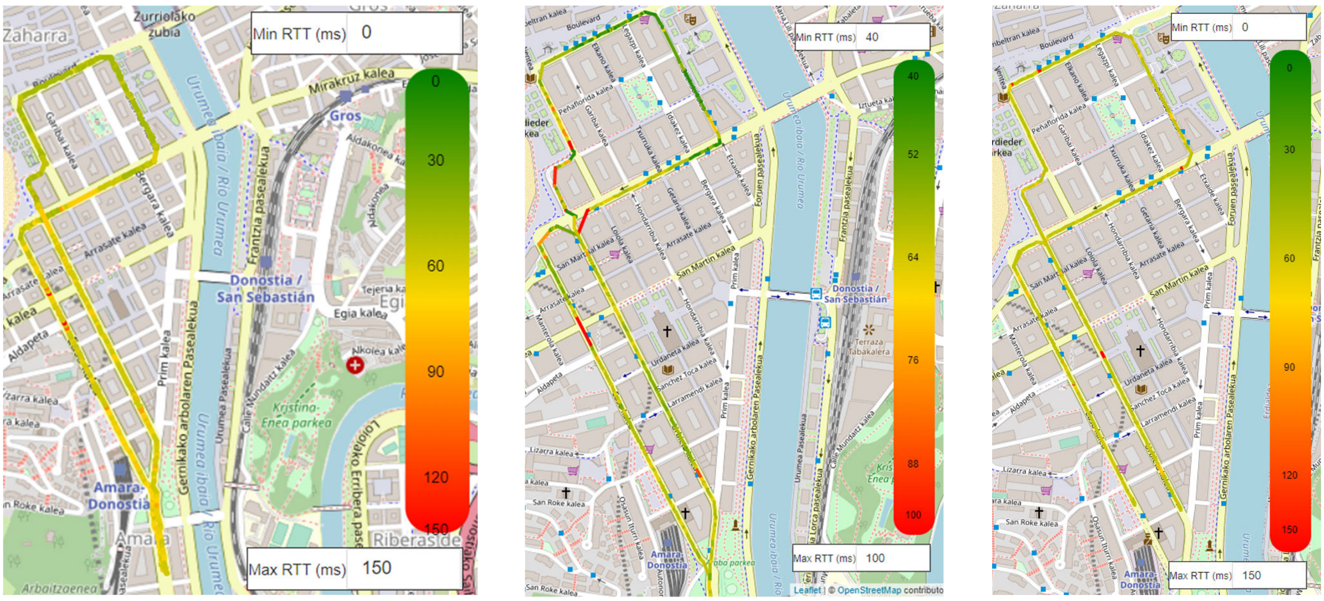
Furthermore, Figure 18, Figure 19, and Figure 20 give a graphical view of how the behavior of the different technologies is by means of Cumulative Distribution Functions (CDF) charts.

Figure 18 shows the CDF chart for the bandwidth downlink. It is remarkable the high improvement from LTE to 5G technology in general and especially to 5GSA in Mbps. Then, this last technology provides a considerable enhancement in the downlink data rate and consequently, the services related to it.

Nevertheless, the bandwidth uplink has a big difference between LTE and 5G (NSA and SA) but not between the different types of 5G technology. Figure 19 shows this behavior in the CDF chart respecting the bandwidth uplink measurements. As already stated, the difference in Mbps in the 5G technology is not significant although the 5GSA should provide higher data rates. However, it has to be considered that at the moment of the on-site testing, the 5GSA network was just deployed existing the possibility of future improvements. One of these improvements in the 5GSA could be done by the network operators via managing the allocation of the frequencies and reflushing the frequencies regarding the uplink ones in 5GSA.

TABLE 4. Obtained measurements from the test campaign.

		LTE	5G NSA	5G SA
Bandwidth downlink (Mbps)	Average	73	232	321
	Maximum	238	390	649
Bandwidth uplink (Mbps)	Average	22	63	62
	Maximum	48.67	122	124
RTT (ms)	Average	64	72	62
	Minimum	47.6	42.8	54.37
	Maximum	2753	8523	692



(a) LTE (b) 5G NSA (c) 5G SA

FIGURE 16. **RTT measurements for LTE, 5G NSA, and 5G SA.**

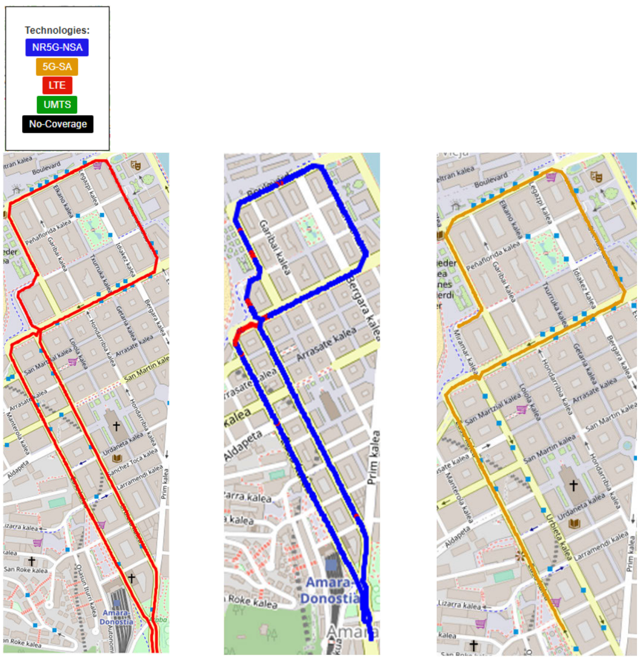


FIGURE 17. **Coverage for LTE, 5G NSA, and 5G SA.**

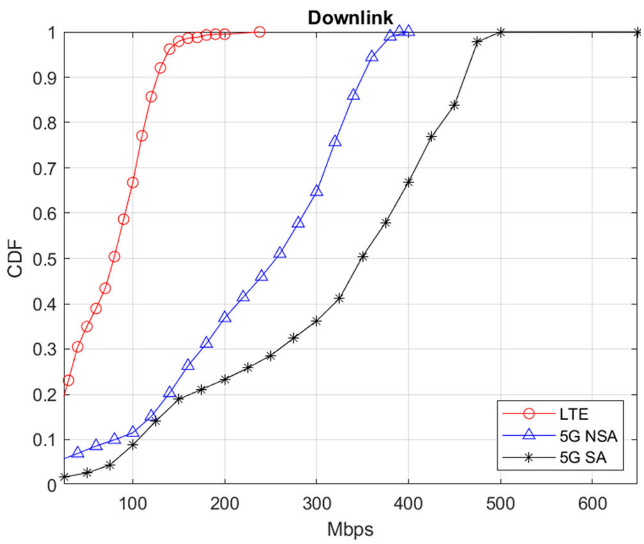


FIGURE 18. **CDF chart for the bandwidth downlink.**

Figure 20 shows the RTT values in the CDF chart which indicates that the values, in general, are similar between the three technologies.

After the explanation of the obtained results from the different measurements, a comparison between them and the KPIs established and mentioned in Section II gives a general idea of the applications' behavior on the road. Consequently, after the comparison between the obtained results from on-site testing and the KPIs for the different applications (see Table 5), it can be said that LTE technology is far from fulfilling the KPIs. Nevertheless, 5G is neither fulfilling every parameter, but it gets closer to 100% than LTE technology.

Consequently, it can be stated that no technology on this road would currently fulfill the requirements set in terms of data rate. Nevertheless, the 5G technology provides better performance in terms of % than the LTE; it is closer to fulfilling the KPIs than LTE.

Regarding other requirements apart from the KPIs established for these measurements as the ones for advanced driving, the results would neither fulfill them. This application

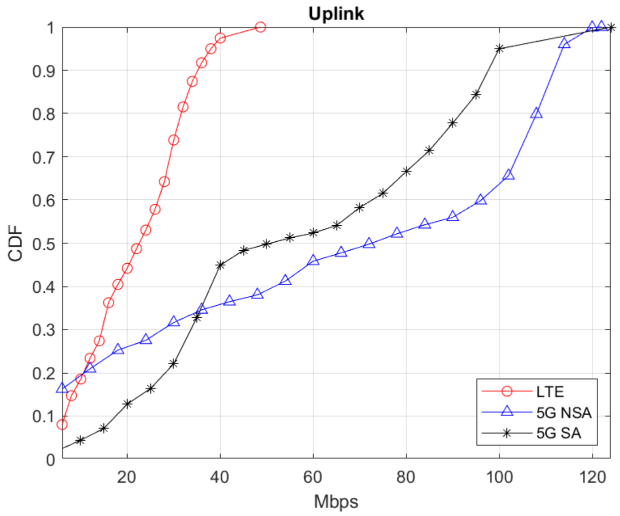


FIGURE 19. CDF chart for the bandwidth uplink.

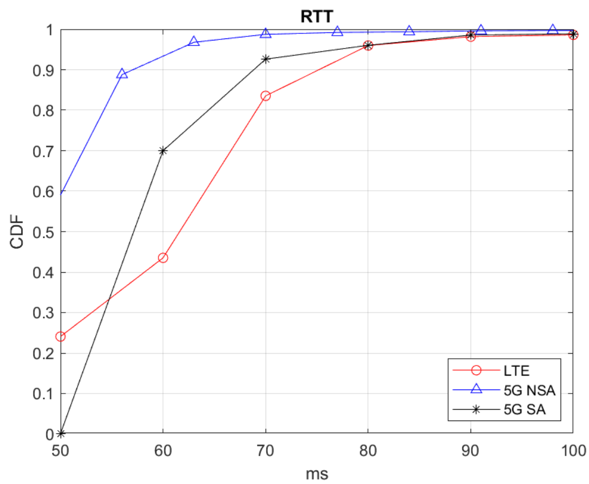


FIGURE 20. CDF chart for the RTT.

TABLE 5. Values from the test campaign measurements that fulfill the KPIs in %.

	LTE	5G NSA	5G SA
Bandwidth downlink	33.25%	88.49%	91.2%
Bandwidth uplink	68.86%	76.5%	92.83%
RTT	95.97%	99.21%	96.03%

needs ultra-low latency. Theoretically, 5G should provide ultra-low latency reaching 20 ms. Nevertheless, this 5G network is in the deployment phase; there is room for improvements in different aspects, such as ultra-low latency or coverage.

VII. CONCLUSION

This paper contributes to measuring the 5G technology, in a dynamic and real mode where there are no tools available to do it. The CCT can measure the performance of different technologies, allowing knowing how a given application could behave on this road and even helping the network operators to validate if the deployed approach of the network covers every desired point of the target area.

Although the 5G, both NSA, and SA are stated as a technology capable of providing better capabilities for many applications of the transportation system, there is room for improvements in terms of performance. Regarding the test campaign on this specific road, some critical areas were identified: some areas with no 5G coverage were available, and other areas where the data rate was reduced. Moreover, other areas with maximum values of data rates and minimum values of RTT were found.

It can be stated from the results that there is a conflictive area in the area of the intersection of Easo Street with Avenida de la Libertad. Regarding 5G NSA technology results, there is a vertical handover to the LTE technology, therefore, a lower data rate. Moreover, in 5G SA, there is a loss of connection in the same area, having no results from this point.

The obtained values from the different technologies measurements do not fulfill the KPIs. Therefore, the applications selected to be deployed in this bus line would not currently work properly. Nevertheless, it has to be considered that the 5G network is in the deployment phase making it possible for an improvement to get higher values and no gaps in coverage. After the improvements of the network, another test campaign would be useful to carry out, employing the CCT as the tool for the measurements to know if, at that moment, the applications would work properly.

Moreover, there is room for improvement in terms of latency/RTT. For better low latency measurements, a server closer to the BS would allow a reduction in the latency. In fact, the location of equipment closer to the BS, called Mobile Edge Computing (MEC), is planned to be done in the near future with the 5G network. In this way, the most critical applications could obtain better values in terms of RTT than the ones shown in this paper. In this case, theoretically, the RTT associated with the measurements should be the one caused by the air gap in the 5G network.

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