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RESEARCH ARTICLE

Feasibility Study of V2X Communications in Initial 5G NR Deployments

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ABSTRACT Advancements in intelligent vehicles and Intelligent Transport Systems (ITS) have shown that they are now feasible in both technology and commerce. However, there are still significant challenges to overcome, particularly regarding the perception and coordination of intelligent vehicles in unfavourable conditions. Vehicle-to-Everything (V2X) communications is a technology that aims to enable intelligent vehicles to communicate with other road users and infrastructure to increase their range of perception and coordination capabilities. While the 4th generation of cellular technology (4G LTE) is capable of supporting V2X communications to some extent, its multimedia and telephony-centric design does not translate well to safety-critical applications. As a result, the 5th generation of cellular technology (5G NR) is being developed to improve V2X communications. To investigate the effectiveness of 5G NR in V2X communications, a driving-based measurement campaign of a commercial cellular network with early 5G NR deployments was conducted. Results showed that the existing 4G LTE network is limited in its capability, and early 5G NR deployments can in fact outperform it. However, neither 4G LTE nor 5G NR can reliably support advanced V2X applications. Early 5G NR deployments suffer from significant reliability issues compared to existing 4G LTE deployments. These reliability issues are of particular concern, as they impact the vehicle's ability to trust the information it receives. These findings highlight the need for further design and implementation of intelligent vehicles and future 5G NR networks to address these reliability concerns and ensure the safe and efficient operation of intelligent vehicles in all conditions.

INDEX TERMS V2X, V2X communications, vehicle-to-everything, vehicular networks, intelligent transport systems, ITS, cellular, C-V2X, 4G LTE, 5G NR.

I. INTRODUCTION

Following the advent of the fourth Industrial Revolution, Industry 4.0 [1], the autonomous vehicle concept has become a distinct technological and commercial reality. This is highlighted by commercial deployments of advanced driving features from automotive companies such as Tesla [2], Cruise [3], Mercedes-Benz [4] and Alphabet's Waymo [5]. Following this introduction of advanced driving technologies, the concept of the "connected car" and Vehicle-to-Everything (V2X) communications has entered the industry and research spotlight. This is reflected in the most recent standards for cellular communications from the 3GPP [6], [7] and for WLAN communications from the IEEE [8].

V2X communications is the term used to describe a communications system that surrounds a connected car. The

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system allows a connected car to exchange information with other vehicles (Vehicle-to-Vehicle or V2V), pedestrians (Vehicle-to-Pedestrian or V2P), roadside infrastructure (Vehicle-to-Infrastructure or V2I) and the wider internet (Vehicle-to-Network or V2N). The focal aim of a V2X communications system is to improve automotive safety and efficiency by enabling stakeholders in road traffic environments to communicate and coordinate with one another. A large range of applications and use cases become available with the introduction of a V2X communications system, including safety, traffic efficiency and infotainment. The potential applications and use cases of V2X involve a non-trivial number and variance of stakeholders and as such requires quite a robust and reliable underlying wireless communications technology.

Cellular V2X (C-V2X) communications, standardised by the 3GPP [9], has been considered as a potential candidate wireless access technology for V2X communications for many years [10]. Focused interest in C-V2X followed the release of vehicular standards for cellular communications as part of 3GPP Release 14 [11] in 2017, known as LTE-V2X. The widespread infrastructure available to cellular communications, alongside the introduction of direct device-to-device communications, allows C-V2X to cover all communication archetypes of the V2X system. However, this interest grew significantly with the release of the 5th generation of cellular communications, 5G NR, as part of 3GPP Release 15 [12] in 2019. The intended overhaul of the cellular network as part of this new generation was towards applications such as smart cities, the Internet-of-Things (IoT) and autonomous driving. This in turn increased the attractiveness of cellular as a potential candidate for V2X communications.

Previous studies on current deployments of commercial LTE networks [13], [14], [15] indicate that C-V2X shows promise as a solution for V2X communications. Even though C-V2X may be able to support basic V2X applications, it is still not yet sufficient to support more advanced V2X applications due to an inability to reliably maintain low latencies [13]. While 5G NR presents significant promise towards these advanced applications, the path the relevant industry and research communities must take to enable these advanced applications with 5G NR is not yet clear.

In this work, similar to other works, a driving-based measurement campaign in a commercial cellular network is presented. However, unlike previous works, the aim is to evaluate an early commercial 5G NR deployment. Results presented here can be used by automotive and network operators to inform the planning, design, and implementation of vehicles and future 5G NR networks capable of supporting advanced applications like V2X communications. Additionally, the chosen methodology and analysis techniques can be replicated using off-the-shelf equipment and therefore can be easily repeated and augmented.

The remainder of this paper is structured as follows, in Section II related work is revised. Section III presents an overview of the applications and requirements for V2X communications that will be used to evaluate the cellular network. The experimental methodology used to conduct measurements is outlined in Section IV. Section V presents the results of the measurement study, discusses the effects of certain parameters and phenomena and proposes methods to address them. Section VI discusses the limitations of this study and future work. Finally, Section VII concludes this paper.

II. RELATED WORK

Evaluating cellular communications as a potential V2X communications candidate is a well-studied notion in the Intelligent Transport Systems (ITS) literature. However, there are significantly fewer driving-based studies evaluating either commercial or private cellular networks compared to those conducted through theoretical analysis or simulation. This trend is likely attributed to the costs associated with the procurement of the necessary networking equipment and suitable test vehicles, alongside the operational costs associated with carrying out these measurement campaigns.

The cellular network is typically studied with driving-based mobile measurements in one of two ways: with an existing commercial network or a private test cellular network with a limited number of cells. While cost is a significant constraint on the choice of methodology, there are trade-offs associated with both methodologies. A commercial network presents benefits such as a live network with real data and users alongside widespread cell deployments over different geographic areas. However, control and transparency are sacrificed. Network topology, handover strategies and data flow control mechanisms are all unknowns. Conversely, a private cellular network allows full control over the operation and architecture of the system but at the cost of realism in terms of the number of users, data flows and geographic coverage.

In general, it has been shown that on average cellular can uphold Quality-of-Service (QoS) metrics [14], [16], [17] to support more basic V2X communications use cases such as traffic information, traffic flow management and infotainment services. Particular attention has been paid to teleoperation type use cases [13], [16], [17], typically studied using commercial networks. These works follow a consensus showing that teleoperation is feasible to achieve in ideal conditions, however, there exist many problem areas, in terms of adequate cell coverage, that significantly reduce feasibility. Those works completed with private cellular networks show that in very controlled scenarios with ideal radio conditions, 4G LTE could support even more advanced use cases [18], [19]. More recent works studying the enhancements introduced with 5G NR have demonstrated very high-performance results in these controlled environments [20], [21], [22], [23], showing significant promise for the technology's capabilities.

Regardless of whether the network under study was commercial or private, the air interface of the cellular network i.e., the wireless link between the end user to base station connection, has a significant impact on performance metrics. An analysis completed by Inam et al. [17] shows that latency

TABLE 1. Summarised basic application requirements [35], [37].

Category	Examples	Max. Latency	Min. Frequency	Rel. Velocity
Safety Critical	Collision warning, Vulnerable Road User Warning	20-100ms	1-10Hz	160-280km/h
Traffic Efficiency	Intersection Management, Co-operative Adaptive Cruise Control	100-1000ms	1-2Hz	160km/h
Infotainment Services	Multimedia streaming, remote diagnosis	500-1000ms	1Hz	160km/h

is mostly unaffected by signal strength and quality unless the signal is very poor (-83dBm or poorer). Whereas, studies from Akselrod et al. [15] and Neumeier et al. [13] demonstrate that signal strength and quality have a significant effect on throughput. Algorithms used by cellular operators for the selection of the modulation technique in use, such as BPSK, QAM, and 16-QAM, are the primary explanation for this dependency and require revision for V2X communications. Line-of-sight (LOS) or shadowing effects (a.k.a slow fading) from buildings, other vehicles, flora or geographic topology appears to be the dominant component of signal degradation in automotive environments [24], [25], particularly at higher frequencies. The impact of the air interface is further exemplified by Niebisch et al. [26] demonstrating that even antenna placement on the roof of the vehicle can have a significant effect on the transmission capabilities of the vehicle.

Aside from the impact of the air interface, there remain a significant number of issues surrounding the Radio Access Network (RAN) architecture and management of the cellular network. Existing handover techniques are designed and optimised towards mobile handsets which have different mobility characteristics to cellular-enabled vehicles. Handover between cells and between cellular technologies i.e., 2G, 3G, 4G, 5G has been shown to have a significant effect on performance metrics [13], [14], [24]. Countries with several Mobile Network Operators (MNOs) offering different coverage capabilities also present a significant concern [14], [16], [27]. Sliwa and Wietfeld [27] in particular highlight, via proposal of shared infrastructure, that for cellular to succeed as a V2X communications solution, inter-MNO coordination is a key issue that requires consideration.

The control plane of the centralised core network architecture of 4G LTE has been shown to be the source of many of the latency issues associated with cellular communications [14], [25]. The need for inter-MNO coordination is further exemplified as 5G NR aims to address this issue by decentralising the cellular core network via technologies such as Software-Defined Networking (SDN), Network Function Virtualisation (NFV) and Mobile Edge Computing (MEC) [28]. A centralised core network also exacerbates another hurdle with which cellular must contend, which is congestion. Performance degradation due to the effects of congestion on routing and resource management protocols has been demonstrated in several situations [29], [30], [31]. Akselrod et al. [15] and Walelgne et al. [32] have noted that the time of day has a noticeable effect on network performance as more people connect and utilise the cellular network. Also noted by authors, were sudden drop-outs in connectivity that last for at least 200ms.

III. V2X APPLICATIONS AND REQUIREMENTS

To evaluate V2X communications, the network Key Performance Indicator (KPI) requirements for potential use cases and applications must first be identified. Organisations such as ETSI [33], U.S. Society of Automotive Engineers (SAE) [34] and 3GPP [35], [36] have conducted studies to determine these network KPI requirements. The use cases and applications studied can be broadly arranged into two categories: basic use cases and advanced use cases. The basic use cases can be further arranged into three categories: *safety critical, traffic efficiency and infotainment services*. The advanced use cases can be arranged into four categories: *vehicle platooning, advanced driving, extended sensors, and remote driving*. The following subsections will detail the use case categories and the network KPI requirements necessary to achieve them that will be used for this feasibility study.

A. BASIC SET OF APPLICATIONS (BSA)

Initially, the studies conducted by regulatory bodies were to investigate the possible network KPI requirements that would be necessary to achieve a Basic Set of Applications (BSA), mainly concerning driver assistance use cases that could be achieved with current wireless technologies. A summary of the BSA categories: *safety critical, traffic efficiency and infotainment services*, is presented in Table 1. The ranges given are the minimum or maximum values required to enable distinct use cases in each of the categories e.g. the *Forward Collision Warning* use case requires a maximum latency of 20ms to operate safely. Whereas, the *Vulnerable Road User (VRU) Warning* use case requires a maximum latency of 100ms to operate safely. A detailed outline of the network KPI requirements for each use case can be found in [35] and [37].

It should be noted that reliability and throughput requirements are not defined for the BSA. Reliability requirements for the BSA are quoted as "*…high reliability without requiring application-layer message re-transmissions.*" [35], although example reliability metrics of 80-99% are given in [37]. Throughput requirements are not imposed as these driver assistance-based applications utilise message sizes on the order of hundreds to low-thousands of bytes.

B. ADVANCED SET OF APPLICATIONS (ASA)

Following the specification of the BSA, a more rigorous and stringent network KPI requirement set was developed to address enhanced V2X (eV2X) or advanced V2X use cases and applications. This Advanced Set of Applications (ASA) [36], [38] was primarily developed by the 3GPP, building on the work in [35] and [37]. The ASA focuses on addressing use cases and applications that would be classified under the higher levels of the SAE Levels of Automation (LoA) [39], specifically levels 2-5.

Due to the inclusion of the higher levels of automation, the ASA is not categorised like the BSA i.e., *safety critical, traffic efficiency and infotainment*. Instead, it is categorised into the four aforementioned sections: *vehicle platooning, advanced driving, extended sensors, and remote driving*. These four sections are intended to encapsulate the overarching scenarios that intelligent vehicles with higher levels of automation may encounter. A summary of the network KPI requirements for the ASA are presented in Table 2. As with the BSA, the ranges given for each metric are the minimum and maximum values for the network KPI requirements in the ASA categories. A detailed outline of the network KPI requirements for each use case can be found in [36], [38]. It should be noted that for the majority of ASA, and for V2X applications in general, the upload and download directions are treated as the same and are referred to simply as "Data Rate" in Table 2.

IV. EXPERIMENTAL METHODOLOGY

In the following section, the experimental hardware and software setup, measurement methodology, data processing and analysis approach are outlined.

A. MEASUREMENT SETUP

1) HARDWARE

Two Unix-based *VirtualAccess* rugged automotive cellular routers; a *GW3300* (4G LTE) [40] and a *GW1400* [41] (5G NR), installed in a test vehicle, were used to conduct the measurements. Both routers were mounted in the trunk of the vehicle and connected to their own individual shark-fin antennae, mounted on the roof of the vehicle, illustrated in Figure 1. Both routers were connected to a Windows-based PC via Ethernet. To avoid radio and network usage interference only one router was used at a time to conduct measurements.

FIGURE 1. Sharkfin antennae mounts on test vehicle.

2) SOFTWARE

A custom application, written in Python, was used to interface with the cellular routers and conduct the network measurements. Two sets of measurements were collected: passive and active. Passive measurements included low-level radio measurements queried via AT commands from the router's cellular modems. The *Quectel* cellular modems [42], [43] installed in the routers impose a 300ms response latency for AT commands. Therefore, to provide ample communication and processing time, passive measurements were conducted every 500ms or with a frequency of 2Hz. These passive measurements include metrics such as network status, serving cell ID, frequency band (ARFCN), radio access technology (RAT), signal strength (RSRP), signal quality (RSRQ) and SINR.

Active measurements were collected by utilising ICMP and TCP packets to estimate latency and throughput respectively. Active measurements were not conducted simultaneously to avoid the effects of collisions or delays from scheduling or routing of the ICMP and TCP packets. The *SpeedTest.net* [44] API was utilised to leverage its widespread server distribution to select remote servers for the active measurements. For this measurement campaign, the chosen remote server was located in Dublin City (∼200km from Galway City), to maintain as close proximity as possible to the core of the cellular network under study, also located in Dublin City. To provide consistency with the passive measurements, *ping* (ICMP) packets were sent to the selected remote server at the same 2Hz frequency to capture round-trip-time (RTT), emulating end-to-end (E2E) delay, during latency tests. Throughput measurements via the *SpeedTest.net* API were run consecutively with an average run time of ∼20-40s for the duration of the test runs. Every measurement collected was temporally and geo-spatially stamped at the time of collection.

B. MEASUREMENT ROUTES

To reasonably evaluate the performance of the commercial cellular network, several driving routes were chosen to provide wide coverage of possible road scenarios. The first measurement route (centred at 53.285955, -9.066378), is intended as a more focused study of a sub-urban driving route, following a ∼4km loop through the University of Galway campus. This route, highlighted in Figure 2, features large sections of dense foliage, buildings and car parks.

The second measurement route (centred at 53.351526, −9.196307), is a ∼50km loop intended to capture a rural driving environment along the N59 secondary national road, illustrated in Figure 3. This rural route begins at the Alice Perry Engineering Building (53.284135, −9.063901) on the University of Galway campus and terminates in the town of Oughterard (53.429693, −9.318869) approximately 25km away. The rural route also features many gentle gradient hills and valleys alongside a significant degree of roadside foliage. The route features very few buildings except for the townships of Moycullen (53.338700, −9.179409) and Rosscahill (53.387158, −9.244689).

The third measurement route (centred at 53.274393, -9.060635), shown in Figure 4, is a ∼13km loop that navigates through Galway City to capture the busiest urban roads and junctions. This urban route is characterised by a large density of buildings, blind junctions and narrow streets.

TABLE 2. Summary of advanced set of applications [36], [38].

Category	Max. Latency	Min. Frequency	Payload	Data Rate	Reliability	Communication Range
Vehicle Platooning	10-500ms	2-50Hz	50-6500bytes	50-65Mbps	90-99.99%	80-350m
Advanced Driving	3-100ms	10-100Hz	300-12000bytes	0.25-53Mbps	90-99.999%	360-700m
Extended Sensors	3-100ms	10Hz	1600bytes	10-1000Mbps	90-99.999%	50-1000m
Remote Driving	5ms	N/A	N/A	25Mbps	99.999%	N/A

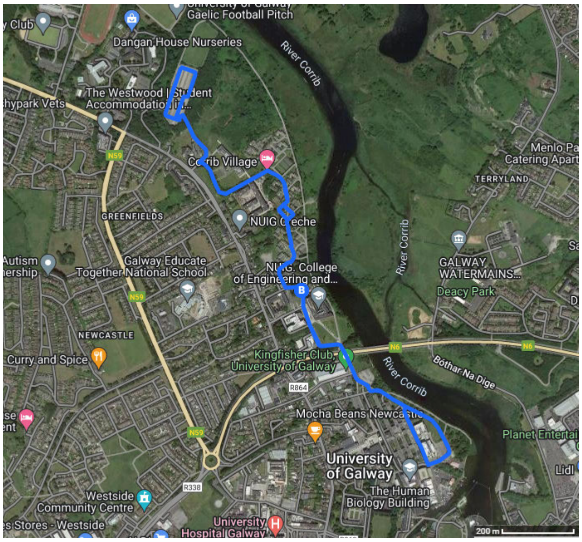

FIGURE 2. Map of sub-urban driving route through university of galway campus (centred at 53.285955, -9.066378) (Map data ©2023 Google).

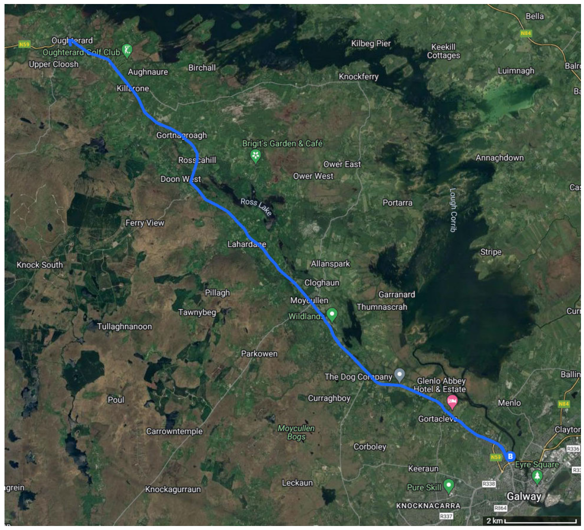

FIGURE 3. Map of rural driving route to and from Oughterard town (centred at 53.351526, -9.196307) (Map data ©2023 Google).

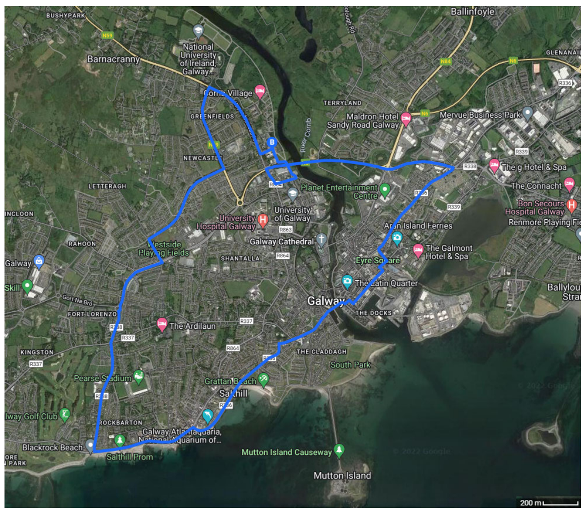

FIGURE 4. Map of urban driving route through galway city (centred at 53.274393, -9.060635) (Map data ©2023 Google).

The final route (centred at 53.299666, -8.903497), intended to capture highway driving environments, is ∼47km loop that follows the M6 motorway away from Galway City to the nearby town of Athenry (53.301198, -8.745321). Similar to the rural route, the highway driving route sparsely features buildings and in addition gentle gradient topology and very little foliage. Like the Rural route, the Sub-Urban, Urban and Highway routes all begin and end at the Alice Perry Engineering Building on the University of Galway campus.

In addition, to the measurement routes, a series of static measurements are taken at key points to assess the effect of vehicle mobility on network KPIs.

C. DATA PROCESSING AND ANALYSIS

Following the collection of the dataset, each of the GPS, active and passive measurements are stored as separate time-stamped trace files. Aside from unit conversions, the primary processing effort arises from using the time stamps to synthesise all raw traces that share the same collection time into a single measurement trace. An initial analysis of the GPS traces revealed that the onboard GPS of the cellular routers will return null values if the vehicle location remains the same for more than 1s. These null traces can simply be filled forward with the previous stationary traces. Alongside redundant stationary null traces, mobile null traces occurred in specific areas with poor GPS signal e.g. driving under overpasses or sections of road with heavy foliage. These mobile null traces only accounted for one to three consecutive traces (0.5-1.5s) along straight segments of road, as such simple linear interpolation can be applied between the traces on either side of the null gap.

V. RESULTS AND ANALYSIS

The aim of the analysis in this work is to estimate the general performance characteristics of the early 5G NR deployments

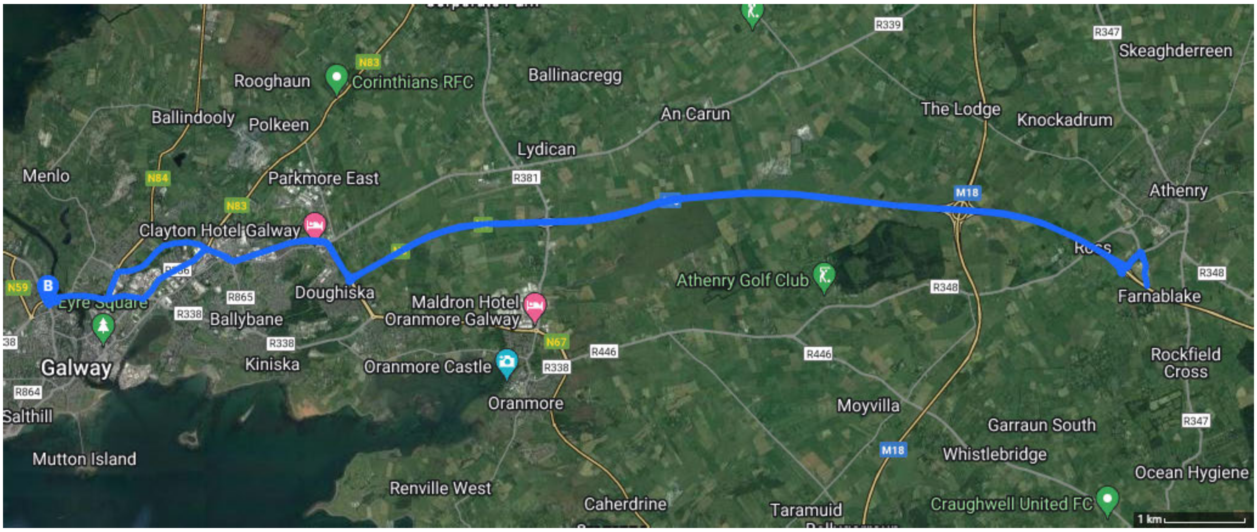

FIGURE 5. Map of highway driving route to and from Athenry town (centred at 53.299666, -8.903497) (Map data ©2023 Google).

such that the feasibility of V2X applications can be evaluated. To do so, we analyse two key metrics: latency and throughput. Firstly, the overall performance of both devices (5G NR-enabled GW1400 & 4G LTE-only GW3300) regarding these metrics will be presented and evaluated against the requirements outlined in Section III. Following this, the performance of each of the driving routes outlined in Section IV-B will be compared for each device individually. It should be noted that the figures presented in this analysis utilise a log axis for display purposes, however, the analysis is performed irrespective of this. In addition, the upper and lower fences of the box plots presented in this section are determined by Equations 1 & 2, where IQR is the inter-quartile range.

$$LowerFence = Q_1 - 1.5(IQR) \quad (1)$$

$$UpperFence = Q_3 + 1.5(IQR) \quad (2)$$

For each of the two devices, the access technology or connection type was collected. The distribution of samples is presented in Figure 6. The 4G LTE-only GW3300 device maintained a 4G LTE-type connection across all measurement runs. However, the 5G NR-enabled GW1400 device was found to have switched between 5G NR (62.3%), 4G LTE (32.4%) and 3G UMTS (5.35%) connection types. The performance difference between each of the access technologies for the 5G NR-enabled GW1400 device will be discussed alongside the device-device comparison.

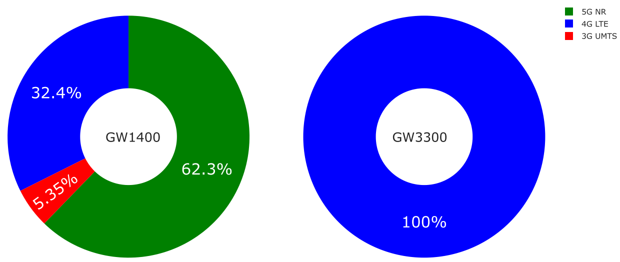

FIGURE 6. Pie chart of cellular generation usage for 5G NR-enabled GW1400 and 4G LTE-only GW3300.

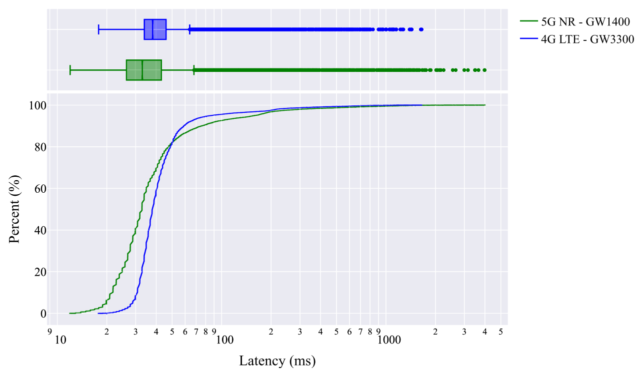

FIGURE 7. eCDF + Marginal box plot of latency performance distribution for 5G NR-enabled GW1400 and 4G LTE-only GW3300 (GW1400: 32.91ms, GW3300: 38.02ms median latency).

A. LATENCY

1) OVERALL PERFORMANCE

Aside from reliability, latency is viewed as the key metric for safety-critical applications. Delayed information can lead to an intelligent vehicle making a misinformed decision. In safety-critical applications, this can lead to significant consequences such as accidents. In non-safety applications, this can lead to degradation in traffic efficiency and fuel economy. Table 3 and Figure 7 present the latency performance statistics and distributions for each of the two cellular routers (5G NR-enabled GW1400 and 4G LTE-only GW3300).

Between the two measurement devices, the 5G NR-enabled GW1400 achieved on average the lowest latencies, as is shown by the quartiles in Table 3, with a minimum latency

TABLE 3. Latency performance statistics.

Latency (ms)	Mean	StD.	Skew	Kurt.	Min.	25%	50%	75%	Max.	<20ms	<100ms	<1,000ms	Abs. Loss
5G-en.	57.52	135.99	11.95	210.87	11.97	26.36	32.91	43.00	3,988.73	6.29%	92.58%	99.50%	1.64%
4G-only	51.67	73.41	9.75	124.38	17.83	33.87	38.02	45.89	1,648.93	0.17%	95.55%	99.86%	0.54%

at 11.97ms. This performance difference is evident from the median latency of both devices (32.91ms for GW1400 vs. 38.02ms for GW3300) and from the larger positive skew of the empirical CDF for the 5G NR-enabled GW1400. However, the 4G LTE-only GW3300 displayed a higher degree of reliability and stability, resulting in a lower mean overall latency of 51.67ms compared to the 57.52ms overall mean latency of the 5G NR-enabled GW1400. This stability difference between devices is highlighted by the size of the inter-quartile ranges in Figure 7.

A similar trend to the device comparison is observed between the connection types experienced by the 5G NR-enabled GW1400 in Figure 8. It is immediately clear that even though 3G UMTS only accounts for 5.35% of samples, its latency performance is significantly worse than its successors. There is again a larger positive skew in the empirical CDF for the 5G NR connection type, illustrating that 5G NR on average offers lower latencies, however, from the box plot, the size of the inter-quartile range highlights again that the 4G LTE connection has distinctly higher reliability.

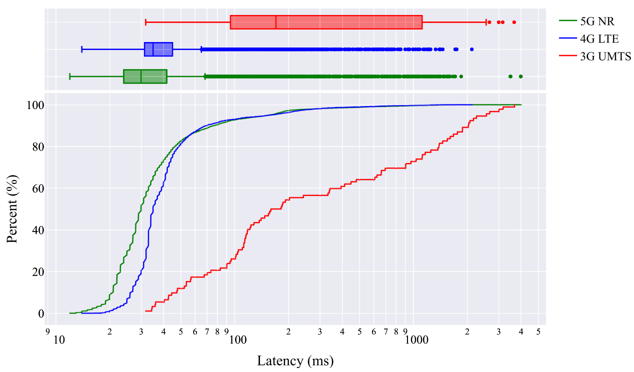

FIGURE 8. eCDF + Marginal box plot of latency performance distribution for 5G NR-enabled GW1400 Access Technologies (5G NR: 29.92ms, 4G LTE: 34.93ms, 3G UMTS: 170.03ms median latency).

There exist many methods to evaluate the stability and reliability of a network's latency performance. The two most common are the packet loss ratio (PLR) or packet reception ratio (PRR) and jitter or packet delay variation (PDV).

Within the scope of this analysis, there are several maximum latency thresholds to determine PLR/PRR. The least stringent is given by the *ping* utility itself with a threshold of 4,000ms, referred to herein as *absolute packet loss*. The various use cases of the BSA/ASA provide increasingly stringent thresholds i.e., 1,000ms, 100ms, 50ms, 20ms etc., with the most common being 100ms. Packet loss and jitter further exemplify the reliability disparity between both devices.

The overall (100% - absolute packet loss) reliability of the 5G NR-enabled GW1400 has an overall reliability of 98.36%, whereas the 4G LTE-only GW3300 device is 99.46%. Both drop significantly, when only packet latencies below 100ms are considered, to 92.58% (GW1400) and 95.55% (GW3300) respectively. While the reliability of both devices is within the same 80-99% "high reliability" requirement of the BSA and the 90-95% reliability requirement of the lower automation use cases of the ASA, the ∼5.78% (GW1400) and ∼3.96% (GW3300) drops in reliability are significant. Moreover, the absolute and relative changes in PRR further highlight that the 4G LTE-only system has an appreciably larger degree of reliability than the new 5G NR-enabled system.

Regarding PDV, from Table 4 it is clear the overall jitter of both devices is quite low with 82.12% (GW1400) and 86.30% (GW3300) of packets having a jitter lower than 20ms. There is little difference in the mean jitter of both devices (∼4.5ms), however, there is a significant difference in the maximum observed jitter i.e., worst case is 3,959.52ms (GW1400) and 1,600.48ms (GW3300). The ∼4.18% difference in jitter samples <20ms is further highlighted by the larger positive skew of the empirical CDF for the 4G LTE-only GW3300 in Figure 9, again indicating that 4G LTE has a higher degree of reliability than 5G NR. It should be noted that the distinct spikes in the graph that occur every 1ms are an artefact of the minimum scheduling unit in cellular systems i.e. 1ms.

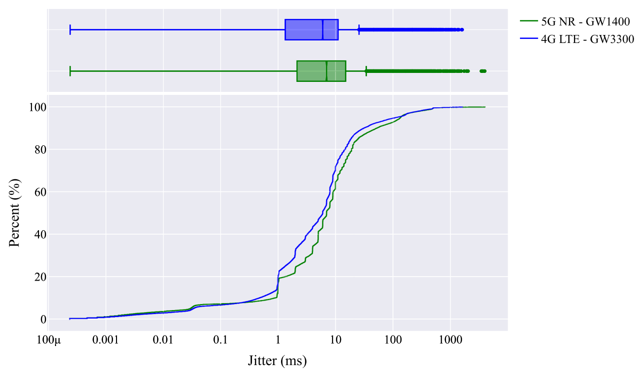

FIGURE 9. eCDF + Marginal box plot of jitter performance distribution for 5G NR-enabled GW1400 and 4G LTE-only GW3300 (GW1400: 6.98ms, GW3300: 5.98ms median jitter).

2) ROUTE COMPARISON

Following the presentation of the overall latency performance of both devices, the following subsection will compare the latency performance of both devices across each of the four driving routes used to conduct the measurements.

TABLE 4. Jitter statistics.

Jitter (ms)	Mean	StD.	Skew	Kurt.	Min.	25%	50%	75%	Max.	<20ms	<100ms	<1,000ms
5G-en.	28.45	99.43	14.76	402.48	2.38×10^{-4}	2.15	6.98	14.99	3,959.53	82.12%	92.82%	99.85%
4G-only	23.24	77.89	7.66	82.55	2.38×10^{-4}	1.33	5.98	11.07	1,600.49	86.30%	94.72%	99.89%

a: 5G NR-ENABLED GW1400

When only considering the samples from the 5G NR-enabled GW1400, see Figure 10 and Table 5, it is clear that there is relatively consistent performance across all driving routes. However, the Sub-Urban route displays the lowest reported latencies while the Rural route was found to have the highest. This is highlighted by the 12.21% of values measured below 20ms for the Sub-Urban route but only 3% for the Rural route. However, the Sub-Urban route appears to have the worst reliability of the four routes, as is evident from the large inter-quartile range presented in the box plot of Figure 10 alongside the highest mean latency of 75.78ms. The Rural route has a comparatively smaller inter-quartile range with a median latency of 33.91ms, however, also has a larger number of outliers above 1,000ms.

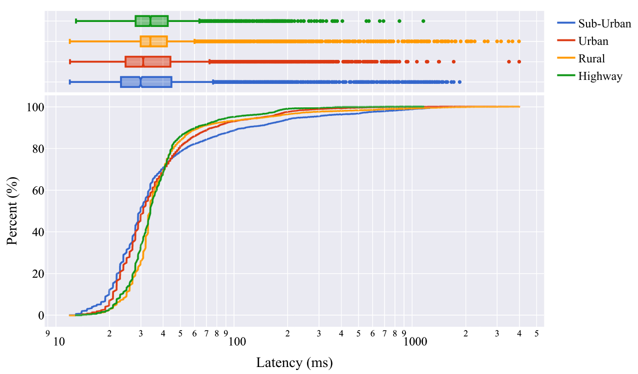

FIGURE 10. eCDF + Marginal box plot of latency performance distribution for each route measured by 5G NR-enabled GW1400 (Sub-Urban: 29.92ms, Urban: 30.92ms, Rural: 33.91ms, Highway: 33.93ms median latency).

Overall, the results indicate that the Sub-Urban and Urban routes have on average lower reported latencies, whereas the Rural and Highway report on average higher latencies. However, both Rural and Highway routes display a higher degree of reliability, which is highlighted by the on average lower absolute loss rates and smaller inter-quartile ranges. This trend is most likely due to the density of cells in the regions. In the Sub-Urban and Urban scenarios, the cells with which the device uses to connect to the network are closer to the core network. However, the higher density of cells results in a higher number of handovers which increases the degree of variability of latency.

The opposite is apparent in the Rural and Highway scenarios, where the density of cells is lower but the cells are farther from the cellular core network. This results in a slightly higher average latency but the decreased likelihood of handover increases reliability. However, there is little difference in the jitter performance, shown in Figure 12, between the four measurement routes. Though the insights regarding cell density are still evident via the smaller positive skew present for the Sub-Urban route and the larger positive skew present for the Rural route.

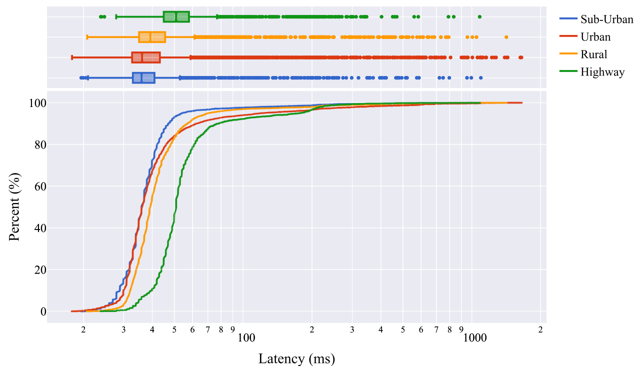

FIGURE 11. eCDF + Marginal box plot of latency performance distribution for each route measured by 4G LTE-only GW3300 (Sub-Urban: 35.94ms, Urban: 36.11ms, Rural: 39.22ms, Highway: 50.86ms median latency).

b: 4G LTE-ONLY GW3300

When only considering the samples from the 4G LTE-only GW3300, see Figure 11 and Table 6, there is a more distinct difference in the performance between routes. Overall, very few of the samples (<1%) across any of the routes were below 20ms, however, the absolute loss rates were very low (<1%). Likewise, with the 5G NR-enabled GW1400, the Sub-Urban route displays the lowest reported latencies, however, for the 4G LTE-only GW3300 the Highway route reported the highest average latencies. This is clear from the mean latency (42.33ms for Sub-Urban and 63.14ms for Highway) and the percentage of samples below 100ms (97.62% for Sub-Urban and 92.24% for Highway). In addition, the Sub-Urban route appears to have the highest reliability of the four routes, which is evident from the small inter-quartile range presented in the box plot of Figure 11. Conversely, it is the Urban route which displays the poorest reliability as is shown by the largest number of outliers and a larger inter-quartile range.

Likewise, with the 5G NR-enabled GW1400, it appears that the Sub-Urban and Urban routes have on average lower latencies, whereas the Rural and Highway report on average higher latencies. However, unlike the 5G NR-enabled GW1400, for the 4G LTE-only GW3300, the Urban route has distinctly lower reliability in terms of the size of its inter-quartile range and the number of outliers above 100ms. Similar to the 5G NR-enabled GW1400, this is again most

TABLE 5. 5G NR-enabled GW1400 latency performance route comparison.

Latency (ms)	Mean	StD.	Skew	Kurt.	Min.	25%	50%	75%	Max.	<20ms	<100ms	<1,000ms	Abs. Loss
Sub-Urban	75.78	176.53	5.56	34.71	11.97	23.20	29.92	44.56	1,848.19	12.21%	88.62%	98.80%	1.29%
Urban	49.46	90.95	19.46	661.5	12.00	24.62	30.92	43.92	3,988.73	7.09%	92.94%	99.90%	2.08%
Rural	64.84	183.08	10.73	149.5	11.97	29.92	33.91	41.96	3,978.03	3.00%	93.25%	99.10%	1.62%
Highway	44.12	47.77	9.85	157.37	12.96	28.04	33.93	42.44	1,155.77	3.07%	95.07%	99.97%	0.81%

TABLE 6. 4G LTE-only GW3300 latency performance route comparison.

Latency (ms)	Mean	StD.	Skew	Kurt.	Min.	25%	50%	75%	Max.	<20ms	<100ms	<1,000ms	Abs. Loss
Sub-Urban	42.33	45.00	12.24	198.57	19.56	32.90	35.94	40.89	1,095.76	0.06%	97.62%	99.98%	0.21%
Urban	56.42	99.53	8.03	79.35	17.83	32.67	36.11	43.17	1,648.93	0.43%	94.04%	99.67%	0.55%
Rural	49.20	57.82	10.15	138.76	20.77	35.05	39.22	45.55	1,417.24	0.00%	96.92%	99.95%	0.51%
Highway	63.14	54.84	7.58	93.39	23.82	44.92	50.86	57.88	1,082.63	0.00%	92.24%	99.96%	1.31%

likely attributed to the density of cells and therefore handovers in Urban scenarios.

For the 4G LTE-only GW3300, there is little difference in the jitter performance, shown in Figure 12, between the four measurement routes. However, the inter-quartile ranges across all four routes are distinctly larger for the jitter performance of the 4G LTE-only GW3300 compared to the 5G NR-enabled GW1400. Given that this occurs across all routes, it is likely that packets from a 4G LTE-only device are given different priorities when traversing the cellular backhaul network.

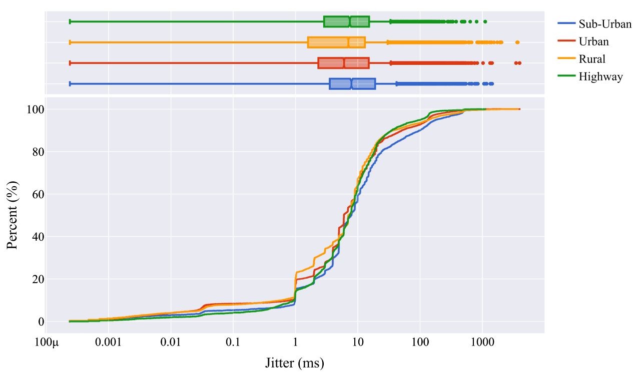

FIGURE 12. eCDF + Marginal box plot of jitter performance distribution for each route measured by 5G NR-enabled GW1400 (Sub-Urban: 7.9ms, Urban: 6.01ms, Rural: 7.06ms, Highway: 7.45ms median latency).

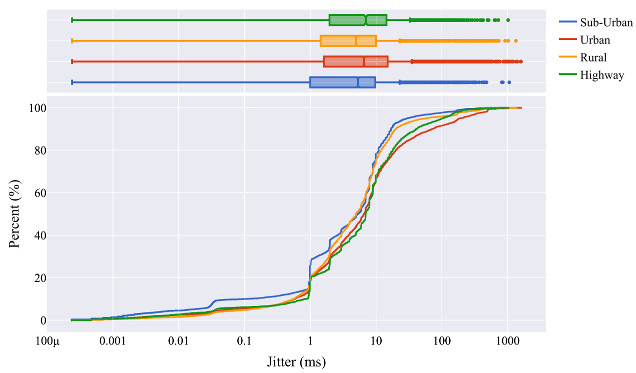

FIGURE 13. eCDF + Marginal box plot of latency performance distribution for each route measured by 4G LTE-only GW3300 (Sub-Urban: 5.31ms, Urban: 6.56ms, Rural: 5.99ms, Highway: 6.99ms median latency).

3) DISCUSSION

With the latency performance results of both measurement devices presented, the feasibility of the various V2X use cases across the BSA/ASA must be discussed.

Results demonstrate that neither the new 5G NR deployments nor, as is confirmed by previous works [13], [16], the existing 4G LTE system can uphold the very stringent latency requirements imposed by the safety-critical applications of the BSA (<20ms) and the higher automation use cases of the ASA (3-50ms) with a high degree of reliability. Though the traffic efficiency and infotainment use cases of the BSA i.e., intersection management, multimedia streaming and map updates, could be supported by the 92-95% 100ms latency reliability demonstrated by the measurement devices.

In addition, while there is a clear latency improvement provided by the 5G NR deployments, the reliability of these deployments is noticeably lower than their 4G LTE counterparts. This reliability issue is most likely attributed to optimisation challenges associated with deploying new cells and challenges surrounding packet routing for a new technology on top of an existing one. Additionally, there are distinct reliability differences between measurement routes, likely attributable to the density of cell deployments in different regions.

In general, these results show that the new radio enhancements [45] associated with 5G NR are alone not sufficient to improve the latency performance of cellular communications to the point of supporting V2X applications in their entirety. It is clear that a significant amount of the latency associated with cellular communications still remains in the back-haul and core networks. Therefore, the new architectural enhancements of 5G NR [28] regarding the distributed 5G NR core are likely necessary to bridge the gap toward the most stringent latency requirements for V2X applications. Results from the route comparison also highlight that, in order to uphold reliability requirements, current handover strategies will require revision to accommodate for devices with higher mobility i.e. vehicles.

However, deploying a fully integrated 5G core network is far more costly than deploying new 5G NR base stations. Until such a point that MNOs can justify the costs associated with a full transition to the 5G core network, the development of an "Application Map" is likely the most feasible route to enabling as many V2X applications as possible.

An "Application Map" is a mapping of a road network or geographic area, where segments of road are assigned particular applications which can be supported there. The Sub-Urban route used in this work can be used as an example of this. Samples collected for this route using the 5G NR-enabled GW1400 showed that 88.62% of latency measurements were below 100ms, which is the latency requirement for the majority of the BSA. A map like the one presented in Figure 14 can be generated to inform an intelligent vehicle where it can and cannot rely on the communications network for extra information about its environment. Moreover, maps like the one in Figure 14 can be used by MNOs to identify areas of concern where specific action can be taken to address the reliability concerns present in both generations of cellular technology.

FIGURE 14. Terrain map view of sub-urban route with latency samples <=100ms.

B. THROUGHPUT

Aside from latency, throughput i.e., download and upload rates, is another key family of metrics for V2X communications. Many of the more advanced applications of V2X communications, such as teleoperation or sensor sharing, require the transfer of audio, video and map data. These advanced applications are infeasible if the throughput QoS is too low or changes too often for the applications to adapt to.

1) OVERALL PERFORMANCE

a: DOWNLOAD

Statistics for the download performance of both measurement devices are presented in Table 7 and their corresponding distributions in Figure 15. As can be seen, as expected the mean download performance of 5G NR-enabled GW1400 (51.83Mbps) exceeds that of the 4G LTE-only GW3300 (17.85Mbps) by a factor of ~2.9x. This is further exemplified by the difference in maximum download performance between the two devices (92.07Mbps for 5G NR-enabled GW1400 vs. 62.2Mbps for 4G LTE-only GW3300) and the negative skew present for the 5G NR-enabled GW1400.

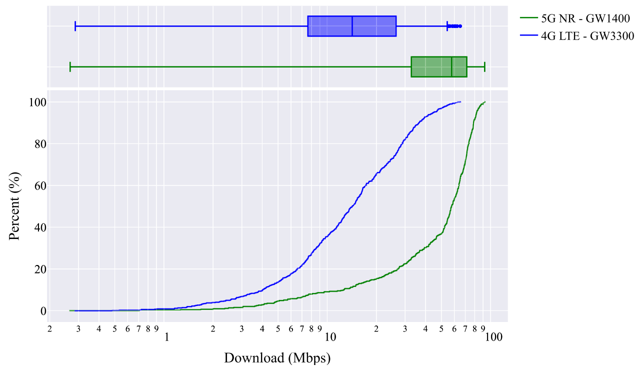

FIGURE 15. eCDF + Marginal box plot of download performance distribution for 5G NR-enabled GW1400 and 4G LTE-only GW3300 (GW1400: 57.79Mbps, GW3300: 14.23Mbps median download).

A similar trend to the device comparison is observed between the connection types experienced by the 5G NR-enabled GW1400 in Figure 16. It should be noted that there were no 3G UMTS samples collected throughout the entirety of the data collection for throughput statistics. Interestingly, for the 5G NR connection type on the 5G NR-enabled GW1400 device, no download rates less than 5Mbps were recorded. Likely this is a consequence of the lighter congestion of the 5G NR base stations compared to their 4G LTE counterparts.

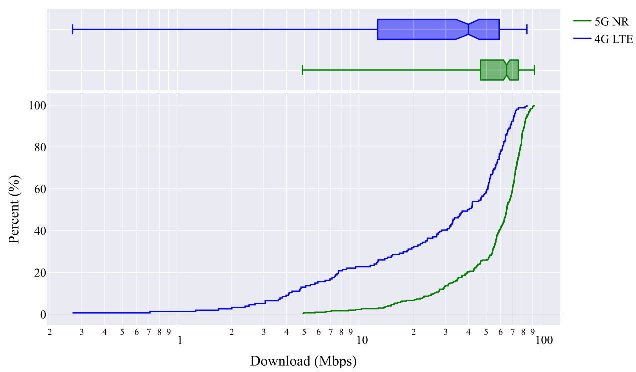

FIGURE 16. eCDF + Marginal box plot of download performance distribution for 5G NR-enabled GW1400 Access Technologies (5G NR: 64.7Mbps, 4G LTE: 39.9Mbps median download).

As with latency performance, there are several maximum download performance thresholds to determine the reliability of the system. The least stringent is given by the BSA where payloads of 1,200bytes are sent at a maximum of 10Hz, giving ~12Kbps. The various use cases of the ASA provide increasingly stringent thresholds i.e., 0.25Mbps, 10Mbps, 25Mbps, 50Mbps, 1000Mbps etc., with the most common

TABLE 7. Download statistics.

Download (Mbps)	Mean	StD.	Skew	Kurt.	Min.	25%	50%	75%	Max.	>5Mbps	>10Mbps	>25Mbps	>50Mbps
5G-en.	51.83	24.40	-0.59	-0.82	0.27	32.77	57.79	71.47	92.07	95.16%	90.77%	81.32%	63.08%
4G-only	17.85	13.31	1.06	0.65	0.29	7.62	14.23	26.39	65.20	86.25%	64.35%	27.19%	3.17%

being ranging between 1-50Mbps. Given that the maximum recorded download rate was 92.07Mbps, the columns presented in Table 7 highlight the degree of reliability with which the most common download performance requirements. From these columns, it is clear that the 5G NR system can more reliably provide download rates required for the more common requirements of the ASA than the 4G LTE system. However, the reliability is still not sufficient to meet the stringent 90-99.999% requirement.

b: UPLOAD

Table 8 and Figure 17 present the upload performance statistics and distribution plots for both measurement devices. Similar to the download performance, the mean upload performance of the 5G NR-enabled GW1400 outperforms the 4G LTE-only GW3300 by a factor of ~1.31x. However, there is a significant difference in the reliability of the two devices as can be seen in the inter-quartile range of Figure 17, the 5G NR-enabled GW1400 has significantly more samples in the <10Mbps range and >40Mbps range compared to the 4G LTE-only GW3300.

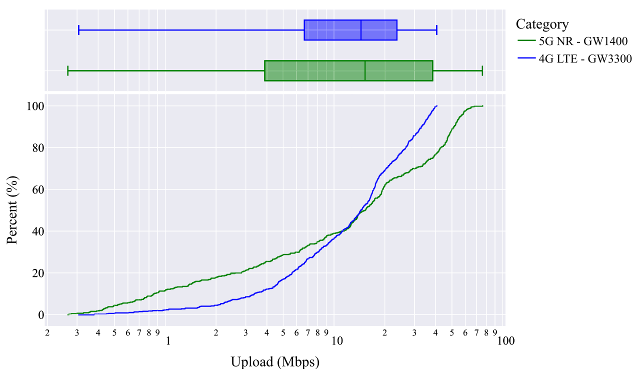

FIGURE 17. eCDF + Marginal Box plot of upload performance distribution for 5G NR-enabled GW1400 and 4G LTE-only GW3300 (GW1400: 15.28Mbps, GW3300: 14.45Mbps median upload).

When considering the connection types experienced by the 5G NR-enabled GW1400 in Figure 18, there is a clear trend similar to that of the download performance. The 5G NR connection type performs significantly better than its 4G LTE counterpart. Again, it should be noted that there were no 3G UMTS samples collected throughout the entirety of the data collection for throughput statistics.

As previously mentioned, it should be noted that the majority of V2X applications regard upload and download directions as the same. However, in practice typically the upload direction will have a lower data rate due to power constraints associated with mobile transceivers. In addition

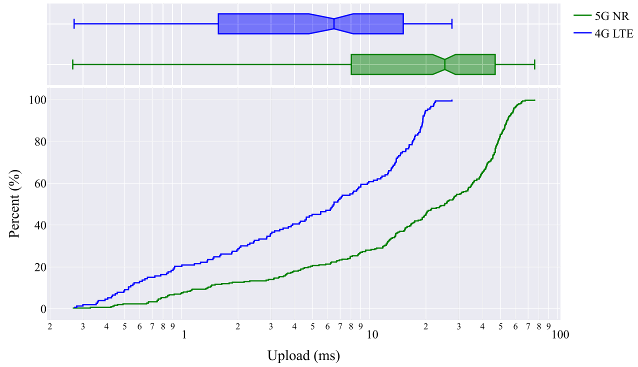

FIGURE 18. eCDF + Marginal box plot of upload performance distribution for 5G NR-enabled GW1400 Access Technologies (5G NR: 25.23Mbps, 4G LTE: 6.49Mbps median upload).

to power constraints, it is also typical for MNOs to configure more wireless resources for download as typical applications e.g., multimedia streaming, have users receiving information more often than sending. Upload requirements for the various use cases of the ASA, like the download requirements, provide increasingly stringent thresholds i.e., 0.25Mbps, 50Mbps, 1000Mbps etc., with the most common being ranging between 1-50Mbps. Given that the maximum recorded download rate was 75.81Mbps, the columns presented in Table 8 highlight the degree of reliability with which the most common upload performance requirements. As was apparent from the download performance, it is clear that the 5G NR system can more reliably provide upload rates required for the more common requirements of the ASA than the 4G LTE system. However, the reliability is still not sufficient to meet the stringent 90-99.999% requirement.

2) ROUTE COMPARISON

Following the presentation of the overall throughput performance of both devices, the following subsection will compare the throughput performance of both devices across each of the four driving routes used to conduct the measurements.

a: 5G NR-ENABLED GW1400

When only considering the download samples from the 5G NR-enabled GW1400, see Figure 19 and Table 9, it is clear that there is relatively similar performance across all driving routes. However, the Urban route displays marginally higher download rates throughout its quartiles while the Rural route was found to have the lowest. This is highlighted by the mean 55.14Mbps download rate for the Urban route and only 48.88Mbps for the Rural route. There is little difference in the distributions across the four routes, though the Sub-Urban

TABLE 8. Upload statistics.

Upload (Mbps)	Mean	StD.	Skew	Kurt.	Min.	25%	50%	75%	Max.	>5Mbps	>10Mbps	>25Mbps	>50Mbps
5G-en.	21.03	19.20	0.72	-0.79	0.26	3.90	15.28	38.44	75.81	71.08%	60.93%	33.77%	11.04%
4G-only	15.96	10.74	0.55	-0.73	0.31	6.67	14.45	23.59	40.62	82.75%	63.24%	22.54%	0.00%

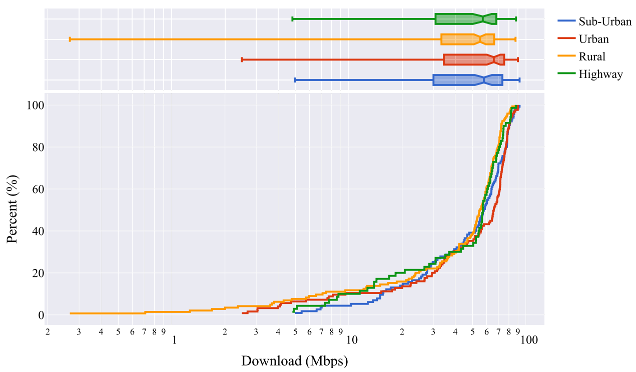

FIGURE 19. eCDF + Marginal box plot of download performance distribution for each route measured by 5G NR-enabled GW1400 (Sub-Urban: 57.86Mbps, Urban: 65.86Mbps, Rural: 55.08Mbps, Highway: 57.07Mbps median download).

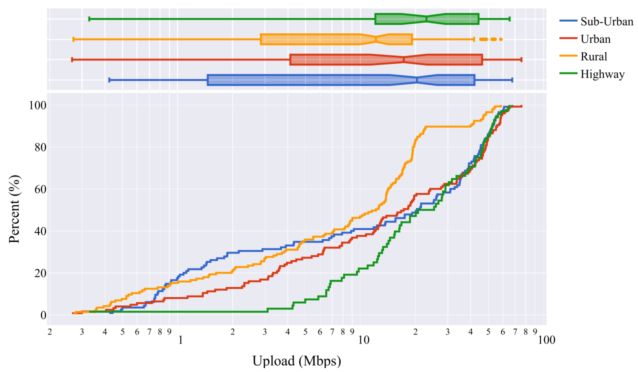

FIGURE 20. eCDF + Marginal box plot of upload performance distribution for each route measured by 5G NR-enabled GW1400 (Sub-Urban: 20.34Mbps, Urban: 17.23Mbps, Rural: 12.13Mbps, Highway: 22.94Mbps median upload).

route has a larger inter-quartile range, and thus slightly lower reliability, compared to the others.

The upload samples for each of the four routes from the 5G NR-enabled GW1400, see Figure 20 and Table 10, do not follow the same trend as the download samples. In general, the Highway route exhibited significantly more reliable high upload rates compared to the other routes, with the Rural route performing the poorest. This difference between the Highway and Rural routes can likely be attributed to the number of obstructions, particularly foliage, present along the route. This trend is further highlighted by the mean upload rates (26.85Mbps for Highway and 13.67Mbps for Rural), and the percentage of samples above 25Mbps (50% for Highway and 10.34% for Rural). Compared to the download rates, there is a far more significant spread of upload rates across the four routes, as is shown by the inter-quartile ranges in the box plot of Figure 20.

b: 4G LTE-ONLY GW3300

A more distinct divergence occurs when only considering the download samples from the 4G LTE-enabled GW3300 compared to the 5G NR-enabled GW1400, presented in Figure 21 and Table 11. Interestingly, there is a clear split where the Sub-Urban (mean 21.23Mbps) and Highway (mean 22.21Mbps) routes perform similarly while outperforming the Urban (mean 15.22Mbps) and Rural (mean 16.41Mbps) routes which also perform similarly. The Sub-Urban route has the highest degree of reliability as is exemplified by its inter-quartile range in Figure 21.

Likewise, when only the upload samples for each of the four routes from the 4G LTE-only GW3300 are considered, see Figure 22 and Table 12, there is a clear difference

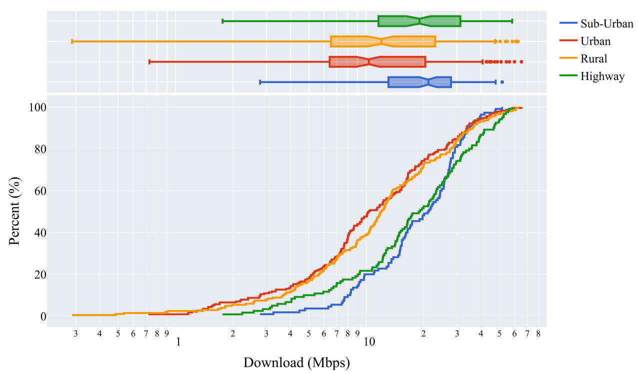

FIGURE 21. eCDF + Marginal Box Plot of Download Performance Distribution for each route measured by 4G LTE-only GW3300 (Sub-Urban: 21.18Mbps, Urban: 10.33Mbps, Rural: 12.01Mbps, Highway: 19.03Mbps median download).

between routes compared to samples from the 5G NR-enabled GW1400. Overall, the Sub-Urban route displayed both higher average upload rates alongside a high degree of reliability as is seen from the mean upload rate (22.24Mbps) and the box plot in Figure 22. By comparison, the Rural route performed the most poorly with a mean upload rate of 10.52Mbps and a significantly lower percentage of samples above 25Mbps (42.73% for Sub-Urban, 4.46% for Rural).

3) DISCUSSION

With the download and upload performance results of both measurement devices presented, the feasibility of the various V2X use cases across the BSA/ASA must be discussed.

As with the latency performance, results show that the new 5G NR deployments do in fact offer improvements in both download and upload over the existing 4G LTE system. This

TABLE 9. 5G NR-enabled GW1400 download performance route comparison statistics.

Download (Mbps)	Mean	StD.	Skew	Kurt.	Min.	25%	50%	75%	Max.	>5Mbps	>10Mbps	>25Mbps	>50Mbps
Sub-Urban	52.90	24.32	-0.41	-1.05	4.97	30.38	57.86	73.47	92.07	99.13%	95.65%	82.61%	60.87%
Urban	55.14	25.55	-0.71	-0.76	2.49	34.58	65.86	75.26	90.11	93.60%	89.60%	84.00%	64.80%
Rural	48.88	23.32	-0.70	-0.61	0.27	33.52	55.08	65.92	87.33	92.41%	88.28%	79.31%	61.38%
Highway	50.25	24.24	-0.62	-0.87	4.81	30.89	57.07	67.93	87.92	97.14%	90.00%	78.57%	67.14%

TABLE 10. 5G NR-enabled GW1400 upload performance route comparison statistics.

Upload (Mbps)	Mean	StD.	Skew	Kurt.	Min.	25%	50%	75%	Max.	>5Mbps	>10Mbps	>25Mbps	>50Mbps
Sub-Urban	23.39	20.77	0.32	-1.39	0.42	1.48	20.34	41.92	67.53	65.22%	59.13%	46.96%	13.91%
Urban	24.23	21.27	0.52	-1.18	0.26	4.19	17.23	46.19	75.81	72.80%	62.40%	40.00%	15.20%
Rural	13.67	13.74	1.53	2.01	0.27	2.85	12.13	19.10	58.52	64.14%	53.10%	10.34%	3.45%
Highway	26.85	18.18	0.43	-1.12	0.33	12.18	22.94	43.53	65.36	92.65%	77.94%	50.00%	14.71%

TABLE 11. 4G LTE-only GW3300 download performance route comparison statistics.

Download (Mbps)	Mean	StD.	Skew	Kurt.	Min.	25%	50%	75%	Max.	>5Mbps	>10Mbps	>25Mbps	>50Mbps
Sub-Urban	21.23	10.61	0.44	-0.25	2.77	13.20	21.18	27.83	51.67	96.36%	80.00%	39.09%	0.91%
Urban	15.22	12.76	1.38	1.67	0.73	6.44	10.33	20.21	65.20	82.10%	52.40%	20.52%	2.18%
Rural	16.41	13.54	1.35	1.47	0.29	6.62	12.01	22.97	62.49	83.25%	61.08%	22.66%	3.45%
Highway	22.21	14.56	0.71	-0.34	1.76	11.64	19.03	31.13	58.33	90.00%	78.33%	36.67%	6.67%

TABLE 12. 4G LTE-only GW3300 upload performance route comparison statistics.

Upload (Mbps)	Mean	StD.	Skew	Kurt.	Min.	25%	50%	75%	Max.	>5Mbps	>10Mbps	>25Mbps	>50Mbps
Sub-Urban	22.24	8.80	-0.47	-0.11	0.45	17.38	23.73	27.69	40.45	94.55%	89.09%	42.73%	0.00%
Urban	15.11	10.07	0.81	-0.25	0.38	6.87	13.18	19.92	39.75	85.59%	62.01%	17.03%	0.00%
Rural	10.53	7.11	0.69	0.09	0.31	4.72	9.14	16.21	34.07	73.27%	47.03%	4.46%	0.00%
Highway	20.95	13.27	-0.06	-1.51	0.80	7.95	20.91	34.31	40.62	82.50%	69.17%	45.00%	0.00%

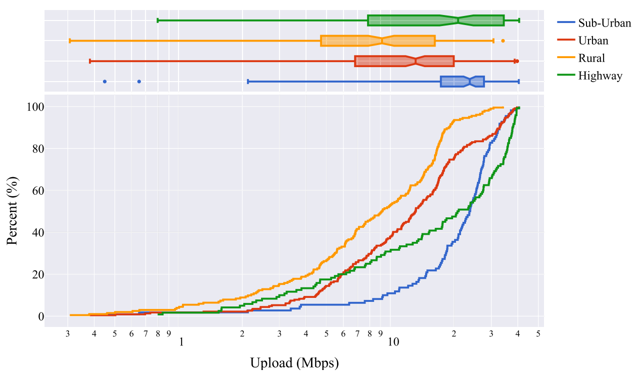

FIGURE 22. eCDF + Marginal Box Plot of Upload Performance Distribution for each route measured by 4G LTE-only GW3300 (Sub-Urban: 23.73Mbps, Urban: 13.18Mbps, Rural: 9.14Mbps, Highway: 20.91Mbps median upload).

improvement in both download and upload performance can be attributed to the newer radio technology introduced by 5G NR. In addition, the reliability of these new 5G NR deployments is noticeably higher than their 4G LTE counterparts. However, there is a high likelihood that the new 5G NR base stations are less congested than the 4G LTE base stations. Additionally, there are notable differences in download and upload reliability between measurement routes. These differences between the measurement routes are likely attributable to the average distance to the serving cell, the average level of congestion of the serving cell and particularly, the average level of obstruction present along the route in each scenario.

Overall, while it appears both technologies can support the throughput requirement of the BSA (12Kbps), results illustrate that neither can reasonably support the more stringent requirements i.e., >50Mbps, of use cases such as vehicle platooning and extended sensors. Moreover, there still exists an uneven weighting between the download and upload rates which severely hinders either technologies ability to support many V2X use cases.

Unlike the findings regarding the latency performance, these results show that the new radio enhancements [45] associated with 5G NR play a significant role in the ability of cellular communications to support V2X communications as a whole. It is clear that there is still a limitation on what the new 5G NR deployments can provide in terms of throughput, which may be solved by technologies such as mmWave [46]. In the mmWave frequency bands, introduced as part of the new 5G NR specifications in the FR2 band [47], [48], there is sufficient bandwidth available such that the most stringent throughput requirements imposed by V2X communications (>500Mbps) may be supported.

VI. LIMITATIONS AND FUTURE WORK

The results and findings presented in this work are primarily limited by the practical limitations of using a single test vehicle to conduct measurements, only a portion of the total road network within the coverage of an MNO can be covered. Given that the network under study was a commercial network, it must be treated as a black box and therefore the results reflect only the end user's experience. As a consequence, information regarding session handling, cell congestion, routing protocols etc. cannot be obtained. In addition, the cellular sidelink was not included as part of this measurement campaign. Regardless, these results and findings can be used to advise MNOs and automotive manufacturers on how 5G NR needs to mature as a technology in order to support applications such as V2X communications.

In future, the current dataset will be expanded to encapsulate more of the available road network across different times of day, days of the week and seasons of the year. This can be further bolstered by the inclusion of an increased number of test vehicles across several MNOs. A deeper analysis of more specific factors such as handover, static obstructions, environmental factors and vehicle telemetries will be carried out to isolate the parameters that have the greatest effect on the KPIs studied in this work. Additionally, a re-creation of the conducted driving-based measurement campaign will be repeated utilising the cellular sidelink to more accurately represent the whole capabilities of cellular technology as a V2X communications system.

VII. CONCLUSION

In this work, we present a driving-based measurement campaign conducted to assess the feasibility of V2X applications in early 5G NR deployments. This measurement campaign was conducted by collecting passive and active network measurements from two cellular routers; one with 5G NR capabilities and the other without, installed in a test vehicle. This test vehicle was driven throughout sub-urban, urban, rural and motorway areas to provide a reasonable representation of typical driving environments.

In general, results show that new 5G NR deployments can indeed outperform the existing 4G LTE system in ideal conditions. Particularly, the new 5G NR system has been demonstrated to be more performant and subject to less variability in terms of both download and upload performance compared to the 4G LTE system. Interestingly, it has been found that the latency performance of new 5G NR deployments is subject to a significant degree of variability and as such is less much reliable than the 4G LTE system.

However, even with the benefits provided by the new 5G NR deployments, neither technology can support the stringent requirements of the entire suite of V2X applications. While the stringent requirements associated with safety-critical V2X use cases are not currently feasible, the improvements demonstrated illustrate that the non-safety-critical use cases, such as general traffic efficiency, just-in-time repair and infotainment can be supported.

To address the latency challenges still present in the cellular network, it is likely that some form of implementation of the distributed 5G core network is necessary to support the very stringent latency requirements imposed by safety-critical applications. Likewise, there is a distinct limitation in throughput, which will likely be addressed by the introduction of mmWave radios, as part of the 5G NR FR2 band, where there exists a large amount of bandwidth available. Lastly, given the distinct differences in performance across the various driving routes, it is clear that further planning is required in terms of cell placement and distribution. In order to ensure that the cellular network is capable of upholding the stringent requirements necessary for V2X communications, so-called ''Application Maps'' should be generated such that MNOs can identify geographic areas or road segments of concern.

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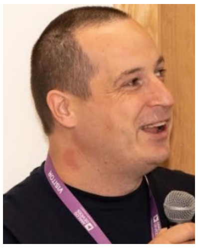

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