Project Report

Automated Mobility for Elderly and People with Disability: How 5G Can Help

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0 Summary

Background

Limited field of view is currently the main limitation affecting the safety of autonomous driving. Intelligent car perception hardware systems at the moment depend on direct line-of-sight senses. As these systems are mounted on vehicles, there will inevitably be a "blind spot" phenomenon. No matter how smart the on-board equipment is, it cannot compute unseen information.

Hence, driving safety can be improved if on-board equipment can cooperate with Roadside Units (RSUs) that can look further ahead and even around the corner to extend the obstacle detection range. As connected vehicles will enter the market before automated vehicles, RSUs can improve road safety even in the short to midterm in line with the penetration of connected cars. An additional benefit of RSU is that, compared to single-vehicle intelligence, vehicle-road collaboration can become a more affordable choice, as it can reduce the dependence of smart cars on high-performance chips. Lastly, using the RSUs, automated vehicles will be able to drive smoother with fewer abrupt stops and potentially a higher average speed because they can drive with the confidence of an expanded field of view, which has significance to improve the riding experience of elderly and disabled people.

Role of 5G

The above benefits rely on fast and reliable communication networks, such as LTE (4G) and 5G. Experts from various sectors, such as the 5G Automotive Association (5GAA), define the basics for common standards to meet the specific requirements for interconnecting with the various road users and for autonomous driving. The 5G network will offer high-performance communication advancing the development of autonomous cars. With the development of new generations of wireless communication for ITS, i.e., 5G-V2X, 5G will be a critical feature for autonomous vehicles to provide fast and reliable communications. The necessity of integrating and using 5G technology in autonomous vehicles is more prominent, which is also the key force to promote the development of vehicle-road collaborative autonomous driving.

Trial outcomes

In this report, we provide the performance evaluation of 4G and 5G communications on an OHMIO autonomous vehicle at Sydney Olympic Park, and La Trobe Bundoora Campus. An RSU is set up in the T intersection of the trial site to improve the perception capability of OHMIO vehicles. The tests include the 5G communication performance baseline reference testing and RSU-to-vehicle complex road scenario testing. Remote monitoring and control capacities via 4G/5G communication were tested using Zao-X software suites.

Our trials show that the OHMIO autonomous vehicles are able to drive using single-vehicle intelligence in conjunction with the RSU via 4G/5G communication. The RSU can provide the capability to detect the obstacles from the side roads where line-of-sight is not able to achieve. The vehicle or RSU analyses the traffic environment, such as accidents, abnormal vehicle behaviour, and various obstacles in its path. This is accomplished through the use of lidars, cameras and other sensing devices. It then communicates the data through V2V/V2I (Vehicle to Vehicle/Vehicle to Infrastructure) communication protocols. The detection results can be shared among other vehicles within the network. Through the real-time interaction of shared detection data, the range of the vehicle's understanding of the perceived environment is expanded. This will provide the information that can avoid traffic hazards caused by insufficient vehicle perception capacities or blind spots. The RSU enables the vehicle to obtain the information of traffic participants outside its own perception range, and assist itself to make safer driving decisions, which can reduce traffic accidents, and improve driving safety. We also trialled the network performance of remote monitoring and control functions using

the Zao-X software suites. In summary, the trial results demonstrated that today's 5G communication is capable of providing fast and efficient communication between the RSU and OHMIO autonomous vehicles and providing sufficient low-latency communication for remote monitoring and control functions, to enhance the riding experience of elderly and disabled passengers.

1 Automated Mobility for Elderly and People with Disability

Self-driving cars may change the lives of the elderly and disabled people. The potential of this new technology to save lives and provide more mobility to the elderly and disabled people has been widely recognised. For those elderly and disable people who cannot drive, this technology may be most useful. The elderly or disabled people will find freedom and independence with the widely deployed self-driving cars.

5G is the fifth generation of wireless cellular technology that offers higher upload and download speeds, more consistent connections, and higher capacity than previous networks. 5G is faster and more reliable than the currently popular 4G LTE network and has the potential to change the way we use the Internet information. 5G is not only a new generation of mobile communication technology, but also a new infrastructure for network, economic and social development. There is no doubt that technologies such as self-driving cars and live streaming that require very reliable high-speed data connections will greatly benefit from 5G connectivity. 5G offers automakers various options to adapt to the changing transportation market. Although 5G also needs to rely on infrastructure, its ultra-fast network connection function is the key to the development of CAV (Connected Autonomous Vehicle), which still needs to rely on a lot of high-speed data transmission.

At present, automakers and technology companies are developing 5G technology, and we can see the huge potential of 5G technology in the context of CAV. The purpose of our research is to explore opportunities that 5G offers to improve the performance of CAV shuttles and their accessibility to elderly and people with disability. A trial will be conducted testing 5G and use cases that are enabled by 5G that will enhance the accessibility of CAV for the elderly and people with disability. The trial will deliver an evaluation of the 5G communication performance in the trial site, to provide a baseline reference data for the 5G communication performance measurement on the RSU and shuttle vehicles. For remote monitoring and controlling, the video system is an important part of the CAV end to ensure the disabled passengers' safety. It is used to provide real-time status of the surrounding environment of the CAV and provide driving vision for the remote operator. Therefore, it is necessary to ensure the range of viewing angle and the clarity of the picture without distortion. Generally, 3 cameras can ensure the driver's perspective as much as possible. 5G communication will ensure the long latency data transmission between the CAV and the remote-control centre. One of the key tasks in this project is to measure the 5G communication performance in CAV road trial scenarios to understand the network quality for the bi-directional data communications optimisations.

In this report, we will see the following 5G applications implemented:

1. Low-latency real-time transmission of encrypted vehicle sensor and operational data, and high-resolution video from a CAV to a control room to support remote monitoring and control of the vehicle.
2. Remotely control a CAV from a control room through the use of highly reliable and ultralow latency communications to send encrypted movement commands and receive real-time status updates.
3. High-speed low-latency transmission of encrypted sensor data to enable the real-time analysis and fusion of sensor data from multiple stations, including on-vehicle and roadside sensors, which will then be used to assist an ASV to negotiate difficult road and traffic scenarios, as depicted in the diagram below.

2 5G Communication Testing Methodology

To evaluate the 5G communication performance while also meeting the expectation on the trial site, a baseline testing of 5G communication was conducted by CTI. RantCell software is used to measure the 5G signal strength, Downlink/Uplink speed, bandwidth, etc. The baseline test results are expected to demonstrate that the 5G communication performance satisfies the requirement from a user's perspective.

Another objective is to ensure the RSU performs well in any trial site with a 4G or 5G network. It is expected that the vehicle can handle complex road and traffic scenarios more efficiently with an RSU. For example, the RSU can improve safety and speed in an intersection where the line of sight cannot be achieved by the vehicle. The vehicle can successfully detect obstacles approaching a T intersection and pass the intersection with the assistance of the RSU. The 4G and 5G communication performance must meet the requirements of operating the OHMIO shuttle vehicle. When the vehicle drives on the trial site at different speeds, the RSU must then send Obstacle Warning messages with very low latency and very low packet loss through 4G or 5G communication. To evaluate this, CTI measures the accurate end-to-end latency (ms) and reliability (%) of the message delivery from the RSU to the vehicle as the key metrics. A GPS timing synchronisation device is connected to the RSU and the vehicle separately to achieve micro-second level synchronisation accuracy.

2.1 RantCell 5G Communication Measurement Software

With traditional 5G NR test equipment, network testing is time-consuming and requires a lot of effort to prepare data for the analysis phase. RantCell Pro is a smart 5G RF drive testing and monitoring tool which uses the app and cloud-based technology. An Android 5G phone has the RantCell Pro app installed and can act as the 5G measuring equipment. RantCell is one of the ideal 5G testing tools which can accurately measure KPIs and provide results in real-time with no post-processing efforts and other time-saving functionalities.

RantCell can provide:

- RantCell pro app supports 5G NSA measurement suitable for drive testing and static testing.
- Supporting commercial grade 5G Android phones, no need to purchase any hardware
- Real-time upload of QoE data to RantCell cloud from app, no post-processing efforts.
- Generating reports in near real-time.
- Idle mode outdoor and indoor measurement; supports floor plan loading.
- RantCell pro can work as monitoring the performance of 5G base stations and remotely trigger on-demand tests.

In the trial, A Samsung Galaxy A53 5G mobile phone was used as a client terminal. The test data has been uploaded to the RantCell Cloud in real time. The tests that were run on the mobile phone include:

- Speed Test (upload and downloads tests)
- Ping Test
- Network Coverage Test
- Latency Test
- Web Test

The outcome results include latency, packet loss, and signal strength such as RSRP, network data type, and network type (4G or 5G).

2.2 GPS Timing Synchronisation

To accurately measure the end-to-end latency on different devices on the RSU and vehicle, a timing synchronisation approach is needed. In this trial, the hardware chosen for this project is the CohdaWireless MK5 OBU devices employing an advanced u-blox8 GNSS receiver. The MAC provides full IEEE 802.11p support and full support for MAC time-synchronisation utilising the provided time information and 1PPS signal from the GNSS receiver. Two CohdaWireless DSRC devices (with GPS sensor and antenna) were provided by CTI, with the same subnet setting as the RSU and vehicle. One DSRC device is connected to the RSU subnet, and the other DSRC device is connected to the vehicle subnet. An adaptor was used to supply a clean 7V to 36V supply to the Cohda devices. Depending on the application the typical power consumption is 5 to 6W with a maximum of 8W.

CTI configured the RSU and vehicle NTP server to the DSRC Device to synchronise GPS time. The OHMIO used the latency measurement software to record the sending timestamp of the RSU and the received message timestamp of the vehicle (with an index number of each packet). Therefore, the end-to-end latency can then be very accurately measured on two devices simultaneously with microsecond level accuracy. Within the Matlab software, the log files are analysed and used to calculate the end-to-end latency of the same packet index, and the packet loss number.

In a nutshell, the selected solution between two machines synchronised over the Internet has a typical accuracy within a few milliseconds; on a LAN, the accuracy is typically in the tens of microseconds. With hardware timestamping, or a hardware reference clock, sub-microsecond accuracy may be possible.

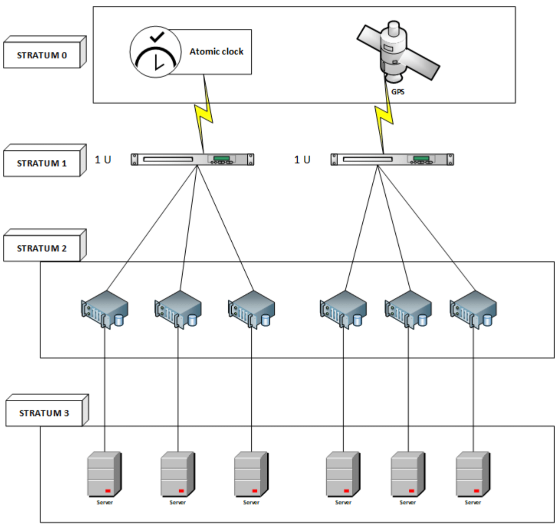

Figure 1. Block diagram of stratum levels of time synchronization using NTP/PTP protocols.

The tools used in this test:

The CohdaWireless MK5 unit utilises the Ubuntu 14 OS and chrony package to operate as an NTPv4 (RFC 5905) server and peer to provide a time service to the other computers within the network. Unlike ntpd, the chrony supports synchronising the system clock via hardware timestamping, which improves the accuracy of time synchronisation between devices on a LAN. It also can perform time correction within an isolated network. And last but not least, chrony time correction uses fade in algorithms by adjusting the system clock speed in order to avoid sudden jumps in the system time. Installation steps include:

1. Install chrony package on Ubuntu OS:

   # sudo apt install chrony

2. Add the new IP to NTP source list
3. reboot
4. chrony – Introduction
5. ethtool -T eth0 returns – hardware timestamp
6. iperf or iper3

Verification steps include:

1. chrony sources
2. chrony tracking
3. chrony statistic

2.3 Bandwidth and Packet Loss Measurement

The network analysis tool iPerf3 was used to measure the maximum achievable bandwidth, jitter, and packet loss, on the 5G communication between the RSUs and the vehicles. iPerf3 supports the tuning of various parameters related to timing, buffers and protocols (TCP, UDP, SCTP with IPv4 and IPv6). iPerf3 can be used to measure the download and upload throughput, Round-trip Time (RTT), jitter (latency variation), and packet loss rate. The iPerf3 server was installed on the RSU. The iPerf3 client was installed on the vehicle's computer (Ubuntu). 5G communication protocols were then used for the communication between the two devices (server and client). Variable parameters, interval, packet size, and bandwidth, can be configured to test different traffic conditions.

3 Sydney Olympic Park Trial

3.1 Trial Scenarios

On the 1st of July 2022, CTI conducted the trial of the OHMIO autonomous vehicle (as shown in Figure 2) in Sydney Olympic Park. The vehicle drove around the trial route at various speeds (max speed is 20km/h). The trial site is shown in Figure 4. The shuttle moved around the warehouse buildings that blocked the line of sight. The onboard Lidar was turned on to monitor the obstacles on the route. The onboard camera was turned on to capture the video of road conditions. As shown in Figure 3, the driver can configure the direction, move/stop the vehicle, adjust the speed, and record the tracks of the route on the onboard control panel. The vehicle status such as the battery level, position, and speed, can also be shown on the control panel.

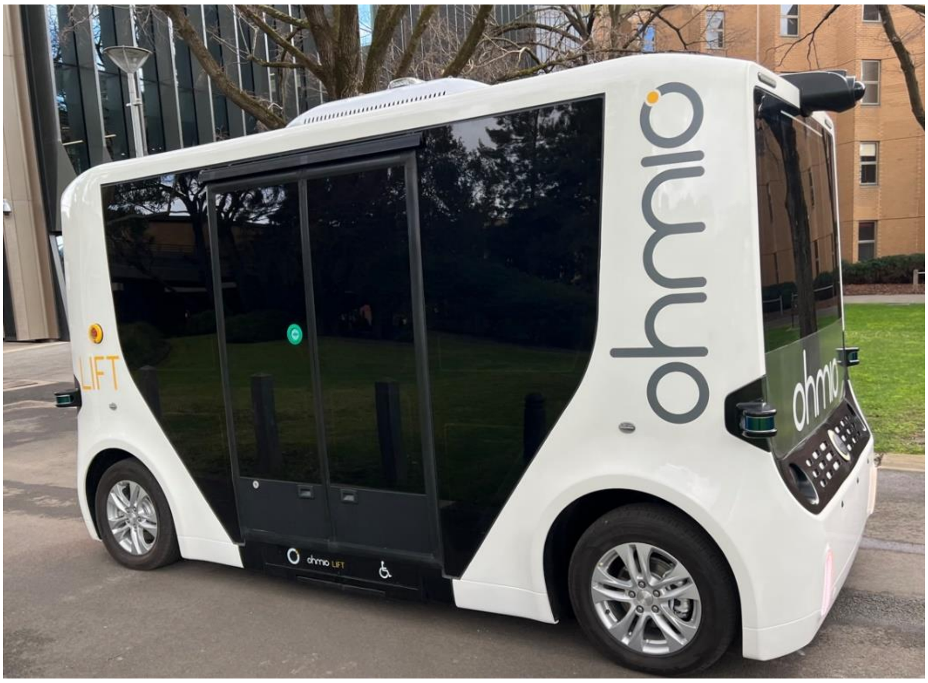

Figure 2 OHMIO Autonomous Shuttle

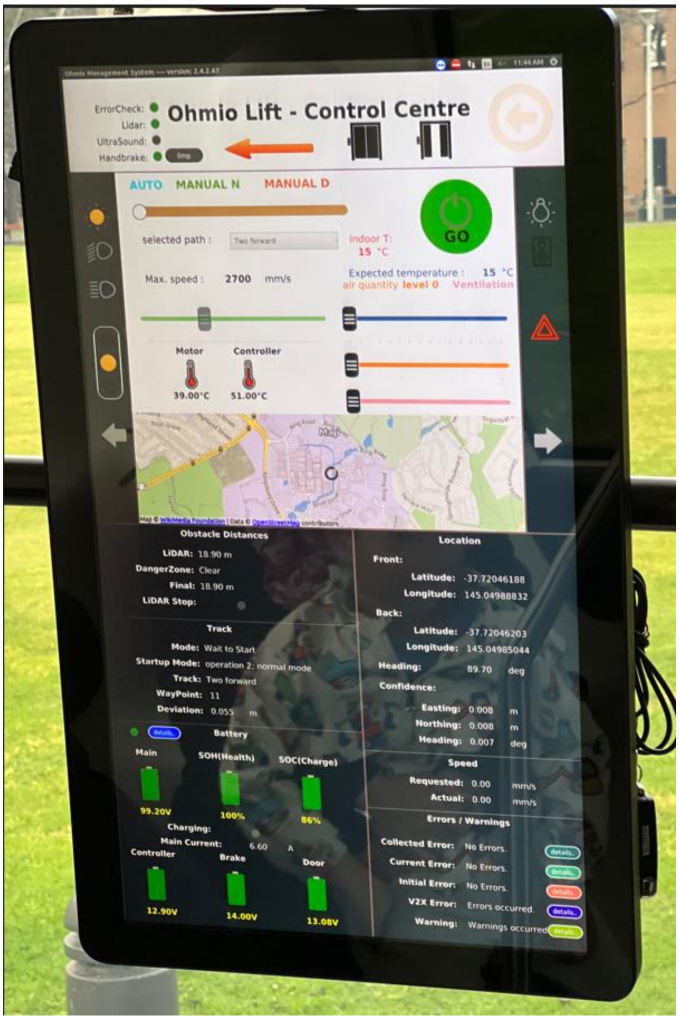

Figure 3 OHMIO Autonomous Shuttle Control Panel

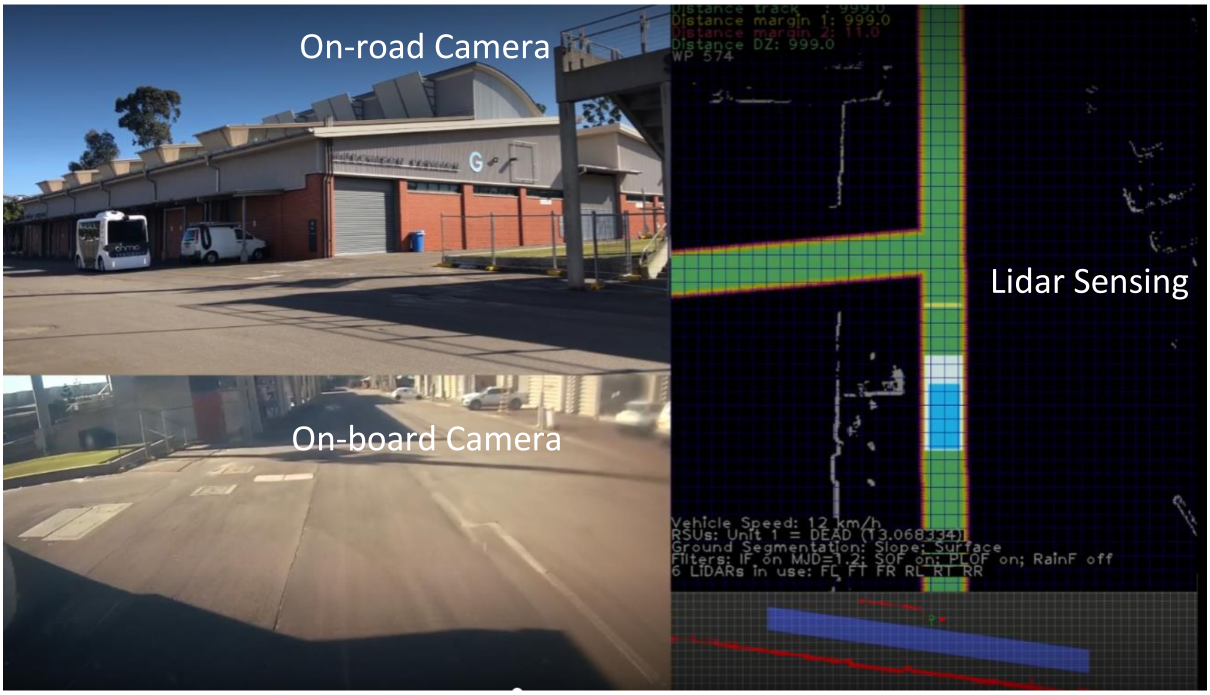

Figure 4 Sydney Trial Site

3.2 Network Performance Test

During the trial, the RantCell software was used to measure the baseline network performance. Figure 5 shows the RantCell trial site signal strength mapping. The client device is the Samsung Galaxy A53 5G mobile phone with the Telstra and Vodafone SIM card. The test data was automatically uploaded to the RantCell Cloud. The shuttle bus drove around the trial site for almost 4 hours in total, during this time it accumulated the data which provided 2023 valid test samples in total.

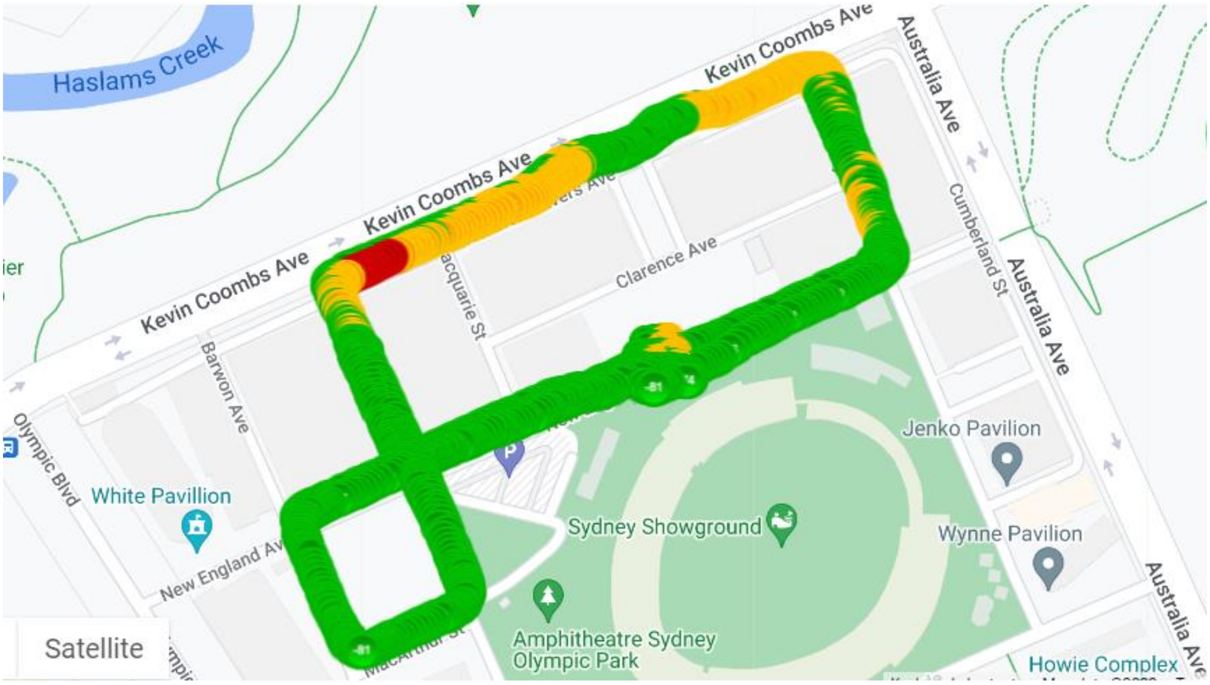

Figure 5 Sydney Olympic Park Trial Signal Strength Mapping

Table 1 Signal Strength RSRP Statistics

RSRP- Signal Strength	Percentage
>= to -89dBm	80.6228 % (count : 1631)
B/w -99dBm to -90dBm	16.0652 % (count : 325)
B/w -112dBm to -100dBm	3.3119 % (count : 67)
Total Geo samples	2023

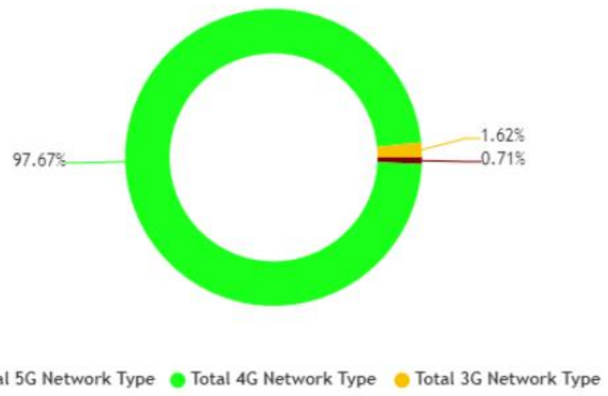

Figure 6 Network Type

As shown in Figure 6, because the Telstra/Vodafone base station deployed in the trial site is 4G, the mobile terminal can mostly receive the 4G signal rather than 5G. Almost 97.67% signal received was 4G signal. Table 1 shows that 80.62% signals strengths are greater than -89dBm, which means very good signal coverage. As shown in Figure 7, 100% packet have been successful delivered without any loss.

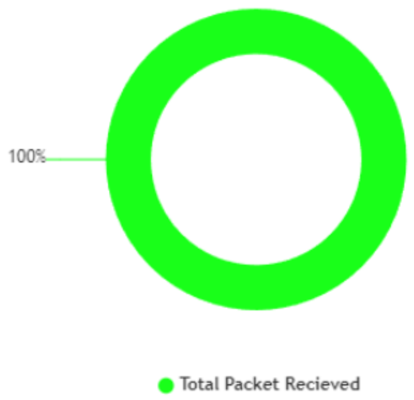

Figure 7 Total Packet Received

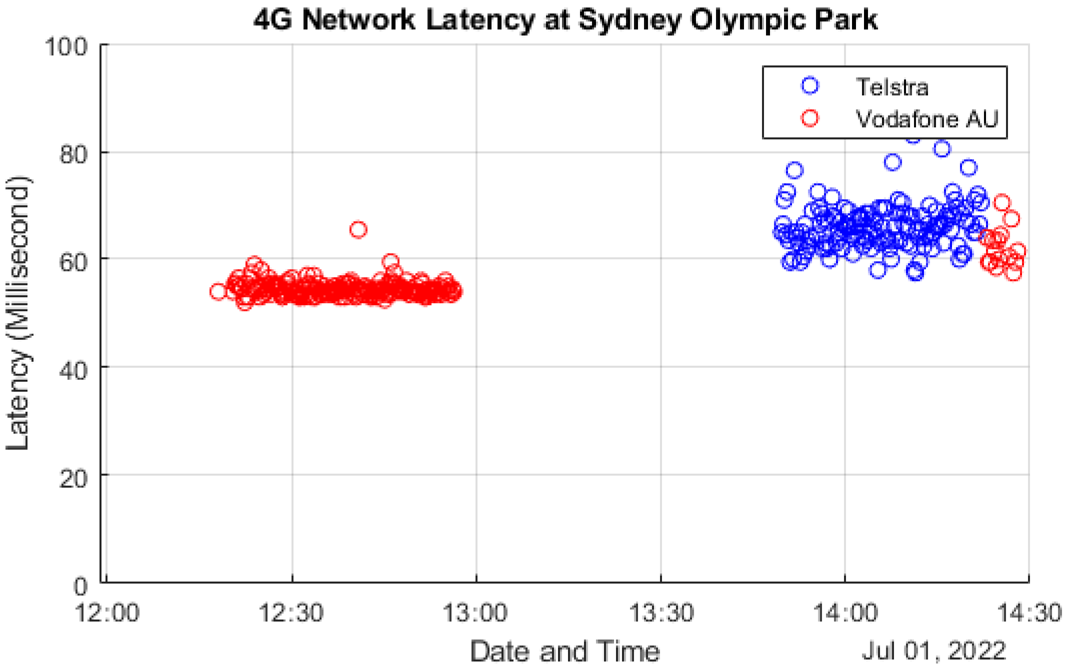

Figure 8 Latency Test on Telstra and Vodafone 4G Network

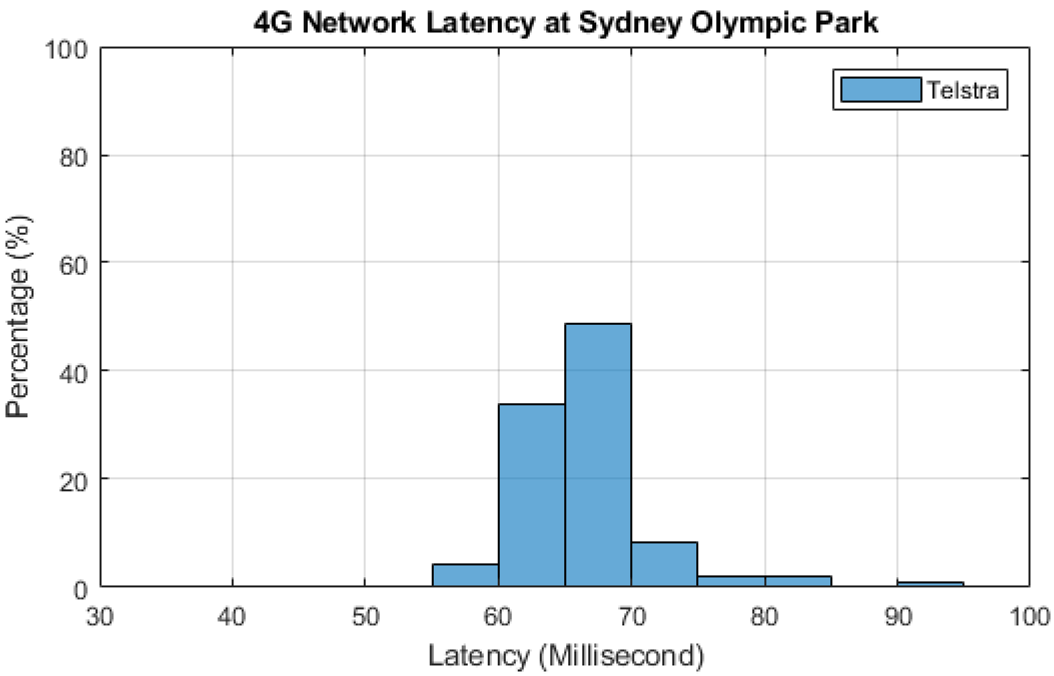

Figure 9 Histogram of Network Latency of Sydney Trial – Telstra

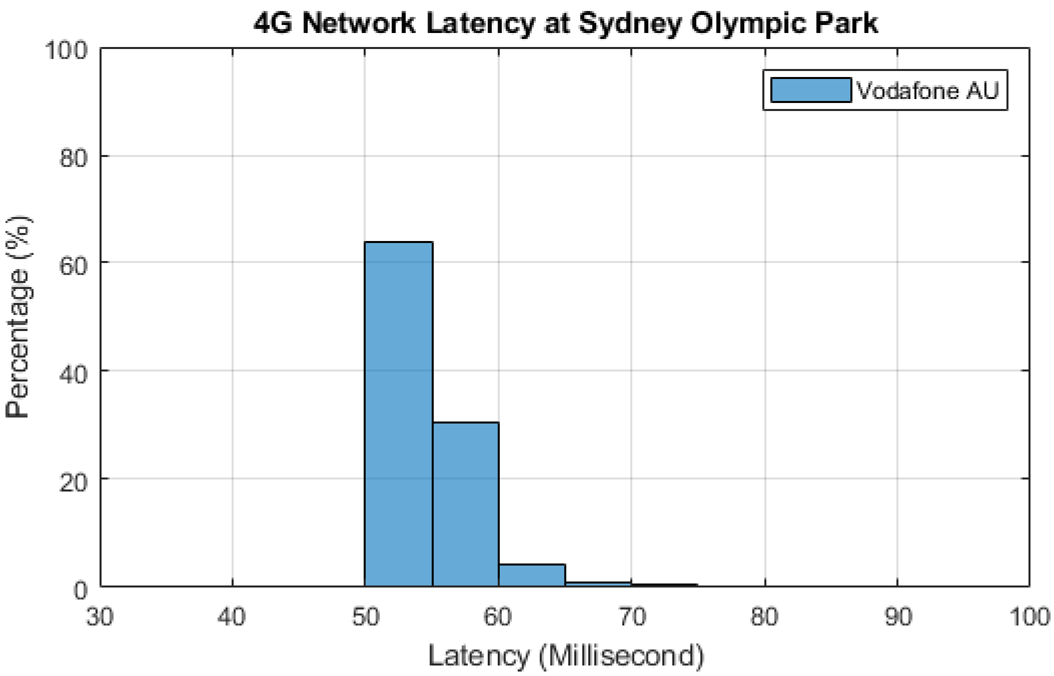

Figure 10 Histogram of Network Latency of Sydney Trial – Vodafone

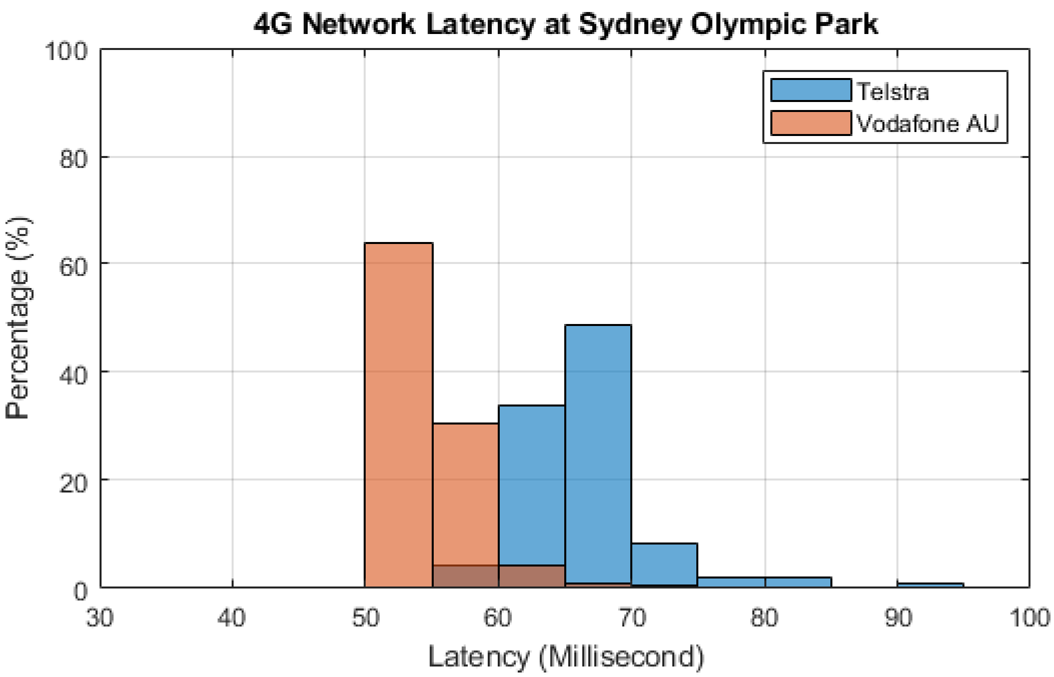

Figure 11 Histogram of Network Latency of Sydney Trial – Vodafone vs Telstra

Figure 8 shows the one-way latency (millisecond) between the mobile terminal and the network through the Ping Test. The RantCell network server is in UK. We can see most latency values are between 50-80ms, either Vodafone, or Telstra, which are consistent as a baseline testing.

Figure 9 shows the histogram result of Telstra latency test. We can see the main latency values are between 60ms to 70ms. Figure 10 shows the histogram result of Vodafone latency test. We can see the main latency values are between 50ms to 60ms. Figure 11 shows the comparison of Telstra and

Vodafone test results – Vodafone performs slightly better than Telstra. These results indicate that the 4G network available at the Sydney Olympic Park, either Telstra, or Vodafone, can both provide satisfactory performance. Network latency is an important performance indicator, indicating the total delay experienced from the time the sender sends data until the sender receives the acknowledgment from the receiver (the receiver sends the acknowledgment immediately after receiving the data). The delay is determined by three components: the propagation time of the link, the processing time of the end systems, and the queuing and processing time in the router's cache. Among them, the values of the first two parts are relatively fixed as a TCP connection, and the queuing and processing time in the router's cache will change with the change of the entire network congestion degree. Therefore, the change of latency reflects the change of the degree of network congestion to a certain extent.

We can conclude that in the Sydney trial, the network latency and packet loss are all satisfactory as baseline testing, even on the 4G network connection. The latency values are stable and in a satisfied range within this site where both Telstra and Vodafone operate.

3.3 Vehicle-RSU Communication Test

5G modems on Vehicle and RSU were both configured with Telstra SIM cards. The RSU will send messages to the vehicle, directly, or via the OHMIO network Amazon server. The user can control sending messages from the RSU to the vehicle directly via Telstra base stations and networks. The user can also control sending messages from the RSU to OHMIO server, and the server sends the message to the vehicle finally. The results shown here are the two different scenarios, end-to-end latency from RSU to vehicle, or RSU-server-vehicle.

Figure 12 shows the latency measurement for the RSU and vehicle communication via the server. The source IP address is RSU's IP address. The destination IP address will be different for the OHMIO server and the vehicle, i.e., the server is on 13.236.x.x and the vehicle is at 120.9.x.x., by which the user can send messages directly to the vehicle, or via the OHMIO server to vehicle. From Figure 12**Error! Reference source not found.**, we can see most latencies are around 15ms-70ms. Figure 13 shows the histogram of latency of RSU-Server-Vehicle communication. It shows that the latency values are 15ms -25ms mostly. Figure 14 shows the latency measurement for the RSU and vehicle communication. From Figure 14, we can see most latencies are around 10ms-70ms. Figure 15 shows the histogram of latency of RSU-Vehicle communication. It shows that the latency values are 15ms -25ms mostly. So, the two communication scenarios have very similar latency results. We can conclude that the latency meets the expectation for both direct communication or via OHMIO server, between RSU and vehicle.

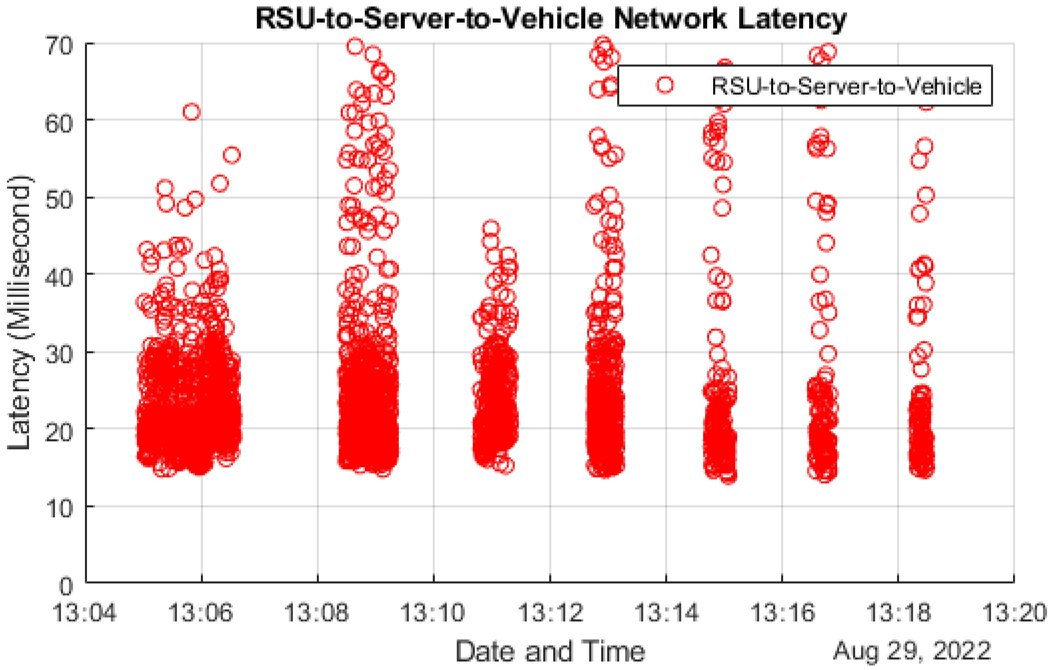

Figure 12 Latency of RSU-Server-Vehicle communication

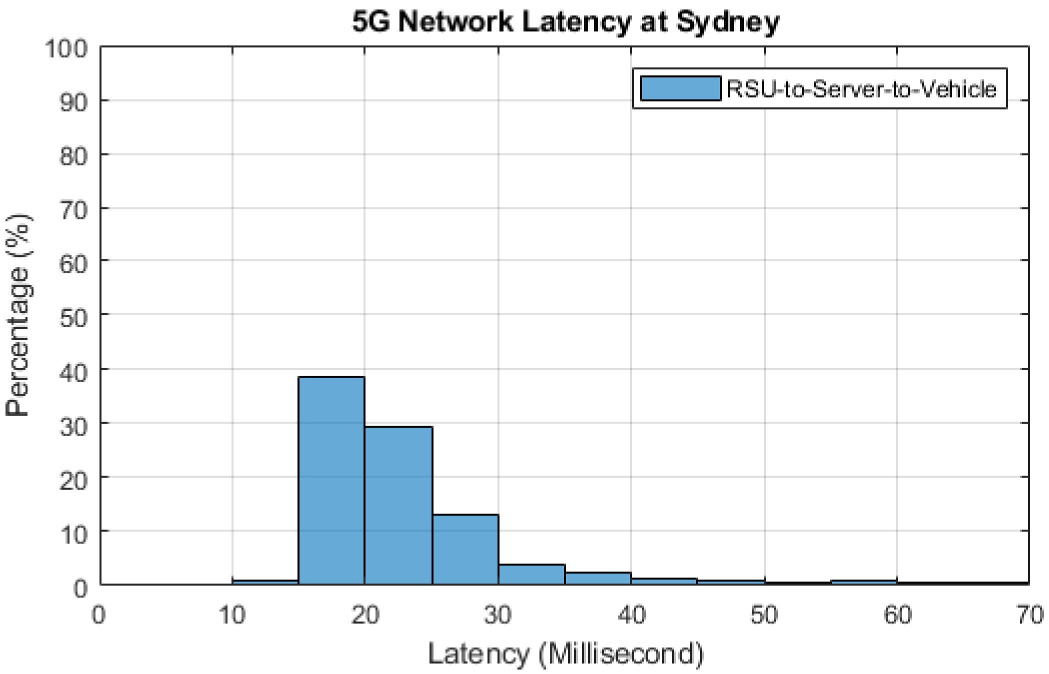

Figure 13 Histogram of Latency of RSU-Server-Vehicle Communication

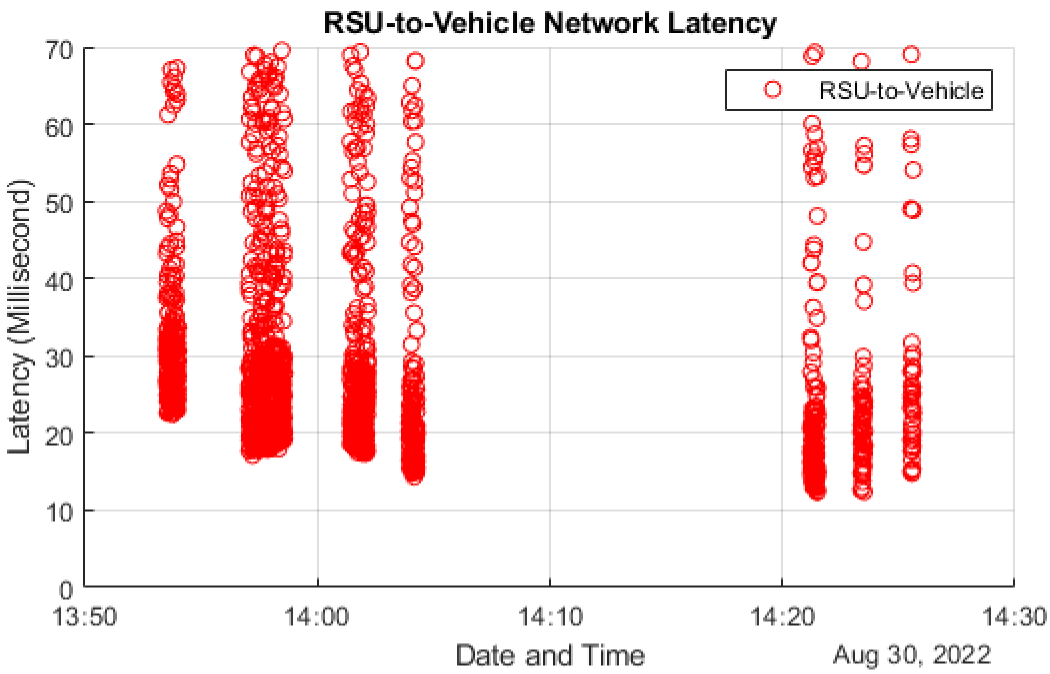

Figure 14 Latency of RSU-Vehicle Communication

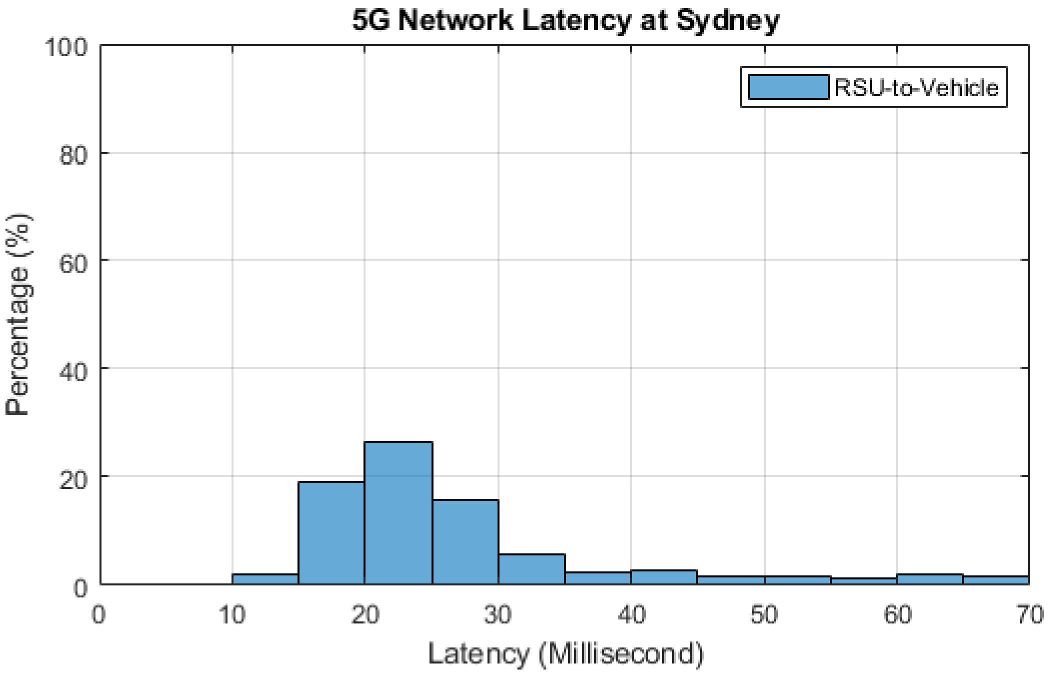

Figure 15 Histogram of Latency of RSU-Vehicle Communication

3.4 Complex Scenarios of RSU-Vehicle Collision Detection

3.4.1 Objectives

In Sydney Olympic Park, we conducted a few trials to test the complex traffic scenarios where the vehicle cannot detect obstacles independently but needs the RSU's assistance to successfully detect obstacles. The objectives are to prove:

- RSU can improve safety and speed in a defined set of complex road situations, e.g., blind spots in intersections
- Vehicle can detect complex road and traffic scenarios safer and more efficient with RSU's cooperative communications.

3.4.2 Trial Scenario

We design intersection situations where the vehicle is expected to handle traffics without the RSU and where the vehicle can handle road situations with the RSU. The test scenarios include:

- The shuttle is driving towards the intersection, while another car is approaching to the intersection from the side road.
- In order to prove that the vehicle can successfully detect obstacles approaching to intersection and can pass the intersection with or without RSU, we configure the RSU to be 3 different operation modes:
    - Mode A: Connected to vehicle and working normally. This is to allow the RSU in fully working order and assistant the vehicle to detect all obstacles from side roads.
    - Mode B: RSU does not connect to vehicle. This is to allow the vehicle works independently, as the vehicle did not detect any working RSU in connection. The vehicle will purely depend on its own intelligence to detect the obstacles. Obviously, the vision of the vehicle is limited by its own Lidar detection capacity, so the obstacle detection performance will not be very optimal.
    - Mode C: RSU is connected to vehicle but do not send any warning messages. In this mode, the vehicle can detect there is a RSU in connection, but it cannot receive any warning messages from the RSU (even there is an obstacle approaching). Therefore, the vehicle assumes there is no obstacles detected by RSU and it can pass the intersection safely. This is to simulate the worst-case scenario where the RSU did not work properly (e.g., the RSU lidar fails or 5G communication fails), whether the vehicle can still pass the intersection safely.

3.4.3 Analysis Method

The following measurement performance are collected:

- Lidar records- the computer's vision to "see" the obstacles by analysing Lidar results
- On-board and in-site camera video to capture the hazard detection (reliability, various types of hazards) in real world.
- Compare the Lidar and camera results to analyse the shuttle behaviour responding to the obstacles detection (e.g., max deceleration, stop and speed crossing a road)

3.4.4 Trial Results

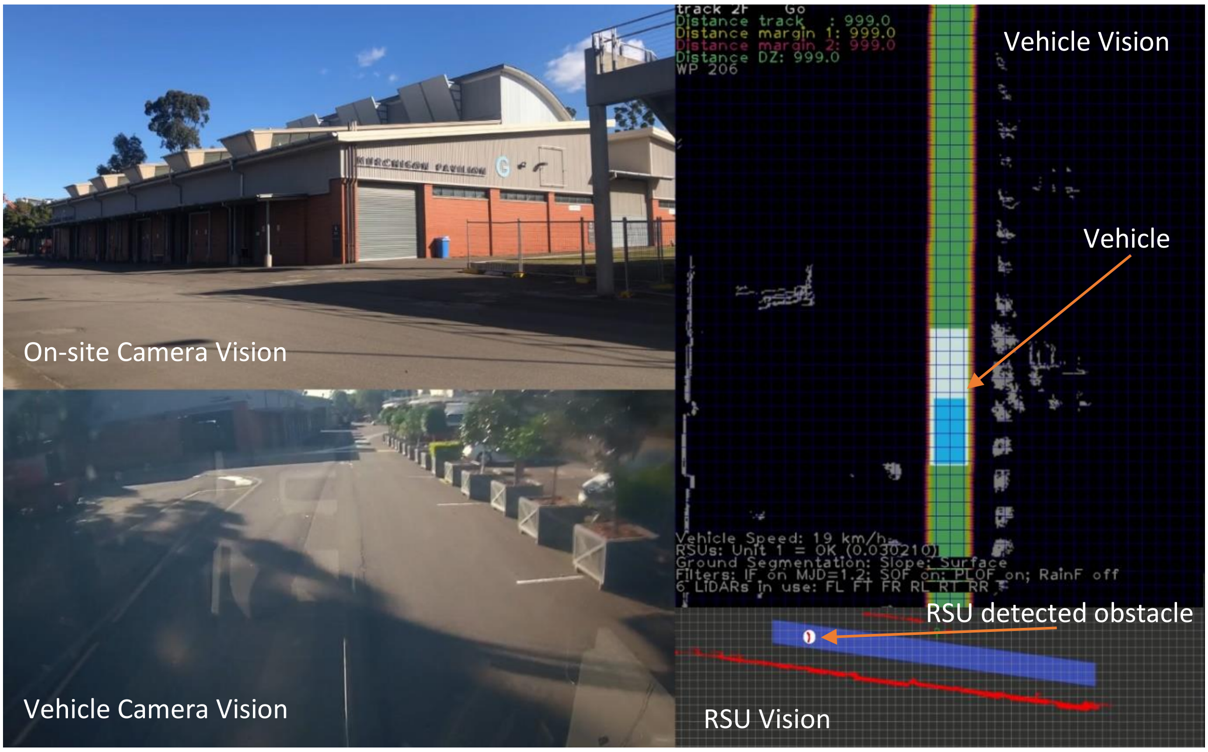

Figure 16 Mode A - RSU starts detecting the obstacle

As shown in Figure 16, the RSU equipped with one Lidar, detected the obstacle in its vision once the obstacle entered the sensing range. The vehicle moved towards the intersection at the speed 19km/h. At this moment, the vehicle still did not detect any obstacle in its vision, which is because the RSU warning hasn't been sent to the vehicle, as the vehicle hasn't entered the alert zone that RSU defined to warn the vehicle. Currently the alert zone is around 90 meters towards the intersection. Note that the vehicle is still receiving messages from the RSU here but the track is designed so that the vehicle doesn't consider obstacles until it reaches a certain point on the track (alert zone).

As shown in Figure 17, the vehicle detected the obstacle was approaching to the intersection in its vision, when its distance to the obstacle was less than 35 meters, and the vehicle started deceleration. Note that the distance (DZ) on the vehicle vision is the distance from the front of the vehicle along the track path to an obstacle. We can see the vehicle's speed decreased to 17-18km/h, which means the vehicle started to prepare to stop to avoid collision. We can also see that in the vehicle's camera (Line-of-Sight), there was no any obstacle seen. However, in the vehicle's vision, with the assistance of RSU warning messages, the vehicle already had the capacity to detect the obstacle approaching to the intersection that maybe a potential hazard.

The vehicle vision shows that the vehicle is receiving messages from the RSU. The first orange bubbles appearing earlier comes from the RSU messages and then a second set of bubbles appear when the vehicle Lidar detects the obstacle. Note that the discrepancy between the two sets of bubbles is because the vehicle is detecting the front of the obstacle while the RSU detects the back of the obstacle.

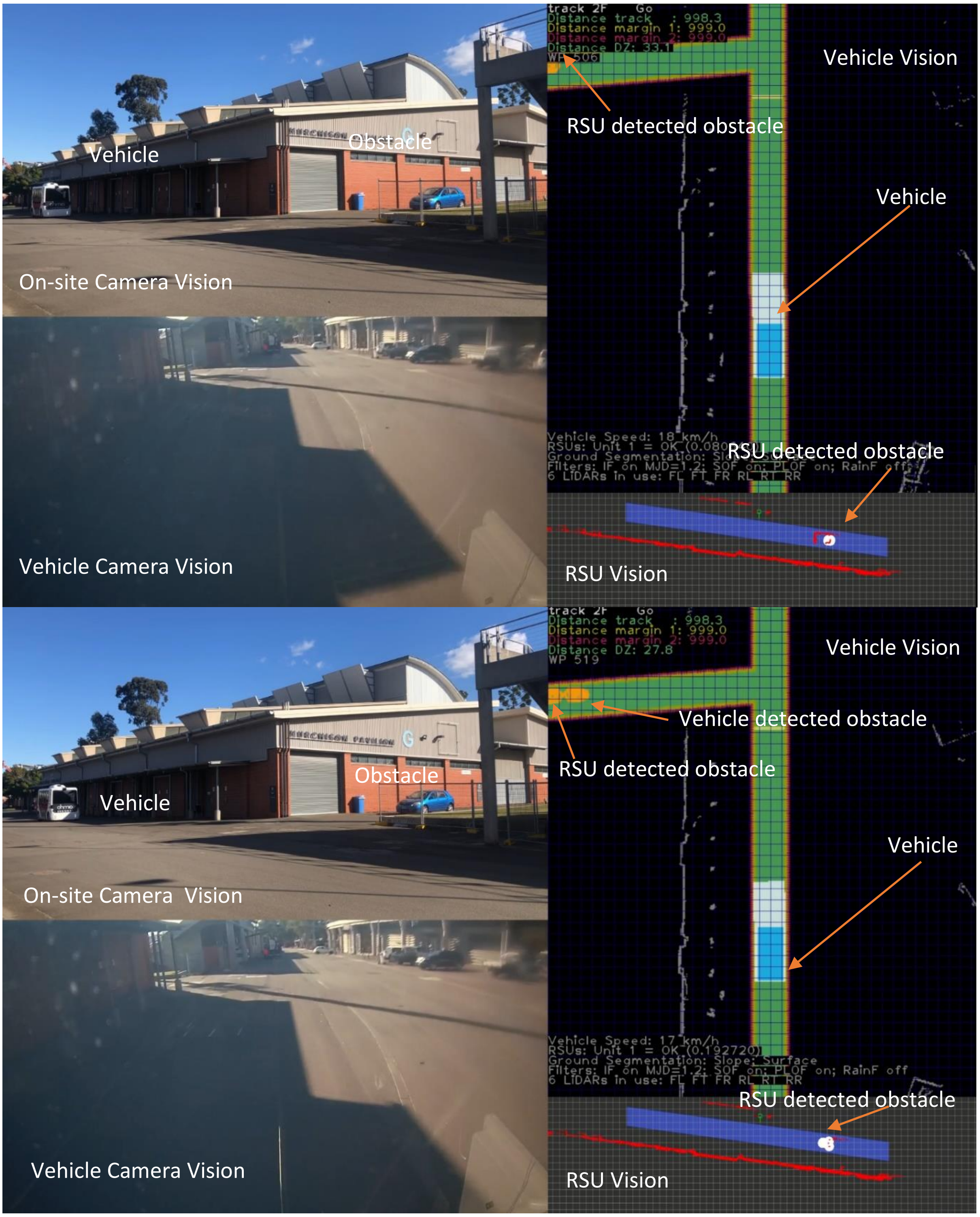

Figure 17 Mode A - Vehicle detects obstacles with RSU's assistance and decelerates

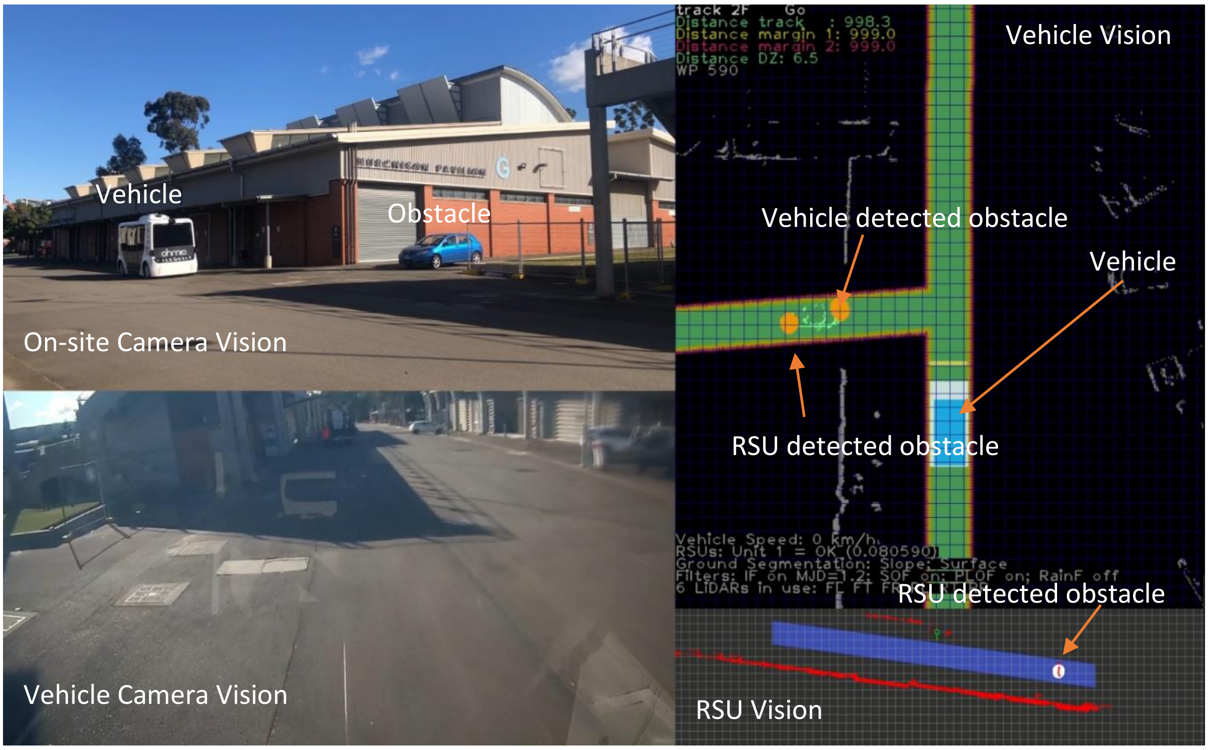

Figure 18 Mode A - Vehicle detects obstacles with RSU's assistance and stops

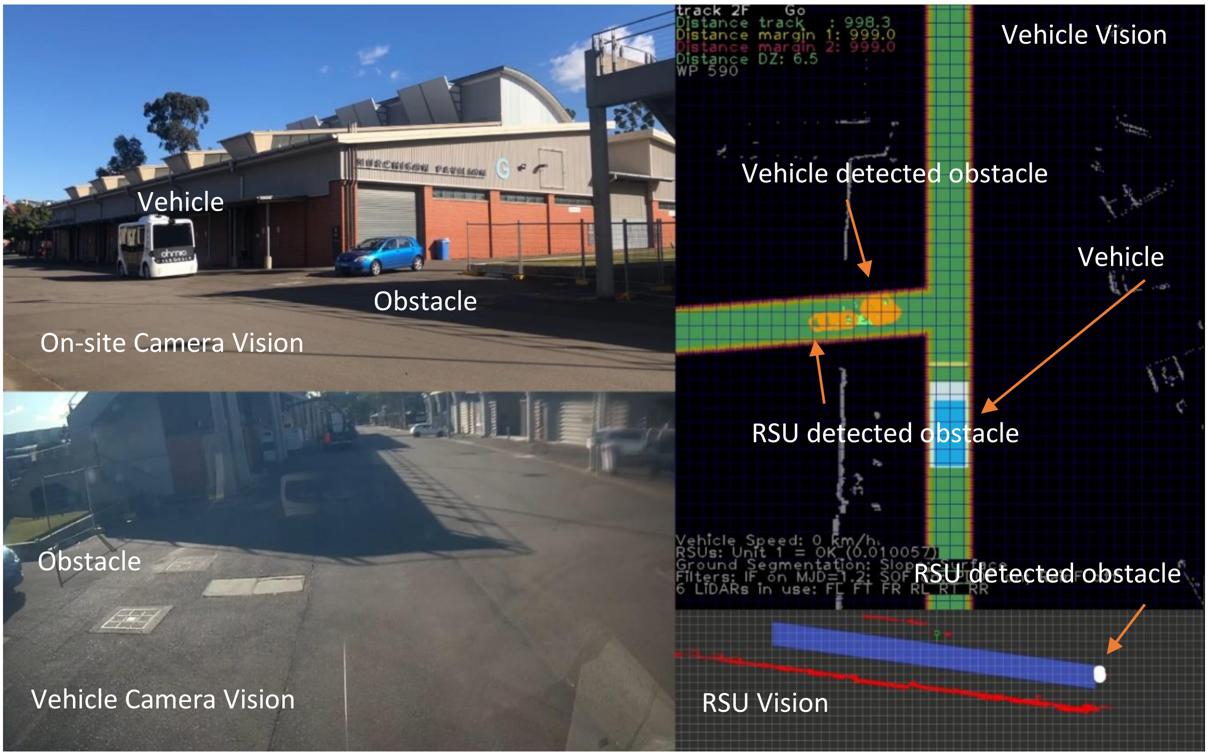

Figure 19 Mode A - Vehicle detects obstacles with RSU's assistance and stops to give way

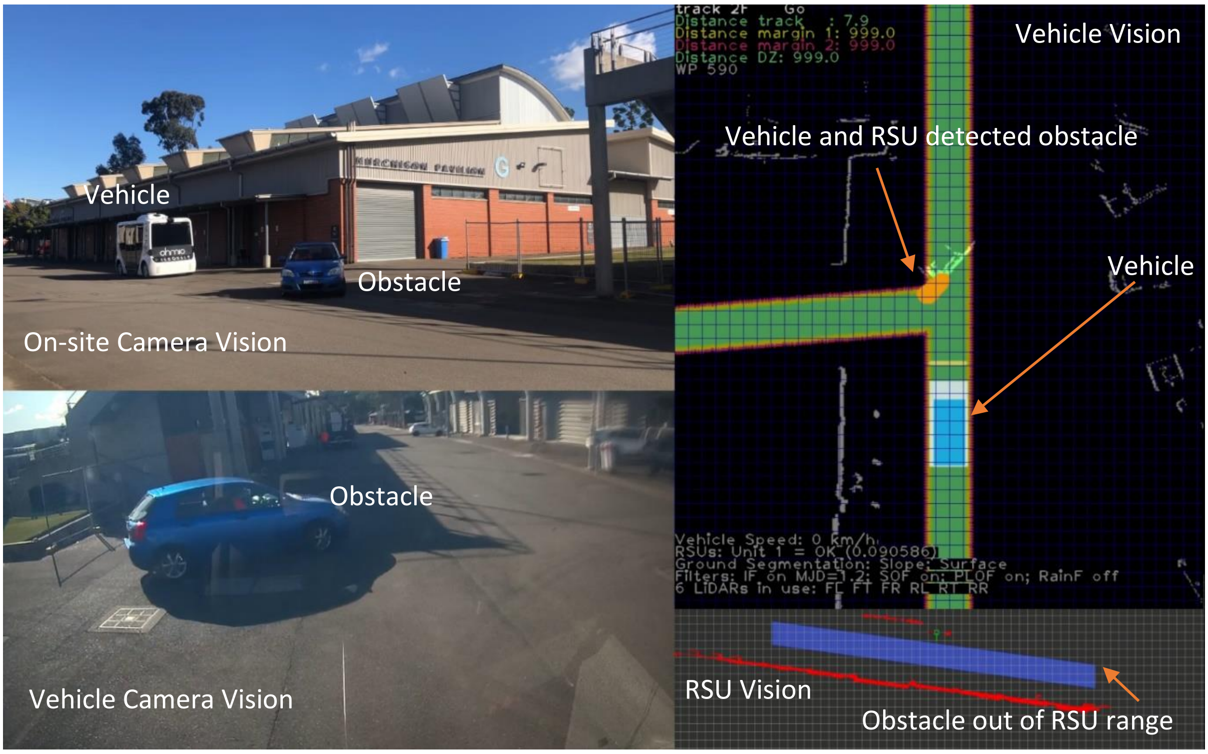

Figure 20 Mode A - Vehicle detects obstacles with RSU's assistance and stops to give way to turning obstacle

As shown in Figure 18, the vehicle has fully stopped before entering the intersection (speed = 0) with the distance 6.5m to the obstacle. At this moment, the vehicle's camera still hasn't seen any obstacles, while with the assistance of RSU, the vehicle has successfully stopped to avoid the collision.

As shown in Figure 19 and Figure 20, the obstacle has come into the vehicle's camera range. The obstacle was going to turn at the intersection, and it will move out of the range of RSU detection. So, we can see the obstacle moved out of the RSU vision. The vehicle still stopped to give way to the obstacle that was turning. At this point, the whole collision avoidance for the vehicle has been completed successfully.

From all above results, we can conclude that the RSU assisted collision avoidance is successful. The vehicle is able to detect the obstacle from at least 35 meters away when the on-board Lidar still hasn't detected any obstacle.

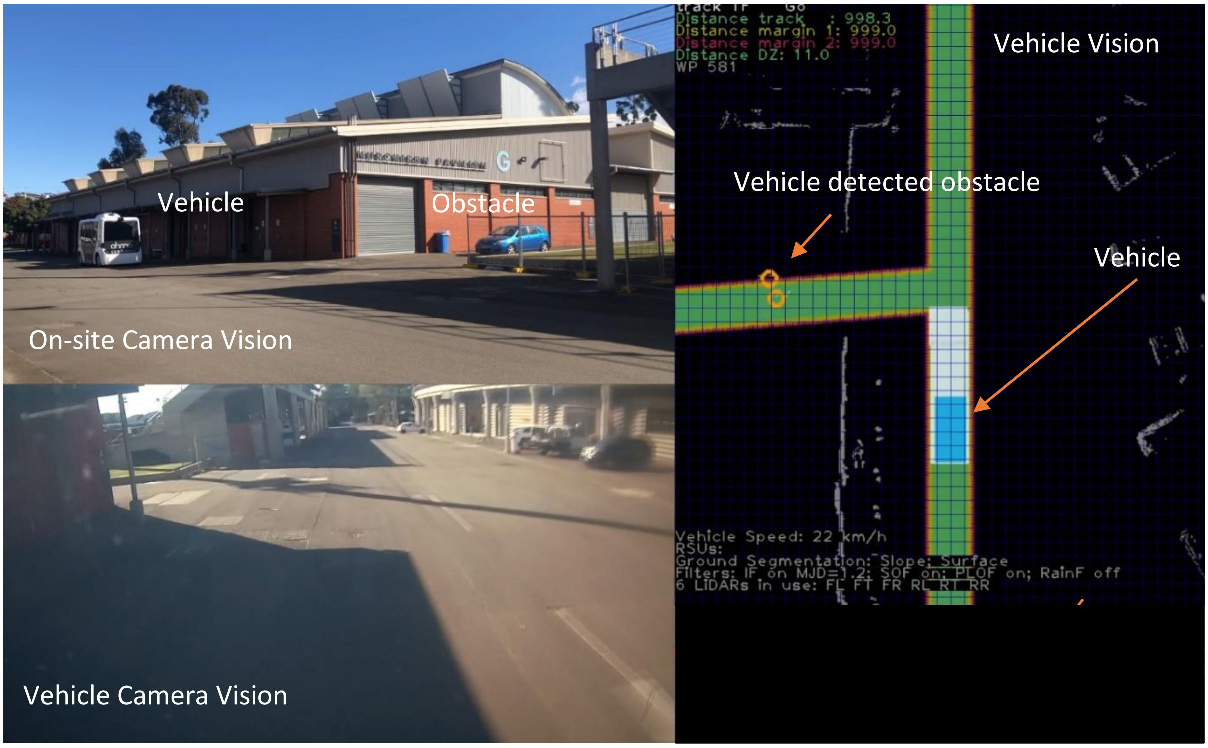

Figure 21 Mode B - Vehicle detects obstacle without RSU assistance

As shown in Figure 21, when there is no RSU assistance, the vehicle will depend on its own Lidar to detect the obstacle, which is very limited. We can see it is not until only 11 meters to the intersection, the vehicle detected the obstacle. However, at this moment, the vehicle speed was still 22km/h, which is a dangerous situation as the vehicle needs some time to brake. Therefore, we can state that the vehicle's own Lidar vision is not an optimal solution as the detection is late.

The RSU vision shows that the RSU can detect the obstacle as usual. However, as the RSU is not connected to the vehicle, the information is not shared to the vehicle. The vehicle did not take any advantages of using the RSU information to improve its detection capacity.

As a result, the vehicle had to take a sharp brake to avoid collision. As shown in Figure 22, the vehicle speed sharply decreased from 22km/h to 1km/h in one second, at the distance 1.7m to the obstacle, to avoid the collision to the obstacle. Such sharp braking is not very safe and may cause disabled passengers' accidents. The on-board camera shows that the vehicle still can't see the obstacle until the very last second. Finally, from the test results, the vehicle fully stopped at the distance 1.4m, to give way to the obstacle turning left.

We can conclude that the vehicle's own intelligence to detect the obstacle is not optimal if there is no RSU assistance. The vehicle can detect the obstacle around 11m to the obstacle, and it can still stop before the intersection (1.4m distance to the obstacle), but the sharp braking is not safe and unpleasant (22km/h per second deceleration) to the passengers with disabilities.

Figure 22 Mode B- Vehicle detects obstacle without RSU assistance

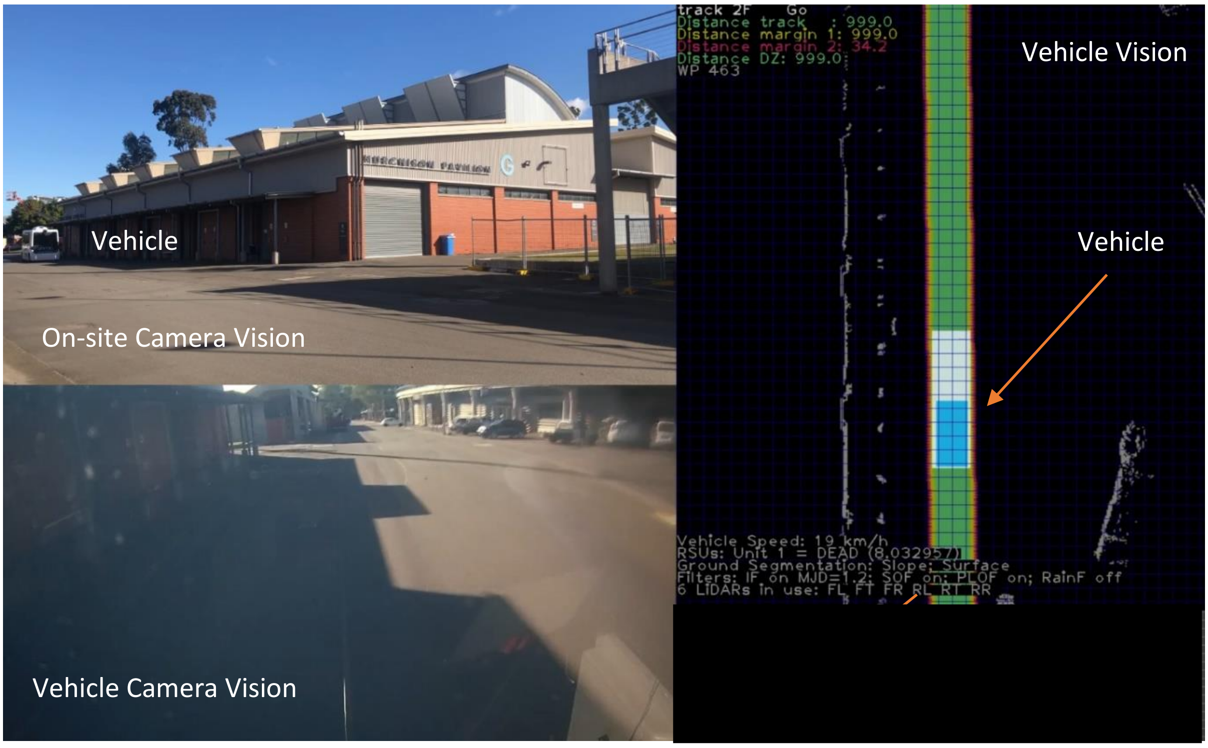

Figure 23 Mode C - Vehicle slows down when detecting RSU is connected

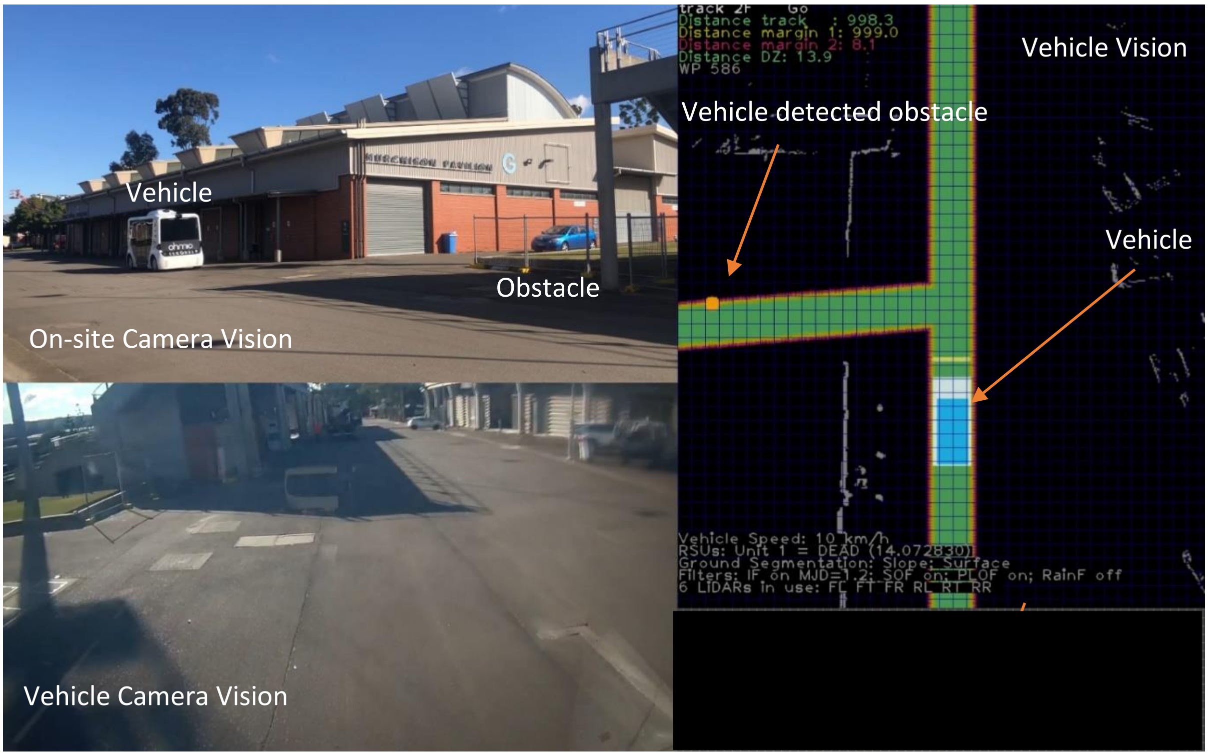

Figure 24 Mode C- Vehicle detects obstacle with RSU connected but not sending warning messages

As shown in Figure 23, the vehicle started to slow down once it detected that there is RSU connected, which means the vehicle knew that an intersection is ahead. Although we configured the RSU did not send any warning messages, the vehicle still gradually slowed down from 22km/h to 19km/h. At this moment, the distance to the intersection is still more than 40 meters. Therefore, we can state that the existence of RSU is helpful to the vehicle to slow down in advance to prepare the stop even there is no warning message is received from RSU yet.

As shown in Figure 24, without receiving warning messages from RSU, the vehicle relied on its own Lidar and intelligence to detect the obstacle was approaching, when the distance to the obstacle is 13.9m, at speed 10km/h. Compared with Mode B, where there is no RSU connected at all, this situation is more safe and less hazard. The vehicle speed has been slowed down and the distance to the intersection is longer.

As shown in Figure 25, after detecting the obstacle, the vehicle fully stopped from 10km/h to 0km/h in 3 seconds, at the distance 2.7m to the obstacle. Compared with Mode B, the deceleration is very gradual and safe, and the distance to the intersection is longer. The vehicle successfully stopped before the intersection to avoid collision, relying on its own intelligence.

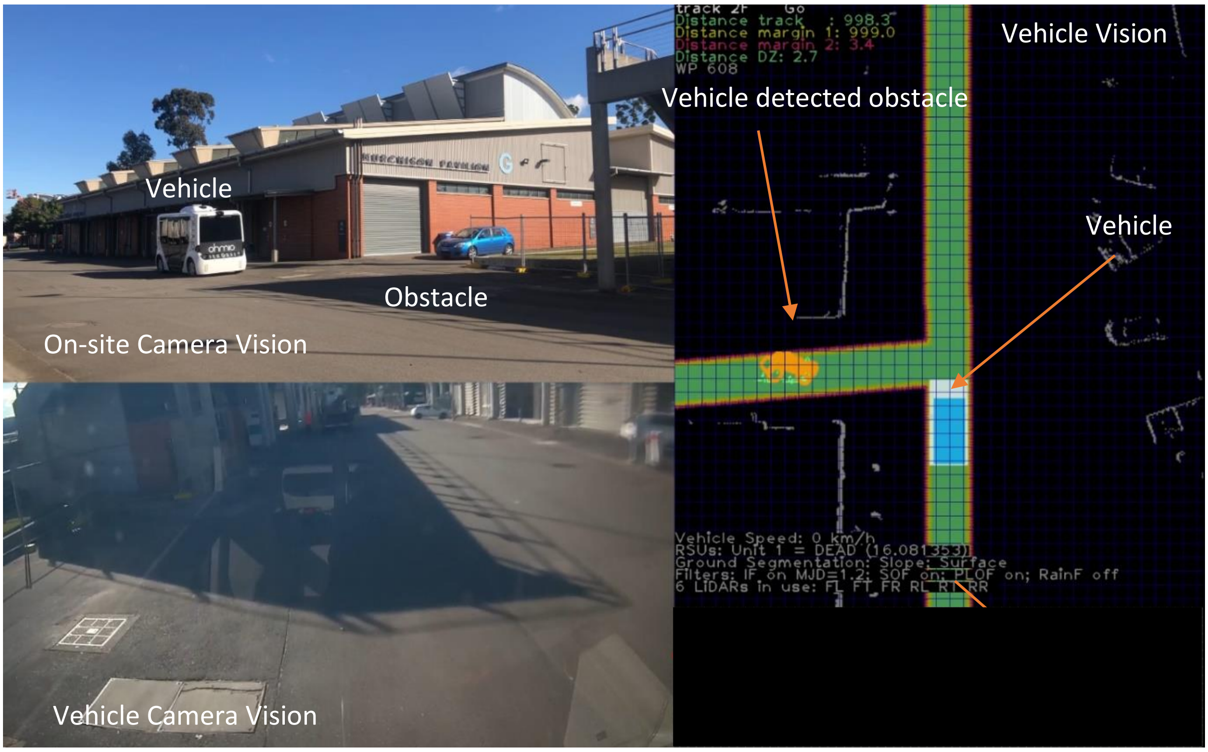

Figure 25 Mode C - Vehicle stops before intersection

As summary, we can conclude the usage of RSU is advantageous. When the RSU is fully working, the assistance to the vehicle is optimal. The vehicle can detect the obstacle when it is still 35 meters away. Even the RSU does not send any warning messages (assuming its Lidar fails), the vehicle still can prepare to stop in advance (40 meters away) as the vehicle assumes the intersection equipped with RSU may have hazard. The worst case is, the vehicle does not use any connected RSU, and only relies on its own intelligence to detect obstacles. In this case, the vehicle detects obstacle late and the braking is sharp that may not be safe to the passengers with disabilities on the vehicle. In conclusion, we recommend the usage of RSU to assist the vehicle to successfully detect the obstacle and avoid collision in advance, on public roads in the future.

3.5 Remote Monitoring via 5G

In the near future it will be a common occurrence to see driverless buses on streets. A key step towards deploying autonomously driven buses into the public transport system is the capacity of remote monitoring and remote-control functions, which will introduce more safety by the assistance of the remote operators. In this project, OHMIO tested the remote monitoring and control capacities on the OHMIO shuttle bus.

3.5.1 Video Transmission Devices

As shown in Figure 26, the Zao-X is a low-delay portable video transmission transmitter. A low-delay transmission system is fully realized by connecting to a compatible receiver, such as HD-View or Zao View. There are two methods:

- Transmitting video directly to the receiving PC (Direct Mode)
- Connecting to the cloud (Cloud Mode)- Cloud connection is not supported in the current version.

Figure 26 Zao-X Device

Zao-X First Edition has the following connection destinations. The first edition only supports the Direct version for the following Soliton receiver software:

- Zao View
- HD View V5

Zao-X View software is installed on receiver PC to monitor the transmitted video quality, as shown in Figure 27.

Figure 27 Zao-X View UI Software

3.5.2 Video Transmission Setup

Figure 28 Video monitoring configuration diagram of end-to-end set up

Zao-X View is used in conjunction with the Zao-X transmitter where it is utilized as a Linux based decoding platform to re-create native video feeds at the receiving location. Figure 28 shows the setup configuration diagram. Multi Link Unit (MLU) has up to 6 nano-SIMs inserted. We insert 3 SIM cards (Telstra, Vodafone 4G/5G) inside MLU. The Zao-X View is used for streaming video from the Zao-X from 3 cameras via network switch and Mini PC. The receiving PC needs a network connection with a connection with a 5G modem. UDP is used for communication between Zao-X and Zao-X View. Only one port is used for communication. By default, [42000] is set.

Depending on the receiving network configuration, it may take some time to start up if the receiving PC is not under the DHCP server. In some cases, the delay may increase depending on the type of connected camera.

Figure 29 Remote Monitoring Operation Room Demo

As seen in Figure 29, the administrator can monitor the vehicle in a remote monitoring room. The cameras send real-time video to the monitoring PC installed with Zao-X View software. The administrator can monitor the vehicle's cameras on 3 screens separately.

Figure 30 Remote monitoring of detected obstacle

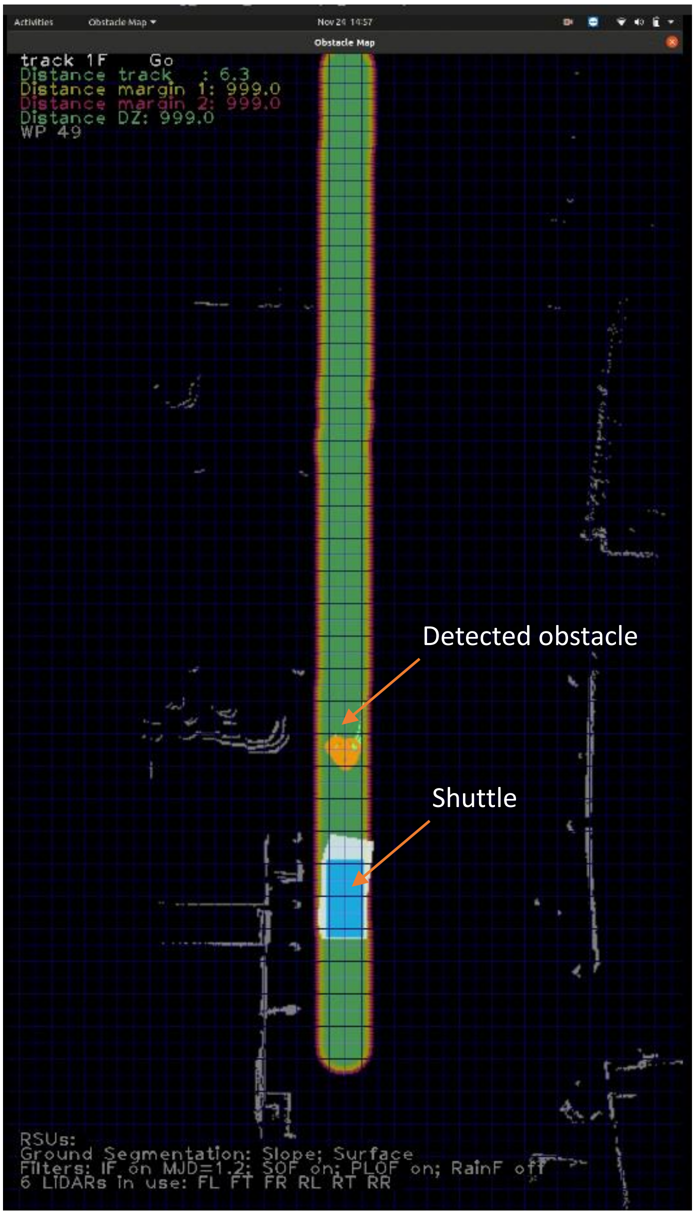

Figure 31 In vehicle's Lidar view of detecting obstacle

The vehicle detected there was obstacle on the way by its Lidar. The cameras transmitted the video to the remote monitoring room, as shown in Figure 30. The vehicle’s lidar detection of obstacle is shown in Figure 31. The orange dot is the white vehicle in front of the shuttle.

Figure 32 Vehicle overtakes obstacle

The vehicle overtook the obstacle automatically to avoid the collision. As shown in Figure 32, the vehicle has bypassed the obstacle successfully. In the meantime, the remote monitoring PC has received the video transmitted from the vehicle. We can clearly see the shuttle's cameras' video that the shuttle has bypassed the obstacle. The demonstration has proved the remote monitoring operation is effective.

Figure 33 Remote monitoring vehicle bypassing obstacle

3.5.3 Remote Monitoring Performance

The remote monitoring is real-time. The administrator can hardly feel the delay on the monitoring screen when the vehicle was in operation. To demonstrate the quantified performance of the remote monitoring operation, we use the following metrics:

- **End-to-end (E2E) latency**: The latency between the timestamp of sending the video from the Zao-X device, and the timestamp of receiving the video on the Zao-X view software. We set the video transmission up with 1 of 3 cameras connected and conducted the latency test with 3 different sim card setups (4G, 5G & 4G5G5G). The traffic is balanced among 3 Sim cards if there were 3 Sim cards in operation.
- **Bandwidth**: The available bandwidth of the data transmission in Mbps.
- **Network latency**: The air transmission latency of the video data between two 5G modems from vehicle to the monitoring PC. This latency is inclusive in the overall latency.
- **FPS**: Frame rate, measured in frames per second (fps), describes how smoothly a given video quality runs on your receiving PC. Frame rates have been around since the dawn of cameras. The term applies equally to film and video cameras, computer graphics, and other forms of motion capture.

First, we expect to measure the performance in a very busy communication environment. The data was measured during two events (Celtic vs Everton @ Accor Stadium, Sydney Kings vs Illawarra Hawks @ Qudos Bank Arena) where 60,000 people gathered.

Second, we measured the performance in a lab environment where the communication is normal, in order to compare with the congested communication environment.

Figure 34 Zao-X Transmitting Device

As shown in Figure 34, the transmission Zao-X device transmitted the video data at 60 FPS. Table 2 shows the performance of the remote monitoring in a congested communication environment. Table 3 shows the performance of the remote monitoring in a non-congested communication environment.

From the results, we can summarize the E2E latencies and network latencies are similar in congested and non-congested communication, around 150ms and 70ms.

The shuttle's max speed is 30km/h. So, the moving distance within 150ms is around 1.25m when the vehicle is driving at the max speed. This E2E latency range has significance for the operator to understand the potential risks when operating the vehicle remotely and take precautions.

In non-congested environment, the bandwidth is significantly better than congested communication environment, more than 5Mbps. In non-congested environment, the FPS is slightly better than congested communication environment.

In conclusion, we can conclude the OHMIO vehicle has successfully implemented the remote monitoring function. The real-time monitoring has been proved working and effective to monitor the vehicle remotely by the operator. The operator can hardly feel the latency of monitoring the vehicle.

By measuring the performance in a busy/non-busy communication environment, the E2E latency, Bandwidth, and network latency, are all in reasonable range, when using 4G and/or 5G sim cards.

Table 2 Remote Monitoring Performance in Congested Communication Environment

Sim Cards Used	E2E Latency (ms)	Network Latency (ms)	Bandwidth (Mbps)	FPS
4G	139	84.6	1.072	56.994
4G, 5G, 5G	132	69.2	1.1682	59.186
5G	145	71.8	2.1106	58.996

Table 3 Remote Monitoring Performance in Non-Congested Communication Environment

Sim Cards Used	E2E Latency (ms)	Network Latency (ms)	Bandwidth (Mbps)	FPS
4G	144	70.8	5.558	59.204
4G, 5G, 5G	152	73.8	5.3596	60.228
5G	158	72.8	5.6644	60.002

3.6 Remote Control via 5G

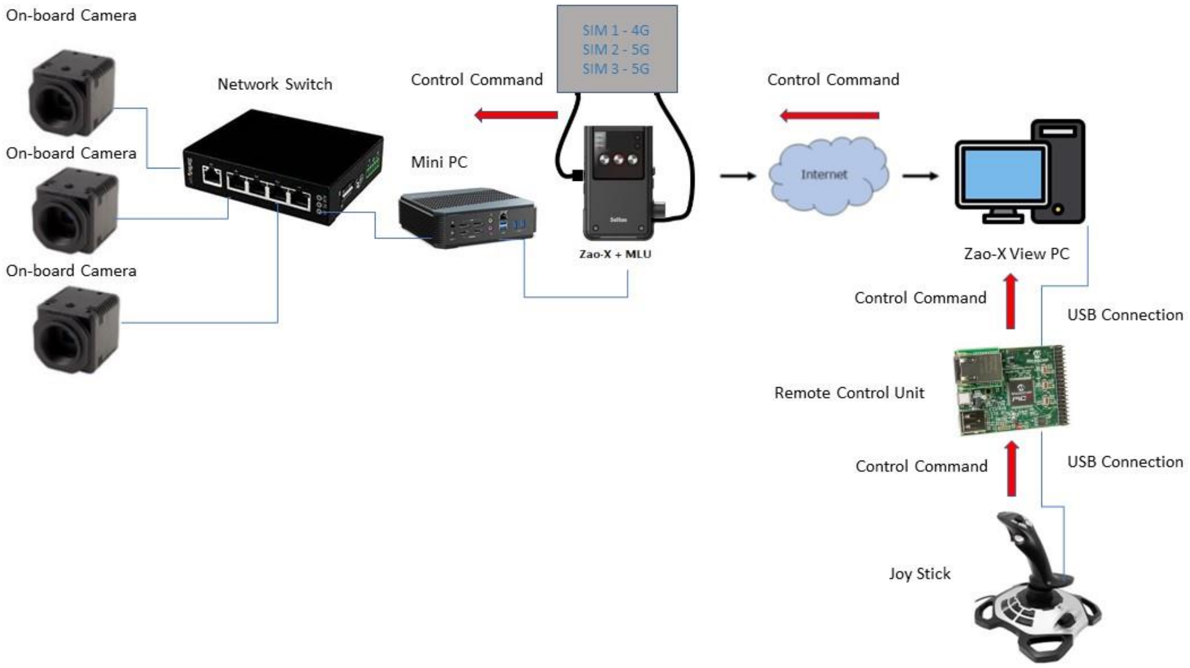

Figure 35 Remote Control Network Architecture

3.6.1 Remote Control Device

As shown in Figure 35, the remote control setup is similar to the remote monitoring setup. Zao-X View is used in conjunction with the Zao-X transmitter where it is utilized as a Linux based decoding platform to re-create native video feeds at the receiving location. 3 Cameras are connected with switch and on-board PC. A new unit is introduced, which is the Remote Control Unit. Remote Control Unit is used to convert the Joystick's movement into control command that can be transmitted to the 5G network.

3.6.2 Remote Control Setup

The Joystick connects to this Remote Control Unit via USB, and this Remote Control Unit connects to the monitoring PC (Zao-X View) via USB. This device will convert the Joystick signal into a control command (Move Forwards, Move Backwards, or Stop). The Zao-X MLU device receives the control command, and transfers the control command to the on-board computer. The on-board computer will actually control the vehicle's movement.

On the screen of the monitoring PC running Zao-X View UI software, the operator can clearly view the cameras' video when the vehicle is moving on the road. The operator can hardly feel the latency between the video and the actual vehicle movement.

3.6.3 Remote Control Performance

The metric is the average latency between the timestamp of the Joystick's movement and the vehicle on-board PC receiving the control command. We tested three scenarios with 5G modem setups: 5G sim card, 4G sim card, 5G+5G+4G sim cards. The average latency is calculated based on 3000+ samples. From Table 4, we can see the average latencies are around 50ms; 5G sim card only has the lowest latency value. Combined 5G+5G+4G sim cards has the largest latency, which indicates the combined sim cards may not be an optimal solution to ensure the most efficient usage of the network resources. In general, the average latency value is all at reasonable level.

Table 4 Remote Control Average Latency

Sim Cards	**Average Latency (ms)**
5G	48.27
5G+5G+4G	53.56
4G	50.02

In conclusion, during the test run, a remote operator was able to control the car while watching the live feed of road conditions via 5G network. As the control command is relatively smaller size of messages, compared to the camera video streaming, the latency is around 50ms from moving the Joystick until the vehicle's on-board PC receiving the control command. The Zao-X software is able to provide sufficient remote monitoring/control solution that provides enhanced road environment awareness. We recommend Zao-X software suites for the future road trial and deployment when 5G remote monitoring/control is required.

4 La Trobe Bundoora Campus Trial

4.1 Trial Scenarios

The trial in Melbourne was conducted between the 8th Aug and the 10th Aug in the La Trobe Bundoora Campus. The trial site (Red Circle) is shown in Figure 36. The shuttle bus comes back and forth along the route during the trial autonomously. As shown in Figure 37, approximately 5 meters to the T-intersection, the RSU was deployed to assist the vehicle to detect the obstacles.

The RSU setup includes: Milesight 5G modem, Cohda DSRC devices, RSU Linux computer, switch, PoE injector, and a Lidar (1m high from ground), as shown in Figure 38. On the vehicle and the RSU, Telstra SIM cards have been used.

The RantCell network performance was used as a benchmark to compare the results obtained in the trial site.

Figure 36 La Trobe Campus Trial Site

Figure 37 Trial Site

Figure 38 Roadside Unit Setup

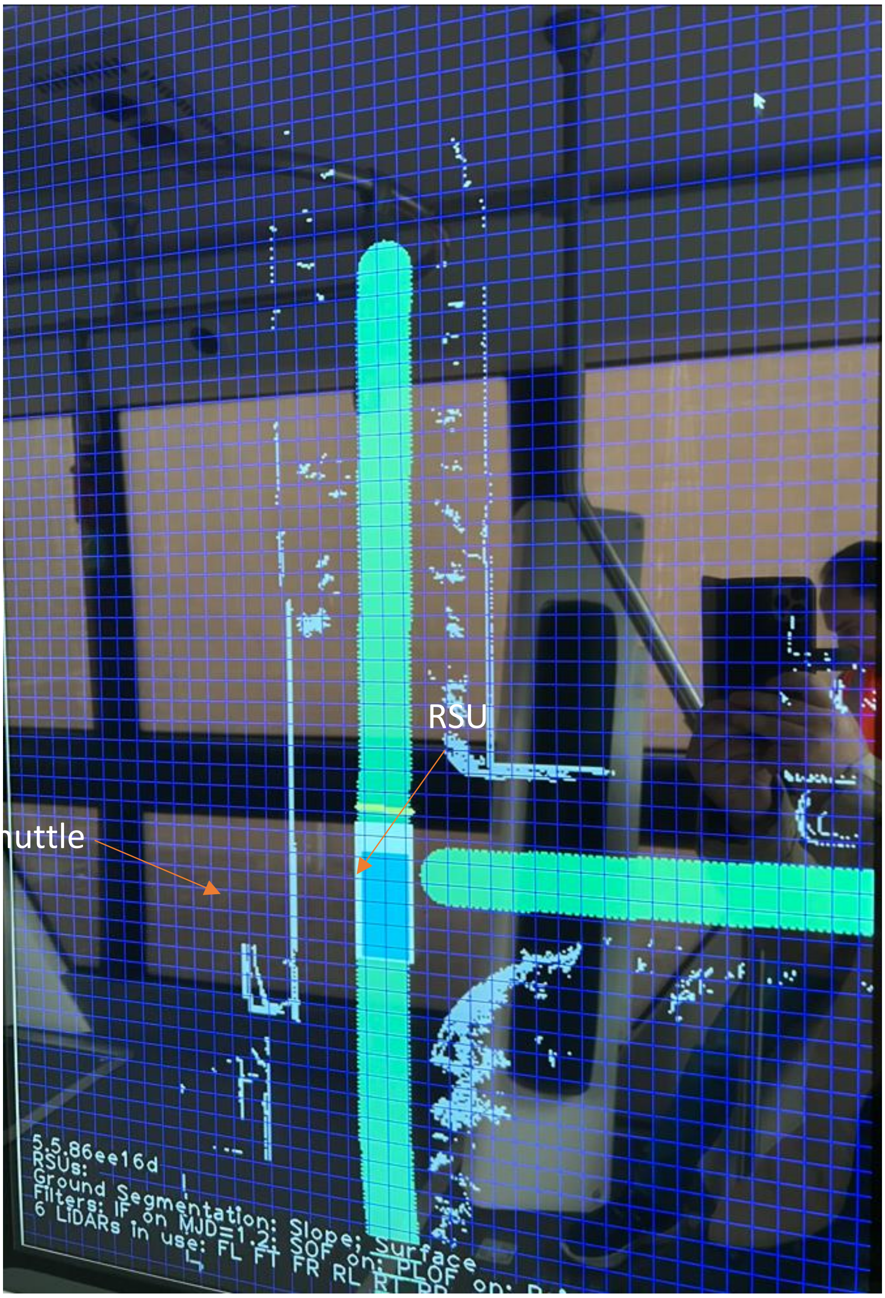

Figure 39 Vehicle Lidar Sensing Environment (picture of on-board screen)

After setting up the RSU, the in-vehicle Lidar is able to extend its perception range to the non-line-of-sight road (max 20 meters for single RSU). As shown in Figure 39 and Figure 40, the range of in-vehicle Lidar covers the T intersection by detecting the vehicle approaching the intersection from the side road.

4.2 Network Performance Test

As shown in Table 5, we can consider the performance requirements for remote driving defined by ETSI: The 3GPP system shall support message exchange between a UE supporting V2X application and V2X application server for an absolute speed of up to 250 km/h [1, 2]. So 5ms is a desired end-to-end latency value for information exchange between autonomous vehicle supporting V2X application and a V2X Application Server,

Table 5 Performance requirements for remote driving [2]

Communication scenario description	**Req #**	**Max end-to-end latency (ms)**	**Reliability (%)**	**Data rate (Mbps)**
Information exchange between Autonomous vehicle supporting V2X application and a V2X Application Server	[R.5.5-002]	5	99.999	UL: 25 DL: 1

Table 6 Speed test result

Date	Time	5G Modem	Ping Latency	Download	Upload
8/9/2022	17:06	Vehicle Modem	33 ms	612.10 Mbps	86.14 Mbps
8/10/2022	11:22	RSU Modem	20 ms	590.73 Mbps	106.00 Mbps
8/9/2022	20:09	Azure gateway	1.52 ms	15155.20 Mbps	952.90 Mbps

Table 6 shows the on-line speed testing results. The throughput speeds (Mbps) and ping latency (ms) for the laptop connected to the vehicles 5G modem, the RSU 5G modem, and Azure gateway were obtained by the speedtest.net website. As a reference test, the Azure gateway connection can be seen as the fastest download/upload speed and lowest latency that can be achieved for existing 5G connection. As shown in the results, the 5G connection on the vehicle and RSU both achieved excellent latency and download/upload speed.

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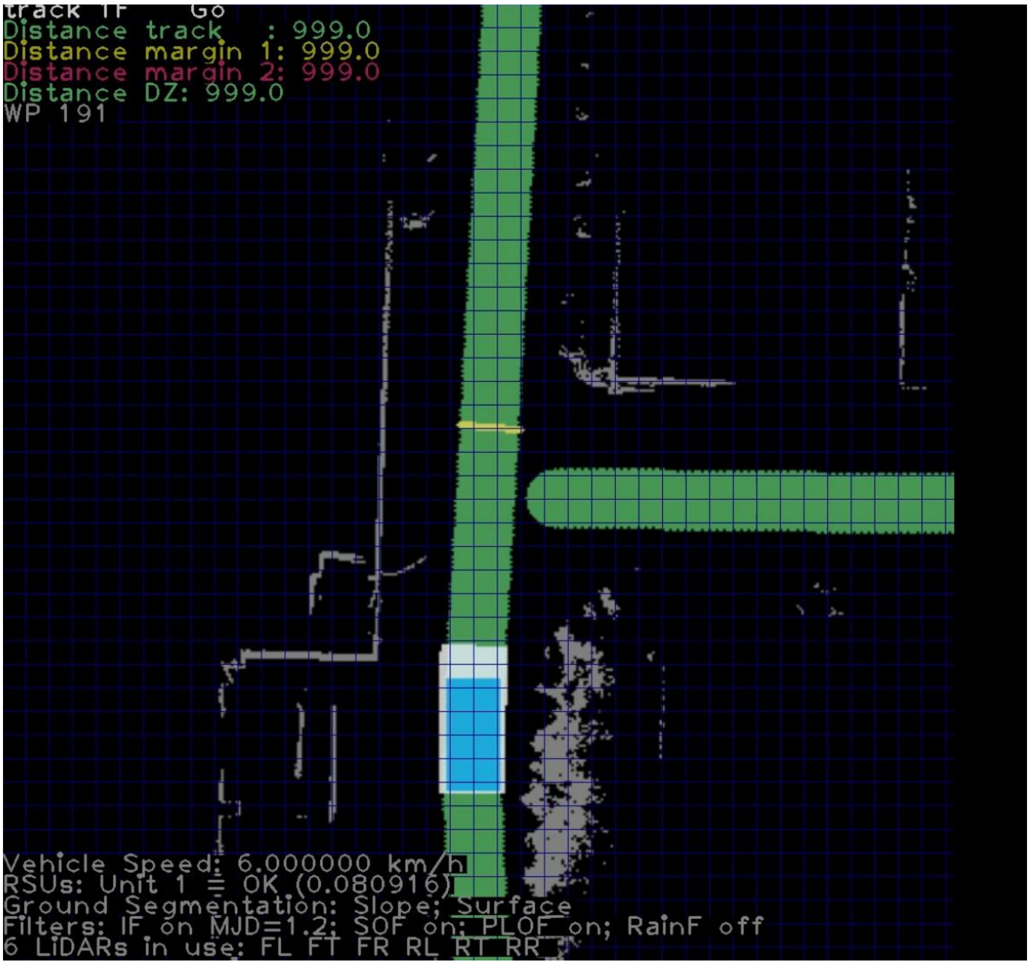

Figure 40 Record of Moving Shuttle Lidar Sensing Environment

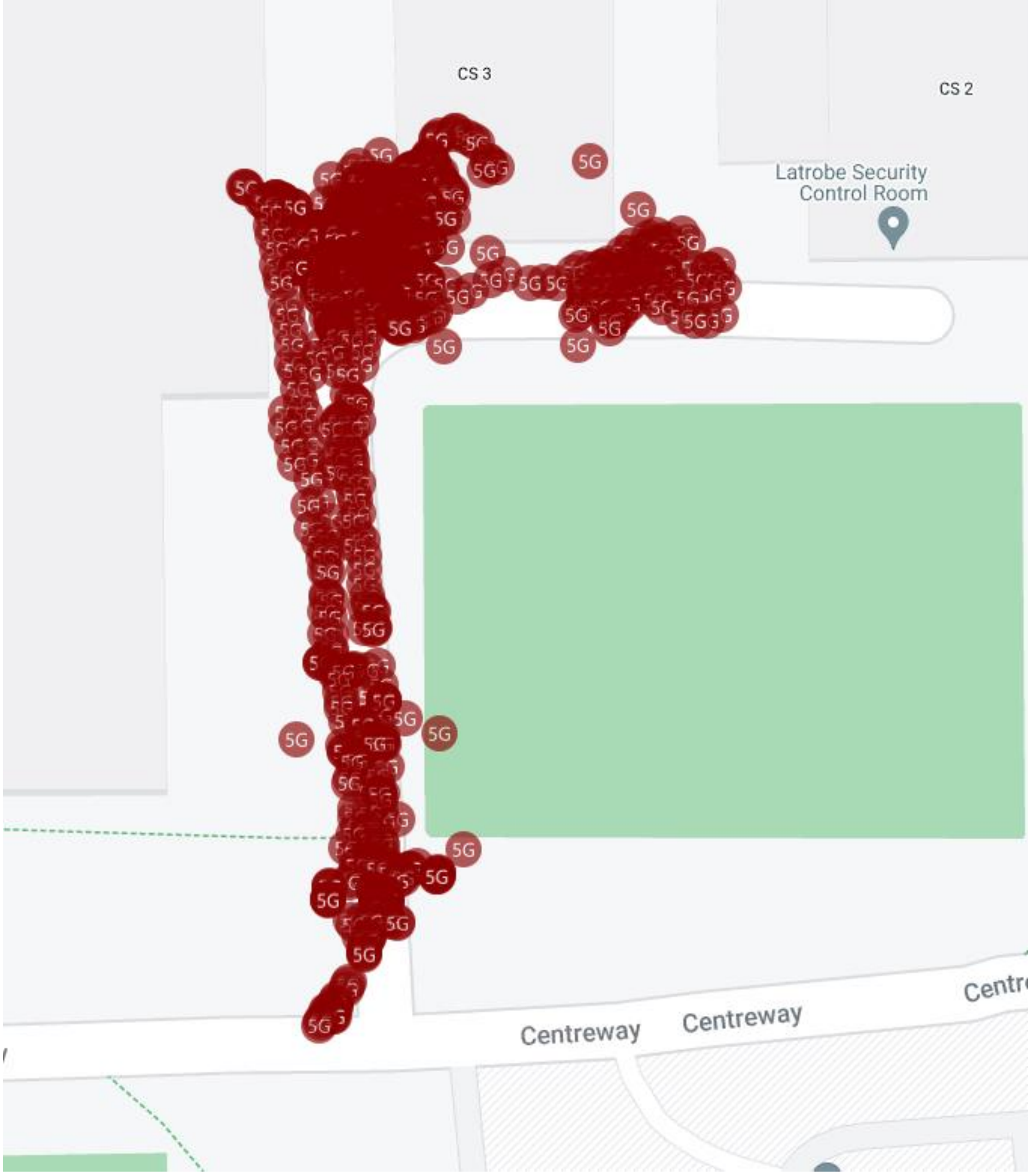

Figure 41 5G communication network coverage map

Table 7 Network type

Network Type	**Percentage**
5G	100.0000%
4G	0.0000%
3G	0.0000%
2G	0.0000%
CDMA	0.0000%
	0.0000%
Total Geo samples	3198

CTI conducted the RantCell test using Samsung Galaxy A53 5G mobile phone. The data is collected and uploaded to the RantCell Cloud. 3198 valid data records were collected in the trial. As shown in Figure 41, the full 5G connection in the trial site has been achieved. As shown in Table 7, 100% 5G network type has been achieved during the trial, which is an optimal scenario.

Table 8 Signal Strength RSRP

RSRP	Percentage
>= to -89dBm	99.8749 % (count : 3194)
B/w -99dBm to -90dBm	0.1251 % (count : 4)
B/w -112dBm to -100dBm	0 % (count : 0)
	0 % (count : 0)
Total Geo samples	3198

Table 8 shows the signal strength (RSRP) results using RantCell. We can see 99.8749% RSRP has the values greater than -89dBm. Higher dBm indicates the better signal strength and larger coverage range. In Figure 42, the distribution of RSRP is indicated, with -83dBm as the most likely value distributed in the whole trials. This indicates that the signal strength and coverage of the 5G network communication in the trial site is excellent and optimal.

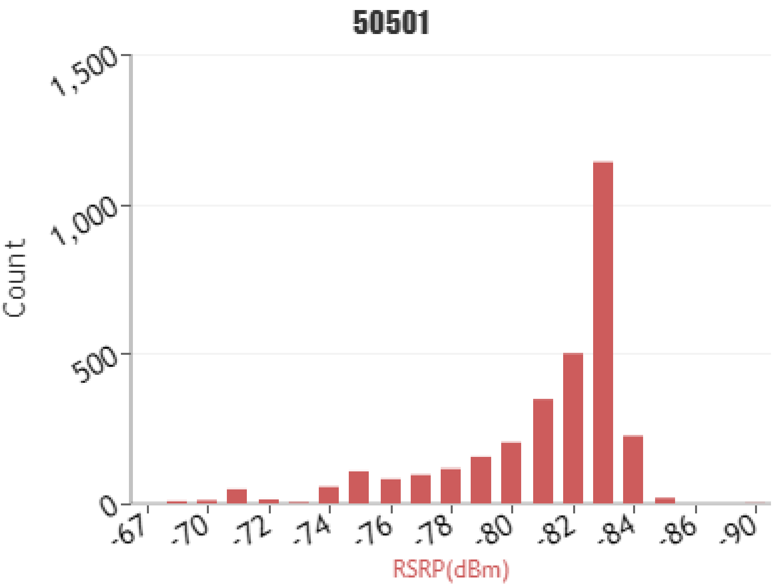

Figure 42 RSRP distribution

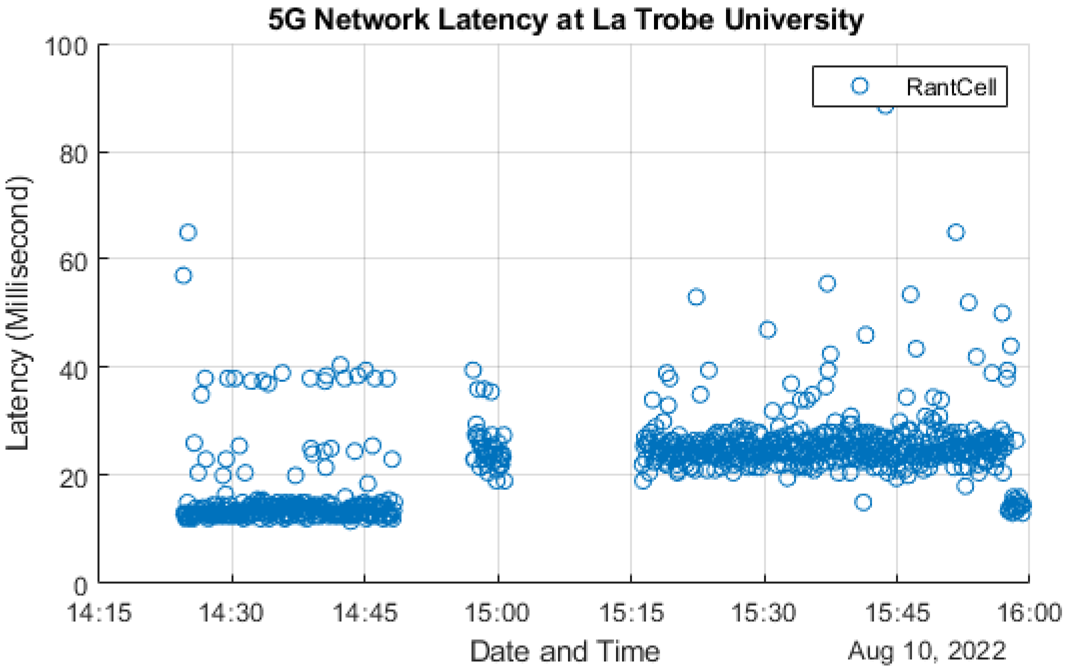

Figure 43 RantCell Latency Test Result

Figure 43 shows the RantCell one-way latency test result against the time from 14:15 to 16:00. We can see most latency values are around 10-30ms, which indicated excellent latency performance. This proves the 5G communication in the trial site can provide fast data transmission. As shown in Figure 44, 100% packets have been successfully received, which demonstrated excellent packet delivery performance.

Although the recommended latency metric defined in [2] -5ms, is not achieved in the RantCell test, excellent and acceptable latency values were seen from the results of the tests. From the RantCell 5G performance baseline testing, we can conclude that the 5G network in the trial site performed excellent in terms of latency, packet loss, signal strength, and full 5G availability.

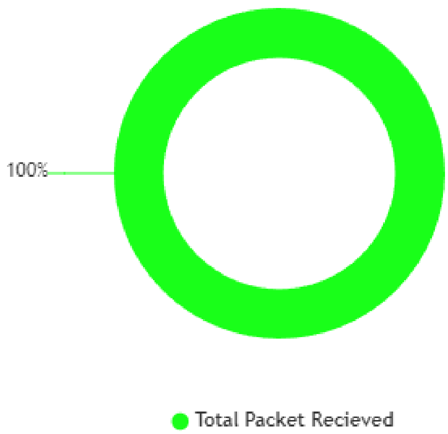

Figure 44 Total packet received

4.3 Vehicle-RSU Communication Test

The time synchronisation accuracy is shown in Figure 45. For RSU GPS timing, very high accuracy up to 30 micro-second is achieved; for OBU on vehicle, up to 20 micro-second accuracy is achieved.

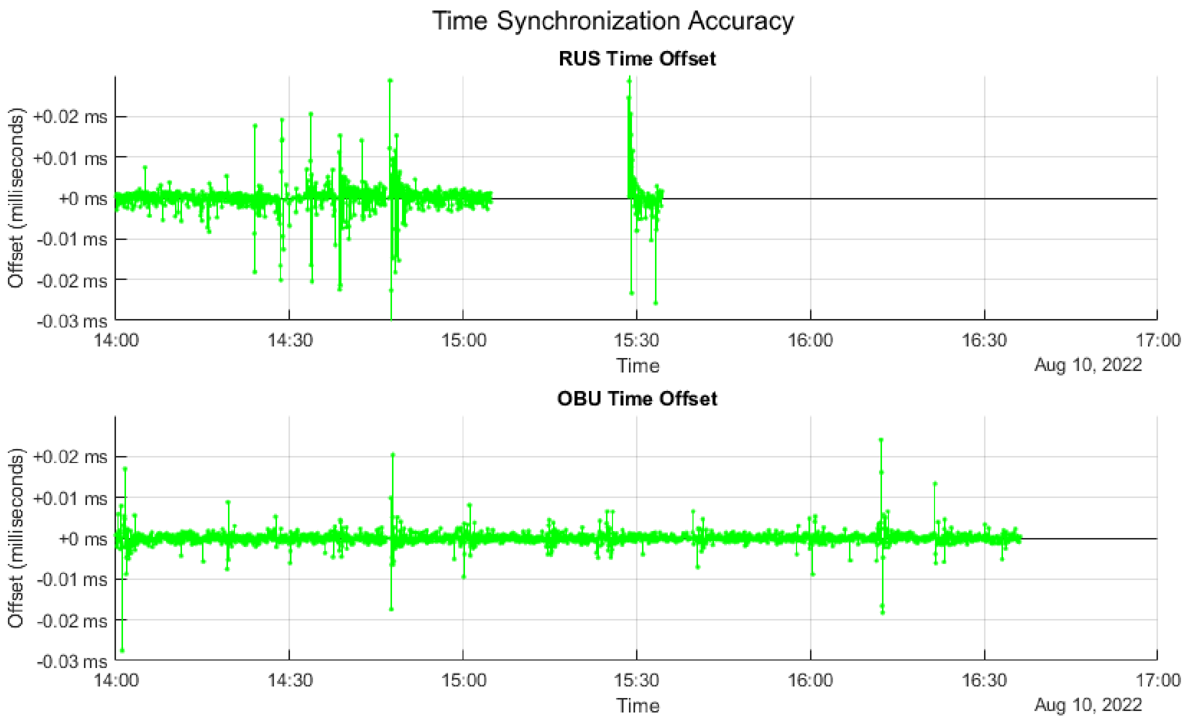

Figure 45 Time Synchronization Accuracy

The shuttle moved along the route towards the intersection. Two DSRC devices connected to the RSU and vehicle separately to ensure the timing is synchronized via GPS sensors. The end-to-end latency is calculated by comparing the timestamps on the receiving side and sending side. The accuracy has been proved to be micro-second level. In Figure 46, we can see the whole trial is comprised of appropriately 30 minutes, and the shuttle moved 3 times towards the intersection. The RantCell baseline testing latency values predominantly fall into the 10-40ms range. The latency values of the RSU to the vehicle are in a similar range. Figure 49 shows the histogram results of the RantCell latency. It shows that the most possible RantCell latency value is 10ms. Figure 50 shows the RSU-Vehicle latency histogram results, which shows the most possible latency value is 20ms. Figure 51 shows the comparison of RantCell and RSU-Vehicle latency histogram results, which indicates that RantCell latency test results are slightly better than RSU-Vehicle latency test. From these results, we can summarise that, although the full benefits of the 3GPP 5G NR are not achieved, the high speed 5G communication still provides very low latency results.

Figure 47 shows the test results when we select a time range of 10 minutes to clearly see the statistics. We can see mostly the latency values of RSU-vehicle fall into the 10-30ms range. As shown in this chart, the RantCell latency is at the similar range, which decides the network baseline performance. Ideally, we should achieve the recommended latency metric defined in [2], 5ms. But the baseline network performance will decide the best latency value we can achieve, which involves many factors such as network server latency, base station distance, etc. Figure 48 indicates the similar results to Figure 47.

The max latency is able to meet the communication requirements between RSU and vehicles. We can also see the latency values at different moving speed, while there are no obvious correlations. From these results, we can conclude that the 5G communication performed excellently to satisfy the vehicle-RSU use cases.

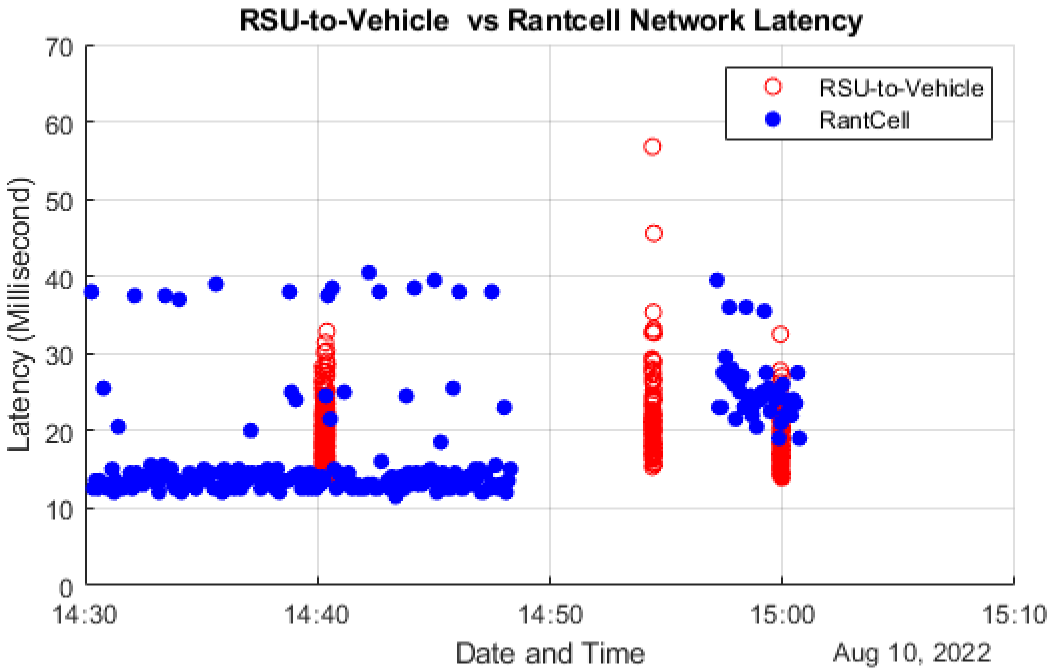

Figure 46 RantCell Test vs Vehicle-RSU Test – all tests

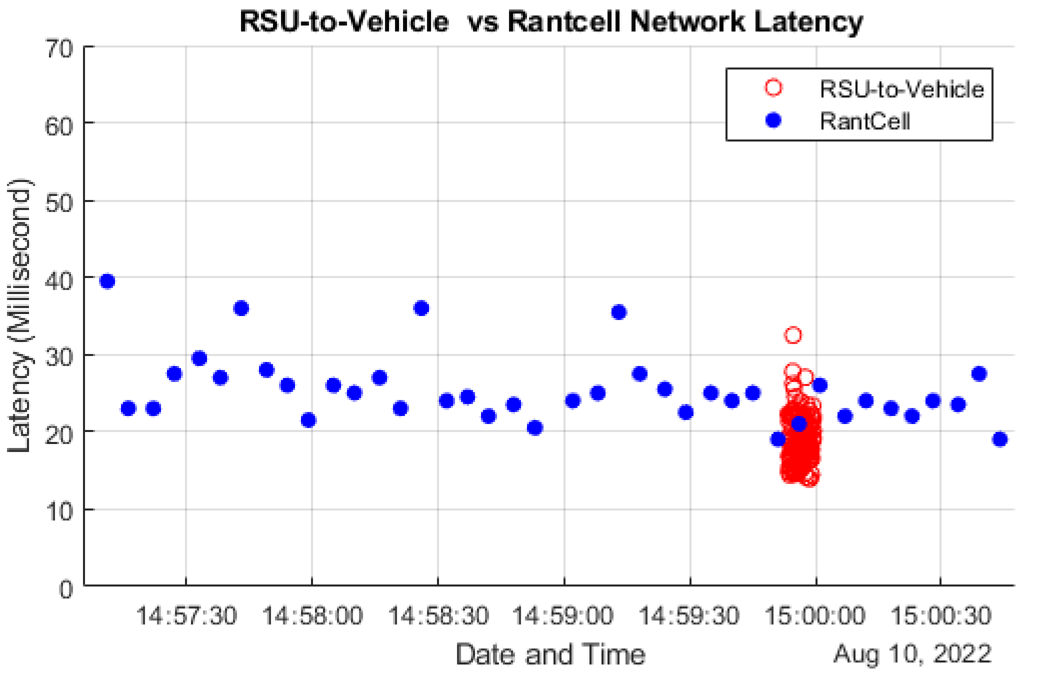

Figure 47 RantCell Test vs Vehicle-RSU Test – test sample B

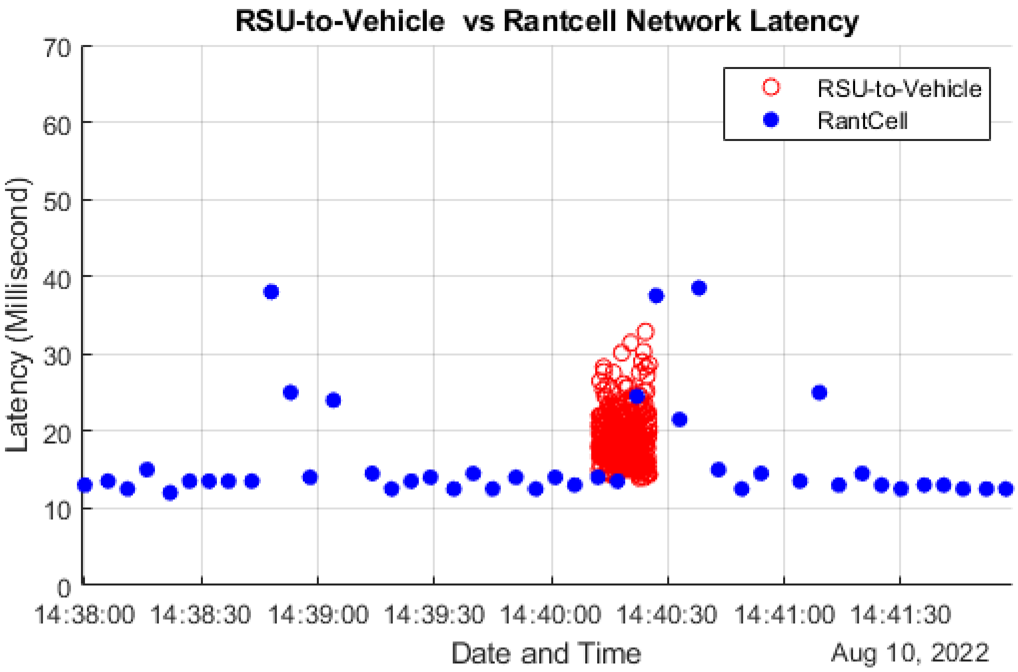

Figure 48 RantCell Test vs Vehicle-RSU Test – test sample A

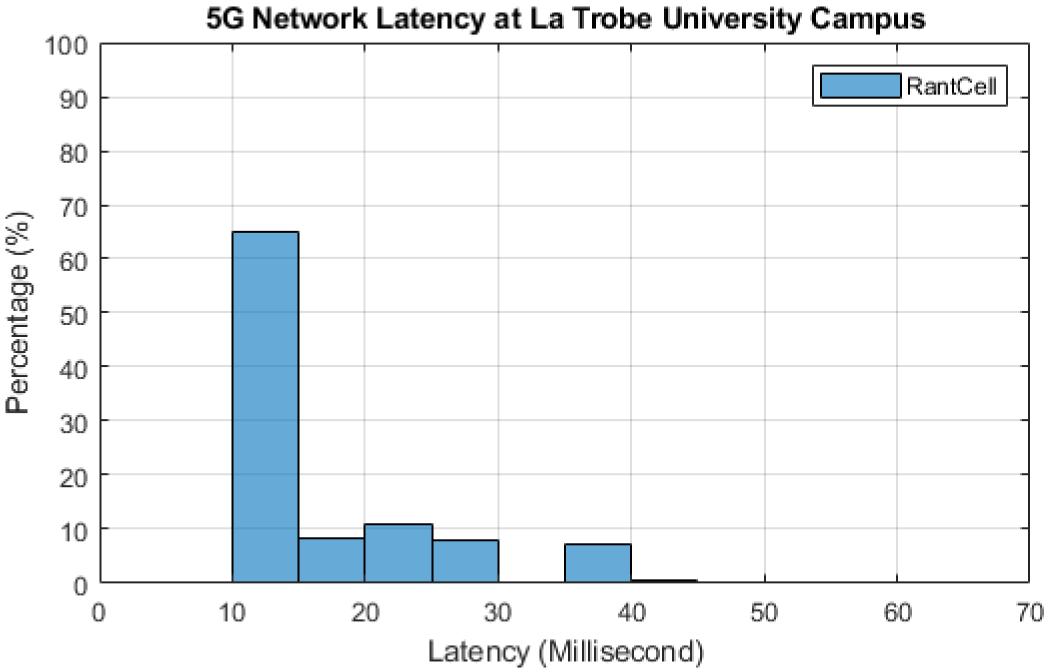

Figure 49 Histogram of 5G Network Latency in La Trobe- RantCell

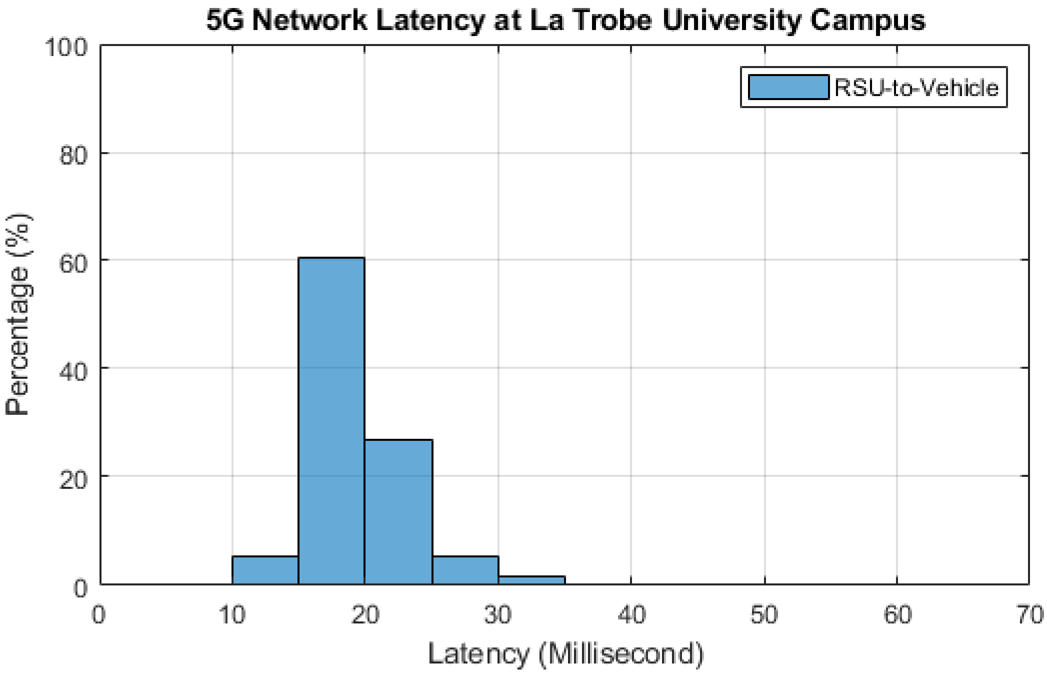

Figure 50 Histogram of 5G Network Latency in La Trobe- RSU to Vehicle

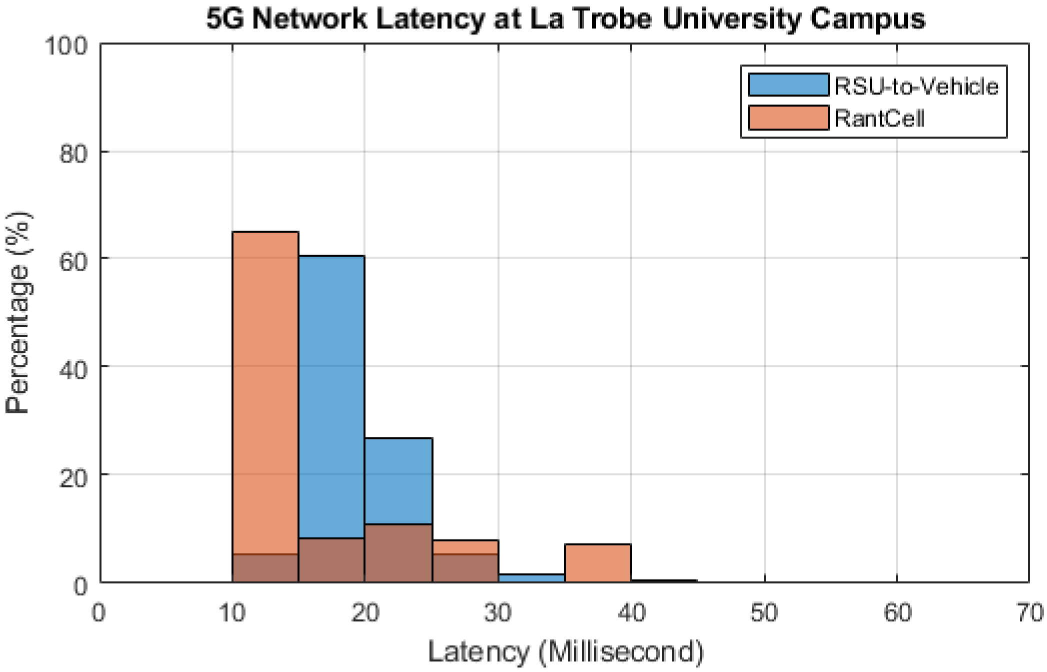

Figure 51 Histogram of 5G Network Latency in La Trobe- RSU to Vehicle vs RantCell

5 Conclusion

In the trials that were conducted in Sydney and Melbourne, it can be concluded that the 4G and 5G communication meet the requirement formulated by ETSI [2]. Network requirements are met for the RSU assisted vehicle operations of obstacle detections. The key contribution of this trial is to measure network latency and the message delivery provided by 4G/5G networks. To accurately measure the latency on the RSU and the vehicle, it is critical for the use of GPS timing synchronisation to ensure that all devices are synchronised correctly. The analysis results show that the GPS timing synchronisation accuracy is 20-30 microsecond.

Although the full benefits of the 5G network were not achieved, in the performance comparison of RantCell and RSU-Vehicle communication, a very low latency can be achieved in most cases. As a baseline performance test, RantCell tests performed consistently to the RSU-Vehicle tests. Although we did not achieve the recommended latency metric defined in [2] - 5ms, which is based on V2X communications, the latency values in our trial are close to that value. In our trial, the 5G network is not utilising the C-V2X features, but it was only able to utilise the normal network communications. The baseline network performance will decide the best latency value we can achieve in certain trial sites, which involves many factors such as network server latency, base station distance, etc. The RantCell baseline testing results show that most of the latency values came to approximately 10ms - 20ms. The RSU-Vehicle latency is approximately 15ms-25ms in most cases, which also included the software processing time. We can see the RSU-Vehicle latency is very close to the RantCell latency time. Therefore, we can confidently claim that the latency test in our trial meet the requirements formulated by ETSI [2].

According to the RSU-Vehicle trial results, we can conclude the usage of RSU is advantageous. When the RSU is fully working, the assistance to the vehicle is optimal. The vehicle can detect the obstacle when it is still 35 meters away. Even the RSU does not send any warning messages (assuming its Lidar fails), the vehicle still can prepare to stop in advance (40 meters away) as the vehicle assumes the intersection equipped with RSU may have hazard. The worst case is, the vehicle does not use any connected RSU, and only relies on its own intelligence to detect obstacles. In this case, the vehicle detects obstacle late and the braking is sharp that may not be safe to the passengers with disabilities on the vehicle. The usage of RSU can assist the vehicle to successfully detect the obstacle and avoid collision in advance, on public roads in the future. Especially for elderly and disabled people, this is significant to reduce sudden stops and potential falls.

In the remote monitoring/control trials, OHIMO has successfully established the Zao-X view monitoring platform, and successfully implemented the remote monitoring and control function. The real-time monitoring has been proved working and effective to monitor the vehicle remotely by the operator. The operator can hardly feel the latency of monitoring the vehicle. By measuring the performance in a busy/non-busy communication environment, the end-to-end latency, Bandwidth, and network latency, are all in reasonable range, in testing scenarios of using 4G and/or 5G sim cards, according to the performance metrics defined in [3-5].

In the remote-control tests, a remote operator was able to control the car while watching the live feed of road conditions via 5G network. Potentially, in case of emergency and accidents, the remote operators can monitor and control the vehicle to park safely in order to reduce the hazard. The Zao-X software is able to provide sufficient remote monitoring/control solution that provides enhanced road environment awareness. We tested three scenarios with 5G modem setups: 5G sim card, 4G sim card, 5G+5G+4G sim cards. Compared with the performance metrics in [2], the average latency is reasonable and practical, around 50ms, which is sufficient to handle the remote monitoring and control. It shows that Zao-X software suites is suitable for the future road trial and deployment when 5G remote monitoring/control is required.

In summary, the results demonstrate that the 5G network is able to provide broad coverage, high data throughput and low latency to enable continuous data transmission which allows for the sending of commands between an RSU and a vehicle, handling complex road scenarios, and remote monitoring/controlling. The elderly and disable people will take advantages of the 5G technology support CAV, to enjoy safe and comfortable rides.

6 References

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