Vehicular Distributed Antenna System (Vehicular-DAS)

5G Automotive Association
White Paper

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VERSION:	1.0
DATE OF PUBLICATION:	2 December 2022
DOCUMENT TYPE:	White Paper
EXTERNAL PUBLICATION:	YES
DATE OF APPROVAL BY 5GAA BOARD:	17 November 2022

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1. Introduction

The current development of communication technologies opens up new opportunities and enables novel V2X (Vehicle-to-Everything) services in the automotive area. Specifically, in order to introduce advanced V2X use cases requiring high reliability and/or high data rate, technologies such as multi-antenna technologies (e.g. massive MIMO (Multiple-Input-Multiple-Output)), broadband technologies (e.g. carrier aggregation or dual connectivity), but also FR2 (Frequency Range 2 (24250 MHz – 52600 MHz)) spectrum usage might be essential for efficient V2X communications. Also, the number of required antennas mounted on vehicles will keep growing for both PC5 and Uu to support such advanced use cases. However, the allowed positions and mounting spaces for antennas, communication module and the required cabling are limited, which leads to complex implementations. The main reason for this limitation is the automotive-specific design constraints including shape/form factors for different vehicle types, automotive certification aspect, etc. All these challenges have to be resolved in order to enable the full range of use cases in the automotive area, and it is commonly accepted within the industry that these constraints/challenges require vehicular Distributed Antenna System (vehicular-DAS) approaches.

This white paper provides analysis on both the motivation for and needs associated with vehicular-DAS, as well as some vehicular-DAS design solutions (proposals). In addition, it describes the implementation feasibility and potential benefits of vehicular-DAS based on measured computer simulation results. It also includes the analysis of potential vehicular-DAS impacts on current specifications.

2. References

[1] 3GPP TS 38.101-1 17.1.0, (2021-03), User Equipment (UE) Radio Transmission and Reception; Part W1: Range 1 Standalone.

[2] 5GAA, (2020-09), A Visionary Roadmap for Advanced Driving Use Cases, Connectivity Technologies, and Radio Spectrum Needs, https://5gaa.org/wp-content/uploads/2020/10/5GAA_White-Paper_C-V2X-Use-Cases-Volume-II.pdf.

[3] 5GAA, (2019-07) White Paper on C-V2X Use Cases: Methodology, Examples and Service Level Requirements, https://5gaa.org/news/5gaa-releases-white-paper-on-c-v2x-use-cases-methodology-examples-and-service-level-requirements/

[4] 5GAA, (2020-10), C-V2X Use Cases Volume II: Examples and Service Level Requirements, https://5gaa.org/news/c-v2x-use-cases-volume-ii-examples-and-service-level-requirements/.

[5] 3GPP TS 22.186 16.2.0, (2019-06), Service Requirements for Enhanced V2X Scenarios.

[6] 3GPP TR 38.826 16.0.0, (2018-12), Study on Evaluation for 2 Receiver Exception in Rel-15 Vehicle Mounted User Equipment (UE) for NR.

[7] A. Kwoczek, Z. Raida, J. Láčík, M. Pokorny, J. Puskelý and P. Vágner, (2011), Influence of Car Panorama Glass Roofs on Car-2-Car Communication (poster), 2011 IEEE Vehicular Networking Conference (VNC), Amsterdam, pp. 246-251.

[8] General Motors, 3GPP R1-1807613, V2X NR Evaluation Methodology – Vehicle UE Antenna Radiation Patterns.

[9] 3GPP TR 37.885, (2019-06), Study on Evaluation Methodology of New Vehicle-to-Everything (V2X) Use Cases for LTE and NR.

[10] 3GPP TS 38.401, (2020-10), NG-RAN; Architecture Description.

[11] 3GPP TR 38.801, (2018-03), Study on New Radio Access Technology: Radio Access Architecture and Interfaces.W

[12] 3GPP TS 38.101-2 17.1.0, (2021-03), User Equipment (UE) Radio Transmission and Reception; Part 2: Range 2 Standalone (Release-17).

[13] 3GPP R4-2017811, LS on Rel-16 RAN4 Clarification for UE Antenna Connector Interpretation, 3GPP RAN4 Meeting #97-e.

[14] IEEE, (2020-05), IEEE 802.3 Greater than 10 Gb/s Electrical Automotive Ethernet PHYs (P802.3cy) IEEE 802.3 WG Approved Objectives, https://www.ieee802.org/3/cy/P802d3cy_OBJ_WG_0520.pdf.

[15] IEEE, (2020-08), IEEE P802.3cy Greater than 10 Gb/s Electrical Automotive Ethernet Task Force, https://www.ieee802.org/3/cy/.

[16] IEEE, (2022-07), IEEE IEEE P802.3cy Task Force approved updated objectives, https://www.ieee802.org/3/cy/P802d3cy_OBJ_UPDATED_APPROVED_07_14_22.pdf.

[17] IEEE, (2021-01), P802.3cy Task Force Timeline, https://www.ieee802.org/3/cy/P802_3cy_timeline_01_22_21.pdf.

[18] 3GPP TS 38.215, (2020-12), Physical Layer Measurements (Release 16).

[19] 5GAA, (2021-02), V2XHAP WI TR: System Architecture and Solution Development; High-Accuracy Positioning for C-V2X, https://5gaa.org/wp-content/uploads/2021/02/5GAA_A-200118_TR_V2XHAP.pdf

[20] 3GPP TR 38.901, (2019-12), Channel Model for Frequencies from 0.5 to 100 GHz.

[21] 3GPP TR 36.885, (2016-06), Study on LTE-based V2X Services

3. Abbreviations

ADC/DAC	Analogue-to-Digital Converter/Digital-to-Analogue Converter
AoA	Angle-of-Arrival
AoD	Angle-of-Departure
BLER	BLock Error Rate
BW	Bandwidth
CA	Carrier Aggregation
C-V2X	Cellular-V2X
DL	Downlink
EMC	Electromagnetic Compatibility
FDD	Frequency Division Duplex
FR1	Frequency Range 1 (410 MHz – 7125 MHz [1])
FR2	Frequency Range 2 (24250 MHz – 52600 MHz [1])
gNB	Next-Generation Node B
GNSS	Global Navigation Satellite System
HARQ	Hybrid Automatic Repeat and Request
IEEE	Institute of Electrical and Electronics Engineers
IoT	Internet of Things
LAA	Licence-Assisted Access
LoS	Line-of-Sight
LTE	Long-Term Evolution
MIMO	Multiple-Input-Multiple-Output
MNO	Mobile Network Operator
NLoS	Non-LoS (Non-Line-of-Sight)
NR	New Radio

OEM	Original Equipment Manufacturer
OTDOA	Observed Time Difference of Arrival
PRR	Packet Reception Ratio
PRS	Positioning Reference Signal
QAM	Quadrature Amplitude Modulation
RSRP	Reference Signal Received Power
RSU	Road-Side Unit
SCS	Sub-Carrier Spacing
SL	Side-Link
SNR	Signal-to-Noise Ratio
TAE	Time Alignment Error
TCU	Telematics Control Unit
TDD	Time Division Duplex
TDoA	Time Difference of Arrival
ToA	Time of Arrival
UE	User Equipment
Vehicular-CU	Vehicular Centre Unit
Vehicular-DAS	Vehicular Distributed Antenna System
Vehicular-DU	Vehicular Distributed Unit
V2N	Vehicle-to-Network
V2V	Vehicle-to-Vehicle
V2X	Vehicle-to-Everything
UL	Up-Link
3GPP	Third-Generation Partnership Project

4. Definitions

For the purposes of the present document, the following definitions apply:

Vehicular-DAS	In vehicular Distributed Antenna System (DAS), functions of vehicular UEs (vehicle-mounted UEs) are split and performed in vehicular Distributed Units (vehicular-DUs) and the vehicular Central Unit (vehicular-CU)
Vehicular-DU	Vehicular Distributed Unit that includes a subset of functions of vehicular UEs (vehicle-mounted UE). Depending on function split options listed in Section 6.1, the functions implemented in the vehicular DU can be different
Vehicular-CU	Vehicular Central Unit that includes functions of vehicular UE (vehicle mounted UE), excepting those functions implemented in the vehicular-DU. The vehicular-CU controls the operation of one or multiple vehicular-DUs

5. Vehicular-DAS motivation and needs

5.1 The OEM perspective

The vehicular industry has started a huge transformation process towards digitalization in the area of transportation and mobility services. This process has been induced by the amazing development of internet technologies, services, and the creativity of the user community during the last decades. This has already shattered experts' expectations regarding technology limitations and continues to do so. The engine for the transition is customers' craving for new services in all aspects of life (e.g., health, work, education, mobility, etc.), stimulated by the creativity and dedication of the new economy big players. It is obvious that the impact of digitalization in the automotive industry will grow greatly over the next 10 years and dominate vehicle manufactures' business during this time. This motivates and inspires manufacturers to continuously develop and deliver new functions and services to improve road safety, traffic efficiency, but also to deliver customer services that while not specific to the automotive sector are used or provided in vehicles. Existing services such as High-Definition (HD) Content Delivery and new services such as Tele-Operated Driving and Automated Driving offer new customer/driver experiences affecting work and home lives [2][3][4].

To illustrate this fact, 5GAA [3][4] selected more than 50 use cases divided into the following classes:

- Autonomous Driving
- Convenience
- Convenience and Vehicle Operations Management
- Convenience and Advanced Driving Assistance
- Convenience In-Vehicle Entertainment
- Platooning

- Safety
- Safety and Automated Driving
- Traffic Efficiency
- Traffic Efficiency and Environmental Friendliness
- Vehicle Operations Management

Due to the nature of services in the automotive area, only wireless communication can enable these use cases and the related businesses. Two types of radio technology are required for all types of services provided to OEMs' customers: cellular mobile communication and V2V direct communication [2][3][4]. To develop and select the right radio technology, all relevant communication system- and implementation-related requirements must be carefully reviewed. In addition to parameters, such as latency and data rate, service reliability is fundamental for road safety-based services. Beyond this, aspects such as service and implementation cost, technology availability and compatibility issues all need to be considered.

The imminent challenges of implementing wireless communication in vehicles are numerous. Firstly, the above-listed 5GAA use cases require latencies below 20 ms and rates per vehicle/service use up to 250 Mbps and higher (3 ms or up to 1000 Mbps), as presented by 3GPP TS 22.186 for release 16 [5]. These values are far beyond the capability of current communication solutions. Secondly, as also seen in the following examples, these types of services have an impact which goes beyond the cost and complexity of the in-vehicle implementation. The number of vehicles, especially in mega-cities, and the very stringent automotive requirements on service quality (e.g. data rate, latency, service availability/continuity, vehicle mobility and density, Table 1) will clearly impact the whole system, including the mobile network/infrastructure operator domain and the service provider domain.

UC	Rate	Latency ms	Reliability %	UE per km2 (vehicle or bus)	Velocity km/H
High-Definition (HD) Content Delivery: On-line Gaming and Virtual Reality – High-End Service for Cars	<250 Mbps	20	99	500 or 30	<250
High-Definition (HD) Content Delivery: Low-End Service for Car	50 Mbps	20	99	500 or 30	<150
High-Definition (HD) Content Delivery: Bus Passenger Service	50 Mbps	20	99	500 or 30	<100
Automated Intersection Crossing		10	99.9	3200	20-35 ms
Cooperative Lane Change	Total 64 Mbps	"4*40"	99.9	4500…12,000	<150
Infrastructure-based Tele-Operated Driving	UL: 5-8 Mbps				
Tele-Operated Driving	UL:>30 Mbps				

Table 1: Section of V2X service requirements to indicate the challenges to mobile network operators

As indicated above, these new services demand much higher requirements compared to conventional service types (e.g. voice calls or browsing). This, in turn, leads to much higher demands on the implementation of the communication systems in vehicles as well as on the networks. Several standards organisations, such as 3GPP and IEEE, provide good solutions or are developing solutions to enable these services. To fulfil these extremely high requirements for all customers in certain areas, solutions such as multi-antenna technologies (including massive MIMO), broadband technologies (carrier aggregation) and frequency range 2 (FR2, 24,250 MHz – 52,600 MHz) solutions will be essential in the next five-to-ten years. However, the allowed positions and mounting spaces for antennas, the communication module (TCU) – and required cabling to connect both – are limited and/or lead to complex implementations brought on by certain automotive-specific design constraints, as noted:

- Specific vehicle-type design constraints (e.g. shape/form factor and design elements of convertibles, trucks and other vehicle types, or designs which require concealed antennas, smart antennas, flat conformal antennas, etc.)
- Specific product usage (e.g. safety critical, outdoor, life cycles of 15-20 years, weight-dependent fuel consumption)
- High number of implemented radio technologies
- Regulatory aspects (e.g. SAR, eCall)
- Automotive certification aspects (e.g. temperature aspects)

Therefore, a further increase in the number of antennas, higher carrier aggregation levels and the introduction of FR2 solutions pose extreme challenges for vehicle manufacturers in terms of implementation. All these challenges must be resolved to enable the full range of use cases in the automotive area. It is commonly accepted within the automotive industry that these constraints compel the use of DAS approaches, allowing separate implementation of antenna units and the TCUs, where both units are connected via coaxial cables. Yet this vehicular-DAS solution is costly, complex and unlikely to meet future needs in terms of data rates, frequency bands, use cases and business opportunities likely to arise in the next decade. New vehicular-DAS strategies are therefore needed to meet the demands of 5G and beyond, solutions which are scalable, efficient and future-proof.

5.2 The MNO perspective

For the efficient use of high-performing cellular-to-air interface (LTE or NR Uu) antennas on the UE side (i.e. the car) are essential. With LTE and especially NR, due to the increased data rates provided to mobile users the number of antennas required for the UE is constantly increasing (2 Rx antennas are the mandatory baseline for LTE UE and 2 Rx/4Rx antennas are the mandatory baseline for NR UEs defined in 3GPP). At the request of the car industry, and regarding NR in particular, a so-called "automotive antenna exception" [1] has been discussed and decided upon, allowing cars to be equipped with only two antennas for NR bands which, in turn, require four antennas for normal UEs [6]. This exceptional setup is needed because it calls for a fixed mounting of the UE in the car and fixed connection to the car's antenna system, which typically provides better antenna gain than other form factors (e.g. smartphones or other devices).

Due to their significant investment in spectrum licence fees, operators are interested in the most efficient use of their spectrum, while aiming to provide the best connectivity to all users including customers moving around in vehicles. To allow the efficient installation of multiple antennas in that environment, operators support the adoption of vehicular-DAS in the automotive industry for multiple reasons:

- Decorrelation of antennas due to increased spacing, instead of ultra-compact “shark-fin” antenna design
- Increased antenna performance due to better placement opportunities for RF-optimised antennas (less size constraints, wavelength optimised antenna length)
- Resulting in better spectrum efficiency and, in turn, resulting data rates provided to/from the car (better service experience)
- Enhanced cell-edge performance due to better reception/transmission efficiency (better coverage experience)
- Possibility to increase the number of vehicle-mounted antennas, as cabling is less an issue with disaggregated vehicular-DAS based on digital interfaces between vehicular-DU and vehicular-CU (instead of bulky and inflexible low loss coaxial cabling, and no longer need to be limited to two or even a single Rx antenna)

For these reasons, cellular operators support the development and large-scale application of vehicular-DAS systems in modern cars, requiring enhanced mobile broadband and IoT connectivity based on optimised multiple antenna transmission and reception, and resulting in better network utilisation, coverage and service experience.

5.3 The supplier perspective

To support advanced V2X use cases requiring higher radio-link reliability and data rates, one key requirement of vehicular-UE implementation is to provide full 360-degree (omnidirectional) coverage, ideally with no power dips and concentrated in the horizontal plane. However, this is hard to achieve with conventional antenna systems and co-located arrays for the vehicular-UE because power dips occur in some directions when the vehicle itself blocks the signal. In [7], real-world antenna patterns for various vehicle models are presented. As visualised in Figure 1 (Source: [7]), these patterns show significant power dips, especially when vehicles with glass roofs are considered. The configuration for a panorama roof, for example, shows reduced performance in the direction of the glass panel in the range of 15 to 20 dB which results in a drastically lower communication range towards the front. This confirms that co-located antenna systems are not sufficient for some vehicle types/designs/form factors. This was also observed and discussed by 3GPP RAN1, based on input from car OEMs. In [8], it is shown that different antenna locations generate different radiation patterns and the conventional shark-fin antenna location (e.g. rear rooftop) causes up to 5 dB power dips in certain directions due to the “self-blockage” effect described earlier. Vehicular-DAS can further improve the antenna radiation characteristics by adapting the antenna design to new mounting positions. Specifically, vehicular-DAS covers each spatially divided configuration with different vehicular-DUs located further away from each other. As to the antenna radiation characteristics, the pattern for vehicular-DAS UE with two antenna panels has been introduced in the evaluation assumptions put forward by 3GPP RAN1 since its Release 15 (e.g. one panel on the front section of the rooftop and the other on the rear) [9].

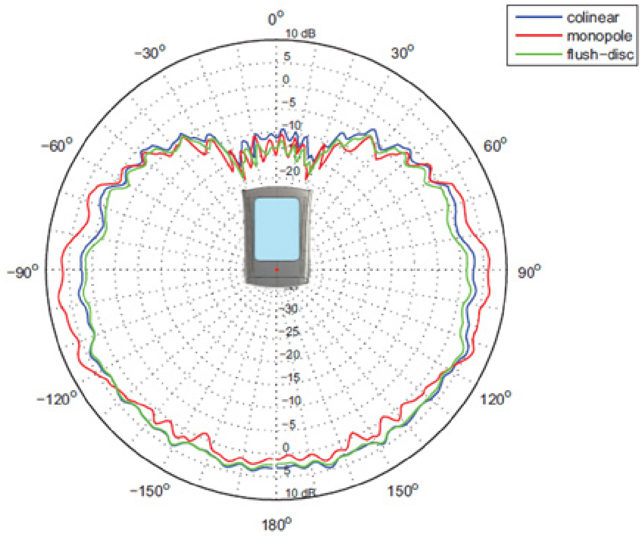


Figure 1: Antenna pattern for vehicles with glass roof, Source: [7]

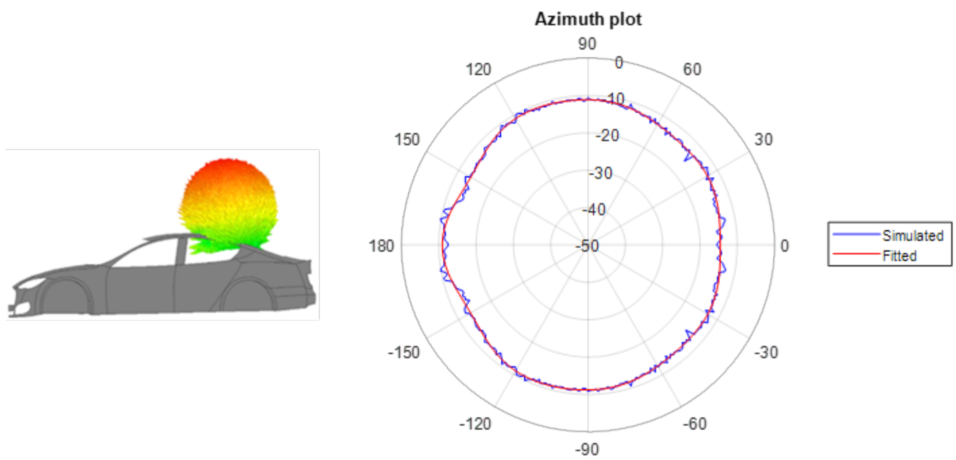


Figure 2: Antenna pattern for rear rooftop antenna, Source: [8]

In addition, the number of required antennas mounted on vehicles keeps growing for both PC5 and Uu communication with the introduction of advanced V2X use cases, which raises the question as to the optimum deployment of multiple antennas. Considering automotive-specific design constraints, vehicular-DAS deployment can be considered essential for some types of vehicles and a suitable antenna solution for the industry as a whole.

6. Design options for vehicular-DAS

6.1 CU/DU function-split options

In vehicular-DAS, the functions of vehicular UEs (vehicle-mounted UE) are split and performed in vehicular-DUs and vehicular-CUs. Vehicular-DUs include a subset of functions of the vehicular UE, and the functions implemented in the vehicular-DUs can be different depending on function split options described in the vehicular-DAS. Nine potential function-split options are identified and described in Figure 3, and their pros and cons are analysed in various aspects (e.g. implementation complexity, MIMO gain achieved by using vehicular-DUs, interface bandwidth requirement, etc.). It should be noted that the figure does not provide an exhaustive list of vehicular-DAS function-split options. Additionally, the numbering of function split options in this document is different from the split-numbering described in the (NG-) RAN architecture decomposition used in 3GPP specification [10]. The result of the analysis on function-split options is summarised in Table 2.

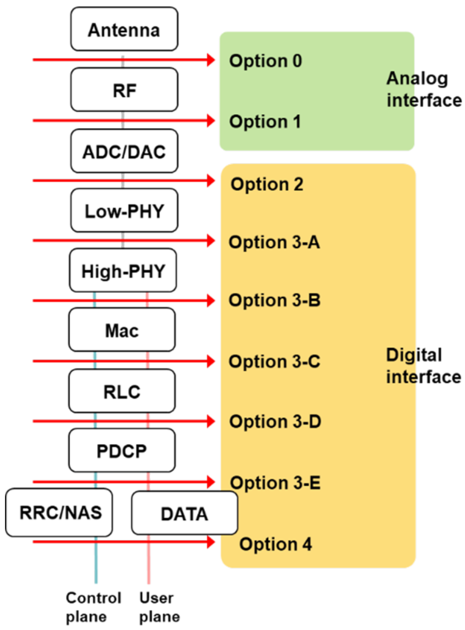


Figure 3: Function-split options of vehicular-DAS

Analogue interface	Option 0 (Antenna – RF split)		Only antennas are in the vehicular-DU and the other functionalities are in the vehicular-CU Extending the (copper) cabling between the antenna and RF unit is the most common solution when the antenna and RF unit are not in the same place
		Pros	Passive antenna has less demand on installation space and it is flexible to mount The complexity of vehicular-DU is the lowest among all options
		Cons	Radio performance is impacted by cable length; as the cable loss scales with the frequency this gets more critical the higher the carrier frequency, e.g. at FR2 band Number of cables linearly increases with the number of MIMO ports at each panel
	Option 1 (RF – PHY split)		Antennas and RF are in the vehicular-DU and the other functionalities are in the vehicular-CU The cable loss can be reduced when the RF signal is converted to intermediate frequency band, however cable length remains a limitation in the system design
		Pros	Less cable loss (if intermediate frequency conversion is applied) Possible to multiplex the MIMO stream from the same panel
		Cons	Radio performance is impacted by cable length
Digital interface	Option 2 (RF + ADC/ DAC – PHY split)		Antennas, RF and ADC/DAC are in the vehicular-DU and the other functionalities are in the vehicular-CU Time-domain I/Q samples are transmitted via the interface between vehicular-CU and vehicular-DU
		Pros	Not limited by cable length Joint processing for the signal from/to different vehicular-DUs in the physical layer operation can be supported efficiently (e.g. joint MIMO equalisation, LLR combining) Possible to multiplex the MIMO stream Multiple vehicular-DUs can be utilised to gain the selection diversity, or redundant/duplicated packet TX/RX
		Cons	Throughput requirement between vehicular-CU and vehicular-DU increases linearly with the number of bands, bandwidth per band, and number of antennas at each vehicular-DU

Digital interface	Option 3 (Intra-modem function split)	Option 3-A (Low PHY – High PHY split)	Part of physical layer function (Low-PHY) and RF are in the vehicular-DU. Upper layers and the other part of the physical layer function (High-PHY) are in the vehicular-CU. There could be several variants of High/Low-PHY function split	
			Pros	Same with the benefits of Option 2, plus: Much lower throughput demand between vehicular-CU and vehicular-DU (compared to Option 2)
			Cons	Additional complexity in the vehicular-DU (compared to Option 2)
		Option 3-B (PHY – MAC split	The higher layer and MAC functions are performed in the vehicular-CU, and all physical layer operation is supported in the vehicular-DU. (e.g. HARQ operation of the same MAC PDU for multiple vehicular-DUs can be supported in a centralised manner)	
			Pros	Much lower throughput demand between vehicular-CU and vehicular-DU
			Cons	No PHY layer coordination between vehicular-DUs, which reduces the efficiency of MIMO gain
		Other 3-X options (including 3-C, D, E)	Pros	The throughput demands reduce further, when the function split takes place in the higher layer, but it is not more significant
			Cons	No PHY layer coordination between vehicular-DUs, which reduces the efficiency of MIMO gain
	Option 4 (split into individual UEs)		Application is in the vehicular-CU only. NAS, RRC, PDCP, RLC, MAC, physical layer and RF are in the vehicular-DU, thus the entire control and user plane are in the vehicular-DU Different from other options, each vehicular-DU is interpreted as an individual UE, and this means the vehicular-DAS UE is regarded as a group of UEs, or multiple UEs in 3GPP topology	
			Pros	Each vehicular-DU can be updated/replaced individually
			Cons	Vehicular-DAS UE with Option 4 is not a typical UE in 3GPP topology; the operational mechanism (e.g. required application layer coordination, how to handle a vehicle with multiple UEs at the network end) with Option 4 is unclear Cost of multiple UEs Highest power consumption Less efficient due to coordination uncertainties between vehicular-DUs (e.g. vehicular-DUs (UEs) might compete for radio resource and might even interfere with each other)

Table 2: Analysis on the function split options

Based on the analysis and for further clarity, these nine options can be arranged into two categories (Group A and B). Effort can then be focused on design options in Group A, with options in Group B considered low priority, as designated in Table 3.

Group A	Group B
1. Option 0 (Antenna – RF split 2. Option 1 (RF – PHY split) 3. Option 2 (RF + ADC/DAC – PHY split) 4. Option 3-A (Low/High PHY split)	1. Option 3-B (PHY-MAC split) 2. Option 3-C (MAC-RLC split) 3. Option 3-D (RLC-PDCP split) 4. Option 3-E (RLC-RRC split) 5. Option 4 (Split into individual UEs)

Table 3: Classification of spilt options for a decision on vehicular-DAS design options.

Specifically, it was decided to deprioritise options in Group B for the following reasons:

- According to analysis on potential performance gain of vehicular-DAS in the work item, some options where physical layer operation is performed at each vehicular-DU individually can achieve very limited performance gain (e.g. throughput, reliability) in vehicular-DAS. Specifically, Option 3-B, 3-C, 3-D, 3-E and 4 are not able to provide MIMO gain (e.g. combined gain) using vehicular-DAS.
- In the analysis on required interface bandwidth, it is observed that the more functions located in the vehicular-DU, the lower the bandwidth required in the interface between vehicular-CU and vehicular-DU. However, when comparing different design options in terms of interface bandwidth, the reduction is not significant in Option 3-C, 3-D, and 3-E.
- In Option 4, each vehicular-DU is interpreted as an individual UE, and thus a vehicle with this vehicular-DAS option is not a typical/traditional UE in 3GPP topology. The operation mechanism/procedure of the vehicle with Option 4 is thus unclear.

Regarding the design options in Group A, as the state of the art, Option 0 and 1 will be implemented first, and then the vehicular-DAS design will move to Option 2 and/or 3-A. In the early stage of vehicular-DAS implementation, it is expected that Option 0 or 1 is used. In Option 0 and 1, an analogue interface (e.g. coaxial cable) is used, in contrast to other design options. As coaxial cables have been standardised and widely used in the automotive industry for several decades, these two options can be considered as appropriate design options in initial vehicular-DAS implementation. Cabling loss at the interface is expected to result in performance degradation, but this issue can be resolved/relaxed by introducing a digital interface for vehicular-DAS. Therefore, we expect the migration of analogue interface to digital interface in the implementation of vehicular-DAS interface. Additionally, when a digital interface is adopted for vehicular-DAS (especially for V2X communication only in FR1), Option 2 will be implemented for vehicular-DAS because it makes it possible to achieve MIMO gain easily/efficiently for the UE, which also means implementation cost/complexity could be lower compared to Option 3A. Also, as the usage of FR2 will further increase data rate requirements at the interface, Option 3A is considered feasible when the UE needs to support V2X operation in both frequency ranges (FR1 and FR2).

6.2 Interface

In this section, several requirements that need to be taken into account in vehicular-DAS interface design are identified and elaborated upon. These are data rate, delay, and synchronisation aspects.

Data rate requirement

The throughput/bandwidth requirement at the interfaces varies among the different vehicular-CU/vehicular-DU splitting options. Meanwhile, the throughput/bandwidth requirement is also impacted by the type of V2X services that vehicular-DAS should support. In order to enable a quantitative comparison between vehicular-CU/vehicular-DU splitting options, the formulation and methodology to calculate the bandwidth requirement is given in Table 4. The analogue interface has a fundamentally different definition of bandwidth, so it is not included in this analysis; the focus is on design options with digital interfaces. As can be seen in the table, in general, the more functionalities implemented in the vehicular-CU, the higher the data rate support needed at the interface.

Design option	**Formula for calculation of the data rate requirement**	**Examples for the requirement**
		Scenario 1: LTE system with 2048 subcarriers, 15 kHz subcarrier spacing, bit width 2*10 bits for uplink and downlink, and 2 antenna ports at vehicular-DU **Scenario 2: 5G system with 4096 subcarriers (100 MHz band), 30 kHz subcarrier spacing, 2*16 bit width (assuming 256 QAM need to be supported) and 4 antenna ports at vehicular-DU**
Option 2 (RF + ADC/ DAC – PHY split)	$R_{RF\text{-}PHY} = N_{subcarrier} * \Delta f *$ Bitwidth * $N_{antennaports\_DU}$	Scenario 1: 1.23 Gbps Scenario 2: 15.73 Gbps
Option 3-A (Low/ High PHY split)	$R_{IntraPHY} = (N_{subcarrier\_active} * N_{symbol} * N_{antennaports\_DU} *$ Bitwidth + MAC_Info)/TTI	The requirement on the interface is roughly equal to the actual payload of V2X services supported by vehicular-DAS UE.

	[Note] $N_{subcarrier}$: Total number of subcarriers that a single UE can/should support (including non-active subcarriers) $N_{subcarrier\_active}$: The maximum number of active subcarriers that a single UE can/should support Δf: Subcarrier spacing BitWidth: Bit width of the IQ symbol $N_{antennaports\_DU}$: The number of antenna ports at the vehicular-DU TTI: Length of Transmission Time Interval MAC_Info: Information about antenna configuration, beamforming factor, resource block assignment, etc.; compared to the bandwidth demand for data and control channel, the actual overhead for MAC information is much less and therefore can be ignored N_{symbol}: The number of symbols per subcarrier and time interval N_{layer_DU}: The number of layers at one vehicular-DU	

Table 4: Data rate requirement for DAS interface

Delay requirement

Increased delay in the interface can impact the vehicular-DAS UE performance.

- In Option 2 and 3-A, the system performance can be sensitive to jitter and synchronisation of the interface. In this WI, based on the computer simulations, it is observed that the delay caused by the interface does not affect the throughput performance in both Uu and sidelink communication (when the interface delay is smaller than 3 ms). However, further analysis of the delay requirement could be needed.
- Regarding Option 3-B and 3-C, the delay of the vehicular-CU/vehicular-DU interface is mainly restricted by the HARQ processes. The total delay, including the time for RF/PHY/MAC processing, should be less than the duration of HARQ, which is 4 ms for a LTE system. Taking the description of the requirement on the vehicular-CU/vehicular-DU interface at the base station as the reference [11], the maximum latency

on the interface should be less than 250 µs. A 5G system may have faster HARQ processing (e.g. for URLLC services) and, hence, the maximum delay requirement on the interface needs to be reduced or adjusted accordingly.

- In Option 3-D and 3-E, the maximum transmission latency of the interface between vehicular-CU and vehicular-DU is not limited by HARQ because it is moved to vehicular-DU. In these cases, the E2E latency requirement of the V2X services, in particular the delay-sensitive services, can be taken as the guideline to estimate the interface delay.

Synchronisation requirement

The time and frequency synchronisation of the different vehicular-DUs needs to be guaranteed in order to ensure that vehicular-DAS does not experience a drop in performance.

In 3GPP RAN4 specification [1][12], the time and frequency synchronisation requirement for a UE is given, as shown below:

- Time synchronisation

	Time Alignment Error (TAE) requirement
Uu (for both FR1 and FR2)	130 ns (for UL-MIMO) [1] [12]
Sidelink (for FR1)	260 ns [1]

- Frequency synchronisation

	Frequency error
Uu (for both FR1 and FR2)	130 ns (for UL-MIMO) [1] [12]
Sidelink (for FR1)	±0.1ppm [1]

According to the specification, the time synchronisation requirement for a UE is defined using the metric Time Alignment Error (TAE) where TAE is described as follows:

- For FR1 UL MIMO, TAE is defined as the average frame-timing difference between any two transmissions on different transmit antenna connectors.
- For FR1 sidelink (V2X), TAE is defined as the average slot-timing difference between transmissions on two transmit antenna connectors.
- For FR2 UL MIMO, TAE is defined as the average frame-timing difference between any two transmissions on different physical antenna ports.

As can be seen in the above tables, the TAE requirement for the Uu link is stricter than the one for the sidelink. This means if the aim is to design a unified antenna system supporting both Uu link and sidelink, it is sufficient for an UE with vehicular-DAS to fulfil the requirement for the Uu link (specifically for UL MIMO).

Also, in FR1, TAE requirements for the UE should be fulfilled at different transmit antenna connectors, whereas the requirement needs to be satisfied at different physical antenna ports in FR2. Recently, the definition of antenna connector for vehicular UE has been clarified by 3GPP RAN4 [13]. In [13], RAN4 explained that external components, such as cables and compensators, may be used to connect the UE antenna connector to a vehicle- mounted antenna connector, as shown in Figure 4. And this means that the TAE requirement for vehicular UE should be met at the UE antenna connector depicted below, excluding any external components.

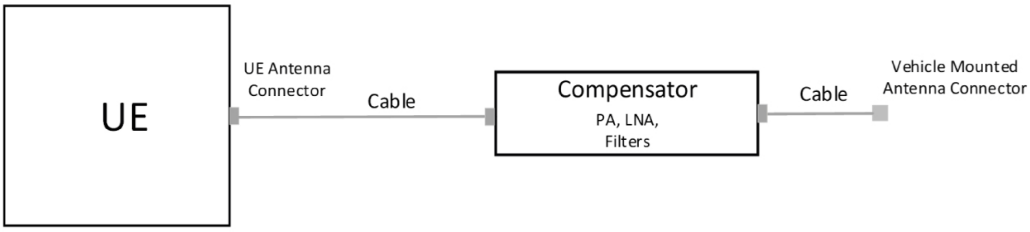


Figure 4: Definition of antenna connectors for vehicular UE [13]

The TAE requirement should be satisfied at the UE antenna connectors for vehicular UEs. However, for a UE with vehicular-DAS, the UE antenna connector can be included in the vehicular-CU or the vehicular-DU, depending on the function-split option implemented for the vehicular UE.

- In function-split Option 0 and 1, where the analogue interface is used to connect vehicular-DUs and vehicular-CU, each vehicular-DU and interface are interpreted as “external components” described in [13], as shown in Figure 5. This means that the TAE requirement defined by 3GPP RAN4 needs to be satisfied through antenna connectors “in the vehicular-CU” and detailed design of the external components including vehicular-DU and interface is up to UE implementation.

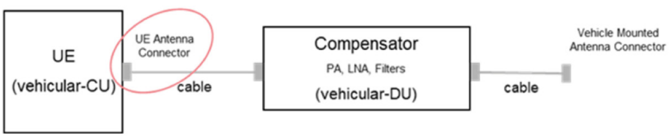


Figure 5: Antenna connector for vehicular UE in function split Option 0 and 1

- In function-split Option 2 and 3 (including their sub-options), the UE antenna connector of the vehicular UE is equivalent to vehicle-mounted antenna connectors implemented at the vehicular-DU end, as depicted in Figure 6. Therefore, for simultaneous transmission using multiple vehicular-DUs, the TAE between different UE antenna connectors should meet the requirement defined by 3GPP RAN4. However, if vehicular-DU selection-based transmission is assumed (e.g. only a selected single vehicular-DU is used for transmission in a single time instance), the TAE requirement considering the timing error across different vehicular-DUs may not be needed since the UE with vehicular-DAS can be seen as a vehicular UE with co-located antennas (e.g. antennas located only in the selected single DU) at each time instance.

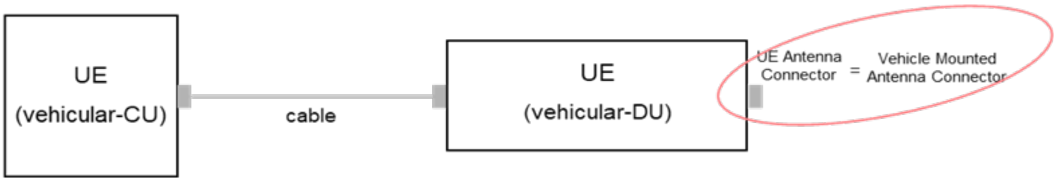


Figure 6: Antenna connector for vehicular UE in function split Option 2 and 3

- In function-split Option 4, the UE antenna connectors can be interpreted as antenna connectors in the same vehicular UE since each vehicular-DU represents an individual (vehicular) UE according to the 3GPP topology. In other words, synchronisation between different vehicular-DUs is not considered as they are different "individual" UEs.

Regarding the frequency synchronisation requirement in RAN4 specification, the frequency error is described as follows:

- For FR1 and FR2, UL frequency error is defined as the UE modulated carrier frequency and should be within the given accuracy range of the carrier frequency received from the NR Node B observed over a period of 1 ms.
- For FR1 sidelink (V2X) frequency error is defined as the UE modulated carrier frequency and should be within the given accuracy of the carrier frequency received from the absolute frequency in case of GNSS synchronization observed over a period of 1 ms (0.5 ms in case of SL MIMO support). The same requirement is applied relative to the NR Node B and V2X synchronisation reference UE, in the event these are used as synchronisation sources.

From these definitions it is clear that, for a vehicular-DAS system, synchronisation at each vehicular-DU is required. No additional system synchronisation requirements are needed, as this can be implemented at each vehicular-CU independently.

7. Analysis on feasibility and potential benefits of vehicular-DAS

7.1 Implementation feasibility

Some of the most important aspects in 5GAA's study on vehicular-DAS were

- the definition of the requirements of a digital interface between vehicular-CU and -DU, and
- the analysis of the feasibility of a sufficient vehicular-DAS solution with a digital interface according to predefined metrics (maximum data, minimum latency, flexibility, and scalability).

Accordingly, the following evaluation of the needed data bandwidth of the potential vehicular-CU and vehicular-DU interface was performed to

- identify the corresponding requirement for the digital interface,
- verify the availability of an existing technology, and
- identify technology gaps of vehicular-DAS enabling technologies.

Additionally, a first view on flexibility and scalability aspects pertaining to vehicular-DAS were discussed.

Note that due to the high number vehicle type variations as well as unknowns in the roadmaps and technology development, only a coarse estimation of some aspects was performed in this 5GAA work item. Although, this decision may have limited the evaluation, it still presents a sufficient and general understanding of the limitations and benefits of vehicular-DAS. Also note that this analysis mainly focuses on the 3GPP-based radio technologies, in particular LTE and 5G, as 3GPP's most demanding technologies (this mostly relates to rate and latency aspects). However, non-3GPP technologies, such as WLAN-based wireless communication technologies, must also be included in the final evaluation of vehicular-DAS.

In the following, an introduction of the expected communication system setup is presented. Based on this reference system, communication as well as implementation aspects are discussed. Finally, an evaluation of the expected data rates is performed, which leads to a basic set of requirements for the data rate bandwidth of the interface.

Figure 7 illustrates the essence of the evaluation performed on the main data-rate calculation relationship as well as for the discussion on flexibility and scalability issues. The basic assumption applied to this is that future implementation should be expected to perform

- simultaneous operation of 5G-V2X and LTE-V2X, which results in
- simultaneous operation of 5G PC5 and LTE PC5 as well as
- simultaneous operation of 5G Uu and LTE Uu.

Based on this assumption, the following aspects and parameters determine the evaluation results:

- Number of antennas
- Number of aggregated bands (carrier aggregation level) across all the RATs (including solutions, e.g. DC-EN)
- Usage of FR2 but also FR1

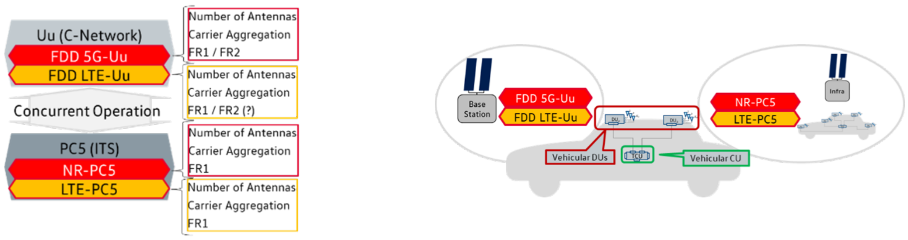


Figure 7: Concurrent operation of 5G and LTE as well as V2N and V2V communication

Number of antennas

Table 5 presents the number of antennas for Uu and SL which can be expected in current and future network deployments (3GPP).

Uu		SL	
Tx	Rx	Tx	Rx
1	2	1	2
2	2	2	2
2	3	2	3
2	4	2	3

Table 5: Number of Tx and Rx Antennas for V2N (Uu) and V2V (SL)

Number of aggregated bands

Based on the public deployment plans and spectrum allocations, the expected aggregated bandwidths grow far beyond 100 MHz within the next decade. Table 6 and Table 7 present the resulting allocation for the three largest MNOs in Germany as of September 2021 (some of the spectrum allocations shown in Figure 8.2-2 will only become effective in the future). Especially, the TDD case clearly shows a potential for a minimum aggregated spectrum of 50 MHz. However, regarding to MNOs CA and dual-connectivity plans, the total aggregated bandwidth will extend even beyond 120 MHz in the coming years. Further, combining FDD and TDD bands, the total aggregation of bands is expected to grow up to 200 MHz over the next decade.

	Band 20 (700 MHz)	Band 28 (800 MHz)	Band 8 (900 MHz)	Band 32 SDL only (1500 MHz)	Band 3 (1800 MHz)	Band 1 (2100 MHz)	Band 7 (2600 MHz)	Max.	Total
Telekom Deutschland	10	10	15	20	30	20	20	30	105 (125 DL)
Vodafone	10	10	10	20	25	20	20	25	95 (115 DL)
Telefonica	10	10	10	-	20	20	60	60	130

Table 6: FDD Spectrum holdings in Germany [MHz] – status September 2021

	Band 34 (1900 MHz)	Band 38 (2600 MHz)	Band 78 (3500 MHz)	Max.	Total
Telekom Deutschland	-	5	90	90	95
Vodafone	-	25	90	90	115
Telefonica	14.2	20	70	70	104.2
Drillisch	-	-	50	50	50
Industry, individual/ local	-	-	(100)	(100)	100

Table 7: TDD Spectrum holdings in Germany [MHz] – status September 2021

The high number of required antennas makes implementing vehicular communication systems in FR1 a challenge, and which only increases with further enhancements and ensuing network deployments.

FR2 spectrum

FR2 offers a huge improvement in data rate (beyond 10 Gbps without CA). As several MNOs start to deploy FR2 networks to enlarge their service, FR2 is a promising additional solution to be used for a variety of high date rate services. Due to the high frequency, it is clear that these types of networks mostly target low mobility or quasi-stationary use cases/scenarios. From this point of view, this makes the usage of FR2 networks in vehicles problematic. However, some of the vehicular use cases (e.g. parking position, slow mobility in parking areas, traffic jams, etc.) might benefit from FR2 networks, especially in congested network situations. This would improve the service quality and availability as well as reduce the load on FR1 for the MNOs.

In an internal 5GAA survey on FR2 deployments, some MNOs confirmed their intention or desire to deploy at least 400 MHz in FR2 in coming years; several have already deployed at least 400 MHz in FR2. It is also expected that the bandwidth will increase to 0.8 GHz or more over the next ten years.
Due to the very high frequency, it is known that the main obstacles to using wireless communication technologies via FR2 are the “high attenuation” and “low penetration” of the transmitted signals, which demand two contradicting implementation strategies:

- Reduced distance between antenna and AD converters to overcome the length-dependent attenuation (only affecting the analogue interface)
- Distribution of antennas on several positions to ensure "full coverage" for a full 360° (Azimuth) reception and transmission

With the expected enhancements of the radio technologies and MNO network deployment scenarios, both of these strategies limit the usage of the conventional analogue interface-based implementations, such as design Option 1 previously described. These strategies are compatible with digital interface-based designs, such as Option 3.

V2V spectrum

In the EU, the current C-V2X ITS spectrum is up to 70 MHz. A recently discussed within 5GAA, C-V2X direct communication might use 40 MHz for 5G direct communication (advanced ITS services) and 20 MHz for LTE-V2X direct communication (basic safety services).

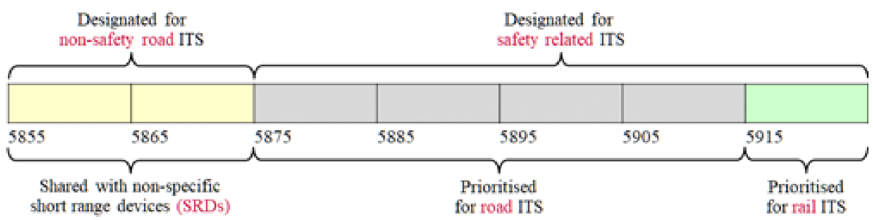


Figure 8: Spectrum designations at 5.9 GHz in Europe

Because a high level of service is required for some of the direct communication use cases, a network operator managed direct communication (PC5) operation might be a promising solution. Therefore, potential direct communication-related implementation in the licence spectrum should be considered, in addition to the current spectrum plans. However, operations/parameters considering the licence spectrum have not been factored into this evaluation because there is no detailed MNO deployment information related to this.

Unlicenced network access (Wifi and LAA deployment)

Other use cases worth considering include data offloading, in-vehicle hot spots, special area hot spots, etc. This type of link enables communication services in very crowded places (e.g. parking bays, traffic jams) or those not reliably covered by MNO networks. This requires enhanced implementation measures supporting broadband communication in non-licenced bands. Depending on the use case, situation, and implementation strategy, the usage of radio technology will further increase the requirements of the implementation in the field of antenna design and interface design.

Implementation

Beyond the communication system and service-level parameters, implementation aspects impact the evaluation and decision metrics such as complexity, power consumption, scalability, and flexibility.

Flexibility

The variety of vehicle types (vehicle size and make-up) is diverse and demands a certain degree of type-specific implementation, such as different antennas , special components (e.g. connectors for the vehicle door or mirror antennas) and longer distances (up to 10 m or more) between vehicular-CU and vehicular-DUs. In particular, the latter is one of the most challenging parameters, especially in high frequencies, and can seriously impact FR2 communication. In contrast to RF-signal transfer via cable (design Option 0 and 1), digital data transfer offers much higher flexibility and suffers much less from the high attenuation of frequency signals.

Complexity

One of the determining aspects for this evaluation is the choice of the vehicular-CU/ vehicular-DU interface solution. Aside from the cable type, the main metric is the required maximum data rate to be supported. As the user interface technology should ideally be identical for all vehicular-DUs, the one with the most challenging implementation setup (e.g. highest number of antennas and bands, C-V2X Uu and PC5, dual connectivity) determines the interface requirements. Figure 9 presents the implementation and communication model with all relevant Tx/Rx antennas combined for the C-V2X Uu (mobile network) and the PC5 (direct) communication.

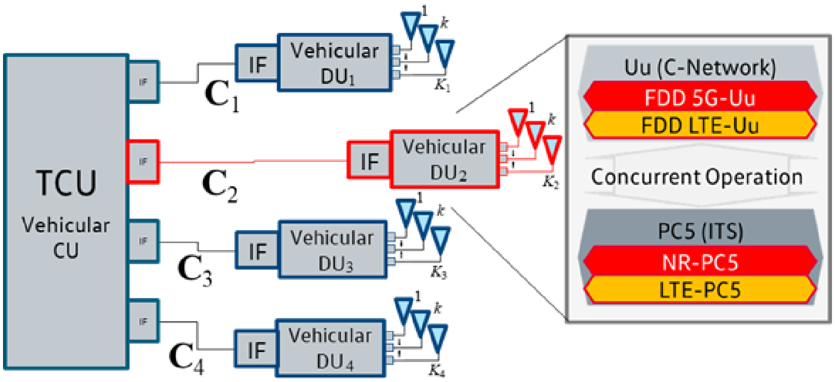


Figure 9: Focus on the most challenging DU

Based on the above observations, the following evaluation of the interface helped to identify the required data rate to be supported by this technology. As also above mentioned, due to the unknowns and diversity of the specific implementations, the evaluation focus is on an estimation of the maximum peak raw data rate. Depending on the antenna combinations, the relationship between the expected raw data rate and an assumed total aggregated bandwidth is calculated in the following figure.

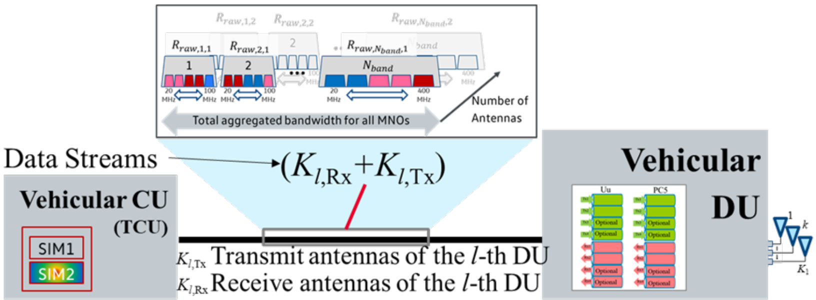


Figure 10: Model assumption for the peak data rate estimation

<u>Data rate calculation</u>

The following formula represents the raw (sample) data rate per antenna stream and band, assuming Option 3A (Low PHY – High PHY split):

$$R_{raw,i,n} = N_{RB,i,n} * N_{SCPRB,i,n} * L * N_{S,i,n} * N_{bit}$$

Where N_{SCPRB} is the number of subcarriers (SCs) per Physical Resource Block (PRB),L is the number of OFDM symbols in a slot, N_S is the number of slots per second, and N_{bit} is the number of bits used to represent each symbol (I and Q) per subcarrier. The overall data rate for the total "aggregated bandwidth" depends on the number of antennas (indicated by n-index), number of bands (indicated by i-index), and the bit resolution of the I and Q samples (N_{bit}).

For a coarse rate estimation, this can be further elaborated focusing on a resolution of 14 bits for 256 QAM, with a proposed rate density per 10 MHz of

$$R_{raw,average-10MHz} = \frac{1}{N_{carriers}} \sum R_{raw,i,n}$$

Figure 11 illustrates the results of Eq. (2) for several SCS and BWs (values can be found in the figure).

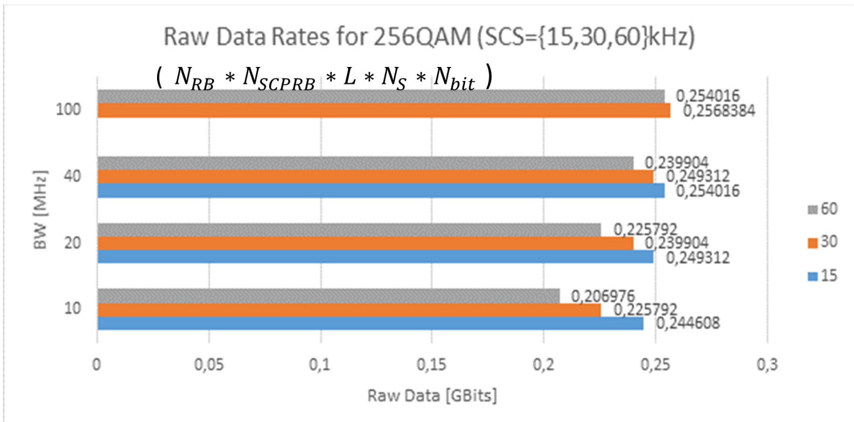


Figure 11: Average raw data rate for 256 QAM (with 14 bits per I/Q sample)

Figure 11 illustrates the resulting $R_{raw256QAM}$, $\textit{average-10MHz}(N_{RB,i})$ of approximately 0.24 Gbits including the minimum and maximum deviation.

Values	Band 20 (700 MHz)	Band 28 (800 MHz)
Min.	0.206976	<-14%
Average	0.240588	0
Max	0.256838	<+7%

Table 8: Minimum, average and maximum raw data rate based on calculations shown in Figure 11

It is assumed that the automotive network between the vehicular-CU and vehicular-DU is symmetrical and the same data rates are supported in both directions. In non-symmetrical cases, the required vehicular-DAS interface rate must support the sum of DL and UL rates. Using the expected deployments of future MNO networks, the following evaluation is offered as a minimum required rate for the digital interface (design Option 3A):

- For two Rx antennas and vehicular-DU implementation within 2-5 years, the rate will grow up to 5 Gbps and will most probably reach 10 Gbps at the end of the decade,
- For three Rx and higher antennas and vehicular-DU implementations, a rate of over 10 Gbps will be reached in the next few years. Fortunately, the rates will most probably not exceed 25G bps at the end of the next decade.

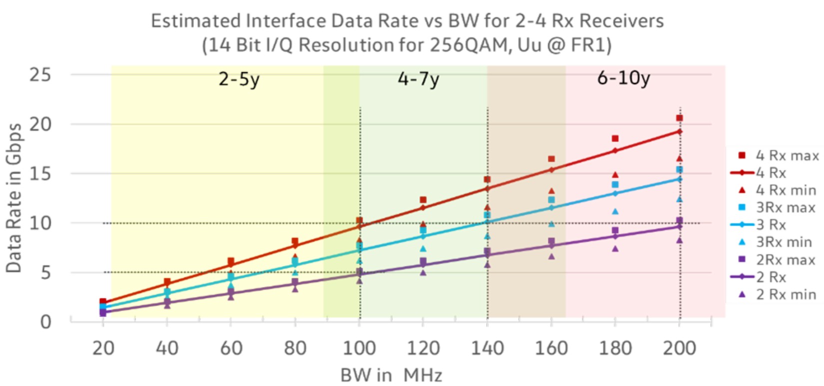


Figure 12: Data rate relation vs. number of Rx antennas and total aggregated bandwidth

In addition to Uu-based communication, other wireless connectivity systems are likely to be used in future vehicle deployments. The most demanding connectivity technologies used as direct communication and connectivity solutions for non-licence spectrum (e.g. Wi-Fi, LAA) offer a very similar high spectrum efficiency to the Uu link. The spectrum usages can be assumed as follows:

- Direct communication with at least 60 MHz (40 MHz 5G C-V2X and 20 MHz LTE-V2X),
- Connectivity of at least 80 MHz non-licence spectrum (Wi-Fi, LAA).

With this assumption, the interface must support a much higher bandwidth. Figure 13 illustrates the estimated data rate vs. total aggregated bandwidth. For instance, including direct communication and LAA with a total bandwidth of 120 MHz, the data rate of the aggregated bandwidth over all radio technologies will increase by 10-15 Gbps, depending on the number of antennas.

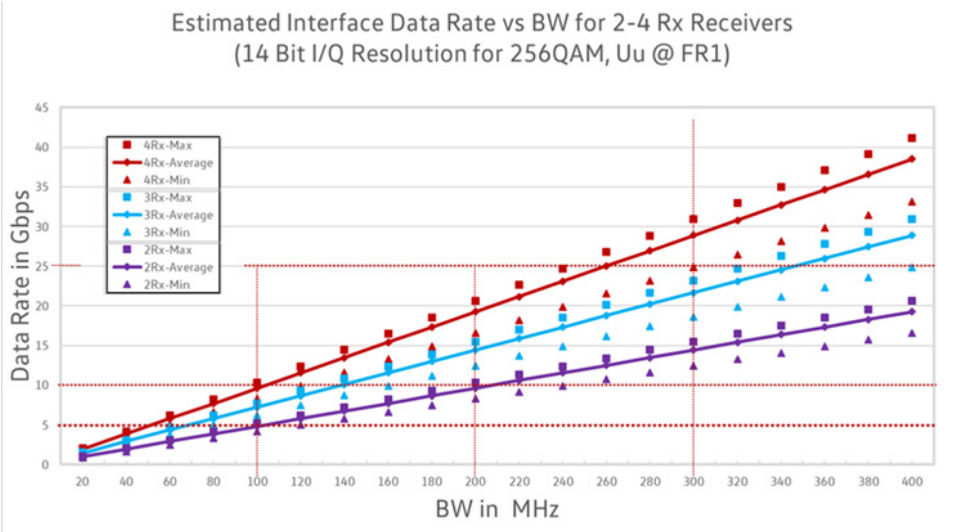


Figure 13: Data rate relation vs. number of Rx antennas and aggregated bandwidth over all communication technologies (assumption: 0.24 Gbits per 10 MHz)

Summary

Several mitigating factors for the data rate requirement were presented and discussed. As future deployments, technology developments as well as customer needs are unpredictable, the number of antennas and bandwidths were used to estimate the data rate required to implement the proposed Option 3 design. Based on current and expected network deployments, data rates close to 5 Gbps are expected in the short term and beyond 15 or even 20 Gbps within a the next decade depending on the implemented antennas per distributed antenna unit and bandwidth. Including wireless connectivity solution for non-licenced implementations, these requirements will increase by up to a factor of two. Lastly, the usage of FR2 will also further increase the rate requirements by some 10 Gbps.

This situation demands new interface technology solutions for automotive implementations. For instance, Automotive Ethernet 802.3bp with 1 Gbps does not meet the needs of the Option 3 DAS design. Even the Automotive Ethernet 802.3ch 10GBASE-T1 alternative, which supports 10 Gbps, would struggle to cope with the demand. Up to 40 Gbps Ethernet would be a sufficient wireless communication solution for all types of V2X-based use cases introduced in this technical report.

As of 21 May 2020, [14], the IEEE 802.3 Ethernet Working Group started a taskforce on bandwidths above 10 Gbps [15] with a set of approved objectives, for example:

- The support of data rates of 25 Gbps at the MAC/PLS interface [16]
- Point-to-point operation over the automotive link segment and electrical PHY supporting two in-line connectors spanning 11 m or more on at least one type of automotive cabling
- Exclusive duplex operation
- Optional support of Energy Efficient Ethernet optimised for automotive applications
- Operational considerations in automotive environments (e.g. EMC, temperature, etc.)

According to the timeline published on 26 January 2021 [17], the P802.3cy standard should become available sometime in 2023. The IEEE 802.3cy could support the data rates expected within the next decade depending on implemented antennas and bandwidth. Full support with usage of FR2 and non-licensed spectrum would require new automotive Ethernet developments beyond 40Gbps.

This evaluation is far from complete and should be a simple tool set to understand the basic relationship between some of the most impactful factors, such as the data rate requirements. It is noted that the data rate requirements may differ for a specific vehicle type or OEM segment. It is also necessary to understand that the DU does not have to include the maximum number of antennas and bandwidth, nor cover all radio technologies in use. Each OEM is free to apply the described formulas and formats to develop its own requirements. However, this evaluation has showed that changes in the implementation strategy of wireless communication systems and technology development is required.

7.2 Potential benefits

Enhanced Tx/Rx coverage

As described in Section 5.3, it is difficult to guarantee 360-degree (omni-directional) coverage with a conventional antenna system using co-located antenna arrays the so-called “self-blockage” effect experienced by the vehicular UE. However, antenna radiation characteristics can be further improved by employing the vehicular-DAS as it implements antennas in new mounting positions and distributes antennas far apart from each other. For instance, vehicular-DUs can be located in the bumper, mirror, glass as well as on the vehicle roof. Also, as vehicular-DUs deployed in different positions can cover spatially separated areas, the composite coverage of the vehicular UE with multiple vehicular-DUs in different locations can be further enhanced compared to the conventional UE with co-located antennas.

In this study, we verify the performance gain of vehicular-DAS over the conventional vehicular UE with co-located antennas (e.g. antenna array on the rear rooftop, like conventional shark-fin antenna) through computer simulation and the measurement. Firstly, using the antenna pattern for the vehicular UE specified in [9], the coverage of antenna radiation patterns of three types of vehicular UEs with two antennas is plotted in Figure 14 (e.g. vehicular-DAS UE with vehicular-DUs on front/rear bumper, vehicular-

DAS UE with vehicular-DUs on the front/rear rooftop, and conventional vehicular UE with co-located antennas on the roof). In Figure 15, assuming a co-phased received signal combination (i.e. maximum-ratio combining or MRC), antenna pattern and coverage is presented. By comparing the performance of vehicular-DAS UE with particular DUs on the front/rear rooftop (illustrated by the blue line) with co-located antenna UEs (illustrated by the red line), it is confirmed that vehicular-DAS can exploit antenna power gain of up to 4 dB, which is entirely attributed to the "distribution of antenna location" over the co-located antenna system.

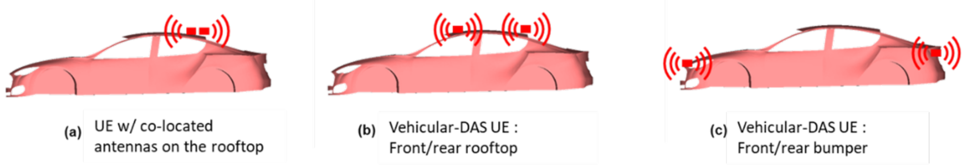


Figure 14: Antenna deployment scenarios considered in the computer simulation

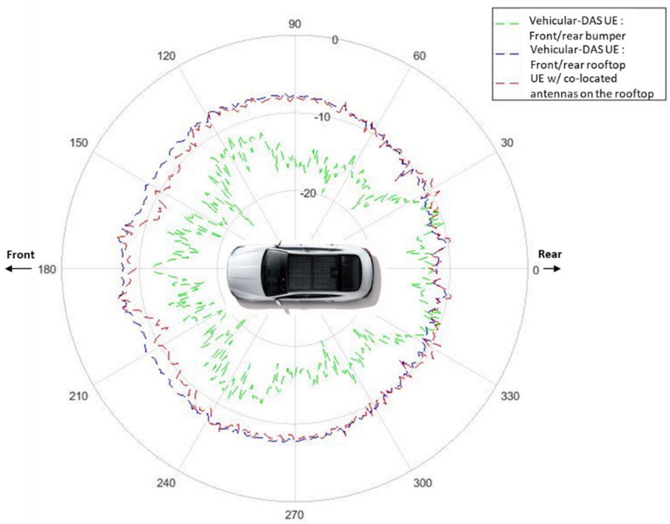


Figure 15: Comparison on coverage of antenna radiation pattern (in 2D horizontal domain)

A similar trend is observed in performance tests comparing the vehicular-DAS UE with four vehicular-DUs at bumper level and a conventional UE with co-located antennas on the rooftop, assuming both vehicles have four antennas. As shown in Figure 17, the Tx vehicle drives a full circle keeping a constant distance between Tx and Rx vehicle in order to examine the 360-degree coverage, and RSRP is measured for two different types of Rx vehicle, as presented in Figure 16. In Figure 18, it can be observed that the vehicular-DAS UE has higher RSRP performance than the conventional UE with co-located antennas. In this measurement, a sedan was with a flat rooftop. However, when considering vehicles with a curved rooftop or one covered with glass (e.g. sunroof), it is expected that the reception performance gap between these two vehicles increases; and a greater loss is observed in the conventional UE setup with co-located antennas due to a higher self-blocking effect. Detailed assumptions and parameters used in this test are summarised in A.1.

Figure 16: Antenna deployment scenarios considered in the measurement

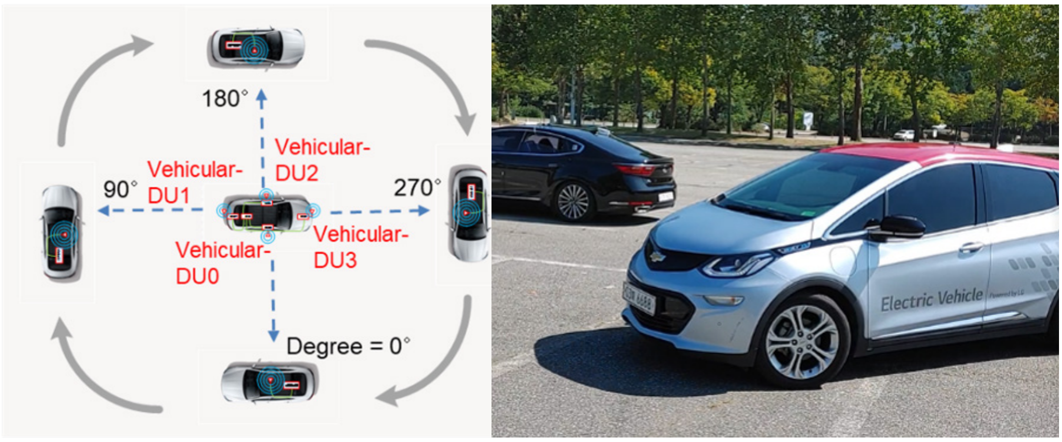


Figure 17: Test scenario

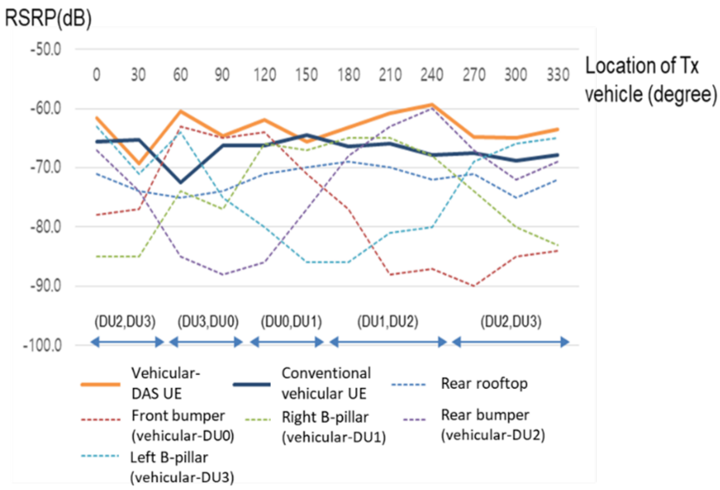


Figure 18: RSRP measurement result

Enhancement in communication reliability

As can be seen in Figure 18, the strength of received signals measured at each vehicular-DU is different. This implies that each vehicular-DU experiences different channel fading, and more reliable communication can be supported for vehicular-DAS UE by exploiting multiple vehicular-DUs in different locations. To verify the reliability of vehicular-DAS, a comparison (e.g. Block Error Rate (BLER) and communication distance) is performed using measurement data and computer simulations.

The test establishes the BLER performance of vehicular-DAS UE while receiving signals from a Tx UE when there is something big blocking them, such as a bus. Specifically, as shown in Figure 19, the Tx vehicle approaches the vehicular-DAS UE in a different lane, and there is a “big blocker” between the two vehicles. The Line-of-Sight (LoS) path is briefly guaranteed between Tx and Rx vehicles, but it is subsequently obstructed. The BLER performance of two Rx vehicles with different antenna locations or spacing is compared in the scenario. As shown in Figure 20 and Figure 21, the vehicular-DAS UE (Vehicle #1 in the graphs) achieves much more reliable BLER performance compared to the conventional vehicular UE with co-located antennas (Vehicle #2). The performance gain of the vehicular-DAS UE is achieved because the LoS path could be maintained for longer than the conventional UE case, and the quality/strength of the received signals improves thanks to ground-reflected signals received using vehicular-DUs located at the bumper level. Detailed assumptions and parameters used in this test are summarised in A.1.

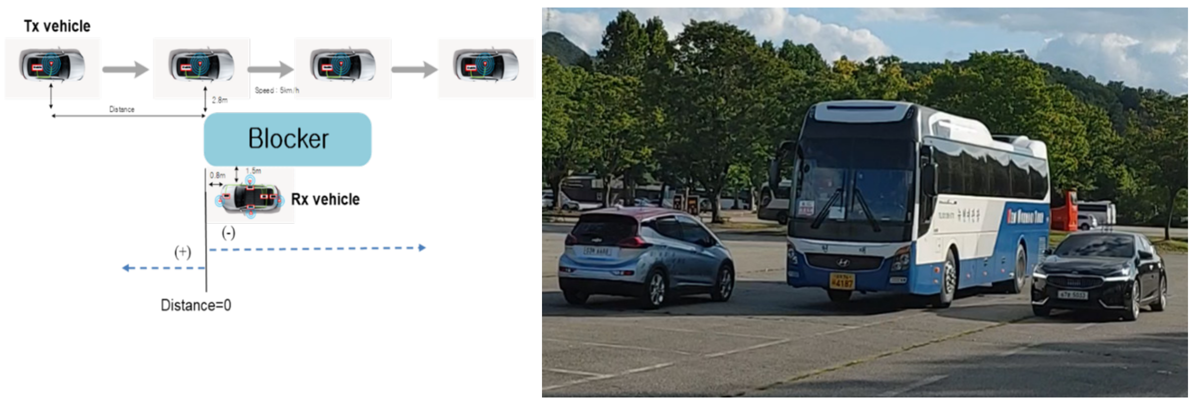


Figure 19: Test scenario

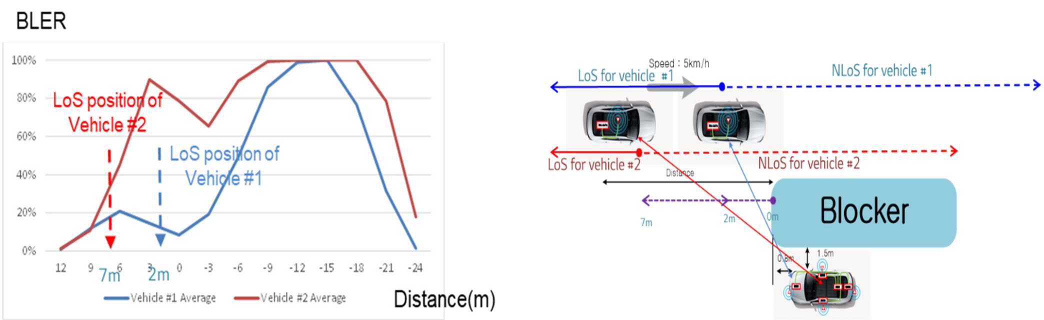


Figure 20: Test result 1: Comparison of BLER performance between two vehicles with different antenna location/spacing (1 layer transmission with MCS 11)

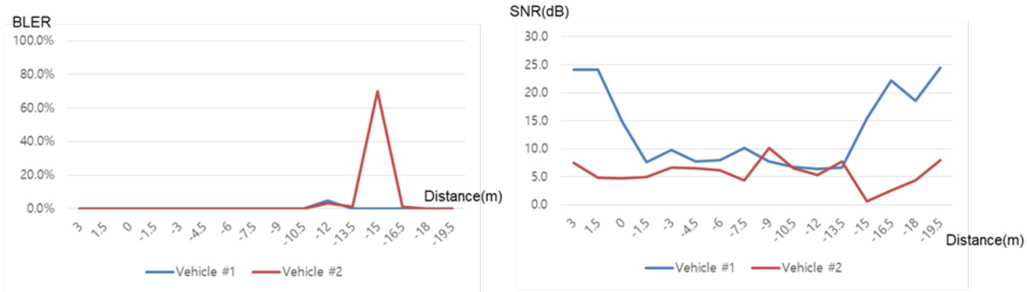


Figure 21: Test result 2: Comparison of BLER performance between two vehicles with different antenna location/spacing (1 layer transmission with MCS 0)

Additionally, through the computer simulation, the average packet reception ratio (PRR) of two different antenna systems with different antenna locations is compared to a vehicular-DAS UE and a conventional UE with a co-located antenna system. Assumptions and parameters used in this simulation are provided in A.2. As shown in Figure 22 and Table 9, vehicular-DAS can achieve 95% and 99% PRR performance with a reliable communication distance gain of 82.5 m (44%) and 40 m (50%), respectively, compared to the co-located antenna system. In the vehicular-DAS case, the probability of all rays being blocked by other vehicles is reduced, and performance degradation due to any self-blocking effect could be overcome by distributing vehicular-DUs in different locations. Vehicular-DAS thus generates a clear performance benefit compared to the conventional co-located antenna system. Additional performance gains can come from "channel diversity" – relatively low-correlated channels achieved by spacing vehicular-DUs further apart from each other.

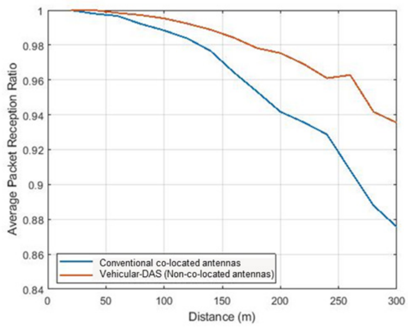


Figure 22: Average PRR of vehicular-DAS vs. conventional co-located antennas in highway scenario

	Highway scenario		
Average PRR	Vehicular-DAS	Co-located antenna system	Reliable communication distance gain of vehicular-DAS over co-located antenna system
99%	120 m	80 m	40 m (50%)
95%	270 m	187.5 m	82.5 m (44%)

Table 9: Comparison of reliable communication distance for vehicular-DAS and co-located antenna system with 95% and 99% PRR

Robust performance degradation caused by carrier phase offset

In wireless communications, carrier phase offset occurs due to the difference in distance that LoS and NLoS waves travel from the Tx antenna to Rx antenna (e.g. phase difference = 2π (path difference)/λ, where λ denotes the wavelength). The phase offset is a characteristic of the carrier frequency band, and it degrades communication performance when "destructive interference" (or destructive sum) of LoS and NLoS waves occurs.

This test examines the impact of the carrier phase offset on the performance of vehicular UE with different antenna heights under the scenario presented in Figure 23. As can be seen in Figure 24, it is observed the SNR decreases when LoS and NLoS waves are out-of-phase in the 5.9 GHz frequency band. Also, when the height of the Tx antenna is fixed, the lower the height of the Rx antenna, the lower the performance degradation caused by the carrier-phase offset. This is because the path difference between LoS and NLoS decreases and changes more slightly and slowly when the antenna is in the lower position. The performance degradation due to the path difference and phase offset might be difficult to counter using the usual baseband signal processing enhancement because of the already decreased signal power received by the antenna/RF when LoS and NLoS waves are out-of-phase. But this issue can be resolved or relaxed by distributing antennas in different locations and at different heights on the vehicle; the probability of simultaneous power dips at all vehicular-DUs implemented in different locations is very low, as shown in Figure 24. Therefore, vehicular-DAS deal with performance degradation caused by carrier frequency offset in 5.9GHz frequency band better than the conventional co-located antenna arrays. This is a powerful advantage of vehicular-DAS.

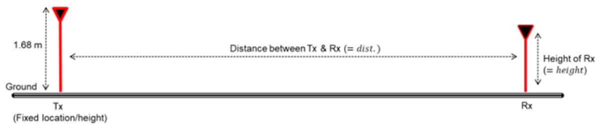


Figure 23: Scenario used in the measurement

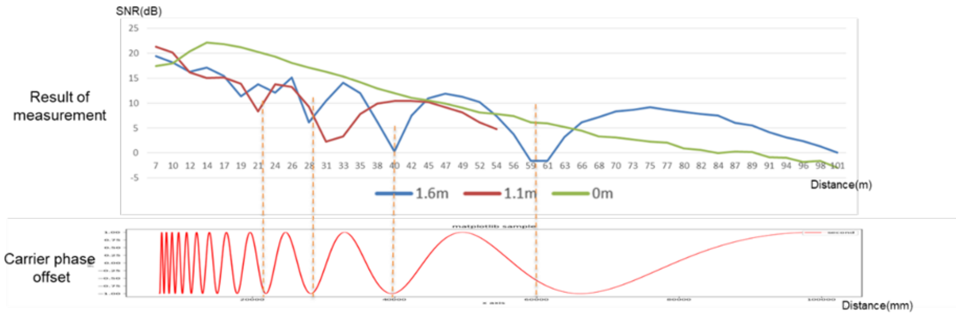


Figure 24: Measurement of SNR performance with different Rx antenna heights (0m, 1.1 m, 1.6 m)

Enhancement in positioning performance

In addition to highly accurate localisation of a vehicle equipped with vehicular-DAS, as shown in Figure 25, this setup can also be used for enhanced positioning.

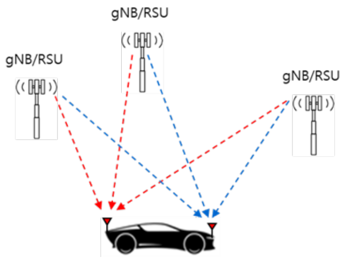


Figure 25: Example of positioning with vehicular-DAS

The vehicular-DAS can be used to improve positioning performance such as accuracy, reliability, and availability. Specifically, positioning accuracy enhancement can be achieved by properly combining measurements from the vehicular-DUs deployed in different places on a vehicle. For instance, the vehicle location can be independently estimated based on each vehicular-DAS antenna, and those locations can be combined to improve the overall accuracy of the vehicle positioning.

As another aspect of improved accuracy and reliability, a vehicular-DAS can be used to overcome the degradation of positioning accuracy and reliability, which is caused by imperfect synchronisation among gNBs/RSUs. For example, when a TDoA-based positioning such as OTDoA is supported from gNBs/RSUs, the accuracy and reliability of positioning can be affected by synchronisation timing errors, which can be mitigated by vehicular-DAS, for example by using difference between two TDoA measurements – obtained over the same pair of gNBs/RSUs – from the different vehicular-DUs.

Such antenna distribution techniques enable the position to be acquired with fewer gNB/RSUs, compared to the conventional OTDoA technique requiring at least three gNBs. For instance, as presented in Figure 26, utilising the known distance between two antennas enables a vehicle to accurately calculate the position based on TDoA, even with two gNBs/RSUs.

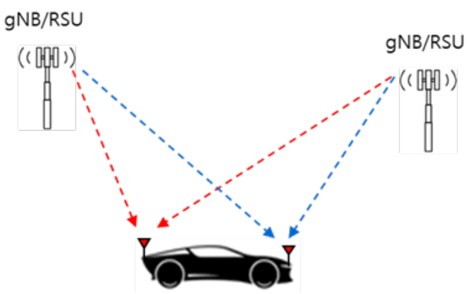


Figure 26: Example of positioning using DAS with two gNBs/RSUs

Utilising vehicular-DAS for positioning, the location of the distributed antennas (or vehicular-DUs) on the vehicle may affect the performance. There are two aspects that need to be considered in determining the antenna positions and the distance between them – PRS receiving path discrimination and positioning diversity.

As for path discrimination, if the antennas are too close (e.g. back-to-back panel type) to each other, no discernible difference is observed between TOA or AOA measured at each antenna over the PRS transmitted from RSUs. This makes it difficult to calculate the AoA or AoD, and thereby the position of the antennas/vehicular-DUs and, indeed, the vehicle itself. From the positioning diversity perspective, if the calculation is not possible with one of the vehicular-DAS antennas (e.g. insufficient RSUs), then the other antennas can be used for positioning measurement. This kind of "diversity" cannot be achieved if the distance between two antennas is too small (e.g. less than a half of the PRS wavelength). Thus, greater distances between antennas on or in a vehicle improve vehicular-DAS-based sidelink positioning performance

8. Potential specification impact

8.1 Modem aspect

The potential impact on 3GPP specifications is analysed along three main lines: V2X communication, positioning, and performance requirements. It is noted that the analysis in this section may not be exhaustive.

V2X communication aspect

Deploying a vehicular-DAS system can provide a significant diversity gain even without enhanced transmission schemes, as the channel observed from and to each of the antenna panels will be significantly more "uncorrelated" compared to co-located antennas (see Section 7.2). On top of this diversity gain, smart selection/management of the transmitting antenna panels has potential to improve communication performance when a UE is equipped with vehicular-DAS.

For sidelink operation, the current 3GPP standard does not support directional transmissions and thus sidelink signals/channels should be transmitted over all equipped panels in the vehicular-DAS UE. This may lead to inefficient transmissions as signal transmitted in a panel may suffer significant loss in some directions. Therefore, especially in an operation where channel status information-based link adaptation is feasible, there is room to improve the V2X operation by enabling the transmitter to acquire the channel status directed at the target receiver and select the direction of the transmission via vehicular-DAS UE (e.g. by sending the sidelink signal/channel only from the best-performing panel). This can improve the signal quality by boosting the power received in the target UE. Also, it can avoid unnecessary interference emitted in other directions, thereby improving the interference load and enabling better geographical resource reuse.

For Uu operation, such transmit panel selection/management can be supported by the uplink beam management for both FR1 and FR2.

Positioning aspect

The reference point from 3GPP for positioning is associated with the position of a single antenna (RF antenna connector or RF antenna position see [18]). Therefore, the conventional positioning mechanism cannot be directly applied to pinpoint a UE with multiple antenna panels in different locations (e.g. 3-4 m of inter-panel/antenna distance). If the conventional positioning technique is to be reused for this case, we could consider using only a single panel at one time for vehicular-DAS UE for positioning purposes (e.g., by implementation). Each antenna could be positioned separately to obtain the estimated position at each of the different locations on the vehicle. In this case, the entity doing the position calculation (i.e. network or UE) needs to know that each Tx/Rx antenna is associated with a different point on the UE.

Therefore, the positioning mechanism in the current 3GPP standards could be extended to cover vehicular-DAS UEs with multiple panels, and to indicate that they are at different locations. The entity calculating the UE location based on sidelink-PRS Tx/Rx may need to know the exact location of each panel in the UE. To this end, signalling between the entity and the UE could be necessary. As described in [19], positioning performance improves (i.e. accuracy, reliability, and availability) thanks to better processing of the measurements from the distributed antennas.

Performance requirement aspect

Some potential impacts on the RAN4 specification could be envisaged to facilitate vehicular-DAS UEs, including (re)defined UE capabilities and performance requirements.

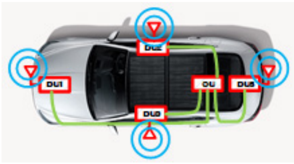
8.2 Interface and protocol aspect

On the interfacing and protocol side, the focus is on how it impacts the IEEE 802.3 Automotive Ethernet specification. According to the published timeline, as of 26 January 2021 [17], the standard should enter into force in 2023. IEEE 802.3cy could support the data rates expected within the next decade depending on implemented antennas and bandwidth. However, full support with usage of FR2 and non-licensed spectrum would require new automotive Ethernet developments beyond 40Gbps. From a delay and synchronisation requirements point of view, further analysis on the impact to the current specification is necessary. Further monitoring of progress in this field is recommended to ensure this work can be achieved within a similar timeframe (e.g. data rate, power consumption, temperature, implementation aspects, etc.).

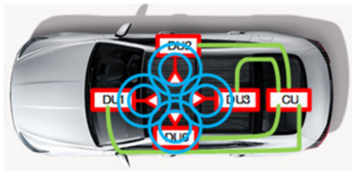
Annex

A.1. Assumptions and parameters used in the measurement

- Features of the PoC platform used in this test (Rx vehicle with a non-co-located antenna system (vehicular-DAS UE), "Vehicle #1")

<table>
<tr><th>Type of vehicle</th><th colspan="3">A sedan, parked in an open area</th></tr>
<tr><td>Design option</td><td colspan="3">Design Option #2 (RF + ADC/DAC – PHY split described)
Co-located antenna system</td></tr>
<tr><td rowspan="3">Design of vehicular-CU and vehicular-DU 95%</td><td rowspan="2">Vehicular-DU</td><td>Number of vehicular-DUs in the vehicle</td><td>4 vehicular-DUs

Location of each vehicular-DU
vehicular-DU1 and vehicular-DU4: front/ rear bumper
vehicular-DU2 and vehicular-DU3: right/ left B-pillar
Each DU is deployed in the middle of each vehicle's side
</td></tr>
<tr><td>Number of antennas for each vehicular-DU</td><td>1 omni-directional antenna per vehicular-DU</td></tr>
<tr><td>Vehicular-CU</td><td>Number of vehicular-CUs in the vehicle</td><td>1 vehicular-CU</td></tr>
<tr><td>Cabling between vehicular-CU and Vehicular-DUs</td><td colspan="3">- UTP cable (length: up to 20 m)
- High-speed serial bus
- Protocol:
• Physical layer: IEEE 802.3 standard 10GBase-T(UTP)
• Mac and higher layer: LG Electronics' own solution</td></tr>
<tr><td>Rx scheme</td><td colspan="3">When a vehicle receives signals using multiple antennas, out of 4 vehicular-DUs, only 2 vehicular-DUs (maximise total SNRs) are selected. Also, signals received using the 2 selected vehicular-DUs are combined at the receiver side</td></tr>
</table>

- Features of the Rx vehicle with a co-located antenna system (for comparison, “Vehicle #2”)

Type of vehicle	**A sedan, parked in an open area**	
Antenna configuration	Number of vehicular-DUs	4 vehicular-DU on the rooftop (similar to the conventional shark-fin antennas)  
	Number of antennas for each vehicular-DU	1 omni-directional antenna per vehicular-DU
	Number of vehicular-CU in the vehicle	1 vehicular-CU
Cabling between vehicular-CU and vehicular-DUs	- UTP cable (length: up to 20 m) - High-speed serial bus - Protocol: • Physical layer: IEEE 802.3 standard 10GBase-T(UTP) • Mac and higher layer: LG Electronics’ own solution	
Rx scheme	When a vehicle receives signals using multiple antennas, out of 4 vehicular-DUs, only 2 vehicular-DUs (maximised total SNRs) are selected. Also, signals received using the 2 selected vehicular-DUs are combined at the receiver side	

- Comparison between “Vehicle #1” and “Vehicle #2”

	Vehicle #1 (Non-co-located)	**Vehicle #2, (Co-located)**	
Antenna (DU) position/ height	Front/rear bumper and B pillar	Middle of vehicle rooftop	Different
Distance between antennas	Far apart from each other (2-5 m)	Closely placed (about 5 cm)	Different
# of antennas, type	4, omni-directional	4, omni-directional	Same
Rx scheme	Diversity scheme (2Rx, selection-based combining)	Diversity scheme (2Rx, selection-based combining)	Same
Interface between CU-DU	Digital/UTP, 10 m	Digital/UTP, 10 m	Same

- Features of the Tx vehicle

<table>
<tr><th>Type of vehicle</th><th colspan="2">A sedan moving around/near the Rx vehicle
Vehicle #2,</th></tr>
<tr><td rowspan="2">Antenna configuration</td><td colspan="2">- Co-located antenna system with a single omni-directional antenna
- The antenna is located in the middle of the vehicle rooftop


</td></tr>
<tr><td>Antenna gain</td><td>5 dBi</td></tr>
<tr><td>Tx power</td><td colspan="2">10 dBm (constant)</td></tr>
</table>

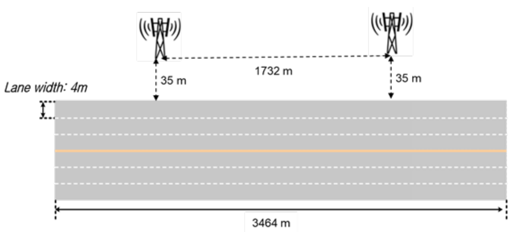
- Radio configuration

Radio-access technology	5G Uu
Centre frequency	5.8 GHz
Channel bandwidth	100 MHz
Subcarrier spacing	30 kHz
Transmission scheme	- No MCS adaptation (MCS11 (64 QAM) or MCS17 (64 QAM)) - No HARQ - Single-layer transmission

A.2. Assumptions and parameters used in the computer simulation

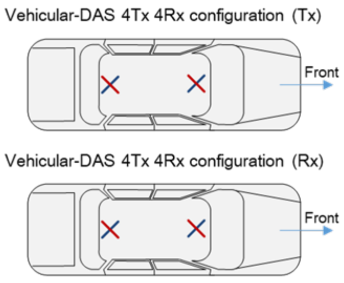
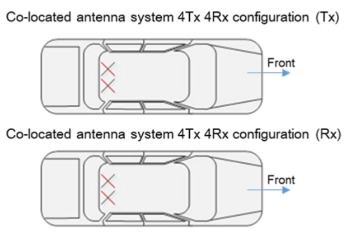
The evaluation methodology and the simulation setup in this simulation follows the 3GPP guidelines specified in [9] and [20], and the parameters used in the simulation are provided in the following tables.

- Simulation parameters commonly used for both the vehicular-DAS and co-located antenna system

Parameter		**Value**
Carrier frequency	6 GHz	
Bandwidth	20 MHz	
Subcarrier number per PRB	12	
Subcarrier spacing	15 kHz	
Noise figure	9 dB	
Polarisation	Cross-pol (0 and 90 degree)	
TTI duration	1 ms	
HARQ	Type	Blind HARQ
	Number of retransmissions	1
Traffic model	Type	Periodic traffic model with pattern {300 bytes, 190 bytes, 190 bytes, 190 bytes, 190 bytes}
Subchannel size	10 PRB	
Resource allocation	Mode 1	
Scenario	Highway scenario in [9]	
gNB drop	gNBs are located along the highway 35 m away with 1732 m ISD (2 BS total) 	

Vehicle drop	- 100% vehicle type 2, vehicle speed is 140 km/h in all lanes - The distance between the rear bumper of a vehicle and the front bumper of the following vehicle in the same lane is maximum 2 m, an exponential random variable with the average of the speed * 2 sec, as specified in [9]
Geometry	Highway length – 3464 m, 6 lanes total with 4 m width
Location update	Object positions are updated every 100 ms
Channel model	Channel models in [9] and [20] are used
All other parameters and simulation setups used in this simulation follow the 3GPP's evaluation assumptions specified in [9] and [20]	

- Antenna configuration for vehicular-DAS and co-located antenna system

Antenna configuration	Vehicular-DAS	(Conventional) co-located antenna system
	4Tx, 4Rx (with antenna element patterns reflecting the self-blockage effect in Table 6.1.4-10B and Table 6.1.4-10C in [9])  	4Tx, 4Rx (with antenna element pattern reflecting the self-blockage effect in Table 6.1.4-10C in [9]) 
[Note 1] When path loss for vehicular-DAS is calculated, the actual location of each vehicular-DU is considered. The model for spatial correlation defined in [21] is used to calculate larger-scale vehicular-DU parameters. It should be noted that the same formulas for the calculating path loss/large-scale parameters in [9] are used for both vehicular-DAS and the co-located antenna system. [Note 2] Regarding the blockage caused by other vehicles, geometry-based blockage modelling is used for both the vehicular-DAS and co-located antenna system and take into consideration actual antenna location based on the blockage model B in [20].		

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