# Distributed vehicular antenna system

5GAA Automotive Association
Technical Report

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# Contents

# Foreword

This Technical Report has been produced by 5GAA.

The contents of the present document are subject to continuing work within the Working Groups (WG) and may change following formal WG approval. Should the WG modify the contents of the present document, it will be re-released by the WG with an identifying change of the consistent numbering that all WG meeting documents and files should follow (according to 5GAA Rules of Procedure):

x-nnzzzz

(1) This numbering system has six logical elements:

(a) x: a single letter corresponding to the working group:

where x =

T (Use cases and Technical Requirements)

A (System Architecture and Solution Development)

P (Evaluation, Testbed and Pilots)

S (Standards and Spectrum)

B (Business Models and Go-To-Market Strategies)

(b) nn: two digits to indicate the year. i.e. ,17,18 19, etc

(c) zzzz: unique number of the document

(2) No provision is made for the use of revision numbers. Documents which are a revision of a previous version should indicate the document number of that previous version

(3) The file name of documents shall be the document number. For example, document S-160357 will be contained in file S-160357.doc

# Introduction

This document address the 5GAA WG2 work item ‘Distributed vehicular antenna system’ (DAS).

# 1 Scope

A study on the ‘Distributed vehicular antennas system’, or vehicular-DAS, was initiated in Seventh Face-to-Face meeting [1] which was carried out under the scope of eCV2X WI [2]. In the study, a list of potential implementation options for vehicular-DAS was provided with brief analysis of impacts to 3GPP specifications and implementation costs. In addition, the potential performance gain of DAS over co-located antennas was verified through simulations, and the evaluation results and analysis were included in eCV2X WI TR based on agreement in WG2.

Upon conclusion of the eCV2X WI, some follow-up on DAS-related matters is needed with input from car-makers in order to address detailed design options for DAS, and to provide a feasibility analysis of DAS in more varied aspects not covered in the previous study. After this feasibility analysis, the analysis on specification impact of DAS will be performed. Particularly, the objectives of this work item (WI) are:

- Feasibility analysis from an implementation perspectives (i.e. durability, power consumption, packaging, operational feasibility, etc.)
- Identification of detailed design options for antennas, interfaces and protocols
- Evaluation of the potential performance benefit over co-located antennas
- Analysis of how DAS impacts specifications and input to SDOs (e.g. 3GPP, MIPI, PCIe) if needed

WG2 understands that the present document is updated at each WG2 meeting during the WI and captures the list and the description of technical features to be considered in this WI.

# 2 References

The following documents contain provisions which, through reference in this text, constitute provisions of the present document.

- References are either specific (identified by date of publication, edition number, version number, etc.) or non-specific.
- For a specific reference, subsequent revisions do not apply.
- For a non-specific reference, the latest version applies.

[1] 5GAA_A-180206: ‘Study Proposal on Distributed Antenna System for Vehicles’

[2] 5GAA_A-190188: ‘New WI proposal: Enhanced Cellular V2X Study’

[3] 3GPP TS 38.101-1 17.1.0, (2021-03), User Equipment (UE) radio transmission and reception; Part 1: Range 1 Standalone (Release-17)

[4] 5GAA XW6-190040 (2019-11), Overview of UCs and SLRs (November 2019)_master_v15

[5] 3GPP TS 22.186 16.2.0, (2019-06), ‘Service requirements for enhanced V2X scenarios’

[6] 5GAA A-190229, ‘Technical report outlining the 5G NR requirements and architectural enhancements’, 5GAA WG2 Technical Report, Nov. 2019

[7] 5GAA A-200089, ‘Review for DAS WI call #4 : CU/DU function split options’, 5GAA DAS WI call #4, Apr. 2020

[8] 3GPP TS 38.401, ‘NG-RAN; Architecture description’, V15.9.0, Oct. 2020

[9] O-RAN Alliance, ‘O-RAN Fronthaul Working Group: Control, User and Synchronization Plane Specification’, ORAN-WG4.CUS.0-v02.00, Aug. 2019

[10] 3GPP TS 38.101-2 17.1.0, (2021-03), User Equipment (UE) radio transmission and reception; Part 2: Range 2 Standalone (Release-17)

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

[12] 3GPP TR 38.801, ‘Study on new radio access technology: Radio access architecture and interfaces’, V14.0.0, March 2017

[13] 3GPP TR 37.885, ‘Study on evaluation methodology of new Vehicle-to-Everything (V2X) use cases for LTE and NR’, V15.3.0, June 2019

[14] 3GPP R1-1812083, ‘Link Level CDL Models for NR-V2X Channels’, Qualcomm, 3GPP TSG RAN WG1 Meeting #94bis, Chengdu, China, Oct. 2018

[15] 5GAA TR S-200137, ‘Study of spectrum needs for safety related intelligent transportation systems – day 1 and advanced use cases’, June 2020

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[17] 3GPP TR 36.885, ‘Study on LTE-based V2X Services’, V14.0.0, June 2016.

[18] ‘Übersicht Mobilfunkspektrum nach der Auktion (pdf / 163 KB)’, The Bundesnetzagentur (Federal Network Agency for Electricity, Gas, Telecommunications, Post and Railway), 2019, Download: https://www.bundesnetzagentur.de/DE/Sachgebiete/Telekommunikation/Unternehmen_Institutionen/Breitband/MobilesBreitband/Frequenzauktion/2019/Auktion2019.html

[19] https://www.ieee802.org/3/cy/P802d3cy_OBJ_WG_0520.pdf

[20] https://www.ieee802.org/3/cy/

[21] 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

[22] https://www.ieee802.org/3/cy/P802_3cy_timeline_01_22_21.pdf

[23] 3GPP TS 38. 215 V16.4.0 (2020-12), Physical layer measurements (Release 16)

[24] V2XHAP WI TR : ‘System Architecture and Solution Development; High-Accuracy Positioning for C-V2X’

# 3 Definitions, symbols and abbreviations

## 3.1 Definitions

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

| | |
|---|---|
| vehicular-DAS | In vehicular distributed antenna system (DAS), functions of vehicular UE (vehicle-mounted UE) are split and performed in vehicular distributed units (vehicular-DUs) and vehicular central unit (vehicular-CU). |
| vehicular-DU | Vehicular distributed unit that includes a subset of functions of vehicular UE (vehicle-mounted UE). Depending on function split options listed in Section 6.1.1 Design options and function split, the functions implemented in the vehicular DU can be different. |
| vehicular-CU | Vehicular central unit that includes functions of vehicular UE (vehicle-mounted UE), except those functions implemented in the vehicular-DU. The vehicular-CU controls the operation of one or multiple vehicular-DUs. |

## 3.2 Abbreviations

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

| | |
|---|---|
| ADC/DAC | Analog-to-Digital Converter/Digital-to-Analog converter |
| ARQ | Automatic Repeat reQuest |
| BLER | BLock Error Rate |
| BW | Bandwidth |
| CA | Carrier Aggregation |
| CP | Cyclic Prefix |

| | |
|---|---|
| C-V2X | Cellular-V2X |
| DL | Downlink |
| E2E | End to End |
| EMC | Electromagnetic Compatibility |
| FDD | Frequency Division Duplex |
| FFT | Fast Fourier Transform |
| FR1 | Frequency Range 1 (410 MHz - 7125 MHz [3]) |
| FR2 | Frequency Range 2 (24250 MHz - 52600 MHz [3]) |
| gNB | Next Generation Node B |
| HARQ | Hybrid Automatic Repeat and request |
| IEEE | Institute of Electrical and Electronics Engineers |
| iFFT | Inverse Fast Fourier Transform |
| I/Q | In-phase and Quadrature |
| LAA | License-Assisted Access |
| LoS | Line-of-Sight |
| LTE | Long-Term Evolution |
| MAC | Medium Access Layer |
| MIMO | Multiple-Input Multiple-Output |
| MIPI | Mobile Industry Processor Interface |
| MNO | Mobile Network Operator |
| NAS | Non Access Stratum |
| NR | New Radio |
| PCIe | Peripheral Component Interconnect Express PDCP Packet Data Convergence Control |
| PoC | Proof-of-Concept |
| PRR | Packet Reception Ratio |
| QAM | Quadrature Amplitude Modulation |
| RLC | Radio Link Control |
| RRC | Radio Resource Control |
| RRM | Radio Resource Management |
| RSRP | Reference Signal Received Power |
| SAR | Specific Absorption Rat |
| SC | SubCarrier |
| SL | Sidelink |
| SNR | Signal-to-Noise Ratio |
| TAE | Time Alignment Error |
| TCU | Telematics Control Unit |
| TDD | Time Division Duplex |
| 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 | Uplink |
| 3GPP | 3rd Generation Partnership Project |

# 4 Motivation of vehicular-DAS

This section summarises the situation and the challenges facing the automotive industry related to future businesses and services based on wireless communication technologies. With this understanding, it provides a clear motivation for the new vehicular distributed antenna system approach to implementing wireless communication systems in the automotive area. It should be clear that the main target of this work item is to provide a 5G solution for these future communication systems and further enhance (rather than modify) the existing solution which has inherent limitations.

Advances in communication technologies open up new opportunities and enable new types of services in the automotive area. These include road safety, traffic efficiency and customer services which are not specifically meant for automotive applications, but can be used or provided within the vehicle. For instance, 5GAA [4] and 3GPP [5] provide lists of potential use cases which are interesting for vehicle manufacturers.

5GAA [4] selected more than 50 use cases divided in the following classes:

- Autonomous Driving
- Convenience
- Convenience and Vehicle Operations Management
- Convenience and Advanced Driving Assistance
- Convenience and In-Vehicle Entertainment
- Platooning
- Safety
- Safety and Automated Driving
- Traffic Efficiency
- Traffic Efficiency and Environmental Friendliness
- Vehicle Operations Management

The use cases defined in [4] require latencies below 20ms and rates per vehicle/service use up to 250Mbits. These use cases also require sidelink and Uu-Link 3GPP technologies.

Even higher requirements are presented by 3GPP TS 22.186 for release 16 (**Table 4-1**).

**Table 4-1: 3GPP TS 22.186 eV2X requirements [5]**

| Communication scenario description | | Req # | Payload (Bytes) | Tx rate (Message /Sec) | Max end-to-end latency (ms) | Reliability (%) | Data rate (Mbps) | Min required communication range (meters) |
|---|---|---|---|---|---|---|---|---|
| Scenario | Degree | | | | | | | |
| Sensor information sharing between UEs supporting V2X application | Lower degree of automation | [R.5.4-001] | 1600 | 10 | 100 | 99 | | 1000 |
| | Higher degree of automation | [R.5.4-002] | | | 10 | 95 | 25 (NOTE 1) | |
| | | [R.5.4-003] | | | 3 | 99.999 | 50 | 200 |
| | | [R.5.4-004] | | | 10 | 99.99 | 25 | 500 |
| | | [R.5.4-005] | | | 50 | 99 | 10 | 1000 |
| | | [R.5.4-006] (NOTE 2) | | | 10 | 99.99 | 1000 | 50 |
| Video sharing between UEs supporting V2X application | Lower degree of automation | [R.5.4-007] | | | 50 | 90 | 10 | 100 |
| | Higher degree of automation | [R.5.4-008] | | | 10 | 99.99 | 700 | 200 |
| | | [R.5.4-009] | | | 10 | 99.99 | 90 | 400 |
| NOTE 1: This is peak data rate.<br>NOTE 2: This is for imminent collision scenario. | | | | | | | | |

As indicated above, these new services have much higher requirements compared to conventional service types, such as voice call, and compared to normal handheld/UE usage. These requirements lead to much higher challenges in the implementation of the communication systems in vehicles as well as on the network. To fulfil these extremely high requirements for all customers in a certain area, technologies such as multi-antenna solutions (including massive MIMO), broadband technologies (carrier aggregation) and FR2 solutions may be essential. Unfortunately, the allowed positions and mounting spaces for antennas, communication module (TCU) and the required cabling to connect them is limited and/or leads to complex implementations. These limitations are typically automotive-specific design constraints which result from the following aspects:

- Vehicle-type specific design constraints (e.g. shape/form factor and design elements found in convertibles, trucks and other vehicle types requiring 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 issues, etc.)
- High number of implemented radio technologies
- Regulatory aspects (e.g. SAR, eCall)
- Automotive certification aspect (e.g. temperature aspect)

Furthermore, the increasing number of antennas and FR2 solutions, in particular, poses extreme implementation challenges for vehicle manufacturers, which have to be resolved to enable the full range of use cases. It is commonly accepted within the automotive industry that these constraints demand implementation approach for distributed antenna systems. The resulting architecture of this commonly used approach has the following elements and represents a simple working assumption to launch this work item:

1) TCU (vehicular-CU): implemented in crash-proofed positions inside the vehicle and separate from the antenna unit (distance range: a few centimetres up to 12 metres)

2) Antenna-unit (vehicular-DU): reference implementation positions are:

2.1) Roof-top antenna (good 360° azimuth coverage)

2.2) Bumper, glass and mirror (limited azimuth coverage [azimuth range below 360°])

It should be noted that this working assumption represents a simplified model (not a general implementation requirement), which is defined and illustrated in **Figure 4-2**. Besides the TCU, this model consists of several vehicular-DUs represented by vehicular-$DU_1$ to vehicular-$DU_L$ with vehicular-DU index $l$. Each vehicular-$DU_l$ is connected to the TCU via an interface IF and a set of cables $\mathbf{C}_l$, with a length $L_l$ and with frequency and cable length increasing attenuation $a_l$. As each vehicular-DU has an individual position, each cable length is also independent. Lastly, each vehicular-$DU_l$ relates to a communication sub-system or element/component with $K_l$ antennas designed for a specific set of bands $B_l$.

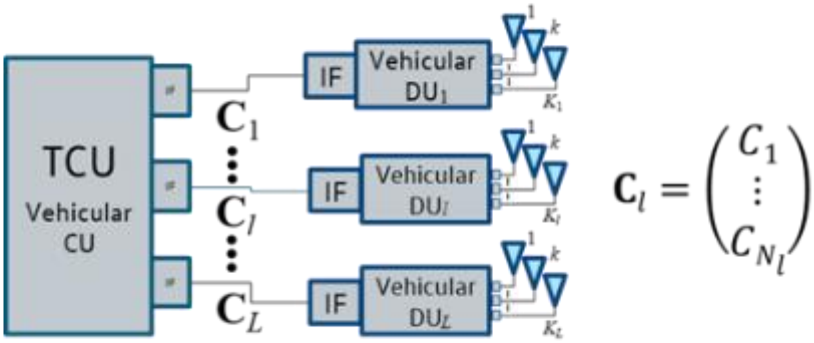



**Figure 4-2: Simplified vehicular-DAS implementation**

As shown in this section, the realisation of future use cases demands higher service requirements. These requirements, combined with automotive-specific constraints, result in much higher complexity and vehicle-DAS implementation problems, especially because of further increase of the number of antennas and the very demanding FR2 needs. Thus, new implementation strategies for 5G and 5G-enhancements are needed to deliver a scalable, efficient and future-proofed solution to these challenges.

# 5 Evaluation metrics and requirements in communication performance and implementation aspect

This section provides the set of the most important requirements and metrics which will be used in the evaluation of the vehicular-DAS solutions and in the decision process as well as in the conclusion task of this work item. In the evaluation process, these metrics should measure how good the requirements referring to communication performance and to implementation aspect are meet.

In addition to the set of metrics and requirements, this section provides the motivation and information about the selection process.

## 5.1 Selection of Metrics for vehicular-DAS

The metrics and requirements are determined by the use cases and services offered. **Figure 5.1-1** illustrates the basic relationship between the use cases as well as services and the final low-level requirements and corresponding metrics. Starting with service requirements under the expected use cases, combined with automotive constraints and network deployment (green boxes), the system's basic assumptions and corresponding metrics can be established. The metrics and the requirements for vehicular-DAS are derived based on high-level requirements (red box). Selected design options (orange box) represent additional metrics, parameters and requirements provided as part of the evaluation work in this work item (blue box).

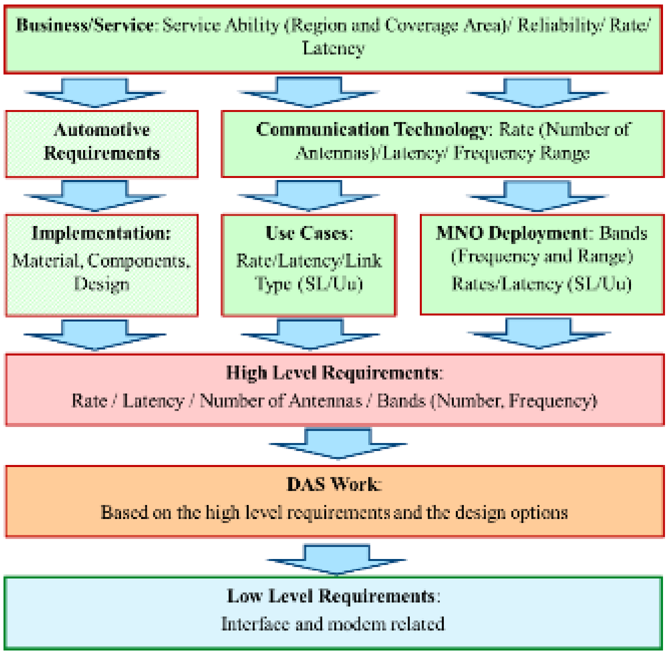



**Figure 5.1-1: Requirement and associated metrics**

**Figure 5.1-1** illustrates the simplified vehicular-DAS introduced in Section 4 Motivation of vehicular-DAS. This model contains all relevant elements (vehicular-CU and vehicular-DUs, cables, antennas, etc.) and, depending on the initial 3GPP release to be supported, the deployed network in the target region and the type of target use cases, it can be used for evaluating the complexity of a potential vehicular-DAS implementation.

The following example should illustrate the procedure for developing the requirement and corresponding metrics. It starts with the selection of a specific service and use case which requires, for example, a rate (or throughput) and latency. This information determines a specific 3GPP release, for instance, and deployed network. Both aspects determine the number of antennas and bands as well as the peak rates (throughputs). This information is used to decide the various antenna system design elements for a specific vehicle type.

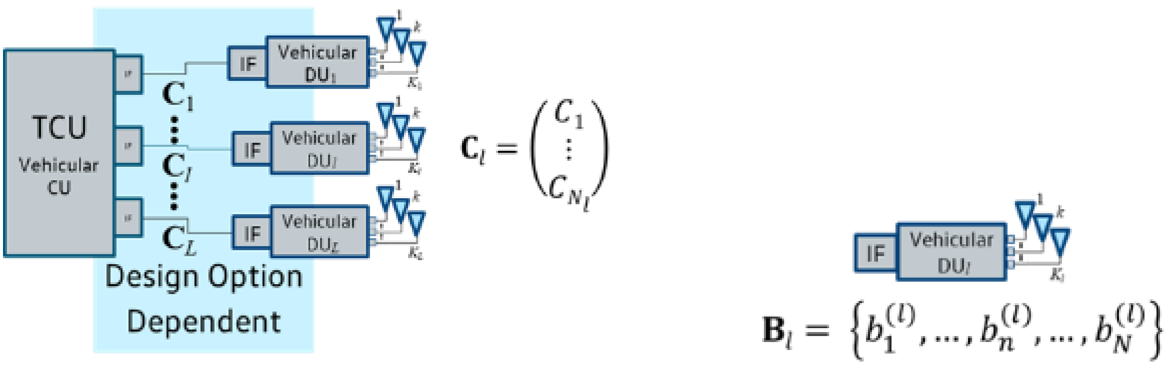



**Figure 5.1-2: Simplified vehicular-DAS implementation (each DU is design for a specific set of bands $B^{(l)}$)**

## 5.2 Metrics for vehicular-DAS

Based on the above simplified distributed vehicular antenna systems assumption in Section 5.1 Selection of Metrics for vehicular-DAS, the following set of metrics is used in the DAS WI evaluation process:

**Table 5.2-1: Metrics for evaluation of vehicular-DAS solutions**

| Type | Requirement | Definition | Value |
|---|---|---|---|
| Link Performance | [Min throughput] | Minimum required throughput for a reference wireless channel.<br>BW, modulation format | Requirement from latest 3GPP Release (e.g. 3GPP TS 22.186) |
| | [Explicit diversity Ggain (dB)] | The effective gain achieved using diversity techniques. | Requirement from latest 3GPP Release (e.g. 3GPP TS 22.186) |
| | [Reliability] | The success probability of transmitting X bytes within a certain delay, which is the time it takes to deliver a small data packet from the radio protocol layer 2/3 SDU ingress point to the radio protocol layer 2/3 SDU egress point of the radio interface. [5]<br>PER | Requirement from latest 3GPP Release (e.g. 3GPP TS 22.186) |
| | [End-to-end latency] | Time it takes to transfer a given piece of information from a source to a destination, measured at the application level, from the moment it is transmitted by the source to the moment it is received at the destination. [5] | Requirement from latest 3GPP Release (e.g. 3GPP TS 22.186) |

As vehicular-DAS needs to be integrated within the vehicle's electronic/electrical system it calls for careful implementation taking into consideration specific design details (including weight, size, energy consumption, etc.), and how each module interacts with other components in the system/vehicle.

The four values shown in the **Table 5.2-2** can be used as a reference to compare the implementation impact of one design against another.

**Table 5.2-2: Metrics for evaluation of vehicular-DAS solutions**

| Requirement | Definition | Value | Priority<br>Decisiveness |
|---|---|---|---|
| Relative Complexity | Number of (additional) components | Number of components | high |
| | Type of (additional) components | Type of components | high |
| | Coupling points aspects | Type of components | med |

| | | | |
|---|---|---|---|
| | Bending radius | Degree | med |
| | Space - diameter | M | med-high |
| | Space - weight | Kg | med |
| | Durability | Number of years | high |
| Scalability | Releases (Number of Antennas, Throughput, Reliability, etc.) | Release range in numbers | high |
| | Implication on frequency range (FR1, FR2, FR3, etc.) | Carrier/Bands/Tp/latency | high |
| | Number of additional bands | Number and band width | high |
| | Upgrade in carrier aggregations levels | Number and band width | high |
| | Variation in regions | Number and band width | high |
| Flexibility | Vehicle type | Types (cable lengths, special components, etc.) | high |
| | Customer customisation | Types and range of customisations | high |
| | Region specific customisation | Types and range of customisations | high |
| Power/Energy Efficiency | Power efficiency | Maximum power consumption | high |
| | Temperature | Maximum temperature | high |
| | eCall (emergency antennas/battery) | Phantom power | high |

## 5.3 Basic set of requirements for vehicular-DAS

Table 5.3-1 illustrates the basic set of requirement for the vehicular-DAS.

**Table 5.3-1: Requirements for vehicular-DAS**

| |
|---|
| [DAS-Req 1] The target vehicular-DAS solution shall operate in the FR2 frequency range.<br><br>[DAS-Req 2] The target vehicular-DAS solution shall operate in FR1 frequency range (incl. ITS spectrum).<br><br>[DAS-Req 3] The target communication system versions are at least 3GPP Rel. 16 and 17 including older releases which refers to the number of antennas needed and communication performance requirements as specified (rate/latency and range/speed, as e.g. in TS 22.186).<br><br>[DAS-Req 4] The target vehicular-DAS solution shall be scalable for future RAT releases. |

[DAS-Req 5] The target vehicular-DAS solution shall be flexible for use in different vehicle types/designs.

[DAS-Req 6] The target vehicular-DAS solution shall meet/comply with all automotive-related certificates and regulations (incl. all eCall versions).

[DAS-Req 7] The target vehicular-DAS solution shall meet/fulfil implementation requirements related to cost and energy efficiency.

# 6 Potential implementation options for vehicular-DAS

## 6.1 Design options for vehicular-DUs and vehicular-CU

### 6.1.1 Design options and function split

eCV2X TR [6] describes four potential implementation options (see **Figure 6.1.1-1**).

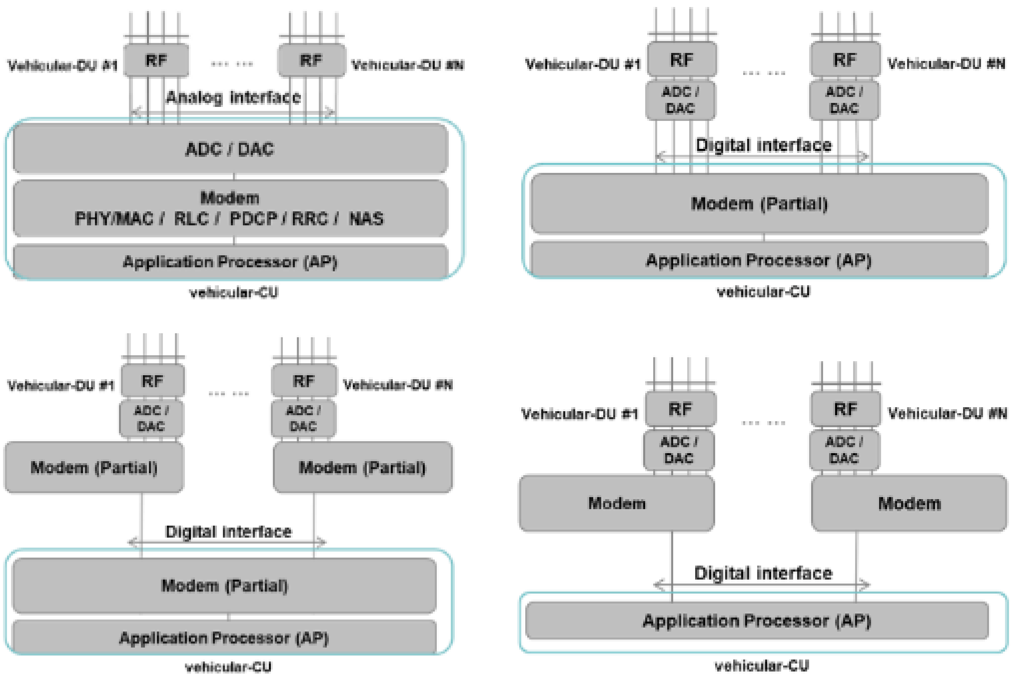



**Figure 6.1.1-1: Potential implementation options for vehicular-DAS [6]**

The design options are further elaborated with sub-options [7] as illustrated in **Figure 6.1.1-2**.

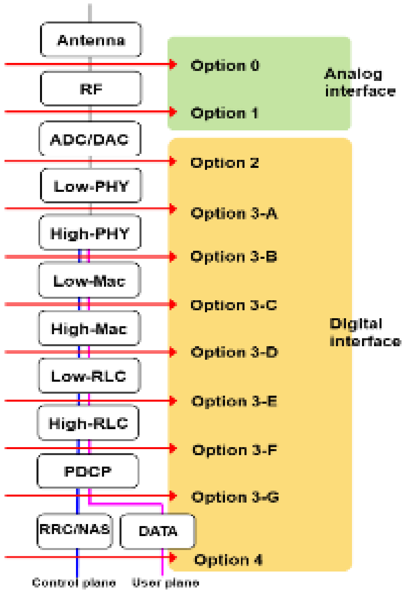



**Figure 6.1.1-2: Function split and potential implementation options of vehicular-DAS**

It should be noted that the numbering of function split options for vehicular-DAS in this document is different from the numbering for (NG-) RAN architecture decomposition used in 3GPP specification [8] and ORAN [9].

## 6.1.2 Justification of vehicular-CU/vehicular-DU options

### 6.1.2.1 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 or one RF unit is designed to drive multiple antennas. Since the RF signal is attenuated in the cable, the length of the cable (i.e. the distance between the remote antenna and the central unit) has a big impact on radio performance. This should be taken into consideration in particular when FR2 bands are used for vehicular communication. Instead of a passive antenna, an amplifier can be built in to compensate for the cable limitations. This is considered as part of option 1.

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 (cable loss scales with the frequency) which is 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.
- Implications of analogue beamforming in FR2 unclear.

### 6.1.2.2 Option 1: RF - PHY split (analogue interface)

Antennas and radio frequency are in the vehicular-DU and the other functionalities are in the vehicular-CU. RF signals from different vehicular-DUs can be combined at vehicular-CU.

The cable loss can be reduced when the RF signal is converted to intermediate frequency band. However, the cable length remains as a limitation in the system design. One more advantage of the frequency converter is in the multi-panel MIMO scenario. With the frequency converter, multiple streams from one MIMO panel can be multiplexed and transferred in one cable.

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.

#### 6.1.2.3 Option 2: RF + ADC/DAC - PHY split (digital interface)

Antennas, RF and ADC/DAC are in the vehicular-DU and the other functionalities are in the vehicular-CU. Moving ADC/DAC to the remote unit enables the digital transmission between the vehicular-CU and vehicular-DU. In this option, time-domain I/Q samples are transmitted via interface between vehicular-CU and vehicular-DU.

As a product of the vehicle size, the cable length and distance between vehicular-CU and vehicular-DU is no longer the bottleneck for the system design. Both copper and fibre solutions can be used for the cabling. However, the capability of current copper cable might be critical for a multi-panel MIMO system. In addition, if FR2 is applied in the future and more than 100MHz is available for V2X communication, fibre might be the only solution for this option.

Pros:

- Not limited by cable length.
- Possible to multiplex the MIMO streams from the same panel.
- Joint processing for the signal from/to different vehicular-DUs in physical layer operation can be supported efficiently (e.g. joint MIMO equalisation, LLR combining) when channel decoding is performed in the vehicular-CU.
- Multiple vehicular-DUs can be utilised to achieve 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.
- Greater cost due to fibre solution (increases with the throughput demand on vehicular-CU/vehicular-DU interface).

#### 6.1.2.4 Option 3: Intra-modem function split

Several sub-options with different protocols for splitting the stack layers can be considered. In these sub-options of option 3, multiple vehicular-DUs can be utilised to gain in selection diversity or transmit/receive redundant/duplicated packets.

If the functions are split to the vehicular-DUs, it is still possible to have a direct physical/logical link between the vehicular-DUs, enabling direct coordination between them. However, such a link will introduce additional overheads and complexity to the system. In the remaining part of this report, **we always refer to a split without direct connection between vehicular-DUs if it is not specified in the text**.

Note: To comply with the 3GPP communication standards, for some of option 3’s intra-modem splits coordination of different functions across vehicular-DUs is required.

##### 6.1.2.4.1 Option 3A: 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 physical layer function (=High-PHY) are in the vehicular-CU. There would be several variants of High/Low-PHY function split.

Pros (Common for both option 3A-1 and 3A-2):

- Much lower throughput demand between vehicular-CU and vehicular-DU compared to option 2. Through certain PHY processes (e.g. FFT/IFFT, CP removal/addition) only part of the information which is relevant for the particular UE (vehicle) is needed to be transferred between vehicular-CU and vehicular-DU.
- In this split, 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) when channel decoding is performed in vehicular-CU.

Cons:

- Additional complexity in the vehicular-DU.

There would be several variants of High/Low-PHY function split, and some possible (non-exhaustive) sub-options of option 3A are illustrated in **Figure 6.1.2.4.1-1**.

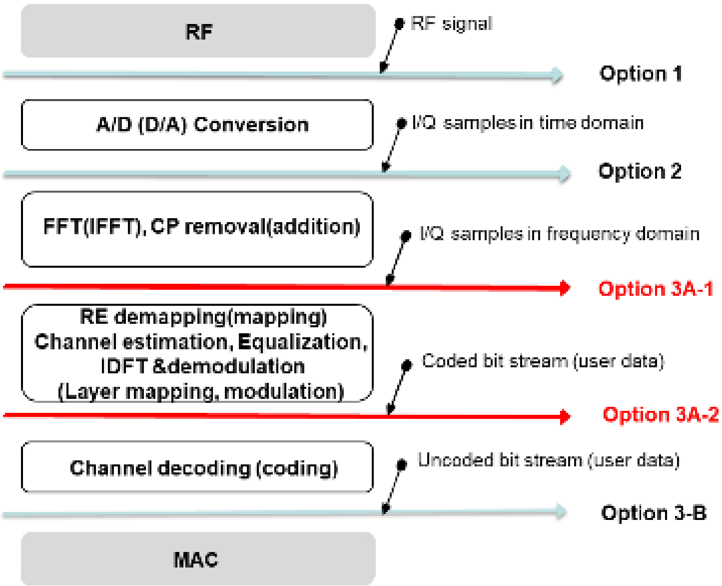



**Figure 6.1.2.4.1-1: Sub-options of option 3A**

**Option 3A-1**

In this function split, FFT/iFFT and CP removal/addition functions reside in the vehicular-DU, and the rest of PHY functions reside in the vehicular-CU. This split allows joint channel estimation and equalisation in the DAS. Also, as FFT is located locally in the vehicular-DU, frequency-domain I/Q samples are transmitted via interface between vehicular-CU and vehicular-DU.

**Option 3A-2**

In this function split, only the channel decoding/coding function resides in the vehicular-CU, and the rest of the PHY functions reside in the vehicular-DU. Combining gain can be obtained through joint bit-level processing in this option (e.g. LLR combining).

It should be noted that Figure 6.1.2.4.1-1 shows the sub-options considering one possible implementation of physical layer processing chain. Other implementations could be possible with a different function description and/or functional chain order.

### 6.1.2.4.2 Option 3B: 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. For instance, HARQ operation of the same MAC PDU for multiple vehicular-DUs can be supported in a centralised manner.

In this option the throughput demand is further reduced compared to option 3A. Only MAC package and MAC layer signalling is transferred between vehicular-CU and vehicular-DU.

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.

#### 6.1.2.4.3 Other 3X options

The throughput demands reduce further when the vehicular-CU/vehicular-DU split takes place in the higher layer. However, the reduction is no more significant as the differences noted in the above options. As a trade-off, the efficiency of multi-antenna coordination and MIMO gain goes down. The latency due to the transmission between vehicular-CU and vehicular-DU may cause performance degradation, since the scheduling, RRM and HARQ/ARQ processes will be impacted by the additional delay. However, such degradation might be minor from the UE side. Further study might be needed to confirm these assumptions.

Pros:

- Further reduced throughput demand between vehicular-CU and vehicular-DU.

Cons:

- Reduction of the efficiency of MIMO gain.

### 6.1.2.5 Option 4: Split into individual UEs

In this split option, the 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.

In 3GPP topology, each vehicular-DU is interpreted as an individual UE. Each UE may have different UE ID, and the vehicle with multiple vehicular-DUs is regarded as a group of UEs, or multiple UEs. This could be an attribute which differentiates option 4 from the other options (option 1, 2 and 3).

No coordination is required between the vehicular-DUs in the communication layer. However, coordination on the application layer is still possible, or in some cases is required.

Pros:

- Each vehicular-DU can be updated and replaced individually.
- It is possible to integrate with other active devices or sensors in the vehicle.

Cons:

- Cost of multiple UE.
- Each UE needs individual space.
- Less efficient due to lack of coordination; vehicular-DUs (UEs) might compete for radio resources and even interfere with each other.

## 6.1.3 Protection and functional safety considerations

If a 'protect mechanism' is required, which is foreseeable in the V2X system, an additional protection cycle and stack duplication will be implemented in the system. Given a rough assumption that the reliability of each function unit in the communication chain is $P_i$, the reliability of a complete central system is then

$$P = P_1 * P_2 * \ldots * P_i \ldots$$

The reliability of a distributed system is then

$$P = (1-(1-P_1)^n) * (1-(1-P_2)^n) * \ldots * (1-(1-P_i)^n) \ldots,$$

if the function is split to *n* vehicular distributed unit(s) at layer *i*. Here, we can make a rough conclusion that the functional safety can be achieved with a higher grade of distribution.

## 6.1.4 Summary table

Summary on characteristics of different vehicular-CU/vehicular-DU split options is shown in **Table 6.1.4-1**.

**Table 6.1.4-1: Overview of different split options corresponding to a single or multiple UE implementation characteristic**

| | Opt. 0 | Opt. 1 | Opt. 2 | Opt. 3 | Opt. 4 |
|---|---|---|---|---|---|
| Type of interface | Analogue interface | | Digital interface | | |
| Interpretation for the vehicle in 3GPP topology | Single UE | | | | Multi-UE, or a group of multiple UEs |

The main purpose of this work item and report is to provide guidance and recommendations on design options of vehicular-DAS to industries. Based on the analysis, WG2 agreed to categorise 11 options into two groups (Group A and B) and to down-select some design option(s) in Group A. The list of options for Group A and B is shown in **Table 6.1.4-2.**

**Table 6.1.4-2: Classification of spilt options for a decision on vehicular-DAS design options**

| Group A | Group B |
|---|---|
| 1. Option 0<br>2. Option 1 (RF - PHY split)<br>3. Option 2 (RF + ADC/DAC - PHY split )<br>4. Option 3-A (Low/ High PHY split) | 1. Option 3-B (PHY-MAC split)<br>2. Option 3-C (Intra-MAC split)<br>3. Option 3-D (MAC-RLC split)<br>4. Option 3-E (Intra-RLC split)<br>5. Option 3-F (RLC-PDCP split)<br>6. Option 3-G (RLC-RRC split)<br>7. Option 4 (Split into individual UEs) |

For the following reasons, it has been decided to de-prioritise options in Group B in this WI, as follows:

- Analysis shows limited performance gains (throughput, reliability) with some options where the physical layer operation is performed at each vehicular-DU individually. Specifically, options 3-B, 3-C, 3-D, 3-E, 3-F, 3-G and 4 are not able to provide MIMO gain (e.g. combining gain) using vehicular-DAS.
- The more functions are located in the vehicular-DU, the lower the bandwidth required in the interface between vehicular-CU and vehicular-DU. This observation was less pronounced in option 3-C, 3-D, 3-E, 3-F and 3-G.
- When each vehicular-DU is treated as an individual UE (thus a vehicular-DAS), option 4 is not considered a typical/traditional UE in 3GPP topology. The operation mechanism/procedure (e.g. coordination needed in the application layer to handle a vehicle with multiple UEs at the network) of a vehicle operating under option 4 is unclear.

In the early stage of vehicular-DAS implementation, option 0 or 1 are likely candidates. In option 0 and 1, an analogue interface (e.g. coaxial cable) is used in different design options. As coaxial cables have been standardised and widely used in the automotive industry for several decades, these two design options can be considered as appropriate in initial vehicular-DAS implementation. However, it is clear that cabling loss caused by the interface results in the performance degradation of vehicular-DAS UE and this issue can be resolved/relaxed by introducing digital interface for vehicular-DAS. Therefore, we anticipate the migration of analogue interfaces to digital interfaces in the implementation of vehicular-DAS processes. When digital interfaces are adopted for vehicular-DAS (especially for V2X communication only in FR1), option 2 can be implemented; thus generating MIMO efficiency gains for the UE and reduced implementation cost/complexity compared to option 3A. But as the usage of FR2 further raises data rate requirements for interfacing, option 3A becomes a frontrunner for vehicular-DAS when the UE needs to support V2X operations in FR2 (or in both FR1 and FR2).

# 6.2 Design options for interfacing and protocols between vehicular-DU and vehicular-CU

## 6.2.1 Requirements on interfaces between vehicular-CU and vehicular-DU

### 6.2.1.1 Bandwidth requirement

The throughput/bandwidth requirement on the interfaces varies among the different vehicular-CU/vehicular-DU splitting options. The throughput/bandwidth requirement is also impacted by the type of V2X services that vehicular-DAS should support. In order to compare vehicular-CU/vehicular-DU splitting options, the formulation and methodology to calculate the bandwidth requirement is given in this section. Since analogue interfacing has fundamentally different bandwidth parameters, we exclude that from the calculations in this section, focusing only on the design options with digital interfaces, i.e. option 2-option 4 in Section 6.1.

#### 6.2.1.1.1 Option 2: RF + ADC/DAC - PHY split (digital interface)

The complete baseband signal is transmitted between vehicular-CU/vehicular-DU on the digital interface. Unless there is additional mechanism implemented, which can support the dynamic down-selection of the spectrum partitions (e.g. only the spectrum partitioning allocated to the particular UE will be transmitted over the interface), the bandwidth requirement is constant and is determined by the system configuration. It can be calculated as

$$R_{RF\text{-}PHY} = N_{subcarrier} * \Delta f * Bitwidth * N_{antennaports}, \qquad (1)$$

where $N_{subcarrier}$ is the total number of subcarriers that a single UE can/should support (including non-active subcarriers), $\Delta f$ is the subcarrier spacing, *BitWidth* is the bit width of the IQ symbol, $N_{antennaport}$ is the number of the antenna ports on the DU.

As an example, assuming a LTE system with 2048 subcarriers and 15kHz subcarrier spacing, bit width 2*10 bits for uplink and downlink, and 2 antenna ports at vehicular-DU, the vehicular-CU/vehicular-DU interface requires 1.23Gbps in both uplink and downlink.

For a 5G system with 4096 subcarriers (100MHz band), 30kHz subcarrier spacing, 2*16 bit width (assuming 256QAM need to be supported) and 4 antenna ports at vehicular-DU, the vehicular-CU/vehicular-DU interface requires 15.73Gbps.

#### 6.2.1.1.2 Option 3A: Low PHY - High PHY split

If FFT/IFFT, CP removal/addition are moved to vehicular-DU, the information to be transmitted between vehicular-CU/vehicular-DU becomes less. The bandwidth requirement can be calculated as

$$R_{IntraPHY} = (N_{subcarrier\_active} * N_{symbol} * N_{antennaports\_DU} * Bitwidth + MAC\_Info)/TTI \qquad (2)$$

where $N_{subcarrier\_active}$ is defined as the maximum number of active subcarriers that a single UE can/should support. $N_{symbol}$ is the number of symbols per subcarrier and time interval, $N_{antennaports\_DU}$ is the number of antenna ports at the vehicular-DU, *TTI* is the length of Transmission Time Interval. Depending on UE capability, $N_{subcarrier\_active}$ can be equal to the total number of active subcarriers of the system. The MAC information includes 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.

Taking the same assumption of the LTE system in section 6.2.1.1, with TTI length of 1ms, 14 symbols, and 2 antenna ports on each vehicular-DU, and maximum 1200 subcarriers can be used, the bandwidth requirement on the vehicular-CU/vehicular-DU interface is therefore 672Mbps.

A 5G system such as in Section 6.2.1.1 may have 4 antenna ports on each vehicular-DU. Its frame structure has 14 symbols in one time slot, and each time slot takes 0.5ms. A total of 3300 subcarriers can be used for resource blocks, and the bandwidth requirement on the vehicular-CU/vehicular-DU interface in this case is 11.82Gbps.

#### 6.2.1.1.2.1 Option 3A-1: Based on Low Phy - High Phy split using O-RAN FH protocol on an ethernet physical layer

Several simplifying assumptions need to be made:

- **Reception data only:** As any device is likely to receive more information than it is transmitting, it means the load on the FH interface associated with reception is higher than the one for transmission. Thus, it can be considered, as a worst case, one-directional FH interface load.
- **Ethernet interface:** The O-RAN FH interface supports different underlying interfaces for transporting the data. As automotive ethernet is a likely candidate for implementing vehicular-DAS, the ethernet-based option was selected for this evaluation.
- **Single antenna only:** In this first assessment only a single antenna is evaluated. As for multiple antennas in the same vehicular-DU, multiplying the load by the number of antennas also gives the worst-case load for reception.
- **Bandwidth part (BWP) spans the full band:** The device is assumed to be configured with a BWP that spans the whole band.
- **SL synchronisation and Uu cell search excluded:** Traffic related to cell search or SL synchronisation is assumed to be only a minor part of the overall FH traffic.
- **Used bandwidth (BW) and subcarriers (SCs):** BW of 10, 20, 40 and 100MHz with a SCS of 15, 30 and 60kHz is evaluated.
- **Compression of the frequency domain symbols:** Symbols in this frequency domain are transported in the fronthaul so a suitable compression needs to be defined. In this case O-RAN defines a maximum of 32bits to represent I and Q, but 24bits should be sufficient (12 bits each for I and Q) for most cases.
- **Multiple component carriers (CCs):** Based on one CC evaluation it was assessed that, in the worst case, the FH load for multiple CCs is equivalent to adding up the total of each individual interface.

Spacing (SCS) and bandwidth are evaluated:

| BW / SCs (kHz) | 10MHz | 20MHz | 40MHz | 100MHz |
|---|---|---|---|---|
| | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ | $N_{RB}$ |
| **15** | 52 | 106 | 216 | N/A |
| **30** | 24 | 51 | 106 | 273 |
| **60** | 11 | 24 | 51 | 135 |

This means that the raw flow rate of only the user data would can be calculated as

$$N_{RB} * N_{SCPRB} * L * N_S * N_{bit}, \quad (3)$$

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.

This results in the following data rates:

| BW / SCs (kHz) | 10MHz | 20MHz | 40MHz | 100MHz |
|---|---|---|---|---|
| | FH rate Gbit/s | FH rate Gbit/s | FH rate Gbit/s | FH rate Gbit/s |
| **15** | 0.210 | 0.427 | 0.871 | N/A |
| **30** | 0.194 | 0.411 | 0.855 | 2.20 |
| **60** | 0.177 | 0.387 | 0.823 | 2.18 |

Based on the message sequence chart for transmitting user data on page 102 of [9] it is evident that for each OFDM symbol a separate message is sent. In addition, a control message for each data slot also needs to be exchanged between the vehicular-DU and the vehicular-CU for each slot. However, this is sent from the vehicular-CU to the vehicular-DU, thus there is no additional load. According to the definition of the message format in [9] this would add another 80bits per message. Adding this to the data the representation of the symbol results in a packet of the following size for each OFDM symbol:

| BW / SCs (kHz) | 10MHz | 20MHz | 40MHz | 100MHz |
|---|---|---|---|---|
| | **Bits per packet** | **Bits per packet** | **Bits per packet** | **Bits per packet** |
| **15** | 15056 | 30608 | 62288 | N/A |
| **30** | 6992 | 14768 | 30608 | 78704 |
| **60** | 3248 | 6992 | 14768 | 38960 |

Now this raw data needs to be encapsulated in ethernet frames. Some of these configurations require multiple frames per packet. The following table shows the number of bits per packet after ethernet encapsulation as well as the number of required ethernet frames:

| BW / SCs (kHz) | 10MHz | 20MHz | 40MHz | 100MHz |
|---|---|---|---|---|
| | **Bits per packet (Nr frames)** | **Bits per packet (Nr frames)** | **Bits per packet (Nr frames)** | **Bits per packet (Nr frames)** |
| **15** | 15728 (2) | 31616 (3) | 64304 (6) | N/A |
| **30** | 7328 (1) | 15458 (2) | 31616 (3) | 81056 (7) |
| **60** | 3584 (1) | 7328 (1) | 15458 (2) | 40304 (4) |

Combining this information with the number of OFDM symbols that need to be transferred per second we arrive at the following data rate including all encapsulation overhead:

| BW / SCS (kHz) | 10 MHz | 20 MHz | 40 MHz | 100 MHz |
|---|---|---|---|---|
| | **FH rate Gbit/s** | **FH rate Gbit/s** | **FH rate Gbit/s** | **FH rate Gbit/s** |
| **15** | 0.220 | 0.443 | 0.900 | N/A |
| **30** | 0.205 | 0.433 | 0.885 | 2.27 |
| **60** | 0.201 | 0.410 | 0.855 | 2.26 |

Looking at this data rate calculation and considering all ethernet encapsulations, it is obvious that the additional overhead is below 10%. That means an extra 10% of raw data rate would be only enough to cover it.

#### 6.2.1.1.3 Option 3B: PHY - MAC split

When splitting the vehicular-CU/vehicular-DU between the PHY- and MAC-layer, MAC control information needs to be exchanged on top of the actual data payload. However, the MAC control information for a single user is usually lower than 10% of the data payload and therefore negligible. Overhead such as PDCP-, RLC-header is also negligible. Therefore, the bandwidth demand on the vehicular-CU/vehicular-DU interface is roughly equal to the actual payload of the V2X services in this option. The bandwidth requirement can thus be estimated as

$$R_{IntraPHY} = (N_{subcarrier\_active} * N_{symbol} * N_{layer\_DU} * Bitwidth + MAC\_Info)/TTI \quad (4)$$

where $N_{layer\_DU}$ is the number of layers at one vehicular-DU, and the other parameters are the same as defined in Section 6.2.1.1.2. This estimation can also apply to further splitting options above option 3B.

#### 6.2.1.1.4 Option 4: Split into individual UEs

In this option only application information and data payload need to be exchanged between vehicular-CU (application) and vehicular-DU. Some additional information exchange might be used for coordination, but bandwidth demand is almost equal to actual data payload.

### 6.2.1.2 Delay requirement

#### 6.2.1.2.1 Option 1, 2 and 3A

The delay requirement on the vehicular-CU/vehicular-DU interface is restricted for these options, but increased delay will have an impact on system performance, which is also very sensitive to jitter and synchronisation processes. A detailed analysis of the timing and delay requirements should be carried out later via simulation or measurement.

#### 6.2.1.2.2 Option 3B to option 3D

The delay of the vehicular-CU/vehicular-DU interface is mainly restricted by the HARQ processes. The total processing delay (i.e. RF/PHY/MAC) should be less than the duration of HARQ, which is 4ms for an LTE system. Taking the description of the requirement on the vehicular-CU/vehicular-DU interface at the base station as the reference [9], the maximum latency on the interface should be less than 250us. A 5G system may have faster HARQ processing (e.g. for URLLC services) so the maximum delay requirement on the interface needs to be reduced accordingly.

#### 6.2.1.2.3 Option 3E and above

Since the HARQ process is moved to vehicular-DU, the maximum transmission latency of the interface between vehicular-CU and vehicular-DU remains unaffected. In this 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.

### 6.2.1.3 Synchronisation requirement

Time and frequency synchronisation of the different vehicular-DUs needs to be guaranteed to avoid problems with performance in the vehicular-DAS. In this section, we discuss the synchronisation requirements for UEs (including vehicular UEs) defined by 3GPP RAN4 and interpret the requirements for vehicular UEs with vehicular-DAS. Information about synchronisation for (NG-) RAN architecture decomposition used in O-RAN specification [9] is also presented.

#### 6.2.1.3.1 Requirement defined by 3GPP RAN4

Time and frequency synchronisation requirement for a UE is given as below:

- for time synchronisation

| | Time alignment error requirement |
|---|---|
| Uu (for both FR1 and FR2) | 130ns (for UL-MIMO) [3][10] |
| Sidelink (for FR1) | 260ns [3] |

- for frequency synchronisation

| | Frequency error |
|---|---|
| Uu (for both FR1 and FR2) | ±0.1ppm [3][10] |
| Sidelink (for FR1) | ±0.1ppm [3] |

According to the specification [3] and [10], the time synchronisation requirement for a UE is defined using the metric time alignment error (TAE), and frequency error. TAE is defined as follows:

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

Also, 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 we aim to design a unified antenna system supporting both Uu link and sidelink it is sufficient for a UE with vehicular-DAS to fulfil the requirement for the Uu link (specifically for UL MIMO).

As explained above, 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 [11]. In [11], RAN4 explained that external components, such as cables and compensators, may be used to connect the UE antenna connector to a vehicle-mounted antenna as shown in **Figure 6.2.1.3.1-1**. And this means that the TAE requirement for vehicular UE should be met at the UE antenna connector, as depicted, but excluding external components.

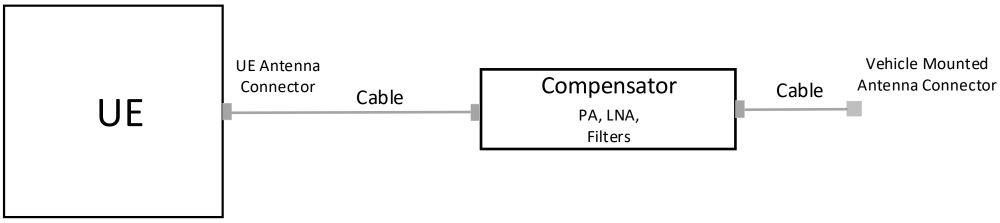



**Figure 6.2.1.3.1-1: Definition of antenna connectors for vehicular UE [11]**

The frequency error requirement is defined as follows [3] [10]:

- For UL in FR1 and FR2, the UE modulated carrier frequency shall be accurate to within the given accuracy observed over a period of 1msec of cumulated measurement intervals compared to the carrier frequency received from the NR Node B.
- For sidelink (V2X) FR1, the UE modulated carrier frequency shall be accurate to within given accuracy observed over a period of 1 ms or more (0.5ms for SL MIMO support) compared to the absolute frequency in case of using GNSS synchronization source. The same requirement is applied to NR Node B and V2X UE when these are used as synchronisation sources.

### 6.2.1.3.2 Interpretation on TAE requirement in vehicular-DAS for FR1

The TAE requirement should be be met by 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 [11], as shown in **Figure 6.2.1.3.2-1**. And this means that the TAE requirement defined by 3GPP RAN4 needs to be met by antenna connectors “in the vehicular-CU” and detailed design of the external components including vehicular-DU and interface is up to UE implementation.


**Figure 6.2.1.3.2-1: 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 a vehicle-mounted antenna connector implemented on the vehicular-DU side, as depicted in **Figure 6.2.1.3.2-2**. Therefore, if we consider 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 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. Measurement results for timing error between different vehicular-DUs for function split option 2 are provided in Section 7.2.1 Timing error between different vehicular-DUs.


**Figure 6.2.1.3.2-2: Antenna connector for vehicular UE in function split option 2 and 3**

- In function split option 4, the UE antenna connectors explained in [11] 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, we do not need to consider synchronisation between different vehicular-DUs as they are different individual UEs.

O-RAN is specifying a fronthaul interfaces for the network side [9]. One of the function-splits is denoted as option 3-A for vehicular-DAS. The 3GPP RAN4 TAE requirement is considered to run from one antenna connector to another. Therefore, this does require a specific synchronisation of the vehicular-DUs relative to each other. Thus, O-RAN broke the TAE synchronisation requirement down into parts to achieve the requirement on a system level. This also considers the different network topologies that can be utilised to connect the vehicular-CU and vehicular-DUs. To implement a vehicular-DAS system, such steps also need to be taken. O-RAN can serve as a first step towards a vehicular-DAS implementation.

#### 6.2.1.3.3 Interpretation on frequency error in vehicular-DAS

From the above descriptions, it is clear that for a vehicular-DAS system synchronisation at each vehicular-DU is required, independent of other vehicular-DUs and the vehicular-CU. Therefore, no additional system synchronisation requirements are called for as this can be implemented at each vehicular-CU independently. However, this will also depend on the function split interaction of the vehicular-CU and vehicular-DUs, to ensure this synchronisation is necessary.

## 6.2.2 Interfaces and protocols for vehicular-CU/vehicular-DU splitting

The design options for different vehicular-CU/vehicular-DU splitting are discussed in Section 6.1. In this section we discuss functions that need to be supported on the interfaces.[1] It is worth mentioning that the functions listed in this section may not be complete. Further functions could be included which may not have been identified at the current stage of the study.

[1] In order to support these functions, standardisation of the interfaces and protocols might be needed for all options using digital interface, i.e. option 2, 3 and 4 including their sub-options.

#### 6.2.2.1 General functions of the interface

Independent of the particular splitting options, certain functions are generally required for management and maintenance of the interfaces. These functions include:

- **Setup function**
  During a setup procedure the necessary information enabling the vehicular-CU/vehicular-DU connection is exchanged between vehicular-CU and vehicular-DU. The exchanged information includes, for example, the description of vehicular-CU and vehicular-DU, the ID of vehicular-DU for addressing, the initial configuration of vehicular-CU/vehicular-DU, etc.
- **Removal function**
  Corresponding to the setup procedure, this procedure removes the connection between vehicular-CU and vehicular-DU in a controlled manner.
- **Update function**
  In certain conditions, the configuration on vehicular-CU/vehicular-DU requires modification and update. This procedure is triggered to update the configuration of vehicular-CU/vehicular-DU.
- **Error indication function**
  The error indication function reports to vehicular-CU and vehicular-DU when a failure has occurred on the interface. It is an additional error identification mechanism in case that the failure cannot be detected by the vehicular-CU/vehicular-DU itself.
- **Reset function**
  If an error is detected or the interface does not work properly, the reset procedure is trigged to re-setup the interface between vehicular-CU/vehicular-DU based on the stored configuration.
- **Monitoring function**
  Vehicular-CU should be able to monitor the status of the vehicular-DU via the interface. Optionally, the performance of the interface itself (e.g. latency) can be reported to the vehicular-CU/vehicular-DU to optimise the overall system.

# 7 Evaluation of communication performance for DAS

## 7.1 Evaluation based on computer simulation

### 7.1.1 Potential impact of vehicular-CU/vehicular-DU latency on the sidelink and downlink throughput

#### 7.1.1.1 Assumptions and related parameters

The evaluation methodology and the simulation setup in this document follow the 3GPP guidelines specified in [13]. The CDL model for NR-V2X channels [14] is used in the simulations conducted.

According to the 5GAA study of expected spectrum needs [15], 70-75MHz of ITS spectrum at the 5.9GHz band is estimated to be required in order to support day-1 ITS and advanced driving use cases via C-V2X direct communication (V2V/I/P). The C-V2X network-based (V2N) communications require at least 500MHz of additional service-agnostic mid-band (1 to 7GHz) spectrum. Therefore, it is assumed in the simulation that the sidelink is going to support 70MHz spectrum and the Uu link is going to support 500MHz spectrum. The goal of the current analysis is to provide some useful insights for the design of distributed vehicle antenna systems.

##### 7.1.1.1.1 Sidelink

Following the specification in [3], 189 resource blocks (RB) are used, which corresponds to the bandwidth of 70MHz. The other parameter settings applied in the simulation are provided in **Table 7.1.1.1.1-1**.

**Table 7.1.1.1.1-1: Simulation parameters of sidelink DAS**

| Simulation parameter | Value |
|---|---|
| Carrier frequency | 6GHz |

| | |
|---|---|
| Subcarrier spacing | 30kHz |
| Bandwidth | 189RB |
| Channel | highway-LOS |
| Speed | 120km/h |
| MCS | Dynamic based on CQI and OLLA |
| Waveform | CP-OFDM |
| Channel coding | LDPC |
| DMRS configuration | 3DMRS for 120km/h |
| Number of transmission layer | 1 |
| Frequency synchronisation error | 0 |
| Time error | 0 |
| Antenna configuration | 2T2R, 4T4R |
| UE receiver algorithm | MMSE |
| Normal MIMO CSI delay | 3ms |
| Additional vehicular-CU/vehicular-DU delay | 0.5ms (maximum delay) |

#### 7.1.1.1.2 Uu link

The simulation parameters of Uu link are provided in **Table 7.1.1.1.1-2**. The performance of vehicular-DAS is evaluated for downlink (DL) transmission case, where 500MHz of spectrum bandwidth (1365RBs) is available.

**Table 7.1.1.1.1-2: Simulation parameters of sidelink DAS**

| **Simulation parameter** | **Value** |
|---|---|
| Carrier frequency | 6GHz |
| Sub-Carrier Spacing | 30kHz (downlink) |
| Bandwidth | 273RB*5 |
| Channel | CDL-D, DS = 10 |
| Speed | 120km/h |
| MCS | Dynamic based on CQI and OLLA |
| Waveform | CP-OFDM |
| Channel coding | LDPC |
| DMRS configuration | 3DMRS for 120km/h |
| Number of transmission layer | 2 |
| Frequency synchronisation error | 0 |
| Time error | 0 |

| | |
|---|---|
| Antenna configuration | 8T2R, 8T4R |
| UE receiver algorithm | MMSE |
| Normal MIMO CSI delay | 3ms |
| Additional vehicular-CU/vehicular-DU delay | 0.5ms (this is the maximum value) |

### 7.1.1.2 Results and analysis

#### 7.1.1.2.1 Sidelink

The simulation results show the throughput performance of ideal CSI reporting (noted as “V3 with no delay”) and practical CSI reporting with 3ms delay. In vehicular-CU/vehicular-DU splitting options 0 - 3A, extra delay may occur during the exchange between vehicular-CU and vehicular-DU.

- If the vehicular-CU/vehicular-DU is connected via fibre and uses protocols similar to CPRI/eCPRI, the extra delay is usually at the level of hundreds of nanoseconds, which is negligible compared to the 3ms delay of the normal CSI reporting.
- If the vehicular-CU/vehicular-DU interface is using an ethernet solution then the delay on the vehicular-CU/vehicular-DU interface depends on the compression rate and packet size of the ethernet connection. We assume therefore a maximum delay of 0.5ms on the vehicular-CU/ vehicular-DU interface.

It should be noted that we assume the required data rate on the vehicular-CU/vehicular-DU interface is below the maximum capacity of the interface, i.e. fibre or ethernet. Otherwise, the delay of the vehicular-CU/vehicular-DU interface could be higher due to the potential congestion.

The throughput performance of vehicular-DAS on the sidelink is shown in **Figure 7.1.1.2.1-1**.

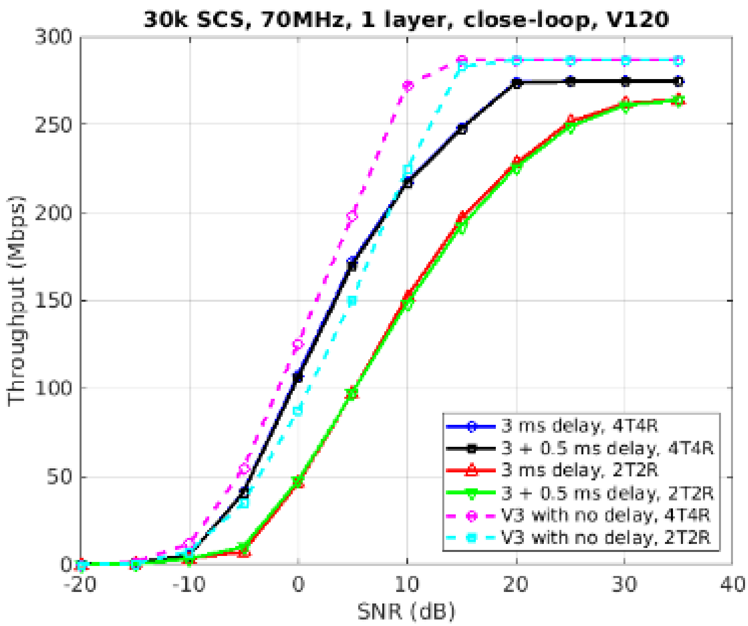



**Figure 7.1.1.2.1-1: Comparison of sidelink throughput**

It can be observed that 4T4R antenna configuration provides better sidelink throughput performance compared to the 2T2R case. In the “V3 with no delay” case, 4T4R provides nearly 3dB gain, which is in accordance with the theoretical analysis. Furthermore, the additional delay caused by vehicular-CU/vehicular-DU separation does not affect the sidelink throughput performance.

#### 7.1.1.2.2 Uu

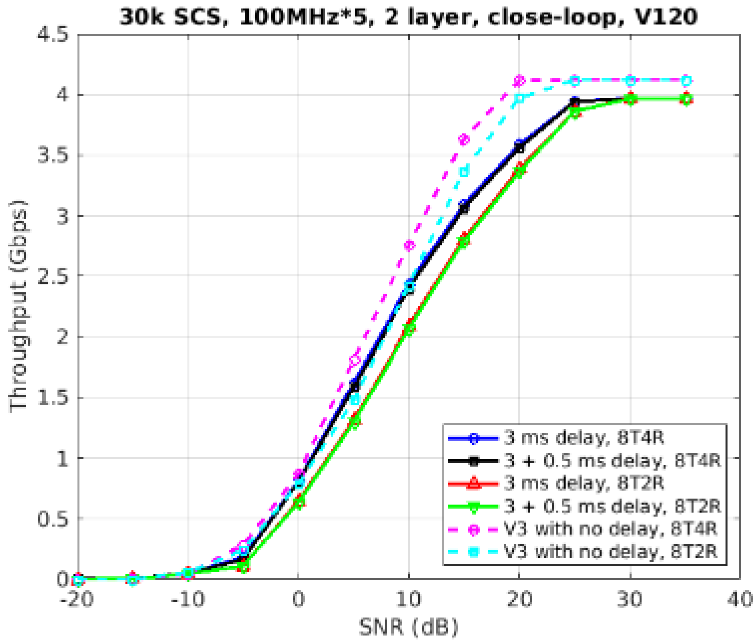



**Figure 7.1.1.2.2-1: Comparison of Uu downlink throughput**

**Figure 7.1.1.2.2-1** shows similar benefits of vehicular-DAS in the Uu downlink scenario. The 8T4R antenna configuration provides better throughput performance compared with the 8T2R configuration. The additional delay caused by vehicular-CU/vehicular-DU separation does not affect the throughput performance loss in the Uu scenario.

## 7.1.2 Performance comparison between vehicular-DAS and conventional co-located antenna system on the vehicle rooftop

### 7.1.2.1 Assumptions and related parameters

The evaluation methodology and the simulation setup in this document follow the 3GPP guidelines specified in [13] and [16], and the parameters used in the simulation are provided in **Table 7.1.2.1-1** and **7.1.2.1-2**.

**Table 7.1.2.1-1: Simulation parameters commonly used for both vehicular-DAS and co-located antenna system**

| Parameter | | Value |
|---|---|---|
| Carrier frequency | | 6GHz |
| Bandwidth | | 20MHz |
| Subcarrier number per PRB | | 12 |
| Subcarrier spacing | | 15kHz |
| Noise figure | | 9dB |
| Polarisation | | Cross-pol (0 and 90 degree) |
| TTI duration | | ms |
| HARQ | Type | Blind HARQ |
| | Number of retransmissions | 1 |
| Traffic model | Type | Periodic traffic model with pattern |

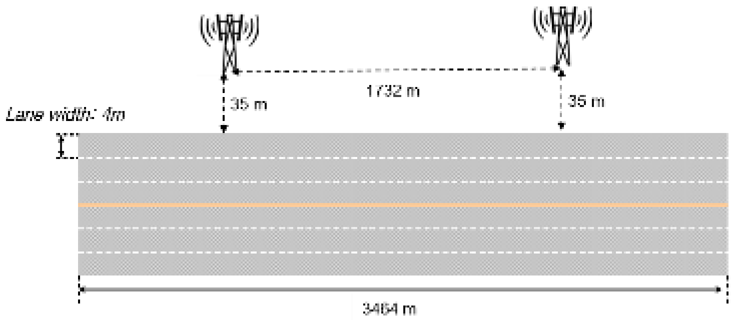
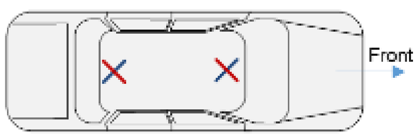
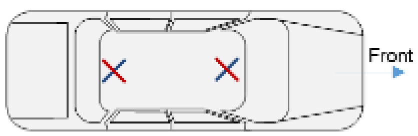
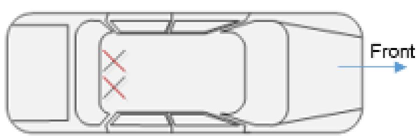
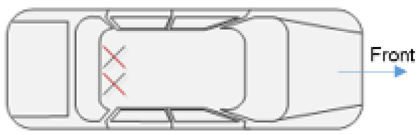
| | |
|---|---|
| | {300bytes, 190bytes, 190bytes, 190bytes, 190bytes} |
| Subchannel size | 10PRB |
| Resource allocation | Mode 1 |
| Scenario | Highway scenario in [13] |
| gNB drop | gNBs are located along the highway 35m away with 1732m ISD (2BS total)<br> |
| Vehicle drop | - 100% vehicle type 2, vehicle speed is 140km/h in all the lanes<br>- The distance between the rear bumper of a vehicle and the front bumper of the following vehicle in the same lane is max {2m, an exponential random variable with the average of the speed * 2s}, as specified in [13] |
| Geometry | Highway length – 3464m, 6 lanes total with 4m width |
| Location update | Object positions are updated every 100ms |
| Channel model | Channel models in [13] and [16] are used |
| All other parameters and simulation setup used in this simulation follow the 3GPP's evaluation assumptions specified in [13] and [16]. | |

**Table 7.1.2.1-2: Antenna configuration for vehicular-DAS and co-located antenna system**

| | Vehicular-DAS | Co-located antenna system |
|---|---|---|
| Antenna configuration | 4Tx, 4Rx (with antenna element patterns reflecting the self-blockage effect in Table 6.1.4-10B and Table 6.1.4-10C in [13])<br>Vehicular-DAS 4Tx 4Rx configuration (Tx)<br><br>Vehicular-DAS 4Tx 4Rx configuration (Rx)<br> | 4Tx, 4Rx (with antenna element pattern reflecting the self-blockage effect in Table 6.1.4-10C in [13])<br>Co-located antenna system 4Tx 4Rx configuration (Tx)<br><br>Co-located antenna system 4Tx 4Rx configuration (Rx)<br> |
| [Note 1] When we calculate path loss for vehicular-DAS, the actual location of each vehicular-DU is considered. The model for spatial correlation defined in [17] is used to calculate large-scale parameters of vehicular-DUs. It should be noted that the same formulas for the calculation of path loss/large-scale parameters in [13] are used for both vehicular-DAS and co-located antenna system. | | |

[Note 2] Regarding the blockage caused by other vehicles, geometry-based blockage modelling is used for both vehicular-DAS and co-located antenna system with the consideration of actual antenna location, which is based on the blockage model B in [16].

### 7.1.2.2 Results and analysis

In this simulation, we compare the average packet reception ratio (PRR) of two different antenna systems having different antenna locations, vehicular-DAS and conventional co-located antenna system. As shown in **Figure 7.1.2.2-1** and **Table 7.1.2.2-1**, vehicular-DAS can achieve 95% and 99% PRR performance with the reliable communication distance gain of 82.5m (44%) and 40m (50%), respectively, compared to the co-located antenna system. In the DAS case, the probability of all rays being blocked by the other vehicles would be reduced, and performance degradation due to the self-blockage effect could be overcome by distributing vehicular-DUs in different locations. These characteristics of the vehicular-DAS highlight the performance benefit compared to the conventional co-located antenna system.

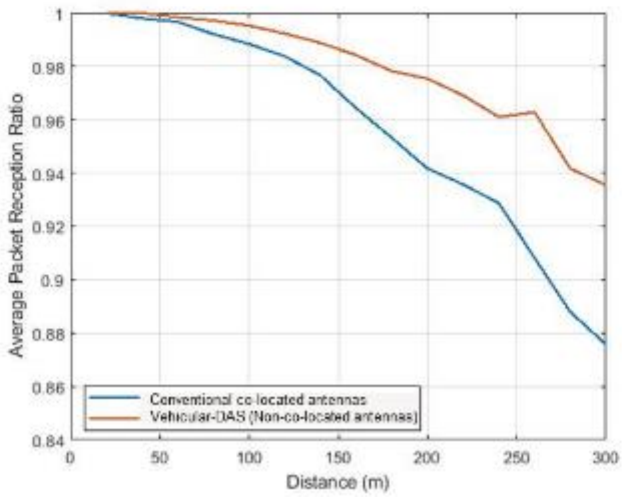



**Figure 7.1.2.2-1: Average PRR of vehicular-DAS vs. conventional co-located antennas in highway scenario**

Further vehicular-DAS performance gains come from the channel diversity, i.e. channels can be (relatively) low correlated by spacing vehicular-DUs further apart from each other.

**Table 7.1.2.2-1: Comparison of reliable communication distance for Vehicular-DAS and Co-located antenna system with 99% and 95% PRR**

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

## 7.2 Evaluation based on measurement

### 7.2.1 Timing error between different vehicular-DUs

As described in Section 6.2.1.3 Synchronisation requirement, the synchronisation requirement (e.g. timing alignment error) should be fulfilled between different vehicular-DUs, in order to ensure that vehicular-DAS does not experience any performance loss and the vehicular UE with vehicular-DAS complies with 3GPP RAN specifications in terms of the synchronisation requirement. In this section, the measured timing error across vehicular-DUs is provided.

### 7.2.1.1 Assumptions and related parameters

In this measurement, the function split option 2 (RF and ADC/DAC - PHY split) is assumed for vehicular UE with four vehicular-DUs. Also, ethernet-based optical fibre is used for cabling between the vehicular-CU and vehicular-DUs for vehicular-DAS.

Jitter error and frequency error are measured, where:

- The jitter error denotes the time difference caused by the asynchronous interface. Specifically, as illustrated in **Figure 7.2.1.1-1**, although a signal is transmitted from the vehicular-CU to each vehicular-DU at the same time, the signal reaches its destination at different times. To simplify the measurement, we measured the round-trip time (RTT) difference of the signal between the vehicular-CU and each vehicular-DU. Therefore, jitter errors measured in this test are greater than actual jitter errors in vehicular-DAS.

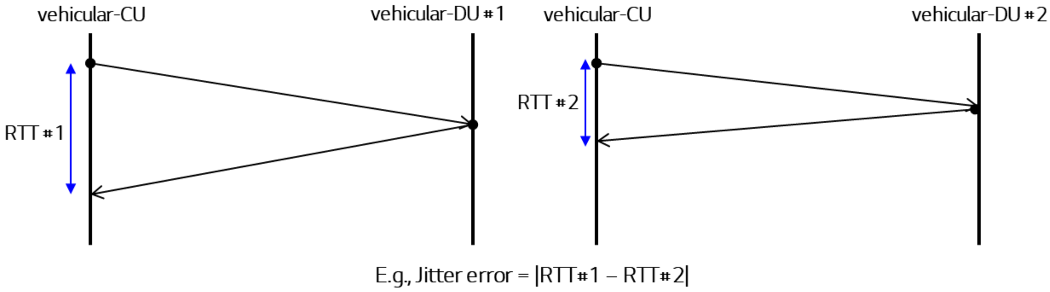



**Figure 7.2.1.1-1: Definition of jitter error in this measurement**

- The frequency error is defined as the error caused by clock drift. In vehicular-DAS implementation with function split option 2, each vehicular-DU has its own clock which may not be perfectly synchronised with other vehicular DU clocks. The clocks can be set to synchronise initially, but after some time they begin to differ due to clock (frequency) drift.

In this test, assuming vehicular-DAS with four vehicular-DUs, the frequency difference between the vehicular-CU and each vehicular-DU is adjusted periodically (every 10ms), and at the moment just before the frequency difference adjustment, i.e. the frequency difference between the vehicular-CU and each vehicular-DU is measured according to the following: $freq_{\_e1}$, $freq_{\_e2}$, ⋯, $freq_{\_e6}$. The maximum frequency difference among $freq_{\_ei}$ (i=1,…,6) is chosen as a sample for the frequency error, and these are gathered over quite long period of time (e.g. 2 hours).

### 7.2.1.2 Results and analysis

**Figure 7.2.1.2-1** illustrates the distribution of jitter error and frequency error measured in this test. The synchronisation errors between different vehicular-DUs are thus shown in **Table 7.2.1.2-1**. The total timing error (which is a sum of jitter error and frequency error) between different vehicular-DUs is about 22ns on average, and the maximum of the total timing error is close to 77ns. However, it should be noted that the actual average and the maximum timing error are smaller than the timing error measured in this test, as we measured the difference of round-trip time between the vehicular-CU and vehicular-DU to attain the jitter error.

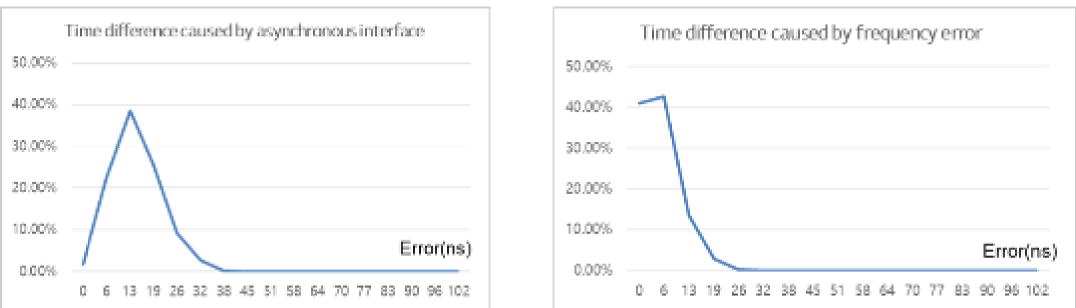



**Figure 7.2.1.2-1: Measurement of jitter error and frequency error**

**Table 7.2.1.2-1: Average and maximum of timing error measured in the test**

| | Metrics | Result |
|---|---|---|
| Average | Jitter error (sample) | 2.3 |
| | Frequency error (sample) | 1.1 |
| | Total error (sample) | 3.4 |
| | Total error (ns) | **21.9** |
| Maximum | Jitter error (sample) | 7 |
| | Frequency error (sample) | 5 |
| | Total error (sample) | 12 |
| | Total error (ns) | **76.8** |
| [Note] 1 sample = 6.4ns = 156.25MHz clock (clock freq. used in ethernet HW) | | |

As explained in Section 6.2.1.3 Synchronisation requirement, the most stringent timing synchronisation requirement for the UE in current RAN4 specification is 130ns, and the requirement should be fulfilled when we transmit signals using multiple antennas included in different vehicular-DUs simultaneously. The timing error between vehicular-DUs measured in this test is the "additional" synchronisation (timing) error component to be added to the timing error between the antenna elements in different vehicular-DUs, and it could make it difficult for vehicular-DAS to meet the TAE requirement in the current specification.

Depending on the detailed implementation of clocks in the vehicular-CU/vehicular-DU and the frequency error correction/adjustment method, the timing error between different vehicular-DUs could vary.

## 7.2.2 Measurement on communication performance for vehicular-DAS in various scenarios

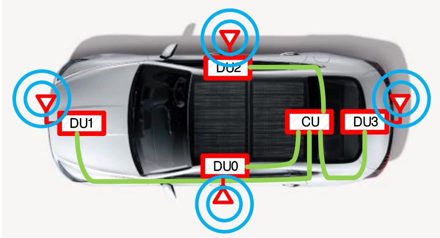
In this section, the vehicular-DAS' communication performance measurements are provided, especially focusing on the reception performance. (e.g. signal-to-noise ratio (SNR), reliability, and reception coverage of the vehicle). By comparing the performance of two vehicles with different antenna locations, the vehicular-DAS and the conventional co-located antenna system, the potential performance benefit of the vehicular-DAS over the conventional antenna system can be verified.

### 7.2.2.1 Assumptions and related parameters

The following assumptions and parameters are considered in the measurement:

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

| | | | |
|---|---|---|---|
| Type of the vehicle | A sedan, parked in open area | | |
| Design option | Design option #2 (RF + ADC/DAC - PHY split described ) | | |
| Design of vehicular-CU and | Vehicular-DU | Number of vehicular- | 4 vehicular-DUs |

<table>
<tr><td rowspan="3">vehicular-DU</td><td rowspan="2"></td><td>DUs in the vehicle</td><td>

<br>- Location of each vehicular-DU<br>• Vehicular-DU1 and vehicular-DU4: front/rear bumper<br>• Vehicular-DU2 and vehicular-DU3: right/left B-pillar<br>Each DU is deployed in the middle of each vehicle’s side<br>  </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-CU 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 20m)<br>- High-speed serial bus<br>- Protocol:<br>• Physical layer: IEEE 802.3 standard 10GBase-T(UTP)<br>• 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, 2 vehicular-DUs with the largest sum of SNRs are selected. Also, signals received using the 2 selected vehicular-DUs are combined at the receiver.</td></tr>
</table>

- Features of the Rx vehicle with co-located antenna system (for comparison, ‘Vehicle #2’)

<table>
<tr><td>Type of the vehicle</td><td colspan="2">A sedan, parked in open area</td></tr>
<tr><td>Antenna configuration</td><td>Number of vehicular-DUs</td><td>4 vehicular-DU on the rooftop (similar to the conventional shark-fin antennas)</td></tr>
</table>

| | | |
|---|---|---|
| | | <br> |
| | 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 20m)<br>- High-speed serial bus<br>- Protocol:<br>• Physical layer: IEEE 802.3 standard 10GBase-T(UTP)<br>• MAC and higher layer: LG Electronics' own solution | |
| Rx scheme | When a vehicle receives signals using multiple antennas, out of 4 vehicular-DUs, 2 vehicular-DUs with the largest sum of SNRs are selected. Also, signals received using the 2 selected vehicular-DUs are combined at the receiver. | |

- Comparison between 'Vehicle #1' and 'Vehicle #2'

| | **Vehicle #1**<br>**(Non-co-located)** | **Vehicle #2**<br>**(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 (2m~5m) | Closely placed (about 5cm) | 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, 10m | Digital/UTP,10m | Same |

- Features of the Tx vehicle

| | |
|---|---|
| Type of the vehicle | A sedan moving around/near the Rx vehicle |

| | | |
|---|---|---|
| Antenna configuration | - Co-located antenna system with a single omni-directional antenna<br>- The antenna is located in the middle of the vehicle rooftop<br>   | |
| | Antenna gain | 5dBi |
| Tx power | 10dBm (constant) | |

- Radio configuration

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

### 7.2.2.2 Results and analysis

#### 7.2.2.2.1 Scenario 1

In scenario 1, in order to measure the reference reception performance of Vehicle #1, the Tx vehicle drives a full circle keeping a consistent distance between Tx and Rx vehicles. In order to examine the 360 degree coverage, SNR is measured at Rx vehicle, Vehicle #1.

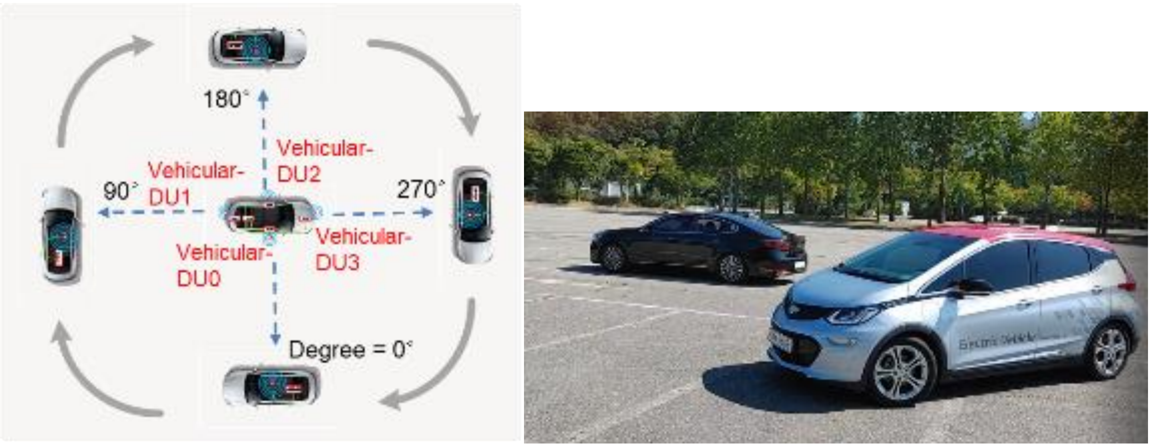
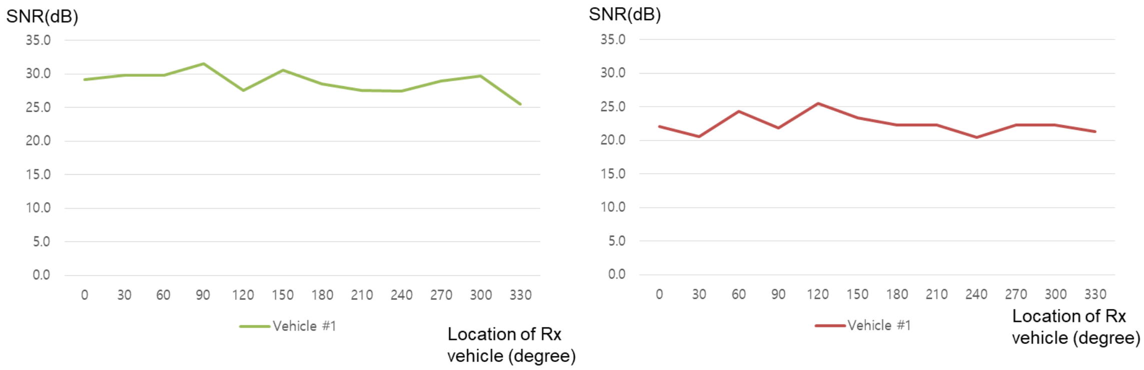



**Figure 7.2.2.2.1-1: Scenario 1**

As can be seen in **Figure 7.2.2.2.1-2-(a),** reliable SNR is achieved for Vehicle #1 (non-co-located antennas) in 360 degrees in horizontal domain, when the distance between Tx and Rx vehicle is 8m. Also, in this case, the block error rate (BLER) is close to 0% with MCS 17 (64QAM). Additionally, even when the distance between two vehicles increases from 8m to 15m, it is observed that quite consistent SNR performance can be obtained in Vehicle #1 as illustrated in **Figure 7.2.2.2.1-2-(b).**




**(a) distance between Tx and Rx vehicle = 8 meter** **(b) distance between Tx and Rx vehicle = 15 meter**

**Figure 7.2.2.2.1-2: SNR measured at Vehicle #1**

In **Figure 7.2.2.2.1-3**, we compare the RSRP of two types of Rx vehicle, Vehicle #1 and #2. The first vehicle has higher RSRP performance than Vehicle #2 with antennas on the rooftop (conventional shark-fin configuration). In this measurement, we used a sedan with a flat rooftop. However, if we consider vehicles with a curved rooftop or one covered with glass (e.g. sunroof), it is expected that the reception performance gap between the two vehicles would increase, because Vehicle #2's performance would suffer from a self-blockage effect. Also, we observed that each vehicular-DU exhibits different RSRP performance depending on the location of the Tx vehicle. This implies that each vehicular-DU may meet only part of the required angular coverage in transmissions and receptions.

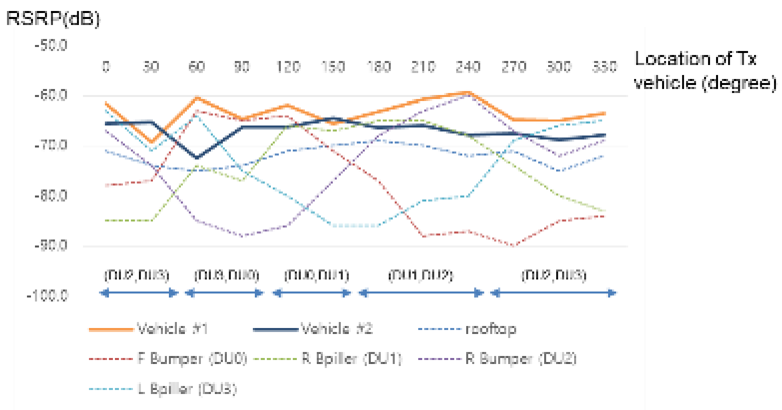



**Figure 7.2.2.2.1-3: RSRP measured at Vehicle #1 and each vehicular-DU**

### 7.2.2.2.2 Scenario 2

In this scenario, as depicted in **Figure 7.2.2.2.2-1**, the Tx vehicle approaches the Rx vehicle in a different lane, and there is a significant obstacle between the Tx and Rx vehicles. In other words, line-of-sight (LoS) path is typically guaranteed between Tx and Rx vehicles, but the obstacle blocks the LoS. In this scenario, we compare the reception performance of Vehicle #1 and #2, in terms of the BLER.


**Figure 7.2.2.2.2-1: Scenario 2**

As can be seen in **Figure 7.2.2.2.2-2**, Vehicle #1 shows more reliable BLER performance by exploiting the vehicular-DUs deployed on the bumper or at the bumper level. Due to the difference in antenna position of the two vehicles, the LoS path disappears or obscured when the Tx vehicle is at different locations. For instance, as presented in **Figure 7.2.2.2.2-3**, the LoS path disappears for Vehicle #2 at a distance of 7m, while the LoS path is guaranteed for Vehicle #1 until the distance between the two vehicles is as close as 2m. This aspect impacts the BLER performance gap between the two test vehicles.

In addition, BLER increases at a distance of between 3m and 6m for both Vehicle #1 and #2 because the vehicles are moving and due to the road condition (the reflectiveness of ground surfaces). As the photo illustrates, it seems that the ground-reflected pathway is obscured even at close range because of the bus wheel (the blocker), which means the signal cannot reach the Rx vehicle and performance is degraded accordingly.

When the LoS path is not guaranteed, 100% of BLER performance is observed in Vehicle #2, while much more reliable performance is reported for Vehicle #1 thanks to the ground-reflected signal using vehicular-DUs located at the bumper-level.

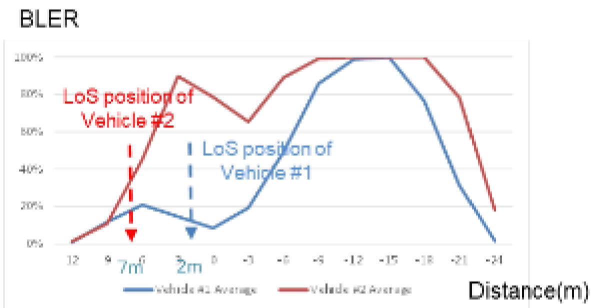



**Figure 7.2.2.2.2-2: Comparison of BLER performance between Vehicle #1 and #2 (1 layer transmission with MCS 11)**

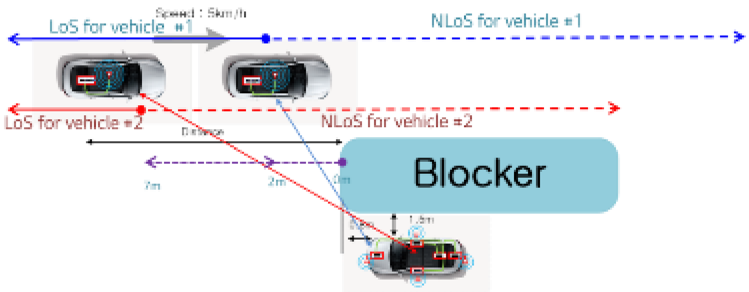



**Figure 7.2.2.2.2-3: Blockage caused by other vehicle in scenario 2**

In **Figure 7.2.2.2.2-4**, assuming a single layer transmission with MCS 0, we compare the performance of Vehicle #1 and #2 in terms of BLER and SNR. Similar to the results shown in **Figure 7.2.2.2.2-2**, Vehicle #1 outperforms Vehicle #2 even in this case with different MCS level, MCS 0, and Vehicle #1 shows BLER performance close to 0%.

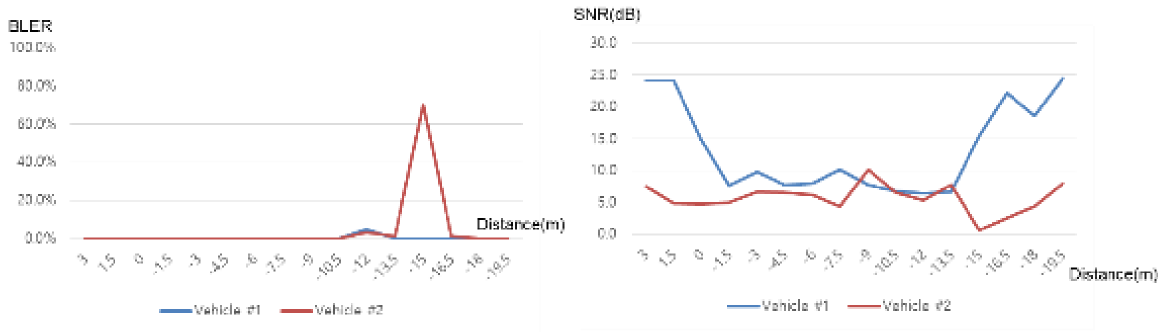



**Figure 7.2.2.2.2-4: Comparison of BLER/SNR performance between Vehicle #1 and #2 (1 layer transmission with MCS 0)**

### 7.2.2.2.3 Scenario 3

In scenario 3, as illustrated in **Figure 7.2.2.2.3-1**, the performance of Vehicle #1 and #2 is measured considering the vehicular communication at an intersection. The Tx vehicle comes from the right-hand side of the Rx vehicle and there is a bus acting as a 'blocker' between the two vehicles. Thus, in this scenario, there is no LoS path between Tx and Rx vehicles until the two vehicles get very closer to each other.

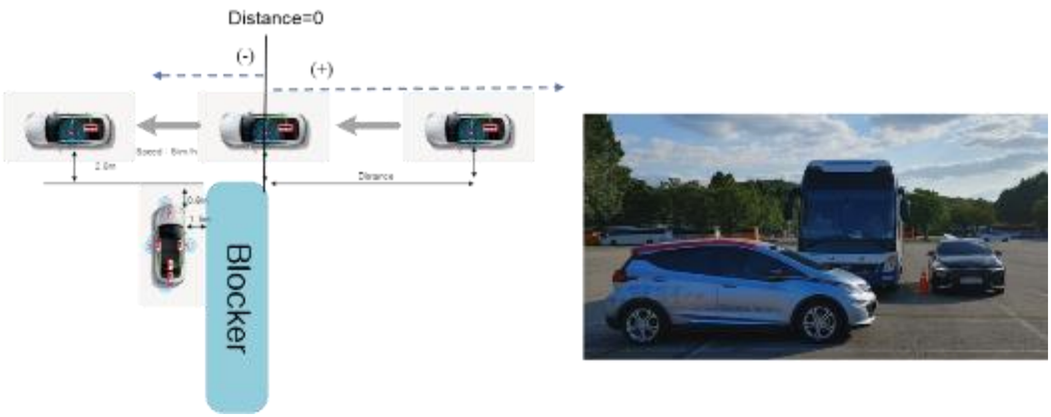



**Figure 7.2.2.2.3-1: Scenario 3**

Similar to the result of the previous scenario, it is found that the Vehicle #1 performs better than Vehicle #2. The different antenna locations applied to the two vehicles affects the NLoS for Vehicle #2 more than Vehicle #1, which severely degrades its relative performance.

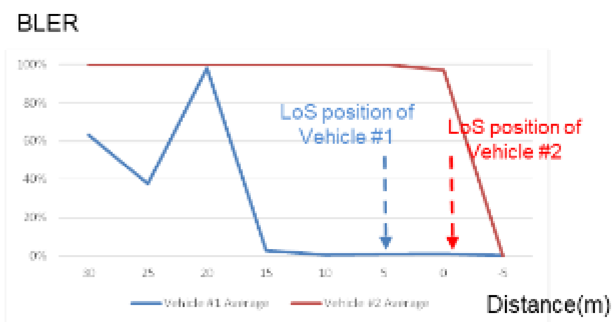
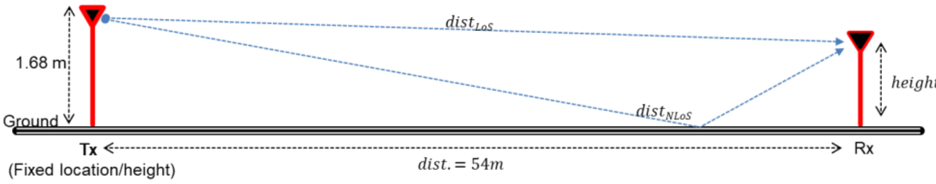



**Figure 7.2.2.2.3-2: Measurement result for scenario 3**

### 7.2.2.2.4 Scenario 4

In this scenario, we observe the reception performance of vehicles with Rx antennas at different heights. A single omni-directional antenna is used for both Tx and Rx antennas, and SNR is measured at the Rx antenna.




As shown in **Figure 7.2.2.2.4-1**, SNR performance fluctuates a lot depending on the height of the Rx antenna, as illustrated by the variation in the crests and troughs in the SNR curve. Here, the fluctuation of the SNR is due to the carrier frequency offset in 5.9GHz frequency band, where the carrier phase offset is caused by the difference in distance that LoS and NLoS waves travel from the Tx antenna to Rx antenna (e.g., $\varphi = 2\pi(dist_{NLoS} - dist_{LoS})/\lambda$, λ denotes the wavelength). We can observe a similar trend for carrier frequency offset in 5.9GHz band, as depicted in **Figure 7.2.2.2.4-2**, where the highest and lowest points of these two curves are very similar. Also, it is observed that the performance is degraded when destructive interference (or destructive sum) of LoS and NLoS waves occurs.

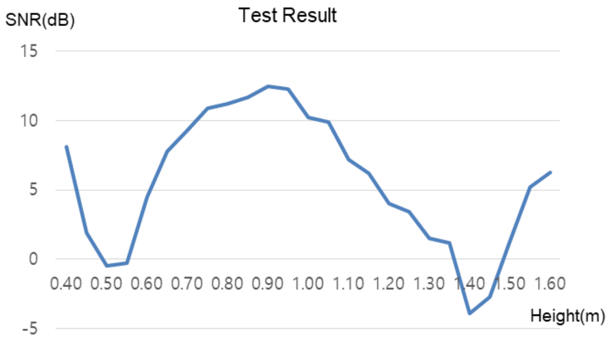



**Figure 7.2.2.2.4-1: Measurement result for scenario 4 (with fixed distance between Tx and Rx antennas)**

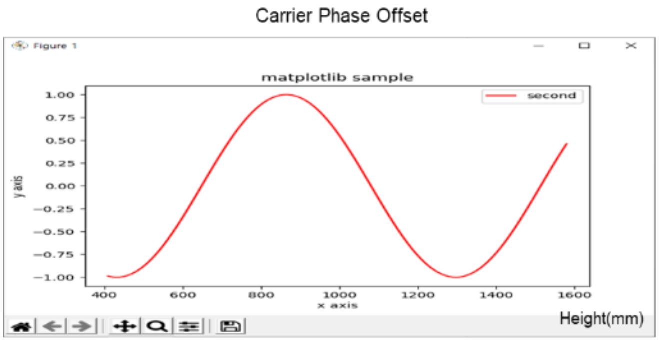



**Figure 7.2.2.2.4-2: Carrier phase offset (plotted by computer simulation, in 5.9GHz)**

We repeat the test with different Rx antenna heights and distances between Tx and Rx antennas. As can be seen in **Figure 7.2.2.2.4-3**, similar trends are observed in this test. Due to the carrier phase offset in 5.9GHz frequency band, the communication performance is degraded when LoS and NLoS waves are out-of-phase. 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 changing characteristics of waves in the carrier phase offset. And this is because the path difference between LoS and NLoS decreases and changes more slowly and mildly. The performance degradation due to the path difference and phase offset may not be able to be overcome by baseband signal processing enhancement, because the signal strength reaching the antenna/RF is already weaker when LoS and NLoS waves are out-of-phase. But this issue can be resolved or alleviated by distributing antenna in different locations and/or heights on the vehicle. So it is clear that vehicular-DAS can be a potential solution to overcome the performance degradation caused by carrier phase offset.

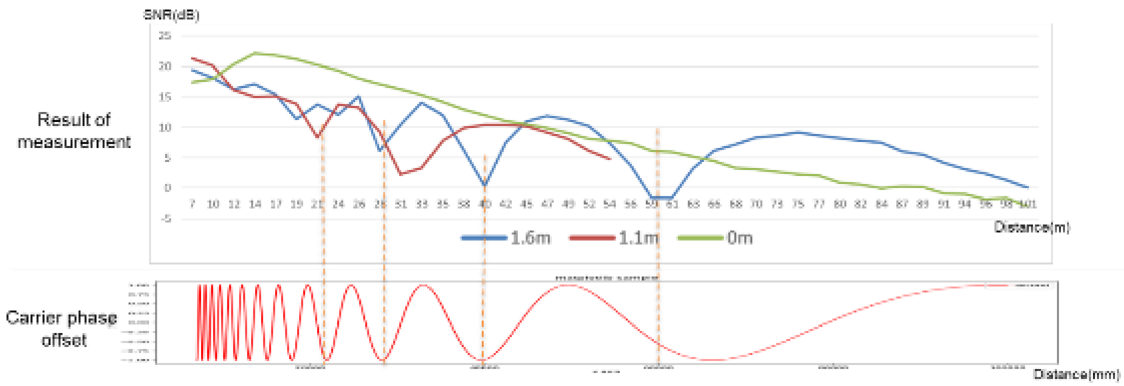



**Figure 7.2.2.2.4-3: Measurement result for scenario 4**

In Section 7.2.2.2, we compare the performance of two vehicles with different antenna location/height/spacing, Vehicle #1 and #2, and it is observed that Vehicle #1 has improved reception performance in terms of BLER, SNR and reception coverage. In the tests, sedans with a flat rooftop are used. On the other hand, when we consider vehicles with a curved rooftop or sunroof, the performance gap between two vehicles is more prominent (Vehicle #2's performance is lower due to self-blockage effects). It should be noted that digital interfacing is used for both Rx vehicles for this measurement. Analogue interfacing is only used to connect the vehicular-CU and vehicular-DU, but this lowers performance due to the effects of cabling loss.

# 8. Analysis on implementation feasibility of DAS

## 8.1 Comparison of design options in implementation feasibility perspective

We can agree on certain design rules common for each design option (DO) and different between them. With increased functionalities of each vehicular-DU more electronic elements need to be added.

**Table 8.1-1: Building blocks per design option (orientative)**

| | **DO 01** | **DO2** | **DO3** | **DO4** |
|---|---|---|---|---|
| RFIC | 1 or 2[1] | 1xRU | 1xRU | 1xRU |
| Additional processing units | 0 | 0 | 1xRU[2] | 0 |
| Baseband and higher layer proc. | 1 | 1 | 1[3] | 1xRU |

Also, the power needed to be supplied and its distribution (and inherent losses) will increase along with the complexity and redundancy of elements of each design: D00 < D01 < D02 < D03 < D04

The power needed for the system to correctly operate has escalated in importance and will continue doing so, while the automotive industry is shifting from internal combustion engines to electrified powertrains. Since the electric energy stored in the vehicle is used to power all the systems and the powertrain itself, the 'energetic cost' of each system will be examined in detail.

[1] Dependent on how many antennas can be supported per RFIC.

[2] The more capabilities that need to be integrated into the vehicular-DU the more processing is needed at each of these units.

[3] The more capabilities that need to be integrated into the vehicular-DU the less processing is needed at the vehicular-CU.

Mileage can be improved by switching off certain systems (e.g. air conditioning systems notoriously consume a lot of electricity). Vehicular-DAS is designed not only for infotainment antennas but also for safety-related communications, so parts of the system will always be powered on. Therefore, average consumption will have a direct impact on the possible maximum mileage of the vehicle.

The operating range of temperature for devices in the automotive industry is usually between -40°C and 85°C. It has to be noted that a higher temperature during operation may require thermal management. Both passive and active thermal management will take space and affect the size and design of systems, while active cooling will also consume extra energy.

For the transmission of analogue signals from antennas to the processing unit (vehicular-CU), coaxial cables have been the standard in the automotive industry for several decades. As the vehicular-DAS is expected to transition from analogue signals to digital solutions, the physical electrical distribution system will have to adapt.

Once the information has been sampled, a digital interface can be used. The two most used digital physical interfaces are the twisted pair (shielded and unshielded) and optical fibre.

**Table 8.1-2: Comparison between different types of interfaces**

| | Coaxial Cable | UTP | Optical Fiber |
|---|---|---|---|
| Applicable design options | Option 0, 1 | Option 2, 3, 4 | Option 2, 3, 4 |
| Cost | 🟡 | 🟢 | 🟡 |
| Weight | 🟡 | 🟡 | 🟢 |
| Handling (bending, termination, etc) | 🟢 | 🟢 | 🟡 |
| Bandwidth and latency | 🟢 | 🟡 | 🟢 |
| Signal degradation and electromagnetic interference | 🟡 | 🟡 | 🟢 |
| Life cycle | 🟢 | 🟡 | 🟢 |
| Power consumption in interface | 🟢 | 🟡 | 🟢 |
| Etc. | Additional control interface can be needed. | PoE can be supported. | |

## 8.2 Interface data rate evaluation

In this section, the evaluation of the needed data bandwidth of the potential vehicular-CU and vehicular-DU interface is performed to:

- Identify the corresponding requirement for the digital interface
- Verify the availability of an existing technology
- Identify technology gaps of vehicular-DAS enabling technologies

Due to a variety of product types and unknowns in the roadmaps and technology development, only a coarse estimation of some aspects can be performed in this work item. This limits the evaluation, on the one hand, but it presents a good enough and general understanding of the limitation and benefits of vehicular-DAS, on the other hand.

As stated in previous chapters, 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, also have to be included for a fuller evaluation of vehicular-DAS.

**Figure 8.2-1** illustrates the main factors of the data rate calculation relationship in this evaluation. The basic assumption applied is that there is concurrent operation of C-V2X direct communications mode and C-V2X mobile network communication, as well as a complementary use of LTE-V2X and 5G direct communication mode operation, but also a concurrent LTE-V2X and 5G mobile network communication mode operation (including non-vehicular services, such as multimedia broadband services for passengers' services).

Based on this assumption, the following aspects and parameters determine the evaluation results (Reference 3GPP, RAN4):

- Number of antennas
- Number of aggregated bands (carrier aggregation level) across all the RATs (including solutions e.g. DC-EN)
- Use of frequency range 2 (FR2) in addition to FR1

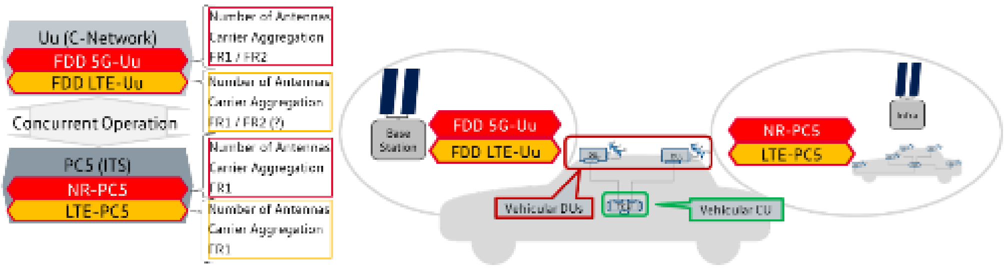



**Figure 8.2-1: Concurrent operation of 5G and LTE as well as V2N (Uu) and V2V (SL) communication**

## Number of antennas

**Table 8.2-1** presents the number of antennas for Uu and SL which can be expected in current and future network deployments (3GPP), and are thus relevant.

**Table 8.2-1: Number of Tx and Rx Antennas for V2N (Uu) and V2V (SL)**

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

**Number of aggregated bands**

Based on the public deployment plans and spectrum allocations, aggregated bandwidths are expected to grow far beyond 100MHz over the next decade. **Figure 8.2-2** illustrates the current spectrum holding situation in Germany.

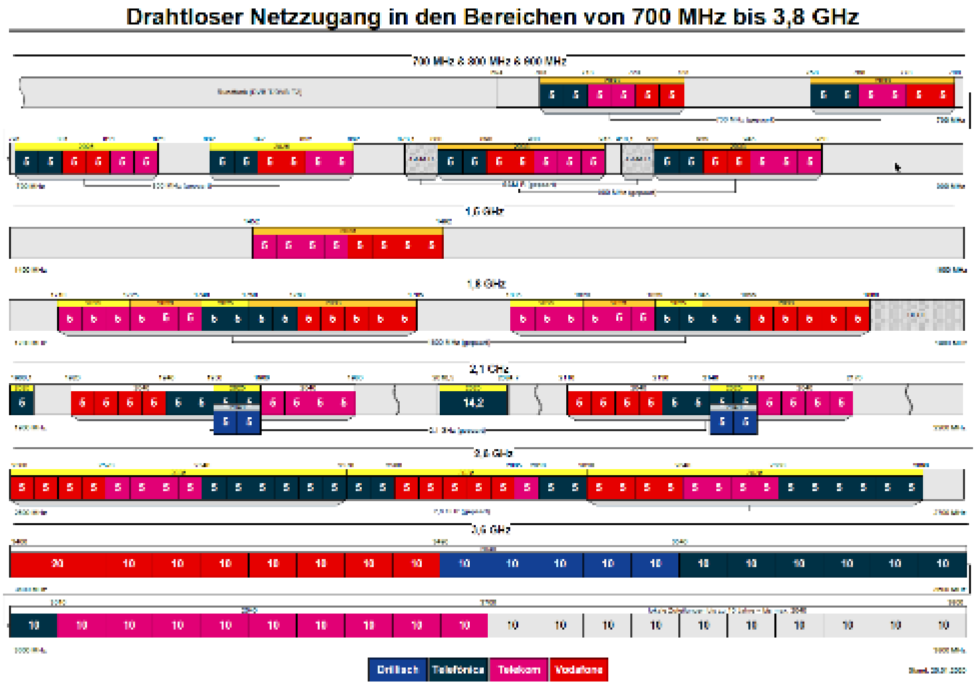



Figure 8.2-2: Frequency allocation in Germany [18]

**Table 8.2-2** and **Table 8.2-3** present the resulting allocation for the largest MNOs in Germany as of September 2021 (some of the spectrum allocations shown on **Figure 8.2-2** will only become effective in the future).

The TDD case clearly shows a minimum aggregated spectrum of 50MHz. However, regarding to MNOs CA and dual-connectivity plans, the total aggregated bandwidth shows signs of growing beyond 120MHz in the near future. What's more, the total aggregation of bands is expected to reach 200MHz over the next ten years.

**Table 8.2-2: FDD Spectrum holdings in Germany [MHz] – status 09.2021**

| | Band 20 (700MHz) | Band 28 (800MHz) | Band 8 (900MHz) | Band 32 SDL only (1500MHz) | Band 3 (1800MHz) | Band 1 (2100MHz) | Band 7 (2600MHz) | Max | SUM |
|---|---|---|---|---|---|---|---|---|---|
| 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 8.2-3: TDD Spectrum holdings in Germany [MHz] – status 09.2021**

| | Band 34 (1900MHz) | Band 38 (2600MHz) | Band 78 (3500MHz) | Max | SUM |
|---|---|---|---|---|---|
| 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 |

The increasing number of antennas poses a challenge for implementing vehicular communication system in the FR1 spectrum. This will be exacerbated as further enhancements are introduced and with new network deployments.

**FR2 spectrum**

FR2 offers a huge improvement in data rate (beyond 10Gbps w/o CA). As several MNOs have started to deploy FR2 networks to enlarge their service, FR2 is definitely a promising additional solution for a variety of high data-rate services. Due to the high frequency, it is obvious that this type of network mostly targets low mobility or quasi-stationary use cases/scenarios. At first glance, this makes the usage of FR2 networks for vehicular services impossible. However, some of the vehicular use cases (e.g. parking position, slow movements 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 frequency for the MNOs.

In an internal 5GAA survey on FR2 deployments, some MNOs confirmed their intention to deploy at least 400MHz in FR2 in coming years, or they have already deployed at least 400MHz in FR2. It is also expected that the bandwidth will increase to 0.8GHz or more over the next 2-10 years.

Due to its very high frequency, it is known that the main obstacles to using wireless communication technologies via FR2 are high attenuation and the low penetration of the transmitted signals, which demand two contradicting implementation strategies:

- Reduced distance between antenna and AD converters to overcome length-dependent attenuation (only for analogue interface).
- Distribution of antennas over several positions to ensure full coverage; 360 degree reception and transmission.

With the expected enhancements in radio technologies and MNO network deployment scenarios, both of these strategies limit the application of conventional implementation options, such as DO1. Fortunately, these strategies can work with digital interface-based design options, such as DO3.

**V2V (SL) spectrum**

The spectrum currently available in the EU is C-V2X ITS (up to 70MHz). Recently discussed in 5GAA, C-V2X direct communication might use 40MHz for 5G direct communication (advanced ITS services) and 20MHz for LTE-V2X direct communication (basic safety services).

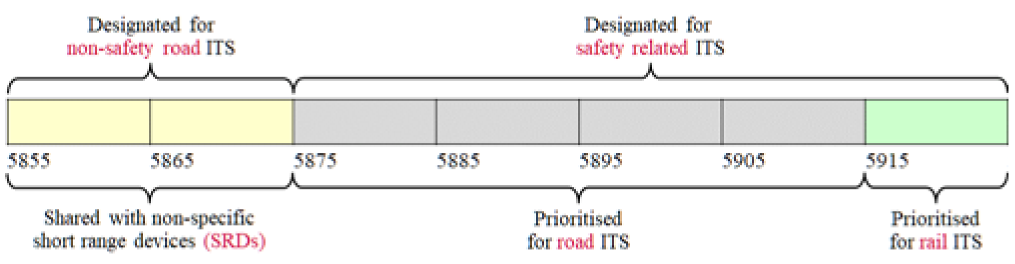



**Figure 8.2-3: Spectrum designations at 5.9GHz in Europe**

As high-level quality 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, a potential direct communication related implementation in the licensed spectrum should be taken into account on top of the current spectrum plans. Note: operating in the licensed spectrum is not factored into this evaluation because there is no detailed information available on MNO deployments related to this.

**Unlicensed network access (Wifi and LAA deployment)**

Other interesting use cases in this regard include in-vehicle hot spots, data off-loading, hot spots in special areas etc. This type of access/connection enables communication services in areas that are often very crowded (parking places, traffic jams) or not reliably covered by the MNO network. This requires enhanced implementation to support broadband communication in non-licensed bands. Depending on the use case, situation and implementation strategies, advances and new applications in radio technology will further increase the implementation requirements in the field of antenna design and interface design.

**Implementation**

Beyond the communication system and service-level parameters, implementation aspects have an impact on the evaluation and decision metrics, including complexity, power consumption, scalability and flexibility.

**Flexibility**

There are many different sizes and types of vehicles which demand, to some extent, some type-specific implementations. Examples are different types of antennas, special components (e.g. connectors at the vehicle door for mirror antennas) and different operating distances (up to 10m or more) between the vehicular-CU and vehicular-DUs. The latter is a particularly challenging parameter, especially for high frequencies and in FR2 communication. In contrast to RF signal transfer via cable (DO0 and DO1), digital data transfer offers much greater flexibility and suffers less from attenuation problems typically affecting high-frequency signals.

**Complexity**

One of the determining aspects for this evaluation is the choice of the vehicular-CU/vehicular-DU interface solution. Besides the cable type, the required data rate to be supported has to be known. Ideally, as the interface technology has to be the same or very similar for all implementations, the vehicular-DU with the most challenging conditions (e.g. highest number of antennas and bands, C-V2X Uu and PC5, dual connectivity) sets the requirement for the interface by default. **Figure 8.2-4** presents the implementation and communication model with all relevant Tx/Rx antenna combinations for the C-V2X Uu (mobile network communication) and the PC5 (direct communication).

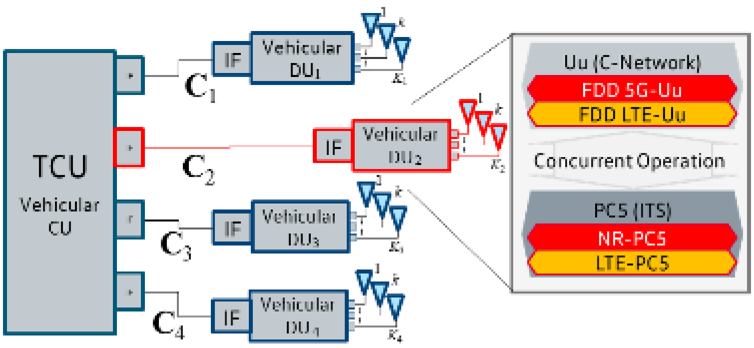



**Figure 8.2-4: Focus on the most challenging DU**

Based on the above observations, the following evaluation of the interface will help to identify the required data rate to be supported by this technology. Due to the unknowns and diversity of the specific implementations, the focus of the evaluation is on estimating the maximum peak raw data rate. Depending on the antenna combinations (as shown in **Figure 8.2-5**), the relationship between the expected raw data rate and an assumed total aggregated bandwidth is calculated in the following.

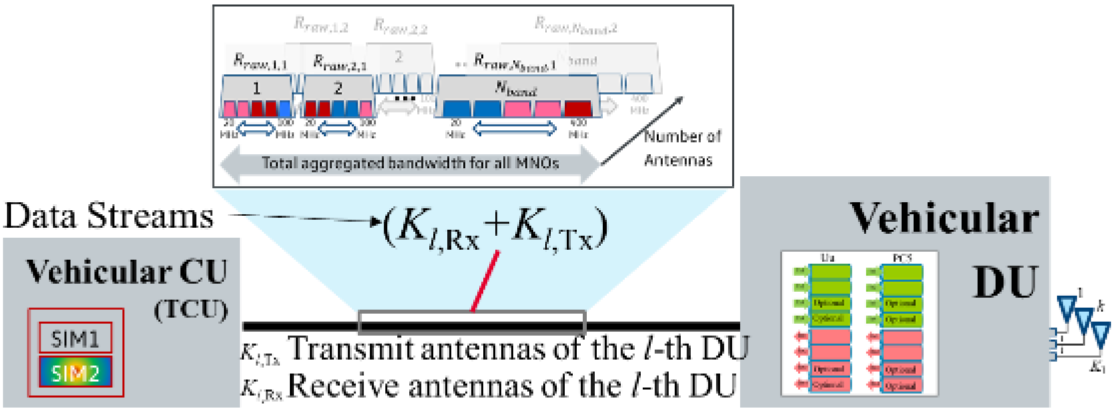



**Figure 8.2-5: Model assumption for the peak data rate estimation**

**Data rate calculation**

As introduced in Section 6.2.1.1.2, the raw (sample) data rate per antenna stream and band, assuming option 3A (Low PHY - High PHY split) is

$$R_{raw,i,n} = N_{RB,i,n} * N_{SCPRB,i,n} * L * N_{S,i,n} * N_{bit} \quad (5).$$

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 ($N_{bit}$).
As a coarse estimation of the rate, this relation can be further simplified. Focusing on a resolution of 14bits for 256QAM, it is proposed to introduce a rate density per 10MHz

$$R_{raw,average-10MHz} = \frac{1}{N_{carriers}} \sum R_{raw,i,n} \quad (6),$$

**Figure 8.2-6** illustrates the results of Eq. (6) for several SCS and BWs (values in the figure).

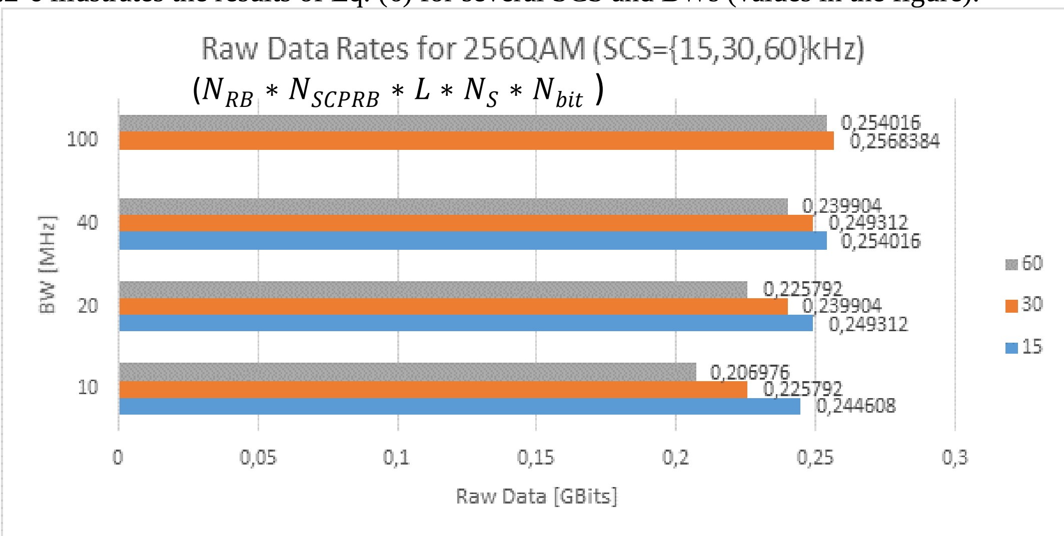



**Figure 8.2-6: Average raw data rate for 256QAM (with 14bits per I/Q sample) for the cases shown in Section 6.2.1.1.2.1**

**Table 8.2-4** illustrates the resulting $R_{raw256QAM,\ average\text{-}10MHz}(N_{RB,i})$ of approximately 0.24Gbits including the minimum and maximum deviation.

**Table 8.2-4: Minimum, average and maximum raw data rate based on calculations shown in Figure 8.2-6**

| Values | **Gbit/s** | **Deviation from Average in %** |
|---|---|---|
| **Min** | 0,206976 | <-14% |
| **Average** | **0,240588** | **0** |

| | | |
|---|---|---|
| **Max** | 0,256838 | < +7% |

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 has to support the sum of DL and UL rates.

Using the expected deployments of future MNO networks, the following evaluation conclusion can be found:

- Minimum required rate for the digital interface (design option 3A):
    - For 2 Rx antenna vehicular-DU implementation in 2-5 years, the rate will increase to 5Gbps and most probably reach 10Gbps at the end of the decade.
    - For 3 Rx and higher antenna vehicular-DU implementations, a rate of above 10Gbps will be reached in the next few years. Fortunately, the rates will most probably not exceed 25Gbps at the end of the next decade.

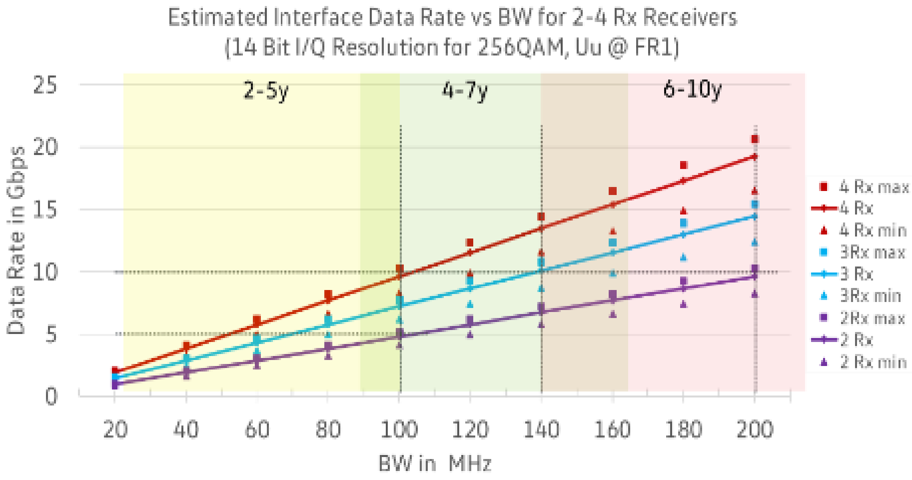



**Figure 8.2-7: Data rate relation vs. number of Rx antennas and total aggregated bandwidth**

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

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

With this assumption the interface has to support a much higher bandwidth. **Figure 8.2-8** illustrates the estimated data rate vs. total aggregated bandwidth. For instance, including direct communication and LAA, and with a bandwidth of 120MHz, the data rate of the total aggregated bandwidth over all radio technologies will increase by 10 to 15Gbps, depending on the number of antennas.

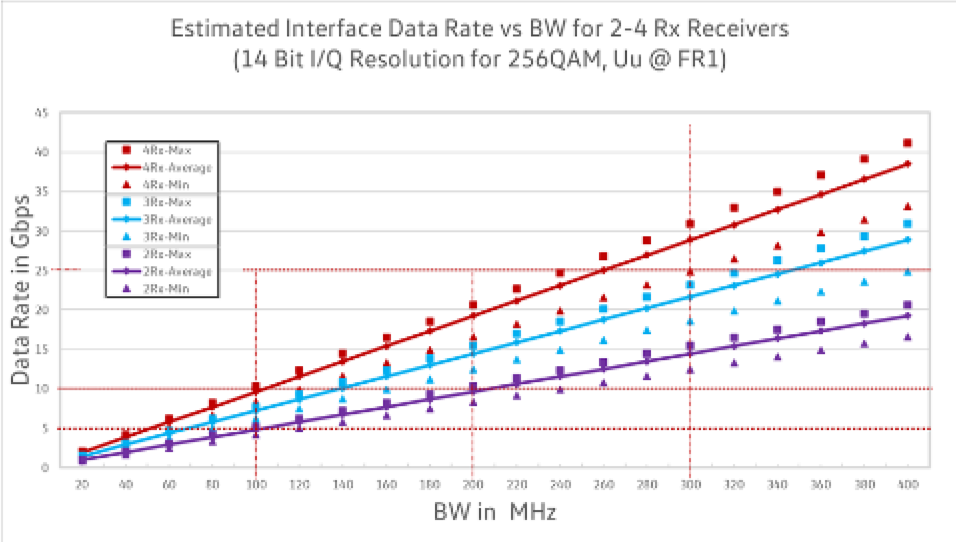



**Figure 8.2-8: Data rate relation vs. number of Rx antennas and total aggregated bandwidth over all communication technologies (assumption: 0.24Gbits per 10MHz)**

**Summary**

Several factors which can impact on the data rate requirement were presented and discussed. As future deployments, technology developments and customer needs cannot be precisely foreseen, the interplay between the number of antennas and bandwidth was used to estimate the data rate requirement for a potential design option 3 implementation. Based on current and expected network deployments, data rates close to 5Gbps are expected in a short term and beyond 15 or even 20Gbps over the longer term (up to10 years), depending on the implementation scenario (number of antennas per vehicular-DU unit and bandwidth). If a non-licensed wireless connectivity solution is also considered, total requirements could increase by up to factor 2. If FR2 is added, the rate requirements will further increased by a factor of [x] times the 10Gbps.

This situation demands new solutions both in terms of interface technology and automotive implementations. For instance, Automotive Ethernet 802.3bp with 1Gbps does not meet the needs of DAS design option 3. Even the augmented Automotive Ethernet 802.3ch 10GBASE-T1, which supports 10Gbps, would offer only a limited solution. To fully support the requirements spelt out in this WI, 40Gbps ethernet would be needed for a wireless communication solution covering all types of V2X-based use cases introduced in this technical report.

As of 21 May 2020 [19], the IEEE 802.3 ethernet working group started a task force regarding the support of bandwidths above 10Gbps [20] with a set of approved objectives, for example:

- The support of data rates of 25Gbps at the MAC/PLS interface
- Point-to-point operation over the automotive link segment and electrical PHY supporting [21] two inline connectors for at least 11m on at least one type of automotive cabling
- Exclusive duplex operation
- Optional support of energy efficient ethernet optimised for automotive applications
- Considerations for operation in automotive environments (e.g. EMC, temperature, etc.)

According to the timeline published on 26 January 2021 [22], 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 does not purport to be complete and should be seen as a toolset to understand the basic relations between some of the most impactful factors including the data-rate requirements. It is noted that the data-rate requirements differ depending on the vehicle type or OEM segment. It is also necessary to understand that the DU is not always expected to have the maximum number of antennas, the highest bandwidth, or to all use radio technologies. Each OEM is free to use the described relations and scenarios to develop its own requirements. The evaluation shows that changes in the implementation strategy of wireless communication systems and technology development is required across the board.

# 9. Analysis on potential specification impact and necessary changes

## 9.1 Modem aspect

In this section, the potential impacts of this ongoing work on 3GPP specifications is analysed in terms of V2X communication, positioning, and performance requirements. It is noted that the analysis in this section may not be exhaustive.

### 9.1.1 V2X communication aspect

Deploying a vehicular-DAS system itself 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 described in Section 7.1.2.2 Results and analysis. On top of this diversity gain, smart selection/management of the transmit antenna panels has potential to improve the communication performance when a UE is equipped with vehicular-DAS.

For sidelink operation, the current 3GPP standard does not support directive transmissions and thus sidelink signals/channels should be relayed over all equipped panels in the vehicular-DAS UE. This may lead to inefficiencies as a signal transmitted in a panel may suffer significant loss in some directions, which is described in Section 7.2.2.2.1 Scenario 1. By enabling the transmitter to 'acquire' the channel status, find the target receiver, and select the direction of the transmission in the vehicular-DAS UE (e.g. by sending the sidelink signal/channel only from the panel, achieving the best performance for the target receiver), the V2X operation can be improved. This can improve the signal quality by boosting the power received in the target UE. Also, this can avoid unnecessary interference emitted in the 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.

### 9.1.2 Positioning aspect

The reference from 3GPP for positioning is associated with the location of the individual antenna (RF antenna connector or RF antenna position see [23]). Therefore, the conventional positioning mechanism cannot be directly applied to localising tasks in the UE that involve multiple antenna panels in different locations (e.g. 3~4m inter-panel/antenna distance). If the conventional positioning technique is to be reused for this case, we could consider using a single panel at a time for vehicular-DAS UE (e.g. implementation). We could consider each antenna separately to estimate the position at different locations on or around 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, we can consider extending the positioning mechanism in the current 3GPP standards to cover positioning of vehicular-DAS UEs with multiple panels, and to indicate that they are at different locations. The entity calculating the UE location based on a per-panel (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 [24], this change would be expected to improve positioning performance, including accuracy, reliability and availability, by properly processing the measurements from the distributed antennas.

### 9.1.3 Performance requirement aspect

There could be potential impacts to the RAN4 specification to facilitate vehicular-DAS UEs. Examples include the definition of UE capabilities and performance requirements in support of features related to vehicular-DAS.

## 9.2 Interface and protocol aspect

In this WI, we mainly discuss the impact on the IEEE 802.3 Automotive Ethernet specification. According to the published timeline as of 26 January 2021 [22], the standard should become available 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 the delay and synchronisation requirements point of view, further analysis on the impact to the current specification is necessary. 5GAA recommends that developments in this field be further monitored to ensure that the objectives can be achieved (e.g. data rate, power consumption, temperature, implementation aspects, etc.).

# 10. Conclusion

This document presents a strong case for vehicular-DAS, potential design options (e.g. vehicular-CU/DU functional split options), and requirements for interfaces/protocols in the vehicular-DAS space. The document also contains results of an evaluation of vehicular-DAS aspects both in terms of communication performance and implementation feasibility.

As advanced V2X use cases requiring high reliability and/or high data rate are introduced, technologies such as multi-antenna solutions (e.g. massive MIMO), broadband (e.g. carrier aggregation), and FR2 solutions will be essential for V2X communications, and thus the number of required antennas mounted on vehicles will keep growing. However, the positions and mounting spaces currently allowed for antennas, the communication module and the required cabling are limited by automotive-specific design constraints including the shape/form of different vehicle types, automotive certification aspects, and other specifications. Therefore, the growing number of antennas in vehicular UEs poses extreme challenges for vehicle manufacturers needing to implement them. All these challenges have to be solved to enable the full range of automotive use cases, and it is commonly accepted within the industry that these constraints/challenges point to the need for a vehicular-DAS approach.

In this document, 11 possible function split options for vehicular-CU/DU implementation and their pros/cons are described. In the early stage of vehicular-DAS implementation, it is expected that option 0 or 1 would be taken up as coaxial cables have been standardised and widely used in the automotive industry for several decades. However, it is clear that cabling loss at the interface can lower the vehicular-DAS UE's performance. Introducing a digital interface for vehicular-DAS can resolve this issue, so we expect to see a migration of analogue to digital interfacing in the implementation phases. And when digital interfacing is more widely adopted for vehicular-DAS (especially for V2X communication only in FR1), option 2 and/or option 3A can be implemented because they offer MIMO gains/efficiencies (e.g. combining gain) by using vehicular-DUs located in different locations on the vehicle with negligible cabling loss. We also analyse and outline protocols for interface requirements, bandwidth, latency and synchronisation.

Based on the analysis and computer simulations, we also verify the feasibility of vehicular-DAS with some selected split options. It is shown that vehicular-DAS can improve performance (e.g. reliability, 360 degree Tx/Rx coverage, target PRR performance, etc.) compared to the conventional co-located antenna system. In addition, vehicular-DAS addresses communication issues, such as when LoS and NLoS waves are out-of-phase or offset in carrier phase, because the antennas are at different locations and/or heights on the vehicle.

Lastly, we analyse how feasible it is to implement vehicular-DAS using the metrics identified in this WI, including implementation complexity, flexibility, and scalability. The work also provides insights into the potential impacts on technical specifications in this domain.

# Annex <A>: Change history

| Date | Meeting | TDoc | Subject/Comment |
|---|---|---|---|
| 2020-02 | 13th F2F, Brussels | A-200053 | Initial draft ToC for discussion |
| 2020-05 | 14th F2F, virtual meeting | A-200102 | Include all contributions approved at 14th VF2F:<br>- A-200084 : TR skeleton update (Addition of section 4 & 5)<br>- A-200095 : captured in section 6.1<br>- A-200097 : captured in section 4<br>- A-200098 : captured in section 5.3<br>- A-200099 : captured in section 5 (5.1, 5.2)<br>Update abbreviations list<br>-FR1 & FR2 |
| 2020-08 | WG2 Call #32 | A-200102_v1 | Include contribution approved at 15th VF2F:<br>- A-200117(v4) : captured in section 6.2 |
| 2021-01 | WG2 Call #35 | A-200102_v2 | Include all contributions approved at 16th VF2F and DAS call #10~#12:<br>- 5GAA_201028_DAS_Text proposal for CU-DU design options_v0 : captured in section 6.1.2.4.1 and 6.1.4<br>- 5GAA_A-200147 : captured in section 7.2.1<br>- 5GAA_A-200102_DAS_Baseline_TR_v3.3_vF2F#14_BMW (submitted to 16th VF2F) : captured in section 5.2<br>- 5GAA_201216_TP_Needs for standardization of DAS interface_v0 : captured in section 6.1.2.3, 6.1.2.4.1, 6.1.2.4.2, 6.1.2.4.3, 6.2.2 |
| 2021-04 | DAS WI Call #16 | A-200102_v2.1 | - Correction for interface bandwidth analysis for option 3A in section 6.2.1.1.2 (“5GAA_Molex_Text Proposal to A-200102_DAS_Baseline_TR_v2_tc-v02”, presented/agreed in DAS call #16)<br>- Addition of equation for interface bandwidth calculation of option 3B in section 6.2.1.1.3 (“TP for section 6.2.1.1.3”, presented/agreed in DAS call #16)<br>- Addition of equation numbers in section 6.2.1.1.1, section 6.2.1.1.2, section 6.2.1.1.2.1, and section 6.2.1.1.3 |
| 2021-05 | WG2 Call #XX | A-200102_v3 | Include all contributions agreed in 18th VF2F and DAS call #15:<br>- TP for section 3.1 and 6.1.1_v1 : captured in section 3.1 and 3.3<br>- 5GAA_210427_WI DAS_Performance comparison between DAS and CAS (simulation)_v0.2 : captured in section 7.2.2<br>- 5GAA_210427_WI DAS_TP for Sync requirement_v0 : captured in section 6.2.1.3<br>- 5GAA_210427_WI DAS_TP for Sync error measurement_v1 : captured in section 7.3.1<br>- 5GAA_210427_WI DAS_TP for demo results_v0 : captured in section 7.3.2<br>- A-210027_290427_WI_DAS_TP_for_Interface_Data_Rate_Evaluation_V06_5GAA_TermsUpdate2: captured in section 8.2<br>- 5GAA_A-200102_DAS_Baseline_TR_v2_tc_BMW_20210216 : captured in section 8.1 (← This contribution is presented in call #14 and agreed in call #15.)<br>Remove section 9 “Analysis on potential specification impact and necessary changes” (in the previous version)<br>Add conclusion in section 9 |
| 2021-07 | 19th F2F, virtual meeting | A-200102_v4 | Include all contributions agreed in 19th VF2F:<br>- 5GAA_210728_WI DAS_TP for section 6.1.4_v1 : section 6.1.4 is updated based on this TP<br>- 5GAA_210728_WI DAS_TP for section 9.1_v2 : captured in section 9<br>- 5GAA_2021-07-28_DAS_WP_Interface_Feasibility_Evaluation_v0.3 : section 8.2 is revised based on this TP<br>All editor’s notes are removed.<br>Minor editorial changes |