Study of spectrum needs for safety related intelligent transportation systems – day 1 and advanced use cases

5GAA Automotive Association
Technical Report

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VERSION:	Version 2.0
DATE OF PUBLICATION:	18 October 2021
DOCUMENT TYPE:	Technical Report
EXTERNAL PUBLICATION:	Yes
DATE OF APPROVAL BY 5GAA BOARD:	29 June 2021

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Scope

This report presents a study by the 5GAA on the spectrum needs of so-called day-1 and advanced use cases for intelligent transport systems (ITS) as implemented by LTE-V2X and NR-V2X cellular V2X (C-V2X) technologies, respectively.

The study estimates the amounts of bandwidth required for the introduction of use cases for direct communications (via the cellular V2X PC5 interface in the 5.9 GHz band harmonised globally for ITS) and for network-based communications (via the cellular-V2X Uu interface in spectrum designated for use by mobile communication networks).

Executive summary

This report is based on a study undertaken by the 5GAA in relation to the spectrum needs of use cases for intelligent transport systems (ITS) and advanced driving as implemented by cellular vehicle-to-everything (C-V2X) technologies.

Starting from a list of over 40 use cases, we first categorise these as "initial/day-1" or "advanced". It is the view of the 5GAA that LTE-V2X and NR-V2X are the most suitable technologies for the support of day-1 ITS and advanced driving use cases, respectively. We subsequently classify these as

- use cases which involve direct communications among road users or between road users and ITS roadside infrastructure (so-called V2V, V2I, V2P) as supported by the C-V2X (PC5) interface in the 5.9 GHz band harmonised globally for ITS, and
- use cases which involve network-based communications between road users and mobile network base stations (so-called V2N) as supported by the C-V2X (Uu) interface in bands designated and licensed for use by mobile communication networks,

where the term "road user" includes vehicles 'V' and pedestrians 'P'. Unless otherwise stated in this report, the term V2X may refer to both V2X and X2V communications.

We further sub-classify the use cases which use direct communications according to whether they employ continual (typically repetitive) messages or event triggered messages, respectively.

For each sub-class of use case, we then estimate the spectrum needs for the relevant V2V, V2P, V2I, or V2N communications by accounting for 1) road geometries, e.g. freeways and intersections, 2) the geographic density and speed of the road users, 3) the size, repetition rate, data rate, or latency of the required messages for the support of the service, and 4) the effective spectral efficiency of the relevant C-V2X radio access technology.

Based on the results of our studies of the spectrum needs of C-V2X direct communications (V2V/I/P), we can draw the following conclusions:

a) We expect that the delivery of day-1 use cases via LTE-V2X for the support of basic safety ITS services will require between 10 and 20 MHz of spectrum at 5.9 GHz for V2V/I communications.

b) We expect that the delivery of advanced use cases via LTE-V2X and NR-V2X for the support of advanced driving services will require an additional 40 MHz or more of spectrum at 5.9 GHz for V2V/I/P communications.

The above conclusion with regards to advanced use cases deserves some elaboration:

- "Sensor Sharing for Autonomous Vehicles" is an important advanced driving use case which involves the ability of road users to share their processed sensor data with other road users on a continual basis for what is known as *cooperative perception*, to provide advanced driver assistance and to facilitate autonomous driving. The appropriate amount of sensor data which should be shared is an open question for the industry, and directly impacts the required spectrum. Our lower estimates of spectrum needs for this use case suggest that it can be accommodated in a 10 MHz channel. However, our analysis also indicates that, depending on the extent of required redundancy in the sharing of sensor information for the implementation of automated driving, the spectrum needs can be as high as a few tens of MHz or even more.
- Another example is the "Vulnerable Road User" advanced use case, whereby vulnerable road users (VRUs) such as pedestrians or cyclists share information about themselves by broadcasting continual repetitive messages to other road users. Our analysis of this use case for pedestrian VRUs indicates that, depending on the extent of clustering among the VRUs, the spectrum needs in dense urban environments can be up to several MHz (but less than 10 MHz).
- Many other advanced driving use cases are event triggered (e.g. cooperative manoeuvres), whereby messages are exchanged over the air only in response to a desire by a road user to undertake a specific manoeuvre (e.g., crossing an intersection, changing lanes, joining a freeway, or the like). Here, the road user shares its intended trajectory with other road users as part of a *handshake* exchange of information, in order to provide advanced driver assistance and to facilitate autonomous driving. Specifically, our analysis indicates that the spectrum needs for "Group Start" are of the order of several hundred kHz (approaching 1 MHz), whereas the spectrum needs for "Cooperative Lane Merging" (and other similar trajectory information sharing use cases) are of the order of around 150 kHz, both considerably lower than the spectrum needs of the "Cooperative Perception" use case. Notably, the contribution of these event triggered use cases to the overall ITS spectrum needs is stochastic, in

the sense that such use cases may or may not occur at the same time and place, and this can result in a highly time variable demand for spectrum at any given location.

- We have also examined a number of miscellaneous advanced use cases which do not fall under the above categorisations (including "Platooning", "Vehicle Decision Assist", "See Through for Passing", "Speed Harmonisation", and "Automated Intersection Manager"). Our analysis indicates that with the exception of "See Through for Passing" which may require several MHz (less than 10 MHz) for the communication of high-definition video, the spectrum needs of each of the remaining use cases is unlikely to exceed at most several hundred kHz. Again, the contribution of these use cases to the overall ITS spectrum needs depends on the extent to which they might occur at the same time and place.

As a result, the evaluation of the spectrum needs for advanced use cases is not a trivial task. Nevertheless, it is clear that the 70-75 MHz of ITS spectrum in the 5.9 GHz band (as presently allocated in many regions and under consideration in other regions) is needed to support the basic safety and advanced use cases under consideration today. Like any emerging sector, there could be unforeseen ITS use cases that would require even more spectrum as the market evolves.

As the ITS industry develops further, and we begin to better understand the demands of advanced driver assistance and autonomous driving, we will assess the extent to which the 5.9 GHz band (5850-5925 MHz) – which is globally harmonised for ITS by the ITU-R – is sufficient to meet the spectrum needs of the road users, and whether additional spectrum designated for ITS will be required.

Furthermore, based on the results of our studies of the spectrum needs of C-V2X network-based (V2N) communications, we can draw the following conclusions:

a) At least 50 MHz of additional service-agnostic low-band (< 1 GHz) spectrum would be required for mobile operators to provide advanced automotive V2N services in rural environments with affordable deployment costs.

b) At least 500 MHz of additional service-agnostic mid-band (1 to 7 GHz) spectrum would be required for mobile operators to provide high-capacity, citywide advanced automotive V2N services.

In the above, the term "additional" means availability of spectrum in addition to the bands that are currently identified for International Mobile Telecommunications (IMT) use by mobile communication networks.

The 5GAA places great value on the importance of V2N communications in enabling future advanced driving use cases, as supported by the Uu interface of C-V2X. Accordingly, the 5GAA recommends that national and regional administrations ensure the availability of sufficient spectrum for mobile communication networks in the so-called low-bands and mid-bands for the support of services, including ITS, in the coming decade.

It should be emphasised that unless otherwise stated, the spectrum needs values estimated in this report are based on the assumption of a 100% penetration of ITS equipment among the population of road users, and also account for overheads which might be required for security certificates and signatures. Furthermore, it should also be pointed out that estimated spectrum needs for the advanced use cases are based on our current understanding of how these use cases will be implemented in practice. Finally, the 3GPP specifications on C-V2X allow for a broad range of parameterisations, including different trade-offs between reliability and redundancy levels (e.g., packet retransmissions optionally employing a two transmission time interval mode). It should be noted that increased levels of redundancy will affect the spectrum needs requirements accordingly.

1. Use cases for ITS

1.1. List of use cases

5GAA has been developing descriptions and specifications for a number of V2X use cases [1][2]. These are listed in Table 1.1 below along with their category, type, mode of communication, and employed messaging.

In terms of *category*, we classify the use cases according to whether they serve users' safety needs, assist driving, enhance vehicle operation, provide convenience, improve traffic efficiency, or enable autonomous driving.

In the context of *type*, the use cases are classified as "initial/day-1" or "advanced", partly based on the extent to which they are supported in various releases of 3GPP cellular-V2X (C-V2X) specifications, and partly based on 5GAA's analysis of whether we think the use case will be deployed in the first phase of C-V2X deployments or in later phases.

We note that LTE-V2X relates to 3GPP Rel. 14 or 15 specifications (LTE based), whereas NR-V2X relates to 3GPP Rel. 16 and beyond specifications (NR based). The term 5G-V2X relates to the combination of LTE-V2X and NR-V2X, whereas C-V2X is an umbrella term which encapsulates all 3GPP V2X technologies. Unless explicitly stated otherwise, the term C-V2X encompasses both direct (PC5) and network-based (Uu) modes of communication. If only PC5 or only Uu are addressed, then the terms C-V2X PC5 and C-V2X Uu are used, respectively.

We classify the mode of *communication* as follows:

> **V2V** refers to direct communication between on-board units (OBUs) of different vehicles, using the C-V2X (PC5) interface, and in bands that are designated to ITS services (e.g., the globally harmonised 5.9 GHz band). We note that V2V communications using the C-V2X (PC5) interface (also called sidelink) can in principle also be accommodated in bands that are designated for use by mobile communication networks. However, for the purposes of this report, we assume that V2V refers to the former model.
>
> **V2I** refers to communication between the OBUs of vehicles and roadside units (RSUs) of ITS infrastructure, using the C-V2X (PC5) interface (also called sidelink), and in bands that are designated to ITS services (e.g., 5.9 GHz). We again note that V2I communications using the C-V2X (PC5) interface can in principle also be accommodated in bands that are designated for use by mobile communication networks; i.e., where the RSU is operated by a mobile network operator. However, for the purposes of this report, we assume that V2I refers to the former model, unless explicitly indicated by reference to "V2I (MCN)".
>
> **V2N** refers to communication between the OBUs of vehicles and the base stations of mobile communication networks, using the C-V2X (Uu) interface, and in bands that are designated for use by mobile communication networks.
>
> Where the letter 'V' is replaced by 'P', this represents communications which involve radio equipment carried by pedestrians (as opposed to OBUs in vehicles). Unless otherwise stated in this report, the term V2X may refer to both V2X and X2V communications.

It should be noted that the association of a use case with a specific V2X communication mode is strictly for the purposes of estimating spectrum needs in this report, and does not preclude parties from deploying a different communication mode in practice.

Finally, we indicate the kind of messages which the different use cases might employ. Note that the mapping of messages to use cases is not necessarily one to one; i.e., a message may be used to meet the demands of more than one use case. At the highest level, the messages can be categorised as those which occur *continually* and those which are *event triggered*:

> **Continual messages –** These are used where the road users, infrastructure or network continually share information with other entities. This may include information about the location and movements of the road users, sensor data, or information about objects on the road. These continual messages are typically also repetitive (such as CAM/BSM) and tend to support broadcast communications.
>
> **Event triggered messages –** These are only used in special circumstances. This might be when a road user intends to perform a special manoeuvre and wishes to inform (or seek the cooperation of) other users, or when a road user requests specific information from an infrastructure or network, or where an infrastructure or network wishes to provide specific information to a road user. Depending on the use case, these messages may be repetitive (during the event) or non-repetitive, and in the latter case, they might be delay sensitive or delay non-sensitive (best effort). Event triggered messages may support broadcast, groupcast or unicast communications depending on the use case.

Continual repetitive messages define a relatively deterministic baseline for the ITS spectrum needs. This is because road users transmit such messages regularly and at all times when active. The contribution of event triggered messages to the overall ITS spectrum needs is, on the other hand, more stochastic, in the sense that use cases which employ such messages may or may not occur at the same time at any given location, and this can result in a highly variable demand for spectrum.

The above message categories are illustrated in Figure 1.1.

It should be noted that the list of use cases in Table 1.1 and their technical requirements are subject to on-going review by the 5GAA. In particular, the details of some advanced use cases are still under discussion. Furthermore, there are a number of important V2N use cases which are relevant for automotive and transportation applications in general, for example in the areas of proprietary OEM services, logistics and public transportation. These use cases are for further study.

Note that the message sizes and data rates described in Table 1.1 refer to individual communication links and not aggregate data rates, and furthermore do not include any of the overheads which might be associated with security related data.

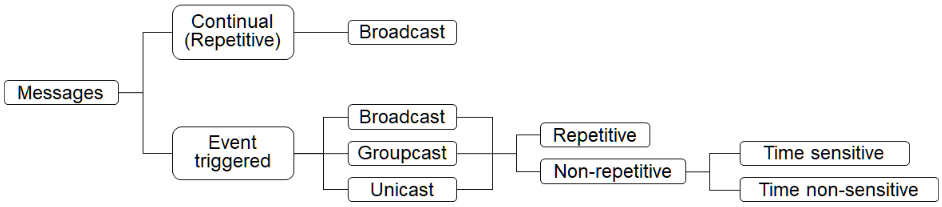

Figure 1.1: Message categories.

Table 1.1: V2X use cases.

	Use case	Category	Type (3GPP rel.)	Mode	Required messaging (a message may serve multiple use cases)
1	Cross-Traffic Left-Turn Assist	Safety	Day 1 ------- Advanced (R14)	V2V	300 B messages at a repetition rate of ≤ 10 Hz (≤ 24 kbit/s) (continual)(broadcast). ------- 1000 B messages at a repetition rate of ≤ 100 Hz (≤ 800 kbit/s) (event triggered)(broadcast).
2	Intersection Movement Assist	Safety	Day 1 (R14)	V2V	300 B messages at a repetition rate of ≤ 10 Hz (≤ 24 kbit/s) (continual)(broadcast).
3	Emergency Brake Warning	Safety	Day 1 (R14)	V2V	300 B messages at a repetition rate of ≤ 10 Hz (≤ 24 kbit/s) (continual/event driven)(broadcast).
4	Traffic Jam Warning	Safety, Convenience	Day 1 (R14)	V2V, V2I ------- V2N	300 B messages at a repetition rate of ≤ 10 Hz (≤ 24 kbit/s) (continual)(broadcast). ------- DL: 24 kbit/s (event triggered)(groupcast).
5	Software Update	Convenience, Maintenance, Safety	Day 1, Advanced (R8, R16)	V2N	DL: 3 – 300 Mbit/s (event triggered)(unicast).
6	Vehicle Health Monitoring	Operations Management	Day 1 (R14)	V2N	UL: 1000 B message in ≤ 30 s (~300 bit/s) (event triggered)(unicast).
7	Real-Time Situational Awareness	Safety, Advanced Driving Assistance	Day 1 (R14)	V2V ------- V2N	300 B messages at a repetition rate of ≤ 10 Hz (≤ 24 kbit/s) (continual)(broadcast). ------- UL or DL: 8 kbit/s (event triggered)(unicast/groupcast).

8	Speed Harmonization	Traffic Efficiency	Advanced (R14)	V2I (V2N)	UL or DL: 300 B messages at a repetition rate of ≤ 2.5 Hz (≤ 6 kbit/s) (event triggered)(broadcast).
9a	Sensor Sharing for Autonomous Vehicles (cooperative perception)	Convenience, Advanced Driving Assistance	Advanced (R16 and beyond)	V2V	Under discussion, ~1000 B messages at a repetition rate of ≤ 10 Hz (continual)(broadcast).
9b	High-Definition Sensor Sharing	Convenience, Advanced Driving Assistance	Advanced (R16 and beyond)	V2V	Under discussion, 8 Mbit/s (continual)(broadcast).
10	See Through for Passing	Safety, Advanced Driving Assistance	Advanced (R16 and beyond)	V2V	A video stream of 8 Mbit/s (event triggered)(unicast).
11	Lane Change Warning	Safety	Day 1 (R15)	V2V	300 B messages at a repetition rate of ≤ 10 Hz (≤ 24 kbit/s) (event triggered)(broadcast).
12	Vulnerable Road User (VRU)	Safety	Advanced (R16)	V2P ------- V2I, V2N	Sidelink: Under discussion (broadcast/groupcast/unicast). ------- DL: 2 video streams of 12 Mbit/s each (24 Mbit/s) (event triggered) (broadcast/groupcast).
13	Group Start	Traffic Efficiency	Advanced (R16)	V2I V2V	Under discussion, 300 B messages at a repetition rate of ≤ 20 Hz (≤ 48 kbit/s) (continual)(broadcast/unicast).
14	Tele-Operated Driving	Autonomous Driving	Advanced (R16)	V2N	UL: 4 video streams of 8 Mbit/s each, plus 4 Mbit/s sensor data (36 Mbit/s). DL: 400 kbit/s. (continual)(unicast).
15	Tele-operated Driving Support	Autonomous Driving	Advanced (R16)	V2N	UL: 4 video streams of 8 Mbit/s each, plus 4 Mbit/s sensor data (36 Mbit/s). DL: 400 kbit/s. (continual)(unicast).
16	Tele-Operated Driving for Automated Parking	Autonomous Driving	Advanced (R15 and beyond)	V2N (V2I)	UL: 4 video streams of 8 Mbit/s each, plus 4 Mbit/s sensor data (36 Mbit/s). DL: 400 kbit/s. (continual)(unicast).
17	Obstructed View Assist	Convenience, Advanced Driving Assistance	Advanced (R16)	V2N V2I V2V	DL/sidelink: Video stream of 5 Mbit/s (event triggered)(unicast).
18	Cooperative Manoeuvres of Autonomous Vehicles in Emergency Situations	Autonomous Driving	Advanced (R16 and beyond)	V2V	Under discussion, 300 B messages at a repetition rate of ≤ 20 Hz (≤ 48 kbit/s) (event triggered) (broadcast/groupcast/unicast).
19	Continuous Traffic Flow via Green Lights Coordination	Traffic Efficiency	Day 1, Advanced (R14)	V2N	UL: 300 B messages at a repetition rate of ≤ 20 Hz (≤ 48 kbit/s). DL: 300 B messages at a repetition rate of ≤ 1 Hz (≤ 2.4 kbit/s). (continual)(unicast).

20	Remote Automated Driving Cancellation	Autonomous Driving	Advanced (R16)	V2N (V2I) (V2V)	Cancellation: 300 B messages at repetition rate of 0.02 Hz (48 bit/s). Acknowledgement: Same. (event triggered)(unicast).
21	High-Definition Map Collection and sharing	Autonomous Driving	Advanced (R16)	V2N	UL: 4 Mbit/s (sensors) or 8+35+4 = 47 Mbit/s (video+lidar+sensors) (continual/event triggered) (broadcast)(unicast). DL: 16 Mbit/s (continual/event triggered) (broadcast).
22	Automated Intersection Crossing	Autonomous Driving	Day 1 ------- Advanced (R14, R16 and beyond)	V2I, V2V (V2N) ------- V2I (V2N)	300 B messages at a repetition rate of ≤ 10 Hz (≤ 24 kbit/s), SPaT: 100 B messages at a repetition rate of 1 Hz (800 bit/s) (continual)(broadcast). MAP: 1000 bytes in 1 second (8 kbit/s) (continual)(broadcast). ------- Under discussion HD map: 1 MB, Trajectory: 25 kbit/s (event triggered)(broadcast/unicast).
23	In-Vehicle Entertainment	Convenience	Advanced (R16)	V2N	DL: 4 video (8k) streams of 250 Mbit/s each (continual)(unicast).
24	Security Credentials	Vehicle Operations Management	Day 1, (R14)	V2N	300 kB per month
25	Vehicle Shares Information on Road Hazards /Events	Autonomous Driving	Advanced (R15, R16)	V2V (V2N, V2I)	UL/DL/sidelink: A single 300 B message in 20 ms (120 kbit/s) (event triggered)(broadcast).
26	Software Update of Reconfigurable Radio System	Vehicle Operations Management	Advanced (R14)	V2N	DL: 200 MB in 1 hour (event triggered)(unicast).
27	Vehicles Platooning in Steady State	Traffic Efficiency	Advanced (R16 and beyond)	V2V V2N	MV to MV: 100 B messages at a repetition rate of 10 Hz (8 kbit/s) (continual)(groupcast). HV to MV: 300 B messages at a repetition rate of 20 Hz (48 kbit/s) (continual)(groupcast). DL: 1000 B messages (event triggered)(groupcast).
28	Cooperative Lane Merging	Autonomous Driving	Advanced (R16)	V2V	Under discussion, RV to HV: 300 B message HV to RV: 300 B message RV to HV: 300 B message each with latency of 20 ms (120 kbit/s) (event triggered) (broadcast/groupcast/unicast).
29	Autonomous Vehicle Disengagement Report	Autonomous Driving	Advanced (R16)	V2N V2V	UL: 2 GB in 10 min (27 Mbit/s) (event triggered)(unicast).
30	Law Enforcement Messaging	Society and Community	Advanced (R16)	V2V V2N (V2I)	300 B messages at a repetition rate of ≤ 10 Hz (≤ 24 kbit/s) (event triggered)(unicast).

31	Patient Transport Monitoring	Society and Community	Advanced (R16)	V2N	UL: 1+8+0.064 ~ 9 Mbit/s (data+video+voice) (continual)(unicast).
32	Accident Report	Society and Community	Advanced (R16 and beyond)	V2N	UL: BSM/CAM for 50 vehicles (50×24 kbit/s), two video streams (2×8 Mbit/s), and 60 seconds of data delivered in 10 mins (0.86 Mbit/s) (event triggered)(unicast).
33	Infrastructure Assisted Environment Perception	Autonomous Driving	Advanced (R16 and beyond)	V2I (V2N)	UL: 70-155 Mbit/s, DL: 4 Mbit/s (event triggered)(broadcast/unicast).
34	Infrastructure Based Tele-Operated Driving	Autonomous Driving	Advanced (R16)	V2N	Covered by Autonomous Vehicle Disengagement Report and Tele-Operated Driving
35	Automated Valet Parking: Joint Authentication and Proof of Localisation	Convenience, Autonomous Driving	Advanced (R16)	V2N (V2I)	1000 B in 500 ms (16 kbps) (event triggered)(unicast).
36	Automated Valet Parking: Wake up	Convenience	Advanced (R16)	V2N (V2I)	DL: 3.2 kbps (event triggered)(unicast).
37	Awareness Confirmation	Convenience, Advanced Driving Assistance	Advanced (R16)	V2V (V2I) (V2N)	Request for confirmation 40 kbit/s (event triggered)(broadcast). Subsequent confirmations under discussion (continual)(unicast).
38	Coordinated, Cooperative Driving Manoeuvre	Autonomous Driving	Advanced (R16)	V2V V2P	Under discussion (event triggered)(groupcast).
39	Curbside Management	Convenience	Advanced (R16)	V2N (V2I) V2P	Under discussion, 64 kbit/s (event triggered)(unicast).
40	Interactive VRU Crossing	Safety	Advanced (R14)	V2P	Under discussion, 64 kbit/s (event triggered) (broadcast/groupcast/unicast).
41	Cooperative Lateral Parking	Convenience	Advanced (R16)	V2V	Under discussion, (event triggered)(broadcast/groupcast).
42	Cooperative Traffic Gap	Safety Convenience	Advanced (R16)	V2V	Under discussion, 2 Mbit/s (broadcast/groupcast/unicast).
43	Vehicle Decision Assist	Safety Advanced Driving Assistance	Advanced (R16)	V2V V2P	1000 B in 100 ms (80 kbit/s) (event triggered)(unicast).
44	Bus Lane Sharing Request and Revoke	Traffic Efficiency, Convenience, Autonomous Driving	Advanced (R12)	V2N	UL: 1000 B in 200 ms (40 kbit/s). DL: 1000 B in 200 ms (40 kbit/s). (event triggered)(unicast).

1. Cross-Traffic Left-Turn Assist – A host vehicle wishes to turn left across traffic approaching from the opposite direction, and exchanges awareness (CAM/BSM) messages with remote vehicles. In a more advanced version, vehicles also exchange future trajectories.

2. Intersection Movement Assist – A stationary host vehicle proceeds straight from stop at an intersection, and is alerted if it is unsafe to proceed through the intersection based on awareness messages (CAM/BSM).

3. Emergency Brake Warning – A host vehicle is alerted based on awareness messages (CAM/BSM) that a remote vehicle ahead is undergoing an emergency brake.

4. Traffic Jam Warning – A host vehicle is made aware of a traffic jam ahead.

5. Software Update – A host vehicle receives software updates from the manufacturer.

6. Vehicle Health Monitoring – Owners, fleet operators and authorised vehicle service providers monitor the health of a host vehicle and are alerted when maintenance or service is required.

7. Real-Time Situational Awareness and High-Definition Maps – Remote vehicles share with the host vehicle information on unsafe conditions ahead (accidents, weather, traffic, construction).

8. Speed Harmonisation – The host vehicle is notified of posted speed recommendations/limits based on traffic, road and weather conditions.

9a. Sensor Sharing for Autonomous Vehicles – Vehicles collect information on dynamic objects on the road and other traffic participants based on vehicle sensor data. They share the relevant information as processed data.

9b. High-Definition Sensor Sharing – Host vehicle shares sensor information (video, lidar, etc.) with remote vehicles.

10. See Through for Passing – Host vehicle signals an intention to pass a remote vehicle. The remote vehicle sends a video stream showing its front view to the host vehicle.

11. Lane Change Warning – A host vehicle which has signalled its intention to change lanes is alerted of a collision with a leading/lagging remote vehicle.

12. Vulnerable Road User – A host vehicle is alerted of VRUs on the road or crossing an intersection and is warned of any risk of collision.

13. Group Start – Autonomous or semi-autonomous vehicles form a group to jointly start at a traffic light, with a traffic control centre providing information for coordination.

14. Tele-Operated Driving – Remote driver (human or machine) operates a host vehicle.

15. Tele-Operated Driving Support – Same as Tele-Operated Driving, but where the host vehicle is autonomous.

16. Tele-Operated Driving for Automated Parking – Remote driver (human or machine) operates a host vehicle for the purpose of parking. Similarities to the other two tele-operation use cases.

17. Obstructed View Assist – Host vehicle queries, and receives video information from surveillance cameras (where available) or other vehicles.

18. Cooperative Manoeuvres of Autonomous Vehicles in Emergency Situations – An autonomous host vehicle shares with remote autonomous vehicles its planned trajectory with regards to an emergency, and receives feedback from the remote vehicles on the risks involved in executing the trajectory.

19. Continuous Traffic Flow via Green Lights Coordination – A host vehicle regularly reports its status to a traffic management server, which in turn sends timing and/or speed recommendations to the host vehicle.

20. Remote Automated Driving Cancellation – The autonomous operation of an autonomous host vehicle is disabled via messages transmitted by a mobile network. Where coverage is not available, communication can be via roadside infrastructure or remote vehicles.

21. High-Definition Map Collecting and Sharing – Vehicles share their sensor data with an HD map provider, which then builds and shares HD maps with vehicles.

22. Automated Intersection Crossing – Autonomous host vehicle receives traffic light timing information and HD map from intersection manager. Other vehicles and VRUs may also share their status. The intersection manager may provide a suggested trajectory to the host vehicle.

23. In-Vehicle Entertainment – The delivery of entertainment content to vehicle passengers.

24. Security Credentials – Host vehicle receives security credentials from the certification authority and performs an update according to related rules.

25. Vehicle Shares Information on Road Hazards/Events – A host vehicle shares information for use by autonomous vehicles.

26. Software Update of Reconfigurable Radio System – Update of the software/firmware of the reconfigurable radio system of a host vehicle.

27. Vehicles Platooning in Steady State – A group of vehicles driving closer in a coordinated manner.

28. Cooperative Lane Merging – A host vehicle accommodates a remote vehicle that is merging into the host vehicle's traffic lane. The remote vehicle shares its location and intended trajectory, the host feeds back its intention to accommodate or not, the remote vehicle confirms initiation of the manoeuvre.

29. Autonomous Vehicle Disengagement Report – When the autonomous operation of a host vehicle disengages, it submits to the car OEM (or other entity) a report of recorded data.

30. Law Enforcement Messaging – A police vehicle alerts a host vehicle that it should pull over.

31. Patient Transport Monitoring – Vital patient data is shared with a hospital during patient transport.

32. Accident Report – Host vehicle involved in an accident submits a report to the car OEM (or other entity).

33. Infrastructure Assisted Environment Perception – Infrastructure transmits to a host vehicle information on dynamic and static objects on the road, as well as information on a recommended trajectory for the host vehicle.

34. Infrastructure Based Tele-Operated Driving – When a host vehicle detects a failure in its autonomous operation, it submits a status report to the tele-operator, and this is complemented by data from infrastructure sensors.

35. Automated Valet Parking: Proof of Authentication and Localisation – A host vehicle is placed in an assigned zone in a car park by a human driver, and the vehicle asks parking infrastructure for access to the parking facility, the infrastructure verifies the position of the vehicle and, subject to a successful check, the vehicle is admitted for autonomous parking.

36. Automated Valet Parking: Wake-up – Infrastructure sends a wake-up signal to an autonomous host vehicle already parked.

37. Awareness Confirmation – The host vehicle indicates whether it would like to receive confirmation from remote vehicles regarding its transmitted messages.

38. Coordinated Cooperative Driving Manoeuvre – The host vehicle wishing to perform a manoeuvre notifies the remote vehicles, which provide feedback (support/reject). The host vehicle then informs the remote vehicles of its decision, and the remote vehicles confirm.

39. Curbside Management – A pedestrian and a vehicle coordinate (via a third party with an infrastructure node) a pickup at a crowded curbside area.

40. Interactive VRU Crossing – A VRU announces its intent to cross the road, the remote vehicles acknowledge the VRUs presence, the VRU continues to exchange with the vehicles while crossing the road, and informs them when crossing is complete.

41. Cooperative Lateral Parking – A host vehicle announces to remote vehicles (autonomous) its intent to park, requesting them to move sufficiently in order to "make room". The remote vehicles confirm their awareness and willingness to cooperate. The host vehicle announces the completion of parking.

42. Cooperative Traffic Gap – A host vehicle wishing to make a manoeuvre announces information such as location, velocity, trajectory to remote vehicles, which in turn communicate among one another to see if sufficient vehicles are willing to cooperate, and if so, proceed to create a traffic gap to accommodate the host vehicle, and accordingly inform the host which – where permitted – performs the manoeuvre.

43. Vehicle Decision Assist – A host vehicle detects a stationary (or slow moving) remote vehicle ahead, and enquires about the vehicle's status in order to decide whether it should overtake or not.

44. Bus Lane Sharing Request (and Revoke) – A host vehicle notifies the relevant authority of its intention to use (share) a bus lane, and if subsequently authorised it regularly reports its status to the authority. Once a bus arrives, the authorisation is revoked.

1.2. Day-1 use cases

A total of 11 day-1 use cases can be identified in Table 1.1.

Five of the day-1 use cases in Table 1.1, namely “Cross-Traffic Left-Turn Assist”, “Intersection Movement Assist”, “Emergency Brake Warning”, “Traffic Jam Warning”, and “Real-Time Situational Awareness” employ the same continual repetitive broadcast CAM/BSM messages in a direct V2V communication mode (without involvement of a network/infrastructure). A sixth use case, “Lane Change Warning”, employs event triggered direct communication messages that are nevertheless specified to be repetitive during the event, and which we expect can be accommodated within the spectrum needs of the continual repetitive broadcast CAM/BSM messages of the other five use cases. A review of Table 1.1 indicates that an upper bound on the data rate for these continual repetitive messages is 24 kbit/s, corresponding to 300 byte messages at a repetition rate of up to 10 Hz. The spectrum needs for these use cases are addressed in Section 2.1 and Section 4.1.

A seventh day-1 use case, “Automated Intersection Crossing/Manager”, employs the same continual repetitive broadcast CAM/BSM messages in a direct V2V communication mode (without involvement of a network/infrastructure), as in the above use cases. But this use case also employs other continual repetitive broadcast messages in a V2I communication mode (involving an RSU) in both day-1 and advanced modes. The spectrum needs for this use case are addressed in Section 2.1, Section 4.1.1 and Section 5.4.

The above is summarised in Tables 1.2 and Table 1.3 below. These use cases can be accommodated in spectrum designated for ITS services (e.g., 5.9 GHz).

Table 1.2: Day-1 use cases which use V2V communications and the same continual repetitive messages.

Messages per link	Use case[(a)]
Continual repetitive messages (V2V)(broadcast)	(1) Cross-Traffic Left-Turn Assist (2) Intersection Movement Assist (3) Emergency Brake Warning (4) Traffic Jam Warning (7) Real-Time Situational Awareness (11) Lane Change Warning (22) Automated Intersection Crossing
(a) Supported by the same messages.	

Table 1.3: Day-1 use case which uses V2I communications.

Messages per link	Use case
Continual repetitive messages (V2I)(broadcast)	(22) Automated Intersection Crossing

Finally, six of the day-1 use cases in Table 1.1 employ different event triggered groupcast/unicast messages in a V2N communication mode. The required data rates range, from as little as 300 bit/s for “Vehicle Health Monitoring”, to 48 kbit/s for “Traffic Light Coordination”, to potentially as high as 300 Mbit/s for certain extreme cases of “Software Updates”.

The above is summarised in Table 1.4 below. The spectrum needs for these use cases are not addressed in this report because (with the exception of some extreme examples) they can be – and some are today – accommodated in spectrum already designated for mobile communication networks.

Table 1.4: Day-1 use cases which use V2N communications.

Messages per link	Use case[a]
Event triggered messages (V2N) (groupcast/unicast)	(4) Traffic Jam Warning (5) Software Update (6) Vehicle Health Monitoring (7) Real-Time Situational Awareness (19) Continuous Traffic Flow via Green Lights Coordination (24) Security Credentials
(a) Supported by different messages.	

1.3. Advanced use cases

A total of 38 advanced use cases can be identified in Table 1.1. These may be classified as described next.

V2V communications

A total of 11 advanced use cases in Table 1.1 involve V2V (or V2P) communications alone; i.e., they do not involve V2I or V2N communications. The following can be observed:

- Only two use cases, namely “Sensor Sharing for AVs” and “High-Definition Sensor Sharing”, employ continual repetitive messages broadcast by the host vehicle. The spectrum needs for “Sensor Sharing for AVs” are addressed in Section 2.1 and Section 5.1.
- The remaining nine use cases employ event triggered messages. The spectrum needs for “See Through for Passing” (an event triggered element of “High-Definition Sensor Sharing”) and “Vehicle Decision Assist” are addressed in Section 5.4.
- Six of the remaining seven use cases, namely “Cross-Traffic Left-Turn Assist”, “Cooperative Manoeuvre for Autonomous Vehicles in Emergency Situations”, “Cooperative Lane Merging”, “Coordinated Cooperative Driving Manoeuvre”, “Interactive VRU Crossing” and “Cooperative Traffic Gap” all involve variations of a *trajectory information sharing* scenario. This is where a host road user notifies nearby remote road users of its intention to perform a manoeuvre, and subsequently broadcasts/groupcasts information on its status and planned trajectory to nearby remote road users, and receives confirmation/rejection from the said users. “Cooperative Lateral Parking” can also be considered to involve a *trajectory information sharing* scenario, except that the remote road users are parked/stationary vehicles. The spectrum needs for these use cases are addressed in Section 2.2 and Section 5.3.

The above is summarised in Table 1.5 below. These use cases can be accommodated in spectrum designated for ITS services (e.g., 5.9 GHz).

Table 1.5: Advanced use cases which use V2V or V2P communications alone.

Messages per link	Use case
Continual repetitive messages (V2V)(broadcast)	(9a) Sensor Sharing for Autonomous Vehicles (9b) High-Definition Sensor Sharing
Event triggered messages (V2V)(broadcast/groupcast/unicast)	(10) See Through for Passing (43) Vehicle Decision Assist
	Trajectory information sharing: (1) Cross-Traffic Left-Turn Assist (18) Cooperative Manoeuvres in Emergency Situations (28) Cooperative Lane Merging (38) Coordinated Cooperative Driving Manoeuvre (40) Interactive VRU Crossing (41) Cooperative Lateral Parking (42) Cooperative Traffic Gap

V2V communications in combination with V2I/V2N

Nine of the advanced use cases in Table 1.1 involve V2V communications in combination with either V2I or V2N communications. The following can be observed:

- The “Vulnerable Road User” use case involves continual repetitive messages, and its spectrum needs are addressed in Section 2.1 and Section 5.2.
- Other use cases rely on a combination of specific event triggered messages and continual repetitive messages. Important examples include “Group Start”, “Automated Intersection Crossing/Manager”, and “Vehicles Platooning in Steady State”, whose spectrum needs are also addressed in Section 2.2, Section 5.3 and Section 5.4.
- “Obstructed View Assist”, “Remote Automated Driving Cancellation” and “Law Enforcement Messaging” involve unicast communications. “Obstructed View Assist” bears close similarities to “See Through for Passing” but its spectrum needs are addressed in the context of V2N (rather than V2V) communications in Section 6.5 of this report. “Remote Automated Driving Cancellation” and “Law Enforcement Messaging” can also be supported by V2N communications, and where V2V communications is required as an alternative, these are not expected to have significant spectrum needs, and are not addressed in the context of V2V communications in this report.
- “Vehicle Shares Information on Road Hazards/Events” and “Awareness Confirmation” involve a combination of broadcast/groupcast/unicast communications. The “Vehicle Shares Information on Road Hazards/Events” use case can be supported by the messages employed in other use cases such as “Sensor Sharing for Autonomous Vehicles” and “High-Definition Sensor Sharing” and is not considered further. The spectrum needs for “Awareness Confirmation” is also not addressed in this report.

The above is summarised in Table 1.6 below. These use cases can be accommodated in spectrum designated for ITS services (e.g., 5.9 GHz).

Table 1.6: Advanced use cases which use V2V or V2P communications in combination with V2I or V2N communications.

Messages per link	Use case
Continual repetitive messages (V2V)(broadcast/groupcast)	(12) Vulnerable Road User
Continual repetitive messages (V2V/V2I)(broadcast/groupcast) Event triggered messages (V2V/V2I)(broadcast/groupcast/unicast)	(13) Group Start (22) Automated Intersection Crossing/Manager (27) Vehicles Platooning in Steady State (17) Obstructed View Assist (20) Remote Automated Driving Cancellation (30) Law Enforcement Messaging (25) Vehicle Shares Information on Road Hazards/Events (37) Awareness Confirmation

V2I communications

Two advanced use cases in Table 1.1 involve V2I communications only. We have excluded here those use cases which could involve V2I communications, but where we consider that V2N communications is the more likely option. The following can be observed:

- The two use cases employ event triggered messages.
- “Speed Harmonisation” and “Infrastructure Assisted Environment Perception” involve a combination of broadcast, groupcast and unicast communications. The spectrum needs for “Speed Harmonisation” is addressed in Section 5.4, whereas “Infrastructure Assisted Environment Perception” is addressed in the context of V2N communications in Section 3 and Section 6.6.

The above is summarised in Table 1.7 below. These use cases can be accommodated in spectrum designated for ITS services (e.g., 5.9 GHz).

Table 1.7: Advanced use cases which use V2I communications.

Messages per link	Use case
Event triggered messages (V2I)(broadcast/groupcast/unicast)	(8) Speed Harmonisation (33) Infrastructure Assisted Environment Perception

V2N communications

A total of 21 advanced use cases in Table 1.1 involve V2N communications. We have excluded here those use cases which could involve V2N communications, but where we consider that V2I communications is the more likely option. The following can be observed:

- Most of the advanced V2N use cases involve unicast communications. This is with the exception of "Vulnerable Road User", "High-Definition Map Collection and Sharing", "Vehicles Platooning in Steady State" and possibly "Law Enforcement Messaging" which may also include elements of broadcast and groupcast communications.
- Thirteen use cases can be described as delay sensitive, in the sense that delays in successful communications would have a significant impact on the quality of service and road safety. The remaining seven use cases can be described as delay non-sensitive.

The spectrum needs for a selection of these use cases are addressed in Section 3 and Section 6.

The above is summarised in Table 1.8 below. These use cases can be accommodated in spectrum designated for mobile communication networks.

Table 1.8: Advanced use cases which use V2N communications.

Messages per link	Use case
Delay sensitive Continual[(a)] or event triggered messages (V2N)(broadcast/groupcast/unicast)	(12) Vulnerable Road User (VRU) (14) Tele-Operated Driving (15) Tele-Operated Driving Support (16) Tele-Operated Driving for Automated Parking (17) Obstructed View Assist (19) Continuous Traffic Flow via Green Lights Coordination (20) Remote Automated Driving Cancellation (21) High-Definition Map Collecting and Sharing (27) Vehicles Platooning in Steady State (30) Law Enforcement Messaging (31) Patient Transport Monitoring (34) Infrastructure Based Tele-Operated Driving (44) Bus Lane Sharing Request and Revoke
Delay non-sensitive Event triggered messages (V2N)(unicast)	(5) Software Update (23) In-Vehicle Entertainment (IVE) (26) Software Update of Reconfigurable Radio System (29) Autonomous Vehicle Disengagement Report (32) Accident Report (35) Automated Valet Parking: Joint Authentication and Proof of Localisation (36) Automated Valet Parking: Wake-up (39) Curbside Management
(a) Continual during the use case.	

2. Spectrum needs evaluation methodologies for V2V/I/P direct communications

In this section we present methodologies for the estimation of spectrum needs for use cases which rely on V2V, V2I or V2P communications. These include the communication of

a) continual repetitive messages (typically broadcast), or

b) event triggered messages (typically broadcast, groupcast or unicast).

These methodologies form the basis for the spectrum needs calculations presented in Sections 4 and 5.

2.1. Methodology: Use cases involving continual repetitive communications

As discussed in Section 1, there are a number of day-1 ITS and advanced driving direct communication use cases which involve the continual transmission of repetitive messages. In this section, we present a methodology for the calculation of the spectrum needs for these use cases. The methodology accounts for the required communication data rates, the number of transmitting road users within the effective communication range, and the effective spectral efficiency of the radio access technology.

Figure 2.1 illustrates a typical road scenario considered in our analysis, where each vehicle broadcasts repetitive messages for reception by nearby vehicles. The spectrum needs are then equal to the amount of bandwidth required to ensure that the broadcasted messages are correctly received according to a target packet reception ratio (see Annex A) by all other vehicles within the effective communication range.

Note that for purposes of spectrum needs calculations, any one of the vehicles in Figure 2.1 can be considered as a proxy for a roadside unit. Furthermore, the vehicles can also be considered as proxies for VRUs such as pedestrians. For this reason, the spectrum needs methodology presented for continual repetitive messages can be readily applied to V2V, V2I and V2P communication scenarios.

It should also be noted that the spectrum resource is assumed to be re-used outside the effective communication range. This re-use should be accounted for in the calculation of the spectrum needs.

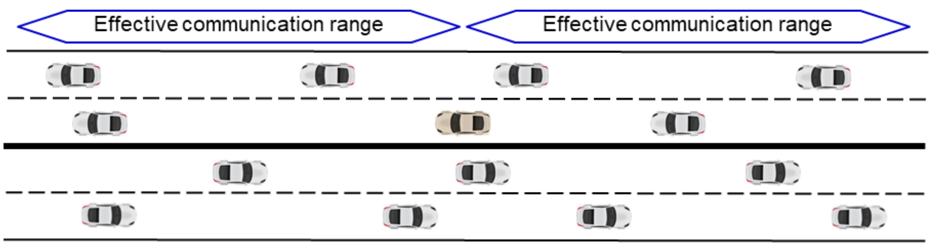

Figure 2.1: Illustration of a scenario which involves V2V direction communication of continual repetitive messages.

We propose to estimate the spectrum needs of continual repetitive messages by accumulating the total offered data traffic and deriving the total amount of bandwidth required for its reliable communication given the spectral efficiency of the C-V2X system.

Specifically, the spectrum needs B (Hz) for continual repetitive messages can be calculated as

$$B = \sum_{i=1}^{M} \frac{R_i a_i}{e_i u_i} = \sum_{i=1}^{M} \frac{N_i F_i a_i}{e_i u_i}, \tag{2.1}$$

where:

- M is the number of vehicles within the effective communication range and is determined by the inter-vehicle separation which is, in turn, a function of vehicle speed. Note that different ITS technologies are optimised for different effective communication ranges based on considerations of QoS requirements.

- R_i is the information data rate in bit/s associated with the i^{th} vehicle in the effective communication range and is determined by the specific use case. This is given by the product, $N_i F_i$, where N_i is the number of information bits in a packet transmitted by the i^{th} vehicle within the effective communication range, and F_i is the repetition rate of the message in Hz.

- a_i = 0 or 1 is the individual activity factor and specifies whether the i^{th} vehicle transmits or not.

- e_i is the spectral efficiency in bit/s/Hz according to which the packets are transmitted by the i^{th} vehicle, and is determined by the modulation and channel coding scheme supported by the radio access technology.

- $u_i \leq 1$ is the channel utilisation factor and defines the maximum rate of utilisation of the radio resource in the wireless channel, and accounts for the reduction in spectral efficiency at the receiver due to the impact of signal attenuation and co-channel interference in fulfilling the packet reception ratio (PRR) requirements.

As outlined in Section 1, continual repetitive messages tend to be broadcast for reception by a wide number of users, and all vehicles tend to use the same packet size N, repetition rate F, and modulation and coding schemes (implying the same e and u). For this reason, Equation 2.1 can be simplified as follows:

$$B = \frac{M\,N\,F\,a}{e\,u}, \qquad (2.2)$$

where the activity factor $0 < a \leq 1$ represents the fraction of vehicles which transmit repetitive messages.

For day-1 basic safety ITS use cases – supported by LTE-V2X – we assume that a = 1; i.e., all vehicles are assumed to transmit repetitive messages continually to ensure basic safety for all. This also implicitly assumes full penetration of ITS among road users, and in this sense represents an upper bound on the spectrum needs. However, as will be seen in Section 5, we assume that $a < 1$ for advanced driving use cases such as “Cooperative Perception”, because transmission by all vehicles may not be necessary to achieve the targets of the use case.

The above approach is used in Sections 4 and 5 to calculate the spectrum needs of day-1 and advanced use cases which use continual repetitive messages, respectively. Examples of the number of vehicles M for urban and freeway topologies are presented in Annex B. Values for the message size and repetition frequency, N and F, are dependent on the use case and are presented in Sections 4 and 5. The values for spectral efficiency and channel utilisation factor, e and u, are discussed next.

2.1.1. Effective spectral efficiency for LTE-V2X (PC5)

The effective spectral efficiency of LTE-V2X, as expressed in the denominator of Equation 2.2, can be described as the product of spectral efficiency e in bit/s/Hz and the channel utilisation factor u. As shown below, we assume that e = 0.6 bit/s/Hz and that u = 0.336, implying an effective spectral efficiency of 0.2 bit/s/Hz for LTE-V2X (PC5).

Spectral efficiency

The spectral efficiency e, as expressed in Equation 2.2 is determined by the modulation and channel coding scheme (MCS), and frame structure employed by the transmitter. Note that this is a measure of spectral efficiency at the transmitter and does not account for the reliability of packet reception. The spectral efficiency of LTE-V2X (PC5) can be calculated by dividing the nominal payload data rate C_N (bit/s) by the corresponding occupied bandwidth W (Hz), i.e.,

$$e = \alpha_{BW} \frac{C_N}{W}. \qquad (2.3)$$

We assume that a portion of the channel bandwidth is not used for actual transmissions in order to provide a guard band at the channel edges. Incorporating this overhead leads to a decreased spectral efficiency by a factor α_{BW}, referred to as the bandwidth utilisation factor. For the LTE-V2X (PC5) interface, α_{BW}= 0.9.

For the LTE-V2X (PC5) interface, C_N is calculated by dividing the message payload size L (in bits) of a V2X message by the transmission time interval (TTI) of 1 ms. The corresponding occupied bandwidth W depends on the number of physical resource blocks (PRBs) required for the transmission of the L bits, which in turn, depends on the selected modulation and coding scheme. Note that to determine the number of PRBs, the overhead at PDCP, RLC and MAC layers should be accounted for. Table 2.1 below shows the calculation of the occupied bandwidth required for transmitting a V2X message of 300 bytes, which is typical in continual repetitive messages.

Table 2.1. Spectral efficiency of LTE-V2X at the transmitter.

Parameter	Value	Note
Message size, L	300 bytes	Typical of continual repetitive messages.
Transmission time interval, T_{TTI}	1 ms	
Normal payload data rate, C_N	2.4 Mbit/s	$C_N = L / T_{TTI}$.
Index of MCS for payload data, I_{MCS}	8 (QPSK)	See Table 8.6.1-1 of 3GPP TS 36.213.
Bandwidth per PRB: W_{PRB}	180 kHz	12 × 15 kHz.
Number of PRBs for payload data and SA, N_{PRB}	20	See Table 7.1.7.2.1-1 of 3GPP TS36.213*.
Occupied bandwidth, W	3.6 MHz	$W = N_{PRB} . W_{PRB}$.
Bandwidth utilisation factor, α_{BW}	0.9	Factor for internal guard band.
Spectral efficiency at the transmitter, u	0.60 bit/s/Hz	$\alpha_{BW} C_N / W$.

* Obtained for data transmission based on L_{PHY} and I_{MCS}. SA transmission uses 2 PRBs.
Note: Sub-band configuration of LTE-V2X PC5 is not considered in this calculation.

Channel utilisation factor

LTE-V2X (PC5) operates as a distributed *ad hoc* network, where the frequency and time resources (resource blocks) are selected by a semi-static sensing mechanism and can be re-used at different locations. Given that LTE-V2X is required to provide high reliability and PRRs without upper layer retransmissions, it is not possible for all the resources within the communication range (a virtual cell) to be used. The channel utilisation rate accounts for this effect.

The channel utilisation factor is defined as the proportion of occupied resource blocks within the communication range (a virtual cell), which meets the target reliability requirements. That is,

$$u = \frac{N_{PRB}\ M}{N_{total\_PRB}}, \tag{2.4}$$

where M is the number of vehicles transmitting within the effective communication range, N_{total_PRB} is the total number of PRBs available in the resource pool, and N_{PRB} is the total number of occupied PRBs in a 100 ms interval averaged over all of the M vehicles within the effective communication range.

According to 3GPP TR 36.885 Section 9.1.1, in the case of freeways and for a 10 MHz channel, the performance of the PC5 interface with enhancements exceeds or approaches an average PRR of 80% at a 320 m range. Assuming a vehicle speed of 70 km/h, a time to collision of 2.5 seconds, and 6 lanes (3 lanes in each direction), this implies that the number of vehicles within the communication range is M = 84.

Note that the optimum choice of N_{PRB} can be derived via simulations. A lower N_{PRB} means lower system level (co-channel inter-cell) interference, while the link-level performance may be worse due to reduced redundancy. Whereas a larger N_{PRB} means a better link-level performance due to increased redundancy, but the system-level interference would be higher. Therefore, N_{PRB} should be configured to achieve a balance between link level and system level performance. A value of N_{PRB} = 20 is widely used in practice for the transmission of 300 byte and 190 byte packets.

In a 10 MHz channel, there are total of N_{Total_PRB} = 50×100 = 5000 PRBs over a 100 ms interval.

Given the above, we have

$$u = \frac{N_{PRB}\ M}{N_{Total\_PRB}} = \frac{20 \times 84}{5000} = 0.336.$$

A loaded LTE-V2X system is an interference limited system, i.e., the effective communication range is determined by both the link level performance (a function of SINR) and the geographic distribution of the vehicles. Higher vehicle speeds lead to greater inter-vehicle separations and lower traffic densities. However, the lower traffic density reduces the levels of co-channel inter-cell interference and therefore increases the effective communication range, meaning that the number of vehicles within the effective communication does not change considerably as a function of vehicle speed. Although the channel utilisation factor varies as a function of a number of system parameters, it is not especially sensitive to the vehicle speed. Accordingly, we assume a value of u = 0.336 to reflect most system configurations.

2.1.2. Effective spectral efficiency for NR-V2X (PC5)

The effective spectral efficiency of NR-V2X, as expressed in the denominator of Equation 2.2, can be described as the product of spectral efficiency e in bit/s/Hz and the channel utilisation factor u. As shown below, we assume that e = 0.712 bit/s/Hz and that u = 0.8, implying an effective spectral efficiency of 0.57 bit/s/Hz for NR-V2X (PC5).

Spectral efficiency

The spectral efficiency e of NR-V2X can be estimated based on the total amount of information transmitted over a 1 second period in a W = 40 MHz channel bandwidth. This can be written as

$$e = \frac{(1-H)R_{Sym}N_{RE}N_B r_{Code}}{W}, \tag{2.5}$$

where H is an overhead factor, R_{Sym} is the number of symbols per second, N_{RE} is the number of resource elements (RE) per symbol, N_B is the number of bits per RE, and r_{Code} is the coding rate.

The assumed values for the above parameters are presented in Table 2.2 below.

Table 2.2. Spectral efficiency of NR-V2X at the transmitter.

Parameter	Value	Note
Overhead, H	0.2	See (1).
Number of symbols per second, R_{sym}	28,000 (symbols/s)	See (1).
Number of REs per symbol, N_{RE}	1272	See (3).
Number of bits per symbol, N_B	2 (bits/symbol)	QPSK.
Coding rate	0.5	
Channel bandwidth, W	40 MHz	
Spectral efficiency, u	0.712 bit/s/Hz	$(1–H)\ R_{\mathrm{Sym}}\ N_{\mathrm{RE}}\ N_{\mathrm{B}}\ r_{Code}\ /\ W$.

(1) Assuming 1 AGC symbol, 1 TX/RX switching symbol, type 1 DMRS in 2 symbols, transmission of 30 RBs with SCI occupying 4 RBs in 3 symbols (SCI coding rate 0.26).
(2) Assuming 14 symbols per slot, a slot length of 0.5 ms (30 kHz subcarrier spacing).
(3) Assuming 12 REs forming a resource block, and 106 RBs within a 40 MHz bandwidth (20 kHz subcarrier spacing).

Note that the above estimated spectral efficiency applies to NR-V2X in broadcast mode, since it targets a certain high PRR over a wide area. For unicast and groupcast modes, the spectral efficiency of NR V2X may be significantly improved since the communication range is shorter and the transmitter and receiver can adapt the MCS to the link conditions.

Channel utilisation factor

Regarding the channel utilisation factor, a range of values might be considered. At the lower end of the range a value of 0.336 similar to that of LTE-V2X can be assumed. At the upper end of the range, as per the study that was conducted to define congestion control for LTE-V2X [3], we can fairly assume a channel utilisation factor of 0.8 or even higher. Note that a channel utilisation factor of 0.8 is reasonable for broadcasting messages that can tolerate a reliability of 90%. However, this factor is too high for certain unicast/groupcast messages that usually need extremely high reliability (such as messages for platooning). If it is intended to have all types of messages transmitted in a single channel, the channel utilisation factor should be reduced in order to make the system stable and the unicast/groupcast communications more reliable.

2.2. Methodology: Use cases involving event triggered communications

As discussed in Section 1, there are a number of advanced driving use cases which involve the direct communication of event triggered messages. This is where, unlike in the case of continual repetitive messages, the messages are only transmitted when this is necessary. This might be when a road user intends to perform a special manoeuvre and wishes to inform (or seek the cooperation of) other users, or when a road user requests specific information from other road users or roadside infrastructure, or where roadside infrastructure provides specific information to a road user. It should be noted that the event triggered messages may themselves be non-repetitive, repetitive, or a mixture of both.

In some use cases such as “See Through for Passing” or “Obstructed View”, a road user seeks video information about the surrounding area from other road users or roadside units. In “Speed Harmonisation”, a roadside unit provides speed limit information to passing road users. Whereas in “Automated Intersection Crossing”, a roadside unit provides traffic signal phase and timing information and suggested trajectories to road users.

In other use cases, event triggered communications are employed when a vehicle intends to cooperate with other road users to change lanes, navigate an intersection, join a freeway, exploit a gap in the traffic or among parked vehicles, form a group or platoon, or a range of other special manoeuvres. Although these event triggered use cases appear to vary widely in nature, the communications in many of these broadly follow the following sequence of steps:

1) A host road user notifies nearby remote road users of its intention to perform a specific manoeuvre and seeks their cooperation. As part of the same message, the host also broadcasts/groupcasts information on its status and potentially its planned trajectory for the attention of nearby remote road users.

2) The host road user receives feedback from the said remote users, either confirming their intention to cooperate, or rejecting the request.

3) Depending on the received feedback, the host road user, in turn, informs the remote road users of its decision as to whether or not to proceed with the manoeuvre. Depending on the specific use case protocol, this may follow further confirmations from the remote road users.

4) During the manoeuvre itself, and again depending on the specific use case protocol, the host road user may broadcast/groupcast regular updates with regards to its intended trajectory, before finally signalling the completion of its manoeuvre.

The above sequence is illustrated in Figure 2.2, and applies to use cases such “Cross-Traffic Left-Turn Assist”, “Group Start”, “Cooperative Manoeuvres in Emergency Situations”, “Vehicle Platooning”, “Cooperative Lane Merging”, “Coordinated Cooperative Driving Manoeuvre”, “Interactive VRU Crossing”, “Cooperative Lateral Parking”, and “Cooperative Traffic Gap”.

In practice, the number of steps can vary from one use case to another and is also dependent on the implementation. Furthermore, given that the steps are sequential and do not occur simultaneously, only one of the steps – that which requires the greatest amount of information communicated in the shortest time – defines the spectrum needs of each use case. It should be pointed out that, event triggered use cases also benefit from the continual repetitive messages addressed elsewhere in this report.

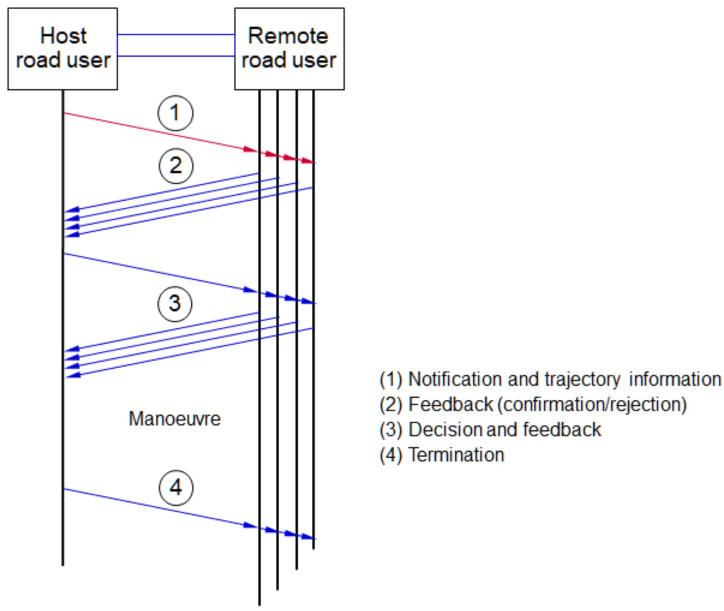

Figure 2.2: Typical message flow for use cases involving event triggered messages.

In general, the spectrum needs B (Hz) of the event triggered communications can be calculated as

$$B = \frac{N}{(e.u)\,T}, \qquad (2.6)$$

where N is the total number of bits to be delivered over a total time period of T seconds, and the product $(e.u)$ is the effective spectral efficiency (as described earlier). For use cases which consist of multiple sequential steps, as shown in Figure 2.2, the above parameters would correspond to the most demanding step.

It should, however, also be pointed out that the aggregate contribution of event triggered use cases to the overall ITS spectrum needs is somewhat stochastic in nature, in the sense that this will depend on the number of simultaneous – or near simultaneous – occurrences of the various use cases (to the extent that their respective messages would overlap in time) within a geographic area. The statistics for the simultaneous occurrence of event triggered use cases can be modelled through simulations of the behaviours of road users in various environments, and is beyond the scope of this report.

2.3. Methodology: Security overheads

We propose to account for the additional spectrum needs of security overheads by appropriately increasing the value of the number of bits N in Equations 2.2 and 2.6. This is in order to include the communication of security certificates and signatures in different messages.

Day-1 use cases

Day-1 use cases are characterised by the use of continual repetitive CAMs/BSMs of around 300 bytes (see Section 4.1). The payload for CAMs/BSMs is considered to already include any security overheads [25][26].

Advanced use cases – continual repetitive communications

Advanced use cases may involve the communication of continual repetitive messages of various sizes (see Section 5).

For the purposes of this report, we consider that one in five transmitted messages should include a security overhead of around 265 bytes (a certificate of 165 bytes[1] plus a signature of 100 bytes[2]), and that the remaining four in five transmitted messages should each include a security overhead of around 100 bytes (signature plus certificate digest only). This implies an added average security overhead of (1/5)265 + (4/5)100 = 133 bytes per continual repetitive message.

We note that the above values are broad estimates, and can vary depending on the certificate contents and uses.

Advanced use cases – event triggered communications

Advanced use cases may involve the communication of event triggered messages of various sizes (see Section 5.3), with the events themselves taking place over relatively short amounts of time (of the order of up to tens of seconds).

For the purposes of this report, we consider that the first event triggered message transmitted by a road user should include a security overhead of 265 bytes (a certificate of 165 bytes plus a signature of 100 bytes), while the subsequent transmitted messages should each include a security overhead of 100 bytes (signature plus certificate digest only).

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[1] In Europe, explicit security certificates of around 165 bytes have been specified [25]. In the US, implicit security certificates of around 100 bytes have been specified [27]. We note that these values are as per the state of the art today, and would need to be revised as and when additional standards emerge in the future. We propose to use the value specified in Europe as an upper bound for purposes of spectrum needs evaluation.

[2] See [27].

3. Spectrum needs evaluation methodology for V2N network-based communications

3.1. Overview

In the following we analyse a selection of the V2N use cases described in Section 1.

For the use cases considered here, we derive capacity density requirements based on the 5GAA use case descriptions. For each case we focus the analysis on rural, urban and dense urban scenarios, or a combination of them depending on the considered use case. This is to account for lower geographic densities of vehicles along rural roads in contrast to high traffic areas such as those in dense urban and dense suburban locations.

3.2. Network deployment

For rural environments, we assume a linear deployment of mobile network sites (eNB/gNB) along the considered road, and we assume that all the traffic is generated along such a road. This is illustrated in Figure 3.1. Mobile network deployments today tend to be different from the assumed deployment as they are optimised to deal with the local data traffic conditions, and do not necessarily consist of dedicated base stations along rural roads. Nevertheless, the assumed geometry is expected to be sufficient to capture the main factors which influence the spectrum needs of the considered use cases.

In the analysis of the spectrum needs, we calculate the network capacity that is required for each eNB/gNB by considering cell sectors that are aligned with the road. We consider a rural inter-site distance (ISD) of 5 km and a sector width of 1 km, implying a sector area of $A = 2.5 \times 1 = 2.5$ km^2 which aims to provide a highly optimised road-coverage deployment.

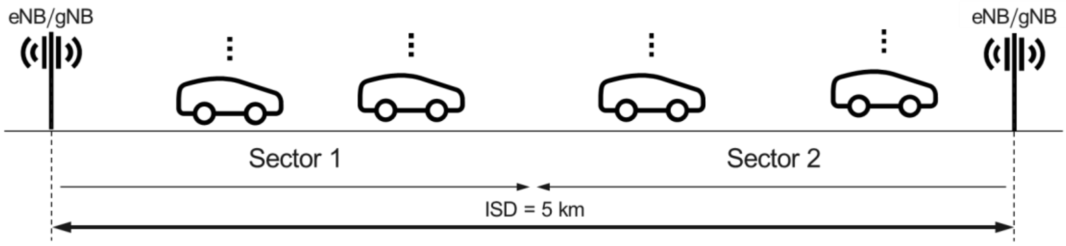

Figure 3.1: Assumed network deployment in rural environments.

For our analysis in urban and dense urban environments, we consider a typical three-sector deployment with an ISD of 500 m. Assuming a conventional hexagonal cell structure, the sector area is then given as $A = (1/2\sqrt{3})$ ISD^2 = 0.072 km^2. This is illustrated in Figure 3.2 below.

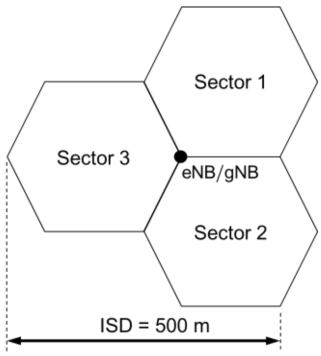

Figure 3.2: Assumed network deployment in urban and dense urban environments.

3.3. Methodology

This analysis derives the amount of spectrum that is required by mobile network operators (MNOs) in order to support the system capacity required for selected automotive services. For practical reasons, a number of simplifications have been consciously applied:

- Cell-edge performance requirements are not explicitly accounted for in this analysis. The calculated spectrum needs may therefore not necessarily be sufficient for demanding applications at cell edge, and should be viewed as a lower bound.
- Only a subset of the many automotive use cases and services identified by 5GAA are included in this analysis. The results should be seen as a minimum requirement for a realistic spectrum demand.
- Mobile operator network capacity is shared between automotive and other customers. Only automotive spectrum needs are considered in this analysis, and the manner in which network capacity is divided among various customers is a matter for MNO policy and business strategy.
- Mobile network deployments for rural environments are assumed to be optimised for automotive traffic, which is not always the case in real-world deployments.
- There is a certain connection between the growth of high-value services and network densification. Current deployment density assumptions are based on the first phase of 5G deployments, and denser deployments may become a reality depending on market growth and supporting public policies.
- The actual performance depends on network and user equipment (UE) capabilities, in addition to available radio resources. Reference values based on field measurements and theoretical studies are used in this work.

Subject to the above caveats, the spectrum needs B (Hz) for V2N communications can be calculated as

$$B = \frac{R_D\,A}{e} = \frac{R\lceil M_D A\rceil}{e}, \tag{3.1}$$

where R_D is the required data rate per unit area in bit/s/km^2, M_D is the density of (transmitting or receiving) vehicles or sensors served per unit area in km^{-2}, R is the required average data rate per link in bit/s, A is the area of the serving sector in km^2, and e is the sector spectral efficiency in bit/s/Hz. The rounding operation avoids fractional numbers of users.

As outlined earlier, we assume A = 2.5 km^2 and 0.072 km^2 in rural and urban environments, respectively. Values for spectral efficiency are discussed next.

The evaluation of spectrum demand is carried out individually per use case. We clarify whether the demand primarily affects the downlink or the uplink, as this may have implications on suitable frequency division duplex (FDD) allocations and time division duplex (TDD) patterns.

3.4. Spectral efficiency

Rural environments

Reference to a commercial rural LTE deployment [4] at 800 MHz indicates a sector capacity of 12 Mbit/s (DL) and 6 Mbit/s (UL) for a 10+10 MHz FDD deployment. This gives an average LTE downlink spectral efficiency of 1.2 bit/s/Hz and an LTE uplink spectral efficiency of 0.6 bit/s/Hz. We remark that these field measurements are not far from indications by IMT-Advanced [5], which can be seen as an indication of the realism of the assumptions.

Assuming a more capable and efficient NR deployment (higher physical resource block density per carrier, improved reliability, lean design without common reference signals for lower cell-edge interference) and better UE capabilities, we assume an increased average spectral efficiency of +20% for 5G-based evaluations. We thereby assume rural environment spectral efficiencies of 1.44 and 0.72 bit/s/Hz on the downlink and uplink, respectively.

It is important to observe that for some use cases that are demanding on the radio link, cell-edge performance will be the critical KPI (more so than system capacity) and the actual spectrum needs might be greater than calculated in this report. Also, MNOs may need to adopt special deployment strategies to meet demand for continuous services across cell edges. Such strategies include increased low-band bandwidth and possibly the addition of mid-band for offloading the low-bands.

Urban environments

Reference to a commercial urban LTE deployment [4] at 1800 MHz indicates a sector capacity of 40 Mbit/s (DL) and 12 Mbit/s (UL) for a 20+20 MHz FDD deployment with 4×4 DL MIMO. This gives an average LTE downlink spectral efficiency of 2 bit/s/Hz and an LTE uplink spectral efficiency of 0.6 bit/s/Hz. Assuming a more capable and efficient NR deployment and better UE capabilities, we assume a doubled average spectral efficiency for 5G-based evaluations. We thereby assume urban spectral efficiencies of 4 bit/s/Hz and 1.2 bit/s/Hz on the downlink and uplink, respectively.

Dense urban environments

Reference to a commercial dense urban LTE deployment [4] at 1800+2600 MHz indicates a sector capacity of 80 Mbit/s (DL) and 12 Mbit/s (UL) for a 20+20 MHz FDD deployment, with DL CoMP and 4×4 DL MIMO. This gives an average LTE downlink spectral efficiency of 2 bit/s/Hz and an LTE uplink spectral efficiency of 0.6 bit/s/Hz. Assuming a more capable and efficient NR deployment and better UE capabilities, we assume a doubled average spectral efficiency for 5G-based evaluations. We thereby assume dense urban spectral efficiencies of 4 bit/s/Hz and 1.2 bit/s/Hz on the downlink and uplink, respectively.

Not surprisingly, this is the same spectral efficiency obtained for the urban case, consistent with the fact that the same ISD is assumed for both scenarios.

4. Evaluation of spectrum needs for day-1 use cases with direct communications

In this section we evaluate the spectrum needs of day-1 use cases which employ direct communications as described in Section 1 and based on the methodology developed in Section 2.

In Section 4.1 we focus on continual repetitive messages (CAM/BSM) [6][7][9] for V2V and V2I communications. These correspond to use cases such as “Cross-Traffic Left-Turn Assist”, “Intersection Movement Assist”, “Emergency Brake Warning”, “Traffic Jam Warning”, “Real-Time Situational Awareness”, “Lane Change Warning”, and “Automated Intersection Crossing”.

4.1. Day-1 use cases involving continual repetitive messages

As described in Section 2, the spectrum needs B (Hz) for continual repetitive messages can be calculated as

$$B = \frac{M\,N\,F}{e\,u}, \tag{4.1}$$

where M is the number of vehicles (transmitting stations), N is the number of bits per message, F is the message repetition rate in Hz, e is the spectral efficiency in bits/s/Hz, and u is the channel utilisation factor. Note that the activity factor a is not included in Equation 4.1. This is because for day-1 basic safety use cases all road users equipped with ITS radio stations are required to transmit the relevant messages, that is to say, a = 1.

As indicated in Section 1, the requirements for continual repetitive messages in day-1 services can be broadly met by messages of N = 300 bytes at a repetition rate F of up to 10 Hz (24 kbit/s) for V2V communications, and the delivery of traffic light and map information at intersections at a rate of 8.8 kbit/s for V2I communications. Furthermore, as shown in Section 2.1.1, we have e = 0.6 bit/s/Hz and u = 0.336 for Rel. 14 C-V2X for application in day-1 use cases.

The matter of repetition rates for CAMs (Europe) and BSMs (US) deserves further elaboration.

- We note that according to specifications in Europe the repetition rate of CAMs varies as a function of vehicle speed. Specifically, according to ETSI EN 302 637-2 [8] the time interval between CAMs is a function of the speed of the vehicle, any change in direction (heading) and any change in speed. Each of these parameters can trigger the generation of a CAM when they exceed a specified threshold[3]. Furthermore, the minimum and maximum time intervals between CAMs are set to 0.1 and 1 seconds, respectively. Therefore, for a vehicle which travels in a straight line and at constant speed v (m/s), a CAM is generated at every 4 m; that is to say, the CAM repetition rate F (Hz) is given as

$$F = max\left\{min\left\{\frac{v}{4}, 10\right\}, 1\right\}. \tag{4.2}$$

- The above is in contrast with the approach in the US where the congestion control mechanism specified in SAE J3161/1 is a vehicle density based rate control algorithm [9][10]. The general principle is to set the maximum BSM generation interval Max_ITT according to the density of surrounding vehicles within a specific range. The density is determined from the number of the detected remote vehicles that transmit BSMs within a specific range as defined by the profile.

  The mechanism calculates the maximum BSM generation interval Max_ITT (ms) as

$$Max\_ITT(k) = \begin{cases} vMin\_ITT & N_s(k) \le B \\ vMin\_ITT \times \dfrac{N_s(k)}{B} & B < N_s(k) < \dfrac{vMax\_ITT}{vMin\_ITT} \times B \\ vMax\_ITT & \dfrac{vMax\_ITT}{vMin\_ITT} \times B \le N_s(k) \end{cases} \tag{4.3}$$

  where $N_s(k)$ is the number of vehicles observed within a specific range at the k^{th} instance [9], B is the density co-efficient *vDensityCoefficient*, and $vMin\_ITT$ and $vMax\_ITT$ are the minimum and maximum thresholds, respectively.

[3] A CAM is generated as a result of any of the following events: A change in position by 4 m or more, a change of direction of +/- 4° or more, or a change of speed of 0.5 m/s or more.

SAE J3161/1 specifies *vDensityCoefficient* as 25, $vMin\_ITT$ as 100 ms, and *vMax_IT* as 600 ms [10]. That is to say, maximum BSM generation interval Max_ITT (ms), and consequently the repetition rate F (Hz), is given as

$$Max\_ITT = max\{min\{4N_S, 600\}, 100\} = 10^3 F^{-1} \,. \tag{4.4}$$

This means that if the number of remote vehicles within the relevant range is less than 25, BSMs are transmitted every 100 ms, whereas if the number of remote vehicles is greater than 150, BSMs are transmitted every 600 ms. If the number of remote vehicles is between 25 and 150, then BSMs are transmitted every 100 to 600 ms.

Furthermore, the range, i.e., the maximum distance between the host vehicle and the remote vehicles, that is used to calculate N_S in Equations 4.3 and 4.4 is set to 100 m in SAE J3161/1. However, the range is also impacted by the environment. If the actual communication range is less than 100 m, this means that the host vehicle can only receive the BSMs reliably from vehicles that are less than 100 m away. For the purpose of this study, the range value used for the calculation of N_S is set to the minimum of 100 m and the effective communication range.

The implications of ETSI and SAE specifications on the CAM and BSM generation rates are illustrated in Figure 4.1.

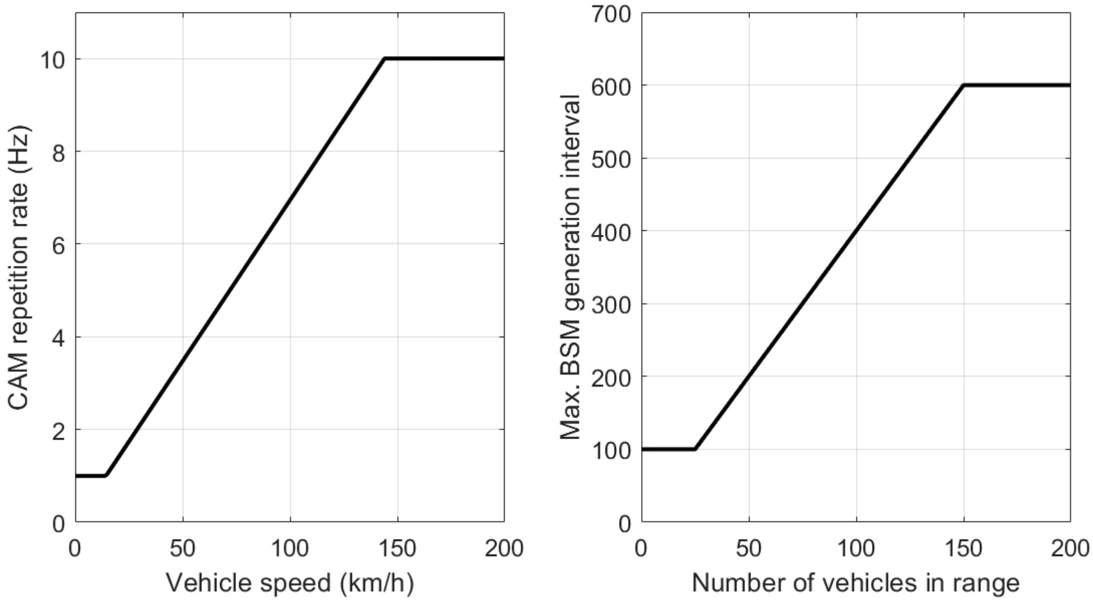

Figure 4.1: CAM and BSM generation parameters based on ETSI and SAE specifications.

4.1.1. Urban scenario

In this section we evaluate the spectrum needs for continual repetitive messages which might be expected for day-1 services in urban scenarios. We use the urban intersection topology which is described in Annex B, with 90 stationary vehicles and a varying number of moving vehicles depending on the number of flyovers and vehicle speeds.

Table 4.1 shows the estimated spectrum needs for repetitive CAMs for V2V communications in these urban scenarios. Note that the CAM repetition rate F for vehicles speeds of 0, 5, and 15 km/h is 1 Hz, and for 30 km/h this is 2.1 Hz.

Table 4.1: Day-1 spectrum needs for repetitive messages in urban scenarios (ETSI speed-dependent repetition rate).

	Speed, *v* (km/h)		
	Case 1	Case 2	Case 3
	5	15	30
Message size, N (byte)	300		
Periodicity of messages, stationary, F_0 (Hz)	1		
Periodicity of messages, moving, F (Hz)	1	1	2.1
Number of stationary vehicles, M_0	90		
Number of moving vehicles, M_1 (no flyover)	78	42	24
Number of moving vehicles, M_2 (+ 1 flyover)	156	84	48
Number of moving vehicles, M_3 (+2 flyover)	234	126	72

Spectral efficiency, e (bits/s/Hz)	0.6		
Channel utilisation factor, u	0.336		
Spectrum needs, B (no flyover) (MHz)[(a)]	2.0	1.6	1.7
Spectrum needs, B (+1 flyover) (MHz)[(b)]	2.9	2.1	2.3
Spectrum needs, B (+2 flyovers) (MHz)[(c)]	3.9	2.6	2.9

a) $B = 8N(M_0F_0 + M_1F)/(e\ u)/10^6$
b) $B = 8N(M_0F_0 + M_2F)/(e\ u)/10^6$
c) $B = 8N(M_0F_0 + M_3F)/(e\ u)/10^6$

We note that the above spectrum needs estimates for scenarios which include flyovers are subject to some additional uncertainty. This is because our evaluation methodology cannot account for the radio propagation effects across the multiple layers of flyovers and the intersection at ground level (namely flyover penetration loss vs. increased range at greater heights).

Accordingly, one can conclude from the above results that the spectrum needs for continual repetitive CAMs (where the message repetition rate is proportional to vehicle speed) for day-1 services in urban settings are likely to be less than 10 MHz.

In order to estimate the spectrum needs for repetitive BSMs for V2V communications, it is first necessary to evaluate the message repetition rate F which – according to SAE congestion control specifications (see Equation 4.4) – is a function of the number of vehicles N_S within the assumed effective communication range of 50 m. These are presented in Table 4.2.

Table 4.2: BSM repetition rate for multiple flyover scenarios and vehicle speeds.

Number of vehicles N_S, Max. interval between BSMs *Max_ITT*, BSM repetition rate F	Vehicle speed (km/h)		
	5	15	30
No flyover	168, 600 ms, 1.7 Hz	132, 528 ms, 1.9 Hz	114, 456 ms, 2.2 Hz
One-layer flyover	246, 600 ms, 1.7 Hz	174, 600 ms, 1.7 Hz	138, 552 ms, 1.8 Hz
Two-layer flyover	324, 600 ms, 1.7 Hz	216, 600 ms, 1.7 Hz	162, 600 ms, 1.7 Hz

Based on the above values of F, Table 4.3 below shows the resulting estimated spectrum needs for repetitive BSMs for V2V communications in urban scenarios.

Table 4.3: Day-1 spectrum needs for repetitive BSMs in urban scenarios (SAE congestion control).

	Speed, v (km/h)		
	Case 1	Case 2	Case 3
	5	15	30
Message size, N (byte)	300		
Periodicity of messages, no flyover F_1 (Hz)	1.7	1.9	2.2
Periodicity of messages, one-layer flyover F_2 (Hz)	1.7	1.7	1.8
Periodicity of messages, two-layer flyover F_3 (Hz)	1.7	1.7	1.7
Number of vehicles, M_1 (no flyover)	168	132	114
Number of vehicles, M_2 (+ 1 flyover)	246	174	138
Number of vehicles, M_3 (+2 flyover)	324	216	162
Spectral efficiency, e (bits/s/Hz)	0.6		
Channel utilisation factor, u	0.336		
Spectrum needs, B (no flyover) (MHz)[(a)]	3.4	3.0	3.0
Spectrum needs, B (+1 flyover) (MHz)[(b)]	5.0	3.5	3.0
Spectrum needs, B (+2 flyovers) (MHz)[(c)]	6.6	4.4	3.3

a) $B = 8N(M_1F_1)/(e\ u)/10^6$
b) $B = 8N(M_2F_2)/(e\ u)/10^6$
c) $B = 8N(M_3F_3)/(e\ u)/10^6$

A comparison of Table 4.1 and Table 4.3 indicates that the estimated spectrum needs for BSMs (based on the SAE specifications of congestion control) are broadly similar to those for CAMs (based on ETSI specification of speed-dependent repetition rates) in the examined urban scenario.

Accordingly, one can conclude from the above results that the spectrum needs for continual repetitive messages (CAMs or BSMs) for day-1 services in urban settings are likely to be less than 10 MHz.

Note that the above analysis corresponds to those day-1 use cases which use V2V communications (see Section 1). We noted there that the day-1 service, "Automated Intersection Crossing", additionally uses V2I communications. These correspond to the transmission of SPaT and MAP [9][11][12] information by an RSU at a data rate of 8.8 kbit/s, as compared to 2.4 to 4.8 kbit/s (300 bytes at about 1 to 2 Hz) transmitted by each of the 168 to 558 vehicles considered. For this reason, we can conclude that V2I communications for the "Automated Intersection Crossing" use case do not make a significant contribution to the spectrum needs in this scenario.

4.1.2. Freeway scenario

In this section we evaluate the spectrum needs for continual repetitive messages which might be expected for day-1 services in freeway scenarios. We use the multi-speed freeway topology which is described in Annex B, with a communication range of 320 m, six lanes in each direction, and with vehicle speeds of 0, 10, 60, 90, 120 and 170 km/h from the slow lane to the fast lane.

Table 4.4 shows the estimated spectrum needs for repetitive CAMs for V2V communications in this freeway scenario. Note that the message repetition rate in each lane is set in proportion to the assumed vehicle speed in that lane.

Table 4.4: Day-1 spectrum needs for repetitive CAMs in freeway scenarios (ETSI speed dependent repetition rate).

Lanes, *L*	2	2	2	2	2	2
Speed, *v* (km/h)	0	10	60	90	120	170
Message size, *N* (byte)	300					
Periodicity of messages, *F* (Hz)	1.0	1.0	4.2	6.3	8.3	10.0
Number of vehicles, *M*	214	112	28	20	16	12
Spectral efficiency, *e* (bits/s/Hz)	0.6					
Channel utilisation factor, *u*	0.336					
Spectrum needs for respective lanes (MHz)[(a)]	2.5	1.3	1.4	1.5	1.6	1.4
Total (MHz)	9.8					

a) $B = 8N\,M\,F/(e\,u)/10^6$

We can conclude from the above results that the spectrum needs for continual repetitive CAMs (where the message repetition rate is proportional to vehicle speed) for day-1 services in freeway settings are likely to be less than 10 MHz.

As outlined earlier, according to the SAE congestion control algorithm and profile, a range of 100 m is assumed to calculate the number of remote vehicles N_S. In the freeway scenario under consideration, the total number of remote vehicles that a host vehicle can detect within a range of 100 m is about 125 (i.e., 402×100/320, given the 402 vehicles within the communication range of 320 m as indicated in Table 4.4). According to the SAE congestion control algorithm, the maximum BSM generation interval is 500 ms, and so the BSM repetition rate is 2 Hz, when 125 vehicles are detected within the 100 m range.

Table 4.5 shows the resulting estimated spectrum needs for repetitive BSMs for V2V communications in this freeway scenario. Note that the message repetition rate F is fixed at 2 Hz.

Table 4.5: Day-1 spectrum needs for repetitive BSMs in freeway scenarios (SAE congestion control).

Lanes, L	2	2	2	2	2	2
Speed, v (km/h)	0	10	60	90	120	170
Message size, N (byte)	300					
Periodicity of messages, F (Hz)	2					
Number of vehicles, M	214	112	28	20	16	12
Spectral efficiency, e (bits/s/Hz)	0.6					
Channel utilisation factor, u	0.336					
Spectrum needs for respective lanes (MHz)[(a)]	5.1	2.7	0.7	0.5	0.4	0.3
Total (MHz)	9.6					

a) $B = 8N\,M\,F/(e\,u)/10^6$

Again, a comparison of the results of Table 4.4 and Table 4.6 indicates that the estimated spectrum needs for BSMs (based on the SAE specifications of congestion control) are broadly similar to those for CAMs (based on ETSI specification of speed dependent repetition rates) in the examined freeway scenario.

Accordingly, one can conclude from the above results that the spectrum needs for continual repetitive messages (CAMs or BSMs) for day-1 basic safety services in freeway settings are likely to be less than 10 MHz.

4.2. Considerations on shockwaves

According to SAE and ETSI specifications, road users must transmit high priority messages and at high repetition rates when they are involved in special events. Some of these events happen occasionally, and last just a few seconds, resulting in event triggered messages (e.g., ABS warnings) from a vehicle. The traffic generated by such event triggered messages – along with their corresponding spectrum needs – tend to be marginal. However, other events may cause a chain reaction, and result in bursts of event triggered messages transmitted from multiple vehicles in a geographic area. These events are known as shockwaves. Shockwaves can be seen in the cascading of brake lights upstream along a highway. They are often caused by, for example, a change in capacity on the roadways (a four-lane road drops to three), an incident, a traffic signal on an arterial, or a merge on the freeway. Sometimes, just heavy traffic flow alone (flow above capacity) can also induce shockwaves [13].

Let us consider an example of a shockwave that is caused by an accident. In one direction of a six-lane freeway, a vehicle's tyre punctures, and the vehicle starts sliding laterally. Here all lanes can be impacted, and the vehicles in the adjacent lanes may also have to brake hard, subsequently resulting in the vehicles following behind doing the same thing. The shockwave may last for tens to hundreds of seconds and can involve hundreds of vehicles.

In high traffic environments, the event triggered messages caused by a shockwave could be transmitted more frequently than the regular BSM transmission whose repetition rate is controlled by congestion control mechanisms. In the event of a shockwave, event triggered BSMs would be transmitted at intervals of 100 ms. Once the shockwave has died away, the transmission rate of BSMs can once again be determined by the congestion control mechanism. So the transmission of BSMs is significantly increased when a shockwave event occurs, and additional spectrum would be required to address road user safety in such scenarios.

Figure 4.2 further illustrates an example of a shockwave in a high traffic freeway environment. Here, in one direction of the freeway, vehicles transmit event triggered messages (to signal hard braking or lateral slides) at a high repetition rate due to the occurrence of a shockwave. In the opposite direction, the vehicles continue to transmit periodic BSMs under steady state conditions and subject to a repetition rate that is defined by the congestion control mechanism. The overall spectrum needs is then the sum of the spectrum needs of the event triggered BSMs (in one direction) and periodic BSMs (in the opposite direction).

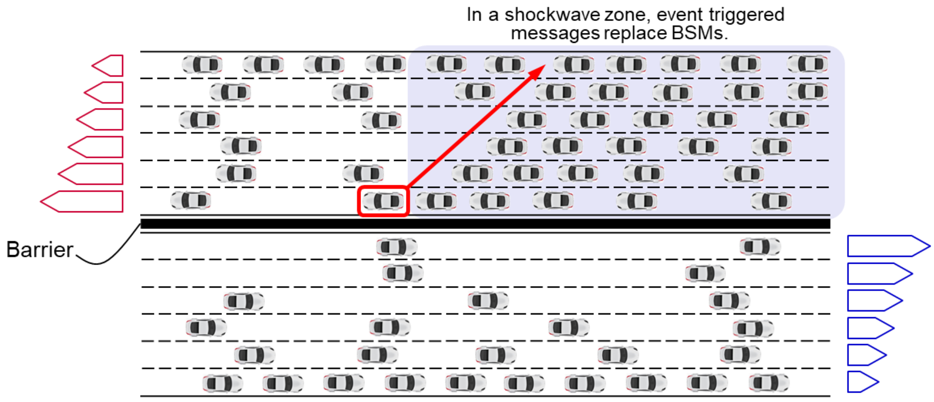

Figure 4.2. Illustration of a shockwave event due to a tyre puncture.

Shockwaves are complicated events, and deserve careful examination. Shockwaves are of major concern for transportation agencies because the sudden change of conditions which drivers experience as they pass through a shockwave often cause accidents. The traffic burst introduced by the event-trigger messages from a group of vehicles results in a chain reaction which demands additional spectrum, and because these messages are of higher priority to ensure the safety of road users, measures such as congestion control are not applicable.

We intend to investigate shockwave events and the parameters of the required messages, such as the size of the relevant event triggered BSM and DENM messages, the duration of the event, the number of involved vehicles, and the geographic extent of the shockwave, etc. Based on these parameters, we can further study the amount of spectrum that is necessary to accommodate vehicles that are involved in such shockwave events and which transmit BSMs/DENMs to alert other road users in order to reduce casualties.

4.3. Summary: Spectrum needs for day-1 use cases

In this section, we have analysed the spectrum needs of continual repetitive CAMs and BSMs in urban and freeway scenarios. This analysis is based on CAM and BSM repetition rates as specified by ETSI and SAE, respectively. Based on the results, we conclude that the spectrum needs for continual repetitive messages in day-1 basic safety use cases are at least 10 MHz under nominal traffic dynamics.

However, in practice, vehicles need to transmit additional CAMs/BSMs in response to abnormal traffic dynamics, or if the tracking error exceeds a certain threshold. For example, more frequent CAM/BSM transmissions are necessary when vehicles pass through an accident-prone curvature in the road. Additional spectrum may be needed in such circumstances and is for further study in a future edition of this report.

Traffic shockwaves are another example of the types of event which can lead to more frequent C-V2X message transmissions. This is the case where vehicles perform hard brakes to avoid collisions, and result in a frontline of hard braking which back propagates along the road. The vehicles along the shockwave frontline then also perform hard brakes and need to transmit DENMs or BSMs to alert the vehicles behind. Shockwaves cause instances of message outbreaks, and additional spectrum may be needed to accommodate such emergency circumstances. This is for further study in a future edition of this report.

Taking the above considerations into account, we recommend that at least 20 MHz of spectrum be allocated at 5.9 GHz to support continual repetitive messages for direct communications in day-1 basic safety use cases to accommodate both nominal and abnormal traffic dynamics.

5. Evaluation of spectrum needs for advanced use cases with direct communications

In this section we evaluate the spectrum needs of advanced use cases which employ direct communications as described in Section 1 and based on the methodology developed in Section 2.

In Section 5.1 we focus on the spectrum needs of continual repetitive messages in V2V direct communications for use cases such as “Sensor Sharing for AVs” and variations thereof (cooperative perception) in a freeway environment.

In Section 5.2 we analyse the spectrum needs of continual repetitive messages in V2P direct communications for the use case “Vulnerable Road User” in a densely populated urban environment.

In Section 5.3 we investigate the spectrum needs of a number of direct communications use cases which involve event triggered messages, with specific focus on “Group Start” and “Cooperative Lane Merging”.

Finally, in Section 5.4 we consider the spectrum needs of a number of miscellaneous advanced use case.

5.1. Advanced use cases involving continual repetitive messages (cooperative perception)

“Cooperative Perception” involves the sharing of information about the current driving environment among ITS stations. For this purpose, a host vehicle provides data about surrounding objects/road users in the form of abstract descriptions. Cooperative perception is often also referred to as “Sensor Sharing”.

In evaluating the spectrum needs of “Cooperative Perception”, we must establish the number of road users which are sensed by a host vehicle. This number depends on the specific scenario, the diminishing returns of sensing increasing numbers of road users, as well as the computational load which can be supported by the host vehicle. This is an important area for future research. For the purposes of this report, we consider a range of 9 to 100 for the number of sensed road users.

It is also important to note that it would not be necessary for a host vehicle to sense – or share information about – road users which are equipped with ITS. This is because such road users will already be sharing information about themselves via continual repetitive CAMs or BSMs. In other words, it is only necessary for a host vehicle to sense – or share information about – road users which are not equipped with ITS. The implication is that:

- Where the penetration of ITS among road users is low, there are relatively few host vehicles to transmit cooperative perception messages, although those few which do transmit would sense many road users (those not equipped with ITS). One might expect the spectrum needs to be low here (in fact, zero, where ITS penetration is zero).
- Where the penetration of ITS among road users is high, many host vehicles would transmit cooperative perception messages, but they would be sensing very few road users (those not equipped with ITS). Again, one might expect the spectrum needs to be low here (in fact, zero, where there is full ITS penetration).

It would then stand to reason that the amount of transmitted cooperative messages (and hence the spectrum needs) would be maximised for a specific level of ITS penetration among road users.

Let us consider an ITS penetration rate of p ($0 \leq p \leq 1$) among M road users. Then the number of vehicles which would transmit cooperative perception messages would be pM, with the messages containing information on $(1-p)M$ road users (those not equipped with ITS). The spectrum needs would then be proportional to the product of the two terms, i.e., $p(1-p)M^2$, and would in turn be maximised at $p = 0.5$.

We therefore propose to use an ITS penetration rate of p = 0.5 in evaluating an upper bound on the spectrum needs of “Cooperative Perception”. Note that the penetration rate p is also equal to the maximum activity factor a (see Section 2); i.e., $a \leq p$. Accordingly, we also propose to consider a maximum activity factor of a = 0.5.

Notably, “Cooperative Perception” may include redundancy mitigation techniques [17] to reduce duplication of sensor sharing information communicated by different ITS stations. On the one hand, in order to avoid the broadcasting of information about the same road user by multiple ITS stations, information on detected road users may be filtered prior to inclusion in the sensor sharing messages. On the other hand, the accuracy of (and confidence in) the estimated parameters – such as the position and speed of sensed road users – increases with the number of ITS stations which share information about the same road users.

Ultimately, the nature of the road users whose information is included in the sensor sharing messages would be decided by proprietary redundancy mitigation algorithms implemented by vehicle OEMs, and is a topic for future research. For the purposes of this study, we consider that zero redundancy – while efficient from a spectrum needs perspective – is not strictly a desired feature, and that a redundancy factor of around 2 to 3 might be more appropriate. Therefore, we first calculate the activity factor which would result in zero information sharing redundancy; i.e., full redundancy mitigation. We subsequently multiply this by 3 for the purposes of calculating the spectrum needs.

We must emphasise that the assumed redundancy factor of 3 is based on our current expectation of what might be required. But this is an open issue for the industry, and other levels of redundancy in sensor sharing may actually be implemented in the future in support of automated driving.

"Cooperative Perception" use cases have been studied by multiple organisations, and several solutions have been proposed [14][15][16]. Although the proposed solutions have not yet fully converged, they can be used to guide our spectrum needs study, and are described next.

Solution 1 – Toyota

According to a study by Toyota Research [14], the sensor sharing message size can be modelled as (350 + 50n) bytes, where 350 bytes is assumed to be the average payload size for repetitive messages and n is the number of other road users that are being observed by the host vehicle's sensors, each represented by 50 bytes of information. We consider that the 350 bytes includes any overheads associated with security certificates and signatures.

However, the study itself does not give an indication of the expected number of road users which might be sensed, nor the repetition rate of the messages.

Considering the scenario of Figure 5.1, the central red host vehicle may wish to sense a total of 25 surrounding road users. We assume an ITS penetration rate of 50% (see earlier); i.e., half of the vehicles transmit continual repetitive CAMs or BSMs, and sensed data in relation to these vehicles need not be shared. Consequently, the number of sensed road users whose information is shared by the host vehicle would be $n = 12$, resulting in a sensor sharing message size of 350 + (50×12) = 950 bytes. We assume a message repetition rate of 10 Hz, noting that the repetition rate may be reduced subject to congestion control mechanisms (not quantified in this study).

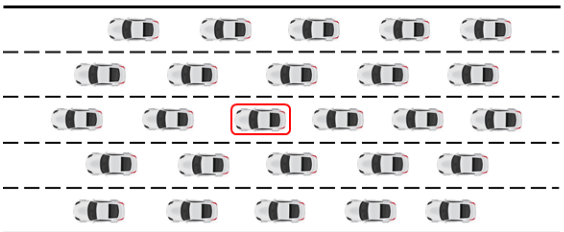

Figure 5.1: Host vehicle (red) senses surrounding vehicles.

In the absence of any redundancy mitigation mechanisms, we assume a maximum activity factor of $a = 0.5$, consistent with the ITS penetration rate of 50%.

Naturally, there would be a great deal of redundancy if every vehicle equipped with ITS shared information regarding its surrounding road users ($a = 0.5$). To reduce the redundancy, mitigation mechanisms can ensure that only a subset of ITS equipped vehicles are required to transmit and share sensing information with the surrounding road users. For example, given Figure 5.1, it is evident that zero redundancy can be achieved with an activity factor of $a = 1/(25+1)$. For the purposes of this study, we propose to consider a redundancy factor of 3, and therefore use a minimum activity factor of $a = 3/26 = 0.12$ in this scenario.

Solution 2 – ETSI

ETSI has developed a technical report and specification on a Collective Perception Service [15][17]. Repetitive collective perception messages (CPMs) are exchanged between ITS stations to enable collective perception of road users that have been detected and recognised as entities that are not themselves equipped with ITS stations.

According to [17], the CPM size can be modelled as (121 + 35 + 35n) bytes, where n is the number of other road users that are being observed by the host vehicle's sensors, each represented by 35 bytes of information, and the CPM generation frequency can be up to 10 Hz. We consider that the cited CPM size does not include any security overheads. The generation frequency is determined by taking into account the dynamic behaviour/status of the detected objects (e.g., change of location, speed or direction), the communication of CPMs relating to road users that are also sensed by other ITS stations, as well as the radio channel load as determined by decentralised congestion control. We assume a generation frequency of 10 Hz.

The ETSI CPM model [17] considers that in order to reduce information duplication, CPMs exclude information on vehicles which themselves transmit CAMs/BSMs. CPMs may also exclude information on objects whose information is being shared via CPMs by other vehicles (redundancy mitigation).

For the purposes of this study, we assume that a maximum of 18 or 60 surrounding road users can be sensed by a host vehicle, corresponding to low and high levels of sensing capability, respectively. We again assume an ITS penetration rate of 50% (see earlier); i.e., half of the vehicles transmit continual repetitive CAMs, and sensed data in relation to these vehicles need not be shared. The CPM payload size can then be calculated as follows:

- **Case-1:** With a total of 18 sensed road users at 35 bytes each, information is shared in relation to only 18×0.5=9 sensed road users, implying a CPM packet size of 156 + (9×35) = 471 bytes.
- **Case-2:** With a total of 60 sensed road users at 50 bytes each, information is shared in relation to only 60×0.5=30 sensed road users, implying a CPM packet size of 156 + (30×35) = 1206 bytes.

We expect that the above message sizes do not include security overheads. These can be accounted for by the addition of an average security overhead of 133 bytes to the above message sizes (a 165+100 byte certificate plus signature once every 5 messages, and 100 byte signatures plus certificate digests in each of the subsequent 4 out of 5 messages). Consequently, the CPM sizes can be calculated as 604 and 1339 bytes for Cases 1 and 2, respectively.

Again, in the absence of any interference mitigation mechanisms, we assume a maximum activity factor of a = 0.5, consistent with the ITS penetration rate of 50%.

Redundancies in information sharing can be eliminated via appropriate redundancy mitigation mechanisms, corresponding to activity factors of a = 1/(18+1) and 1/(60+1) for Cases 1 and 2, respectively. For the purposes of this study, we propose consideration of a redundancy factor of 3, and therefore use minimum activity factors of a = 3/19 = 0.16 and a = 3/61 = 0.05 for Cases 1 and 2, respectively.

We evaluate the spectrum needs of both cases.

Solution 3 – 3GPP

Another example of "Cooperative Perception" is given by 3GPP.

According to 3GPP TR 22.886 [21], the relevant use case "Information Sharing for Partial/Conditional Automated Driving" can be interpreted as automated driving at SAE Level 3 automation, where non-short inter-vehicle distance (e.g. > 2 seconds × vehicle speed) is assumed and abstracted/coarse data exchange is considered sufficient. The service flow is as follows:

1) Each ITS equipped vehicle shares with other vehicles information on objects that are detected by its sensors and/or on its coarse driving intention.
2) Each vehicle obtains the information on surrounding objects that cannot be obtained only from its local sensors and also obtains the driving intention of the other vehicles in its proximity.

According to 3GPP, the message payload size for "Cooperative Perception" can be 6500 bytes. This corresponds to the message size of V2V advanced driving use case R.5.3-002 in 3GPP TS 22.186 [18], which was one of the use cases recommended by SAE in [19]. According to [21], the message size for information sharing corresponds to 60 bytes/object, and the payload includes information on 100 sensed objects. This results in a payload size of 6000 bytes for sensor sharing, and implies an additional 500 bytes used for sharing coarse driving intention by the host vehicle. The messages of 6500 bytes would be transmitted at a repetition rate of 10 Hz, implying a data rate of 520 kbit/s. The effective communication range corresponds to a 10 second interval at the maximum relative speed.

Based on [21], we assume that the above message size does not include security overheads. These can be accounted for by the addition of an average security overhead of 133 bytes to the above message sizes (a 165+100 byte certificate plus signature once every 5 messages, and 100 byte signatures plus certificate digests in each of the subsequent 4 out of 5 messages). Consequently, the message size can be calculated as 6633 bytes.

Again, in the absence of any interference mitigation mechanisms, we assume a maximum activity factor of a = 0.5, consistent with the ITS penetration rate of 50%.

Redundancies in information sharing can be eliminated via appropriate filtering mechanisms, corresponding to a reduced activity factor of a = 1/(200+1). For the purposes of this study, we propose consideration of a redundancy factor of 3, and therefore use minimum activity factor of a = 3/201 = 0.015.

Spectrum needs

As described in Section 2, the spectrum needs B (Hz) for continual repetitive messages can be calculated as

$$B = \frac{M\,N\,F\,a}{e\,u}, \tag{5.1}$$

where M is the number of vehicles (transmitting stations), N is the number of bits per message, F is the message repetition rate in Hz, a is the activity factor, e is the spectral efficiency in bits/s/Hz, and u is the channel utilisation factor.

The message size N and repetition rate F for the considered three "Cooperative Perception" solutions are summarised in Table 5.1.

Table 5.1: Message parameters for the cooperative perception solutions (including security overheads).

Solution		Message parameter		Notes
		N	F	
1) Toyota		950 bytes	10 Hz	(350 + 50*n*) bytes, with *n* = 12 sensed road users.
2) ETSI	Case 1	604 bytes	10 Hz	(289 + 35*n*) bytes for each of *n* = 9 sensed road users.
	Case 2	1339 bytes	10 Hz	(289 + 35*n*) bytes for each of *n* = 30 sensed road users.
3) 3GPP		6633 bytes	10 Hz	(633 + 60*n*) bytes, with *n* = 100 sensed road users.

The number of vehicles M can be derived according to the methodology outlined in Annex B for a multi-speed freeway environment, but adjusted for an effective communication range of 389 m (rather than the 320 m assumed for day-1 use cases) as specified by 3GPP. The total number of vehicles in the effective communication range is then 486.

The above parameter values, along with those of spectral efficiency and channel utilisation factor are summarised in Table 5.2.

Table 5.2: Key parameters for calculation of spectrum needs for cooperative perception.

Key parameters	Value	Notes
Number of lanes	12	Six lanes in each direction.
Time to collision (s)	2.5	For calculation of vehicle spacing.
Vehicle speed (km/h)	0-170	Assumption.
Time to effective range (s)	10	3GPP TR22.886.
Effective communication range (m) (10 seconds at relative speed of 140 km/h)	389	SA1 requirement for information sharing 22.886 Section 5.9.
Number of transmitting vehicles within the effective communication range, *M*	486	SA1 requirement for information sharing 22.886 Section 5.9.
Spectral efficiency for NR, *e* (bit/s/Hz)	0.712	See Section 2.
Channel utilisation factor for NR, *u*	0.8	See Section 2.

Table 5.3 shows the resulting spectrum needs based on Equation 5.1.

Table 5.3: Spectrum needs for cooperative perception.

Message size, *N* (byte)	Toyota	950
	ETSI Case 1	604
	ETSI Case 2	1339
	3GPP	6633
Periodicity of messages, *F* (Hz)[(a)]	Toyota	10.0
	ETSI Case 1	10.0
	ETSI Case 2	10.0
	3GPP	10.0
Activity factor, *a*	Toyota	3/26 to 1/2
	ETSI Case 1	3/19 to 1/2
	ETSI Case 2	3/61 to 1/2
	3GPP	3/201 to 1/2
Number of vehicles, *M*		486
Spectral efficiency, *e* (bits/s/Hz)		0.712
Channel utilisation factor, *u*		0.8
Spectrum needs (MHz)	Toyota	7.5 to 32.4
	ETSI Case 1	6.5 to 20.6
	ETSI Case 2	4.5 to 45.7
	3GPP	6.8 to 226.4

(a) Does not include the impact of any congestion control mechanisms.
(b) $B = 8N\,M\;F\,a\,/\,(e\,u)\,/10^6$.

As can be seen, the upper spectrum needs estimate for the 3GPP solution is quite high. This is due to the assumption that every host vehicle, or one in two vehicles on the road (activity factor of 0.5), would each share information about 100 surrounding road users.

However, in practice not all vehicles will have the capability to sense 100 objects simultaneously. As such, the assumed payload size of 6500 bytes should be strictly considered as an upper bound.

Also, as noted earlier, it is unlikely that every host vehicle would be required to share its sensor information, as this would imply the sharing of duplicated information about the same objects, and potentially significant redundancies in information sharing, especially where the number of sensed objects per vehicle is high. For this reason, in practice redundancy mitigation mechanisms could be used such that only a proportion of host vehicles would be required to share their sensor information, implying activity factors that are substantially lower than the assumed maximum of 0.5 (equal to the ITS penetration), with a proportional reduction in spectrum needs.

Furthermore, where needed, congestion control mechanisms for applications and services run over NR-V2X (yet to be defined) will also result in a reduction in the frequency of transmissions, and effectively reduce the spectrum needs as seen in Section 4 for the case of CAM/BSM in LTE-V2X.

At this stage we are unable to quantify the extent to which redundancy mitigation mechanisms should reduce the activity factor. The activity factor would in any case vary in different scenarios and environments, and would also depend on the number of objects sensed by the vehicles, with greater numbers of sensed objects implying the potential for lower activity factors. We can only provide a range of plausible activity factors from a maximum of 0.5, equal to the assumed ITS penetration rate of 50% (high information sharing redundancy), down to very small values (low information sharing redundancy – we assume a minimum redundancy factor of 3). This implies spectrum needs of the order of several MHz for less extensive sensor sharing scenarios, and up to several tens or even hundreds of MHz for more aggressive sensor sharing cases.

5.2. Advanced use cases involving continual repetitive messages (vulnerable road user)

In this use case, information on VRUs is shared with the host vehicle via roadside units (V2I) and/or mobile networks (V2N) and/or the VRUs themselves (V2P). Here, we address the V2P mode of this use case.

Note that the use case “Interactive VRU Crossing” addressed in Section 1 covers the scenario where a VRU shares its intended trajectory with other road users on an event triggered basis. In the “Vulnerable Road User” use case addressed here we consider scenarios where the VRU broadcasts continual repetitive messages in order to make other road users aware of its status.

For the purposes of this analysis we consider that the VRUs consist of pedestrians. According to [23], the VRU message sizes range from a minimum mandatory 330 bits, extending up to 6951 bits for optional extras. Excluding optional information relating to motion prediction, we assume messages of size N = 818 bits transmitted at a repetition rate of F = 1 Hz. According to [23], the repetition rate can be between 0.2 and 10 Hz. We consider 1 Hz to be a reasonable value in the context of the movement of pedestrians in densely populated environments [28]. Adding 133 bytes for security overheads (a 165 byte certificate plus a 100 byte signature once every 5 messages, and a 100 byte signature in 4 out of 5 messages), we have N = 1882 bits. Based on the urban intersection environment described in Annex B, the number of VRUs (pedestrians) within the 50 m communication range is estimated to be between M = 600 to 1560 in high population density environments. Assuming an activity factor of a = 1, an NR-V2X (PC5) spectral efficiency of e = 0.712, and a channel utilisation factor of u = 0.8 (see Section 2), the spectrum needs for this use case can be estimated as $B = M.N.F.a/(e.u)$ ~ 2 to 5 MHz.

In practice, the VRUs could form clusters of up to 50 pedestrians [23], in which case the resulting activity factor of 0.02 would imply spectrum needs of only ~ 40 to 100 kHz.

The above values are considerably less that the spectrum needs for cooperative perception.

5.3. Advanced use cases involving event triggered messages

5.3.1. Group start

"Group Start" refers to a use case whereby autonomous or semi-autonomous vehicles form a group to jointly start at a traffic light, with a traffic control centre providing information for coordination. "Group Start" can be broken down into four distinct steps/phases [2]:

- **Phase 1: Group formation –** Here the vehicles arriving at the traffic lights form a group with a lead vehicle which is itself identified by a traffic control centre. The traffic control centre – via the group lead vehicle – announces final group properties (e.g. planned manoeuvre and trajectory, including acceleration, yaw rate, etc.) and requests an acknowledgement from each vehicle. Each vehicle has the ability to opt out from the formed group.

- **Phase 2: Manoeuvre selection and initiation** – Here the lead vehicle performs additional double checks to verify that the traffic light information is correct, and initiates the manoeuvre through a message to all group participants. From this point on, the group is considered as closed and communications are within the group only. To the outside world, the lead vehicle announces the intent, position, and progress of the platoon (messages similar to CAMs/BSMs). All vehicles send updates and additional information (e.g. detour or delay due to pedestrians) to the lead vehicle (messages similar to CAMs/BSMs). The lead vehicle stays in contact with the traffic control centre, to report progress of the platoon.

- **Phase 3: Manoeuvre execution** – While executing the manoeuvre, the vehicles constantly monitor the environment. The lead vehicle takes a special role by monitoring ahead for any obstacles. All manoeuvre changes are announced by the lead vehicle.

- **Phase 4: Group release** – Following the execution of the manoeuvre, the lead vehicle signals the termination of the group, and provides a report of the group start manoeuvre to the traffic control centre.

As the above description indicates, "Group Start" includes both V2V and V2I communications. However, given that the V2I communications are only between the traffic control centre and the lead vehicle, we expect that the spectrum needs are primarily defined by the requirements of V2V communications. As such, we only examine V2V communications for the purposes of this analysis.

We also expect that much of the communications required in Phase 2 can be met with the continual repetitive messages (CAMs/BSMs) which would in any case be transmitted by all vehicles at all times, and whose spectrum needs have been investigated in Section 4. Furthermore, we do not expect the spectrum needs of Phase 4 to be demanding, given that it involves communications from the lead vehicle only, and which are not particularly time sensitive. As such, we only examine the spectrum needs of Phase 1 and Phase 3 for the purposes of this analysis.

Figure 5.2 below shows a typical "Group Start" scenario. As an illustrative example, we consider a traffic light intersection with 3 lanes in each direction. We then consider a total of K = 8 groups, with M = 10 vehicles per group.

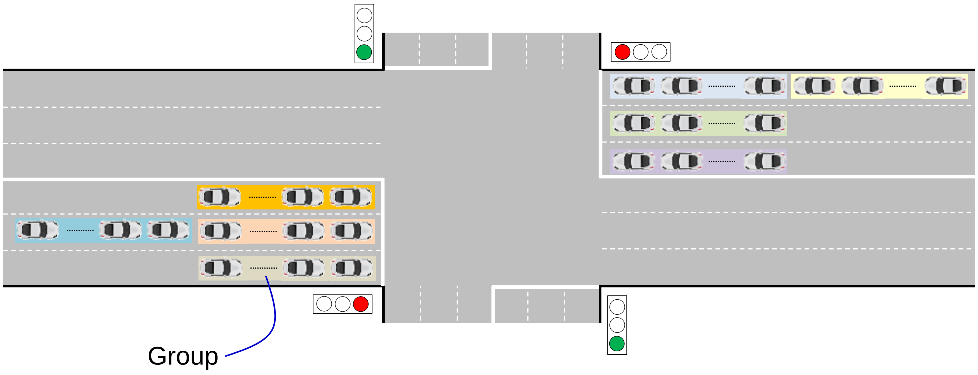

Figure 5.2: Examined "Group Start" scenario with eight groups.

Spectrum needs for group formation

The latency requirements for the communication of information during group formation are not very stringent. We consider that a time budget of T = 250 ms per message is adequate. We also consider an average message size of N = 800 bits, noting that SAE describes a minimum of 160 bits (which can go up to 2000 bits). We consider that a total of J = 7 messages are transmitted by each vehicle in the process of forming the group and exchanging relevant information.

Considering a total of K = 8 groups at the intersection, a nominal effective spectral efficiency of $e.u$ = 1 bit/s/Hz (conservative given the short ranges involved), assuming radio isolation from other nearby intersections, and that a security certificate plus signature of $N_{Cert/Sig}$ = (8×(165+100)) = 2120 bits is transmitted in the first message of each vehicle, and a security signature of N_{Sig} = (8×100) = 800 bits is transmitted in each of the subsequent 6 messages of each vehicle, then the required bandwidth for group formation can be calculated as:

$$B = \frac{N_{Total}}{(e.u)\ T_{Total}} = \frac{K\ M\ \left(N\ J + N_{Cert/Sig} + 6N_{Sig}\right)}{(e.u)\ M\ T\ J} = \frac{8 \times \left((800)(7) + 2120\ + 6(800)\right)}{1 \times 0.25 \times 7} = \ 57{,}234\text{ Hz}$$

where N_{Total} is the total number of bits to be delivered over T_{Total} seconds.

Spectrum needs for manoeuvre execution

This phase involves a single "manoeuvre start" message of up to N = 100 bits broadcast from the group lead to all the group members. We consider that the latency requirements for this communication are more stringent than in the group formation phase, and we assume a time budget of T = 20 ms per message for this purpose.

Considering a total of K = 8 groups at the intersection, a nominal effective spectral efficiency of e = 1 bit/s/Hz (conservative given the short ranges involved), assuming radio isolation from other nearby intersections, and that a security certificate plus signature of $N_{Cert/Sig}$ = (8×(165+100)) = 2120 bits is transmitted in the message by the group lead, then the required bandwidth for manoeuvre execution can be calculated as:

$$B = \frac{N_{Total}}{(e.u)\ T_{Total}} = \frac{K\ (N + N_{Cert/Sig})}{(e.u)\ T} = 8 \times \frac{(100 + 2120)}{1 \times 0.02} = \ 888{,}000\text{ Hz}$$

where N_{Total} is the total number of bits to be delivered over T_{Total} seconds.

In practice, it is possible that only a security signature (100 bytes) rather than a security certificate plus signature (165+100 bytes) would be transmitted by the group lead, in which case the spectrum needs would be lower (360 kHz).

Conclusions

Noting that the above considered phases are sequential in time, we can conclude that the spectrum needs for a "Group Start" event are of the order of several hundred kHz (approaching 1 MHz), and considerably lower than the many tens of MHz or more which might be needed by the "Cooperative Perception" use case examined earlier in Section 5.

It should be noted that the above estimate excludes the spectrum needs for the continual repetitive messages, which would in any case be transmitted by all vehicles at all times, as investigated in Section 4, and which would also support the execution of "Group Start".

5.3.2. Cooperative lane merging

"Cooperative Lane Merging" refers to a use case whereby an autonomous or semi-autonomous vehicle wishes to join the traffic on a freeway via a ramp, and communicates with the vehicles on the freeway in order to facilitate the manoeuvre.

We consider the fundamentals of a lane merge process in terms of the following steps/phases:

- **Phase 1: Request** – here the host vehicle communicates to a number of remote vehicles, announces its intention to perform a lane merge, shares relevant information, and seeks their cooperation.
- **Phase 2: Response** – here the remote vehicles signal their willingness (or not) to cooperate with the merging vehicle.
- **Phase 3: Confirmation** – here the host vehicle confirms its intention to undertake the lane merge.

As the above description indicates, "Cooperative Lane Merging" involves V2V communications. We also note that much of the information required with regards to the various vehicles will be communicated via continual repetitive messages (CAMs/BSMs) which would in any case be transmitted by all vehicles at all times, and whose spectrum needs have already been analysed in Section 4.

Figure 5.3 below shows a typical lane merge scenario. As an illustrative example, we consider a host vehicle merging on to a multi-lane freeway, and communicating with remote vehicles in the first three lanes, with the understanding that the lane merge will likely have little impact on the traffic in lanes further away. We also consider that communications occur with three rows of remote vehicles on the freeway. This identifies a group or *bounding box* which consists of one merging host vehicle, and nine remote vehicles.

Furthermore, we consider that the merge process (from the time when the remote vehicle enters the merging ramp and begins communications to when it joins the traffic on the freeway) takes a total of 20 seconds [24], and that there are 10 host vehicles on the ramp engaged in the lane merge process.

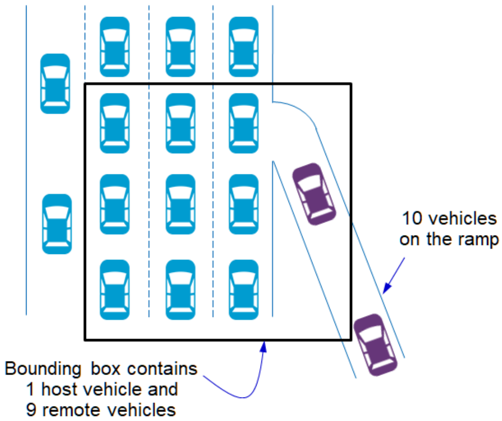

Figure 5.3: Examined lane merge scenario.

Spectrum needs

We consider that the initial lane merge request by the host vehicle is a message of around 173 bytes. This includes information on group establishment, targeted road resource, and desired timing. We consider that each remote vehicle responds with a message of around 188 bytes, which contains ACK/NACK and relevant trajectory data. Finally, we consider that the host vehicle will respond with a go/no-go message of around 29 bytes, which includes the manoeuvre start time.

If we assume that a security certificate plus signature of 165+100 bytes is transmitted in the first message of each vehicle and a security signature of 100 bytes is transmitted in subsequent messages, then with a total of 9 remote vehicles in the bounding box, this implies a total of (173+265+29+100)+(9×(188+265)) = 4644 bytes communicated for each lane merge event.

With a total of 10 vehicles on the merging ramp, and 8 merging points in the local area (e.g., for the case of a complex freeway junction), a total number of N_{Total} = 8×8×10×4644 = 2,972,160 bits would be communicated. These would be delivered over a total time period of T_{Total} = 20 seconds.

Assuming a nominal effective spectral efficiency of $(e.u)$ = 1 bit/s/Hz, the required bandwidth for "Cooperative Lane Merging" can be calculated as:

$$B = \frac{N_{Total}}{(e.u)\ T_{Total}} = \frac{2972160}{1 \times 20} = 148{,}608 \text{ Hz.}$$

Conclusions

We can conclude that the spectrum needs for "Cooperative Lane Merging" are of the order of around 150 kHz, and considerably lower than the many tens of MHz or more which might be needed by the "Cooperative Perception" use case examined earlier in Section 5.

It should be noted that the above estimate excludes the spectrum needs for the continual repetitive messages (CAMs/BSMs) which would in any case be transmitted by all vehicles at all times, as investigated in Section 4, and which would also support the execution of "Cooperative Lane Merge".

5.3.3. Trajectory information sharing use cases

As discussed in Section 2, event triggered communications are often employed in use cases where a vehicle intends to perform a special manoeuvre and wishes to inform (and seek the cooperation of) other road users. "Cooperative Lane Merging" analysed in the previous section is an example of such trajectory information sharing use cases. Table 5.4 below shows other examples of such use cases.

Table 5.4. Trajectory information sharing use cases.

	Use case
(1)	Cross-Traffic Left-Turn Assist
(18)	Cooperative Manoeuvres in Emergency Situations
(28)	Cooperative Lane Merging
(38)	Coordinated Cooperative Driving Manoeuvre
(40)	Interactive VRU Crossing
(41)	Cooperative Lateral Parking
(42)	Cooperative Traffic Gap

While these use cases might appear different, they are fundamentally similar in the sense that they involve a vehicle cooperating with other road users to change lanes, navigate an intersection, join a freeway, exploit a gap in the traffic or among parked vehicles, or perform a range of other special manoeuvres. As such, the communications involve a similar sequence of steps/phases as outlined in Section 2.

We do not present a detailed analysis of each of the above trajectory information sharing use cases in this report. However, we expect that the spectrum needs for each of these use cases are likely to be of the same order as that for "Cooperative Lane Merging" (i.e., of the order of 100 to 200 kHz) and, as such, will not contribute substantially to the overall spectrum needs at 5.9 GHz.

5.4. Advanced use cases: miscellaneous

5.4.1. Vehicles platooning in steady state

"Platooning" enables a group of vehicles of the same vehicle class (e.g., cars, trucks, buses etc.) to drive in close proximity in a coordinated manner. The head of the platoon (host vehicle) is responsible for the coordination of the other vehicles in the platoon (member vehicles), potentially with remote assistance via the cloud. With the sharing of status information (e.g., speed, heading, and intentions such as braking and acceleration) among the member vehicles, and with the support of the head vehicle, the distances between vehicles can be reduced, with resulting reductions in fuel consumption, emissions, and costs. Platooning enhances safety and efficiency by reducing the influence of unanticipated driving behaviour, and by increasing road capacity.

According to the description of the use case [2], the messages involved in the use case are as follows:

- The member vehicles in a platoon broadcast 100 byte messages at a repetition rate of 10 Hz in order to share their status and intentions with other platoon members. The information can be carried by BSMs/CAMs in the

5.9 GHz band, and the required spectrum needs for these (including overheads for security certificates and signatures) are captured in Section 4 in relation to continual repetitive messages.

- The head vehicle provides configuration information (e.g., its intended speed, acceleration and trajectory) to the member vehicles via event triggered messages of 300 bytes groupcast in the 5.9 GHz band with a latency of 100 ms. The delivery of these messages would require access to a bandwidth of up to several tens of kHz (e.g., 45.2 kHz, assuming an additional 165+100 bytes per message for a security certificate plus signature, and a conservative effective spectral efficiency of 1 bit/s/Hz given the short ranges involved), and would not have a significant spectrum need.

- The head vehicle may optionally receive information from the cloud in relation to road, weather and traffic conditions. The mobile network would transmit such information via a message of 1000 bytes at the start of a platoon and only when needed thereafter. This is a small amount of information and is not time sensitive. As a result it is not expected to have a significant spectrum need.

In summary, platooning is not expected to contribute significantly to the spectrum needs of direct or network-based communications. Both the direct communications from the head vehicle to the member vehicles, and the network-based communications to the head vehicle are event triggered and of low data rate with a small demand for spectrum at 5.9 GHz and mobile bands, respectively. The direct communications between the member vehicles are repetitive in nature, and can be accommodated in the 10-20 MHz of spectrum demanded by CAMs/BSMs for V2V communications at 5.9 GHz.

5.4.2. Vehicle decision assist

In this use case, a host vehicle detects a stationary (or slowly moving) remote vehicle ahead, and enquires about the remote vehicle's status in order to decide whether it should overtake or not. The remote vehicle responds with information on its expected duration of stay, potentially along with other information (such as whether an accident has happened, or if help is needed). This can reduce the number of unnecessary and dangerous overtaking events.

The description of the use case [2] indicates that, depending on the circumstances (e.g., whether the remote vehicle is stationary or slow moving), the remote vehicle may need to communicate 1000 bytes of data on a delay-sensitive basis (latency of 100 ms), or up to a few Mbytes but over much longer time periods.

In practice, we expect that 1000 bytes should be sufficient for most circumstances, including information on the short-term trajectory of the remote vehicle (e.g., where the latter is moving). Such communication would be event triggered and unicast over relatively short ranges, and would benefit from the use of high order modulation and coding. This might require access to a bandwidth of around a hundred kHz (e.g., 101.2 kHz, assuming an additional 165+100 bytes per message for a security certificate plus signature, and a conservative effective spectral efficiency of 1 bit/s/Hz), and is not expected to have a significant spectrum need.

In rare scenarios where communication of larger volumes (Mbytes) of data might be required (e.g., where the remote vehicle is slow moving en route), this would occur over long time intervals, and so would not result in material spectrum needs.

5.4.3. See through for passing

In this use case, a host vehicle signals its intention to pass a remote vehicle ahead by using the oncoming traffic lane. The remote vehicle then responds by transmitting a video stream which shows its front view to the host vehicle (and other vehicles) in order to assist and enhance the safety of the manoeuvre.

The description of the use case [1] indicates a data rate of 8 Mbit/s for a high-definition video stream, communicated on a unicast basis by the remote vehicle. Where this information might be useful for multiple vehicles, the communication could be provided on a broadcast or groupcast basis.

Even though the relatively short-range nature of the communication permits the use of higher order modulation and coding schemes, we expect that such video streaming from the remote vehicle to the host vehicle would require access to several MHz of bandwidth. This may place a heavy burden on the 5.9 GHz band – at the expense of other safety related use cases – especially in environments where multiple passing manoeuvres might occur simultaneously within the communication range.

Having said that, this use case is likely to be particularly important along rural roads, where the lower geographic density of vehicles – and by extension the lower overall demand for spectrum for direct communications – would favour its operation at 5.9 GHz.

5.4.4. Speed harmonisation

In this use case, the host vehicle is notified by a roadside unit of the posted speed recommendations or limits based on traffic, road and weather conditions. We assume that this is via I2V direct communications in the 5.9 GHz band, although in principle this can also be implemented via network-based N2V communication in bands designated for use by mobile communication networks.

The description of the use case [1] specifies a 300 byte message delivered with latencies of 2500 down to 400 ms. Such communications would be on an event triggered and broadcast basis. The delivery of such information would require a bandwidth of around 10 kHz (e.g., 11.3 kHz, assuming an additional 165+100 bytes per message for a security certificate plus signature, a 400 ms latency, and a conservative effective spectral efficiency of 1 bit/s/Hz), and is not expected to have a significant spectrum need.

5.4.5. Automated intersection manager/crossing

In this use case, an autonomous host vehicle receives traffic light timing information and HD maps from an intersection manager. Other vehicles and VRUs may also share their status with the host vehicle. The intersection manager may also optionally provide a suggested trajectory to the host vehicle.

We consider that the V2V/V2P communication elements of this use case can be covered via the broadcasted continual repetitive messages (CAMs/BSMs) whose spectrum needs are addressed in Sections 4.1 and 5.1, and are not discussed further.

The data exchanges with the intersection manager can be via a combination of I2V and N2V communications.

The description of the use case [2] specifies SPaT messages of N = 100 bytes broadcasted at a repetition rate of F = 1 Hz by the roadside infrastructure. We consider that this would be via V2I communications in the 5.9 GHz band. Considering a dense urban environment, with a communication range of around 50 m encompassing up to M = 3 intersections (based on a Manhattan grid), an activity factor of a = 1, an NR-V2X (PC5) spectral efficiency of e = 0.712 bit/s/Hz, and a channel utilisation factor of u = 0.8 (see Section 2), the spectrum needs for this use case can be estimated as $B = M.N.F.a/(e.u)$ ~ 4 KHz. We can therefore conclude that this I2V communication element of the use case is not expected to have a significant spectrum need. Any overheads relating to security certificates and signatures would not materially alter this conclusion.

According to the description of the use case, another I2V element includes the communication of suggested trajectories to the host vehicle. The description of the use case [2] specifies a message size of N = 400 bytes for this purpose. Considering up to around M = 80 moving vehicles within the communication range of a dense urban intersection (see Annex B), and trajectory information communicated to 10% to 20% of these (a = 0.1 to 0.2), a delivery time of T = 100 ms, similar conservative NR-V2X (PC5) spectral efficiencies and channel utilisation factors as above, and an additional 165+100 bytes per message for a security certificate plus signature, the spectrum needs for this use case can be estimated as $B = M.N.a/T(e.u)$ ~ 0.75 to 1.5 MHz. We can therefore conclude that this V2I communication element of the use case is expected to have a spectrum needs of around 1 MHz.

Finally, the description of the use case also specifies the communication of a N = 1000 byte map to the host vehicle. We consider that this would be via I2V communications, or via N2V broadcast communications in bands designated for use by mobile networks. Assuming the communication of the map in T = 1 second, similar conservative NR-V2X (PC5) spectral efficiencies and channel utilisation factors as above, and an additional 165+100 bytes per message for a security certificate and signature, the spectrum needs for this use case can be estimated as $B = N/T(e.u)$ ~ 18 kHz. We can therefore conclude that this communication element of the use case is not expected to have a significant spectrum need.

5.5. Summary: Spectrum needs for advanced use cases

In this section, we have analysed the spectrum needs of continual repetitive messages for the support of "Cooperative "Perception" use cases via NR-V2X in a freeway scenario. "Cooperative Perception" includes an important group of advanced driving use cases such as "Sensor Sharing for Autonomous Vehicles" which involve the ability of road users to share their processed sensor data with other road users on a continual basis, to provide advanced driver assistance and to facilitate autonomous driving.

The appropriate amount of sensor data which should be shared is an open question for the industry, and directly impacts the required spectrum. Our estimates of spectrum needs for "Cooperative Perception" range from several MHz up to several tens or even hundreds of MHz depending on the extent of sensing/information-sharing per vehicle, and the number of vehicles required to share their sensor information.

Our analysis of the "Vulnerable Road User" use case – which also involves continual repetitive messages – indicates that, depending on the extent of clustering among the VRUs, the spectrum needs in dense urban environments can range from several tens of kHz up to several MHz (less than 10 MHz).

In addition to the above, many other advanced driving use cases employ event triggered communications, whereby messages are exchanged over the air in response to a desire by a road user to undertake a specific manoeuvre (e.g., changing lanes, joining a freeway, crossing an intersection, or the like). Examples of such use cases include "Group Start", and trajectory information sharing use cases such as "Cooperative Lane Merging" where the road user shares its intended trajectory with other road users as part of a *handshake* exchange of information.

Our analysis indicates that the spectrum needs for "Group Start" are of the order of several hundred kHz (approaching 1 MHz), whereas the spectrum needs of "Cooperative Lane Merging" (and other similar trajectory information sharing use cases[4]) are of the order of around 150 kHz. Both are considerably lower than the spectrum needs of the "Cooperative Perception" use case.

Finally, we have analysed a number of miscellaneous advanced use cases. Our conclusion is that with the exception of "See Through for Passing", which may require several MHz for the communication of high-definition video, the spectrum needs of each of the remaining use cases[5] is unlikely to exceed at most several hundred kHz.

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[4] "Cross-Traffic Left-Turn Assist", "Cooperative Manoeuvres in Emergency Situations", "Cooperative Lane Merging", "Coordinated Cooperative Driving Manoeuvre", "Interactive VRU Crossing", "Cooperative Lateral Parking", and "Cooperative Traffic Gap".

[5] "Vehicles Platooning in Steady State", "Vehicle Decision Assist", "Speed Harmonisation", and "Automated Intersection Manager".

6. Evaluation of spectrum needs for advanced use cases with V2N network-based communications

As described in Section 3, the spectrum needs B (Hz) for V2N communications can be calculated as

$$B = \frac{R_D A}{e} = \frac{R[M_D A]}{e}, \quad (6.1)$$

where R_D is the required data rate per unit area in bit/s/km^2, M_D is the density of (transmitting or receiving) vehicles or sensors served per unit area in km^{-2}, R is the required data rate per link in bit/s, A is the area of the serving sector in km^2, and e is the sector spectral efficiency in bits/s/Hz.

The spectrum needs for a number of V2N use cases are evaluated next, based on the above formulation.

6.1. Software update of reconfigurable radio system

In this use case, the software or firmware of a host vehicle's reconfigurable radio system is updated in order to, for example, install a new feature set, a new standard release, or to comply with regional requirements. While generic software updates can often be delayed until high-capacity connectivity is available, critical updates addressing vulnerabilities require more immediate action.

According to the use case description [2], typically 10-30% of vehicles might require the service at any given time. Here, we assume an average value of 20%. For dense urban environments we assume a vehicle density of 1500 per km^2 as specified in the use case description. We assume reduced vehicle densities of 750 and 75 per km^2 for urban and rural environments, respectively (reductions by factors of 2 and 10 compared to dense urban). This implies that M_D = 15, 150 and 300 km^{-2} for rural, urban and dense urban environments, respectively. The use case description also specifies an update size of 200 Mbytes to be delivered within 1 hour, implying a link data rate of R = 0.44 Mbit/s.

The spectrum needs for this use case can then be calculated as follows:

	Rural	Urban	Dense urban
Density of served vehicles, M_D (km^{-2})	15	150	300
Link data rate, R (Mbit/s)	0.44		
Sector area, A (km^2)	2.5	0.072	
Spectral efficiency, e (bit/s/Hz)	1.44 (DL)	4 (DL)	
Spectrum needs, B (MHz)	11.6	1.2	2.4

6.2. Autonomous vehicle disengagement report

Here, when an autonomous host vehicle's virtual driver system disengages, it submits a disengagement report containing a time-windowed recording of vehicle system data, rich sensory information, and dynamic environmental conditions to the OEM and government data centres.

In this scenario, a vehicle delivers a large amount of uplink data within a short but non-critical amount of time. According to the use case description [2], 10 vehicles per km^2 should be considered as requiring the service at any given time, each uploading 2 GB of data over a minute. However, the use case description also mentions the possibility of data transfer over "hours" and "possibly days". As such, we assume a transfer time of 1 hour, implying a link data rate of R = 4.4 Mbit/s. We also assume vehicle densities of M_D = 0.5, 5 and 10 km^{-2} for rural, urban and dense urban environments, respectively.

The spectrum needs for this use case can then be calculated as follows:

	Rural	Urban	Dense urban
Density of served vehicles, M_D (km^{-2})	0.5	5	10
Link data rate, R (Mbit/s)	4.4		
Sector area, A (km^2)	2.5	0.072	
Spectral efficiency, e (bit/s/Hz)	0.72 (UL)	1.2 (UL)	
Spectrum needs, B (MHz)	12.2	3.7*	3.7*
* The urban and dense urban sectors must both support at least one user.			

6.3. Patient transport monitoring

In this use case, paramedics, patient monitoring equipment, trauma centres and doctors share vital patient telemetry data, images, voice and video during the patient's transport. Here, vital patient data is streamed in real time from an emergency vehicle and real-time feedback from an emergency unit is provided. While a mix of data streams adds to the requirements, for simplicity here we focus on real-time video and data streaming on the uplink.

The use case description [2] specifies an uplink data rate of R = 9 Mbit/s for video streaming and vital signs. The density of emergency vehicles is not provided in the description, but we assume densities of M_D = 0.5, 5 and 10 km^{-2} for rural, urban and dense urban environments, respectively.

The spectrum needs for this use case can then be calculated as follows:

	Rural	Urban	Dense urban
Density of served vehicles, M_D (km^{-2})	0.5	5	10
Link data rate, R (Mbit/s)	9		
Sector area, A (km^2)	2.5	0.072	
Spectral efficiency, e (bit/s/Hz)	0.72 (UL)	1.2 (UL)	
Spectrum needs, B (MHz)	25	7.5*	7.5*
* The urban and dense urban sectors must both support at least one user.			

6.4. Tele-operated driving

In this use case, a remote driver (human or machine) operates a host vehicle. This is achieved by the host vehicle transmitting video and sensor information to the remote driver on the uplink, and in return receiving driving instructions on the downlink.

The use case description [2] specifies 4 video streams on the uplink, each with a data rate of 8 Mbit/s, along with a sensor data rate of 4 Mbit/s, corresponding to an overall uplink data rate of R = 36 Mbit/s. Downlink signalling requires very high reliability but a considerably lower data rate, and is not included in this bandwidth analysis, as other downlink-heavy use cases will dominate spectrum needs on the downlink. The use case description also specifies a density of up to 10 vehicles per km^2. We assume vehicle densities of M_D = 0.5, 5 and 10 km^{-2} for rural, urban and dense urban environments, respectively.

The spectrum needs for this use case can then be calculated as follows:

	Rural	Urban	Dense urban
Density of served vehicles, M_D (km^{-2})	0.5	5	10
Link data rate, R (Mbit/s)	36		
Sector area, A (km^2)	2.5	0.072	
Spectral efficiency, e (bit/s/Hz)	0.72 (UL)	1.2 (UL)	
Spectrum needs, B (MHz)	100	30*	30*
* The urban and dense urban sectors must both support at least one user.			

6.5. Obstructed view assist

An obstructed view is seen as a critical factor by many road operators. Obstructions can be in the form of blind spots, other vehicles, buildings and trees, to name a few. Whether the vehicle is manually driven or autonomous, the driver or virtual driver needs a clear view of the area being obstructed to proceed safely. In the obstructed view use case, this view is provided via road-side infrastructure and shared with the vehicle by means of video streaming.

The use case description [2] specifies a video stream data rate of R = 5 Mbit/s and a vehicle density of 10,000 km^{-2}. The use case description does not indicate which fraction of vehicles would access the service at a given time. In this analysis we assume that this fraction is 10%. We also assume a reduced vehicle density by a factor of 2 in urban environments compared to dense urban. We believe that the presented service requirements are not directly applicable to a rural case, and so focus is exclusively on urban and dense urban environments with vehicle densities of M_D = 1000 and 500 km^{-2}, respectively.

The downlink spectrum needs for this use case can then be calculated as follows:

	Urban	Dense urban
Density of served vehicles, M_D (km^{-2})	500	1000
Link data rate, R (Mbit/s)	5	
Sector area, A (km^2)	0.072	0.072
Spectral efficiency, e (bit/s/Hz)	4 (DL)	4 (DL)
Spectrum needs, B (MHz)	45	90

6.6. Infrastructure assisted environment perception

This use case involves data being disseminated about objects on the road, in the form of object lists or occupancy grids. When an automated host vehicle enters a section of the road that is covered by infrastructure sensors it enrols to receive information from the infrastructure which contains environmental data relating to dynamic and static objects on the road. This data is used to increase the reliability of the car's own sensor observations and also extends the sensors' viewing range. Here we address the spectrum needs for the infrastructure sensors to communicate their data on the uplink of a mobile network to a processing server.

The use case description [2] considers a 1 km stretch of road with 3 crossing bridges and associated infrastructure sensors, and where each group of sensors, depending on the type of sensor (camera, radar, lidar), stream data to a processing server at data rates of between 70 to 155 Mbit/s on the uplink. Here, we assume the mid-value of R = 110 Mbit/s. We also assume that an urban or dense urban sector serves only 1 to 2 groups of infrastructure sensors.

The spectrum needs for this use case can then be calculated as follows:

	Urban
Number of groups of served sensors, M	1 – 2
Link data rate, R (Mbit/s)	110
Spectral efficiency, e (bit/s/Hz)	1.2 (UL)
Spectrum needs, B^* (MHz)	91.7 – 183.4
* $B = MR/e$.	

6.7. In-vehicle entertainment

In-vehicle entertainment is an important business opportunity for both car OEMs and MNOs, especially in the context of increasingly automated vehicles. Despite its name, this use case also offers personal efficiency and productivity services such as video-conferencing and mobile-office.

5GAA defines different levels of in-vehicle entertainment [2], mainly according to the number and quality of streams per vehicle. In this analysis, we consider the most relaxed requirements specified by the use case description, involving a reduced density of M_D = 500 vehicles per km^2 in a dense urban environment, with 2 active streaming users per vehicle and 50 Mbit/s per stream for a total link data rate of R = 100 Mbit/s. We scale down the vehicle density by a factor of 2 for urban environments.

The service requirement of 100 Mbit/s per vehicle is unrealistic in rural scenarios, unless highly optimised network deployments are considered. For this reason, we focus exclusively on urban and dense urban environments for this use case.

The spectrum needs for this use case can then be calculated as follows:

	Urban	Dense urban
Density of served vehicles, M_D (km^{-2})	250	500
Link data rate, R (Mbit/s)	100	
Sector area, A (km^2)	0.072	0.072
Spectral efficiency, e (bit/s/Hz)	4 (DL)	4 (DL)
Spectrum needs, B (MHz)	450	900

6.8. High-definition map collection and sharing

In this use case vehicles share their sensor data with a high-definition map provider (via a cloud server), which then merges the data to create HD maps and subsequently shares these with vehicles.

The use case description [2] specifies a sensor data rate of 4 Mbit/s (relating to 50 objects at 1 kbyte messages per object at a repetition rate of 10 Hz), as well as video and lidar data rates of 8 and 35 Mbit/s, respectively. Here, we assume a data rate of R = 12 Mbit/s on the uplink, excluding the lidar data from our analysis. The use case description also specifies a high-definition map of 2 Mbytes to be delivered in 1 second, implying 16 Mbit/s. Given that the map would be broadcast to the vehicles on the downlink, its spectrum needs would be relatively small, and is not considered here.

The use case description indicates a maximum vehicle density of 10,000 km^{-2}. Here we assume that 10% of vehicles would access the service at any given time. We also assume a reduced vehicle density by a factor of 2 in urban compared to dense urban environments. The use case is not highly applicable to rural scenarios, and so we focus exclusively on urban and dense urban environments with vehicle densities of M_D = 1000 and 500 km^{-2}, respectively.

	Urban	Dense urban
Density of served vehicles, M_D (km^{-2})	500	1000
Link data rate, R (Mbit/s)	12	
Sector area, A (km^2)	0.072	
Spectral efficiency, e (bit/s/Hz)	1.2 (UL)	
Spectrum needs, B (MHz)	360	720

6.9. Summary and conclusions

6.9.1. Considerations on cellular network deployments

There is a strong connection between the available bandwidth, the carrier frequency, and the achievable performance in a cellular network. Given a certain spectrum allocation, different network deployment strategies are also possible, depending on whether the primary goal is to maximise system capacity or to optimise cell-edge performance. Different MNOs may adopt different deployment strategies, also considering the interplay of spectrum and infrastructure assets from different radio access technologies (RATs) such as 2G, 3G, 4G, 5G, and NB-IoT.

Nevertheless, some general considerations apply:

- Larger system bandwidths, possibly aggregated over multiple RATs, benefit both cell-edge performance and system capacity.

- Low-band spectrum (< 1 GHz) is suitable for wide area coverage as it allows for larger inter-site distances, thanks to lower building penetration loss and reduced path loss.

- Mid-band spectrum (1-7 GHz) provides increased capacity – at the expense of some reduction in geographic coverage – and is particularly effective for deployments in citywide urban environments.

Because of the above considerations, low-bands (< 1 GHz) and mid-bands (1-7 GHz) are the primary candidates for the provision of automotive services requiring a combination of good geographic coverage and uniformly reliable performance. The upper mid-band frequencies are especially suitable targets for high-capacity citywide automotive use cases.

It should be noted that cellular deployments at high-band spectrum (so-called mm-Waves above 24 GHz) are expected to become increasingly relevant for automotive use cases in the future, but primarily for those services that are coverage-tolerant (e.g., data showers), or those that would benefit from a localised capacity boost.

It is also important to prioritise spectrum assets that allow for good economies of scale in network equipment and deployment. Because of this, the use of service-agnostic spectrum that is identified for International Mobile Telecommunications (IMT) is the only viable option for MNOs to re-use their existing infrastructure for eMBB and automotive applications. The MNOs can adopt advanced 5G features related to QoS management and network slicing in order to comply with a diversity of service level agreements.

Finally, it is important to point out that network performance is also limited by spectrum fragmentation. Contiguous allocations of large bandwidth allow the network to dynamically and efficiently schedule the available radio resource by exploiting time, frequency and spatial orthogonality. On the contrary, fragmented spectrum creates odd allocations that lead to inefficiency as well as increased deployment and device costs.

6.9.2. Estimated spectrum needs

The estimated spectrum needs for the various V2N use cases examined in this section are summarised in Table 6.1 below, rounded up to the nearest MHz.

It should be noted that these estimates are subject to a number of assumptions relating to data rates and the geographic densities of users, and must be interpreted as only broad indications of the spectrum needs.

Table 6.1: Indicative spectrum needs for advanced V2N use cases.

	Spectrum needs (MHz)		
	Rural	Urban	Dense urban
Software Update of Reconfigurable Radio System (DL)	12	2	3
Autonomous Vehicle Disengagement Report (UL)	13	4*	4*
Patient Transport Monitoring (UL)	25	8*	8*
Tele-Operated Driving (UL)	100	30*	30*
Obstructed View Assist (DL)	**	45	90
Infrastructure Assisted Environment Perception (UL)	**	92 – 184	
In-Vehicle Entertainment (DL)	**	450	900
High-Definition Map Collection and Sharing (UL)	**	360	720

* The urban and dense urban sectors must both support at least one user.
** To meet the use case requirements, an increased spectrum availability is not sufficient in itself, but needs to be complemented with improved network and device capabilities, and is under consideration by 5GAA.

The spectrum needs of the first two use cases are relatively modest and can be more or less covered by about 10 MHz in all environments. This is due to the low data rates associated with the delivery of software updates and disengagement reports, neither of which are highly time critical. It is possible for these use cases to be supported in the existing mid-band spectrum holdings of the MNOs, especially in non-rural settings.

The spectrum needs for "Patient Transport Monitoring" is somewhat greater, as determined by the larger data rate required for delivery of real-time video. Still, this can be managed within 10 MHz, except in rural deployments where the large inter-site distances increase the number of emergency vehicles served per sector (from one to two in this case). In the event of major incidents and larger numbers of ambulances, the spectrum needs would be proportionally greater, potentially extending to tens of MHz.

The spectrum needs for "Tele-Operated Driving" would dominate – and in the case of rural environments, equal or exceed – the spectrum holdings of MNOs in any existing mobile band in use today. In fact, the spectrum needs estimates put into question the feasibility of "Tele-Operated Driving" in rural environments. This is because cost-effective rural coverage is only viable through the use of low bands, and spectrum holdings in these bands are typically no more than 10 MHz per MNO. Tele-Operated Driving in urban environments would require access to a few tens of MHz of mid-band spectrum.

"Obstructed View Assist" and "Infrastructure Assisted Environment Perception" are each likely to require many tens of MHz – perhaps even as much as 100 to 200 MHz – of mid-band spectrum for the wireless communication of information from roadside sensors to processing servers in the cloud, and the delivery of visual information to vehicles, respectively. It is possible that some of this demand could be offloaded to high-bands (mm-Waves).

The spectrum needs for "In-Vehicle Entertainment" can be between 500 MHz to 1 GHz in urban to dense urban environments. Such demand cannot be met by the current spectrum holdings of the MNOs and would require hundreds of MHz of additional mid-band spectrum. It is possible that some of this demand could be off-loaded to high-bands (mm-Waves) in low-mobility conditions and where coverage is available. The spectrum needs could be much higher in rural environments on account of the large inter-site distances, and – given the limited bandwidths available in low-band and the lower mid-bands – it is unlikely that the use case could be implemented with the same performance in such environments.

Finally, the spectrum needs for "High-Definition Map Collection" can be many hundreds of MHz, and far more if we account for the collection of raw lidar data as well as sensor data and video. Such demands cannot be met by the current spectrum holdings of the MNOs and would require hundreds of MHz of additional mid-band spectrum. Again, mm-Wave offload might be an option in low mobility scenarios and where coverage allows.

6.9.3. Considerations on additional spectrum for V2N communications

The spectrum needs of a mobile communication network are in principle the sum of the spectrum needs of each individual use case supported at any given time and place.

Furthermore, it should be noted that mobile operators' networks concurrently support services for consumers as well as a range of industries, including the automotive sector. That is to say, the spectrum holdings of an MNO would not be exclusively available for automotive use cases.

The results of our studies – based on a selection of services – indicate that the spectrum needs for V2N use cases (including eMBB) are likely to extend to many tens of MHz at low-band (< 1 GHz) frequencies, and many hundreds of MHz at mid-band (1-7 GHz) frequencies. It is important to emphasise that the above assessment is based on our current understanding of the technical requirements of V2N use cases. As the ITS industry develops further, and we begin to better understand the demands of advanced driver assistance and autonomous driving in practice, our estimate of the spectrum needs will need to be reviewed. Nevertheless, our studies broadly indicate that the current spectrum allocations available to MNOs are not sufficient to support the full deployment of advanced driving V2N use cases anticipated by the automotive industry.

This can be addressed with the following complementary actions:

- At least 50 MHz of additional service-agnostic low-band (< 1GHz) spectrum be made available for MNOs to provide advanced automotive V2N services in rural environments with affordable deployment costs.

- At least 500 MHz of additional service-agnostic mid-band (1 to 7 GHz) spectrum be made available for MNOs to provide high capacity citywide advanced automotive V2N services.

In the above, the term "additional" means availability of spectrum in addition to the bands that are currently identified for IMT use by mobile communication networks.

It should also be noted that wide blocks of contiguous spectrum are preferred both for enhanced spectral efficiency and from the perspective of infrastructure and device costs, as compared to fragmented spectrum allocations.

We observe that mm-Wave high-bands (above 24 GHz) are a valuable asset for addressing indoor and local eMBB services with extreme performance requirements. However, the characteristics of automotive use cases suggest that low-bands and mid-bands are the primary candidates. We also observe that the roadmap for introduction of mm-Wave radio capabilities in mass-produced personal vehicles is currently unknown. Having said that, it is possible that in the longer term, the demand for some of the identified V2N use cases could be offloaded to mm-Wave bands.

As evident from the results of a members' survey, the 5GAA places great value on the importance of V2N communications between road users and mobile network infrastructures in enabling future advanced driving use cases, as supported by the Uu interface of C-V2X. Accordingly, the 5GAA recommends that national administrations ensure the availability of sufficient spectrum for mobile communication networks in low-bands and mid-bands for the support of services, including ITS, over the coming decade.

7. Conclusions and recommendations

This report presents the results of a study undertaken by the 5GAA in estimating the spectrum needs of a number of use cases for intelligent transport systems (ITS) as implemented by cellular V2X (C-V2X) technologies.

Based on the results of our studies of the spectrum needs of C-V2X direct communications (V2V/I/P), we can draw the following conclusions:

a) We expect that the delivery of day-1 use cases via LTE-V2X for the support of basic safety ITS services will require between 10 and 20 MHz of spectrum at 5.9 GHz for V2V/I communications.

b) We expect that the delivery of advanced use cases via LTE-V2X and NR-V2X for the support of advanced driving services will require an additional 40 MHz or more of spectrum at 5.9 GHz for V2V/I/P communications.

It should be noted that the actual spectrum allocation should exceed the minimum spectrum requirements derived above, otherwise the resource usage would approach a 100% level. At such an operating point, a high level of packet collisions may occur and the system would not operate efficiently.

The above conclusion with regards to advanced use cases deserves some elaboration:

- "Sensor Sharing for Autonomous Vehicles" is an important advanced driving use case which involves the ability of road users to share their processed sensor data with other road users on a continual basis for what is known as *cooperative perception*, to provide advanced driver assistance and to facilitate autonomous driving. The appropriate amount of sensor data which should be shared is an open question for the industry, and directly impacts the required spectrum. Our lower estimates of spectrum needs for this use case suggest that it can be accommodated in a 10 MHz channel. However, our analysis also indicates that, depending on the extent of required redundancy in the sharing of sensor information for the implementation of automated driving, the spectrum needs can be as high as a few tens of MHz or even more.

- Another example is the advanced "Vulnerable Road User" use case, whereby vulnerable road users (VRUs) such as pedestrians or cyclists share information about themselves by broadcasting continual repetitive messages to other road users. Our analysis of this use case for pedestrian VRUs indicates that, depending on the extent of clustering among the VRUs, the spectrum needs in dense urban environments can be up to several MHz (but less than 10 MHz).

- Many other advanced driving use cases are event triggered (e.g. cooperative manoeuvres), whereby messages are exchanged over the air only in response to a desire by a road user to undertake a specific manoeuvre (e.g., crossing an intersection, changing lanes, joining a freeway, or the like). Here, the road user shares its intended trajectory with other road users as part of a *handshake* exchange of information, in order to provide advanced driver assistance and to facilitate autonomous driving. Specifically, our analysis indicates that the spectrum needs for "Group Start" are of the order of several hundred kHz (approaching 1 MHz), whereas the spectrum needs for "Cooperative Lane Merging" (and other similar trajectory information sharing use cases) are of the order of around 150 kHz, both considerably lower than the spectrum needs of the "Cooperative Perception" use case. Notably, the contribution of these event triggered use cases to the overall ITS spectrum needs is stochastic, in the sense that such use cases may or may not occur at the same time and place, and this can result in a highly time variable demand for spectrum at any given location.

- We have also examined a number of miscellaneous advanced use cases which do not fall under the above categorisations (including "Platooning", "Vehicle Decision Assist", "See Through for Passing", "Speed Harmonisation", and "Automated Intersection Manager"). Our analysis indicates that with the exception of "See Through for Passing" which may require several MHz (less than 10 MHz) for the communication of high-definition video, the spectrum needs of each of the remaining use cases is unlikely to exceed at most several hundred kHz. Again, the contribution of these use cases to the overall ITS spectrum needs depends on the extent to which they might occur at the same time and place.

As a result, the evaluation of the spectrum needs for advanced use cases is not a trivial task. Nevertheless, it is clear that the 70-75 MHz of ITS spectrum in the 5.9 GHz band (as presently allocated in many regions and under consideration in other regions) is needed to support the basic safety and advanced use cases under consideration today. Like any emerging sector, there could be unforeseen ITS use cases that would require even more spectrum as the market evolves.

As the ITS industry develops further, and we begin to better understand the demands of advanced driver assistance and autonomous driving, we will assess the extent to which the 5.9 GHz band (5850-5925 MHz), which is globally harmonised for ITS by the ITU-R, is sufficient to meet the spectrum needs of the road users, and whether additional spectrum designated for ITS will be required.

Furthermore, based on the results of our studies of the spectrum needs of C-V2X network-based (V2N) communications, we can draw the following conclusions:

c) At least 50 MHz of additional service-agnostic low-band (< 1 GHz) spectrum would be required for mobile operators to provide advanced automotive V2N services in rural environments with affordable deployment costs.

d) At least 500 MHz of additional service-agnostic mid-band (1 to 7 GHz) spectrum would be required for mobile operators to provide high-capacity citywide advanced automotive V2N services.

In the above, the term “additional” means availability of spectrum in addition to the bands that are currently identified for International Mobile Telecommunications (IMT) use by mobile communication networks.

The 5GAA places great value on the importance of V2N communications in enabling future advanced driving use cases, as supported by the Uu interface of C-V2X. Accordingly, the 5GAA recommends that national and regional administrations ensure the availability of sufficient spectrum for mobile communication networks in the so-called low-bands and mid-bands for the support of services, including ITS, in the coming decade.

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Annex A: Packet reception ratio

As introduced by 3GPP [22], the average packet reception ratio (PRR) is a measure of reliability calculated over receivers located within a ring around a transmitter as depicted in Figure A.1. The ring has a width which is defined as $\sigma = b - a$, where a is the communication range, and $\sigma = 20$ m. The PRR is the ratio of the number of vehicles that successfully receive the transmitted packets over the total number of vehicles located in the ring.

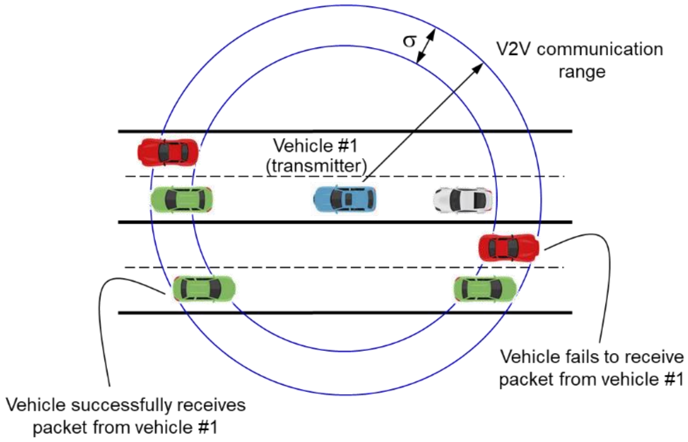

Figure A.1: Illustration of the ring around a transmitting vehicle according to the specification of the 3GPP performance metric PRR.

Moreover, 3GPP has defined the average PRR as

$$PRR_{Avg} = \frac{\sum_{k=1}^{n} X_k}{\sum_{k=1}^{n} Y_k},$$

where n is the total number of messages transmitted by all vehicles, Y_k is the total number of vehicles (able to receive message k) located inside the ring between the radii a and b, and X_k is the number of vehicles (out of Y_k) that successfully receive message k. We can say that the average PRR is the ratio of the total number of vehicles that successfully receive message packets over the total number of all vehicles that are supposed to receive transmitted message packets.

Annex B: Numbers of C-V2X stations assumed in the spectrum needs calculations

Urban scenarios

In this section, the topology assumed for the urban scenarios is first presented. Subsequently, the number of OBUs, VRUs, and RSUs within the effective communication range are calculated.

Assumed topology for urban scenarios

The number of vehicles in the effective communication range can be calculated according to the vehicle speed (impacting inter-vehicle separation), the road topology, and the communication range.

The assumed topology is illustrated in Figure B.1. This consists of an urban intersection, where we assume that there are a total of three lanes in each direction.

As shown in the example of Figure B.2, intersections in the dense urban environments of large cities may also include flyovers. For this reason, we need to account for vehicles in both horizontal and vertical dimensions. As such, we will consider the cases of no flyovers, a one-layer flyover, and a two-layer flyover in the spectrum needs evaluation.

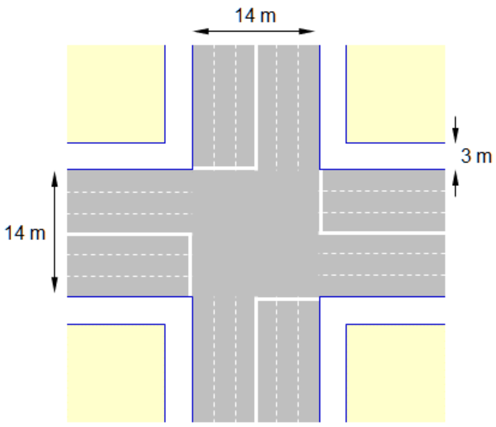

Figure B.1: The assumed topology of an urban intersection.

Figure B.2: Multiple layers of flyovers in dense urban environments.

Assumed number of OBUs

We categorise the vehicles in an urban intersection as moving and stationary vehicles. At any given time, we assume that vehicles are stationary in one direction (red light) and moving in the orthogonal direction (green light). In what follows, we also assume an effective communication range of 50 m measured from the centre of the intersection, which is considered typical at urban intersections.

Number of stationary vehicles – Consider an average vehicle length of 4.5 m, and a bumper-to-bumper separation of 1.5 m. This means that there is one car at every 1.5 + 4.5 = 6 m per lane in the stationary direction of the intersection. An effective communication range of 50 m from the centre of the intersection, and across a total of 6 lanes, implies that the total number of stationary vehicles is

$$\left(\left\lfloor\frac{2\times(50-7)}{6}\right\rfloor+1\right)6=90.$$

Number of moving vehicles – Several cases are considered with different numbers of flyovers and for different vehicle speeds, as shown in Table B.1. The assumed inter-vehicle spacing is given as the sum of typical vehicle length (4.5 m) and a bumper-to-bumper separation which corresponds to a time to collision of 2.5 s.

Table B.1: Number of moving OBUs for multiple flyover scenarios and vehicle speeds.

Total number of vehicles	Vehicle speed (km/h)		
	5	15	30
Inter-vehicle spacing (m)	3.5 + 4.5 = 8	10.4 + 4.5 = 14.9	20.8 + 4.5 = 25.3
No flyover	(floor(2(50)/8)+1)6 = 78	(floor(2(50)/14.9)+1)6 = 42	(floor(2(50)/25.3)+1)6 = 24
One-layer flyover	78 × 2 = 156	42 × 2 = 84	24 × 2 = 48
Two-layer flyover	78 × 3 = 234	42 × 3 = 126	24 × 3 = 72

Assumed number of VRUs

Here, we quantify the assumed number of VRUs by establishing the number of pedestrians in the vicinity of an urban intersection.

Consider the same urban intersection topology discussed earlier, along with a typical sidewalk width of 3 m. The area available to pedestrians within 50 m of the centre of the intersection and in four directions is approximately (50)(2)(3)(4) = 1200 m^2. At typical pedestrian flows, the geographic density of pedestrians will not be high. Here, we assume densities of 0.5 and 1.3 m^{-2}. The number of pedestrians in the effective communication range can then be calculated to be 600 and 1560, respectively.

Assumed number of RSUs

We assume that there is one RSU per urban intersection.

Freeway scenarios

Assumed topology for freeway scenarios

The number of vehicles in the effective communication range can again be calculated according to the vehicle speed (impacting inter-vehicle separation), the freeway topology, and the communication range.

The assumed topology is illustrated in Figure B.3. This consists of a stretch of freeway with a total of 12 lanes, with 6 lanes running in each direction.

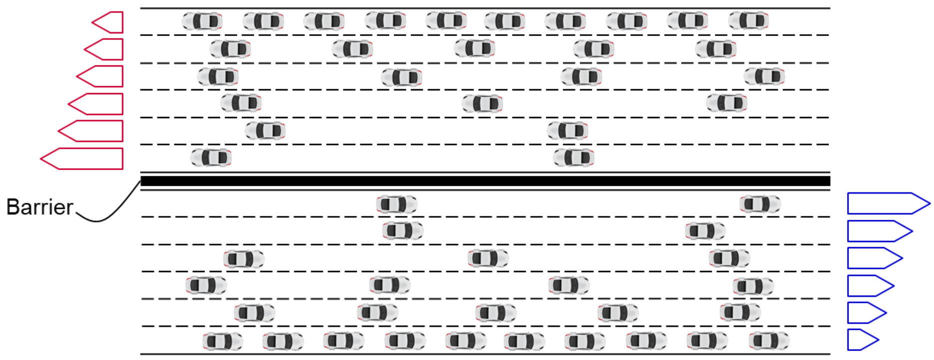

Figure B.3: The assumed topology of a freeway.

Assumed number of OBUs

The number of vehicles, M, in each lane may be written as

$$M = \left\{ \left\lfloor \frac{2d}{\Delta + \delta} \right\rfloor + 1 \right\} = \left\{ \left\lfloor \frac{2d}{\Delta + T_{TTC}\, v} \right\rfloor + 1 \right\},$$

where d is the effective communication range, Δ is the typical vehicle length, and δ is the bumper-to-bumper inter-vehicle separation, which in turn can be modelled as $T_{TTC}\, v$, where T_{TTC} is the time to collision, an v is the vehicle speed.

For the purpose of the spectrum needs studies in Section 4, we assume an effective communication range of d = 320 m (consistent with the value assumed by 3GPP TR 36.885), a typical vehicle length of Δ = 4.5 m, and a time to collision of T_{TTC} = 2.5 s.

We note that a range of different vehicle speeds is typically observed on a freeway. To account for this diversity, we assume speeds of 0, 10, 60, 90, 120 and 170 km/h from the slow lane to the fast lane at any given time. We consider that this is more effective – than assuming a single speed – in capturing realistic spectrum needs.

Accordingly, Table B.2 shows the assumed number of vehicles along a 640 m stretch of freeway. For the case of stationary vehicles in the slowest lane, we assume a bumper-to-bumper separation of 1.5 m.

Table B.2: OBU numbers in the lanes of the freeway (in both directions).

Number of lanes, *L*	2	2	2	2	2	2
Speed, *v* (km/h)	0	10	60	90	120	170
Effective communication range, *d* (m)	320					
Bumper-to-bumper separation, δ (m) [TTC = 2.5 s]	1.50	6.94	41.67	62.50	83.33	118.06
Number of vehicles, *M* (in *L* lanes)	214	112	28	20	16	12
Total number of vehicles	402					

The total number of vehicles along the 640 m stretch of freeway is then 402.

Assumed number of RSUs

Where infrastructure communication is considered, we assume that there is an RSU at every 5 km along the freeway.

Annex C: Monte-Carlo simulations for evaluation of spectrum needs for day-1 basic safety use cases

The main body of the present document provides spectrum needs results derived based on an analytical model of LTE-V2X. In this Annex, we propose to compare those results with a Monte-Carlo simulation-based approach for day-1 basic safety use cases. The objective is to provide some insight into the characteristics of the analytical model and its inherent limitations.

The analytical model applied in the main body of this report makes a number of simplifying assumptions, including the following:

- The evaluations of the communication links are not based on a full modelling of the physical layer, including channel propagation models, etc. Rather, an average spectral efficiency is employed in combination with a bandwidth utilisation factor.

- In addition, the above evaluations do not model the frame structures as defined by the 3GPP LTE standard; consequently, interference effects and similar phenomena are not explicitly considered.

Despite the above limitations, the analytical model is understood to be sufficient to capture the key factors in deriving spectrum needs requirements. Still, it is useful to compare those findings with simulation results based on the 3GPP assumptions summarised in Annex D. Since the simulations also apply simplifications, it is expected that the results will not exactly match.

System-level simulations have been performed based on the 3GPP methodology (as summarised in Annex D). The simulations in Figure C.1 are based on the following configuration:

- Mode 4 operation (i.e., sidelink without network resource selection and allocation).
- Packet size of 300 bytes (i.e., the typical packet size for basic safety messages).
- 2 TTIs per transport block transmission (i.e. employing a repetition of the original message).
- Allocation size of 20 physical resource blocks (PRBs).
- Average packet reception ratio (PRR) results for the bandwidths of 5, 10, 20, 30, 40 and 50 MHz.

In all cases, traffic density assumptions are made based on the 3GPP simulation assumptions (Annex D). However, no congestion control mechanism is applied. All vehicles are assumed to be able to employ LTE C-V2X communications. The simulation results in C.1 indicate the average PRR as a function of the available communication bandwidth. The spectrum needs are identified such that they match a 90% PRR requirement in accordance with the 3GPP methodology (Annex D).

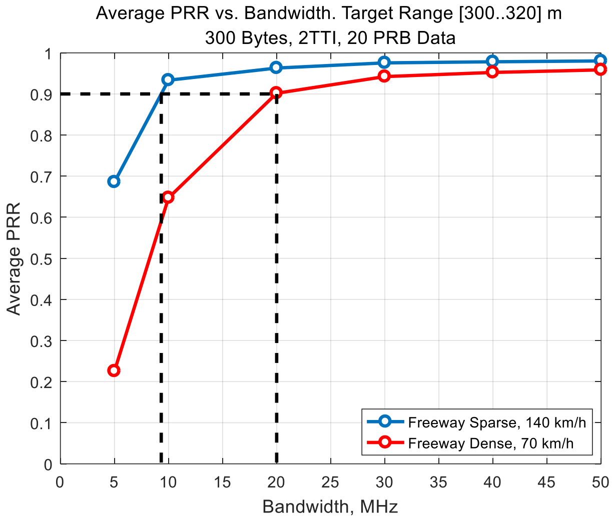

Figure C.1: Average PRR vs bandwidth with 300 byte packet size.

Note that no congestion control has been considered in the simulations. In practice, congestion control would be activated when near-congestion scenarios occur, where the transmission intervals would be correspondingly increased and congestion would be avoided. Following this approach, spectrum needs without congestion control for 300 byte packets in a six-lane freeway environment are estimated as follows:

- Approximately 10 MHz for a sparse freeway environment with a vehicle speed of 140 km/h.
- Approximately 20 MHz for a dense freeway environment with a vehicle speed of 70 km/h.

These simulation results broadly match the spectrum needs results for day-1/basic safety services as derived via the analytical model in the main body of this report. These results indicate spectrum needs in order of magnitude of 10-20 MHz. Obviously, the present comparison only covers a simplified subset of all relevant cases. Nevertheless, the results indicate that the analytical and simulation models provide comparable results at least in the considered context.

Annex D: Evaluation assumptions based on 3GPP system level simulation methodology

These following assumptions are incorporated into the system levels simulations outlined in Annex C.

General evaluation assumptions

Table D.1: General evaluation assumptions for 3GPP simulation methodology.

Parameter	Value
Deployment	
Type	Freeway, 2 directions, 3464 m length
Number of lanes	3 Lanes in each direction
Lane width	4 m
Vehicle speed	Sparse: 140 km/h, Dense: 70 km/h
Vehicle deployment	Poisson distribution in each lane; 2.5 seconds V2V mean time ahead
Spectrum allocation	
Carrier frequency	5.9 GHz
Bandwidth	Single channel; [5, 10, 20, 30, 40, 50] MHz
Channel model	
V2V channel model	According to 3GPP TR 36.885 (LTE V2V R14)
Signal Rx processing	
V2V sensing	According to the LTE R14 procedure
Receiver type	MMSE-IRC
Decoding attempts	Single decoding at each resource
Physical channels	PSCCH and PSSCH

Traffic and resource allocation assumptions

Table D.2: Traffic and resource allocation assumptions for 3GPP simulation methodology

Parameter	Value
Packet generation period	100 ms
Latency	100 ms
Packet size	Option 1: 300 bytes; Option 2: 800 bytes (not used in this report)
Resource allocation	
SCI/Data resource allocation	Adjacent resource allocation
PSSCH transmission parameters (300 byte packet)	
Allocation size	20 PRB
MCS index	7
Modulation	QPSK
Number of TTI	2