

# Spectrum Needs of Cooperative, Connected and Automated Mobility

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**Abstract**—The introduction of cooperative, connected and automated mobility (CCAM) services has a promising business potential. Connected vehicles, however, represent a new kind of resource consumer to mobile network operators. It needs to be assured that existing and future mobile communication networks are capable of supporting the CCAM services. In this analysis, we present an evaluation of the spectrum demands of connected vehicles by comparing their data rate requirements to the resources available in typical 4G and 5G deployments.

**Keywords**—CCAM, V2N, spectrum, Tele-operated Driving, HD Mapping

## I. INTRODUCTION

The future of mobility is inseparably linked with vehicles becoming simultaneously more and more connected and automated [1]. This gives rise to a range of services which are referred to as cooperative, connected and automated mobility (CCAM). The provision of CCAM services has a promising innovative business potential. Automotive connectivity encompasses both vehicle-to-vehicle (V2V) and vehicle-to-network (V2N) communication. In this analysis, we study the spectrum needs of connected vehicles, focusing on V2N, i.e. on services provided through mobile network operators (MNOs) and their public communication networks. The main “resource” for MNOs is the radio spectrum, but since its use is regulated and shared among different users, it is a scarce and expensive resource. Connected vehicles represent a new kind of resource consumer to mobile network operators.

Research related to CCAM has been focused on defining requirements, and on the architecture of CCAM networks, see for example [2], [3], [4]. Another study focuses on mobile edge computing CCAM services, where the authors explore the feasibility of service continuity in cross-border scenarios [5]. One missing feature in this context is the study of the impact of the penetration rate of CCAM services on the network performance. Understanding the capability of the existing networks is however an important topic for the potential deployment of CCAM services.

The use of mmWave bands offers additional spectrum for vehicular services, thanks to the use of beamforming. Nevertheless, the promised/required performance is achieved

only with densely deployed networks and in line-of-sight conditions [6]. Interested readers are referred to the survey provided in [7]. Due to the high costs that are involved in equipping vehicles with this technology today, it is foreseen that the deployment of equipment using those bands on vehicles will only occur in several years. This study focuses on current and available architecture and therefore only considers the sub-6-GHz band.

The analysis presented here is carried out within the EU-funded project 5GCroCo [8], which is trialling three CCAM use cases on the European 5G cross-border corridor connecting France, Germany, and Luxembourg over highways between the cities of Metz, Merzig, and Luxembourg. We consider two of the three use cases, Tele-operated Driving (ToD) and High Definition (HD) Mapping [9]. The third one, Anticipated Cooperative Collision Avoidance (ACCA), is based on the transmission of Cooperative Awareness Message (CAM) and Decentralized Environmental Notification Message (DENM) messages, which have a typical size of a few hundred bytes and are repeated a few times per second. The resulting data rates are thus very small, typically below 10 kbps. Such low data rates are irrelevant for this study and thus neglected here.

The main contributions of this paper are the following:

- we provide the requirements of the most relevant CCAM services in UL and DL,
- we estimate the expected usage for each of these CCAM services,
- we investigate the ability of existing 4G and 5G networks to support the spectrum needs of CCAM services in the sub-6GHz bands,
- we identify potential bottlenecks, which need to be taken into account for future deployments of CCAM services.

We present a general overview of the analysis and the considered use cases in Section II. In Section III, we explain the analysis methodology and the input assumptions used for estimating the vehicle traffic density, for the network deployment density, and for the spectrum calculations. Since uplink (UL) and downlink (DL) have different requirements

and concern different use cases, we split the analysis accordingly. Section IV describes the details and findings of the UL analysis, while Section V does the same for the DL part. We finish with our conclusions in Section VI.

## II. SPECTRUM ANALYSIS OVERVIEW

To estimate the spectrum demands of connected vehicles, we evaluate the data rate requirements (which can be indirectly translated into spectrum needs) against the resources available in typical 4G and 5G deployments. We have defined three reference scenarios – urban road, rural road, and highway – and study average and peak traffic situations for each of these. The scenarios differ in vehicle density, average vehicle speed, and base station (BS) density. From these input parameters, we can calculate the number of vehicles that can be found on a certain road segment during a certain time and thus the number of vehicles that need to be served simultaneously by an individual BS. On the network side, the amount of available spectrum and the spectral efficiency determine the data rates that can be provided. On the user side, the required data rates are determined by the desired service. In this analysis we consider two use cases, ToD in UL and HD Mapping in DL.

With automated vehicles, it is foreseen that there will be situations in which the vehicles are blocked and not able to continue their ride. These situations are called deadlocks. One solution to this problem is to provide external human support to the automated vehicle. This can be provided through ToD, where a remote driver at a command center (CC) takes over and manually commands the vehicle around the blockage, until the automation functions are able to take control again. The vehicle sends its perception data, e.g. video streams, via the UL to the CC. The CC then sends control commands to solve the deadlock situation in the DL. The vehicle continues its ride in a fully automated manner once the deadlock situation is resolved. In many countries, ToD is already a regulatory requirement for automated vehicles, when there is no safety driver. ToD has high requirements in terms of throughput in the UL and of low round trip latencies for the control of the vehicle.

Navigation systems using a digital map are common in modern vehicles. In contrast to today's maps, the term HD map refers to a higher resolution in the map data, offering lane-accurate level of detail. In addition, an HD map must contain information about traffic rules like speed limitations, or more dynamic conditions like road closures or construction areas. Such information forms one of the cornerstones of automated driving. Automated vehicles, however, also require the map to be constantly up-to-date, and thus, when reality changes, the map needs to be updated. Regular map updates by the map provider, typically done a few times per year by driving mapping vans along the roads, are not at all sufficient. To ensure a high reliability of automated vehicles, the map needs to be updated constantly, by as many contributing vehicles as possible. Broadly speaking, the vehicles collect information about their surroundings using their on-board sensors, and then use their connectivity to send this information to some backend. Here, the received data is compared to the existing map, and if differences are found, the map can be updated. The data might even come from sources other than vehicles, e.g. road-side cameras. The HD map can also be used as the base upon which more dynamic information can be stored, for example accidents.

Obviously, automotive use cases are not the only source of data traffic in real mobile networks. This is true in particular in the DL direction, where the majority of data traffic occurs today. To account for this background traffic in our analysis, we also consider other DL traffic sources like video streaming and over-the-air (OTA) updates. To study average and worst-case scenarios in the DL, we have defined parameters for low and high demand for each consuming service, which are combined with the average and peak traffic scenarios, respectively.

## III. ANALYSIS METHODOLOGY

In this section, we describe in detail the methodology and assumptions used for the spectrum analysis.

### A. Vehicle Traffic Density

The first input parameter for our analysis is the vehicle density on the various road types considered here. The road capacity very much depends of the type of road:

- A rural road with 2 lanes (1 per direction) has a capacity of approximately 6000 vehicles per day. It is common to assume that the peak hour traffic is about 10% of the daily traffic [10]. Consequently, we assume 600 vehicles/hour for the peak hour scenario.
- A highway with 2x2 lanes (like the majority of the highways in the 5G CroCo corridor) has a capacity of approximately 30000 vehicles/day. Again, we assume 10% of the daily traffic (3000 vehicles/hour) for the peak hour.
- The capacity of urban roads can vary much more and is thus much harder to estimate. For our urban scenario, we assume an average daily traffic of 6000 vehicles/day, as for the rural scenario, but a higher peak hour traffic with 1500 vehicles/hour.

To calculate the number of vehicles that are at the same time on a certain road section, we also need the average speed. We assume 50 km/h for the urban average scenario, and 30 km/h for the urban peak hour, 75 km/h and 50 km/h for the rural average and peak scenarios, and 100 km/h and 50 km/h for the two highway scenarios.

### B. Network Deployment

The network resources available for serving vehicles on a road depend first on the BS density along the road. With a higher density, each BS serves a shorter section of the road, and thus fewer vehicles, assuming a constant vehicle density. The deployment scenarios used in this analysis are based on the scenarios developed by 3GPP and captured in TR 38.913 [11], with the BS being deployed directly along the road, and with constant distance. In other words, every BS serves an identical section of the road. We use an inter-site distance of 500 m in the urban scenario and 1000 m in the rural and highway scenarios.

### C. Spectrum Calculations

The second factor contributing to the network capacity are the resources available to the individual BS. The main spectrum resource is the carrier bandwidth, or the amount of spectrum available to each BS. From the first release (Release 8), Long Term Evolution (LTE) supports bandwidths of 1.4 MHz - 20 MHz. LTE-Advanced and 5G NR support bandwidths of up to 100 MHz. To translate the amount of spectrum into a data rate, we also need the spectral

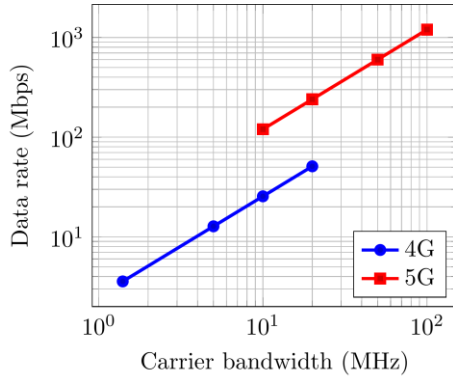


Fig. 1: UL data rate that can be provided by the network as a function of the carrier bandwidth.

efficiency, which describes how much information can be transmitted per time unit over a channel with a certain bandwidth, and which is usually given in bits per second per Hz. For LTE, the spectral efficiency can be calculated as

$$\varepsilon_{LTE} = N_{SC}^{BW} \times N_{sym} \times Q_m \times (1 - OH) / BW$$

The individual parameters are:

- the number of subcarriers used,  $N_{SC}^{BW}$ , which depends on the deployed bandwidth and is usually 300 per 5 MHz,
- the number of symbols per second,  $N_{sym} = 14000$  1/s,
- the modulation order  $Q_m$ , defining the number of bits per symbol,
- the overhead  $OH$  for control channels, reference symbols, etc., which is about 25%,
- and the carrier bandwidth  $BW$  in Hz.

For an LTE system without any MIMO functionality, this results in a DL spectral efficiency of 3.78 bps/Hz, assuming a 64-QAM modulation scheme ( $Q_m = 6$ ). A more high-end system with 4 MIMO layers can theoretically achieve a spectral efficiency four times higher, i.e. up to 15 bps/Hz. Even higher spectral efficiencies are achieved by 5G NR systems. There, the spectral efficiency can be calculated as

$$\varepsilon_{NR} = N_{layers} \times Q_m \times f \times R_{max} \times \frac{N_{PRB}^{BW, \mu} \cdot 12}{T_s^\mu} \times (1 - OH) / BW$$

where the parameters are:

- the number of MIMO layers  $N_{layers}$ ,
- the modulation order  $Q_m$ ,
- a scaling factor  $f$ ,
- the maximum code rate  $R_{max} = 948/1024$ ,
- the average symbol duration  $T_s^\mu = \frac{10^{-3}s}{14 \cdot 2^\mu}$  with the numerology  $\mu$ ,
- the number of resource blocks,  $N_{PRB}^{BW, \mu}$ , again depending on the numerology  $\mu$ ,
- the control channel overhead  $OH$ ,

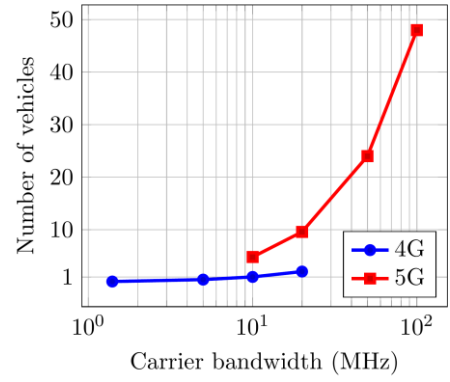


Fig. 2: The number of vehicles that can be served simultaneously with ToD as a function of the carrier bandwidth.

- and the carrier bandwidth  $BW$  in Hz.

For an example system with numerology  $\mu = 1$ , with 100 MHz bandwidth at 30 kHz subcarrier spacing, the maximum number of resource blocks is  $N_{PRB}^{BW, \mu} = 273$ , and we get an average symbol duration of  $T_s^\mu = 35.7 \mu s$ . The overhead in this case is 14% in the DL, which – together with a 256-QAM modulation scheme ( $Q_m = 8$ ), a scaling factor of 1, and 4 MIMO layers – results in a spectral efficiency of about 23 bps/Hz.

In the analysis, we use a DL spectral efficiency of 3.78 bps/Hz for the 4G case and 23 bps/Hz for the 5G case. In the UL, where the spectral efficiency is usually lower, we use 2.55 bps/Hz and 12 bps/Hz for the 4G and 5G case, respectively. As carrier bandwidths, we use 10 MHz for the 4G case and 40 MHz for the 5G case.

#### IV. UPLINK ANALYSIS

Connected vehicles have increasing spectrum needs because of the various applications which require a backend connection. Among those, ToD certainly imposes the highest spectrum needs in the UL. We therefore focus the UL analysis on the ToD application. The vehicle perception (ToD UL) contains multiple video streams. We consider three Full HD cameras generating up to 25 Mbps [9].

Fig. 1 depicts the data rate that can be provided by the network as a function of the carrier bandwidth in the UL, assuming a spectral efficiency of 2.55 and 12 bps/Hz for 4G and 5G, respectively.

The high data rate requirements of the ToD UL yield a limited number of users which can be served simultaneously. Fig. 2 shows the number of vehicles as a function of the carrier bandwidth. It can be observed that with 4G, only one (resp. two) vehicle can use the UL for ToD, when a carrier bandwidth of 10 MHz (resp. 20 MHz) is available. The 5G system enables to support more ToD users at the same time.

TABLE I. FRACTION OF VEHICLES WHICH CAN BE SERVED SIMULTANEOUSLY WITH ToD

|                       | Urban road |      | Rural road |      | Highway |      |
|-----------------------|------------|------|------------|------|---------|------|
|                       | Avg.       | Peak | Avg.       | Peak | Avg.    | Peak |
| 4G (max. 1 vehicle)   | 0.4        | 0.04 | 0.3        | 0.08 | 0.08    | 0.02 |
| 5G (max. 19 vehicles) | 7.6        | 0.76 | 5.7        | 1.6  | 1.5     | 0.32 |

The limit of the 5G system is 48 ToD users with the maximum available carrier bandwidth of 100 MHz. For the reference scenarios with carrier bandwidths of 10 and 40 MHz, 1 and 19 vehicles can be supported with 4G and 5G, respectively.

Table I lists the fraction  $R$  of vehicles that can be served with ToD in the UL for all the considered reference scenarios. Fraction values smaller than one indicate that the corresponding cell is overloaded; a larger  $R$  value means that there are still resources available.

It is noteworthy that ToD is certainly not the only source of traffic in the UL. Besides the ordinary cellular users, which also have increasing spectrum needs, connected vehicles use further applications. A wide-area support of ToD is challenging considering the current spectrum allocations. The most ambitious scenario, i.e. highway at peak hour, would require more than 100 MHz of spectrum to serve all present vehicles at the same time.

## V. DOWNLINK ANALYSIS

In this section, we analyze the spectrum needs for three distinct services in the DL.

### A. HD Mapping

For highly automated or even autonomous driving, downloading an accurate and up-to-date HD map on time is crucial. The required HD map DL data rate depends on the data size of the map tile and the time required for the download.

The data size of a map tile varies a lot depending on the complexity of the road network in the area. For example, with a typical map zoom level setup, a tile covers a rectangular area with a side length of a few hundreds of meters, and its corresponding data size of the lane-geometry map layer varies from a few kilobytes in a rural area to few hundreds of kilobytes in a busy city area. As an example, the data size of a map tile covering about 250 m x 150 m at the AstaZero test track in Sweden is about 10 kilobytes [12]. If adding up all map layers such as lane-geometry-polyline, lane-topology, lane-road-reference, topology-geometry, advanced driver-assistance systems attributes, etc., the data size of a large map tile (1x1 km) in a busy city area is usually below 1.25 MB.

The required download time for an HD map depends on the vehicle driving speed and the map zoom level. For the purpose of this analysis, we consider one of the worst-case scenarios. When a vehicle starts up with an empty map buffer, it needs to download the map tiles as soon as possible. Assuming that it is sufficient if the map tiles can be downloaded in one second, then based on the map tile data size as discussed above, an upper bound of a data rate of 10 Mbps (= 1.25 MB per second) is required.

For our analysis, we consequently assume a data rate of 10 Mbps for the high-demand case, and 0.1 Mbps for the low-demand case. The fraction of vehicles with HD maps is assumed to be 15% in both scenarios.

### B. OTA updates

Updating the software of the electronic control units in vehicles over-the-air (OTA) is a service promising large value for both end customer and original equipment manufacturer (OEM). For the customer, the benefit lies in realizing new features in the vehicle after its initial purchase, while the OEM is being enabled to fix quality or other issues in the software

without having to bring the vehicle in for expensive workshop visits. Even if these updates are not continuous, they do occur and increase the overall download bandwidth needed.

The 5GCAR project established a scenario for OTA updates [13] that we take into account here, that is:

- 1 OTA update per year.
- Vehicles are no longer updated after five years from manufacturing.

The size of the update increases each year according to vehicle evolutions. For this exercise we use two scenarios with update sizes of 3 GB and 32 GB. To estimate the impact, we need two parameters: the fraction of vehicles involved at a particular time and the data rate needed. For the first parameter, we assume that all new vehicles are susceptible to receiving OTA updates, but on the roads are also older vehicles without this feature. To calculate how many vehicles are updated in a specific time slot, we need to calculate the fraction of vehicles where OTA updates are applicable, using as entry points:

- According to the European Automobile Manufacturers Association (ACEA), there are 275 million passenger vehicles in Europe (EU plus Switzerland, Norway, and Iceland) in 2018 [14].
- 15.6 million new vehicles were sold in 2018 [15].

With these premises, for a period of five years, we have a total amount of vehicles that are susceptible to OTA updates that is five times the number of vehicles sold in one year. Assuming that the number of vehicles sold every year and the total number of vehicles remains constant, the ratio of vehicles susceptible to OTA updates from the total is then  $(5 * 15.6) / 275 = 28.4\%$ . However, as each OEM defines its own updates, it is very unlikely that different OEM apply their updates at the same time, as we expect only one update per year. The worst case we assume here is thus when a large OEM pushes an update to all of its vehicles at the same time. To establish this probability, we focus on the market penetration of the leading manufacturer. In 2017, this was Volkswagen AG, selling 3.6 million vehicles, or 23.3% of all new vehicles [16]. The maximum probability for a specific vehicle (choosing the OEM with most penetration) to receive an OTA update is then  $28.4\% * 23.3\% = 6.6\%$ .

The second considered parameter is the required data rate applicable for OTA updates. It depends on the size of the software update and the time target to download the update in the vehicle. We assume two cases, a smaller, more urgent update, and a larger one with a more relaxed time target:

- Low-demand case: 3 GB in 2 hours, resulting in 3 Mbps.
- High-demand case: 32 GB in 12 hours, resulting in 6 Mbps.

### C. Video streaming

In 2020, the user penetration for video streaming is 15.2% and is expected to exceed 16.9% by 2024 [17]. These two figures encompass both mobile and fixed network video streaming. Most of the video streaming traffic is nowadays provided through the fixed broadband connections by Internet Service Providers (ISP). It is however expected that the proportion of mobile video streaming increases in the next

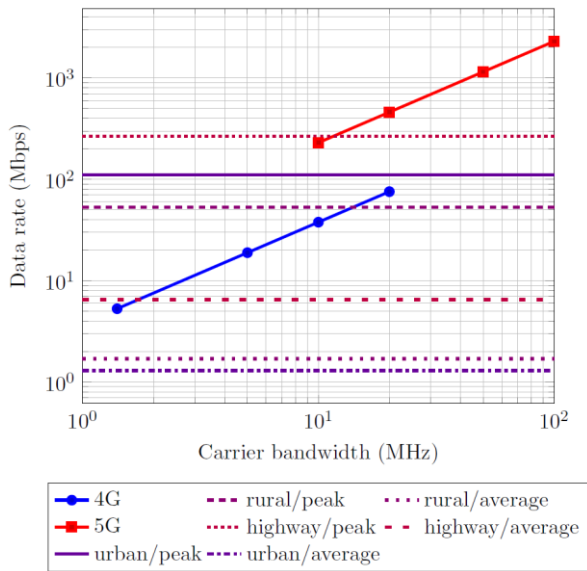


Fig. 3: DL data rate that can be provided as function of the carrier bandwidth and the requirements by the considered use cases.

years. This arises (among other factors) from the 5G technology enabling broader and higher quality of mobile video streaming. Even today, almost one quarter (24%) of all video streaming is consumed on mobile devices [18]. As a result, the user penetration of mobile video streaming is approximately  $15.2\% \times 24\% = 3.6\%$  in 2020.

For the present analysis, we define a low demand and a high demand scenario. In the former case, we consider 3.6 % of the vehicles using video streaming with a data rate of 8 Mbps, assuming Full HD resolution. In the latter case, we assume 16.9% and 15 Mbps, corresponding to 4k video resolution. These figures include every kind of video streaming occurring in a vehicle.

#### D. Analysis

For the DL analysis, we distinguish the following three services: HD Mapping for automated driving, OTA software updates supplied by the OEMs, and video streaming as part of the infotainment provided to the user. The sum of the data rates arising from these services is rather high in comparison to the use cases considered in standardization. Fig. 3 depicts

TABLE II. FRACTION OF THE DATA RATE REQUIRED FOR SIMULTANEOUS SERVICE OF HD MAPPING, OTA UPDATES, AND VIDEO STREAMING THAT CAN BE PROVIDED

| System | Carrier bandwidth | Urban road |      | Rural road |      | Highway |      |
|--------|-------------------|------------|------|------------|------|---------|------|
|        |                   | Avg.       | Peak | Avg.       | Peak | Avg.    | Peak |
| 4G     | 1.4 MHz           | 4.0        | 0.05 | 3.0        | 0.1  | 0.8     | 0.02 |
|        | 5 MHz             | 14.4       | 0.17 | 10.8       | 0.35 | 2.9     | 0.07 |
|        | 10 MHz            | 28.9       | 0.34 | 21.7       | 0.71 | 5.8     | 0.14 |
|        | 20 MHz            | 57.8       | 0.68 | 43.3       | 1.4  | 11.6    | 0.28 |
| 5G     | 10 MHz            | 176        | 2.1  | 132        | 4.3  | 35.2    | 0.87 |
|        | 20 MHz            | 352        | 4.2  | 264        | 8.7  | 70.3    | 1.7  |
|        | 50 MHz            | 879        | 10.4 | 660        | 21.6 | 176     | 4.3  |
|        | 100 MHz           | 1758       | 20.8 | 1319       | 43.3 | 352     | 8.7  |

the DL data rate that can be provided by the network as a function of the carrier bandwidth together with the requirements of the three considered use cases. The spectrum needs in terms of peak requirements are satisfied by 5G when more than 20 MHz of carrier bandwidth are available. For the requirements in terms of average data rate, 4G already provides enough bandwidth for all use cases. Table II shows the fraction R of the data rate that would be required in the DL for simultaneous service with HD Mapping, OTA updates, and video streaming, that can be provided by the network for the three reference scenarios. As in the UL case (Table I), values of R smaller than one indicate that the corresponding cell is overloaded; a larger value means that there are still resources available.

## VI. CONCLUSIONS

The introduction of CCAM services adds significantly to the increasing traffic demand in cellular networks. In our analysis, we have evaluated the spectrum needs of connected vehicles. We have selected use cases both in UL and DL and tried to shed some light on the question if current or future mobile networks can provide these services to a sizeable number of vehicles in three reference scenarios.

Our findings indicate that in the DL, even today's networks would be able to support at least average vehicle densities in our reference scenarios. Higher vehicle densities, however, require a network with higher spectral efficiency, which could be achieved e.g. by a higher modulation order, or a higher number of MIMO layers. In the UL direction, ToD clearly imposes the highest spectrum requirements. Even the 5G network considered in the analysis can support only a limited number of vehicles at the same time, even when we assume that there is no other data traffic in the UL.

These results stand opposed to the traditional traffic patterns in cellular networks, where the majority of data traffic is in DL direction. They therefore challenge the traditional logic of spectrum allocation in FDD networks, where the same amount of spectrum is assigned for UL and DL channels and highlight the importance of flexible TDD schemes, where resources can be assigned to UL or DL, depending on the current demand. The introduction of mmWave bands might offer additional spectrum for CCAM services and their corresponding penetration rates. This is an interesting avenue for further research left for future work.

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