Analysis of Vehicular Scenarios and Mitigation of Cell Overload due to Traffic Congestions

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Abstract—**Vehicular communications are called upon to become one of the services that will benefit the most from 5G networks. The low latency and unprecedented high data rates 5G is expected to deliver are a key enabler for new vehicular services. A booster for this to happen is network slicing, which enables to tailor radio resources to satisfy the different services demand. However, frequent traffic jams in urban scenarios can lead to network overloading, compromising the required Quality of Service by running out of available radio resources. In this paper, we firstly conduct a microscopic analysis of vehicles mobility using realistic vehicular traces to detect traffic jams. Secondly, the network overload introduced by this congestion is studied considering a network slicing environment. Finally, a load balancing approach to mitigate the radio resources demand is proposed. Results show a significant mitigation of the overload situation.**

Keywords— V2X communications, network overload, load balancing.

I. INTRODUCTION

Traditionally, vertical industries have addressed their connectivity and communication needs with dedicated or industry specific solutions. Instead, 5G networks offer a more cost efficient, open, interoperable and large eco-system enabled solution platform for the various vertical industries. 5G has been designed to address the more stringent and business critical requirements of the vertical industries, such as real-time capabilities, latency, reliability or security through guaranteed service level agreement (SLA)'s.

Network slicing is one of the key capabilities that will enable flexibility, as it allows multiple logical networks to be created on top of a common shared physical infrastructure. The greater elasticity brought about by network slicing will help to address the cost, efficiency, and flexibility requirements imposed by the large variety of industrial vertical services. Moreover, network slicing will help new services and new requirements to be quickly addressed, according to the needs of the industries, i.e., a faster Time to Market [1].

One of the wide area services that public 5G networks are called to manage is vehicular-to-everything (V2X) communications. In this framework, telecommunication and automotive industries have joined together forming the 5G Automotive Association (5GAA) [2], an industry association that aims to address connectivity needs arising from cooperative connected and automated mobility (CCAM). To help mobile network operators (MNO) to provide V2X services, the 3rd Generation Partnership Project (3GPP) has standardized a V2X slice in [3].

Due to the inherent mobility associated to V2X services, managing vehicular networks is particularly challenging. In this respect, the work done by Cai et al. in [4] ensures the quality of service (QoS) of basic safety services in a scenario where different vehicular traffic is considered. Zhang et al. propose in [5] a deep reinforcement learning approach to perform resource allocation in cellular V2X communications, where high bandwidth demanding traffic is served using vehicle-to-Infrastructure (V2I) while safety related messages are sent through vehicle-to-vehicle (V2V) communications.

The difficulty to deal with V2X traffic increases in a network slicing environment. In [6] a Q-learning algorithm was implemented to efficiently split the radio resources between different slices in a single cell scenario. Liang et al. propose in [7] a cooperative resource sharing algorithm to optimize the resource allocation in a single cell scenario with enhanced mobile broadband (eMBB) and vehicular slices. Kaytaz et al. in [8] implement a hierarchical reinforcement learning to accommodate different vehicular application categories such as autonomous driving services or infotainment applications. Authors of [9] implement a resource reservation to minimize packet loss in a multicell environment with a vehicular slice and eMBB traffic.

One of the practical problems in vehicular scenarios is that V2X traffic mobility can drain the radio access network (RAN) resources. due to e.g., a traffic jam, putting the QoS at risk. In this respect, Luoto et al. in [10] create vehicle clusters in cell edges to prevent running out of radio resources when vehicle density increases. Similarly, Khan et al. partition in [11] a vehicular network in three different slices depending on each vehicle SNR to ensure all of them seamless QoS for video streaming. Wu et al. implement in [12] a dynamic resource allocation to serve different vehicular services while ensuring QoS for delay-sensitive users. To mitigate the impact of cell overloading problems, also Wu et al. implemented in [13] a joint resource slicing and scheduling algorithm using space networks. Both [12] and [13] tested the algorithms using vehicular taxi traces.

One of the main roadblocks for research in V2X communications is the modelling of vehicles' mobility. In [6]- [9] vehicles are assumed to enter in the cell or network following a Poisson process. In turn, in [10] and in [11] this is tackled through highway synthetic models. Instead, considering realistic datasets enables gaining deeper insight into V2X scenarios and identifying practical situations that may pose challenges on the way that the scarce radio resources are managed. In this respect, the works [14] [15] [16] provide public and realistic datasets of the cities of Cologne, Luxembourg and Bologna respectively. Using the Cologne dataset Uppoor and Fiore performed a macroscopic and microscopic analysis of vehicular mobility in [17], focusing on metrics such as the dwell time and traffic flow across base stations over time. However, the implications the traffic had in terms of radio resources were not discussed. Several works focused on vehicular ad hoc networks (VANETs) have been done exploiting these datasets [18] [19] [20]. Other works have exploited these datasets for evaluating modifications in MAC protocol for LTE-V2X [21] or vehicle rerouting for traffic congestion avoidance [22]. To the best of our knowledge, none of the contributions studied the overloading problems.

With all the above, this paper addresses the problem of V2X traffic overload in a realistic 5G deployment scenario. To this end, the mobility in Cologne's scenario is analysed, which enables identifying traffic jam situations. Then, the impact in terms of cell overload is assessed, considering that the radio resources are shared among different services supported over different radio slices. Finally, a load balancing strategy to alleviate the overload is proposed and evaluated.

The remainder of the paper is as follows. Firstly, the approach 3GPP has taken to accommodate V2X services will be described in Section II. Then, Section III details the considered system model and use case, including the description of the radio slices. In turn, Section IV focus on analysing the vehicular mobility, detecting unusual events such as traffic jams. Subsequently, their traffic load implications are analysed in Section V and a load balancing technique to handle the network overload situation is described and evaluated in Section VI. Finally, we will draw the paper conclusions as well as point to future work to be done in Section VII.

II. V2X Services in 5G Networks

To effectively support V2X services over mobile networks, 3GPP has taken a dual approach. First, it has defined a set of network enablers that facilitate the deployment of V2X services. Then, it has defined a set of application enablers to ease the integration of V2X application functions with the 5G network.

Regarding V2X network enablers, 3GPP TS 23.285 [23] defines a set of architectural enhancements, including a PC5 interface for direct V2V communications, an Uu interface for communication between vehicle and the network (V2N), inter-PLMN (Public Land Mobile Network) integration mechanisms to deliver V2X services spanning multiple public networks, QoS enhancements for V2X, or multicast-Broadcast messaging services (MBMS).

Regarding V2X application enablers, 3GPP TS 23.286 [24] defines a V2X application enabler (VAE) function that abstracts all the previous complex network capabilities into an API that is easy to consume by the V2X application function (AF). The V2X AF is commonly implemented as a V2X gateway component that includes an ETSI G5 facilities layer [25], as well as the ETSI G5 V2X applications. Example of ETSI G5 services are the Cooperative Awareness Message (CAM), which is used to track the position of surrounding vehicles in order for example to anticipate collisions. Another example is the Decentralized Event Notification Message (DENM) used by the vehicles or road infrastructure to notify other vehicles about an unexpected event, such as work-roads or a sudden break.

Following the 3GPP proposed architecture, Fig. 1 depicts an exemplary V2X service architecture based on the Uu interface, a VAE server and a centralized V2X AF that processes all CAM/DENM messages from the vehicles in the network. The V2X AF redistributes the received CAMs and DENMs received in the uplink across a specific geographical area, which is considered a parameter of the V2X service. The V2X AF uses the VAE server to resolve the IP address of the UEs that are within the area of interest, which can be attached to different base stations. In our analysis we consider that the mobile network is not MBMS capable since this feature is not widely supported in current public networks. Furthermore, only V2X Uu interface is considered.

III. Urban Use Case and System Model

The considered scenario is a 12 sq. km urban area placed in the city of Cologne (Germany). The considered NG-RAN access network is composed by a set of C cell sites as depicted in Fig. 2. The location of the cell sites is as defined in the Telekom network available in [26]. We have considered the realistic set of vehicles generated in the Cologne city lab project, available in [14]. The area of study is the central part of Fig. 2 [27], while cell sites at the edge (e.g., BS12, BS14, BS15) are taken into consideration to limit the border effects. In turn, the NG-RAN is assumed to operate 3 different slices (eMBB, massive machine-type communications (mMTC) and V2X).

This section firstly describes the NG-RAN deployment in the considered scenario. Then, the slices and services are described.

A. *NG-RAN deployment*

We consider that each cell site operates a single cell centred at 2.1GHz band, using frequency-division duplexing, with 20MHz channel bandwidth for each uplink and downlink. In terms of physical resources deployed, the number of resource blocks (RB) for the different possible subcarrier spacing (SCS) and channel bandwidth can be found in [28]. For example, for SCS=15 KHz and 20 MHz channel bandwidth, the transmission bandwidth is configured with 106 RBs. Each RB consists of 12 consecutive subcarriers in the frequency domain. For normal cyclic prefix, 14 OFDM symbols can be transmitted per slot and per subcarrier.

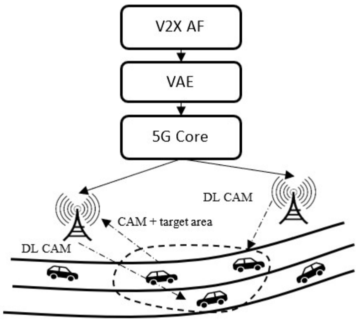

Fig. 1: Architecture of modelled service.

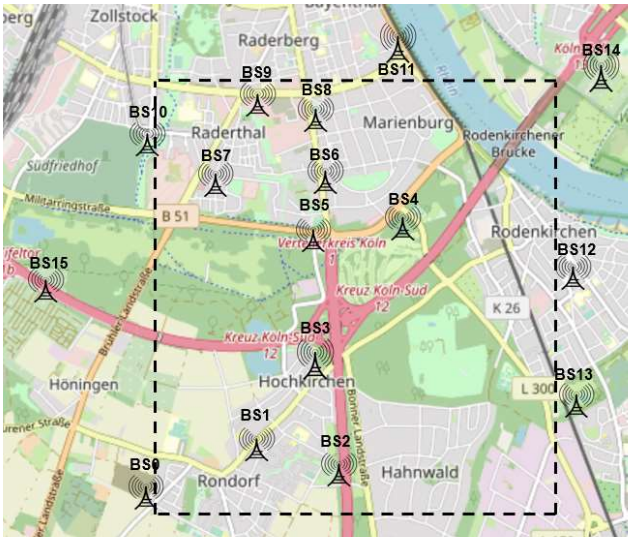

Fig. 2: Considered scenario in Cologne.

The path loss model chosen is the urban area model as defined by 3GPP in Section 4.5.2 of [29]. No slow fading term has been considered. The transmitted power at each base station (BS) has been adjusted to have a data rate around 800 kbps at the cell edge. The rest of the parameters have been chosen from Annex C of [29] and are summarised in Table I

Each user connects to the base station with lowest path loss. For a user experiencing a given signal to noise plus interference ratio (SINR), we consider Shannon's bound to derive the achievable spectral efficiency in the radio link (i.e., log$_2$(1+SINR) bits/s/Hz). Then, we consider that the modulation order (Q) and code rate (R) used in the radio link are properly selected for these radio conditions. To this end, Section 5.1.3.1 in [30] is considered to map the achievable spectral efficiency to a MCS index. As a result, the number of bits that a given user is able to transmit on 1 RB during 1 slot is 12×14×Q×R bits.

B. *Slices and services*

The considered services attempt to replicate the automotive stakeholders defined in Section 6 of [31]. With this objective, three slices have been defined. eMBB serves generic internet traffic. mMTC replicates traffic coming from cameras belonging to a Road Traffic Authority while V2X mimics a service that can be provided by a MNO to a vehicle manufacturer.

Out of the whole vehicular dataset of Cologne, this work takes the recording taken in a 3h 45min time frame (from 13:05 until 16:50). Within this time frame, road occupancy experiments significant variations, presenting from fluid traffic to high road occupancy. There are over 23.000 different vehicles driving in the interest area, with a maximum of 450 simultaneously in the rush hour.

TABLE I: BS AND UE PARAMETERS.

BS parameter	**Value**
Antenna height	30m
Noise figure	9 dB
Antenna gain	15dB
UE parameters	**Value**
Maximum transmitted power	21dBm
Antenna gain	9 dB
Noise figure	9 dB

TABLE II: CONSIDERED TRAFFIC MODELS

V2X slice	**Value**
Packet size	300B with probability 1/5 170B with probability 4/5
Inter-arrival time	500ms
Messages range	16hm^2
mMTC slice	**Value**
Number of users	150
Guaranteed data rate	3Mbps
eMBB slice	**Value**
Number of users	2500
Uplink target data rate	1Mbps
Uplink sessions percentage	20%
Downlink target data rate	2.5Mbps
Downlink sessions percentage	80%
Av session duration	15 seconds
Session generation rate	12sess/user/h

The considered V2X slice delivers ETSI Day 1 safety services for connected cars defined based on [32]. These services comprise the generation of CAM messages, which provide periodic awareness such as the position and basic status of the vehicle. It can be understood as a sort of heartbeat messages that are sent by a connected car to its immediate neighbourhood (single hop). The requirements of this message are available in [33]. Even CAMs have a variable periodicity between 100ms and 1s, for the purpose of this paper it is assumed that the inter arrival packet time for CAM is constant and set to 500ms. The message size modelling is taken from [34] and summarized in Table II. The range at which CAM messages will be forwarded, is a square centred in the vehicle generating the CAM message and with side 400m.

The eMBB slice carries generic Internet traffic. 2500 background users uniformly distributed within the area and moving at a constant speed of 3 Km/h as in [35] are considered. These users generate traffic in session basis as defined in Table II.

Finally, the mMTC slice carries uplink traffic generated from surveillance cameras. These cameras generate a constant data flow and require a guaranteed data rate. Their position has been spread uniformly in the targeted scenario and they are assumed to generate High-Definition video quality constantly.

IV. VEHICLES' MOBILITY ANALYSIS

Considering the urban use case as described in the previous section, this section is devoted to gain further insight on the mobility associated to the vehicles in the scenario. In this respect, after analysing traffic patterns across all BSs, we observe that BS3 has the largest impact of the vehicular mobility. This is due its position in the target area, supporting traffic from two highways and being close to a junction, which also exposes the traffic variations of vehicles exiting a highway and merging to another.

Fig. 3 shows the flow of incoming vehicles to BS3 along the time (averaged in 15-minutes period), depending on the neighbouring origin base station. On the one hand, Fig. 3 allows to quantify the traffic fluctuations during the day in BS3, showing that the busy hour happens at around 16:00 and exhibits more than 100% traffic increase with respect to the traffic observed earlier in the afternoon. On the other hand, this allows to identify that traffic to BS3 mainly comes from BS4, BS5 and BS15. Looking at the scenario in Fig. 2, this traffic increase is coming from either the cross highway (cars entering from BS4 and BS15) or the cars entering from the Cologne city centre (North).

The increase in the number of vehicles traversing BS3 during the busy hour impacts on the dwell time that vehicles spend in BS3. This can be observed in Fig. 4 which shows the cumulative density function (CDF) of the dwell time in BS3 during the busy hour and outside the busy hour. The CDF during the busy hour reflects a shift towards higher values. While in non-congested traffic conditions, only around 1% of the users stay connected to BS3 for more than 150 seconds, the figure shows that during the busy hour around 10% of the vehicles stay in BS3 for over 400 seconds, which indicates that a traffic jam is occurring.

Fig. 5 depicts the average dwell time in BS3 for the incoming traffic from BS2 depending on the outgoing base station. This allows identifying that the increase in dwell time is mostly related to those vehicles heading to BS4. Recalling Fig. 2, it appears that traffic flows from south to north – BS2 to BS3 – then divers at the exit to take the highway from west to east, and a traffic jam is happening at the junction.

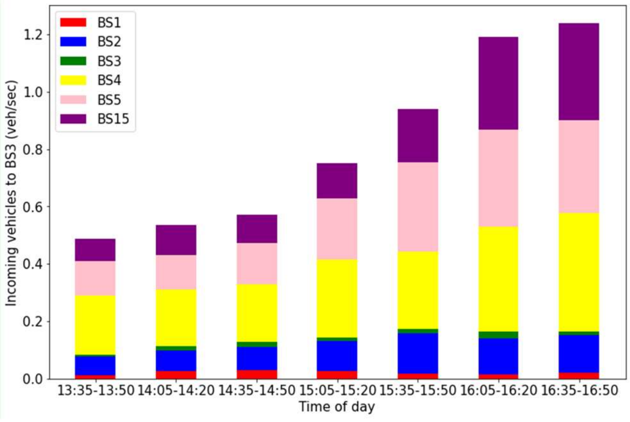

Fig. 3: Fluctuation of vehicles' flow coming to BS3 from different BSs over the afternoon.

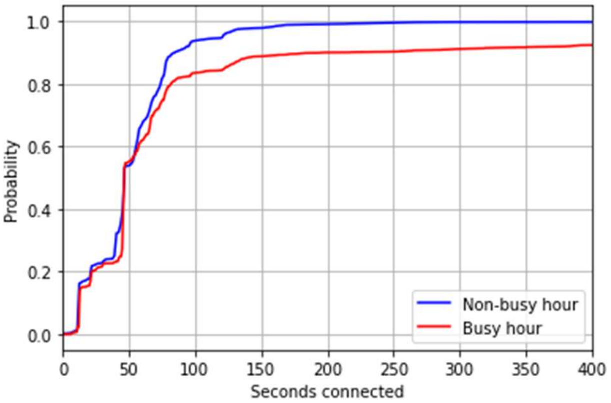

Fig. 4: CDF of dwell time in BS3.

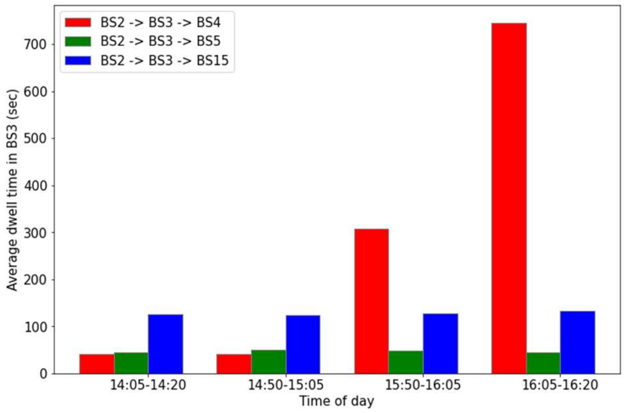

Fig. 5: Average dwell time in BS3 for vehicles coming from BS2 split according to the next hop BS.

V. TRAFFIC LOAD ANALYSIS

Regarding V2X traffic in BS3, Fig. 6 shows the big impact that the traffic jam occurring in the afternoon has on the generated traffic. The V2X traffic increases not only by the fact that the number of vehicles in BS3 increases but also because of the V2X applications' characteristics. Given that a CAM message originated by a certain vehicle is forwarded in downlink to all vehicles within 16hm^2 range, the number of downlink CAM messages significantly increases during the traffic jam. It can be observed that BS3 transmits a peak of around 40 Mbps associated to CAM messages.

In turn, Fig. 7 shows the total occupancy of downlink physical resources (i.e. RBs) in BS3 along time as well as the part associated to V2X slice. The plotted downlink RB demand corresponds to the average RB requirement in a period of 1 second. This demand is associated to downlink eMBB traffic and downlink CAM messages. It is worth noting that the amount of RBs required by each connection is user-specific (i.e., the poorer the SINR observed by a certain user, the higher the amount of required RBs).

It can be observed that while in normal conditions the cell can safely accommodate the generated traffic, during the traffic jam BS3 gets significantly overloaded. Recalling that 106 RB are available in BS3 and that RBs are assigned every millisecond, the available capacity measured in a time window of 1 second is 106.000 RBs.

Fig. 6: Downlink traffic load generated on BS3 associated to CAM.

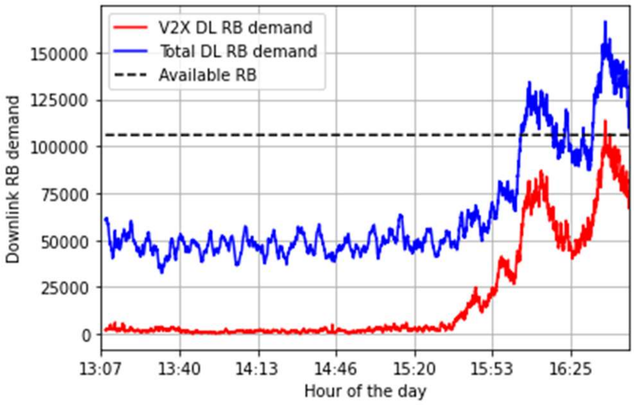

Fig. 7: Generated traffic load at BS3 and its vehicular component.

VI. OVERLOAD CONTROL

In order to alleviate the overload in BS3, the traffic far from BS3 can be diverted to neighbouring BSs. Typically, this can be achieved by adjusting the handover offset and might be automated by exploiting self-optimizing network capabilities such as MLB (Mobility Load Balancing) [36]. MLB aims to optimize cell handover parameters to cope with the unequal traffic load.

In order to illustrate the strategy, we focus on introducing a shift in BS3 to favour early handover to its neighbours in order to mitigate the overload. Let's denote this shift by Δ. Given that no shadowing is considered in this paper, for simplicity we take Δ as distance difference, though in practice Δ would be associated to a path loss or radio signal strength difference. Thus, let us define the distance at a given timestamp between a reference user and BS3 and BS4 as d_{BS3} and d_{BS4} respectively. Then, this user will connect to BS3 if $d_{BS3} + \Delta < d_{BS4}$.

Fig. 8 shows the RB demand in BS3 when the Δ strategy is applied for two values: 100m and 400m. While the first has a limited impact on BS3 load, the latter allows a significant load reduction, to the point that the overload is avoided. It can be observed that, thanks to anticipated handovers for outgoing BS3 traffic, the RB demand in BS3 keeps below the available capacity.

While the key objective of managing BS3 overload is accomplished with this Δ shift, a side effect is worth to be highlighted. Specifically, Fig. 9 illustrates how BS4's RBs demand increases during the traffic jam, though still keeping the total load below the cell's maximum capacity. On the one hand, part of this increase is due to the increase of incoming vehicles from BS15 shown in Fig. 3 which also tightens the highway merging for users coming from BS2 and BS4 and makes BS4 to handle a part of the traffic jam. On the other hand, anticipating the handovers from BS3 to BS4 cause that the radio links with BS4 exhibit lower spectral efficiency than with BS3. Thus, the RB occupancy requirement in BS4 is increased at some extent compared to the one required in BS3. Specifically, it is found that the decrease of spectral efficiency has a limited impact of 6% if a Δ value of 100m is considered. However, for a Δ of 400m, the number of RB needed in BS4 increases by a 25.6% compared to BS3.

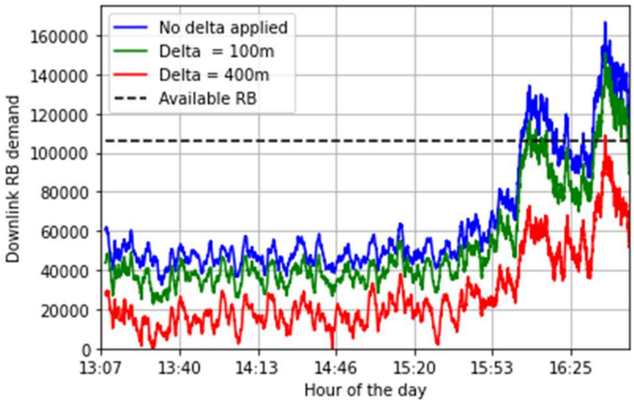

Fig. 8: Mitigated load at BS3

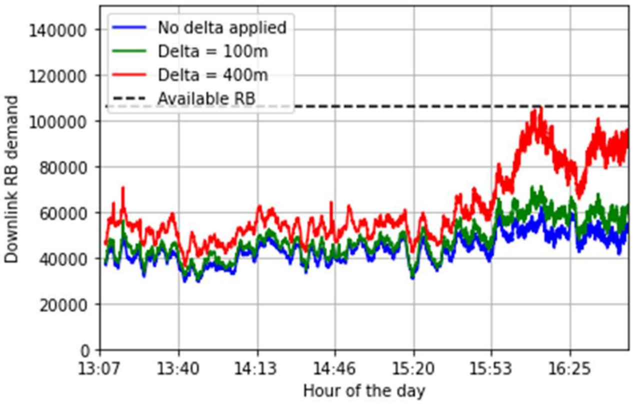

Fig. 9:Transferred load to BS4

VII. CONCLUSIONS AND FUTURE WORK

This paper has analysed the impact of traffic jams in vehicular networks, considering an urban scenario using realistic vehicular traces. Together with V2X services, eMBB and mMTC slices have been considered.

The analysis of vehicles' mobility has enabled to identify a traffic jam occurring within the coverage footprint of a specific BS. Beyond the observation that the dwell time in this BS increases, a closer look into more detailed statistics has revealed the traffic flows among various BSs that are most affected by the traffic jam. Moreover, it has been quantified at what extent the increase of vehicular resources demand has drained the available resources at the BS of interest, leading to significant cell overload. To mitigate this effect, a load balancing approach has been proposed and assessed. Results have shown a significant mitigation of the data traffic overload, diverting part of its load to the neighbouring BSs at which most of the vehicles were heading to.

Based on this work, our future research envisages the formulation of machine learning-based algorithms to exploit the information extracted from the vehicles' mobility. Through these algorithms, the advanced knowledge of the scenario will be exploited, enabling an efficient network operation.

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