Towards Edge Intelligence in the Automotive Scenario: A Discourse on Architecture for Database-Supported Autonomous Platooning

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***Abstract*—Edge intelligence is one of the key paradigms related to the efficient implementation of future wireless networks. In this context, the surrounding telecommunication infrastructure is intended to support the functioning of the wireless system. Thus, it is necessary to offload some computational efforts to the system edge, allowing the infrastructure to learn and make prospective decisions. However, for the reliable realization of the edge intelligence concept, the wireless system architecture should be designed properly to minimize both storage cost and induced latency. In this paper, we compare three architecture proposals (centralized, distributed, and hybrid) tailored to the autonomous driving use case, being one of the key vertical scenarios in contemporary and future wireless networks. We evaluate the performance of an autonomous platooning system, where the operating frequency is selected dynamically with the support of infrastructure to minimize the overall interference level in the whole band. Extensive computer simulations have been carried out to analyze the impact of the induced delay in signal processing and storage efficiency.**

***Index Terms*—Context awareness, edge intelligence for vehicular spectrum access, spectrum sharing, system architecture, V2X communications and autonomous driving.**

I. INTRODUCTION

ONE of the vital use cases for autonomous driving is vehicle platooning when a group of vehicles (typically trucks) forms a convoy. Such a platoon of autonomous cars is typically led by a leader which is responsible for sending steering information to the platoon members and mutual information exchange between them. In turn, reliable communications within the platoon can lead to a significant reduction of inter-car distances, and in consequence, to cost and carbon footprint reduction, as shown in, e.g., [1]. Nowadays, wireless communications between vehicles are realized by means of so-called dedicated short-range communications (DSRC) or cellular networks (cellular-V2X, C-V2X). Unfortunately, the former one, which is based on IEEE 802.11p and wireless access in vehicular environment (WAVE) standards, may suffer from possible medium congestion when the number of communicating cars increases [2], [3], and this may result in car accidents. Thus, following the concept of cognitive radio (CR) [4], it is reasonable to offload a portion of traffic to other, non-congested bands, by applying the idea vehicular dynamic spectrum access (VDSA) [5]. In such an approach, the platoon's wireless data traffic is treated as a secondary service (secondary user, non-licensed user) in a band originally licensed to other systems (known as primary or licensed systems). Although the right selection of the most appropriate frequency band is an engineering task, based on the conducted measurements and without the loss of generality, in our research we concentrated on one specific frequency range. Mainly, we considered the TV band (mostly due to the high stability of frequency allocations plans), where the unoccupied television channels (widely known as TV white spaces, TVWS [6]) are used for data offloading. The second band is around 26 GHz (millimeter waves).

It is important to stress that in such an approach, autonomous platooning is treated as a secondary service, and the existing primary systems have to be protected. While sensing of primary signals is a natural and immediate solution, it fails to provide enough level accuracy and reliability, if the measurements are conducted and decisions on spectrum occupancy are made by a single network node (e.g., by a platoon member or leader) [7]. As the transmission reliability in V2X communications is one of the ultimate needs, other solutions have to be considered. One of the available and widely used options is to apply dedicated geolocation databases, or in a broader sense, context database (CDB) repositories responsible for storing contextual information valuable for fair network functioning. CDBs are part of the proposed edge-intelligence system (EIS) [8], described later in the paper, the role of which is to deliver various services to users. In the considered case, such contextual information will be delivered to the interested nodes (e.g. platoons, platoon leaders, other cars, etc.) to support the self-driving process and - in our case - the offloading of traffic to other bands.

When focusing on TVWS, it may be noticed that the location of digital terrestrial television (DTT) transmitters (being the primary system in the TV band), as well as the frequency plans for TV broadcasters, are not changed that often. Thus, a detailed set of parameters defining existing DTT systems may be stored in a dedicated CDB with high accuracy. They may include information about, e.g., the location of the DTT tower, transmit power, central frequency, applied modulation, etc. But also, CDB can provide access to conducted measurements, where the receive signal strength of DTT transmission was

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observed in various locations on highways and high-speed roads. Thus, such a context database, as a part of the side edge-intelligence system (EIS), may be applied to support the VDSA algorithm in the selection of an appropriate TV band for data transmission.

However, it can be envisaged that the architectural design may have significant impact on the performance of the whole system, and in consequence, on the reliability of inter-car communications and autonomous platooning. If, for example, the data processing time at the network edge is high, as well as if there is a significant communication delay between various entities of EIS, the resultant latency in information delivery may be so high that autonomous platooning will not be possible. Thus, it is important to accurately select the system parameters and the location of EIS entities to guarantee high V2X communication reliability and safe driving. Thus, in this paper, we evaluate the performance of the proposed EIS from various perspectives.

In summary, the novelty and the impact of this paper are as follows:

- First, we propose three EIS architectures tailored to the autonomous platooning scheme and discuss their advantages and disadvantages.
- Second, we evaluate the impact of the CDB design on the performance of the proposed VDSA scheme. Mainly, we consider various ways a CDB with radio maps can be created.
- Third, we showcase the impact of induced delay on the functioning of the whole VDSA procedure with different architectures of EIS. For the centralized approach, we assume no delay on signaled information, as we consider a predictive operation of such a system, accounting for the future position change. In all other cases, we account for latency of information exchanged between different EIS entities involved in VDSA optimization.
- Next, we evaluate the impact of the mobility and speed of the cars on the system performance.
- Finally, based on these observations, we provide a conclusion on the most promising EIS architecture for autonomous driving.

The rest of the paper is organized as follows. First, in Section IV, we present a brief description of the considered system model, followed by an overview of the applied VDSA scheme for traffic offloading from 5.9 GHz to TV bands with the support of EIS. Next, in Section III-C three architectures proposed for EIS are discussed, showing their drawbacks and benefits. Finally, in Section V, a vast bunch of extensive simulation results are presented (where cases with two and four platoons driving simultaneously are considered). The conclusions of our work are presented in Section VI. For the sake of reading clarity, we have provided a glossary of all used acronyms in Table I.

TABLE I
GLOSSARY OF ACRONYMS.

Abbreviation	Description
ACIR	Adjacent channel interference ratio
C-V2X	Cellular V2X
CACC	Cooperative adaptive cruise control
CDB	Context database
CR	Cognitive radio
CSMA-CA	Carrier sense multiple access with collision avoidance
DSRC	Dedicated short-range communications
DTT	Digital terrestrial television
DSU	Data storage unit
EIS	Edge intelligence system
MCD	Measurement capable device
REM	Radio environment maps
RSM	Radio service maps
RX	Receiver
SINR	Signal-to-interference-and-noise ratio
SIR	Signal-to-interference ratio
SM	Spectrum manage
TVWS	TV white space
TX	Transmitter
V2V	Vehicle-to-vehicle
V2X	Vehicle-to-anything
VDSA	Vehicular dynamic spectrum access
WAVE	Wireless access in vehicular environment

II. CONSIDERED SYSTEM MODEL AND RELATED WORK

A. System Model

In this work, we concentrate on a highway or high-speed road scenario, where multiple autonomous platoons travel among other vehicles. The trucks within a platoon are controlled using the cooperative adaptive cruise control (CACC) algorithm [9]. Moreover, to model a high data traffic scenario (so a case when wireless communications channels are congested), every platoon is preceded by a jammer car. The jammer periodically (with a single period duration of 30 s) changes its velocity from 100 km/h to 130 km/h and then back to 100 km/h. In terms of wireless communication between platoon members, messages with mobility information, either from the preceding car or from the platoon leader, are transmitted according to the IEEE 802.11p protocol [10]. The dedicated CACC messages are broadcast periodically to disseminate the mobility properties of cars. Furthermore, the intra-platoon communications are performed in a frequency band dynamically selected from a predefined range that primarily is used by licensed DTT. We consider the presence of several fixed-location DTT receivers around the motorway, that require protection of their TV signal reception. The frequency band selection is done following the VDSA scheme, whose aim is to dynamically switch the frequency bands utilized by the platoon to maximize the signal-to-interference-and-noise ratio (SINR) of the V2V transmission, while keeping interference to the primary system at an acceptable level. We assume that VDSA is aided with context information stored in CDB, processed in EIS and delivered to the platoon leader. The information from CDB is used to enforce a power control mechanism to preserve the quality of the primary transmission. VDSA accuracy depends on the applied model of interference between the primary system (i.e., DTT in our case) and V2X communications. In our work, we consider a propagation model for the DTT frequency bands developed in [11], which is complemented by out-of-band radiation, modelled using accurate adjacent channel interference ratio (ACIR). Finally, we assume that the algorithm has to take into account other existing V2X communications.

In general, we assume M DTT towers are operating in the area of interest, which are broadcasting signals in W TV channels. We also consider that there are K platoons, with I_k transmitters and J_k receivers present within each k-th platoon ($k = 1, 2, \cdots, K$). A graphical representation of the considered scenario is shown in Fig. 1, where 4 platoons are traveling on a high-speed road utilizing a CDB-supported VDSA algorithm. There are two remote (distant) TV towers occupying two DTT channels (denoted in Fig. 1 as X and Y), and a set of roadside transmitters being part of the Edge Intelligence System deployed for supporting autonomous driving. The coverage areas are also shown. One may also observe five households (in general, buildings) that have to be protected from harmful interference, i.e., the quality of the delivered primary DTT signal has to be above an agreed threshold.

The considered communication scheme is graphically presented in Fig. 2 - the messages between platoon members are exchanged in the TV band (following the spectrum sharing principle), whereas the communications between platoon members and the infrastructure (edge intelligence subsystem) is done in regular, 5.9 GHz band, assigned to ITS systems.

B. Reference to Prior and Related Work in the Domain of VDSA

Referring to the concept of VDSA, in [12] the authors have proposed an architecture for optimizing the process of dynamic channel selection in vehicular scenario, benefiting from the reinforcement learning scheme. In particular, vehicle mobility was taken into account in order to accurately protect the primary users. It was achieved by the design of databases and channel priority schemes to record temporal and spatial channel heterogeneity. Finally, the vehicle path prediction techniques was proposed in order to enhance channel access. The performance has been evaluated in terms for computer simulations. This topic has also been further researched in [13]. A similar topic has been investigated in [14], where the authors considered the queuing theory to model a multi-access multi-user architecture. In particular, this work examines the feasibility of VDSA in TVWS by applying the multi-server multi-priority non-preemptive queuing theory (mainly, the M/M/m and M/G/m models were evaluated). The queuing theory has also been considered in the context of VDSA in [15].

In [16], memory aspects have been considered in the context of VDSA, with the authors investigating the application of algorithms that mimic the behavior of bumblebees. These species possess evolutionary decision-making mechanisms so they can adaptively solve similar problems (while foraging in environments with multiple floral resources) as the platoons (cars) need to face during flexible channel selection. The achieved results showed that considering such a memory system can significantly increase channel selection performance when compared to the situation when no access to prior decisions is guaranteed. The gain was as much as 52%. This approach has also been evaluated in the context of C-V2X networks in [17].

In our prior works, mainly [18], [19], we have concentrated on the application of radio environment maps (REM) for the improvement of VDSA for autonomous platooning in TVWS. As mentioned above, the advantage of the selection of the TV band is twofold: first, the low radio frequencies offer wide communication ranges (please note that the convoy may consist of even 10-15 cars, which may result in a total length of around 300–400 meters); second, it lies in the stability of the primary signals allocation. As it was already stated, in the context of TVWS one can notice that the deployment of DTT transmitters is fixed (in a very long time scale). Moreover, the frequency plans for TV broadcasters are not changed that often. Such information may be stored in CDB. Beside that, CDB can store the results of measurements which will be performed in real traffic scenarios, thus numerous aspects have to be considered, such as the velocity and directions of movement of cars, traffic density, weather conditions, etc. All of them will have an impact on the observed mean power of the DTT signal. It means that to guarantee fair protection of primary system users, as well as to utilize resources in a justified way, CDB should store various sets of parameters related to different environmental conditions. In consequence, high storage resources may be necessary. Moreover, the measured values are collected with some assumed spatial resolution (associated with the above mentioned car speed), and in turn, each entry will correspond to one tile of the geographic area. Clearly, the denser the grid, the more accurate the measurement entries. However, on the other hand, by decreasing the tile size, the overall complexity (measured in terms of processing power and storage cost) increases; yet, too low grid density may lead to a significant inefficiency of the whole offloading procedure. Thus, comparing to our prior works, in this paper, we concentrate on the evaluation of the impact of CDB design parameters (i.e., grid type and density) on the performance of the whole VDSA offloading procedure.

Next, besides the applied grid density for data storage, it is evident that some information may be irrelevant at certain locations, e.g., it is not important for a given location what the measured power of the DTT signal is within a far radius. This obvious statement leads to the observation that a fully centralized architecture of EIS (i.e., where all the information is stored in one logic entity) may not be the most suitable solution from the point of view of induced delay, due to increased processing and data delivery. On the other hand, in a fully distributed approach, not all necessary information may be available in each node. Thus, in this paper, we discuss the impact of the EIS architecture design on the functioning

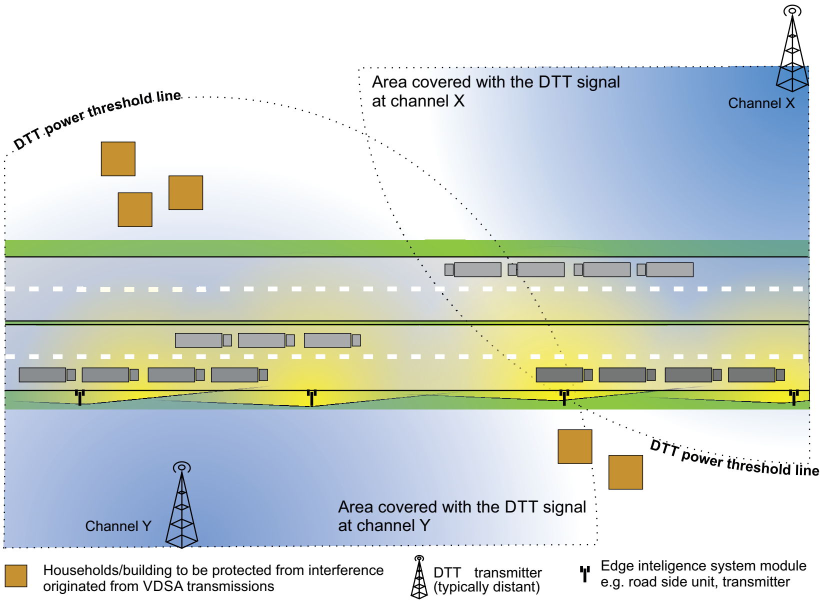

Fig. 1. Considered VDSA scenario for autonomous platooning.

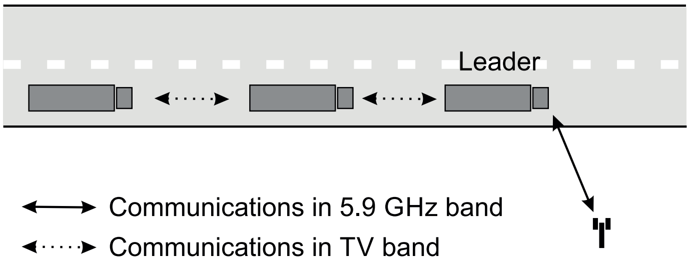

Fig. 2. Applied communications schemes.

of the autonomous platooning use case.

Finally, autonomous platooning is one of the classic examples of ultra-low latency and high-reliability communication schemes, where besides high link quality, the delay in data processing has to be very low. As in this paper we consider EIS-supported autonomous platooning, the influence of induced latency (due to data propagation and processing time in EIS entities) may be significant. In the worst case, it may cause that delivered data will be outdated.

III. EDGE INTELLIGENCE SYSTEM SUPPORT FOR AUTONOMOUS DRIVING

This section outlines the proposed heuristic approaches to solving the optimization problem given in section IV-A with the aid of context information provided from CDB and EIS. Depending on the structure of a database, the overall architecture of EIS and the placement of the decision-making VDSA entity, different configurations are considered.

A. Context Databases Overview

The concept of cognitive radio (CR) has been proposed around two decades ago [4], and, in general, it assumed that wireless systems might benefit from enrichment with an artificial intelligence functionality. The fundamental rule with CR is that the system (and also an individual CR node) should observe and sense the ambient environment, learn it, and make decisions based on the results of such observations. However, numerous studies have shown that single-node spectrum sensing is usually not reliable enough. Hence, for the considered V2V system and dynamic frequency channel selection, standalone platoon decision-making might not be the best solution, taking into account the requirements on system reliability. Therefore, two key solutions have been considered in recent years, namely, cooperative sensing and the utilization of context databases, with the latter analyzed in this paper.

It is, however, worth noticing that in a broader sense (i.e., when one does not focus on spectrum sensing), such context-aware databases may be used to support different functions of the wireless system. Such databases storing data on the radio environment (e.g., propagation conditions) and wireless nodes (parameters of transmission, constraints, etc.) are called radio environment maps (REMs), radio service maps (RSM), or context databases (CDB) (e.g., see [20]). In prior works, REMs have been analyzed in the context of network virtualization [21] and the utilization of DTT coverage for the indoor deployment of wireless access points [22]. In [23], such databases have been successfully used for the improvement of handover procedures, whereas in [24], they have been considered for the optimization of different aspects of 5G networks operation. In [25] , the authors considered a database for wireless network optimization. These applications are good examples of the use of repositories in wireless communications, however, an additional processing engine is still required to facilitate the proper decision making based on the provided data. Moreover, the variety of possible applications is huge, and depending on the scenario the set of information stored in

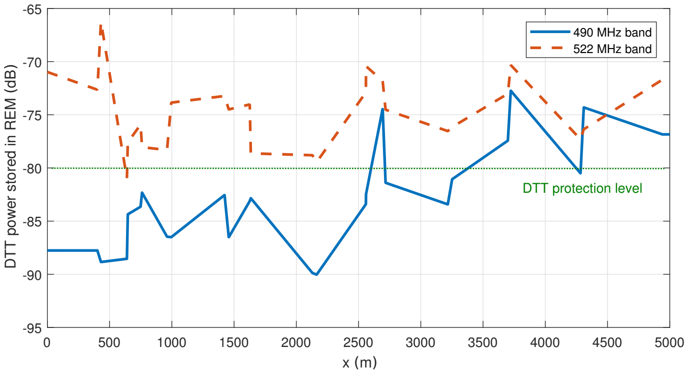

Fig. 3. Received DVB-T signal power at channels 23 and 27 stored in CDB vs. position on a motorway; dotted horizontal line represents the minimum required DVB-T reception threshold.

REM can vary. The repositories may be populated with static policies on the utilization of certain frequency bands, e.g., rules defined by the national regulator, regulations described by professional associations or other legal bodies, or conformance rules derived from other policies by means of analytical modeling. However, databases can also store fast-changing information, such as frequency utilization and observed interference (obtained with sensing or based on control information reported from different devices). Although typically the radio information may be stored together with a geographical tag (constituting a kind of geolocation database), it may also store location-independent data (such as the above-mentioned rules and policies). In consequence, some sort of intelligence (manager, cognitive engine) is necessary to correctly process all the entries saved in the repositories and draw reliable and justified conclusions. Thus, at a high level of generality, the whole context-information subsystem is typically divided into three parts: Database(s), a dedicated manager responsible for analyzing available data and assignment of transmission parameters to wireless devices, and a data acquisition and sensing function responsible for estimating the current status of radio environment based on various information sources [21]. In practice, all the entities for processing context information could create a standalone wireless system, or it may be a part of existing wireless infrastructure (e.g., of the contemporary cellular networks), typically located at the network edge. In the latter case, one may think of an Edge Intelligence System, EIS, as a solution for efficient delivery of context information and artificial intelligence tools for the end-users. In the following sections, three architectural designs of EIS for VDSA will be discussed.

B. CDBs Applied for VDSA

When focusing on autonomous platooning, there are many reasons why CDBs (and in general EIS) should be employed for VDSA. First, it can be used to minimize the interference impacting the reliability of V2V transmission. EIS may be responsible for spectrum assignment in a wide frequency range, providing separated wireless channels for in-platoon communications. Moreover, geolocation-based frequency management can allow many distanced platoons to use the same frequency channel. On the other hand, from the licensed user's perspective, the in-platoon communications must not degrade the quality of DTT transmission, also taking into account the mobility of the platoon. Therefore, in order to support VDSA in the autonomous platooning scenario, we consider that at least the following information is being stored in CDBs:

- Received (measured) DTT signal power level for DTT receivers that need to be protected in the considered area; these measurements vary along the highway (or in a broader scope, in different locations), thus the measurements will be associated with location information (geographical coordinates);
- channels used by the primary system and the corresponding DTT signal power level along the motorway/road that will cause disruptive interference to V2V transmission; depending on the application, the database may also contain information about the applied modulation and coding scheme;
- the presence of other platoons (cars) in the considered vicinity jointly with the selected frequency band and applied transmission power; such information is needed to prevent possible conflicts in spectrum access,
- information about the national and regional rules related to transmission guidelines and limitations defined by, e.g., the national regulation authority.

For this analysis, CDBs storing information on the occupied TV channels and the corresponding DTT signal power levels have been constructed based on measurements described in [18]. Fig. 3 illustrates an example of post-processed DTT signal power measurements stored in CDB as a function of a car's position on a motorway (geographical location). The raw measurements oscillate locally, thus to get the long-term trend, the averaging function jointly with first-order polynomial approximation has been applied, resulting in such smooth characteristics. One may observe the plots for two channels of central frequencies equal to 490 and 522 MHz, but also the horizontal line representing the quality threshold applicable in DTT evaluation (please note that the quality threshold line is also included in Fig. 1 indicating the coverage area of the DTT transmitter). All these types of information are utilized in the VDSA process to find the best (i.e., providing the lowest interference level) frequency band that can be used for intra-platoon communications. Depending on the scenario, the decision on the selection of the best channel is made by the platoon leader or by EIS.

C. Architectural Configurations of EIS

The main approach to VDSA considered in this paper is implemented in a way similar to the one presented in [26], where the spectrum manager entity is responsible for selecting the transmission band for a platoon according to the information provided by EIS. The general system architecture is depicted in Fig. 4 and includes the following entities:

- Data storage unit (DSU) - in our case, a context database, CDB - a database unit used to store selected context

information. Three different layers of data storage are considered depending on the applicability range of the saved data. There is a global storage layer on top, constituted by a wide-range database containing static or very slow-changing information, such as frequency plans, spectrum access rules, policies. Next, there is a medium layer with regional storage with intermediate databases that contain moderately dynamic information relevant for a selected geographical area. It includes, i.a., DTT power levels, occupied DTT channels, protection constraints, etc. Finally, at the lowest tier, there is local storage with small-scale databases (e.g., co-located with infrastructure points along the road) where highly dynamic information is kept (traffic characteristics, platoon parameters).
- Spectrum manager (SM) - which is an entity of EIS responsible for processing context information obtained from CDBs. In this paper, SM performs the proposed VDSA procedure to identify the best communications channels. SM is the entity that allocates certain frequency bands to platoons and sets the constraints on their transmission parameters to fulfill the DTT protection requirement. In general, however, other applications may be considered.
- Measurement capable device (MCD) - any device connected to the considered system that is capable of providing information that will be stored in DSUs. This MCD may be the sensors mounted inside the platoon members (cars in general), but it may also be statically deployed modules responsible only for permanent monitoring of spectrum occupancy in a certain geographical area. In the latter case, MCD will be part of the roadside unit deployed along the streets.

Depending on the location of the VDSA spectrum manager, the structure of CDBs, and the interfaces used to exchange context information, the following architectures can be considered:

- Centralized - in this case, the processing is performed globally for all platoons, and SM allocates frequency bands in full coordination between the platoons. EIS works in a centralized way, i.e., with the information provided from one global entity. The centralized architecture should be considered rather as an idealistic (or reference) approach. In reality, such an architecture would suffer from unacceptable latency in information exchange and processing constraints.
- Distributed - where the context information processing and SM operation takes place individually for each platoon. Thus, just limited coordination is assumed, i.e., the platoons exchange information on the selected bands and transmission power. Moreover, the communication efficiency is affected by the delays due to the non-zero processing and propagation time. In consequence, the information delivered to other platoons may be already outdated.
- Hybrid - that assumes tighter coordination between the platoons located nearby (or close to each other) on the highway. In consequence, SM allocates the resources considering two accuracy levels: first, detailed and up-to-date information on other platoons operating in the same (close) area, and second, coarse information on the other platoons. The latter messages are exchanged in a similar fashion to the distributed approach. In this paper, we assume full and ideal knowledge (available to SM) on the platoons located in the same coordination area, while other information is received with some delay. It reflects the possible case where SM is logically placed in the infrastructure point.

One should also note that the physical architecture of the system might differ from the logical architecture, e.g., with EIS being logically centralized but physically distributed. Therefore, different communication interfaces need to be taken into account with their constraints and limitations, e.g., on their latency. As in autonomous driving communication reliability is crucial for guaranteeing road safety, the latency induced by EIS has to be carefully investigated. Collecting and processing data in one (logically) central entity may be highly ineffective in this respect, as in most cases such a centralized entity will be physically highly distanced from the platoon (user). In consequence, there will be many intermediate communication hops between the user and the central entity, and such a hierarchical solution by assumption induces (relatively) high latency to the system. On the other hand, such a system could act in a predictive manner, accounting for future position changes caused by communication latency. In contrast, in the distributed approach, the distance (and thus, number of intermediate processing nodes between source car and destination, is reduced so the induced delay as well. However, to facilitate coordination between operating platoons, they need to exchange information on their decisions, which can also experience considerable delays. Clearly, the true delay observed in any of these architectures directly depends on the performance of applied hardware and utilized processing algorithms. Nevertheless, the hierarchical and centralized approach is prone to latency issues in terms of distribution of information on the VDSA decisions, which is not considered in this work. On the other hand, the distributed system may suffer from significant delays and insufficient availability of information about other platoons. All the aspects related to the delay induced by EIS should be subject to detailed investigation and this paper provides some initial insights in that context.

D. *Accuracy Aspects of EIS*

To provide accurate and up-to-date information to implement VDSA, the proper creation and maintenance process of CDBs is crucial. Taking into account the used hardware, the different architectures, and interfaces used to exchange information (their capabilities and limitations), the following aspects of data manipulation have to be carefully considered while designing the database subsystems for VDSA-based platooning:

- Regular vs. irregular grid – while creating the map, the stored data are valid only in a specific location, thus it is important to associate it with the corresponding area;

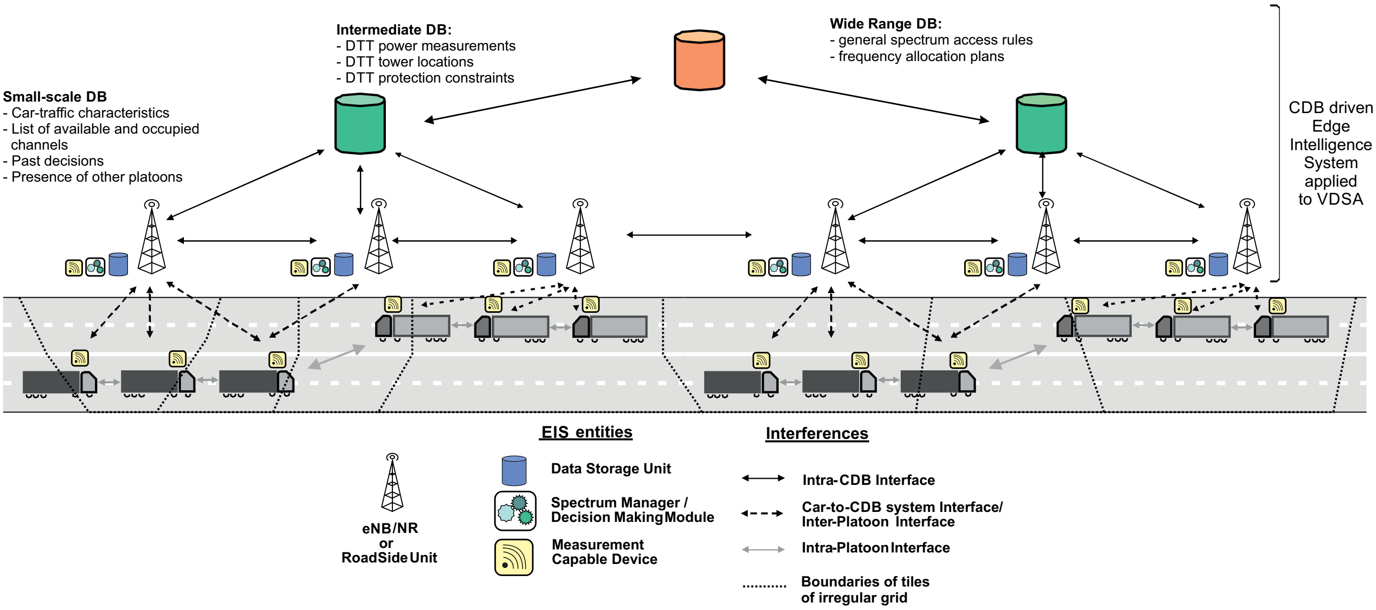

Fig. 4. Proposed architecture for a REM-based system for VDSA in autonomous platooning (CDB – Context Database).

however, the creation of a regular grid (with, e.g., square or hexagonal tiles) may not be the best solution; instead, an irregular grid with changing density of tiles (as a function of the changes of the measured parameter) could be considered; some discussion on the grid creation can be found in, e.g., [27],

- Density of measurement points – in general, the denser the grid, the better; however, in the platooning scenario it may be impossible (or even unnecessary) to work with excessively dense grids, as some metrics – like DTT signal strength – do not change that frequently; moreover, as the platoon can be quite sizable (with the length of tens or hundreds of meters), it seems beneficial to apply various approximation techniques;
- Age of information – in most cases, the problem of information aging has to be considered [28], the ways for permanent measurements of selected metrics have to be found, such as collecting all the data from the driving cars (crowdsourcing) or dedicated sensors; in both cases, it is necessary to find the trade-off between the frequency of updates and the burden related to the processing of the measured data; Furthermore, prediction mechanisms can be applied with SM operation, where the mobility parameters of platoons are accounted for.
- Location of storage – with the considered system architecture, some kind of information could be stored in wide-range repositories (i.e., repositories whose entries describe wide geographical areas), such as DTT frequency plans, whereas other types of data will be valid only in specific, small-scale regions (such as variations of the signal power as a function of the route); it may be necessary to also create an intermediate layer containing information important for several small regions;
- Access time (and induced delay) – the split into large, small and intermediate repositories immediately influences the access time to these data; in some cases, the data (maps) may be preloaded in advance (like a frequency plan for a given route or city), whereas other kinds of data may need instantaneous updates of their values; however, the time required for data processing and propagation may have a highly negative impact on the performance and accuracy of the whole VDSA system;
- Storage architecture – the database system may be logically centralized (following the concept from software-defined networks, the database system will have a global view on the entire network of nodes and all driving platoons), but in practice, it will be physically distributed; in consequence, the problem of overlapping of areas associated with each repository will appear; furthermore, it will be necessary to deal with various aspects of data storage and access, such as replications, transactions, conformance verification or data isolation [29].

The above-mentioned aspects are crucial for CDB-based VDSA operation, as their impact in the form of a limited accuracy of information or latency directly translates into the performance of VDSA-based intra-platoon communications.

IV. EIS-SUPPORTED DYNAMIC TRAFFIC OFFLOADING FOR AUTONOMOUS DRIVING

A. VDSA for Autonomous Platooning

The vehicle dynamic spectrum access problem considered in this paper follows the rationale presented in our prior works, i.e., [18], [26], which we briefly recap here. Joint power and frequency allocation is applied, where the maximum acceptable transmit power for the evaluated frequency band is derived. The calculations are carried out to allow sufficient protection of primary users, while assigning spectrum for a platoon with the aim to guarantee successful data transmissions between the platoon members. To guarantee the high reliability of intra-platoon communications, we aim to maximize the minimum observable probability of detection within the platoon. In other words, it corresponds to improving the worst-link SINR between the platoon leader and the worst-located platoon member.

The observed SINR at the j_k-th receiver ($j_k = 1, 2, \cdots, J_k$) while the i_k-th transmitter ($i_k = 1, 2, \cdots, I_k$) is sending data can be represented as [26]

$$\mathrm{SINR}_{j_k,i_k} = \frac{P_{i_k} \left|h_{i_k,j_k}\right|^2}{N + I_{j_k}^{PU-V} + I_{j_k}^{V-V}}, \tag{1}$$

where P_{i_k} is the transmit power of the i-th transmitter in the k-th platoon, $|h_{i_k,j_k}|^2$ is the channel propagation gain of the link between transmitter i_k and receiver j_k, N stands for additive noise power, and $I_{j_k}^{PU-V}$ is the interference power observed at secondary receiver j_k from the primary DTT system operating in the frequency range of interest. $I_{j_k}^{V-V}$ represents the interference power from all active cars in K platoons. Assuming that f_k is the center frequency used by the k-th platoon, both the $I_{j_k}^{PU-V}$ and $I_{j_k}^{V-V}$ interference components depend on ACIR taking values between $\langle 0; 1\rangle$ and represented as $f_{m,w,k}^{ACIR,PU-V}$ and $f_{l,k}^{ACIR,VV}$, respectively. In particular, $f_{m,w,k}^{ACIR,PU-V}$ describes ACIR as a function of frequency distance between channel f_k and channel w used by the m-th DTT transmitter. Analogously, $f_{l,k}^{ACIR,VV}$ describes ACIR as a function of frequency distance between channels selected by platoons l and k. Thus, focusing on DTT transmission in w channels ($w = 1, 2, \cdots, W$), with the measured power of the m-th DTT by the j_k-th platoon member denoted as P_{m,w,j_k}^{PU}, the effective interference from the primary system can be computed as [26]:

$$I_{j_k}^{PU-V} = \sum_{m=1}^{M} \sum_{w=1}^{W} P_{m,w,j_k}^{PU} f_{m,w,k}^{ACIR,PU-V}. \tag{2}$$

The interference from other active platoons can be described in a similar way as above, however, one should account for the random nature of the IEEE802.11p transmission due to the functioning of the carrier sense multiple access with collision avoidance (CSMA-CA) algorithm. Hence, it can be calculated as [26]:

$$I_{j_k}^{V-V} = \sum_{l=1}^{K} \sum_{\substack{i_l \\ i_l \neq i_k}} Pr\left(i_k \mid i_l\right) P_{i_l} \left|h_{j_k,i_l}\right|^2 f_{l,k}^{ACIR,VV}. \tag{3}$$

$Pr\left(i_k \mid i_l\right)$ represents the probability that i_k transmits while i_l is also active (i.e, an occurrence of a collision), that depends on the parameters of the employed CSMA-CA protocol.

Apart from the optimization of reliability of V2V transmission, the ultimate requirement for the considered platooning system operating in the DTT band is to protect the TV receivers [30], [31]. The DTT receiver has to be protected if the received DTT signal is usable, i.e., its power is above a threshold Γ_{PU}. Therefore, the w-th DTT channel is considered as occupied by the primary system in the vicinity of vehicle i_k if the observed DTT signal power $P_{m,w,i_k}^{PU} > \Gamma_{PU}$.

In order to preserve the primary transmission, additionally, the signal-to-interference ratio (SIR) at any DTT receiver utilizing channel w has to be above the predefined threshold, i.e.,

$$\begin{aligned} &\forall w, m, i_k : P_{m,w,i_k}^{PU} > \Gamma_{PU} \\ &P_{i_k} |h_{m,i_k}^{PU}|^2 f_{m,w,k}^{ACIR,V-PU} < P_{m,w,i_k}^{PU} / SIR_{\min}^{PU}, \end{aligned} \tag{4}$$

where $|h_{m,i_k}^{PU}|^2$ is the channel gain between transmitter i_k and the m-th DTT RX, $f_{m,w,k}^{ACIR,V-PU}$ is a linear ACIR function of the frequency distance between the center of the band used by platoon k and the center frequency of m-th DTT reception at channel w. The value $SIR_{\min}^{PU}$ denotes the minimum required SIR for DTT reception at the presence of platoon-based interference, i.e., the SIR threshold [26].

When estimating the level of interference introduced to the primary system, the wireless propagation effect needs to be accounted for. Thus, information on the distance to the primary receivers is needed. If the information on the location of protected DTT receivers is not known when performing VDSA, it should follow the worst-case assumption, e.g., assuming the primary receivers are located 60 m from the transmitting vehicle [31]. Alternatively, such location information on the protected areas can be made available to the VDSA system via dedicated context information stored in databases. In such a case, more accurate calculations, relying on exact distance information, can be performed.

In the considered VDSA framework, the protection of primary system receivers is achieved with the application of a transmit power control mechanism by the platoon members. The transmit power of each platoon vehicle is adjusted dynamically to the changing situation in the environment, accounting for the maximum interference level that can be introduced to primary users. We assume that the transmit power changes in linear scale from 0 to $P_{i_k}^{\max}$, i.e. $P_{i_k} \in \langle 0; P_{i_k}^{\max}\rangle$, aiming at fulfilling the minimum DTT SIR constraint given in (4).

Taking into account DTT protection constraints and the maximization of intra-platoon communication reliability, the final optimization problem can be formulated as:

$$\begin{aligned} &\max_{\substack{f_k \\ P_{i_k}}} \min_{j_k} SINR_{j_k,i_k} \\ &s.t. \forall m, w, i_k : P_{m,w,i_k}^{PU} > \Gamma_{PU} \\ &P_{i_k} |h_{i_k}^{PU}|^2 f_{m,w,k}^{ACIR,V-PU} < P_{m,w,i_k}^{PU} / SIR_{\min}^{PU}, \\ &P_{i_k} \in \langle 0; P_{i_k}^{\max}\rangle. \end{aligned} \tag{5}$$

In the following section, we evaluate the performance of the proposed EIS-supported VDSA in various scenarios.

V. SIMULATION RESULTS

A. Prerequisite Assumptions

To evaluate the impact of different features of EIS development and management, system-level simulations of a motorway platooning scenario have been carried out using a simulation tool developed in C++ in the framework of analysis described in [18], [26]. The simulation results presented in this section illustrate the impact of selected aspects of the proposed architecture on the achieved performance of the applied VDSA algorithm when multiple platoons operate simultaneously:

- Different system architectures with the three possible configurations described in section III-C, namely: centralized, distributed and hybrid system. They formulate different setups for the location of storage for selected data and data management. Moreover, the VDSA management entity can be co-located with the database, infrastructure points, or operating within each platoon individually.
- Information aging related to latency in the transmission of data to and from the database. The delay of reporting on the selected frequencies for each platoon or the expected DTT signal level influences the results of VDSA and the capability to select the best transmission band.
- CDB structure, with a regular grid of different resolutions used for the representation of data, corresponding to different densities of measurement points.

Moreover, to cope at least partially with the limitations resulting from the latency in acquiring information from databases and the limited resolution of information stored in EIS, a prediction mechanism is considered, where the mobility parameters of platoons are accounted for. The predictive VDSA mechanism, knowing the time span between consecutive band selection procedures and the platoon direction and velocity determines the road section for which a new setup will be applied and acquires context information from the database that corresponds to this section.

The influence of the different considered aspects is evaluated in simulations through observations of intra-platoon transmission reliability when using VDSA, such as the probability of successful reception for the most vulnerable links, which are typically the links between the leader and other cars. Moreover, the ability to protect the primary DTT transmission is verified by observing the SIR cumulative distribution function gathered at fixed-location DTT receivers. Two active DTT bands are considered with center frequencies set to 490 MHz and 522 MHz. To keep the paper concise, only the figures for the 522 MHz band are provided, as the results for both are similar. Finally, VDSA efficiency is also investigated, taking into account the average number of frequency band changes performed in different configurations. The higher the number of switches, the lower the efficiency, as any band change corresponds to the need to distribute the related control information among the platoon cars, and to tune the radio frequency to a new set of parameters.

The following part is split into subsections presenting as follows:

- The simulation setup and parameters,
- The impact of different architectures and latency in acquiring information from the database,
- The impact of the limited accuracy of information stored in the database due to constraints on the resolution of measurement points,
- The improvement of the performance of VDSA with prediction applied, with respect to the different resolutions of measurement points considered.

B. Simulation Setup

To evaluate the performance of VDSA for platooning, we considered a 6-lane motorway scenario, with two possible platooning configurations:

- Two platoons moving in the outer lanes in opposite directions,
- Four platoons moving in the outer and center lanes of the motorway (in two opposite directions), with the cars in the center lane traveling with slightly higher velocity (thus, the inner platoon overtakes the one in the outer lane).

Each platoon was composed of 10 cars, with the average inter-car spacing set to 10 m. Every platoon car transmitted CACC messages every 200 ms in the dynamically selected TVWS band, with each packet holding 300 bytes of data. We assumed the existence of two DTT transmitters using center frequencies at 490 MHz and 522 MHz, respectively. The considered range of frequencies available for VDSA spanned between 490 MHz and 522 MHz with a resolution (frequency step) of 4 MHz. The VDSA procedure was applied periodically every 1 s, with the considered DTT protection threshold values set as follows: the minimum protected DTT receive power $\Gamma_{PU} = -80$ dBm, and the minimum required SIR level $SIR_{min}^{PU} = 39.5$ dB [31]. We assumed that there are 10 DTT receivers present at specific locations around the motorway, with their coordinates and the observed DTT signal power levels stored in CDB for use in VDSA. For each presented value, 50 independent simulation runs were performed, with the duration of a single simulation run set to 140 s.

We evaluated different EIS architectures, with the information aging aspects accounted for only in the distributed and hybrid scenarios. In the case of the centralized architecture, no latency in acquiring information from the database was assumed, while we considered 1, 3, or 5 s delay in providing information on the other platoons for the distributed scenario and on the platoons outside the coordination area for the hybrid case, respectively. For the evaluation of the limited resolution of database, the following set of measurement points spacing was considered: $\{10, 50, 100, 200, 1000\}$ m.

The main simulation parameters are summarized in Table II.

C. Architecture and Latency Analysis

In this part, we analyze the impact of different EIS architectures on intra-platoon communication reliability. The centralized mode is considered as a reference here, as it operates without any delay in acquiring information and makes use of full coordination of all platoons. For the two other architectures, the distributed and hybrid one, we consider latency in obtaining information about other platoons (with the hybrid case only for those outside the coordination area) from the database. The latency may be due to, e.g., non-zero processing time or delay in message delivery.

1) Scenario with 2 platoons: The scenario with two platoons moving in opposite directions is characterized by low inter-platoon interference, as the cars belonging to different platoons remain only shortly in one another's transmission

TABLE II
SIMULATION PARAMETERS.

Parameters	**Values**
Motorway length	5 km
Number of platoons	{2, 4}
Cars in platoon	10
Inter-car spacing in platoon	10 m
CACC message periodicity	200 ms
CACC message size	300 B
Active DTT frequency bands	{490, 522} MHz
Frequency range for VDSA	<490; 522> MHz
VDSA frequency resolution	4 MHz
VDSA procedure periodicity	1 s
Number of protected DTT receivers	10
Minimum protected DTT power Γ_{PU}	-80 dBm
Minimum required DTT SIR SIR_{min}^{PU}	39.5 dBm
Latency of acquiring information	{1, 3, 5} s
Measurement points spacing for CDB	{10,50,100,200,1000} m
Number of simulation runs per point	200 (2 pltns) and 50 (4 pltns)
Single simulation run duration	140 s

TABLE III
AVERAGE NUMBER OF FREQUENCY CHANGES PER PLATOON WITH DIFFERENT CONSIDERED ARCHITECTURES AND CONTEXT INFORMATION LATENCIES.

Scenario	**2 platoons**		**4 platoons**			
Platoon ID	1	2	1	2	3	4
Centralized	3	4	21.1	26.02	22.7	33.68
Distributed (1s latency)	4.81	2.51	139.98	105.12	139.98	110.04
Distributed (3s latency)	5.03	2.35	46.06	54.42	46.54	57.1
Distributed (5s latency)	6.26	2.92	28.96	34.94	29.58	36.06
Hybrid (1s latency)	3	2	17.24	24.04	18.30	21.68
Hybrid (3s latency)	10.91	7.78	20.6	27.46	21.24	27.82
Hybrid (5s latency)	16.54	12.25	24.52	25.6	23.38	28.58

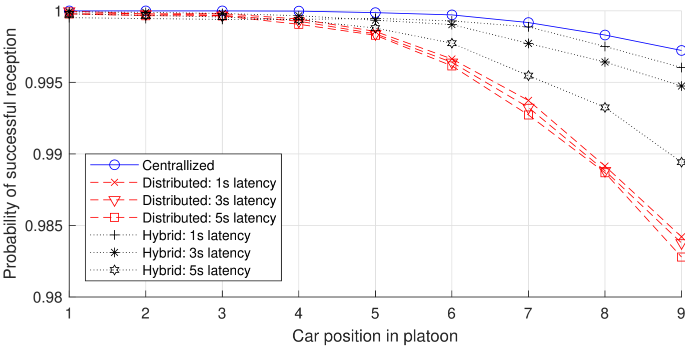

Fig. 5. Reception rate from leading car vs. position in platoon - scenario with 2 platoons (note that the results are discrete and represented by markers, the lines are introduced only to show the trend).

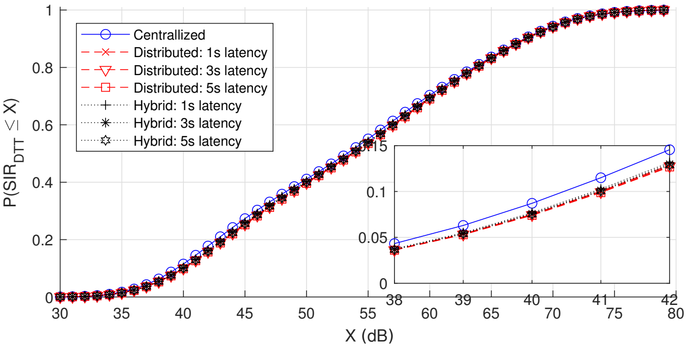

Fig. 6. SIR cumulative distribution obtained in simulations for the primary system receivers that required protection - channel 522 MHz, 2 platoons, full range.

range. This is reflected by the values of estimated probability of successful reception of the leader's packets, shown in Fig. 5. The best performance is obviously achieved with the centralized approach, with the hybrid architecture following closely. This indicates that significant inter-platoon interference from closely located platoons can be effectively removed by the coordination of their VDSA processes. On the other hand, in the distributed approach, the performance decreases significantly with increasing distance between the leader and ego car. This is a result of only limited and delayed information available on the other platoons' parameters, so the inter-platoon interference plays a part here. Moreover, one can easily notice the impact of increasing latency on the probability of successful reception in the case of hybrid and distributed architectures, with the worst results observed with a 5 s delay.

Table III presents the average number of frequency band changes vs. the considered architecture and latency values. It can easily be noted that a low number of switches is required in cases where inter-platoon coordination is applied, as these occur only when platoons are close to each other. The number of switches is increasing when higher delay in providing context information is experienced, with particularly significant change in case of the hybrid approach. This is caused by the uncertainty of information on other platoons' parameters. For the distributed method it still remains within acceptable limits (up to 7 changes per 140 s), while it becomes significant burden (up to 17 switches) in the hybrid case.

The ability of the VDSA process to protect the primary users, assuming different architectures, is presented in Fig. 6. First, one should note that for some samples, SIR lower than the required threshold was observed, which is a result of the shadowing impact, however, all the SIR values are high enough to allow for decoding of DTT. Surprisingly, the best performance is achieved by the distributed architecture, as in this case the information from other platoons is accounted for only to calculate the ego car interference level. Therefore, as there is no real coordination of VDSA processes, the main constraint put on the transmit power and frequency here is to minimize the interference to the primary system, which results in higher DTT SIR than in other cases. The worst performance is noted for the centralized approach, which aims at finding a tradeoff between platoon performance and DTT protection. One should also note that for the 490 MHz band the conclusions are the opposite, with the centralized architecture securing the best protection, while the worst results are observed for the hybrid approach (however, the differences are similar as in the case of 522 MHz). The general conclusion with these results is that for all the considered architectures it is possible to fulfill the primary system protection criterion, accounting for shadowing in the calculation of interference by introducing a fixed gap factor when adapting the transmit power.

In the scenario with two platoons, there are no significant differences in the performance of the considered architectures, except for the lower probability of successful reception of the distributed approach and a significantly higher band switching rate observed for the hybrid architecture with high latency. For both the centralized and hybrid approaches experiencing low latency, the performance is similar. An increase in latency impacts the results, particularly significantly in the hybrid scenario. Such an outcome indicates that the knowledge on the behavior of other platoons has a significant impact on VDSA performance. In both the centralized and hybrid approaches each platoon coordinates its band selection with nearby platoons, thus higher reception rate can be observed. On the other hand, in the distributed approach, each platoon acts in a more selfish manner, accounting only for the past behavior of others. When analyzing the impact of different context information latencies, one can notice that in both the hybrid and distributed approaches a performance degradation is observed with increase of delay, because the information on the interferers is less reliable. Moreover, the lower reliability of context information caused by delays results in higher number of performed frequency changes, that is particularly significant with the hybrid architecture. Hence, one can conclude that the age of information about interference sources has a significant impact on the performance in terms of packet reception rate and the number of performed band changes.

2) Scenario with 4 platoons: The scenario with 4 platoons moving in the outer and center lanes of the motorway is characterized by much higher potential inter-platoon interference, as there is a second platoon in the close vicinity of the considered one for almost the whole duration of the simulation. Therefore, up-to-date information on closely located platoons will play a significant part in the VDSA process.

The reliability of intra-platoon communications, represented as the estimate of the probability of successful reception of the leader's packets, is presented in Fig. 7. Definitely lower values are observed here than in the scenario with 2 platoons, which is a result of significant inter-platoon interference. Moreover, one can notice that the worst performance for the cars at the tail of the platoon is observed for the centralized architecture, which is a result of full coordination of VDSA processes, jointly aiming at limiting the interference to the primary system. With all platoons jointly optimized, some selected frequency bands overlap with DTT bands, resulting in a very low transmit power constraint applied by the power control mechanism. The best performer here is the hybrid system, which effectively avoids interference with closely located platoons, but offers more freedom with selecting frequency bands, as there is no coordination with distant platoons.Similar behavior can be observed for the distributed approach experiencing low latency (1 s) of information exchange. Worse performance is observed for both the hybrid and distributed approaches with higher latency, as they fail to avoid the significant inter-platoon interference due to the delay introduced in acquiring information on other platoons.

The average number of performed frequency band changes, outlined in Table III, is much higher here than in the case of 2 platoons. The highest number of frequency changes is definitely observed in the distributed architecture, with the number of switches reaching almost 140 changes (band change performed in every VDSA algorithm iteration). The reason for such situation is the delay in providing context information, which results in nearby platoons selecting the same frequency bands, as only the information on the past selections of the others is provided. The efficiency of VDSA (the number of switches) improves with the increase in latency, as platoons are able to find some equilibria with allocation of bands. Less band changes are observed with the centralized architecture, with over 30 switches required in the case of platoon 4. For the hybrid case, the number of band changes is the lowest, with high number of switches observed for platoons 2 and 4, exceeding 20 per 140 s.

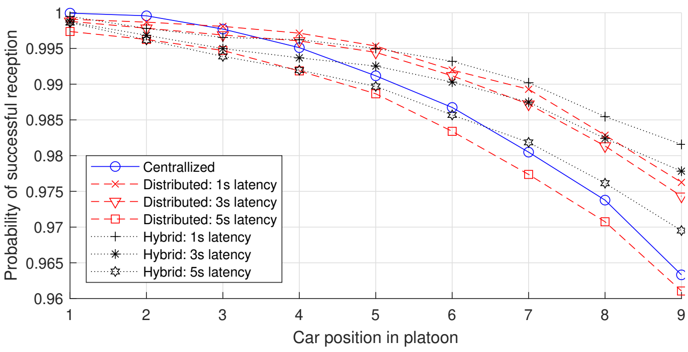

Fig. 7. Reception rate from leading car vs. position in platoon - scenario with 4 platoons (note that the results are discrete and represented by markers, the lines are introduced only to show the trend).

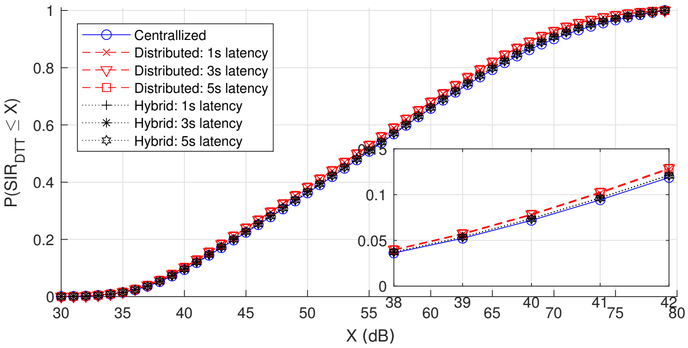

Fig. 8. SIR cumulative distribution obtained in simulations for the primary system receivers that required protection - channel 522 MHz, 4 platoons, full range.

Protection of the primary system is a much more challenging task here than in the case of 2 platoons, as more frequency bands are needed, which can lead to the overlapping of bands used for DTT and intra-platoon transmission. The results of observed DTT SIR values, presented in Fig. 8, indicate that with the distributed approach it is more difficult to maintain the proper protection of the primary system. The results for the centralized and hybrid approaches are almost identical, with both providing satisfactory protection of the DTT system. Similar results were observed for the 490 MHz band, thus we do not show them here.

In conclusion, the performance with the higher number of platoons, with some of them moving in the same direction, thus causing persistent inter-platoon interference, is lower, however, still within acceptable numbers. The best performer here is the hybrid architecture, which offers more freedom in the selection of frequency bands than the centralized one, while simultaneously accounting for significant interference from other platoons. The distributed architecture fails to fulfill all the goals in this scenario, as the observed communication reliability is lower than in the case of the hybrid system, while it is also unable to sufficiently protect the primary system. Furthermore, with the latency of 1 s the distributed VDSA procedure fails to find the proper bands allocation for platoons, as no equlibrium can be reached, with platoons performing band changes every VDSA period. Certainly, the application of VDSA with the higher number of platoons is more costly with all considered architectures, as it requires more frequency band changes. Finally, taking into consideration the impact of context information latency for the hybrid and distributed approaches, one can see its significant influence on the performance. The impact on the reception rate is particularly notable with 5 s latency. This indicates that the availability of up-to-date information on interferers is crucial for finding the proper band for communications. Such information is partially available with the hybrid approach experiencing low latency, while the situation is different in the distributed case, where the latency of information on closely located platoons is the reason of increased interference. Furthermore, the number of performed band changes in case of the distributed architecture shows that the availability of the information on the frequencies selected by nearby platoons is crucial to maintain a stable VDSA algorithm operation.

D. Density of Measurement Points Analysis - CDB Quantization

In this section, we focus on investigating the impact of different spacing of measurement points corresponding to EIS storage resolution. Again, intra-platoon communication reliability is verified by estimating the probability of successful reception of leader packets. Furthermore, as the accuracy of information stored in CDBs has a direct impact on the ability to protect the primary system, DTT SIR empirical cumulative distribution is analyzed. As a reference, EIS without quantization (or with centimeter-level spacing of measurement points) is considered.

1) Scenario with 2 platoons: The estimated probability of successful reception of leader packets vs. different spacing of measurement points for the 2-platoon scenario is presented in Fig. 9. One can notice that the applied regular grid of measurement points does not significantly impact the results compared to the full resolution case. Actually, the worst performance is observed here for the case with 50 m spacing of measurement points, with the results for the case without quantization following closely, however, in all cases the reliability is acceptable. Slightly lower successful reception probability, in this case, is caused by stricter protection of the DTT system with these configurations. One can also notice that, apart from the 50 m case, the use of a regular grid with a lower density of measurement points improves the reliability of V2X communications. The reason for such an observation is that higher transmit power is typically used with larger spacing, as the impact of measured low DTT power points is averaged.

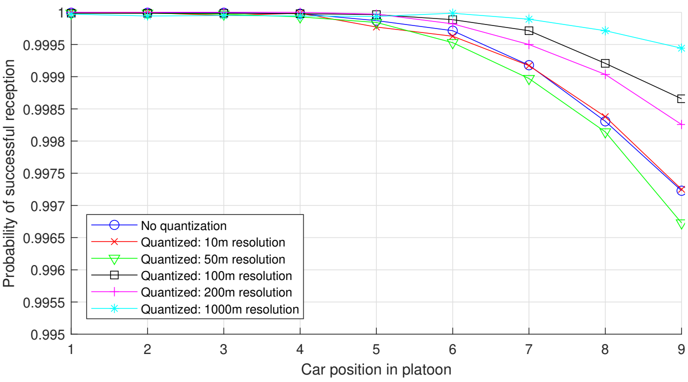

Fig. 9. Reception rate from leading car vs. position in platoon - scenario with 2 platoons (note that the results are discrete and represented by markers, the lines are introduced only to show the trend).

TABLE IV
AVERAGE NUMBER OF FREQUENCY CHANGES PER PLATOON WITH DIFFERENT CDB QUANTIZATION LEVELS.

Scenario	**2 platoons**		**4 platoons**			
Platoon ID	1	2	1	2	3	4
No quantization	3	4	21.10	26.02	22.7	33.68
Quantized: 10 m	3	4	21.06	25.46	22.14	33.90
Quantized: 50 m	2	2	19.50	23.68	17.50	30.84
Quantized: 100 m	2.44	2.72	21.82	26.68	18.48	33.20
Quantized: 200 m	2	3.04	20.38	24.78	21.30	33.44
Quantized: 1000 m	3.4	2	14.50	24.58	15.46	31.30

When analyzing the need for frequency band switching with different quantization levels, presented in Table IV, one can notice that in the 2-platoon scenario, usually between 2 and 4 switches are required. No real relationship between the grid density and the observed number of switches got noted, with a slightly higher number of changes observed for a very dense grid or without quantization.

Interesting observations can be made when analyzing the empirical cumulative distribution of DTT SIR at the protected primary system receivers in the 522 MHz band, presented in Fig. 10. One can note that the best performance is achieved with quantization, where the measurement points are spaced 50 m from one another, with the results for 100 m spacing closely following. It outperforms the scenario without quantization due to the averaging effect of measurement results. As the considered platoons are of significant length (up to 120 m), too high a density of measurement points may lead to a wrong value being selected from the database (the DTT power stored for the leader's position might differ significantly from the values corresponding to the position of cars at platoon tail). When the values collected within 50 or 100 m span are averaged, they accurately capture the aggregate conditions for the whole platoon. Moreover, with averaging over 50 or 100 m the aspects of platoon mobility are partially accounted for, as the position change corresponding to the platoon speed and 1 s interval (VDSA procedure period) corresponds with the spacing of measurement points. Hence, better results were

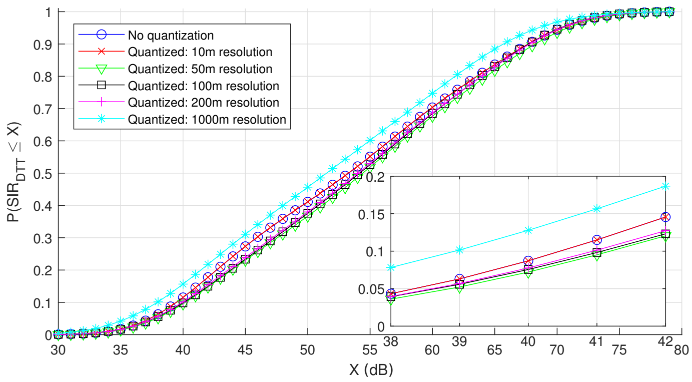

Fig. 10. SIR cumulative distribution obtained in simulations for the primary system receivers that required protection - channel 522 MHz, 2 platoons, full range.

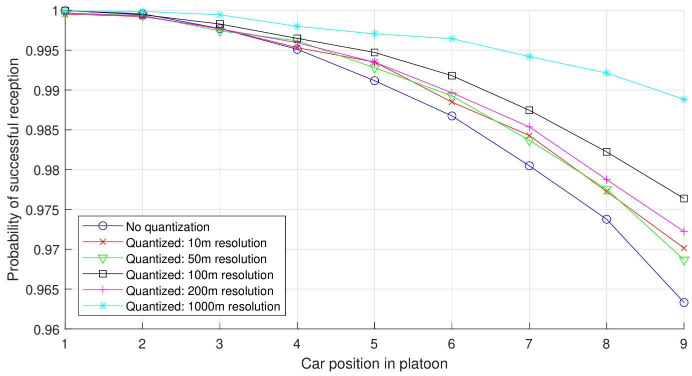

Fig. 11. Reception rate from leading car vs. position in platoon - scenario with 4 platoons (note that the results are discrete and represented by markers, the lines are introduced only to show the trend).

obtained with these configurations. One should also note that too scarce spacing of measurement points causes performance degradation, as important properties of stored data are lost due to averaging over significant distances.

The results and conclusions for the 490 MHz band are similar to those described above, with regular spacing of measurement points equal to 100 m providing the best performance.

2) Scenario with 4 platoons: The scenario with 4 platoons moving in the outer and center lanes of the motorway is characterized by higher inter-platoon interference, and its impact is visible in the analysis of the probability of successful reception of leader packets, presented in Fig. 11. Much lower reliability is observed than in the scenario with 2 platoons. In general, improvement in the probability of successful reception of leader packets can be observed with the increasing distance between the measurement points of the stored grid. The reason for such an observation is the increase in transmit power due to the averaging effect with quantization.

When 4 platoons are present in the simulated system, a significantly higher number of frequency band changes is needed, ranging from 15 to 35 per 140 s time span, as given in Table IV. However, no relationship between the grid density and the required number of switches can be formulated.

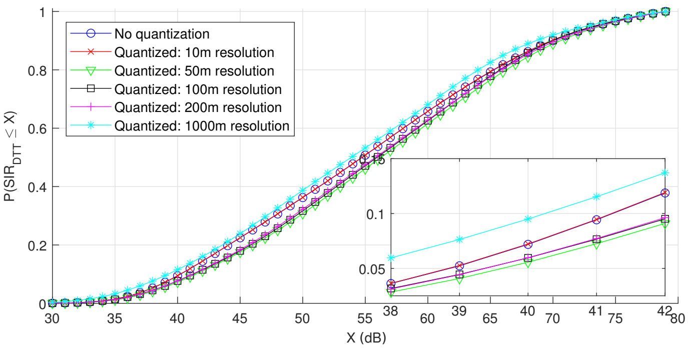

Fig. 12. SIR cumulative distribution obtained in simulations for the primary system receivers that required protection - channel 522 MHz, 4 platoons, full range.

When observing the DTT SIR cumulative distribution for the 522 MHz channel, presented in Fig. 12, one can draw similar conclusions as in the 2-platoon scenario. The best protection level of DTT receivers is achieved with quantization, where the spacing of measurement points ranging from 50 to 200 m is applied. With too dense grid (or without quantization) the mobility aspects and the significant length of a platoon negatively impact the performance, as the values acquired from CDB do not correspond well with the future positions of platoon cars. With the averaging effect of quantization, the reference values from CDB used in the VDSA procedure better reflect the present and future conditions. However, it should be noted that the optimal CDB grid density might be related to the platoon length, velocity, and the VDSA procedure period. The two latter ones indicate the potential future locations of platoon cars that need to be accounted for when acquiring data from CDB, thus they have to be considered jointly.

Similar conclusions can be drawn for the 490 MHz channel analysis.

E. Impact of Platoon Mobility on VDSA Performance

The results shown in Sections III-C and V-D indicate that high mobility may have a negative impact on the VDSA outcomes. In order to verify such a hypothesis, we conducted simulations of a scenario with two platoons moving with different average velocities. In this section, we present only the results of the estimated reception rate of leading cars' packets, as no significant impact of velocity changes on the ability to protect the primary system was observed.

Fig. 13 shows the estimated reception rate of leading cars' packets assuming different VDSA architectures and latencies of context information exchange, with the average platoon speeds of 130 km/h and 80 km/h. One can notice that a significant increase in platoon velocity results in a drop of the successful reception rate. This phenomenon is especially highlighted in the distributed and hybrid approaches, where for a moderately fast-moving platoon (at 80 km/h) very good performance, fulfilling the platoon needs, is achieved. However, when the speed increases to 130 km/h a significant drop in the reception rate is observed for the cars located at the tail of the platoon. The reason for such an outcome is the higher variation in inter-platoon distances and faster changes in selected platoon VDSA parameters, which contribute to

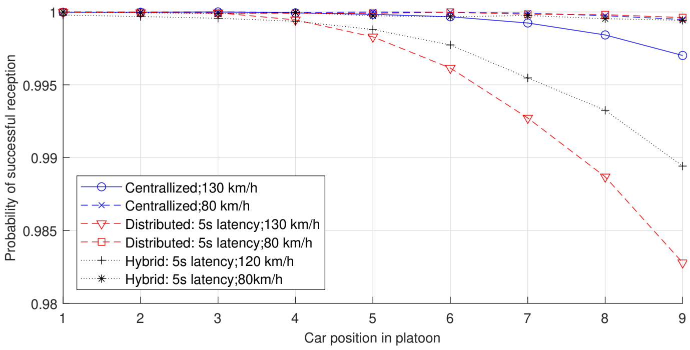

Fig. 13. Reception rate from leading car vs. position in platoon - scenario with 2 platoons, different VDSA architectures and platoon velocities (note that the results are discrete and represented by markers, the lines are introduced only to show the trend).

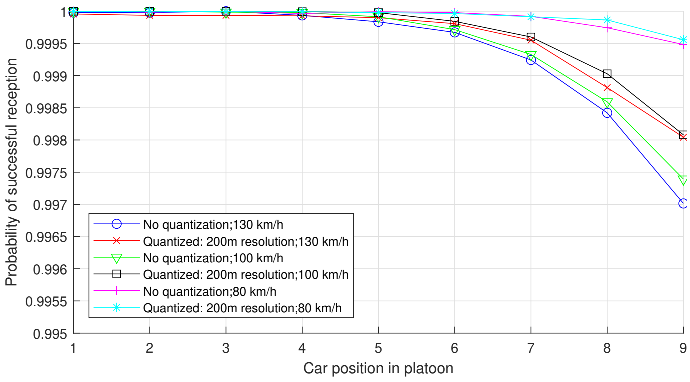

Fig. 14. Reception rate from leading car vs. position in platoon - scenario with 2 platoons, different CDB quantization levels and platoon velocities (note that the results are discrete and represented by markers, the lines are introduced only to show the trend).

information uncertainty. Such a phenomenon is less visible with the centralized approach, as accurate information about the interferers is available in the VDSA procedure. However, the impact of higher variation of inter-vehicle distance can also be seen for the centralized case.

When it comes to the observations of the impact of velocity changes on the performance of VDSA with CDB quantization, with the reception rate of leaders packets shown in Fig. 14, one can notice that there is no significant difference in behavior between the system without and with quantization. For both approaches a negative impact of increasing platoon velocity can be observed, with the overall impact on the reception rate similar for the quantized and full-information case. However, it can be noticed that quantization has a higher impact on the results in the case of higher velocities (the difference between the unquantized and quantized case is bigger for 130 km/h than for 100 km/h and 80 km/h). Such an observation clearly indicates that a quantization level adapted according to the mobility of the platoon would lead to better performance of VDSA. Alternatively, a prediction mechanism of platoon positions based on their mobility can be employed, as proposed in Section V-F.

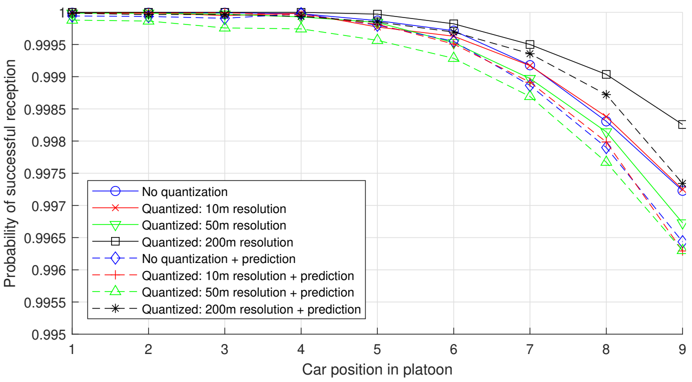

Fig. 15. Reception rate from leading car vs. position in platoon - scenario with 2 platoons (note that the results are discrete and represented by markers, the lines are introduced only to show the trend).

F. Minimizing the Negative Impact of Quantization and Latency - Prediction of Mobility

It has been shown that the mobility of the platoon might have a negative impact on the results of the applied VDSA procedure due to inaccurate values acquired from EIS that do not correspond to the future position of platoon cars. The results presented in Section V-D indicate that averaging of values measurement within the distance of 50 or 100 m improves the performance, as they better reflect the change in conditions when moving along the motorway. Therefore, apart from quantization being considered, a complementary solution is proposed that uses the prediction of future platoon cars' positions to acquire more accurate values from EIS. By predicting the locations that cars may occupy within the time span related to VDSA procedure periodicity, that are derived based on the platoon velocity and direction, CDB data corresponding to all these points are acquired and used in frequency band selection and the power control process. The following sections present a comparison of results obtained with and without such a prediction mechanism.

1) Scenario with 2 platoons: Fig. 15 presents the estimates of the probability of successful reception of leader packets in a scenario with 2 platoons for configurations without and with prediction. One can note that prediction in general results in a slightly lower reception ratio for all the considered cases. However, when analyzing the most interesting configuration with the spacing of measurement points by 50 m, there is very little difference between the system with and without prediction.

The number of frequency band changes required in the scenario with 2 platoons is presented in Table V. One can note that no significant difference can be observed between the configurations with and without prediction. Hence, the conclusion is that prediction does not change the required number of frequency changes.

The benefit from applying prediction can be observed with the plots of DTT SIR cumulative distribution for the 522 MHz channel, presented in Fig. 10. It can be noted that for all configurations employing prediction, gain in DTT SIR is observed with respect to the same quantization configurations without prediction. Therefore, we can state that the mobility prediction

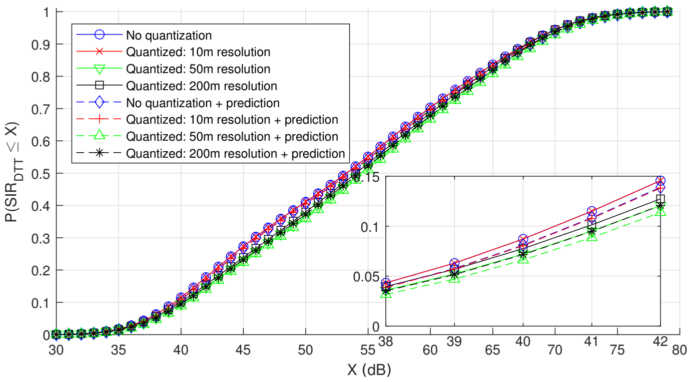

Fig. 16. SIR cumulative distribution obtained in simulations for the primary system receivers that required protection - channel 522 MHz, 2 platoons, full range.

TABLE V
AVERAGE NUMBER OF FREQUENCY CHANGES PER PLATOON WITH CDB QUANTIZATION AND PREDICTION.

Scenario	**2 platoons**		**4 platoons**			
Platoon ID	1	2	1	2	3	4
Quantized: 10 m	3	4	21.06	25.46	22.14	33.90
Quantized: 50 m	2	2	19.50	23.68	17.50	30.84
Quantized: 200 m	2	3.04	20.38	24.78	21.30	33.44
No quantization + prediction	3.22	4	21.20	24.76	23.46	32.76
Quantized: 10 m + prediction	3.24	4	22.62	24.70	24.84	32.96
Quantized: 50 m + prediction	2.28	2	20.1	23.22	19.84	31.04
Quantized: 200 m + prediction	2	2.6	19.72	25.62	19.92	32.6

mechanism captures well the effect of platoon movement, thus helping to acquire proper values from REM. On the other hand, the significant length of the platoon still negatively impacts the performance of dense quantization grids. Hence, the best solution here is to apply prediction in conjunction with quantization assuming a grid with 50 m resolution. A similar conclusion can be reached when analyzing the results for the 490 MHz channel.

2) Scenario with 4 platoons: In the scenario with 4 platoons, due to higher inter-platoon interference, a lower probability of successful reception of leader packets is noted, as presented in Fig. 17. An important observation is that, although for some configurations the prediction mechanism results in slightly lower reliability, for the most interesting case of 50 m spacing between CDB grid points, the application of mobility prediction provides similar results to those with quantization only.

Also, an analysis of the average number of needed frequency band changes, given in Table V, reveals that prediction has no impact on the switching rate.

When observing the DTT SIR cumulative distribution, shown in Fig. 18, similar conclusions can be drawn as in the 2-platoon scenario. For every considered quantization configuration, the application of the prediction mechanism improves the observed DTT SIR distribution. Therefore, one can conclude that the use of prediction helps to better estimate the reference points in CDB that correspond to subsequent platoon cars' locations than quantization only.

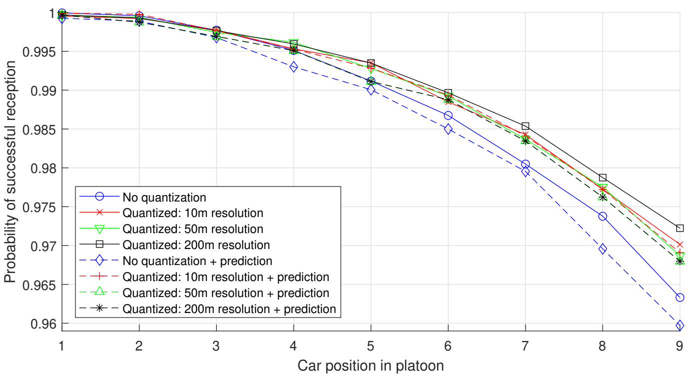

Fig. 17. Reception rate from leading car vs. position in platoon - scenario with 4 platoons (note that the results are discrete and represented by markers, the lines are introduced only to show the trend).

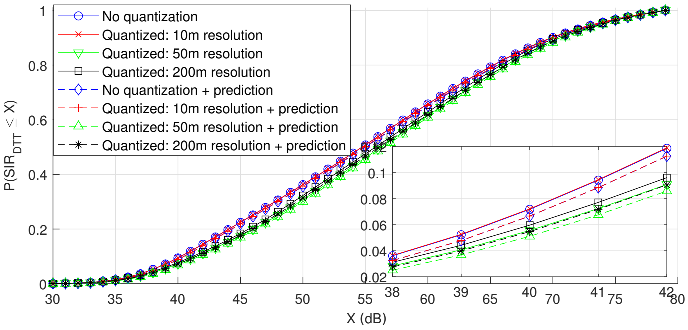

Fig. 18. SIR cumulative distribution obtained in simulations for the primary system receivers that required protection - channel 522 MHz, 4 platoons, full range.

One should also note that with the use of the prediction mechanism, the optimal grid density for REM might no longer be related to the mobility of the platoon and the VDSA procedure period, as these parameters will be captured with the predictive approach. Therefore, it might be easier to find the proper CDB resolution even for multiple platoons moving with different velocities.

VI. CONCLUSIONS

In this work we investigated the aspects of architecture, configuration, and management of a database system, known as EIS, applied for the support of autonomous platooning. Edge intelligence mechanisms, facilitating VDSA procedure in order to select the best frequency band for highly reliable intra-platoon communications, were considered with different layers of data storage and processing taken into account. The split of data storage and management mechanisms into global, regional, and local entities allowed us to formulate three possible architectures: centralized, distributed, and hybrid, for the considered edge intelligence system. We evaluated the proposed configurations in extensive simulations of 2- and 4-platoon scenarios, accounting for several aspects of data management and supply, such as information aging (or latency in providing information from the database) or limited storage resolution, resulting in storage of aggregate or approximate values. Regular grid structure with different densities of reference (measurement) points was investigated. Moreover, a mobility prediction mechanism was proposed to overcome the performance degradation of EIS-based operation due to fast platoon movement.

With the presented abundant simulation results, conclusions on the suggested architecture and EIS configuration were drawn. It turned out that the hybrid architecture, where the frequency band allocation for platoons is coordinated in a single infrastructure point area, aided with information on the DTT power level and protection constraints from the database, provides very good performance of VDSA procedure, while being feasible in practical implementation. Furthermore, it was noted that the application of measurement point locations quantization in the form of a regular grid might actually improve the VDSA performance slightly, compared to full-resolution information being stored in CDB. Due to the significant length of the platoon and its mobility, information acquired from CDBs that corresponds to a specific location might become inaccurate already after a short period of time. Therefore, by assuming the measurement points distance of 50 m for CDB, the accuracy of information used in VDSA improved due to averaging effect. Additionally, the proposed mobility prediction mechanism allows for the acquisition of data from CDB that also corresponds to the platoon cars' location in the near future. Hence, with the aid of such a solution, the problem of platoon movement impact is overcome. The presented simulation results clearly indicate improvement in the protection of the primary DTT system while maintaining the reliability of communications with prediction, compared to the conventional approach with quantization only.

The results of the analysis presented in this paper also indicate the future development areas for edge intelligence applied in the optimization of V2X communications. The aspects of the use of irregular grids and other quantization techniques, delay minimization, or development of interfaces to exchange information within EIS require further detailed studies in order to fully realize the potential of edge intelligence applied to V2X.

REFERENCES

[1] E. Chen, "Overview of the SARTRE platooning project: Technology leadership brief," *SAE International*, p. 4, Oct. 2012.

[2] R. G. Rajeswar and R. Ramanathan, "An empirical study on MAC layer in IEEE 802.11p/WAVE based vehicular Ad hoc networks," *Procedia Computer Science*, vol. 143, pp. 720–727, 2018.

[3] A. Böhm, M. Jonsson, and E. Uhlemann, "Performance comparison of a platooning application using the ieee 802.11p mac on the control channel and a centralized mac on a service channel," in *Proc. IEEE WiMob*, 2013.

[4] J. Mitola and G. Q. Maguire, "Cognitive radio: Making software radios more personal," *IEEE Personal Commun.*, vol. 6, no. 4, pp. 13–18, Aug. 1999.

[5] S. Chen *et al.*, "Learning-based channel selection of vdsa networks in shared TV whitespace," in *Proc. IEEE VTC*, 2012.

[6] K. Harrison, S. M. Mishra, and A. Sahai, "How much white-space capacity is there?," in *Proc. IEEE DySPAN*, 2010.

[7] G. Ganesan and Y. Li, "Cooperative spectrum sensing in cognitive radio networks," in *Proc. IEEE DySPAN*, 2005.

[8] E. Peltonen *et al.*, "6g white paper on edge intelligence," *White paper, University of Oulu*, vol. 8, pp. 1–36, 2020.

[9] R. Rajamani *et al.*, "Demonstration of integrated longitudinal and lateral control for the operation of automated vehicles in platoons," *IEEE Trans. Control Syst. Tech.*, vol. 8, no. 4, pp. 695–708, Jul. 2000.

[10] "IEEE Standard for Information technology–Telecommunications and information exchange between systems local and metropolitan area networks–Specific requirements – Part 11: Wireless LAN Medium Access Control (MAC) and Physical Layer (PHY) Spec.," Dec. 2016.

[11] P. Kryszkiewicz *et al.*, "Modelowanie kanału transmisyjnego dla celów komunikacji między pojazdami," *Przegląd Telekomunikacyjny, Wiadomości Telekomunikacyjne*, 2020.

[12] S. Chen, R. Vuyyuru, O. Altintas, and A. M. Wyglinski, "On optimizing vehicular dynamic spectrum access networks: Automation and learning in mobile wireless environments," in *Proc. IEEE VNC*, 2011.

[13] S. Chen, R. Vuyyuru, O. Altintas, and A. M. Wyglinski, "Learning-based channel selection of vdsa networks in shared TV whitespace," in *Proc. IEEE VTC Fall*, 2012.

[14] N. Sultana and K. S. Kwak, "Non-preemptive queueing-based performance analysis of dynamic spectrum access for vehicular communication system over TV white space," in *Proc. IEEE ICUFN*, 2011.

[15] S. Chen, A. M. Wyglinski, S. Pagadarai, R. Vuyyuru, and O. Altintas, "Feasibility analysis of vehicular dynamic spectrum access via queueing theory model," *IEEE Commun. Mag.*, vol. 49, no. 11, pp. 156–163, 2011.

[16] K. S. Gill *et al.*, "Memory matters: Bumblebee behavioral models for vehicle-to-vehicle communications," *IEEE Access*, vol. 6, pp. 25437–25447, 2018.

[17] K. S. Gill *et al.*, "Bumblebee-inspired C-V2X dynamic spectrum access testbed using openairinterface," in *Proc. IEEE VTC*, 2020.

[18] P. Sroka, P. Kryszkiewicz, and A. Kliks, "Radio environment maps for dynamic frequency selection in V2X communications," in *Proc. IEEE VTC*, 2020.

[19] P. Sroka *et al.*, "Distributed vehicular dynamic spectrum access for platooning environments," in *Proc. IEEE VTC*, 2020.

[20] H. B. Yilmaz, T. Tugcu, F. Alagöz, and S. Bayhan, "Radio environment map as enabler for practical cognitive radio networks," *IEEE Commun. Mag.*, vol. 51, no. 12, pp. 162–169, 2013.

[21] A. Kliks, L. Goratti, and T. Chen, "Rem: Revisiting a cognitive tool for virtualized 5G networks," in *Proc. IEEE ICT*, 2016.

[22] A. Kliks *et al.*, "Application of radio environment maps for dynamic broadband access in TV bands in urban areas," *IEEE Access*, vol. 5, pp. 19842–19863, 2017.

[23] C. Suarez-Rodriguez, Y. He, and E. Dutkiewicz, "Theoretical analysis of REM-based handover algorithm for heterogeneous networks," *IEEE Access*, vol. 7, pp. 96719–96731, 2019.

[24] P. Tengkvist *et al.*, "Multi-dimensional radio service maps for position-based self-organized networks," in *Proc. IEEE CAMAD*, 2017.

[25] A. C. Suarez Rodriguez, N. Haider, Y. He, and E. Dutkiewicz, "Network optimisation in 5G networks: A radio environment map approach," *IEEE Trans. Vehicular Technol.*, vol. 69, no. 10, pp. 12043–12057, 2020.

[26] P. Sroka, A. Kliks, M. Sybis, and P. Kryszkiewicz, "Dynamic power and frequency allocation scheme for autonomous platooning," in *Proc. IEEE VTC*, 2021.

[27] B. Yang, W. Shi, and Q. Li, "An integrated tin and grid method for constructing multi-resolution digital terrain models," *International J. Geographical Inf. Science*, vol. 19, no. 10, pp. 1019–1038, 2005.

[28] A. Kosta, N. Pappas, A. Ephremides, and V. Angelakis, "Age and value of information: Non-linear age case," in *Proc. IEEE ISIT*, 2017.

[29] M. Kleppmann, *Designing data-intensive applications*. London: O'Reilly, 2017.

[30] OFCOM, "Implementing TV white spaces," 2015.

[31] Dynamic spectrum alliance, "Model rules and regulations for the use of television white spaces v2.0," 2017.

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