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Research Article

On the Context-Aware, Dynamic Spectrum Access for Robust Intraplatoon Communications

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Vehicle platooning is a promising technology that allows to improve the traffic efficiency and passengers safety. Platoons that use cooperative adaptive cruise control, however, require a reliable radio link between platoon members to ensure a required distance between the cars within the platoon, thus maintaining platoon safety. Nowadays, the communication can be realized with the use of 802.11p or cellular vehicle-to-vehicle (C-V2V), but none of this technology is able to provide a reliable link especially in the presence of high traffic or urban scenarios. Therefore, in this paper, we propose a dynamic spectrum management mechanism in V2V communications for platooning purposes. A management system architecture is proposed that comprises the use of context-aware databases, sensing nodes, and spectrum allocation entity. The proposed robust system design aims to keep only the minimum necessary information transmitted over the conventional intelligent transportation system (ITS) channel, while moving the remaining data (nonsafety, service-aided, or infotainment) to an alternative channel that is selected from the available pool of spectrum white spaces. The initial analysis indicates that the proposed system may significantly improve the performance of wireless communications for the purpose of vehicle platooning.

1. Introduction

One of the main aims of the future, fifth-generation (5G) wireless systems is to provide ubiquitous communications for many different devices. Among many aspects of the envisioned 5G networks is to provide the so-called ultra-reliable communications (URCs) with minimum latency that can be used to ensure various safety or life-saving services [1]. One of the considered use cases for the URC is to provide wireless links for data exchange between vehicles moving on a road, which is known as vehicle-to-vehicle (V2V) communications. The main purpose of introducing V2V transmission is to improve the safety and efficiency of road traffic using dedicated messages that can be used to warn drivers, enable automated safety systems, or even support autonomous car driving capabilities.

The last mentioned use case, namely, the autonomous driving, is foreseen as an enabler for cost-effective and safe vehicle platooning, which is a coordinated movement of a group of autonomous vehicles forming a convoy led by a platoon leader. According to the study described in [2–4], the use of vehicle platooning may result in an increase of road capacity due to the reduction of intercar spacing and, consequently, reduced fuel consumption and CO_2 emission due to the lower air drag.

An example of such a control system is the cooperative adaptive cruise control (CACC), which makes use of the information received from on-board sensors or exchanged with other cars through wireless links. The key factor limiting the performance of platooning algorithms, and hence enlarging the required intervehicle distance, is the delay of the control system and the accuracy of information describing the surrounding environment, obtained via sensors or wireless communications. The CACC helped to increase the reliability of platooning. However, it requires frequent, highly reliable, and low-latency V2V transmission [5–7]. These requirements cannot be met with the state-of-the-art wireless communication protocols using the ITS frequency band (5.9 GHz band dedicated for vehicle-to-anything (V2X) communications: 5.850–5.925 GHz in USA and

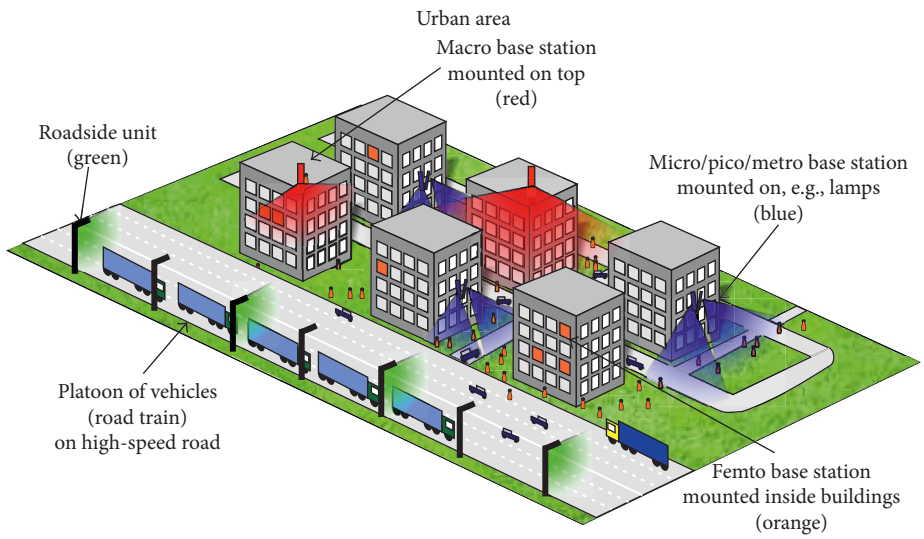

Figure 1: Considered scenario: an urban case.

5.875–5.925 GHz in Europe). The main problems are collisions with packets transmitted by other cars utilizing the ITS band or high latency due to medium access control (MAC) layer processing.

A solution to this problem can be to utilize a wider frequency band. However, nearly whole radio frequency (RF) spectrum is assigned to some existing wireless systems. On the contrary, worldwide measurements reveal that real spectrum utilization at a given location in a given time is very limited [8]. Moreover, the potential of use of frequencies above 6 GHz for V2V communication purposes has gained significant interest in recent years [9, 10]. This gives rise to an idea of opportunistic use of these unused spectrum resources (called white spaces) by unlicensed systems, employing the cognitive radio technology [11]. In the considered scenario, a platoon of vehicles could exchange information using a band licensed to another system, acting as a secondary user. This is acceptable from the primary user's perspective only if its transmission is not disrupted. On the contrary, the advantages of in-platoon communications over white spaces are present only if interference from primary users is low or at least foreseen. This requires context awareness of the whole system, being able to sense and adjust to the current situation in a given white space. A necessary step in dynamic band selection is to acquire and process information from different sources, including the context information stored in databases. A role of such a dynamic spectrum access manager can be played by the Geolocation Database (GLDB), REM [12], or even RSM [13]. In what follows, we will refer to the database-oriented system as the Context-Aware Database (CADB).

The generic scenario considered in this paper is visually presented in Figure 1, where one can observe the road train driving autonomously on a high-speed road in various environments (urban and rural). Depending on the location, another frequency band may be occupied; that is, there is a limited set of active services in the rural area compared to the urban case, where the number of present wireless networks may be high. The communication within the platoon has to be stable and reliable; thus, we claim that the support from surrounding sources of information in the selection of the best frequency band may be highly beneficial.

This position paper is to propose an architecture for 5G systems suitable to solve main problems of V2V communications for platooning purposes using spectrum white spaces. Let us stress that the main aim of this position paper is to propose the design and infrastructure for the platooning support system that realizes the V2X communications with the use of state-of-the-art communication protocols (such as the IEEE 802.11p [14] or 3GPP C-V2X [15]) and spectrum white spaces. The latter ones would be used for intraplatoon communication. For this type of communication, we suggest to use either frequencies lower than 5.9 GHz (reference frequency used by the exemplary 802.11p system) or frequencies higher than 5.9 GHz (e.g., mmWave). Both of these approaches have their advantages and disadvantages. For example, lower frequencies will ensure a broader transmission range (whole platoon will remain within the transmission range), but interference to other systems/platoons may also be higher. On the contrary, the system that works with high frequencies (e.g., mmWave) could be regarded as a remedy for this. The transmission range and interferences are limited, which are positive aspects, but communication within a platoon may suffer from too short transmission range and shadowing; for example, a car-like truck can easily interrupt high-frequency line-of-sight car-to-car transmission.

The new architecture is needed to enable dynamic spectrum management mechanisms based on rich context information collected from different sources. The envisioned platooning support system will be responsible for collecting and storing information describing the spectrum availabilities, and for dynamic spectrum allocation, that will enable ultrareliable exchange of information between platoon vehicles. Hence, definition of the management system entities and the related interfaces is needed.

1.1. Scope and Novelty. This work is a position paper that shows the current status of the V2V communication for platooning purposes with the emphasis on the current system drawbacks, as well as for proposing and discussing a solution based on reusing the spectrum white spaces for intraplatoon communications and the system architecture that would support the dynamic use of the radio spectrum. The main problem formulation is presented in Section 2. This section, apart from presenting the state-of-the-art overview of platooning aided with V2X communications, shows the performance of the platoon in terms of minimal target distances and packet reception rates. Our results clearly present that nowadays, solutions to this kind of communication are inefficient and a new solution should be proposed. In the latter part, we present a possible solution to the problem, that is, possibilities of using the white spaces for V2V communications as well as our spectrum measurements campaign results. In the last part of the paper, we propose new management system architectures that could be used to improve the in-platoon V2V communication.

The novel aspects covered by this paper are the following:

(1) Formulation of the problem of insufficient reliability of V2V communication in particular for in-platoon communication in high traffic/urban areas

(2) Proposition of a system architecture with dynamic spectrum allocation for the dual transceiver communication with the use of 802.11p state-of-the-art V2X communication and white spaces to solve the formulated problem

(3) Considerations on the possible challenges in implementing the proposed system

This paper is organized as follows: Section 2 is devoted to V2V/V2X communication. This section is divided into two parts. The first covers the literature studies in the field of V2V communication, while the second presents the results of simulations of the platooning using the CACC and formulates the problem of reliable in-platoon communications in future V2V systems. In Section 3, the main observations paving the way for dynamic spectrum access are presented. Crucial components of this system are presented including the CADB that can be useful for enhancement of V2V communications within platoons. Existence of white spaces suitable for this purpose in urban areas is shown by the analysis of data coming from spectrum occupancy measurements. Section 4 presents the proposed management system architecture designs that make use of the CADB to dynamically allocate the spectrum for in-platoon communications. In Section 5, the system challenges are presented. This paper ends with conclusions.

2. Contemporary Solutions for V2V and V2X Communications

2.1. State-of-the-Art Overview. A platoon using the CACC has attracted a lot of interest in recent years. A number of empirical studies have been performed to evaluate the performance of the CACC and platooning supported by IEEE 802.11p-based wireless communications. As an example, [16] builds a comprehensive system simulation framework to study the CACC performance in the presence of nonideal communications. The study shows that the CAM broadcast frequency and loss ratio have a strong influence on the performance of the CACC algorithm. A consensus-based approach to the CACC with the use of 802.11p communication is investigated in [17]. In [18], performance comparison of the 802.11p-based (a common control/safety channel and a dedicated service channel) platoon is provided. The performance of the CACC with different CAM beaconing schemes implemented on top of the 802.11p is evaluated in [19]. Further simulation examples presenting the performance of the 802.11p-based CACC are given in [20–22]. The link-level (i.e., block error rate (BLER) versus signal-to-noise ratio (SNR)) and system-level (i.e., packet reception rate (PRR) versus distance) performance of 802.11p and cellular vehicle-to-anything (C-V2X) has been compared in [23–25]. Some examples of research studies that aim to support the requirements of vehicle platooning by improving the existing communication standards can be found in [26, 27]. In [26], the authors study the performance of 802.11p distributed coordination function (DCF) based on a Markov chain model. Moreover, the authors propose a contention window adjustment scheme for 802.11p [26] and resource (i.e., subchannel and power) allocation algorithms for LTE-based multiplatoon communication in [27] to optimize the platoon performance in multiplatoon scenarios.

Investigation of platoon performance is not limited to the simulations only. The SARTRE project [4] conducted an experiment, where a platoon of two trucks and three cars driven autonomously in close formation has been deployed. It turned out that the platoon could drive at speeds of up to 90 km/h with a 5–7 m intervehicle distance. On the contrary, in the framework of the Energy ITS project in Japan, a platoon of three fully automated trucks driving at 80 km/h with a 10 m intervehicle gap was tested on an expressway [28]. In the European Truck Platooning Challenge 2016, automated trucks of six major truck vendors used autonomous driving in platoons on public roads, some of them using IEEE 802.11p for communications [29]. Finally, the PATH Program in the United States demonstrated a platoon of three 802.11p-equipped trucks driving on the busy Interstate 110 freeway in 2017 [30]. The increased interest in platooning is driven by the expected potential revenues. The findings of the SARTRE project show that platooning provides fuel savings from 7 to 15% for trucks travelling behind the platoon leader [4]. Additionally, the fuel savings translate to substantial reduction of CO_2 emission, and according to the study performed in the Energy ITS project [28], when the market penetration of truck platooning increases from 0% to 40% of trucks, CO_2 emission along a highway can be reduced by 2.1% if the gap between trucks is 10 m and by 4.8% if the gap is reduced to 4 m.

The empirical studies described above do not account for one very important factor limiting the use of autonomous driving with the CACC, namely, the reliability of wireless communications in a scenario with a large number of

transmitting devices. Therefore, various simulations have been conducted to study the ability of different V2V technologies to meet the requirements of the ITS applications. The analysis performed in [18, 21] shows that the V2V message broadcast frequency and packet loss ratio have a strong influence on the performance of the CACC algorithm. One of the main problems of the CACC when employing the current state-of-the-art wireless communication protocols is the reliability of information exchange between platoon vehicles. A study on the use of the CACC with communications based on the IEEE 802.11p standard revealed that even a moderate increase in road traffic on a motorway can lead to wireless channel congestion and, consequently, prevent the automated controller from reliable and stable operation [31]. A solution to this problem may be the use of the dual-band transceiver that allows to operate simultaneously in two different frequency bands (as an opposite to the single-band transceiver that is able to operate only in one band). However, one should note that even when two subbands of the ITS frequency range are used, due to the high density of communicating vehicles and the large amount of exchanged data (apart from various safety messages, the so-called infotainment data can be transmitted), still channel congestion is possible for both subbands used. In the following section, we present the simulation evaluation of the performance of CACC-driven platooning when IEEE 802.11p is used for V2V communications. We compare the results obtained with a single-band transceiver and a device that simultaneously uses the ITS control channel (CCH) and a dedicated frequency band for in-platoon communications.

2.2. Identification of the Performance Limitations of CACC Schemes: A Single-Radio Case. To identify the possible drawbacks of the considered system, we used the simulation tool. This allows us to investigate the performance of the platoon itself as well as some selected aspects of V2V platoon communication (e.g., the impact of the message rate or packet collision mitigation mechanism). The obtained results will allow us to answer the question if it is possible to improve the platoon performance. Achieved results are presented in the consecutive subsections.

Let us now consider a scenario where a platoon of ten cars is travelling on the outer lane of a four-lane highway (two lanes in each direction), while the number of nonplatooned cars travelling on the remaining three lanes that are not occupied by the platoon is a simulation parameter. All cars on the highway transmit the CAM with the frequency of 10 Hz on the control channel (CCH). As a baseline system, we consider the use of single-radio transceivers for platooned cars that are continuously tuned to the CCH to transmit and receive CAMs.

2.2.1. Simulation Setup. In the simulations, we assume the 802.11p communication with one transmitting and receiving antenna and the ITU Vehicular-A channel with the path loss according to the Winner + B1 LOS. We consider the densities of nonplatooned cars of 0, 5, 10, 15, and 20 cars/km/lane. Other simulation parameters and assumptions are summarized in Table 1.

2.2.2. Minimum Feasible Target Distance. The first step in the evaluation aims to determine the minimum feasible target distance between platooned cars that can be safely maintained. The target distance is the input parameter of the CACC controller. In particular, we have assumed that the minimum feasible target distance is the one that provides crash-free platoon operation with 99% probability. Namely, we performed 100 simulation runs for different target distances ranging from 1 m to 15 m and then selected the minimum distance for which no more that one out of 100 simulations ended with a crash to be the minimum feasible target distance. One should note that our simulator does not implement any crash mitigation mechanisms (i.e., emergency braking) that would decrease the probability of hazardous situations in real-world implementations. The CACC alone is not meant to deal with such situations. Therefore, the 99% target is sufficient.

From the results presented in Figure 2 and Table 2, we can see that it is possible to achieve crash-free operation only for the scenario with no cars on neighbouring lanes. With the increase in density of cars on neighbouring lanes, namely, in scenarios with 5 to 20 cars/km/lane with the single-radio transceiver configuration, we selected the target distance that results in approximately the smallest number of crashes (the chosen value ensures that there is no crashes for all higher values). It is caused by the fact that not for all scenarios, we are able to find a value for which the platoon is operating with no (or almost no) collisions (further distance extension gives no improvement in terms of the number of collisions per 100 simulations run). In the rest of this section, we present the results obtained for the target distances indicated in Table 2.

These results reveal that the performance of the platoon with single-radio operation is correlated with the overall traffic intensity. Moreover, only for the smallest traffic, the achievable results are of assumed 99% crash free, while for the higher densities observed, the crash rate is significantly higher.

2.2.3. Reliability. In the next step, we analyzed the reliability of 802.11p message transmissions. Thus, we run the simulations with the target distances listed in Table 2 and collected the message reception statistics at each car in the platoon. The reception rates of the messages transmitted by the platoon leader are shown in Figure 3. One may notice from Figure 3 that the reception rate of leader messages drops significantly towards the tail of the platoon when a single radio is used. The last car in the platoon was unable to receive more than 5% of messages due to the low reliability of 802.11p communication with the platoon leader.

2.2.4. Fixed BLER Results. As presented in the previous subsection, the message reception rate drops from 100% for single-line transmission to about 95% for the last vehicle

Table 1: Selected simulation parameters.

Parameter	Assumption
Number of simulation runs	100
Simulation time	900 s
Platoon size	10 cars
Actuation lag	20 ms
ACC headway time	0.2 s
CAM message size	300 bytes
CACC message size	16 bytes
Spectrum band	ITS-G5A (5895–5905 MHz)
Channel estimation	Ideal

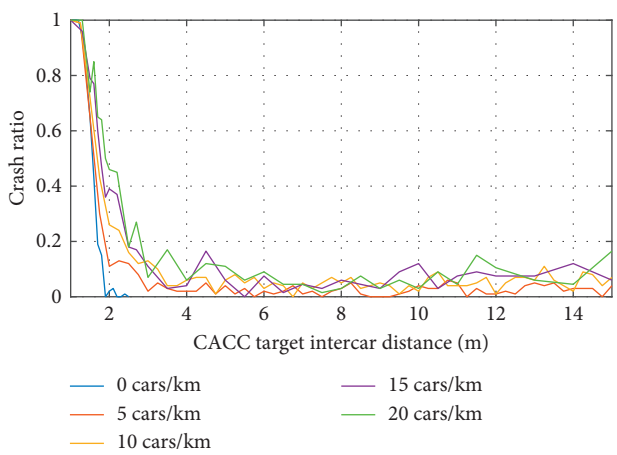

Figure 2: Fraction of simulation runs concluding with an in-platoon crash when using only the CCH.

Table 2: Selected CACC target distances and the corresponding number of simulations with a crash per 100 runs for a single-radio scenario.

Case (cars/km/lane)	Target distance (m)	Number of crashes
0	2.2	1
5	3.5	2
10	4.0	7
15	5.0	6
20	5.5	7

within the platoon for the highest considered traffic density. To investigate the impact of the decreased BLER on the platoon performance, we simulated the platoon performance using an abstract communication system with a predefined BLER value (in this case, the BLER value is fixed for all cars and is a simulation parameter).

Obtained results are presented in Figure 4. In this figure, curves for the reception rate ranging from 1.0 to 0.7 are shown. For the ideal case, the target distance of 2.0 m ensures the collision-free operation of the platoon. Small decrease in the reception rate (to 95%) degrades the platoon performance significantly (an intercar distance of 4.5 m is required). This increase in the required target distance can be regarded as an additional safety distance in the case of erroneous transmission. Obtained results reveal that the

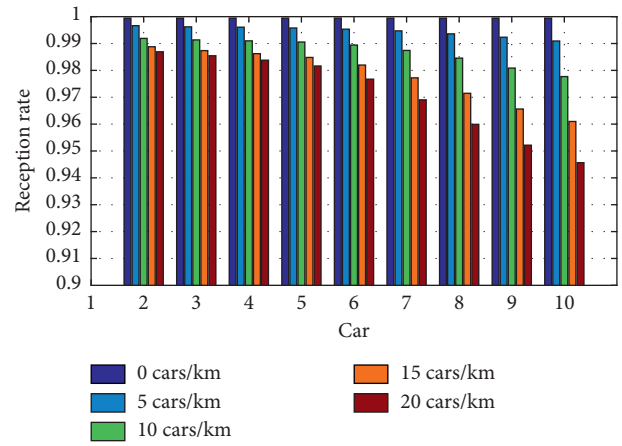

Figure 3: Reception rate of platoon leader CAM packets versus the car position in the platoon.

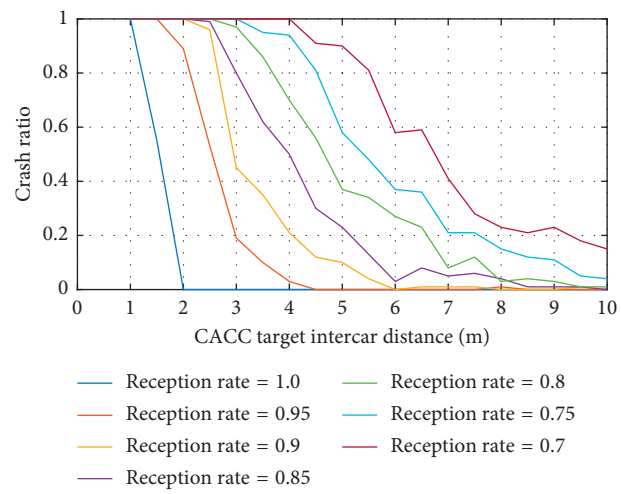

Figure 4: Fraction of simulation runs concluding with an in-platoon crash for an abstract system with a fixed reception rate of leader packets.

minimum target distance of the CACC controller increases significantly with the drop in the BLER of packets received from the leader.

Although for almost every case considered here the minimum target distance (the distance that provides the crash ratio no higher than 1%) can be found, one should note that the considered abstract system uses a fixed BLER value for communications; thus, the increase in distance between the transmitter and the receiver is not accounted for. In a real-life system, such an increase in the target CACC distance would result in a further drop of the leader packets' reception ratio and, consequently, might prevent the automated controller from correct operation (which is the situation observed in Figure 2).

2.3. Solutions. To solve the problem of too low message reception rate, the following solutions can be considered:

(i) Decrease the rate of CAM messaging

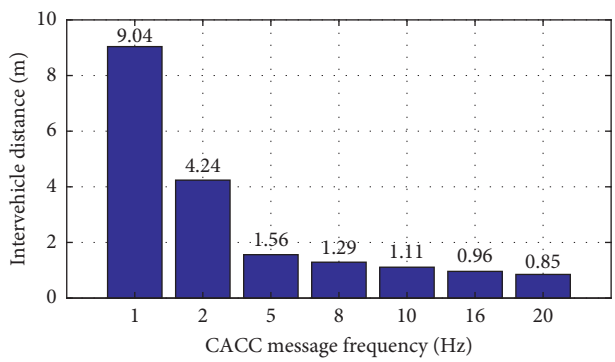

Figure 5: Impact of the CAM message rate on platoon performance.

(ii) Apply the decentralized congestion control (DCC) mechanisms

(iii) Use radio transceivers that can operate in two different frequency bands simultaneously

In this section, we will investigate the aforementioned solutions.

2.3.1. Different CAM Message Rates. The impact of the message broadcast rate on the CACC is shown in Figure 5 with ideal communication assumed. For the purpose of this investigation, message frequencies ranging from 1 to 20 Hz are assumed. For the rates of 1 and 2 Hz, the performance of the platoon is significantly decreased. This is due to the fact that these frequencies correspond to 1 s and 500 ms information update intervals, which at highway speeds translate to a long travelling distance without an information update. For the rates of 8 and 10 Hz, the performance degradation (compared to the 20 Hz performance) is rather small. For the rate of 16 Hz, the platoon performance improvement is insignificant; thus, an increased usage of radio resources has no justification. We therefore conclude that, for the considered scenario, the optimal information update rates are from 8 to 16 Hz (we assume that the increased message rate has a negligible impact on the packet collision probability).

2.3.2. DCC as a Potential Solution. Another option to improve the communication reliability suggested by the European Telecommunications Standards Institute (ETSI) is to apply the DCC mechanism [32] to reduce the load of the used radio channel. The DCC is a threshold-based mechanism that applies different MAC layer policies based on the estimated occupancy rate of the transmission medium. These include transmit power adaptation, data rate control, or adaptation of the carrier-sensing capabilities of the transmitter. The DCC mechanism restrictions are applied when the estimated channel load is above 20% [32, 33]. In order to estimate the average channel load in considered scenarios, we measured the fraction of time that the channel is considered as busy from the user's perspective, with the averaged results presented in Figure 6. This figure presents an average channel occupancy rate for four considered car

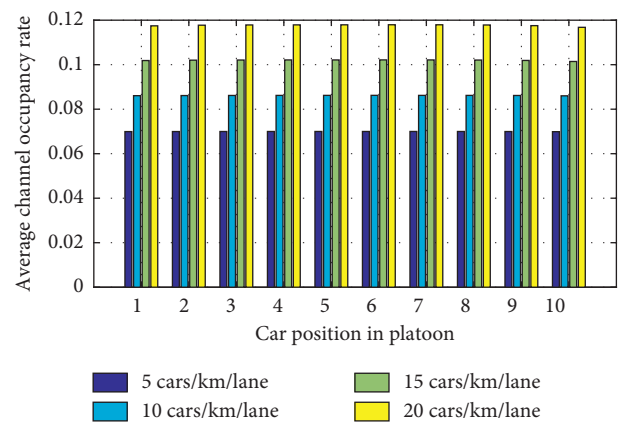

Figure 6: Average estimated channel occupancy rate versus the car position in the platoon.

traffic densities, that is, 5, 10, 15, and 20 cars/km/lane, separately for each vehicle within the platoon. One can note that even for the worst-case scenario with 20 cars distributed uniformly on each lane per km, the average channel load is at most 12%, which is below the DCC threshold. Therefore, we can conclude that application of the DCC mechanism will have no impact on the CACC performance, as the reception rate of leader packets will be too low to enable proper automated control before the DCC restrictions are applied.

2.4. Identification of the Performance Limitations of CACC Schemes: A Dual-Radio Case. The last considered solution is to use the dual-radio transceivers that allow to simultaneously transmit data in the control channel and, additionally, in other frequency channels. In the following part, we consider a dual-radio transceiver, where the first radio is continuously tuned to the CCH to transmit and receive CAMs and the second radio is tuned to another service channel (SCH). We do not consider multichannel operation with a single-radio transceiver (i.e., channel switching), as according to [34], higher collision rates and increased message delays might be experienced in the corresponding alternating mode. Moreover, according to the ETSI specification [35], a vehicle should continuously listen to the CCH for CAMs, thus prohibiting the use of this mode. In order to increase the efficiency of the CACC, we assume that, besides CAMs, every platooned vehicle may broadcast short CACC packets, which contain only speed and acceleration information, on a dedicated SCH. This is possible only with the dual-radio transceiver configuration, since the single-radio transceiver is continuously tuned to the CCH. The transmission frequency of CACC packets is assumed to be 10 Hz (thus, combined with the use of CAMs, we are able to achieve the effective CACC information transmission frequency up to 20 Hz). Moreover, we assume that the additional SCH is reserved for in-platoon communications only, thus preventing other devices from transmitting there.

Similarly, as for the single-radio transceiver, the first step in the evaluation aims to determine the minimum feasible

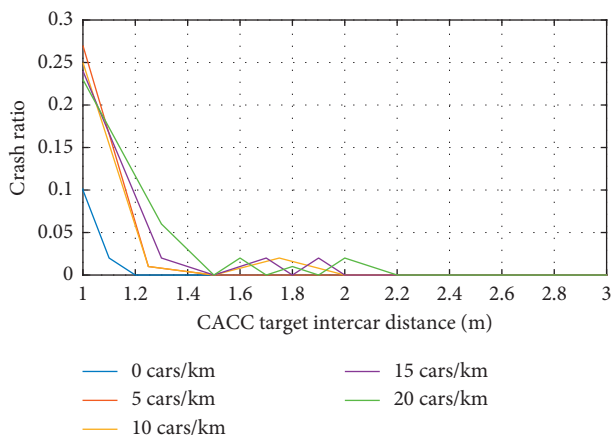

Figure 7: Fraction of simulation runs concluding with an in-platoon crash when using the ITS CCH and additional channel reserved only for in-platoon communications.

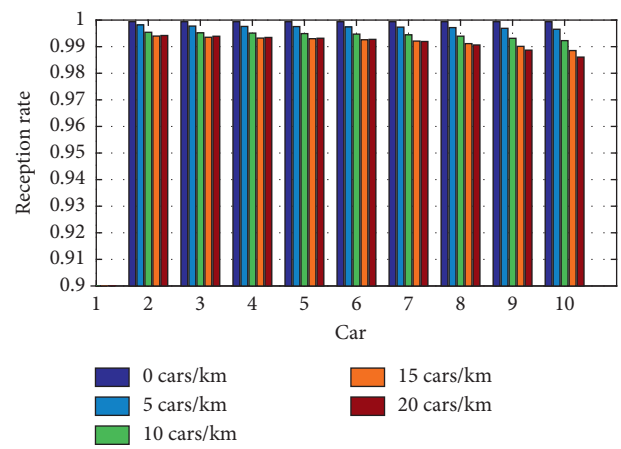

Figure 8: Reception rate of platoon leader CAM packets versus the car position in the platoon with a dual radio.

Table 3: Selected CACC target distances and the corresponding number of simulations with a crash per 100 runs for dual-radio transceivers.

Case (cars/km/lane)	Target distance (m)	Number of crashes
Ideal, dual	1.1	0
0	1.2	0
5	1.5	0
10	2.0	0
15	2.0	0
20	2.2	0

target distance between platooned cars for dual-radio transceivers. The target distance is the input parameter of the CACC controller. Obtained results are shown in Figure 7. This figure presents the crash ratio as a function of intercar distance. The best results are obtained if there is no traffic on the neighbouring lanes of the highway. For this case, the distance required between the cars is equal to 1.2 m. If the traffic intensity is increased from 5 to 20 cars/km/lane, then the required distance increases from 1.5 to 2.2 m.

From the results presented in Figure 7 and Table 3, we can see that, in all scenarios with dual-radio transceivers, it is possible to find such a minimum feasible target distance in the 1.1 m to 2.2 m range. Comparing this to the minimum distance for the single-radio transceiver (Table 2), we observe the significant improvement of the platoon performance. In this case, even for the highest considered traffic density, the platoon is able to fulfill the 99% crash-free assumption. In Table 3, we also provided the target distance for the ideal scenario (perfect packet decoding, infinite transmission range) to show the quality of the dual-radio transceiver performance.

In the rest of this section, we present the results obtained for the target distances indicated in Table 3.

One should note that the use of the dual-radio transceiver and special CACC messages transmitted on the dedicated SCH results in a substantial improvement of CACC performance. The minimum feasible target distances achieved in such a configuration are always better than those in the case of a single radio. This is the result of the increased overall message rate with the dual radio, which is 20 Hz (10 Hz CAM on the CCH plus 10 Hz CACC on the SCH), as well as the improved message reception ratio. While CAM packets might collide frequently, as nonplatooned cars also use the CCH for CAM transmissions, the reliability of CACC messages is much higher because they are transmitted on a dedicated SCH.

To analyze the reliability of 802.11p message transmissions, we collected the message reception statistics at each car in the platoon. The reception rates of the messages transmitted by the platoon leader are shown in Figure 8. For the dual-radio transceiver, the situation is completely different. In this case, the higher transmission reliability of CACC messages may compensate for the loss of CAMs messages to allow crash-free platooning with a shorter target distance, as hardly any CACC packets are lost.

2.5. Conclusions. One can notice that use of an additional frequency channel for in-platoon communications improves significantly the performance of the CACC controller. However, this is valid with an assumption that this additional channel is unoccupied (or at least with extremely low load), and thus, the CACC message transmission is not interrupted. With the current specifications of the IEEE 802.11p standard, only six additional shared channels are available (apart from the control channel) in the ITS frequency band. As low-load requirements stated above cannot be guaranteed with use of these bands, many other services, such as infotainment or nonsafety ones, will use them. Therefore, a very promising solution for IEEE 802.11p-based systems is to search for additional frequency bands that can be used only for platooning purposes.

The reliability problem when using IEEE 802.11p could also be overcome using more advanced communication systems, such as the 3GPP cellular vehicle-to-anything (C-V2X) [15]. It certainly provides higher reliability of the wireless links, especially when working in the assisted mode (mode 3 of C-V2X) with the resource allocation performed

by the base station. It is shown in [36, 37] that platooning using the CACC is fully feasible using C-V2X mode 3. However, when working independently (without the aid of infrastructure (mode 4 of C-V2X)), the collisions in medium access are also possible, and thus, the decreased message reception rate can be observed. Moreover, due to the need to allocate resources in advance in C-V2X, the latency of MAC layer processing is much higher than that in case of IEEE 802.11p, which may affect the quality of received information [37]. Furthermore, the centralized allocation of resources performed by the base station can become difficult with very high density of cars requesting for transmission. The worst-case scenario of 20 cars/km/lane (an average intercar distance of 50 m) considered in this paper translates to an average of 80 cars (assuming 4 lanes) requesting for resources in a cell with a radius of approximately 500 m. One can easily imagine a much worse scenario with a higher number of lanes and a traffic jam, where even hundreds of cars may be served by a single base station. This can result in reduced effectiveness of the system as the necessary control information needs to be transmitted. Therefore, the framework proposed in this paper, although presented in the context of IEEE 802.11p, can be relevant also for the C-V2X or future 5G system, as it provides additional spectrum opportunities for intraplatoon communications, where the resource allocation can be performed independently of the base station.

3. Potential of Dynamic Spectrum Access with Coordination via Context-Aware Databases

It is prominent from the discussion made in the previous section that reliable operation of CACC algorithms requires a wireless channel where collision with any other system or device will be negligible. A straightforward solution would be to provide a number of separate licensed channels, each utilized by a single vehicles' platoon. However, foreseeing future platoon densification, the number of available wireless channels may not be enough in one region, while the licensed spectrum may be vacant in other regions. This is a phenomenon common for most of the wireless systems and observed during many spectrum measurement campaigns [8, 38, 39]. Even though most of the frequencies, for example, up to 3 GHz, are licensed by various wireless systems, in practice, many of them are unused in a given time, at a given location. This gave rise to an idea of a cognitive radio [11], where one can access spectrum resources licensed to another system provided there is no interference generated to it. After years of research on reliable detection of unused frequency resources (called white spaces) [40] and efficient utilization of these white spaces [41], a number of practical solutions have been proposed [42]. The most significant conclusion is that the highest spectral efficiency and low probability of intersystem interference can be obtained only if devices are connected to the spectrum management system utilizing the dedicated database. Field trials of cognitive radio systems using databases for the optimization of spectrum utilization were carried out, for example, in London by the British communications regulator the Office of Communications (Ofcom) [43] and in many other locations. Commonly, GLDB/REM/RSM (covered hereafter under the common name CADB) is proposed for this purpose [12, 13]. The CADB is a database storing data on the radio environment (e.g., propagation conditions) and its users (e.g., parameters of its transmission and sensitivity to interference.). Depending on the scenario, the set of information stored in the CADB can vary. Typically, radio information is stored together with a geographical tag so that it is a kind of geolocation database. The CADB system is typically divided into three parts: the database(s), the CADB manager responsible for analyzing available data and assignment of transmission parameters to wireless devices, and data acquisition and sensing function responsible for obtaining the current status of the radio environment utilizing various information sources. In our case, we call them the CADB, spectrum manager (SM), and measurement capable device (MCD), respectively, as detailed later in the following section. The data stored in the database can vary from relatively static policies on the utilization of a given frequency (based on some regulatory frameworks or in agreement with licensed spectrum users) to rapidly changing status of a given frequency utilization and observed interference. Static data can be obtained from some external database, for example, national regulator, or based on some analytical modeling, for example, received power distribution based on the base station location and power. A more challenging one is acquisition of dynamic, real-time data about a given radio environment. It can be obtained by analyzing control information reported by data-transmitting devices in a given frequency (e.g., user equipments or base stations) or sensing nodes employed purely for this purpose. An example of sensing nodes in the existing dynamic spectrum access standard is a radar-detecting sensor in the Citizens Broadband Radio Service (CBRS).

There are many different reasons why CADB subsystems should be employed. On the one hand, it can allow some existing systems (e.g., LTE) to offload some traffic from the licensed band. On the other hand, it can allow many systems to capitalize advantages of a given frequency band, for example, low path loss at low frequencies. In the case of vehicle platoons, the most important is lack of interference resulting in high reliability of transmission. The CADB can manage frequency assignment in a wide frequency range, providing nearly an unlimited number of separated wireless channels for in-platoon communications; thus, at least one channel should always be detected as unoccupied. Moreover, geolocation-based frequency management can allow many distanced platoons to use the same frequency channel. From the licensed users' perspective, it is important that the in-platoon communications require relatively low power, and even if some marginal interference is observed, it is temporary as the platoon moves.

3.1. Measurement Campaign and Results Analysis. In order to justify the usage of white spaces for V2V communications, let us now analyze the results of the conducted spectrum

measurements. Our goal is to verify if the detected white spaces could reliably be used for V2V communication and if their characteristics (amount, stability, etc.) are suitable for this purpose. The spectrum occupancy measurements were carried out on relatively busy roads in order to keep results possibly close to the V2V scenario.

An omnidirectional antenna AOR DA753 was mounted on a rooftop of a car. It was connected to the spectrum analyzer Rohde & Schwarz FSL6 via a low-loss cable (H155). A laptop with MATLAB and Instrumental Control Toolbox software was connected to the spectrum analyzer via an Ethernet cable in order to configure, trigger, and store measurement results. Measurements were carried out in the frequency range from 75 MHz to 1 GHz with a resolution bandwidth (RBW) of 30 kHz. Ten consecutive power samples at a given frequency were averaged before sending to the PC in order to initially decrease the thermal noise influence. Each measurement trace is tagged with a timestamp and a location obtained from an external GPS module. The measurements were carried out in Poznan, a city in Poland, of around 500000 inhabitants, during a typical working day. The car drove a path of 22 km, mainly in the city center, obtaining 600 power spectral density (PSD) traces, each of 30834 frequency points. The resultant PSDs showing the minimum, mean, and maximum of 600 obtained samples are presented in Figure 9. There are just a few frequency ranges of high received signal power, for example, FM broadcasting around 100 MHz, TETRA and CDMA communications at around 450 MHz, and the GSM band at around 950 MHz. At many other frequencies, the mean received power equals about −110 dBm/30 kHz, being a noise floor of the utilized spectrum analyzer. However, the maximum PSD shows that there are timestamps/locations where the instantaneous received power is high above the mean level. Although it can be a result of a high-power thermal noise, the more probable is an existence of a local transmission. Most interesting from V2V communications' point of view is the terrestrial TV band. The TV transmission is relatively stable in time and covers relatively a wide space. However, the other licensed systems utilizing this band are Programme-Making and Special Events (PMSE) devices, for example, wireless microphones. These can transmit low-power, narrowband (200 kHz) signals that should be detected in order not to be disturbed by V2V transmission. A measured power of each 8 MHz channel in the ultrahigh frequency (UHF) band indexed {21, 22, . . ., 69} (center frequencies {474, 482, . . ., 858} MHz) is shown as a function of time in Figure 10. It is visible that at most 4 channels, that is, nos. 23, 27, 36, and 39, have power higher than −80 dBm. In order to estimate the number of UHF channels not utilized by DVB-T receivers, a methodology presented in [44] can be used. The minimum DVB-T receiver input power can be calculated as the thermal noise over the effective channel bandwidth of 7.61 MHz at a temperature of 290 K, that is, −105.2 dBm, can be increased by a noise figure of 7 dB, and required a carrier-to-noise (C/N) ratio. According to [45], the required C/N ratio in the Rayleigh channel (worst-case scenario) for 64-QAM modulation and code rate of 3/4 (mode commonly used in Poland) is 21.7 dB. In

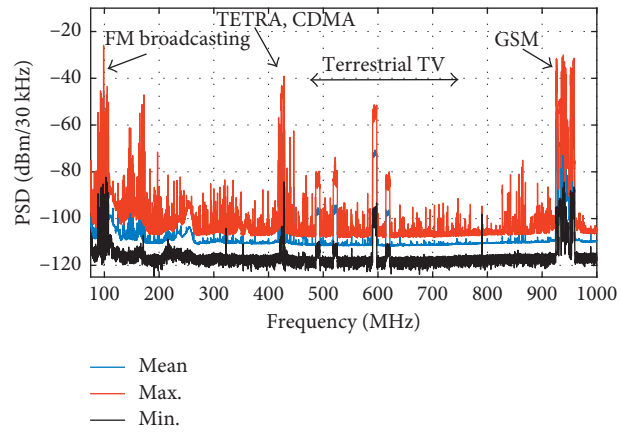

Figure 9: Minimum, mean, and maximal PSDs over the measurement path of 22 km.

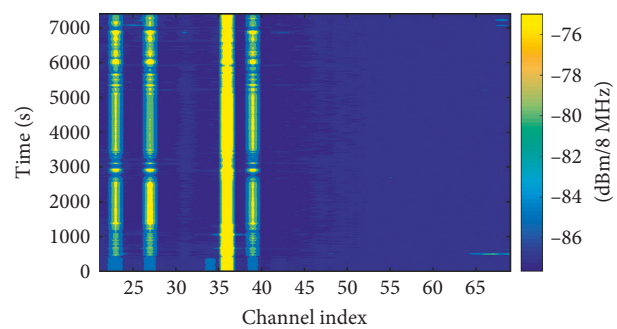

Figure 10: Power of TV channels (indexed from 21 to 69) over measurement time.

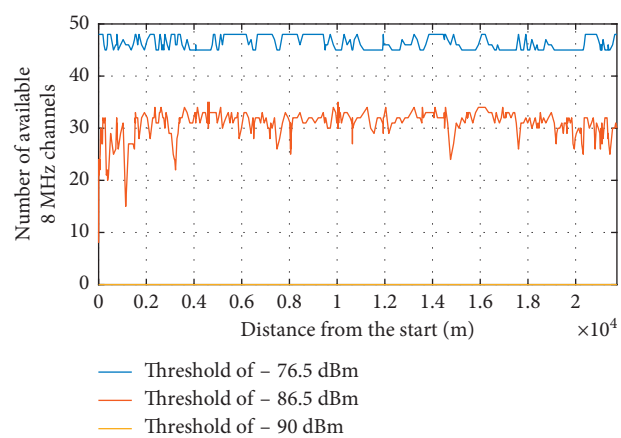

Figure 11: Number of UHF channels available for V2V transmission depending on the minimum required power threshold.

this case, the minimum required DVB-T signal power is −76.5 dBm. All channels of the DVB-T signal power smaller than this value can be treated as unused and potentially be utilized by V2V transmission (although this rough calculation does not consider a hidden node problem or the influence of the chosen V2V transmission power). The results in Figure 11 show that, in any point of the observation path, the number of available channels is greater than or

equal to 45 (out of 49 in total). If the V2V communications struggle to support dynamic band switching, there are still 43 channels that are not occupied at any point of the test path. However, DVB-T receivers commonly use directional antennas located significantly higher over the ground than the 0 dBi antenna used in the measurement. In order to mimic this gain, the threshold was decreased to −86.5 dBm and −90 dBm, giving approximately 30 and 0 UHF channels available, respectively. In the case of continuously vacant channels, the number is 2 and 0, respectively. The significant decrease of the available number of channels is caused by the thermal noise floor of the spectrum analyzer exceeding the threshold. As such, the number of available UHF channels is underestimated. Measurements utilizing a more advanced setup, for example, a high-gain antenna, a low-noise preamplifier, and an advanced sensing algorithm, can be carried out in the future to increase the reliability of these results.

The results of spectrum occupancy measurements presented above prove that there is a vast amount of the underutilized spectrum in the urban areas in the frequency range up to 1 GHz. Limitation of the analysis only to DVB-T channels shows that there are 43 (out of the total of 49) channels permanently unoccupied by the licensed systems in the city of Poznan. It constitutes 344 MHz of the spectrum that can be used potentially for V2V communications within platoons. However, such an application requires an architecture that guarantees sufficient QoS both for licensed users and in-platoon communications. A proposal of such a design will be presented in the next section.

4. A Proposed System Design for Context-Aware Platooning

Based on the analysis outlined in Section 2 on the performance of platooning using the CACC and the results of spectrum measurements presented in Section 3, we can formulate a thesis that the use of spectrum white spaces will improve the CACC operation by increasing the reliability of wireless V2V communications. Hence, in this work, we propose the idea of V2V communications for platooning purposes acting as a secondary system in the cognitive radio concept that will dynamically select the used frequency band based on sensing results and context information acquired from the database. However, the use of spectrum white spaces for in-platoon V2V communications requires coordination and management of different functions, including detection of the available spectrum and selection of the used frequency band.

4.1. Spectrum White Spaces Detection. First, sources of information on the occupancy of the potential frequency bands need to be provided. These will include both the sensing nodes (called the MCD), providing short-term information, and databases (called the CADB), comprising the long-term context information. In the investigated scenario, the following sources of information are considered:

(i) Platoon vehicles that perform spectrum sensing in a cooperative way, where the platoon leader acts as an aggregation node. These can exchange information with other platoon vehicles and the infrastructure (roadside unit (RSU) or base station (BS)) using the V2X communications (e.g., dedicated short-range communication (DSRC) or C-V2X).

(ii) Other vehicles that can be involved in sensing white spaces, with the information reported to the RSU or cellular BS.

(iii) The RSU or cellular BS (in general, any fixed access point) that acts as aggregation nodes for information provided by all vehicles and platoons in their service area. These nodes can also be involved in the spectrum-sensing process.

(iv) The CADB (including REM, RSM, or GLDB) that will provide the long-term information on the spectrum utilization, registered licensed users, interferences, road traffic status, terrain topology, and so on.

We assume that every sensing node is capable of either providing the decision on the availability of the measured band or sending the raw measurements data to an aggregation node, enabling cooperative sensing mechanisms. However, one should note that extensive exchange of the raw data will put further burden on the radio network, so different aggregation levels can be considered. Depending on the current network status, including the data traffic load, the number of available nodes, or the presence of the RSU, different sensing modes will be dynamically selected, with the decision on the spectrum availability being made on the car level, platoon leader level, or RSU/BS level. The decision on the selected sensing mode will be performed at the application level taking into account the global information for the considered sensing region.

4.2. Selection of the Frequency Band. In order to make efficient use of the information stored in the CADB and to select the best frequency band, a functional management architecture of the system is required. This comprises the following elements:

(i) MCD that represents the network nodes capable of providing information on the spectrum availability and reporting it to the CADB.

(ii) Data storage units (CADB) that acquire and store the relevant information provided by different sources, including the MCD.

(iii) An SM unit that is responsible for selecting the optimal frequency band for in-platoon communications; in other words, it makes a decision on the prospective band to be used by the platoon.

(iv) A secondary user, that is, the platoon, that will use the spectrum allocated by the SM for internal V2V communication.

The mapping of listed functionalities to specific elements depends on the architecture of the considered wireless network. Specifically, the MCD will be the nodes that are responsible for providing information on the spectrum

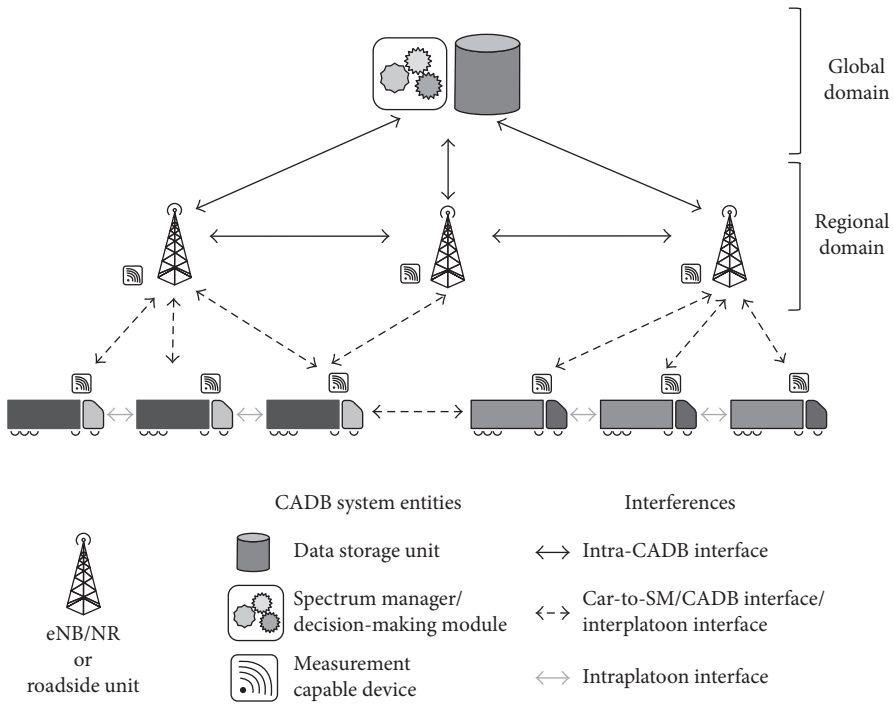

Figure 12: Schematic of the centralized management architecture.

availability, that is, the sensing aggregation nodes. The secondary users will be all platoons that request allocation of a dedicated frequency band. However, the location of data storage units and the SM can be associated with different network entities, depending on the selected centralization level. Although the mapping of the data storage units and the SM to specific elements are independent of each other, we assume that these will be treated jointly when formulating the functional architecture. Hence, we can distinguish the following considered management scenarios:

(i) The centralized architecture (presented in Figure 12), where only one global SM is considered. It is connected to a single CADB that is responsible for collecting the context information from all MCDs and other sources. Such an architecture requires deployment of the dedicated network server that will act as the SM and will be connected to the CADB and the RSU/BS using the backbone network. The decision on spectrum allocation for all platoons will be optimized globally in this scenario.

(ii) The distributed architecture (presented in Figure 13), where every platoon is associated with an individual SM that is located in the leader vehicle. In this case, the CADB may be located both centrally (a single database with global data) and locally in the selected RSU/BS (each RSU stores data relevant only to its region). In this scenario, every platoon will decide on the used frequency band independently of the others, based only on the information received from databases and its individual sensing results.

(iii) The hybrid (partially decentralized) architecture (presented in Figure 14), where the regional SM is located next to the selected RSU/BS. Here, the decision on the frequency band allocation will be made on per-region basis, where every platoon will be provided by information from the corresponding regional SM. Similarly to the distributed case, the CADB may be located here both centrally (a single database with global data) and locally in the selected RSU/BS. One should note here that a communication interface between neighbouring RSUs is needed to coordinate allocation on the boundaries of regions.

Three different communication interface types are defined for the considered management scenarios, namely, the intra-CADB interface, car-to-CADB/SM interface which is also used as an interplatoon interface, and the intraplatoon interface. The intra-CADB communication is assumed to be realized using the fixed wireline or wireless networks (the backbone network) that connect the RSU/BS with the central management entities and with one another (e.g., the S1 and X2 interfaces in LTE). The interplatoon or the car-to-CADB/SM communication can be achieved using, for example, the DSRC, C-V2X [15], or any other V2X systems defined for 5G networks in the future. Finally, the interplatoon interface is intended for further studies due to different frequency bands used here; however, as a baseline, also the use of DSRC or C-V2X can be assumed.

When vehicle platooning is considered, taking into account the results of investigation described in Section 2, the main factors determining the performance of dynamic spectrum management will be the latency of the obtained information and its reliability. Moreover, one should also account for the increase in network load with additional control data and the eventual costs of implementation of

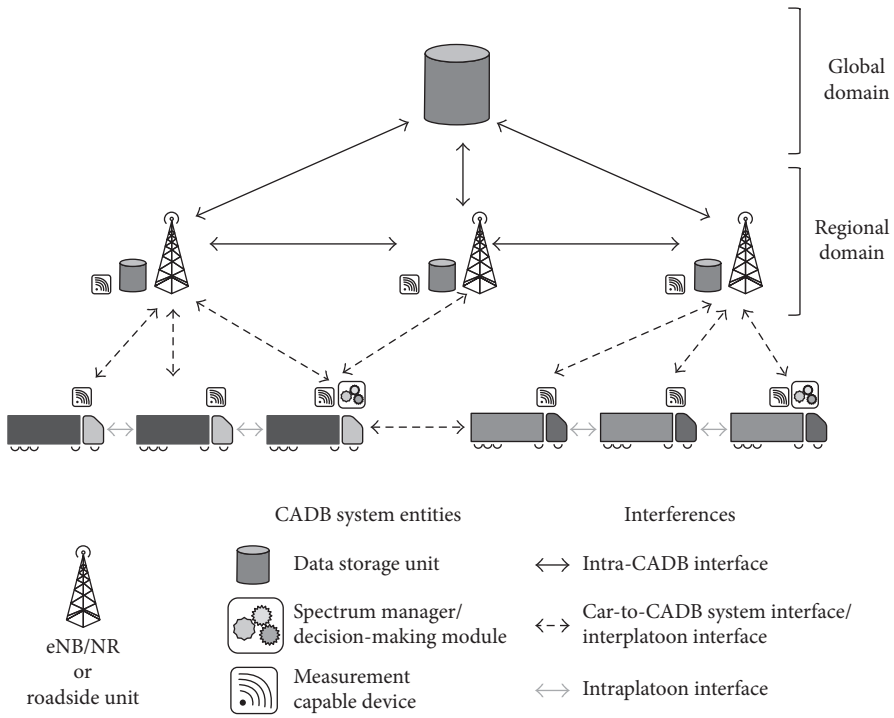

Figure 13: Schematic of the distributed management architecture.

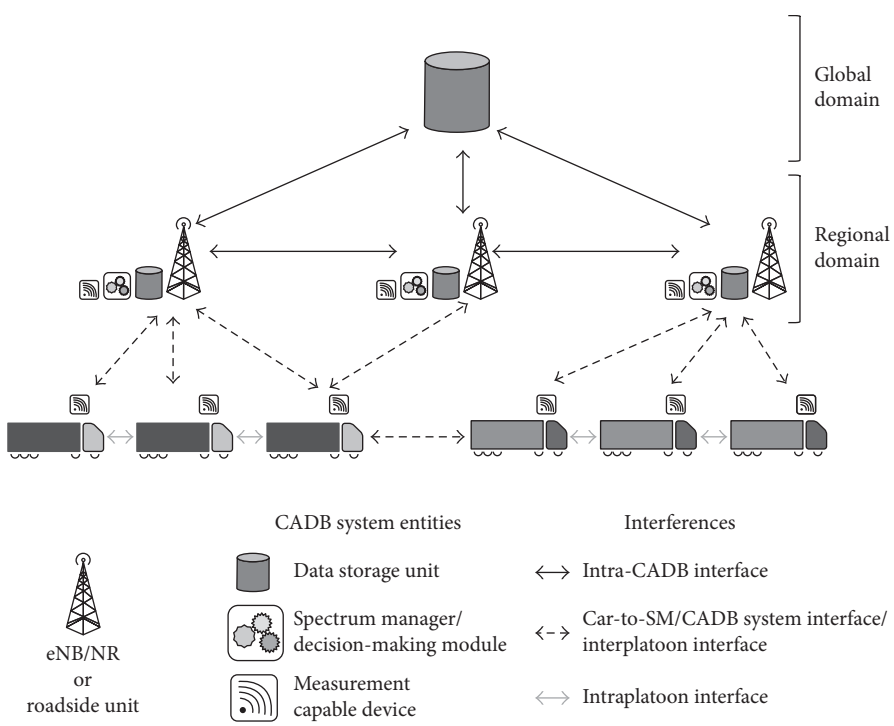

Figure 14: Schematic of the hybrid management architecture.

new hardware or software. All of the architecture scenarios described above are characterized with different advantages and disadvantages concerning these aspects.

Obviously, the advantage of centralized management is the global knowledge on the network status and the possibility to jointly optimize the spectrum allocation to all platoons. One should note here that the term "global" refers here to a large geographical area, such as the administrative region, and the management is performed also within its boundaries. Among other advantages, one can distinguish lower load of the RSU/BS with network control duties, as these will be used only to distribute the information. On the

Table 4: Summary of selected properties of the proposed management architectures.

Property	Centralized	Distributed	Hybrid
SM location	Central management server	Platoon leader	RSU/BS
CADB location	Central CADB	Central CADB and RSU/BS	Central CADB and RSU/BS
SM-CADB connection	Intra-CADB interface (backbone network)	Car-CADB interface (V2X communications) and intra-CADB interface (backbone network)	Intra-CADB interface (backbone network)
SM-platoon connection	Car-CADB/SM interface (V2X communications) and intra-CADB interface (backbone network)	Direct access (leader)	Car-CADB/SM interface (V2X communications)
Advantages	Global knowledge of the network status, joint optimization of spectrum allocation, and lower management load of the RSU/BS	Lowest latency, decreased load of the network with management data, and deployment of an additional server not required	Lower network load and latency than those in the centralized system, partial (regional) coordination of spectrum allocation, and deployment of an additional server not required
Disadvantages	High load of the management server, high latency, increased network load with management data, and dedicated management server (hardware) required	Incomplete information on spectrum availability, no coordination between platoons (interference), and increased vehicle cost (SM inside the vehicle)	Inter-RSU/BS interface needed for coordination of neighbouring SMs and additional load of the RSU/BS with management tasks

contrary, there are several important disadvantages related to the centralized processing. With the large number of managed platoons, the load of the server will increase dramatically. This may influence the decision timing and, eventually, lead to a situation where outdated decision is received by a platoon. Moreover, the need to provide the sensing information to a central database will further increase the decision latency and the network load.

Contrary to the approach described above, in the distributed scenario, the decision on the spectrum use is made by the platoon leaders. The main advantage of such an architecture is that the SM will use the most recent sensing information provided by the platoon vehicles. Aided with the context information from local and global databases, the decision process will be characterized by a very low latency. Moreover, the load of the network will be lower, as the information on band selection needs to be distributed only locally, and there is no need to deploy a dedicated management server. On the contrary, the main disadvantage of this approach is that the information about the surrounding environment and the expected spectrum white spaces might be incomplete, as it will rely mostly on the short-term information collected locally and the long-term information from databases. Furthermore, there will be no up-to-date knowledge on the frequency bands selected by other platoons, hence resulting in interferences. Finally, the distributed architecture will require implementation of the spectrum management functions inside a vehicle, thus having impact on its cost and energy efficiency.

The third considered architecture, namely, the hybrid one, is aimed at combining the advantages of both the centralized and distributed approaches. First, positioning the SM in the RSU/BS does not necessarily require deployment of dedicated hardware, as existing units may be used for this purpose, with just a new functionality implemented. Moreover, energy efficiency is not an issue here, as usually such nodes operate with a fixed power supply. Furthermore, the network load and latency will be lower than those in case of the centralized architecture, as only limited sensing information will be fed to the global database, with the most collected in a local (regional) one. Additionally, the spectrum allocation will be optimized within the region, thus reducing the expected interferences between platoons. However, the interference problem may still persist on the region boundaries; hence, a coordination mechanism of neighbouring SMs is necessary. Finally, the additional load of the RSU/BS with management duties may be considered as a disadvantage, compared to the centralized approach.

The main features, advantages, and disadvantages of the considered management system architectures are summarized in Table 4.

5. Challenges

Despite the functional management architecture selected from the options listed in Section 4, the dynamic use of spectrum white spaces for in-platoon communications poses serious challenges that need to be addressed. Among these, one can distinguish the susceptibility to interference, difficulties in estimation of the predicted quality of transmission in the considered frequency band, requirements on the reporting mechanism of sensing results, and, finally, the problem of maintaining the continuity of service when the frequency band switch is performed.

5.1. Interference Problem. The use of the CACC for vehicle platooning requires radio transmission with the highest

possible quality that can be regarded as low latency and high reliability. Therefore, the considered system is very susceptible to interference. Among the sources of disturbances, one can consider both the primary (licensed) and secondary users (e.g., other platoons). Therefore, detailed analysis of possible interferences in the investigated system is necessary, including identification of potential sources of interference and exploration of the ways of minimizing their negative impact on signal transmission in the platoon. Such an approach can lead to definition of the possible (acceptable) interference level, as well as the properties of the signal that can be exploited to mitigate its impact on the receiver.

5.2. Estimation of the Channel Quality. The dynamic use of spectrum white spaces has a potential to provide frequency bands characterized by a very low load, thus increasing the reliability of in-platoon communications. However, to fully utilize the possibilities of dynamic spectrum usage, one should consider a wide range of frequencies (e.g., the TV white spaces, frequencies around 3.5 GHz, or the mmWave bands). The main problem with operation using the different frequency bands is the need for reconfiguration of the transceiver and estimation of the predicted channel parameters. When low frequencies are used, the transmission can be characterized by a high range and low impact of the Doppler effect. However, due to small signal attenuation, the extensive use of lower frequencies might result in significant interference. On the contrary, when considering the use of frequency bands above 6 GHz, there are numerous challenges in V2V communications, such as high signal attenuation, high mobility impact on the channel characteristics, significant impact of the Doppler effect, high penetration loss that may result in a blockage of transmission, and the lack of realistic channel models [10]. Some of these will have a minimal impact on transmission in a platoon of vehicles, for example, the Doppler effect (as the relative speed of platoon vehicles is close to zero). Others, such as high signal attenuation, might have either positive or negative impact, as the transmission range will be smaller, but also, the interference will be rapidly diminishing with the increase in distance. On the contrary, penetration loss or frequent channel variations will seriously affect the platoon transmission. Therefore, there is a need to create a channel quality evaluation framework that will allow to compare the advantages and disadvantages of every considered frequency band in the spectrum selection process.

5.3. Reporting of Sensing Results. The use of sensing for detection of spectrum white spaces puts additional burden on the wireless network used for V2V communications as its results need to be reported to the relevant data storage unit and, finally, to the SM. Depending on the selected sensing mode, the exchange of information might be in the form of just decisions on the availability of the spectrum, or, in extreme cases, exchange of raw sensing data. As the data storage units are located in the regional or global domain, this information needs to be distributed using the existing network via the RSU or BS. Therefore, an efficient mechanism of reporting needs to be developed, which, preferably, should be adaptive based on the measured network load. Trade-off studies on the frequency of reporting and expected accuracy of sensing should also be considered.

5.4. Maintaining the Continuity of Service. The idea of dynamic spectrum management introduces a serious challenge for platoon communications which is related to the switch timing and continuity of transmission. The procedure of switching between the spectrum white spaces should take into account the need to maintain reliable links between all platoon vehicles until the switching procedure is finished and all devices are ready to operate in a new band. Similarly, the problem of transmission blockage caused, for instance, by a significant geographical separation of the platoon vehicles (e.g., at traffic lights) and by a significant interference or high penetration loss of obstacles (e.g., other cars) when using above 6 GHz bands, requires measures that will maintain the platoon integrity and ability to operate autonomously. Therefore, dedicated medium access control (MAC) layer protocols are required that will control the procedures of band switching and platoon reorganization.

6. Conclusion

In this article, we have considered the problem of V2V intraplatoon communication for the system based on the IEEE 802.11p/C-V2X communication protocols. We proposed a novel concept of the spectrum management system architecture for the dual-radio transceiver communication utilizing the spectrum white spaces. The aim of the proposed dynamic frequency band allocation and related system design is to significantly improve the platooning performance especially in the high-traffic areas/urban areas. In particular, the proposed system design has been developed to support dual-radio communication for platooning purposes, where critical system information to nonplatoon vehicles or the infrastructure is transmitted with the use of a primary radio (in accordance with the 802.11p or C-V2X communication protocols), while other data (platoon management, noncritical, other services, and infotainment) can be transmitted using an additional frequency band dynamically selected from the spectrum white spaces. Our experimental simulation results of the IEEE 802.11p-based system reveal that introduction of the second link allows to improve the performance of the considered platooning using the CACC mechanism significantly. One should also note that the proposed framework can be applied to any current or future V2X standard as a supplementary dynamic spectrum management system is proposed.

As a future work, we plan to perform deeper analysis of the proposed architectures. These include careful scenario definition, performance estimation, and detailed estimation/calculation of data flow within the proposed structures.

Data Availability

The data sets generated during and/or analyzed during the current study are available from the corresponding author on reasonable request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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