5G V2V Communication with Antenna Selection based on Context Awareness: Signaling and Performance Study

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***Abstract*—Enhanced vehicle-to-everything (eV2X) communication is one of the key challenges to be addressed by the fifth generation (5G) of cellular mobile communications. In particular, eV2X includes some 5G vehicular applications targeting fully autonomous driving which require ultra-high reliability. Although vehicular communications are by default assumed between single antennas located on the roof of the transmitter and receiver vehicles, prior art has shown that there are other antenna positions more suitable for V2X communication, depending on the specific communication context. Antenna selection can be used in this case to select one specific antenna or a subset of them better suited for a certain communication link. In this work, we propose a context-aware antenna selection procedure able to enhance the communication with multi-antenna vehicles. To enable such scheme in 5G systems, we discuss the necessary signaling to extend current 5G radio resource control and radio resource management mechanisms, which are mainly focused on single-antenna communication. The signaling overhead caused by context exchange for antenna selection is analyzed and compared to the overhead when reference signals are exchanged for that purpose instead. Finally, simulation results for a 5G platooning use case are presented to show the advantages of antenna selection.**

***Index Terms*—V2V, multi-antenna, antenna selection, context, 5G, signaling.**

I. Introduction

One of the challenges of the 5G of mobile communications is the enhanced support of Vehicle-to-Anything (V2X) communication services, known as enhanced V2X (eV2X) [1], which can be a key enabler for the growing number of connected vehicles in Intelligent Transportation Systems (ITS) [2][3][4]. Essential 5G use cases to be addressed through eV2X include vehicles platooning (grouping of vehicles travelling together [5]), advanced driving (semi- or fully-automated driving), extended sensors, and remote driving. The Quality of Service (QoS) requirements of such ITS-related use cases, which are mainly intended to improve traffic safety and/or traffic efficiency, are very demanding. Besides the need for low latency communication (in the order of tens of milliseconds) [6], eV2X applications also require ultra-high reliability (e.g., fully automated driving requires values of 99.99% within a range of up to 500 meters).

Vehicular communications have typically considered in the past the use of transmitting and receiving antennas located uniquely at the roof of the vehicles. Usually, one antenna is considered at the roof of the transmitter while one or two antennas, which may implement some kind of diversity technique, are assumed at the receiver. However, future vehicles connected to 5G networks are expected to have multiple antennas distributed around their surface. This fact is expected to enable the use of a plurality of multi-antenna techniques to obtain diversity, beamforming and spatial multiplexing gains.

Several previous works [7][8] have considered the availability of antennas at different vehicle positions. Specifically, in [8], two communicating vehicles with 10 antennas distributed over the roof, bumpers and mirrors were considered. A characterization of the channel loss between all the possible combinations arising from the 10 transmitting and 10 receiving antennas was provided, showing substantial variations of this parameter depending on the selected antenna pair. As a conclusion, the work suggests that, being able to dynamically coordinate the selection of the best pair of transmitting and receiving antennas could potentially maximize the coverage in single-antenna communications, and thus, play a critical role in ensuring the best vehicular communication experience.

Simulation of Vehicle-to-Vehicle (V2V) MIMO with multiple antennas located in different parts of the vehicle has shown promising gains in terms of capacity and reliability [9][10][11]. Antenna selection for multiple-input multiple-output (MIMO) is also a topic of active research since several years ago [12][13], but it is recently focused mainly on massive MIMO systems [14][15][16]. It is worth noting that antenna selection at the Tx is usually carried out through optimization techniques with full Channel State Information (CSI) at the Tx side, which is acquired from Rx feedback. The availability of full CSI at the Tx side is, however, a key practical limitation for MIMO communication in vehicular systems, due to the fast variations in V2V channels caused by mobility. The authors in [15] showed that, in real propagation environments, the large-scale fading changes along the antennas belonging to the same massive antenna array. In this scenario, simple average-power-based antenna selection

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schemes provided very competitive results, showing that, when the average channel gain is different among the antennas, the antenna selection may be governed by variations in the large-scale fading instead of variations in the small-scale, as traditionally assumed. Motivated by this fact and, as a more realistic assumption for vehicular environments where the antennas are located in different parts of the vehicle, and the car body obstruction is then different for each antenna, in this work we focus on antenna selection based only on slow-variation parameters.

Although a smart use of the multiple antennas could potentially enhance the V2X links towards the demanding eV2X goals, from a system perspective, the use of multi-antenna direct V2V communication (e.g, through the sidelink) has not yet been solved in 5G. Existing Long Term Evolution (LTE) Radio Resource Control (RRC) and scheduling/Radio Resource Management (RRM) schemes for sidelink enable only single-antenna communication, i.e., they have not been designed for multi-antenna and/or multi-link V2X communication. Since those schemes will be the baseline for sidelink specification in 5G, which is still under definition, they will need a significant extension to support multi-antenna communications. In this direction, this work targets to extend current RRC and RRM schemes for sidelink communication to select the most appropriate set of antennas for V2V communications among two or more vehicles.

The contributions of this paper can be summarized as:

- A proposed antenna selection procedure in multi-antenna vehicles based on slow-variation parameters.
- New signaling to support the proposed antenna selection in which the network is in charge of the antenna selection decision making.
- An analysis of the overhead caused by the part of signaling devoted to support the dynamic antenna selection using either context exchange or reference signals, and a comparison between both alternatives.
- A performance evaluation of a proposed antenna selection in an exemplary 5G eV2X use case: vehicle platooning.

The remainder of the paper is structured as follows. Section II presents our proposal for antenna selection based on the general idea of the paper. In Section III, we describe the current V2V sidelink signaling in fourth generation (4G), which is the basis of our signaling proposal for 5G included in Section IV. In Section V, we analyze and compare the signaling overhead required by our proposed antenna selection based on context information with the one of an antenna selection scheme based on the transmission of reference signals, focusing on signaling to support the dynamic selection of antenna pairs. In Section VI, we address a representative service targeted by eV2X, platooning, to show the potential of the proposed antenna selection. Finally, the conclusions of this work are drawn in Section VII.

II. Antenna selection based on slow-variation parameters

Our proposal focuses on performing antenna selection, that is, choosing a subset of antennas at the Tx vehicle and a subset of antennas at the Rx (the subset could be different or the same at both sides of the communication), leading to an antenna combination to be used for communication in a certain V2X service. Figure 1 shows an example with one vehicle acting as transmitter and two as receivers.Note that this technique is complementary to the use of MIMO, since it provides means to select a subset of antennas in transmission and reception that can be used to implement any MIMO scheme on top of them.

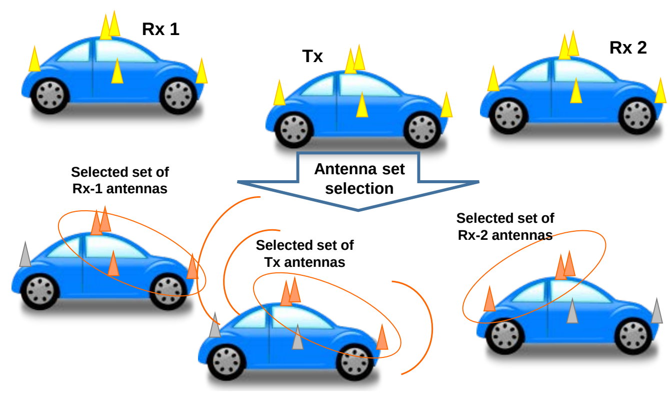

Fig. 1. Example of proposed antenna selection.

In contrast to previous antenna selection proposals, most of them based on the updated knowledge of small-scale channel parameters at the Tx side, we focus on high mobility scenarios and propose a simple selection based on channel characteristics with a much slower variation over time. Furthermore, as it will be later shown through an example in a platooning use case, by combining large-scale channel parameters (e.g. path loss and shadowing) with context awareness, the overhead to select the best antenna combinations per service and Tx-Rx pair can be substantially reduced in comparison to the one of a conventional approach using reference signals. Nevertheless, over the selected subsets of antennas according to slow variation parameters, more advanced antenna selection or MIMO communication mechanisms could be additionally implemented, provided that extra channel information (small-scale) is further available at the Tx side for the antennas of interest. However, the latter schemes are out of the scope of present work.

Figure 2 illustrates the main steps of the general procedure for antenna selection, considering that the decision on the best antenna sets is taken in a centralized manner by the Base Station (BS):

1) To identify the antennas supported by the involved vehicles. To this end, the vehicles will inform the network about their number of antennas, antenna locations, antenna gains, frequency-dependent characteristics (e.g. radiation pattern) and vehicle type (e.g., truck).
2) To check service requirements, including the type of service, needed transmission modes (e.g., platooning service, multicast, etc.), service duration, periodicity and characteristics of the messages to be sent.
3) To check road environment conditions, e.g., surrounding elements such as vehicles, buildings, bridges, etc. Also

check the location of transmitter and receiver vehicles, orientation or relative positions among vehicles: position (x,y,z – UTM + altitude), direction of movement, speed, short-term path of vehicle.

4) To check radio/network conditions, e.g. via a report of total power measured by each antenna (per-antenna Received Signal Strength Indicator (RSSI)-like), report of Channel Busy Ratio (CBR) measured by each antenna [17], etc.)
5) To make the decision on antenna selection.

III. 4G SIGNALING FOR V2V SIDELINK

This section introduces the current 4G signaling in V2V sidelink which has been used in this work as a basis for the signaling proposal.

In LTE, the User Equipments (UEs) transfer radio access capability information to the Radio Access Network (RAN) using a procedure defined in [18], which is known as UE capability transfer. Within this procedure, there is an information element including a field which, being set to TRUE, indicates that the UE is capable of supporting UE transmit antenna selection, as described in [19]. More specifically, antenna selection is only supported in uplink, where one transmit antenna can be selected from a set of only two possible antennas either by the UE (in open loop mode) or by the network through a Downlink Control Indicator (DCI) with format 0 [20]. However, that procedure does not consider the reporting of features for an undefined number of antennas with different capabilities. Besides, it is not valid for antenna selection in sidelink. Similarly, the standard also contemplates the use of MIMO transmission schemes in downlink and in uplink, but not in sidelink.

When a UE has an RRC connection and intends to use the sidelink interface (also known as PC5 interface) for communication, it sends a SidelinkUEInformation message to the serving cell in order to request assignment of dedicated sidelink resources. Then, the UE receives RRCConnectionReconfiguration including the information element known as sl-V2X-ConfigDedicated. Through this information element, the serving BS may allocate resources semi-persistently to the UE. In order to request resources dynamically, the UE sends buffer status reports to the serving BS, which provides resource allocations using DCIs with format 5A. Once the resources for the UE are allocated, the UE can start a sidelink data transmission using the Physical Sidelink Shared Channel (PSSCH) and, at the same time, start a sidelink control transmission using the Physical Sidelink Control Channel (PSCCH) consisting on a scheduling grant message known as Sidelink Control Indicator (SCI). The SCI indicates the format of the data transmission to the potential receivers. In sidelink, only one antenna port is assumed to be available (see [21]). Therefore, neither the sl-V2X-ConfigDedicated information element nor the scheduling grant messages (DCI 5A and SCI) consider the indication of multi-antenna transmission related information.

As a result, the UE capability transfer procedure needs to be extended, as well as the information contained in the resource allocation elements and scheduling grants, in order to consider multiple antennas available for sidelink communication.

IV. PROPOSED SIGNALING FOR ANTENNA SELECTION

For the development of this idea, together with the necessary resource selection in a multi-antenna setup, the following five aspects are specified:

A. Signaling to indicate multi-antenna capabilities

New signaling is needed for a Vehicular User Equipment (VUE) to inform the network about its capability to communicate using multiple antennas and the antenna characteristics, in order to carry out Step 1) of the proposed antenna selection procedure (see Section II). To this aim, the RRC UECapabilityInformation message [18] can be extended with a new Multi-antennaCapability field, as shown in Figure 3. The necessary antenna-related information will be sent either during the attachment process, or after a network request or required update (e.g., antenna on bumper is affected by a collision).

B. Signaling to support the selection of antenna pairs

New signaling is also necessary to provide context information from the VUEs to the network in order to enable Steps 2), 3) and 4) of the antenna selection procedure. We consider two different options: 1) information provision together with specific service request (e.g. RRC Connection Request, Non-access stratum (NAS) Service Request or SidelinkUEInformation) and 2) periodic reporting or event-driven update of context information by VUEs (either with new dedicated messages or by extending existing messages, e.g., UE Assistance Information or RRC Measurement Reports). The second option is, thus, a dynamic reporting to assist the antenna selection while the first option provides a static reporting.

Figure 4 illustrates the signaling options for multi-antenna context information reporting from the VUE to the BS. We propose the inclusion of a new Multi-antennaContextInformation field with at least the following (sub-)elements: service layer information, road environment conditions, location information and radio/network conditions. The periodic or event-driven reporting of context information can be configured by the network either with the RRC-ConnectionReconfiguration message or with new dedicated messages. For event-driven reporting, the criteria for triggering the context update and the required content could be provided by the network, could be fixed beforehand, or could be fixed by default and modified by the network.

C. Signaling to notify antenna selection

Once the antenna selection has been carried out by the network in Step 5), the next step is to notify the involved VUEs of the selection (or update) of appropriate antenna sets and required configuration for Tx and Rx. The BS will be in charge of configuring statically or dynamically the antenna selection for VUE's Tx/Rx.

Figure 5 shows a signaling exchange example to notify the initial antenna selection and two possible antenna selection reconfigurations. For the initial antenna selection notification, we propose to extend the RRCConnectionReconfiguration

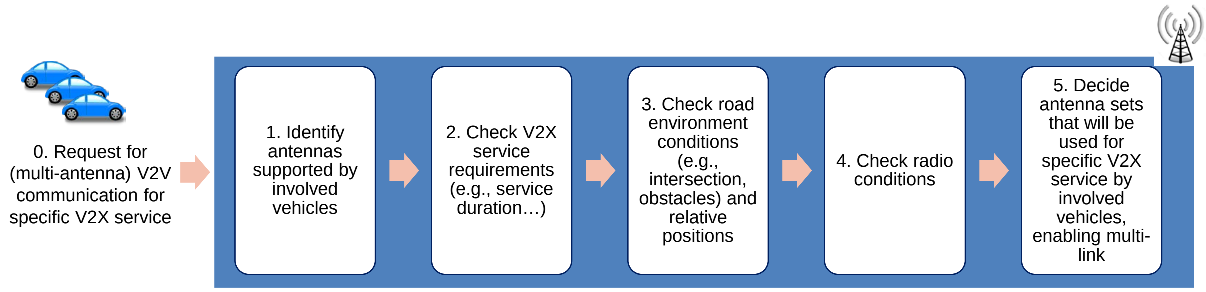

Fig. 2. Example of decision making process located at the network (e.g., BS) for antenna selection.

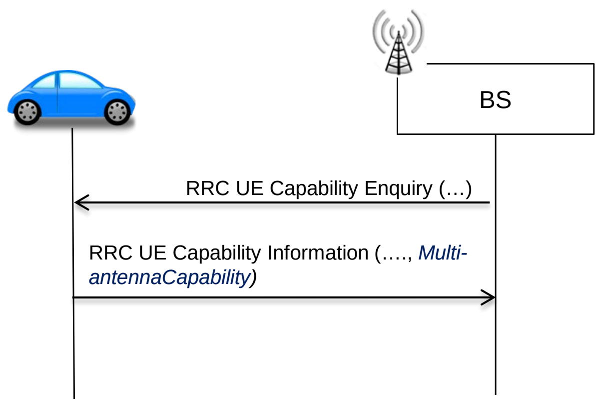

Fig. 3. Indication of multi-antenna capabilities in an RRC message.

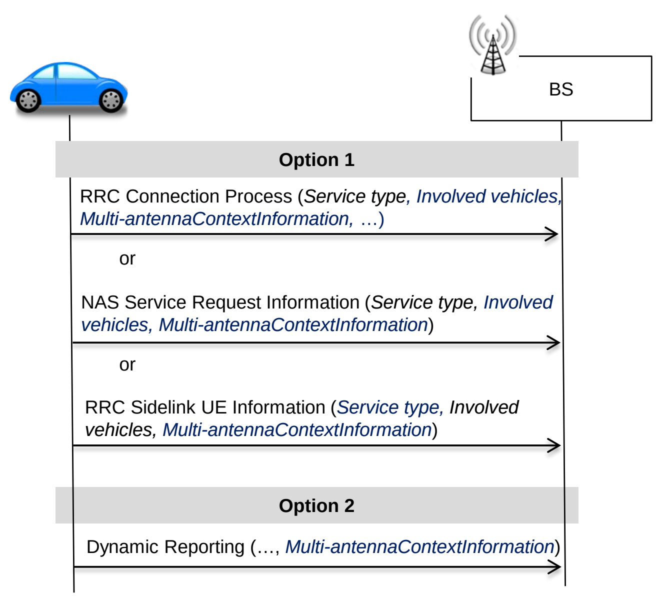

Fig. 4. Options to report multi-antenna context information from the vehicles: static service request and dynamic reporting.

message to assign a certain antenna set for a specific service among the group of involved vehicles. The Tx and/or Rx antennas could be selected for each V2X service through the field sl-V2X-ConfigDedicated extended with multi-antenna configuration information, as shown in Figure 5.

The new fields of sl-V2X-ConfigDedicated, gathered in the new antenna selection information element detailed in Figure 6, will be:

- configurationList, which is a list of destinations lists, each one with all the Layer2-Ids of the possible destination vehicles for the transmitter.
- TxAntennaSelection, which is a list of transmit antenna selection bitmaps, each of them with as many bits as antennas (fixed size of MAX_NB_V2X_ANTENNAS). In the bitmap, bits are set to 1 for selected antennas, and to 0 otherwise.
- RxAntennaSelection, which is a list of receive antenna selection bitmaps, with the same format as the transmit antenna selection bitmaps.

Figure 7 shows an example of use of the antenna selection information element inside the RRCConnection-Reconfiguration message for a platooning service with MAX_NB_V2X_ANTENNAS=10. Considering the Tx is the third platoon vehicle, the configurationList includes two possible destinations, either the platoon head, or the platoon follower. The TxAntennaSelection bitmap selects the rooftop antenna for the communication with the platoon head and two antennas at the rear bumper for the communication with the follower. Similarly, the RxAntennaSelection selects the rooftop antenna for the reception at the platoon head and two antennas at the front bumper for the reception at the platoon follower.

When updates about the initial allocation are needed, due to change of radio/service/road conditions or other context information, there are two options for notification: 1) through updated RRCConnectionReconfiguration messages (see Figure 5), and 2) through scheduling grant messages (DCI and SCI). For the second option, DCI and SCI messages can be extended to assign a transmitter or inform a receiver in a more dynamic way about the antenna set to be used. In Figure 8 it can be observed that, for sidelink, a new version of DCI 5A (referred to as DCI 5AU) is necessary to indicate the transmitter which transmit antenna set to use and, possibly, the antenna set to be used by the receivers. Then, the sidelink Tx uses the SCI with new fields to notify the receivers which

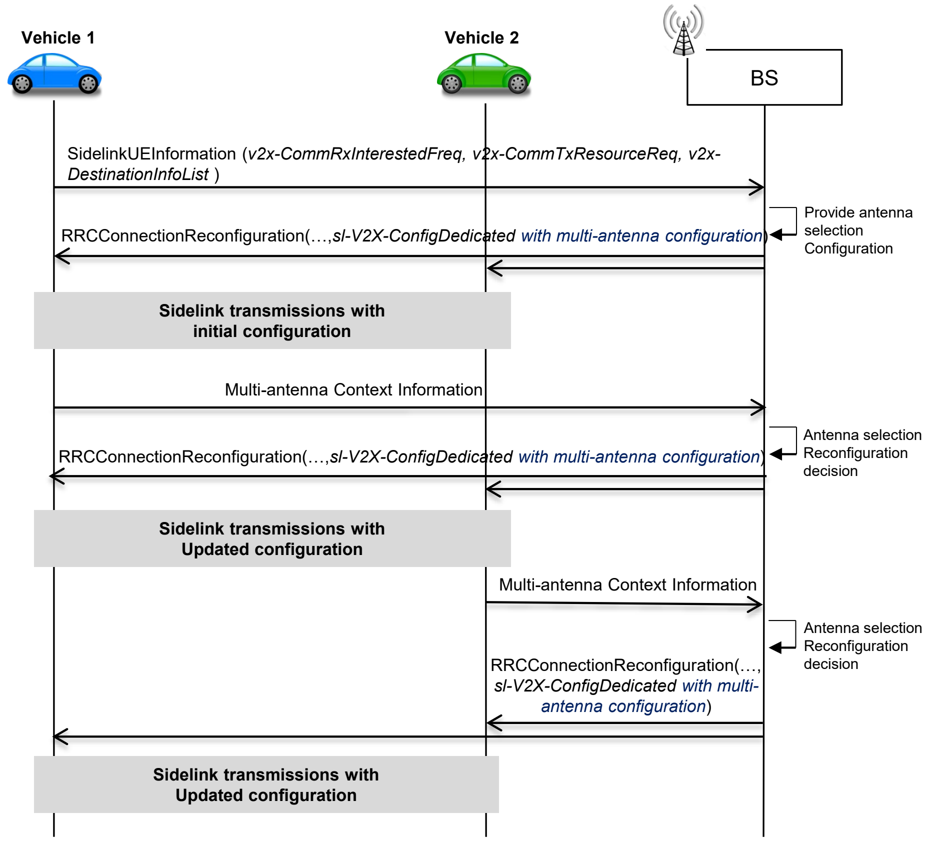

Fig. 5. Initial antenna selection and update of antenna selection using RRCConnectionReconfiguration.

```
antennaSelection {
        configurationList SEQUENCE (SIZE NB_OF_CONFIGURATIONS) OF {
            destinationGroupList  SEQUENCE (SIZE NB_OF_DESTINATIONS_IN_GROUP) OF Layer2-Ids
        }
        TxAntennaSelection SEQUENCE (SIZE NB_OF_TRANSMITTER_GROUPS) OF {
            TxAntennaGroupSelection BIT STRING (SIZE (MAX_NB_V2X_ANTENNAS)), OPTIONAL
        }
        RxAntennaSelection SEQUENCE  (SIZE NB_OF_RECEIVER_GROUPS) OF {
            RxAntennaGroupSelection BIT STRING (SIZE (MAX_NB_V2X_ANTENNAS)), OPTIONAL
       }
}
```

Fig. 6. New antenna selection information element used in several signaling procedures.

transmit antenna set is used and/or which reception antenna set should be used. This requires a new version of SCI as well.

DCI 5A maximum length is 32 bits. In case the information to be allocated is less than this, a padding with zeros is applied. Generally, in a conventional transmission, 23 bits are used, meaning that 9 bits are free of use. Instead of encoding directly the Tx antenna selection and the Rx antenna selection using bitmaps (as in Figure 6), our proposal is to use the DCI free bits to indicate the index of the element within the configurationList, TxAntennaSelection and RxAntennaSelection signaled in the last RRCConnectionReconfiguration message for the specific sidelink transmission indicated in the DCI original fields. An example of this antenna encoding is also included in Figure 7, where the last 9 bits of the DCI are all set to zero to indicate that, for the first configuration (the Rx is the platoon head), rooftop antennas are selected for both the Tx and the Rx. However, for the second configuration (the Rx is the platoon follower), rear bumper antenna is used for Tx and front bumper antenna for Rx, which is indicated by setting the last bit of the DCI to one.

Once the Tx VUE is informed about the network decision with respect to Tx and Rx antennas, it has to inform also the destination vehicle about such antenna selection. This could be made, for instance, via the extension of the SCI message. Again the idea is to use the bits that are currently free of use to embed there the selection information. The original fields of the SCI format 1 are included within 28 bits [20], leaving only 4 bits free for, e.g., a Rx antenna selection bitmap with fixed size MAX_NB_ANTENNAS.

D. Network-scheduled resource allocation

The scheduling grants contained in DCI 5A are used to allocate resources and can be also used in a multi-antenna configuration when all the antennas use the same set of resources. However, if the goal is to allocate different sets of resources to different sets of antennas, two options are possible: a) a new DCI defined as an array of DCI 5AU, with as many elements as sets of antennas to be differentiated, and b) multiple DCI 5AU to be sent to a VUE in a subframe, each one with a different set of selected antennas. In option b) note that the VUE should be capable of receiving multiple DCIs simultaneously.

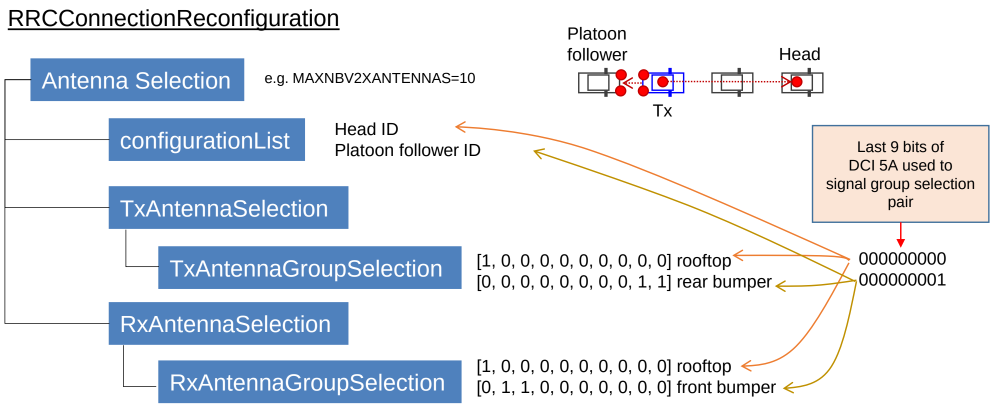

Fig. 7. Example of use of the antenna selection information element in the RRCConnectionReconfiguration message, and of the free DCI 5A bits for dynamic antenna selection.

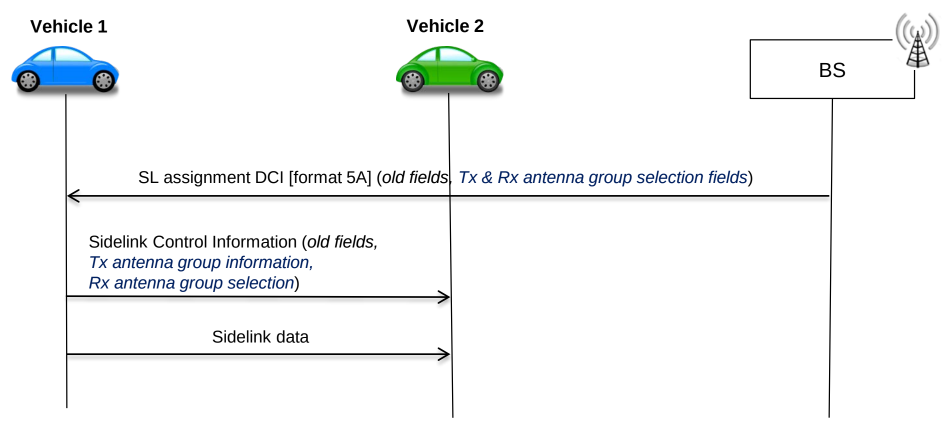

Fig. 8. Dynamic antenna selection using scheduling grant messages (DCI and SCI).

According to 3GPP specifications, it is not possible today to allocate resources explicitly to a specific service since scheduling grants do not have enough information. To make such explicit allocation, we propose two alternatives:

1) DCI 5AU could be extended with the addition of a field with a service indicator.
2) DCI 5AU could have an element (resource-antenna set) per each logical channel identified by the ProSe Per Packet Priority (PPPP) in order of decreasing priority.

The last two capabilities could be further combined to allocate a specific set of resources to a specific set of antennas and a specific service.

Regarding the necessary measurements to make proper scheduling decisions, these could take into account as input information the same context information presented in previous sections to make multi-antenna configuration decisions such as the CBR or RSSI per-antenna measurements.

E. VUE-autonomous resource selection

There are two types of VUE autonomous resource selection:

1) With VUEs in-coverage, as in the network-scheduled case, RRC signaling can be used to modify the antenna selection from the network. However, scheduling grants such as DCI cannot longer be used for such purpose. Therefore, for a fast re-selection of antenna sets, new messages equivalent to the DCI but only with antenna selection fields should be defined.
2) With VUEs out-of-coverage, network-based antenna selection is not feasible since there is no possible connection between the VUEs and the network. Hence, this type of resource selection is out of the scope of this paper.

V. Overhead Analysis of the Signaling to Support Antenna Selection

In this section, we focus on one aspect of the proposed signaling for antenna selection: the signaling to support the dynamic selection of antenna pairs (see section IV-B). Specifically, we compare, in terms of required signaling overhead, our proposed antenna selection based on context information with an antenna selection scheme based on channel knowledge at the transmitter side. Our aim is to show that our proposal can be beneficial under realistic assumptions in some cases.

Note that this signaling overhead comparison does not consider the signaling overhead needed by the demodulation pilots sent in each data transmission. The reason is that the demodulation reference signals overhead would be equal in

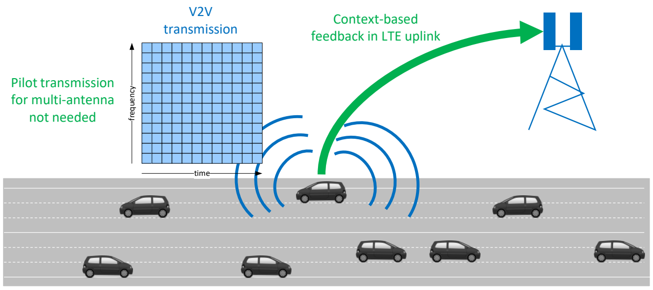

Fig. 9. Context-based antenna selection.

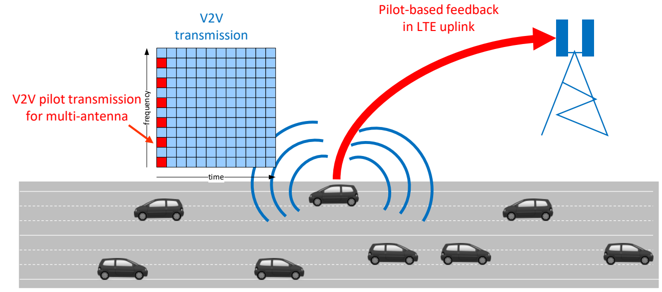

Fig. 10. Pilot-based antenna selection.

the two compared approaches. Therefore, a fair comparison can be conducted considering only the specific signaling for antenna selection.

A. Context-based approach

In our proposal based on context information exchange, the unique source of overhead associated to antenna selection is the transmission of the context-based feedback from the VUEs to the BS through LTE uplink, as shown in Figure 9.

The reported context information can be varied. With the aim of narrowing down the alternatives, we considered in our evaluation three types of context feedback:

1) Basic context feedback: report of position and direction. In this case, the position can be represented using 32 bits for the latitude, 31 bits for the longitude, 20 bits for the altitude and 12 bits for the heading (according to the range and granularity considered for those physical values in [22]). The total size of the report, S, would be 95 bits.
2) Enriched context feedback with planned maneuvers: report of planned positions for the following 2 seconds with a sampling of 100 ms. Using relative values instead of absolute values we would require, according to [22], 18 bits for latitude, 18 bits for longitude and 15 bits for the altitude. For the heading, 12 bits would be used to report absolute values. Therefore, each position would be indicated with 63 bits and the whole maneuver report would require $S = 1260$ bits.
3) Enriched context feedback with neighbor obstacles: report of objects surrounding the vehicle, which are potential obstacles for the communication. We could assume that the 8 nearest objects are reported, which would be sufficient for a vehicle surrounded by vehicles of its same size in a crowded scenario. Each object can be modeled as a rectangular cuboid whose center position, direction, length, width and height are reported. According to [22], position and direction require 95 bits, length requires 10 bits and height 6 bits. For the width we also assume 6 bits. In total, 117 bits are required per reported object. For 8 objects, the report size would be $S = 936$ bits.

In general, for a system with T transmitters, the required rate to send all the feedback can be obtained as:

$$\rho_{context} = \frac{T \cdot S}{\tau}, \tag{1}$$

where τ is the considered reporting period in seconds.

B. Pilot-based approach

If the antenna selection relies on channel information at the Tx, a channel estimation stage needs to be carried out, which, following the usual approach in wireless networks, will be based on the transmission of training data from Tx to Rx in the form of pilot symbols. Two sources of overhead can be identified when pilot-based channel estimation is considered: 1) the transmission of new pilots in the V2V communication link to acquire channel information for all the antennas, and 2) the transmission of the new pilot-based feedback to the BS in LTE uplink to enable the selection decision. It can be observed in Figure 10 that new pilot symbols are allocated in a set of resources of the time-frequency grid, which could have been otherwise devoted to data transmission.

1) Allocation of reference signals in the V2V link: In order to carry out channel estimation for multiple antennas in the V2V link, the transmission of one reference signal per antenna is needed. Since currently there are no standardized reference signals in V2V for channel estimation (apart from demodulation reference signals), one option is to reuse LTE uplink signals structure for that purpose.

In LTE uplink, there is one Orthogonal Frequency Division Multiplexing (OFDM) symbol per subframe used to send Sounding Reference Signals (SRS). In that symbol, signals from 16 users can be multiplexed in the same bandwidth using a single Zadoff-Chu base sequence using either multiple cyclic shifts (8 possibilities) or different comb-like mappings (2 possibilities with resources mapped each 2 subcarriers) [23]. With the considered SRS, it is possible to estimate the channel from one antenna. If the channels from more than one antenna are to be measured, the number of supported users will be divided by the number of antennas. On the other hand, if the period required for the channel estimation is higher than 1 subframe, more users can be supported. Specifically, the number of users supported in the system is multiplied by the number of subframes per reporting period.

In summary, and considering subframes of 1 ms, the number of users supported by a system in which one OFDM symbol per subframe is used to transmit pilots is:

$$U_{pilots} = \frac{16 \cdot (\tau/10^{-3})}{N_{ant}}, \tag{2}$$

where the term $\tau/10^{-3}$ in the numerator stands for the number of subframes of 1 ms in each reporting period.

2) Pilot-based feedback options: In order to report the estimated channel loss between a specific pair of transmitting and a receiving vehicles to the BS, we could consider a granularity of 1 dB in the reporting and a 100 dB margin for loss values. With these assumptions, each particular value could be represented using 7 bits (as occurs in the reporting of Reference Signal Received Power (RSRP) values).

The receiver could follow one of the following options, each of them leading to a different overhead:

a) Channel loss measured for all the antenna combinations, that is to say, from each transmit antenna to each receive antenna. For vehicles with a number of antennas equal to N_{ant}, there are $N_{ant} \times N_{ant}$ possible antenna combinations, and the resulting size of each report is $S = N_{ant}^2 \cdot 7$ bits.

b) Channel loss for the best N_{comb} antenna combinations. In this case, each channel loss value comes with an indication of the antenna combination whose channel loss is reported. For example, with vehicles with $N_{ant} = 10$, 100 combinations exist, which can be identified using 7 bits. Therefore, the number of bits in each report would be $S = N_{comb} \cdot 14$ bits.

The rate required to send all the feedback in a system with T transmitters, each of which has R receivers, would be:

$$\rho_{pilots} = \frac{R \cdot T \cdot S}{\tau}. \tag{3}$$

It can be seen that the rate scales up with R and T, while in the context-based approach it only depends on T.

C. Feedback overhead comparison

In this section we compare the overhead due to feedback transmission sent from the vehicles to the network to support the antenna selection decision for the two alternatives: pilot-based approach and context-based approach. Note that the size of the feedback in the pilot-based approach depends on N_{ant}, while in the context-based approach it does not depend on that value. We focused in this assessment on the specific case of $N_{ant} = 10$ antennas per vehicle.

Figure 11 shows the amount of bits per report period needed to acquire the channel characteristics from the 10 antennas of a transmitter to the 10 antennas of R receivers. The represented value is $\rho_{context}$, for context-based feedback schemes, and ρ_{pilots}, for pilot-based feedback schemes, both after a multiplication by τ and a division by T to dispense with common factors. Results are included for the three presented context feedback options, and the two pilot-based feedback options. For the second pilot-based option, we have further considered two cases: reporting of the best 5 antenna combinations ($N_{comb} = 5$), and reporting of only the best combination ($N_{comb} = 1$).

It can be observed that, in the context-based feedback, the values are constant since only the transmitter VUE is sending feedback to the network. On the contrary, in the pilot-based approach, the feedback overhead scales up with R, since the

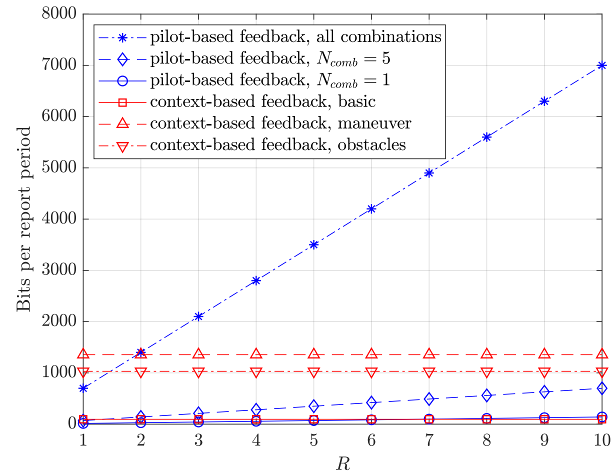

Fig. 11. Comparison of overhead per report period for the feedback to support antenna selection between a single transmitter with 10 antennas and R receivers with 10 antennas.

feedback is sent to the network by each receiver. As a result, as the number of vehicles increases, the context-based feedback is more efficient. It can be observed that the most detailed pilot-based reporting, which reports the channel loss for all antenna combinations, is worse than all context-based options already for $R = 2$. Furthermore, even the pilot-based feedback with reporting of just $N_{comb} = 1$ requires more bits than the basic context-based feedback for $R \geq 7$. Therefore, it is clear that the context-based feedback is an efficient means to send feedback information to the network to support the selection.

D. Overall overhead comparison

The previous section analyzed the overhead due to the feedback but, as mentioned before, the pilot-based approach involves an additional overhead due to the transmission of pilots. For a fair comparison, we transformed the feedback overhead rate and the pilot transmission overhead into a comparable resource usage metric: the number of required OFDM symbols per subframe, denoted by O. To make the conversion, several assumptions regarding the uplink spectral efficiency and the reporting periodicity are needed:

- Given a required feedback rate, we can obtain its equivalence in number of OFDM symbols per subframe after a division by the rate that would be achieved if all the OFDM symbols were devoted to uplink transmissions, and a product by the number of OFDM symbols in each subframe. For instance, using the 4G numerology, the average uplink rate in a system with 10 MHz is 10 Mbps [23], and there are 14 OFDM symbols in each subframe. Therefore, the required feedback rate must be in this case multiplied by 14 and divided by 10^7.
- Regarding the periodicity of pilot transmission and feedback reporting in the uplink (either based on pilots or context), it should depend on the vehicles speed. Since the focus is on antenna selection, it must be ensured that the best antenna combination can be tracked without

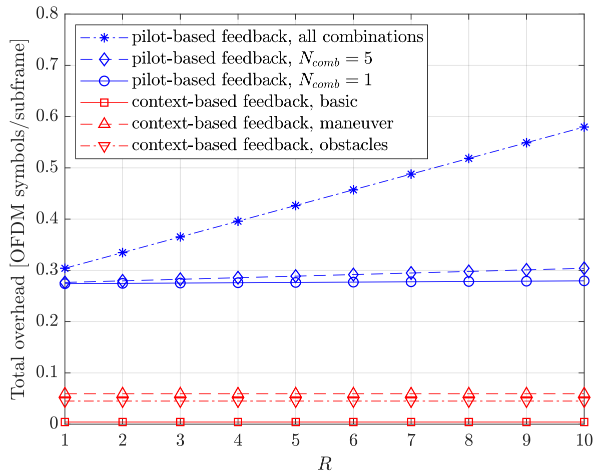

Fig. 12. Comparison of total overhead including resources used by pilots.

skipping significant variations. From the channel loss measurements and best antenna combination for each Rx position and orientation reported in [8] (Figure 16 therein), it can be observed that in 5 meters the best antenna combination may change twice (see the changes between -2.5 m and 2.5 m of frontal position). Therefore, the relative change of position between vehicles to send pilots and feedback must be lower than 5 m, for instance, 2.5 m. In a freeway scenario with vehicles travelling at 140 km/h, and considering different directions (relative speeds of 280 km/h between vehicles), the necessary reporting period is $\tau = 32$ ms.

In the context-based approach, according to the conversion described above, and for $\tau = 32$ ms, the number of OFDM symbols required per subframe is:

$$O_{context} = \rho_{context} \cdot \frac{14}{10^7} = \frac{T \cdot S \cdot 14}{320000}. \tag{4}$$

In the pilot-based approach, the number of OFDM symbols required per subframe, for $\tau = 32$ ms and $N_{ant} = 10$, is:

$$O_{pilots} = \rho_{pilots} \cdot \frac{14}{10^7} + \frac{T}{U_{pilots}} = \frac{T \cdot (R \cdot S \cdot 14 + 10^5/16)}{320000}, \tag{5}$$

where we applied the conversion suggested for the feedback rate in the first term, and the second term accounts for the overhead due to pilot transmission. In the latter, the amount of transmitters, T, is divided by the number of users supported by a system in which one OFDM symbol per subframe is used to transmit pilots, U_{pilots}, resulting in the number of OFDM symbols per subframe required to support T transmitters.

Figure 12 presents the total overhead in terms of OFDM symbols required per subframe, normalized by the number of transmitters. As can be seen, after considering the overhead due to pilot transmission, the context-based approach configurations tested are clearly more efficient than the pilot-based approach in all its configurations.

To complete the comparison, let us consider the freeway scenario defined by the 3GPP [24]. Such scenario consists of six lanes (three in each direction). Note that the worst-case situation appears when the scenario is totally covered by vehicles. Given that the relevance distance for messages reception is usually given as a radius (r) from the transmit vehicle location, and considering vehicles with a length of 4.7 m, in the segment of the freeway within a circle of radius r, the total number of vehicles is $N_v = 2 \times r \times 6/4.7$. For a typical value of r considered in the transmission of eV2X messages ($r = 150$ m), there would be $N_v = 383$ vehicles. If we multiply the values in Figure 12 by this number, it turns out that in the crowded scenario the pilot-based feedback is not possible given that it requires more OFDM symbols per subframe than the available number of symbols. For context-based, the number of symbols required is only feasible with the basic feedback which needs 2 symbols. If we consider an inter-vehicle distance of 2.5 m between vehicles, and assuming a speed of 140 km/h, we would have $N_v = 20$ within the relevance area. In that case, all the feedback approaches are feasible although the percentage of resources devoted to the signaling is at least around 40% for the pilot-based feedback, while it is less than 15% for all the context-based approaches.

Note that the overhead values presented in this overall overhead comparison depend on the assumptions made concerning the feedback and pilots reporting period, the uplink spectral efficiency, and the specific pilots used. However, in the best case for the pilots-based approach, the results shown for the feedback overhead comparison would still be valid, which indicated clearly the advantage of context-based feedback.

VI. Antenna Selection Use Case: Platooning

In order to evaluate the performance of the proposed antenna selection based on slow-variation parameters, we focus on a representative service to be addressed by eV2X, that is, vehicle platooning. In particular, we consider a simple use case in which the antenna selection is static, made at the beginning of the communication, and both the pilot-based antenna selection and the context-based antenna selection are assumed to provide the same decision. Concerning the different signaling overhead, the signaling would only be needed in this case at the beginning of the communication and, then, it does not have a significant impact on the performance. Note that our example does not need a dynamic antenna selection to work and hence there is no need to compare the two antenna selection approaches, whose performance would be the same.

We consider a scenario with multiple platoons, where the platooning service coexists with the transmission of Cooperative Awareness Messages (CAMs) from all the vehicles. Whereas CAMs are of broadcast nature, periodically generated by each VUE, and relevant to all the vehicles within a certain range from the message transmitter [24], the platoon service involves the periodical transmission of messages which are only relevant to the vehicle following each transmitter [25], as shown in Figure 13.

A. Proposed antenna selection in a platoon

Figure 14 shows an example of decision chart to implement context-based antenna selection for the transmission

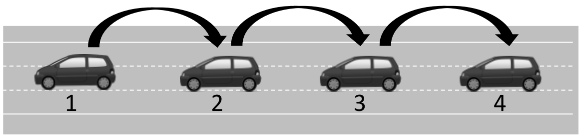

Fig. 13. Transmission of platoon messages in a platoon with 4 vehicles.

of CAM and platoon messages, as a particular case of the procedure introduced in Figure 2. We assume that, during the attachment or after a network request, the VUEs have already notified the BS (through the Multi-antennaCapability field) that they can use either roof or bumper antennas for communication. When the vehicles initiate the transmission, the Multi-antennaContextInformation field is checked and a first decision is made based on the service type. Since CAMs are relevant to all the vehicles within a certain range from the transmitter, the use of roof (R) antennas at the Tx and Rx (R-R combination) is selected as the most suitable option, provided that the road and radio network conditions (also inside the Multi-antennaCapability field) support this selection. For the platoon messages, which are transmitted from one vehicle to its follower, the preferred selection is to transmit from a back bumper antenna (B) to a front bumper (F) antenna. In case the bumpers are unavailable, the second option for platoon messages will be to use the R-R combination (default option in current systems). The decision chart includes the possible selection of a third antenna for those cases where neither the roof nor the bumpers are successfully selected. At the end of the procedure, the VUEs will be notified about the antenna selection through the extended sl-V2X-ConfigDedicated field inside an RRCConnectionReconfiguration message.

Generally speaking, a platooning use case may involve certain transmissions between a given vehicle and other vehicles apart from the nearest vehicle. However, the platoon messages of interest in this example are only those to be transmitted from one vehicle to its follower in just one hop. In practice, bumper antennas are highly susceptible to obstacles and easily blocked by surrounding vehicles in a dense traffic flow. Still, the characteristics of the platoon messages of interest can greatly benefit from the confined short-range communication offered by bumper antennas. Furthermore, the context information considered in the decision chart of Figure 14 would in practice dictate whether the use of bumper antennas is feasible, and recommend an alternative otherwise (e.g. rooftop antenna).

B. Proposed resource reuse with bumper antennas

In V2X sidelink communication, the pool of resources may be divided into a number of data subchannels, each one accompanied by a control channel overhead of 2 resource blocks. In this assessment, we assume that each CAM or platoon message is completely transmitted in one data subchannel in one subframe, and that there is a single V2X data subchannel that spans the whole channel bandwidth (except the 2 control resource blocks). Concerning the resource management, for each transmitter of CAM and each transmitter of platoon

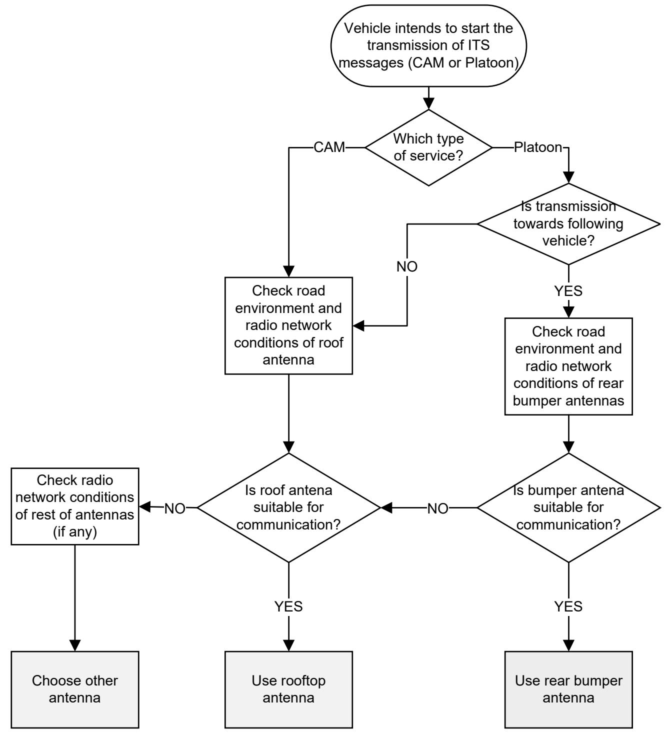

Fig. 14. Example of decision chart for antenna selection with two possible message types: CAM and platoon.

message, a set of resources are semi-persistently allocated by a central controller which knows the positions of all the VUEs of the simulated scenario (sidelink Mode 3). The policy applied by the controller is to maximize the distance among the VUEs that use the same resources. This objective is fulfilled by our allocation, at the same time that the maximum latency is respected thanks to a semi-persistent allocation period sufficiently small. More details can be found in [26].

Although the general assumption is to allocate different resources to the different transmitters in a platoon, a spatial reuse of resources among members of the same platoon is possible in some cases. For instance, the authors in [27] proposed a control system to adjust the spacing and speed in a platoon, which helps to efficiently select the maximum transmitted power to permit spatial reuse. As an alternative approach, we propose to enable spatial resource reuse in a platoon by exploiting antenna selection. The motivation behind is that, when the transmission of a platoon message is made from a back bumper antenna of the Tx to a front bumper antenna of the Rx, the transmission power received by other VUEs in the surroundings is reduced due to the blocking of signals by the vehicles, i.e. there is a power confinement that reduces the interference to others. In fact, it could be possible for two vehicles in the same platoon to send a platoon message through a back bumper antenna without interfering each other or, at least, with low interference. Under this assumption, we propose a resource allocation algorithm in which the same single resource is allocated to all the platoon message transmitters, thus providing a full spatial reuse of resources within the platoon, as illustrated in Figure 15. In the

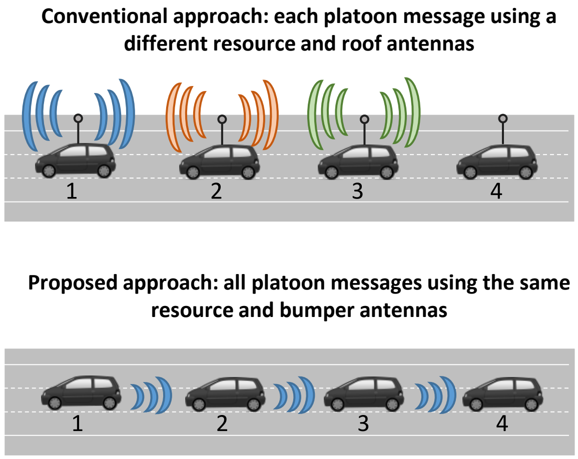

Fig. 15. Comparison between the conventional approach without resource reuse and the proposed resource reuse with bumper antennas.

TABLE I
SYSTEM PARAMETERS

Frequency	5.9 GHz
Bandwidth	10 MHz
VUE antenna gain	2 dBi
VUE cable loss	0.2 dB/m (2 m cable)
VUE implementation loss	5 dB
VUE noise figure	7 dB
VUE Tx power	23 dBm
Thermal noise	-174 dBm/Hz

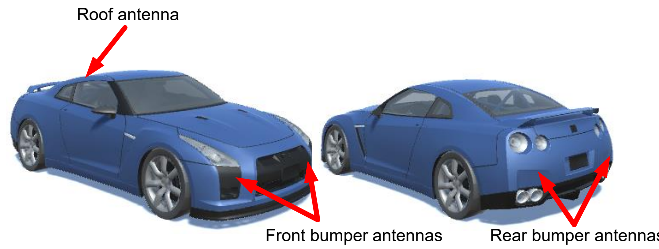

Fig. 16. Antenna positions in the considered multi-antenna vehicle.

following section, we evaluate if this reuse can improve the performance of the transmission of CAM or platoon messages.

C. Simulation setup

Performance results have been obtained with dynamic system level simulations performed on a C++ proprietary simulator with an implementation of LTE. This simulator was used in the framework of the WINNER+ project [28], which was one of the International Mobile Telecommunications-Advanced (IMT-Advanced) evaluation groups of the ITU-R, and more recently in the METIS-II project for the evaluation of the 5G system, e.g. in [29].

The simulation scenario and models used in this assessment are based on the framework presented in [26] with the exception of the channel modelling:

1) Scenario: The simulation scenario is a closed-circuit comprising a 5.2 km rectilinear segment of the German A9 highway in an area nearby Munich. The scenario also includes some intersecting fragments of the national road B471 in the northern part, and of Munich's outer ring road A99 in the southern part, together with all on- and off-ramps.

2) Message types: We consider two types of traffic linked to the two services of interest:

- CAM: their size is 300 bytes, are generated by each vehicle with a periodicity of 100 ms, and are relevant to all the vehicles within a range of 320 m from the message originator with a maximum end-to-end (E2E) delay of 100 ms as in [24].
- Platoon messages: their size is 450 bytes, considering a non-high density platooning they are sent with a periodicity of 100 ms as in [25], with a maximum E2E delay of 100 ms, and are relevant to the vehicle following their originator.

3) Mobility model: Simulation of Urban Mobility (SUMO) is used to generate the mobility traces for 600 cars of length 4.7 m. We consider 20 platoons of 10 cars each, with an inter-vehicle gap of 4 m. The A9 and A99 highway segments have from 3 to 5 lanes per direction (depending on the section) and a speed limit of 120 km/h. The B471 road has 2 lanes per direction and a speed limit of 70 km/h. The on-ramps and off-ramps have either 1 or 2 lanes. The resultant vehicle density is consistent with the assumptions for highway in [24]. The maximum driving speed is 100 km/h for platoons and 120 km/h for other cars.

4) System parameters: For the link between VUEs, we assumed a frequency of 5.9 GHz. Other parameters for the VUEs are summarized in Table I.

5) Channel model: We followed the approach presented in [8] to obtain the channel loss between each Tx antenna and each Rx antenna at 5.9 GHz. In that approach, the propagation of two rays is considered, and real shapes of cars are used to model in detail the shadowing produced by obstacles. Cars are assumed to have five antennas, two of them located on the front bumper (left and right), two of them located on the rear bumper (left and right) and the fifth located on the roof, as shown in Figure 16. These five antenna positions lead to 25 possible Tx-Rx antenna combinations, for which the channel loss has been pre-calculated and stored for a grid of positions. The effect of the small-scale fading is included in the channel model following the approach in [30], where a normally distributed random variable is added on top of the large-scale component. The standard deviation is 3.3 dB as in the open space environment in [30]. In this assessment, the small-scale component for the channels between different antennas is assumed to be independent. For each link, the small-scale component is exponentially time-correlated being the correlation between two samples dependent on the absolute speeds of both link ends. Specifically, the correlation factor between two samples with a time offset of Δt is $\rho = exp(-\Delta t/t_{c_{Tx}}) \cdot exp(-\Delta t/t_{c_{Rx}})$, where $t_{c_{Tx}}$ and $t_{c_{Rx}}$ are the coherence time values for the transmitter and receiver, respectively, calculated taking into account their absolute speeds.

D. Results

In order to evaluate the impact of antenna selection, we considered the transmission of CAMs and platoon messages through the sidelink, with each message transmission occupying the whole channel bandwidth. Note that, in all cases, VUEs will multiplex both services in time, meaning that a single vehicle cannot transmit a CAM and a platoon message in the same subframe.

We assessed a static antenna selection case based on the decision chart of Figure 14. The two relevant antenna setups resulting from the antenna selection are:

1) Baseline scheme: R-R combination for CAM, R-R combination for platoon.
2) Proposed scheme: R-R combination for CAM, B-F combination for platoon.

The first scheme is referred to as baseline scheme because the transmission and reception of messages using the roof antennas is the most common option in the literature.

For antenna selection setup 2), we further evaluated two alternatives of resource allocation: A) the conventional case, that is, assigning a different resource to each platoon message transmission, and B) our proposal for spatial resource reuse described in Section VI-B, where the same single resource is allocated to all the platoon message transmitters. Results were obtained only for the combination with right bumper antennas, which coincide with the ones using left bumper antennas in our scenario due to the car symmetry.

In addition, for the sake of comparison, we included as another baseline scheme a simple random antenna selection at both the Tx and Rx sides, as considered in [15].

The key performance indicator for this assessment is the Packet Reception Ratio (PRR). This metric measures the portion of intended receivers of a message that receive the message successfully. The average packet reception ratio for a number of packets N can be calculated as $\sum_n^N X_n / \sum_n^N Y_n$, where Y_n is the number of VUEs located in the range (a, b) from the transmitter of packet n, and X_n is the number of VUEs with successful reception among Y_n.

Figure 17 shows the Cumulative Distribution Function (CDF) of the PRR for CAM messages using the three considered configurations, where a PRR value has been obtained for each transmitting vehicle in each interval of one second of simulation for the range (0,320). Performance differences can be appreciated depending on the antenna choice for platoon messages. When the platoon messages are transmitted using the bumper antennas instead of the roof antennas, the CAM PRR is enhanced due to the confinement of interference coming from platoon transmissions. When the reuse of platoon message resources is applied, the performance CAM PRR is further enhanced. The random selection scheme is clearly outperformed by the rest of methods. Low PRR values are observed for random selection at distances lower than 60 meters, which are due to significant car body obstructions that occur for some antenna combinations at those short distances, as shown in [8].

Complementary results are shown in Figure 18, which shows the evolution of CAM PRR with the distance. To form the PRR versus distance curves we obtained an average PRR value for each range of values between $a = i \times 20$ meters and $b = (i+1) \times 20$ meters with $i \in \{0, 25\}$, considering in the average all the packets transmitted in the scenario during the whole simulation.

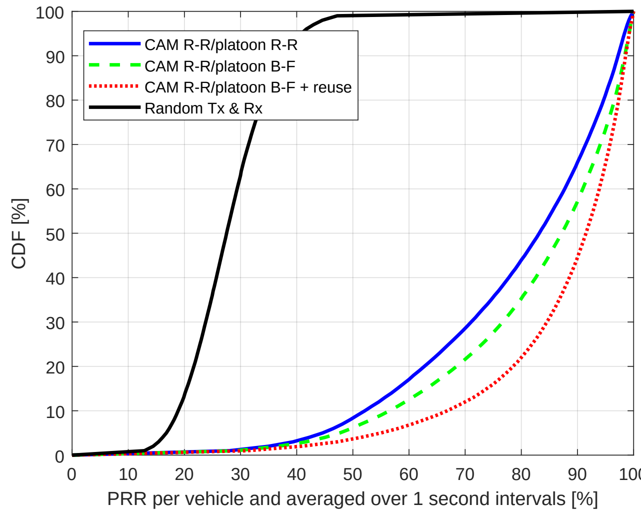

Fig. 17. CDF of PRR for CAM messages.

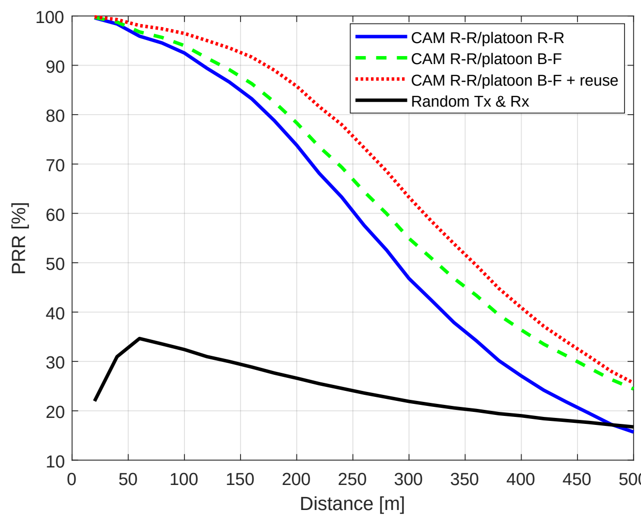

Fig. 18. Evolution of PRR with distance for CAM messages.

Figure 19 shows the CDF of PRR of platoon messages for the considered configurations, where a PRR value has been obtained for each transmitting vehicle in each interval of one second of simulation. As it can be seen, the PRR is nearly 100% for this kind of messages in the three selected configurations with a static combination of antennas, meaning that using B-F antennas instead of R-R does not degrade the performance of platoon messages. Therefore, the use of B-F antennas with or without reuse of resources within the platoon is clearly advantageous since it provides a performance improvement for CAMs without any penalty. Regarding the random selection of antenna combinations, the performance of

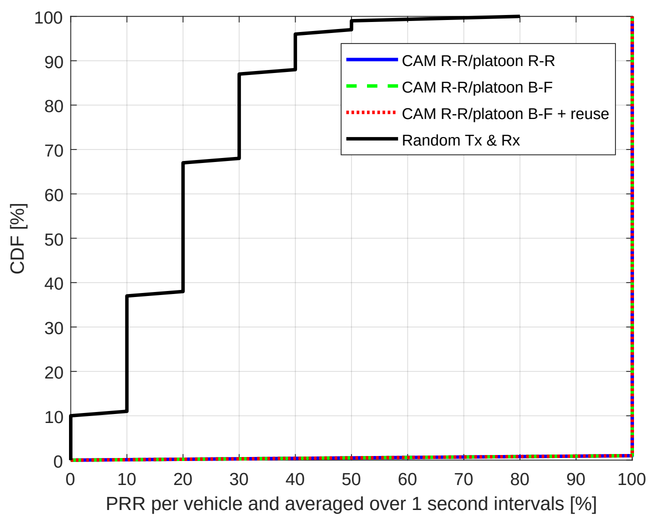

Fig. 19. CDF of PRR for platoon messages.

this baseline is heavily degraded with respect to the previous configurations, as in the CAM transmission. In fact, almost all the vehicles present a PRR lower than 50%.

VII. Conclusion

This work aims at enhancing V2X sidelink communications towards 5G. To this purpose, three keypoints are approached: i) proposing the use of antenna selection in multi-antenna vehicles; ii) considering an antenna selection scheme based on slow-variation parameters to overcome the problems of acquiring small-scale channel information in high-mobility scenarios; and iii) proposing new signaling based on 4G RRC and RRM procedures to enable antenna selection in 5G networks for sidelink communication.

First, to assess the feasibility of the proposed signaling to perform context-based antenna selection, we conducted an analysis of the required signaling overhead for antenna selection in comparison to a reference-signals-based approach. The analysis showed that reporting basic and detailed context feedback is feasible even for a high number of vehicles, while the scheme based on reference signals may face severe problems to support a high number of vehicles.

Then, to show the usefulness of antenna selection for V2X sidelink communications, and, particularly, that of context-based antenna selection, we focused on the performance of a simple context-based selection for a specific used case, namely, vehicle platooning. In this use case, each vehicle transmitted two type of messages: CAMs, to be broadcasted to all the vehicles close to the transmitter, and a specific type of platoon messages intended only for the vehicle following each transmitter. Considering the availability of antennas at the vehicle roof and bumpers, we defined a simple antenna selection algorithm based on context information such as the type of service (CAM or platoon) and its requirements, and the type and location of the available antennas. The outcome of the antenna selection decision was to select roof antennas for CAM messages and back/front bumper antennas for platoon messages. Results showed that this simple context-based antenna selection provides significantly better results than the baseline where all messages are exchanged through roof antennas. It was observed that, for platoon messages, the transmitted power through bumper antennas is more spatially confined, thus reducing the interference to non-intended receivers. Furthermore, the selection of bumper antennas allows the vehicles to transmit CAMs and platoon messages simultaneously over the same resources. As a result, this approach is not detrimental for platoon messages, while it improves the CAMs reception performance due to two effects: the reduction of the interference from platoon messages transmissions, and the increase of the resources available for CAM transmission.

Future work will assess the performance of a dynamic antenna selection scheme, where the signaling overhead for antenna selection should be included within the evaluation for different scenarios and values of the feedback reporting period.

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