An Optimal LTE-V2I-Based Cooperative Communication Scheme for Vehicular Networks

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***Abstract*—In this paper, an optimized cooperative communication scheme based on the recently presented LTE-V2X is introduced. LTE-V2X is the newly proposed technology by 3GPP in its Release 14 in order to obtain a feasible communication scheme between vehicles and infrastructures. This paper investigates the case of centralized network architecture, where the eNodeBs are used as information centers in order to optimize the scheduling scheme by means of clustering the vehicles in their coverage range. The proposed cooperative scheme is based on the shared messages between vehicles using a semi-persistent scheduling (SPS) which fulfills the rigid requirements, i.e., delay and reliability, faced in vehicular communications. In this paper, an enhancement of the SPS is defined using the information gathered by the network infrastructures in order to mitigate the interference. In addition, due to the high mobility of the vehicles, a predictive control model is implemented to estimate the vehicles trajectory, hence, improving the scheduling scheme performance. The aforementioned methods are simulated in a realistic scenario, using a traffic simulator, and compared with the standard LTE-V2X implementation as well as other methods proposed in the literature.**

***Keywords*—vehicular networks, LTE-V2X, cooperative communication, semi-persistent scheduling.**

I. Introduction

Vehicular networks are considered to be the most promising technology to provide connectivity among vehicles. This new paradigm of vehicles is denominated as *connected cars* [1] due to their on-board equipments, which allow them to communicate their status with other vehicles in the network and sense their surrounding environment. The on-board equipments can be classified according to their purpose, i.e., short range sensors are used to acquire the local environment, while the communication modules are used to share information with other vehicles or infrastructures. The final goal is to obtain a full automation level as stated by the SAE International Standard [2] where without any human interaction the vehicles can adjust their behavior automatically to the environment changes. The main characteristics of vehicular communications are the periodicity of the Cooperative Awareness Messages (CAM), usually every 0.1 seconds, and the relatively short messages required to share the sensed knowledge between network members. Due to these characteristics, the main concepts for vehicular communications are similar to the ones of device-to-device (D2D) [3] used in smart meters or sensor networks, where the nodes continuously share their status and information about the environment.

In order to overcome the challenging particularities of vehicular networks, i.e., high density of nodes, fast mobility and highly variable scenario, new communication schemes are proposed to fulfill the Quality of Service (QoS) requirements, namely, IEEE 802.11p and LTE-V2X. The first [4] has been proposed as a candidate for Intelligent Transport Systems (ITS) for the last 10 years. Due to its simplicity and distributed media access control mechanism, this standard is suitable for vehicular network applications. However, by means of the highly dynamic environment of vehicular networks, it does not fulfill the ITS requirements in terms of reliability [5]. The latter, LTE-V2X [6], has been recently proposed as a new scheme extending the services of LTE for vehicular communications. LTE-V2X network is divided into three different layers: LTE-V2I focusing on communications with infrastructures, LTE-V2P for pedestrians and LTE-V2V for inter-vehicular communications. One of the advantages of the LTE scheme is that it offers the possibility of connecting vehicles by reusing the already deployed infrastructures, which helps to reduce the initial deployment cost.

One question remains to be posed: which communication scheme is more suitable for vehicular communications? As discussed in [7], the LTE-V2X technology is more suitable for dense vehicles deployment due to the non-guaranteed QoS in 802.11p. In particular for 802.11p, as the number of nodes increases, the maximum latency of communications cannot be guaranteed. Nonetheless, the ad-hoc nature of the communication scheme allows the nodes to communicate immediately without any additional infrastructure. In contrast, the LTE-V2X protocol is infrastructure-based, i.e., the network is centralized based on Evolved Nodes B (eNBs). Although the requirement of an infrastructure can be considered as a drawback, it still provides practical advantages, i.e., the communication range of the infrastructures is higher and the eNBs play an important role as smart base stations. Moreover, the required infrastructure, or at least most of it, is already deployed, making the cost of deployment relatively low.

In order to achieve the vision of the automotive industry regarding automated driving and road safety services [8], not only the aforementioned communication protocols are important, but the coordination schemes between the vehicles play a major role. The coordination schemes are supported by two main points: sensing the local environment and the communication between vehicles and infrastructures [9]. For this purpose, an explicit coordination scheme, i.e., based on the exchanged messages, is used. This coordination scheme has a hybrid nature [10], i.e., it gathers information from the long-range bidirectional connection between vehicles and eNBs along with the information from the short-range communication link between vehicles. Hence, obtaining global knowledge is possible to predict the future condition of the network and react accordingly [11]. The remainder of this paper is organized as follows. Section II introduces the network architecture. Section III shows the main contributions of this paper where different network optimization schemes are presented. In Section IV, a realistic simulation is performed in order to show the improvements in the network using the concepts from Section IV, followed by the conclusions in Section V.

II. System Model

Consider an urban scenario where $n \in \{1, \ldots, N\}$ eNodeBs are deployed and $v_n \in \{1_n, \ldots, V_n\}$ vehicles are in range of the previously defined eNodeBs, we assume each vehicle v_n to be connected simultaneously only to one eNodeB n as shown in Fig. 1. The vehicles are grouped in $k \in \{1, \ldots, K\}$ clusters using the similarity metric, explained in detail in Section III.B. This is a standard scenario for LTE-V-cell which is the denomination for the LTE centralized architecture designed for vehicular networks.

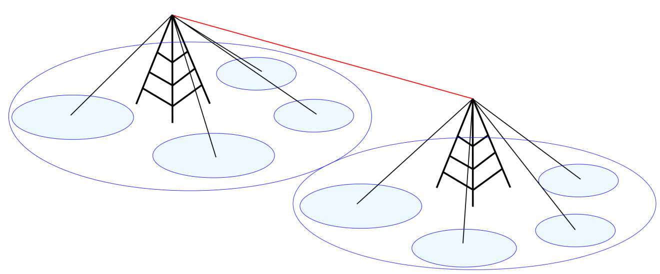

Fig. 1: General Network Framework

This centralized architecture is based on a bidirectional communication between the vehicles and the eNodeBs while at the same time the vehicles interact with each other using the Proximitiy Service (ProSe) sidelink. In the proposed centralized architecture, the eNodeB plays a double role, where it works as a radio resource scheduler for each cluster, and spreads the obtained information to the rest of eNodeBs extending the electronic horizon [12]. In this paper, the focus lies on optimizing a centralized architecture scheme, without considering the out-of-coverage networks. The infrastructure-based network has the advantage of extending the range of perception of the vehicles, since in an urban scenario the majority of V2V links are predominantly non-line-of-sight due to the surrounding obstacles. Moreover, in a highly dense scenario, it is necessary to have an entity to address the network optimization duty. Since we try to maximize the reliability of the link, the signal-to-interference-rate (SINR) for each link between two vehicles v_1^k and v_2^k belonging to the same cluster k and connected to the same eNodeB n is as follows

$$\gamma_{v^k_{n,1},v^k_{n,2}}(t) = \frac{P_{v^k_{n,1},v^k_{n,2}} G_{v^k_{n,1},v^k_{n,2}}}{\sum_{j\in U} P_{n,j} G_{n,j} + \sum_{i \in V} P_{T_{n,i}} G_{n,i} I_{n,i} + \mathcal{N}} \quad (1)$$

where $P_{v^k_{n,1},v^k_{n,2}}$ is the transmitted power and $G_{v^k_{n,1},v^k_{n,2}}$ is the signal gain. The first term in the denominator defines the interference created by collisions, i.e., two vehicles using the same resource block while the second term is the in-band emission interference (IBEI) produced by the leakage between sub-bands modeled as in [13], [14] and $\mathcal{N}$ is the noise power.

One of the main requirements for vehicular communications is the high reliability of 99.999%, therefore, our goal is to reduce the number of collisions and the impact of the IBE interference. In order to achieve both, two different methods are proposed and explained in detail in Section III.

III. Optimal Cooperative Communication Scheme

A. Semi-Persistent Scheduling

Due to the peculiarities and limitations of vehicular networks, a semi-persistent scheduling (SPS), combining a dynamic and persistent scheduling is proposed. SPS is particularly well-suited for vehicular communications due to the periodic nature of the exchanged messages and the required low-latency and reliability. The principle of SPS is based on the following concept: the initial transmissions are persistently scheduled while the retransmissions and sporadic messages are scheduled dynamically. Each vehicle sends an uplink message to the eNodeB once it enters its coverage. Upon receiving the message, the eNB allocates part of the TTI-RU (Transmission Time Interval-Resource Unit) spectrum for the vehicle. These persistent allocated resources remain associated with the vehicle until it abandons the coverage area of the eNB, which are represented by the colored pieces in Fig.2. Each resource unit (RU) lasts for 10 ms and is divided in TTIs of 1 ms, which consists of a signaling access (SA) part and data. Following the standard, the resource units are periodically sent every T = 100 ms.

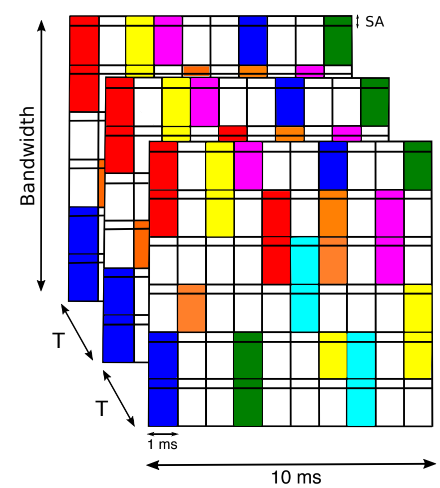

Fig. 2: Semi-Persistent-Scheduling Structure

As shown in Eq.1, the first term in the denominator models the interference created by the collisions of two vehicles using the same TTI-RU. However, using the SPS, this term can be neglected since each vehicle has previously allocated its resources. In addition to the persistently allocated resources, the retransmission needs to be rescheduled in a dynamic way. Therefore, the spectrum cannot be fully occupied only with the persistent resources. In order to model the required spectrum for retransmissions, a stochastic variable $\mathcal{X}(d)$ in function of the distance between each pair of vehicles is used, since the higher the distance is, most likely will the transmission be as well.

B. Clustering Scheme

The second term to optimize is the interference produced by the IBE. This interference is potentially an issue for the communication performance, since its value can be up to 30 dBs [15], if the variation in received power between adjacent TTI-RUs is high. Therefore, a clustering scheme where the vehicles are grouped in terms of their similar position is investigated in order to mitigate the interference.
The clustering scheme proposed here is based on our previous work [16], where the vehicles were grouped using spectral clustering techniques. Nevertheless, the infrastructure is used in this study as a scheduler, making unnecessary the role of a head-cluster. This concept of clustering is an analog to the formation of platoons, since not only the position is used for the similarity metric, but the direction and speed of vehicle are also taken in consideration. In comparison with our previous work, the proposed approach has the advantage that the infrastructure has a higher range, which allows gathering information from all the network elements, and as a consequence, the cooperative scheme can be further optimized. The clusters are formed following a similarity metric as follows:

$$S_{i,j} = exp(-\frac{\|\vec{y}_i - \vec{y}_j\|^2}{2\sigma^2}) \;\; \forall i \neq j \text{ and } S_{i,i} = 0, \tag{2}$$

where vector $\vec{y}$ contains the position, direction and speed of each vehicle i and σ is the parameter that controls the similarity threshold between the neighbor vehicles. The advantage of using three parameters, namely, position, speed and heading, is that the vehicles stay longer in the same cluster, making the SPS more efficient, since the persistently scheduled TTI-RU do not change. Adding the clustering scheme increases the complexity managing the network, however, since an infrastructure-based network is considered, the eNodeB has enough intelligence to optimally handle the resources. In addition, classifying the vehicles in platoons facilitates allocating the resources in an optimal manner, since the number of elements to consider is smaller.

C. Infrastructure-based Prediction Scheme

Traditionally, the SPS continues to allocate resources to a vehicle until it stays inactive for a determined period of time. However, this mechanism is not optimal, specially on a fast changing scenario, where the vehicle frequently changes its position, moving to a different cluster or cell. Hence, using the information gathered by the infrastructure, it is possible to predict the vehicles next position in order to allocate the resources without waiting for inactive periods, based on a trajectory prediction using the physical limitations of the environment along with the vehicles state. This approach works not only in the case of a vehicle moving to a different cell, and hence, connecting to another eNB, but also in the case of merging or leaving a platoon under the coverage of the same eNodeB. The environment information, i.e., the road architecture and traffic information, is used in order to predict the next position of each vehicle. A similar approach has been used in [17], where the authors focused on the density of vehicles without considering the microscopic nature of the traffic, i.e., individual state of each vehicle. An example of a complex scenario where the prediction scenario provides notorious improvement is depicted in Fig. 3.

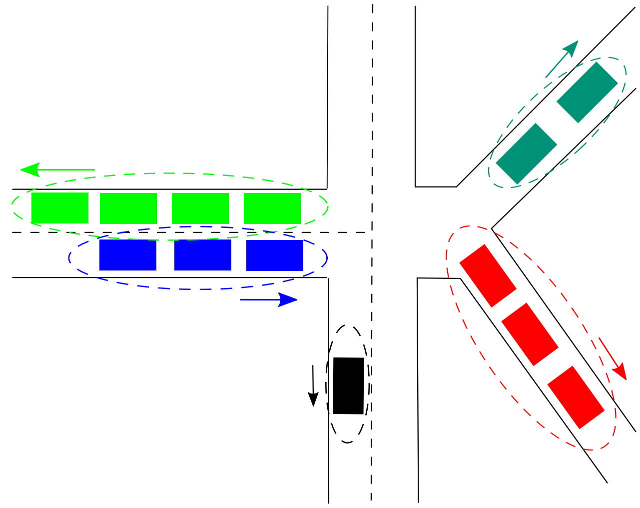

Fig. 3: Complex Prediction Scenario

In this proposed scenario, a crossing is displayed with different intersections and possible directions for each vehicle. Moreover, different platoons are created using the clustering procedure shown in Section III-B. In order to create an accurate prediction, the eNodeB requires the following information:

- updated road information, i.e., connections between roads and traffic flow direction. It is also needed to periodically update this information to have the best prediction possible.
- information of each vehicle and their associated cluster: $Y^k_{n,i}(t) := \{p^k_{n,i}(t), h^k_{n,i}(t), v^k_{n,i}(t)\}$.
- communication link between the different eNodeBs in the area. The interconnection of the eNodeBs has a double goal: first, to obtain a higher range for prediction and second, to add redundancy to the network.

Using the information of the vehicles i and $i+1$, where $i+1$ is the preceding car, the position prediction is done as follows

$$p^k_{n,i}(t_1) = p^k_{n,i}(t_0) + v^k_{n,i}(t_0) \cdot \Delta t \cdot h^k_{n,i}(t_0) \tag{3}$$
$$v^k_{n,i}(t_1) = v^k_{n,i+1}(t_0) \tag{4}$$
$$h^k_{n,i}(t_1) = h^k_{n,i+1}(t_0) \tag{5}$$

where $\Delta t = t_1 - t_0$ is the interval of time between updates. Moreover, in order to predict the position of the first vehicle in the platoon, i.e., the one with no preceding car, the updated road information is used to obtain the potential valid positions. Hence, with this information collected in the eNodeB, it is possible to predict the cluster members and their respective eNodeB connection.

IV. Simulation

In this section, a realistic simulation using real-traffic data, from the TapasCologne project [18], is used to show the improvements obtained by means of the proposed scheme. In order to simulate the SINR using the same formulation as in

Eq.1, the IBEI is modeled as follows:

$$
\begin{aligned}
I = \max\{&-25 - 10log_{10}\frac{N_{RB}}{L_{CRB}} - \mathcal{X}, \\
&20log_{10}EVM - 3 - \frac{5|\Delta_{RB} - 1|}{L_{CRB}} - \mathcal{W}, \\
&\frac{-57dBm}{180kHz} - P_{RB} - \mathcal{X}\},
\end{aligned} \tag{6}
$$

where N_{RB} is the number of RUs used for the transmission bandwidth and L_{CB} is the occupied bandwidth by the transmitted signal. In addition, P_{RB} is the transmitted power over the L_{CB} in dBm. The values of $\mathcal{X}$ and $\mathcal{W}$ are provided by the LTE standard [19]. The additional parameters used for the simulation problem are presented in Table I.

TABLE I: Simulation Parameters

Parameter	Value
Bandwidth	10 MHz
Frequency	2.4 GHz
Transmission Power	23 dBm
Antenna Gain	3 dB
Channel model	Okumura-Hata
N_{RB}	50
L_{RB}	2

A. Results

1) Optimal SPS Perfomance: the simulation results, displayed in Fig. 4, compare three different implementations in terms of SINR: the one used by LTE-V2X Release 14 standard, where the vehicles are randomly allocated in the persistent slots, the orthogonal scheme proposed in [20], where the vehicles are classified in different sub-pools depending on their orthogonal direction, i.e., horizontal or vertical, and the scheme proposed in this paper. Moreover, the three schemes are implemented using the non-SPS and the SPS in order to see the enhancement obtained by means of the interference mitigation.

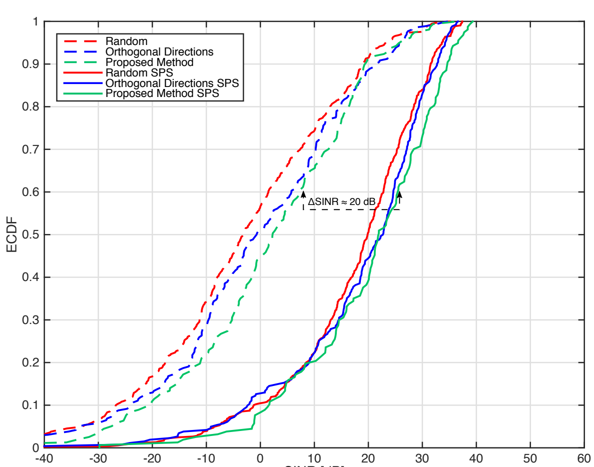

Fig. 4: SINR comparison of the three methods with and without SPS implementation.

The results displayed in Fig. 4 show an improvement of approximately 20 dB between the schemes using the SPS and the ones without it. This improvement is due to the reduction of collisions obtained by the persistent scheduling, first term in the denominator in Eq. 1. Moreover, both the orthogonal and the proposed method in this paper outperform the random scheme proposed by the standard. This enhancement is due to the clustering of vehicles in order to reduce the interference. Regarding the comparison of our method with the existing literature, it improves the already known methods achieving a higher interference mitigation obtained by the vehicle clustering. The main enhancement is based on the IBE reduction, second term of the denominator in Eq. 1, since the spectral clustering creates cluster where the difference between the received power of all the vehicles is minimal. Furthermore, the clustering scheme is based on the similarity matrix and not solely applied on the orthogonal directions, making it more suitable for scenarios where vehicles do not travel in only two directions.

2) Optimal Prediction Scheme: in order to show the estimation accuracy of the prediction scheme described in Section. III-C, the simulation results for different update periods Δt are displayed in Fig. 5.

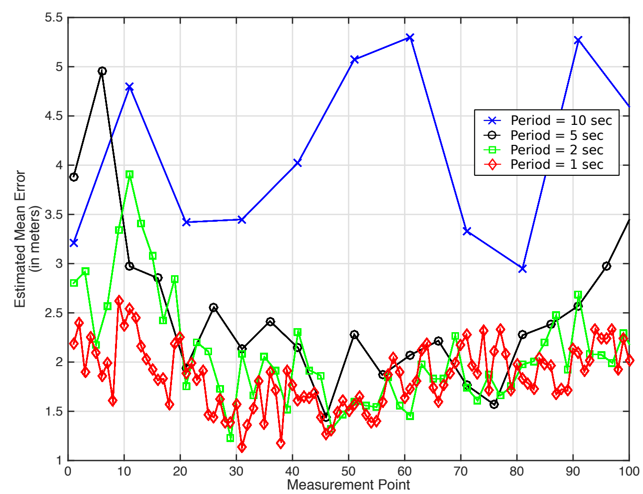

Fig. 5: Estimated Prediction Accuracy for each Update Period.

The results present the estimated mean error for all the vehicles under the coverage of a single eNodeB. The overall accuracy fluctuates in the range of 1 up to 5 meters in the worst case of an update time, $\Delta t = 10$ seconds. It can be observed in Fig. 5 that the schemes with a shorter update period, $\Delta t = \{1, 2, 5\}$, have a similar behavior with an estimated error of 2 meters. However, in the case of $\Delta t = 10$ seconds, the behavior is visibly worse due to the higher deviation in the predicted values. This higher error is a consequence of the longer update time used to adapt the prediction, which can not adapt itself as fast as the movement of the vehicles. The results shown in Table. II, display that the predictive scheme works arguably well under the assumption of having all the required information.

TABLE II: Estimated Mean Values for each Update Period

Parameter	Value [m]
$\hat{\tau}_{10}$	4.1232
$\hat{\tau}_{5}$	2.5157
$\hat{\tau}_{2}$	2.0872
$\hat{\tau}_{1}$	1.8530

Moreover, it can be observed that having an update time, $\Delta t = 5$ sec, does not degrade the prediction results, as it contributes positively to reduce the load between vehicles and infrastructure, specially in highly dense scenarios. Our approach adds more complexity to the network, in comparison with the standard LTE-V2X scheme, due to the clustering and prediction schemes. However, having the division of the radio spectrum in several sub-pools, i.e., for the different clusters, our approach is more suitable for fast changing scenarios.

V. Conclusion and Future Work

An enhancement in the proposed LTE-V2X standard is presented in this paper. Using the infrastructure as a scheduler for the SPS, the vehicles are classified in different clusters using a similarity metric which helps to mitigate the interference. Moreover, due to the large communication range of the infrastructures, a predictive scheme is implemented in order to obtain the future positions of the vehicles, which helps to optimize the SPS since the persistent slots allocated do not need to be recalculated as frequently. The simulations results show an improvement due to the use of SPS, and an even further enhancement due to the use of the proposed clustering scheme in order to mitigate interferences. Furthermore, the prediction scheme helps to reduce the network load, since the spectrum is persistently allocated using the vehicle position estimation. In this study, we only assume the exchange of CAM messages, where safety is the main application. However, following studies will be directed toward allocating more resources to the higher quality channel users, in order to enable the use of infotainment or high-quality video applications.

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