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Optimizing the Resource Allocation of Periodic Messages With Different Sizes in LTE-V2V

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ABSTRACT Recently, 3GPP has added new features to long term evolution (LTE) that allow vehicles to communicate directly with each other and with surrounding objects. These short-range communications will play a key role in the so-called cellular vehicle-to-anything (C-V2X). As a particular service, which will be the basis of most applications for automated and connected cars, each vehicle will periodically broadcast information on its identity, status, and movements through short-range vehicle-to-vehicle (V2V) communications. Given the importance of this service, great attention has been given to the associated resource allocation procedures and the number of vehicles that can be simultaneously communicating in the network. However, little attention has been paid to handling messages of different sizes, which is actually foreseen in practice in order to transmit static information with a reduced periodicity. With this in mind, we evaluate the number of vehicles that can be allocated when parameters are optimized for messages of different sizes. This objective is pursued taking into account the numerous constraints imposed by the standard, through the formalization and solution of a combinatorial optimization problem. Example results, based on 3GPP indications, show that, with respect to the optimization of the allocation based on the larger packets, it is possible to obtain an increase that varies between 10% and 30%, depending on the conditions, with peaks above 150% in specific cases.

INDEX TERMS C-V2X, connected vehicles, cooperative awareness, vehicular and wireless technologies, wireless networks.

I. INTRODUCTION

Connected and automated cars will soon be part of everyday life, completely changing the way transportation is designed [1]–[9]. Various standardization groups have been working for years on specifications that define all aspects of connected vehicles, from the applications down to the networking issues and wireless signals. The main examples are represented by the American pillar often referred to as dedicated short range communication (DSRC), which includes standards from SAE and IEEE all based on IEEE 802.11p, and the European C-ITS, which is mostly defined by ETSI and has ITS-G5 as the main short-range technology (substantially equal to IEEE 802.11p) [10], [11].

In this scenario, a few years ago 3GPP begun to work on new features to create a so-called cellular vehicle-to-anything (C-V2X) technology as a dedicated part of cellular systems [12]–[14]. As a first milestone, Release 14 of long term evolution (LTE) includes specific modifications that allow direct short-range communications between vehicles and surrounding objects, i.e., LTE-V2X. As a subclass, communications between vehicles are called LTE-vehicle-to-vehicle (LTE-V2V). Rather than being independent solutions for the vehicular scenario, C-V2X in general, and LTE-V2V in particular, are designed to be included as lower layers within the already mentioned protocol stacks and to provide both long and short-range connectivity with one technology and a single chipset.

As a basis for most applications, wireless technologies are designed to support the cooperative awareness service, which consists of broadcasting periodic messages, hereafter called beacons, from each vehicle to inform the neighborhood about its identity, status, and movements [15], [16].[1] This service is so relevant that the evolution of cellular systems towards

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[1]What we denote here as beacons are defined as cooperative awareness messages (CAMs) by ETSI [17] or as a special case of basic safety messages (BSMs) by SAE [18].

5G and beyond is planned to maintain its support through LTE-V2X as a basis for guaranteeing back-compatibility for safety purposes.

A frequent assumption in the literature is that all the transmitted beacons have the same size. However, it is worth noting that not all data is equally variable over time, so the use of complete messages could be less frequent and alternated with the transmission of smaller beacons, containing only volatile data such as position and speed. The adoption of messages of different sizes is indeed suggested, for example, by 3GPP in [19]. This suggestion is actually included, without specific details, in several related works, such as [20]–[22]. This observation has virtually no impact on a technology like IEEE 802.11p, which does not have a structured organization of radio resources, but becomes critical when resources are of a given granularity as in LTE, especially if a periodic allocation is foreseen. What is optimal for one size, may not be optimal for the other and a resource allocation performed considering a specific size could lead to an inefficient use of resources in the presence of beacons with different sizes [21].

A relevant observation is that the related work that deals with resource management, either considering messages of single or different sizes, does not pay particular attention to the system settings; some values are assumed, without particular details about their choice. Differently, here we focus in particular on the optimization of the allocation parameters in order to maximize the number of vehicles that can be allocated simultaneously, leaving the design of resource allocation algorithms to the related work. More precisely, the contribution of this paper can be summarized as follows.

- As the main output, we derive the optimal LTE-V2V settings when it is necessary to allocate periodic messages of two different sizes, formalizing and solving a combinatorial optimization problem that considers all the constraints imposed by the standards and maximizes the number of vehicles that can be simultaneously allocated;
- As an added value, we derive the optimal settings of LTE-V2V also under the hypothesis of messages of the same size, which is also used as a benchmark;
- Example results are finally shown assuming that the quality of service requirement is given in terms of coverage and deriving the corresponding settings at physical (PHY) and medium access control (MAC) layers. The results are reported both in terms of the maximum number of vehicles, given the target coverage, and of the trade-off between range and density of vehicles.

The rest of the paper is organized as follows. In Section II, a brief overview of related work is given. In Section III, the basics of LTE-V2V are provided and the main constraints for resource allocation are detailed. In Section IV, the optimization problems, both with a single message size and with two different sizes, are formalized and the algorithms are provided for their solution. Finally, example results are shown in Section V and conclusions in Section VI.

II. RELATED WORK

In recent years, a growing number of research groups have begun to focus on what appears to be a key aspect of C-V2X, which is the allocation of the orthogonal, but limited, resources. Most activities have specifically addressed the design of algorithms aiming to maximize the spatial reuse, identifying and allocating resources with particular attention to received and provided interference. Depending on the entity responsible for the allocation, two modes are defined by 3GPP: Mode 3, where the task is performed by the network, and Mode 4, where each vehicle selects autonomously, in a fully distributed way [23]. Solutions have been thus proposed, mainly with reference to the cooperative awareness service, focusing on both Mode 3, e.g., [24], [25], and Mode 4, e.g., [21], [26].

In most cases, as suggested by 3GPP in [19], periodic messages of different sizes are assumed. To manage this hypothesis, two approaches are possible and they can both be found in the literature. The first approach is to optimize the system by focusing on the larger messages [27], [28]; the smaller packets will occupy the same resources, adopting a more reliable modulation and coding scheme (MCS). With this approach, optimization is simpler, but the use of the spectrum is clearly not maximized. A different approach is to allocate fewer resources to the smaller packets, as proposed in [20]–[22]. With this approach, an increase in terms of supported vehicles is possible, but it requires careful design of the protocols, otherwise inefficiencies may occur (e.g., a reservation may be incorrect when the message size varies, as detailed in [21]).

In all cases, the starting point should be to optimize the network settings, respecting the constraints that are detailed in the following section. Instead, these settings are normally just provided, without any discussion about their derivation. Clearly, this aspect increases in complexity (and therefore in importance) when the messages are not all of the same size, which, as already written, is expected to be the rule and not the exception.

Differently to the related work, the objective here is to optimize the LTE-V2V settings when considering periodic messages of different size. This optimization is intended as a preliminary process, which maximizes the amount of resources that the given resource allocation algorithm is responsible for managing.

III. RESOURCES IN LTE-V2V

In LTE-V2V, single carrier frequency division multiple access (SC-FDMA) is adopted at the PHY and MAC layers. The time and frequency domains are thus organized into resources that are in principle orthogonal to each other.[2] The elementary resource for the transmission of packets is called resource block. It spans in the frequency domain over

[2]For the sake of precision, some residual interference is present when the resources share the time domain, due to non-linearities and non-ideal filters, which is called in-band emission (IBE). Minimizing the IBE between neighboring vehicles is beyond the scope of the present work. To be concise, in this paper we refer simply to vehicles that do not interfere with each other.

12 subcarriers, for a bandwidth of 180 kHz, and in the time domain over one slot, which lasts 0.5 ms. In LTE, two slots are grouped into one subframe and the pairs of resource blocks of one subframe (two slots, same bandwidth) are always allocated together and hereafter denoted as resource block pairs (RBPs).[3]

In LTE-V2V, the RBPs are grouped into subchannels to form the minimum granularity for the resource allocation: each message is sent using one or more subchannels in one subframe. Although various sizes are possible, as better specified later, a single value is selected by the network operator in a given area at a given time. Each message consists of a control part, called sidelink control information (SCI), and a data part, called transport block (TB). One SCI is always transmitted using $r_{\mathrm{SCI}} = 2$ RBPs, whereas the number of RBPs used for the TB, hereafter denoted by r_{TB}, depends on the size of the message.

There are two options for transmitting the SCI. The first option is an *adjacent* allocation, in which the SCI occupies the first two RBPs of the first allocated subchannel. In this case, the subchannel includes the RBPs for the control information. If the TB spans over more than one subchannel, it also occupies those RBPs that can be used for the SCIs. The set of sizes allowed by 3GPP for subchannels in the adjacent configuration is $\mathcal{R}_{\mathrm{A}} = \{5, 6, 10, 15, 20, 25, 50, 75, 100\}$ [29]. If, for example, the TB needs 12 RBPs and the subchannel size is $r_{\mathrm{s}} = 5$, it uses three subchannels, with the first that also carries the SCI.

The second option is a *non-adjacent* allocation, in which per each subchannel there are two RBPs reserved for the associated SCI, outside the subchannel itself and not adjacent to it in the frequency domain. If one TB occupies more than one subchannel, the RBPs corresponding to the SCIs of the additional subchannels remain unused. In this case, the subchannel size does not include the two RBPs for the SCI and the allowed sizes are $\mathcal{R}_{\mathrm{N}} = \{4, 5, 6, 8, 9, 10, 12, 15, 16, 18, 20, 30, 48, 72, 96\}$ [29]. If, for example, the TB needs 12 RBPs and the subchannel size is $r_{\mathrm{s}} = 4$, it completely uses three subchannels.

IV. MAXIMIZING THE NUMBER OF VEHICLES

In this section, given the number of RBPs required to transmit the TB, we formalize and solve the optimization problem of the maximization of the number of vehicles that can be allocated simultaneously without interfering with each other. In accordance with the related literature, we assume that all vehicles in a given area transmit messages of the same size and use the same MCS, so the number of RBPs per TB is known. This is reasonable, given that the messages are transmitted in broadcast and that the same quality of service (QoS) must be satisfied by all vehicles. This assumption does not prevent the configuration from being different according to the area considered and from changing over time due to large-scale variations (such as those of road traffic). The number of RBPs per TB can be obtained by the operator from the beacon sizes and the quality of service requirements; Section V also provides an example of how this task can be accomplished.

In the following, first we focus on the case where all the beacons have the same size (Section IV-B) and then explore the case of beacons with two different sizes (Section IV-C).

A. NOTATION

To improve readability, hereafter we use the letter r for those parameters that correspond to a given number of RBPs, s for subchannels, b for beacons, q for subframes. The main parameters are also listed in Table 1.

In the following, $\lceil\cdot\rceil$ denotes the ceiling function, $\lfloor\cdot\rfloor$ the floor function, $|a|$ is the absolute value of a, $\mathrm{sign}\,(a)$ is the sign of a, and $\mathrm{mod}\,(a, b)$ the reminder of the division between a and b (modulo operation). The cardinality of the generic set $\mathcal{X}$ is denoted by $\#\mathcal{X}$. $\mathbb{N}_0$ is the set of all positive integers, including zero.

TABLE 1. Notation used in section IV.

f_{b}	Beacon periodicity (in Hz)
t_{sf}	Duration of a subframe (always 1 ms)
Q	Number of subframes per beacon period
$\overline{r}$	Number of RBs per subframe
B_{TB}	Beacon size (in bytes)
$\hat{v}$	Maximum number of vehicles not interfering to each other
$\mathcal{R}_{\mathrm{A}}$	Set of possible subchannel sizes for the adjacent configuration
$\mathcal{R}_{\mathrm{N}}$	Set of possible subch. sizes for the non-adjacent configuration
$\mathcal{R}_{\mathrm{X}}$	Used to denote either $\mathcal{R}_{\mathrm{A}}$ or $\mathcal{R}_{\mathrm{N}}$
l_{S}	Number of consecutive smaller beacons
l_{L}	Number of consecutive larger beacons
q_1	Number of subframes of Type 1 in each group
q_2	Number of subframes of Type 2 in each group
Ω	Ratio between q_2 and q_1
$\overline{s}$	Number of subchannels per subframe
s_{b}	Number of subchannels per beacon
r_{s}	Number of RBPs per subchannel
r_{TB}	Number of RBPs occupied by the TB
r_{SCI}	Number of RBPs occupied by the SCI
r_{b}	Number of RBPs occupied by the beacon
b	Number of beacons allocated per subframe
ϵ	Number of unused RBPs
x_{S}	Parameter x referring to the smaller beacons
x_{L}	Parameter x referring to the larger beacons
x_1	Parameter x referring to the subframes of Type 1
x_2	Parameter x referring to the subframes of Type 2
x^*	Optimized value for the parameter x

B. MESSAGES OF THE SAME SIZE

Let us assume that all beacons have the same size B_{TB}, transmitted with the same periodicity f_{b}. Given some criteria, for example the one proposed in Section V, each message requires a given number of RBPs, r_{TB}, for its transmission.

To maximize the number of vehicles that do not interfere with each other, the subchannel size must be properly selected. Among all the possible subchannel sizes, the optimal value r_{s}^* for the detailed purpose can be obtained by minimizing the unused RBPs, i.e., those that do not carry either SCI or TB. Given the optimal subchannel size, each beacon is

[3] The fact that resource blocks are defined over one slot, but then allocated in pairs within a subframe, sometimes leads to ambiguities. In 3GPP and part of literature, actually, the reference is to the resource blocks looking only at the frequency domain. Trying to avoid any confusion, here we refer to RBPs.

transmitted in the minimum number of subchannels, hereafter denoted by s_b^*.

1) SUBCHANNELS

Depending on the adjacent/non-adjacent configuration, the number of RBPs to be allocated in the subchannels, denoted by r_b, might include the SCI or not. In formulas, we have

$$r_b = r_{TB} + \alpha \, r_{SCI} \tag{1}$$

where $\alpha \in \{0, 1\}$ is equal to 1 in the case of adjacent and 0 in the case of non-adjacent configuration.

Furthermore, the number of subchannels $\bar{s}(r_s)$ in each subframe for the given subchannel size r_s can be obtained as

$$\bar{s}(r_s) = \left\lfloor \frac{\bar{r}}{r_s + (1-\alpha)\, r_{SCI}} \right\rfloor . \tag{2}$$

Then, r_s^* and s_b^* can be obtained as the solution to the following optimization problem

$$\begin{aligned} &\underset{r_s}{\text{minimize}} \; \{\bar{r} - \lfloor \bar{s}(r_s)/s_b \rfloor \, r_b\} \\ &\text{subject to } r_s \in \mathcal{R}_X \\ &\qquad 0 < s_b \leq \bar{s}(r_s) \\ &\qquad s_b = \left\lceil \frac{r_b}{r_s} \right\rceil \end{aligned} \tag{3}$$

where $\mathcal{R}_X = \mathcal{R}_A$ in case of adjacent and $\mathcal{R}_X = \mathcal{R}_N$ in case of non-adjacent configuration.

It is worth noting that there might be more than one solution to the maximization problem and all are equivalent from the point of view of the use of resources. Hereafter, among the possible solutions, the one with the smallest r_s^* is selected, as it provides more granularity for any other services.

The given optimization problem has less than $\#\mathcal{R}_X$ possible combinations to check, which makes a full search not an issue. In addition: 1) since the subchannel size cannot exceed $\bar{r}$, the search can be limited to $\mathcal{R}_X^{\triangleleft} \triangleq \{x \in \mathcal{R}_X | x \leq \bar{r}\}$; and 2) if the set $\mathcal{R}_X$ is ordered from the smallest to the largest, the search can stop as soon as the result of the minimization is 0 (can not be further minimized) or $s_b = 1$ (larger subchannels necessarily lead to wasting more RBPs). Pseudo code of the solution is provided as Algorithm 1.

2) NUMBER OF VEHICLES

Once r_s^* and s_b^* are derived, the number of messages that can be allocated in the same subframe b^* is

$$b^* = \left\lfloor \frac{\bar{s}(r_s^*)}{s_b^*} \right\rfloor . \tag{4}$$

Denoting with t_{sf} the duration of a subframe and defining the number of subframes per beacon period as

$$Q \triangleq \frac{1/f_b}{t_{sf}} \tag{5}$$

it follows that the number of vehicles $\hat{v}$ that can be allocated simultaneously without interfering with each other results in

$$\hat{v} = Q \, b^* . \tag{6}$$

Algorithm 1 Messages of the Same Size

Given $\bar{r}$, r_b
Given the ordered set $\mathcal{R}_X$
Derive $\mathcal{R}_X^{\triangleleft}$ *(with elements in ascending order)*
Set $\epsilon_{min} = \bar{r}$, $r_s^* = 0$, $s_b^* = 0$
for all $r_s \in \mathcal{R}_X^{\triangleleft}$ **do**
    Set $\bar{s}(r_s)$ as in (2)
    $s_b = \lceil r_b / r_s \rceil$
    if $s_b > 0$ AND $s_b \leq \bar{s}(r_s)$ **then**
        $\epsilon = \bar{r} - \lfloor \bar{s}(r_s)/s_b \rfloor \, r_b$
        if $\epsilon < \epsilon_{min}$ **then**
            $\epsilon_{min} = \epsilon$, $r_s^* = r_s$, $s_b^* = s_b$
            if $\epsilon_{min} = 0$ OR $s_b^* = 1$ **then**
                Break *(the for-cycle on r_s)*
            end if
        end if
    end if
end for
Solution: r_s^*, s_b^*

3) EXAMPLE

Let us assume $\bar{r} = 50$ and an adjacent configuration. Suppose further that each vehicle transmits beacons, with a frequency $f_b = 10$ Hz that have a TB that requires $r_{TB} = 23$, which means $r_b = 25$ when the SCI is included. This example is represented in Fig. 1(a).

From Algorithm 1, it follows that the optimal solution is $r_s^* = 5$ and $s_b^* = 5$. With these settings, two beacons are allocated in each subframe, occupying five subchannels, each of five RBPs. Given the 100 ms periodicity, $\hat{v} = 200$ vehicles can be allocated simultaneously.

C. MESSAGES OF DIFFERENT SIZES

Let us now assume that messages are sent with the same periodicity f_b, but with two different sizes. More specifically, let us assume that l_S packets are sent with a smaller size B_{TB_S} and l_L with a larger size B_{TB_L}, where S and L are used to mark if a variable is related to the smaller or larger messages.

Under these hypothesis, the equations detailed in Section IV-B can not be used directly, because the subchannel size must be the same for both smaller and larger messages and the optimal value is not necessarily equal to the one obtained by assuming all messages of one of the two sizes.

1) SUBCHANNELS

Whereas (2) remains valid, the number of RBPs required to carry the TB is obtained by rewriting (1) as

$$r_{b_S} = r_{TB_S} + \alpha \, r_{SCI} \tag{7}$$

$$r_{b_L} = r_{TB_L} + \alpha \, r_{SCI} . \tag{8}$$

In general, to accommodate a different number of messages for each size, the subframes can not all be allocated in the same way (with exceptions). Instead, we need to consider groups of subframes that can allocate smaller

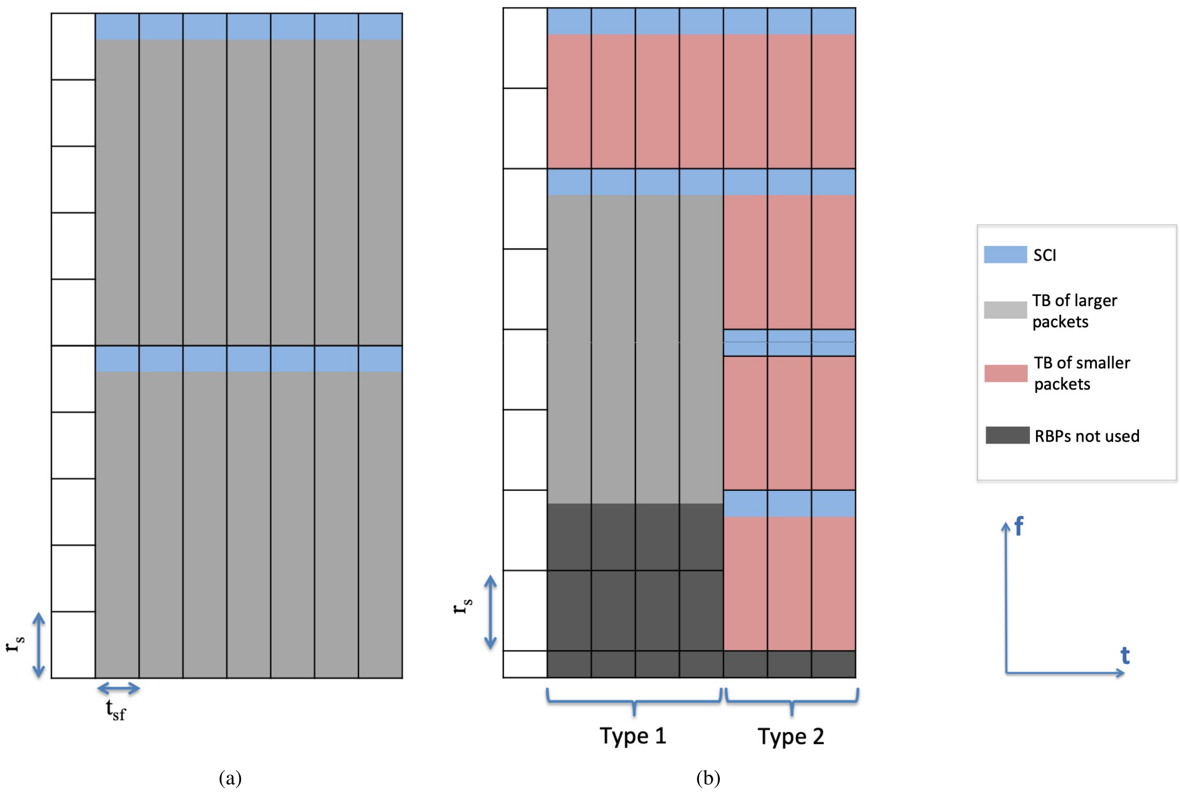

FIGURE 1. **Example of optimized allocation with one or two packet sizes, adopting an adjacent configuration. Each subframe includes 50 RBPs. The SCI occupies 2 RBPs, large packets occupy 23 RBPs, small packets occupy 10 RBPs. The proportion is 1 large packet every 4 small packets. The optimum channel size is 5 RBPs with one size and 6 RBPs with two sizes. (a) One size. (b) Two sizes.**

and larger beacons respecting the right proportion between l_S and l_L. Thus, suppose two types of subframes, hereafter called Type 1 and Type 2. Each of the former carries b_{1S} smaller and b_{1L} larger beacons, while each of the latter carries b_{2S} smaller and b_{2L} larger beacons. Without lack of generality, we can impose $b_{1L} \geq 1$ (the Type 1 carries at least one larger), $b_{2S} \geq 1$ (the Type 2 carries at least one smaller), $b_{2L} \leq b_{1L}$ (the number of larger messages decrease from Type 1 to Type 2), and $b_{2S} \geq b_{1S}$ (the number of smaller messages increase from Type 1 to Type 2).

With the aim of allocating the correct proportion of messages, each group of subframes is made up of a given number q_1 of subframes of Type 1 and a given number q_2 of subframes of Type 2, so that $\frac{(q_1\, b_{1S}+q_2\, b_{2S})}{(q_1\, b_{1L}+q_2\, b_{2L})} = \frac{l_S}{l_L}$.

In each beacon period, the subframes are thus divided into groups of q_1+q_2 elements. The remaining $\mathrm{mod}\,(Q, q_1+q_2)$ subframes are finally allocated assuming only larger beacons, considering that smaller messages can certainly be allocated in the resources designed for larger ones.

This leads to a new optimization problem, where r_s. b_{1S}, b_{1L}, b_{2S}, b_{2L}, q_1, q_2 must all be chosen in such a way that the unused RBPs are minimized.

Before formulating the optimization problem, let us define $\epsilon_1, \epsilon_2, \epsilon_3$ as three separate sources of waste, where ϵ_1 counts the number of unused RBPs in the subframes of Type 1, ϵ_2 in the subframes of Type 2, and ϵ_3 in those that remain out of the two groups.

The values of ϵ_1, ϵ_2, and ϵ_3 can be calculated as

$$\epsilon_1 = \bar{r} - \left(b_{1S}\, r_{b_S} + b_{1L}\, r_{b_L}\right) \tag{9}$$

$$\epsilon_2 = \bar{r} - \left(b_{2S}\, r_{b_S} + b_{2L}\, r_{b_L}\right) \tag{10}$$

$$\epsilon_3 = \left\{\bar{r} - \lfloor \bar{s}(r_s)/s_{b_S} \rfloor\, r_{b_S}\right\} \mathrm{mod}\,(Q, q_1+q_2)\,. \tag{11}$$

The optimization problem can be thus formulated as follows.

$$\begin{aligned}
&\underset{\substack{r_s, b_{1S}, b_{1L},\\ b_{2S}, b_{2L}, q_1, q_2}}{\text{minimize}} \quad (q_1\,\epsilon_1 + q_2\,\epsilon_2)\,\left\lfloor \frac{Q}{q_1+q_2} \right\rfloor + \epsilon_3 \\
&\text{subject to } r_s \in \mathcal{R}_X \\
&\qquad b_{1S}, b_{1L}, b_{2S}, b_{2L}, q_1, q_2 \in \mathbb{N}_0 \\
&\qquad 0 \leq b_{1S} \leq \lfloor \bar{s}(r_s)/s_{b_S} \rfloor \\
&\qquad 1 \leq b_{1L} \leq \lfloor \bar{s}(r_s)/s_{b_L} \rfloor \\
&\qquad 1 \leq b_{2S} \leq \lfloor \bar{s}(r_s)/s_{b_S} \rfloor \\
&\qquad 0 \leq b_{2L} \leq \lfloor \bar{s}(r_s)/s_{b_L} \rfloor \\
&\qquad q_1 \geq 1 \\
&\qquad q_2 \geq 0 \\
&\qquad q_1 + q_2 \leq Q \\
&\qquad \frac{(q_1\, b_{1S} + q_2\, b_{2S})}{(q_1\, b_{1L} + q_2\, b_{2L})} = \frac{l_S}{l_L} \\
&\qquad s_{b_S} = \left\lceil \frac{r_{b_S}}{r_s} \right\rceil \\
&\qquad s_{b_L} = \left\lceil \frac{r_{b_L}}{r_s} \right\rceil .
\end{aligned} \tag{12}$$

Reaching the solution of (12) through an exhaustive search appears possible, although time consuming. However, some considerations can sensibly reduce the complexity.

Focusing on the subframe of Type 1, once b_{1L} is set, the best value of b_{1S} is the one that maximally exploits the remaining RBPs, thus it can be forced to $b_{1S} = \left\lfloor \frac{\bar{s}(r_s) - b_{1L}\, s_{b_L}}{s_{b_S}} \right\rfloor$. Similarly, once b_{2L} is set, the best choice is $b_{2S} = \left\lfloor \frac{\bar{s}(r_s) - b_{2L}\, s_{b_L}}{s_{b_S}} \right\rfloor$. Furthermore, Type 2 subframes do not carry more larger packets than Type 1 subframes, so the search can be limited to $b_{2L} < b_{1L}$. Please note the strictly minor condition, since $b_{2L} = b_{1L}$ is equivalent to $q_2 = 0$ (all subframes are of Type 1) from the point of view of groups, with $q_2 = 0$ being preferable, since it guarantees an ϵ_3 equal to zero.

In addition, the condition involving l_S and l_L directly relates q_2 to q_1. Observing the related equation, it can be noted that, in principle, $q_1 = |l_L b_{2S} - l_S b_{2L}|$ and $q_2 = (l_S b_{1L} - l_L b_{1S})\ \mathrm{sign}\,(l_L b_{2S} - l_S b_{2L})$ is an acceptable solution. However, if we divide both values by the same integer and if the result is also an integer, then we have another acceptable solution. Since the lower is the group of subframes (i.e., $q_1 + q_2$), the lower is ϵ_3, the solution is given by the smallest pair of integers leading to $q_2/q_1 = \Omega$, where we have defined

$$\Omega \triangleq \frac{l_S b_{1L} - l_L b_{1S}}{l_L b_{2S} - l_S b_{2L}}. \tag{13}$$

These considerations allow us to reformulate (12) as

$$\begin{aligned}
\underset{r_s, b_{1L}, b_{2L}, q_1}{\text{minimize}}\quad & (q_1\, \epsilon_1 + q_2\, \epsilon_2) \left\lfloor \frac{Q}{q_1 + q_2} \right\rfloor + \epsilon_3 \\
\text{subject to } & r_s \in \mathcal{R}_X^{\triangleleft} \\
& b_{1L}, b_{2L}, q_1, q_2 \in \mathbb{N}_0 \\
& b_{1S} = \left\lfloor \frac{\bar{s}(r_s) - b_{1L}\, s_{b_L}}{s_{b_S}} \right\rfloor \\
& b_{2S} = \left\lfloor \frac{\bar{s}(r_s) - b_{2L}\, s_{b_L}}{s_{b_S}} \right\rfloor \\
& 1 \le b_{1L} \le \lfloor \bar{s}(r_s)/s_{b_L} \rfloor \\
& 0 \le b_{2L} < b_{1L} \\
& 1 \le q_1 \le |l_L b_{2S} - l_S b_{2L}| \\
& q_2 = \Omega\, q_1 \\
& q_2 \in \mathbb{N}_0 \\
& q_1 + q_2 \le Q \\
& s_{b_S} = \left\lceil \frac{r_{b_S}}{r_s} \right\rceil \\
& s_{b_L} = \left\lceil \frac{r_{b_L}}{r_s} \right\rceil
\end{aligned} \tag{14}$$

which has a smaller set for b_{2L} and only four optimization variables instead of seven, since s_{b_S}, s_{b_L}, and q_2 are derived directly.

As a simplification during the search, it can be noted that if Ω is negative, no combination of q_1 and q_2 is acceptable. In addition, as already mentioned, among all acceptable combinations of q_1 and q_2, the one with the lowest q_1 is preferable (minimizes ϵ_3); this implies that, by increasing q_1 one by one, the search stops as soon as the q_2 obtained is an integer.

Algorithm 2 Messages of Two Sizes

Given $\bar{r}$, r_{b_S}, r_{b_L}
Given the ordered set $\mathcal{R}_X$
Derive $\mathcal{R}_X^{\triangleleft}$ *(with elements in ascending order)*
Set $\epsilon_{\min} = \bar{r}\, Q$, $r_s^* = 0$ $b_{1S}{}^* = 0$, $b_{1L}{}^* = 0$, $b_{2S}{}^* = 0$, $b_{2L}{}^* = 0$, $q_1{}^* = 0$, $q_2{}^* = 0$
for all $r_s \in \mathcal{R}_X^{\triangleleft}$ **do**
  Set $\bar{s}(r_s)$ as in (2)
  $s_{b_S} = \lceil r_{b_S}/r_s \rceil$
  $s_{b_L} = \lceil r_{b_L}/r_s \rceil$
  for $b_{1L} = 1 : \lfloor \bar{s}(r_s)/s_{b_L} \rfloor$ **do**
    $b_{1S} = \lfloor (\bar{s}(r_s) - b_{1L}\, s_{b_L})/s_{b_S} \rfloor$
    for $b_{2L} = 0 : (b_{1L} - 1)$ **do**
      $b_{2S} = \lfloor (\bar{s}(r_s) - b_{2L}\, s_{b_L})/s_{b_S} \rfloor$
      Set Ω as in (13)
      if $\Omega < 0$ **then**
        Break *(the for-cycle on b_{2L})*
      end if
      for $q_1 = 1 : |l_S b_{2L} - l_L b_{2S}|$ **do**
        $q_2 = q_1\, \Omega$
        if $q_2 > Q - q_1$ **then**
          Break *(the for-cycle on q_1)*
        end if
        if mod $(q_2, 1) = 0$ **then**
          Set ϵ_1 as in (9)
          Set ϵ_2 as in (10)
          Set ϵ_3 as in (11)
          $\epsilon = (q_1\, \epsilon_1 + q_2\, \epsilon_2) \left\lfloor \frac{Q}{q_1+q_2} \right\rfloor + \epsilon_3$
          if $\epsilon < \epsilon_{\min}$ **then**
            $\epsilon_{\min} = \epsilon$, $r_s^* = r_s$
            $b_{1S}{}^* = b_{1S}$, $b_{1L}{}^* = b_{1L}$,
            $b_{2S}{}^* = b_{2S}$, $b_{2L}{}^* = b_{2L}$,
            $q_1{}^* = q_1$, $q_2{}^* = q_2$
          end if
          Break *(the for-cycle on q_1)*
        end if
      end for
    end for
  end for
  if $s_{b_L} \le 1$ **then**
    Break *(the for-cycle on r_s)*
  end if
end for
Solution: r_s^*, $b_{1S}{}^*$, $b_{1L}{}^*$, $b_{2S}{}^*$, $b_{2L}{}^*$, $q_1{}^*$, $q_2{}^*$

Finally, if the s_{b_L} deriving from the considered r_s is not greater than one, then the search can be interrupted, since a larger subchannel size necessarily leads to more wasted RBPs. The resulting pseudo-code is shown as Algorithm 2.

Also in this case, the values corresponding to the solution are marked with an asterisk.

2) NUMBER OF VEHICLES

Once the optimization problem is solved, the number of messages that can be allocated in subframes of Type 1 is $b_{1S}{}^* + b_{1L}{}^*$ and in subframes of Type 2 is $b_{2S}{}^* + b_{2L}{}^*$. Then, noting that the number of groups of $q_1{}^*$ subframes of Type 1 and $q_2{}^*$ subframes of Type 2 in a beacon period are $\lfloor \frac{Q}{q_1{}^*+q_2{}^*} \rfloor$ and adding those allocated in subframes that remain outside the groups, the number of vehicles that can be simultaneously allocated without interfering with each other results in

$$\hat{v} = \left\lfloor \frac{Q}{q_1{}^* + q_2{}^*} \right\rfloor \left(q_1{}^*(b_{1S}{}^* + b_{1L}{}^*) + q_2{}^*(b_{2S}{}^* + b_{2L}{}^*)\right) + \mathrm{mod}\,(Q, q_1 + q_2) \left\lfloor \frac{\bar{s}(r_s^*)}{\lceil r_{b_L}/r_s^* \rceil} \right\rfloor. \quad (15)$$

3) COMPLEXITY OF THE SOLUTION

The complexity of the optimization problem given in (14) and resolved using Algorithm 2 is related to the size of the search space. We have thus investigated how large it is considering both allocation types and varying f_b, $\bar{r}$ (directly related to the bandwidth, as specified by 3GPP), s_{b_S} (keeping $s_{b_L} = 1$), r_{b_S}, and r_{b_L}.

TABLE 2. Examples of the search-space size.

Alloc.	f_b	$\bar{r}$ (Bandw.)	s_{b_S}/s_{b_L}	r_{b_S}	r_{b_L}	# of el.
Adj.	10 Hz	50 (10 MHz)	4	3	5	47
Adj.	10 Hz	50 (10 MHz)	2	1	2	115
Adj.	10 Hz	100 (20 MHz)	2	1	2	829
Adj.	10 Hz	200 (40 MHz)	2	1	2	5927
Adj.	1 Hz	200 (40 MHz)	2	1	2	5957
Non-adj.	10 Hz	50 (10 MHz)	4	3	5	64
Non-adj.	10 Hz	50 (10 MHz)	2	1	2	73
Non-adj.	10 Hz	100 (20 MHz)	2	1	2	436
Non-adj.	10 Hz	200 (40 MHz)	2	1	2	1174
Non-adj.	1 Hz	200 (40 MHz)	2	1	2	1174

Selected example outputs of this investigation are reported in Table 2 and the main conclusions can be summarized as follows.

- The search space tends to increase when f_b reduces, but the impact is almost negligible when f_b is lower than 20 Hz;
- The search space is strongly influenced by $\bar{r}$ and increases 7-8 times when $\bar{r}$ doubles; however, $\bar{r}$ corresponds to the allocated bandwidth and is normally fixed to 50 (i.e., 10 MHz like IEEE 802.11p) or at most 100 (i.e., 20 MHz);
- Small values for s_{b_S}, r_{b_S}, and r_{b_L} imply more combinations to evaluate, and the worst case is $s_{b_S} = 2$, $r_{b_S} = 1$, and $r_{b_L} = 2$;
- The adjacent allocation causes in most cases a larger search space; even if $\mathcal{R}_N$ is larger than $\mathcal{R}_A$, the number of channels available with the adjacent allocation under the same settings is actually higher;
- In the worst realistic case, corresponding to adjacent configuration, $f_b = 1$ Hz, $\bar{r} = 100$ (20 MHz bandwidth), $s_{b_S} = 2$, $s_{b_L} = 1$, $r_{b_S} = 1$, and $r_{b_L} = 2$, the size of the search space is less than 1000 elements and doubling the bandwidth to 40 MHz the size of the search space is nearly 6000 elements.

Considering that Algorithm 2 is used only when large-scale changes occur, such as those on road traffic, searching on a set of less than 10000 elements does not appear to be a problem.

4) EXAMPLE

As in the example of Section IV-B, let us assume $\bar{r} = 50$, an adjacent configuration, and $f_b = 10$ Hz. Beacons are here in two sizes, with $l_L = 1$ larger packet every $l_S = 4$ smaller ones. The larger beacons need $r_{TB_L} = 23$ for the TB, thus $r_{b_L} = 25$ in total. The smaller beacons need $r_{TB_S} = 10$ for the TB, thus $r_{b_S} = 12$ in total. This example is represented in Fig. 1(b).

From Algorithm 2, it follows that the optimal solution is $r_s^* = 6$ in this case, with $s_{b_L}{}^* = 5$ and $s_{b_S}{}^* = 2$. This is obtained with $q_1 = 4$ subframes of Type 1, each carrying one smaller packet over two subchannels and one larger packet over five subchannels, and $q_2 = 3$ subframes of Type 2, each carrying four smaller packet using two subchannels each. As a consequence, there are 13 unused RBPs in the subframes of Type 1, and 2 unused RBPs in the subframes of Type 2. Applying (15), we obtain $\hat{v} = 282$, which is 41% vehicles more than an allocation based only on larger packets. Notably, the solution is reached after only 17 combinations of r_s, b_{1L}, b_{2L}, q_1 have been evaluated.

V. EXAMPLE RESULTS

Hereafter, some example results are shown based on the detailed optimizations, preceded by a discussion of the adopted settings.

A. MAIN SETTINGS

In the following, we assume a bandwidth of 10 MHz, which is a common assumption for short-range C-V2X, derived from the channels of IEEE 802.11p. It follows that the number of RBPs per subframe is $\bar{r} = 50$. Beacons are generated at a rate $f_b = 10$ Hz, which is the highest frequency normally considered by ETSI and also the value assumed in most studies on similar topics.

Following 3GPP [19], we assume $l_S = 4$ messages of $B_{TB} = 190$ bytes followed by $l_L = 1$ message of $B_{TB} = 300$ bytes. For each of the two sizes and all possible MCSs, in Table 4 the number of RBPs required for the TB r_{TB}, the minimum signal to noise and interference ratio (SINR) $\underline{\gamma}$, and the maximum distance in the absence of interference d_{max} are obtained by following the method reported in Appendix as a function of the MCS m and the beacon size B_{TB}.

The allocation of the messages is managed through a benchmark or the proposed approach, as follows.[4]

- ***Benchmark:*** the definition of the sub-channel size and the allocation of resources are performed only on the

[4]Please note that the Proposed and Benchmark approaches deal with the system configuration, so they can not be compared with resource allocation algorithms and rather correspond to a preliminary phase.

TABLE 3. Main settings.

Parameter (symbol)	value
Beacon periodicity (f_b)	10 Hz
Number of RBs per subframe ($\overline{r}$)	50
Duration of the slot (t_slot)	0.5 ms
Bandwidth of a RBP (w_RB)	180 kHz
Size of smaller packets (B_{TB_S})	190 bytes
Size of larger packets (B_{TB_L})	300 bytes
Number of consecutive smaller beacons (l_S)	4
Number of consecutive larger beacons (l_L)	1
Implementation loss w.r.t Shannon capacity (ϕ)	0.6
Transmitted power (P_tx)	23 dBm
Antenna gain at the transmitter (G_t)	3 dB
Antenna gain at the receiver (G_r)	3 dB
Path loss at 1 m (L_0)	20.06 dB
Loss exponent (β)	4
Noise figure (F_n)	9 dB

TABLE 4. Number of BRPs, minimum SINR, and maximum distance for beacons of 190 and 300 bytes and per each MCS.

	B_{TB_S} = 190 bytes			B_{TB_S} = 300 bytes		
MCS	r_TB	γ	d_max	r_TB	γ	d_max
0	55	-2.8	467	86	-2.8	418
1	42	-1.3	459	66	-1.4	411
2	34	-0.1	451	54	-0.2	404
3	27	1.3	440	41	1.5	392
4	22	2.7	428	34	2.8	382
5	18	4.2	413	28	4.4	365
6	15	5.6	397	23	5.8	354
7	13	7.3	374	20	7.3	336
8	11	8.6	363	18	8.6	320
9	10	9.6	350	16	9.9	306
10	9	10.8	335	14	11.2	294
11	9	10.8	335	14	11.2	294
12	8	12.9	307	12	12.8	278
13	7	14.8	284	11	14.5	258
14	6	16.6	265	10	16.4	237
15	6	18.8	235	9	18.7	213
16	5	20.0	228	8	20.1	203
17	5	20.9	217	8	21.1	191
18	5	23.4	188	7	23.5	172
19	4	25.1	180	7	25.9	150
20	4	28.2	151	6	28.2	137

basis of the larger messages, i.e., B_TB = 300 bytes, assuming that even the smaller messages are allocated in the same resources. The optimization process follows what is detailed in Section IV-B;

- ***Proposed:*** the definition of the sub-channel size and the allocation of resources take into account both sizes and their occurrence, following what is detailed in Section IV-C;

The parameters used for the path loss modeling are those suggested by 3GPP in [19]. These and the other settings at the PHY layer are summarized in Table 3.

B. MAXIMUM NUMBER OF VEHICLES

In Figs. 2 and 3, the results are provided in terms of the maximum number of vehicles varying what we call *target distance* d^*. More specifically, given d^*, per each value of $B_{\text{TB}_\text{X}} \in \{B_{\text{TB}_\text{S}}, B_{\text{TB}_\text{L}}\}$ the highest MCS m^*_X is selected which provides sufficient coverage, i.e., we calculate

$$m^*_\text{X} = \max\left\{m \in \mathcal{M} : d_\text{max}(m, B_{\text{TB}_\text{X}}) \geq d^*\right\} \qquad (16)$$

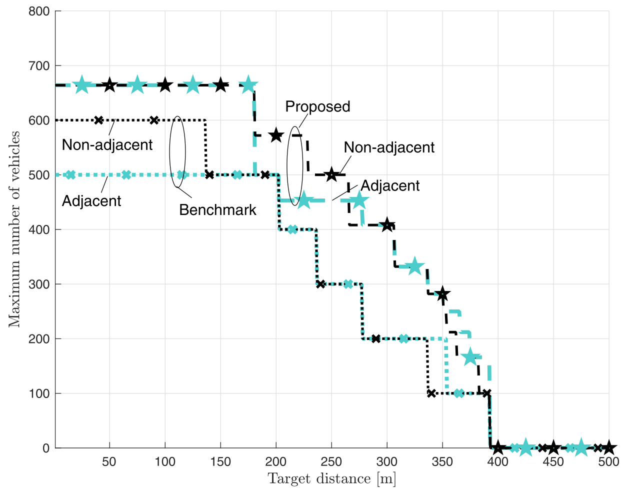

FIGURE 2. Maximum number of vehicles.

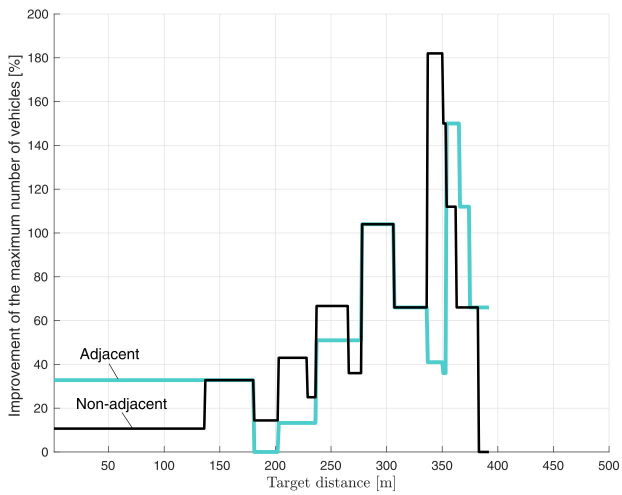

FIGURE 3. Improvement in percentage.

where $\mathcal{M}$ is the set of all possible MCS and the subscript X stands for S or L. The parameter d^* is a reference value used to select the MCSs. We preferred this approach instead of, for example, using a target SINR, which would cause different reliability at the same distance.

In Fig. 2, the maximum number of vehicles that can be allocated is shown varying d^*, both for adjacent and non-adjacent allocations and for both Benchmark and Proposed approaches. As observable, whereas at most 500 or 600 vehicles can be allocated with the Benchmark approach in adjacent and non-adjacent configuration, respectively, the Proposed approach allows up to 665 nodes to transmit simultaneously without interfering with each other. All values decrease with a greater d^* (which is equivalent to requiring greater reliability), but still the gap between Benchmark and Proposed remains significant. If we focus, as an example, on d^* = 340 m and adjacent allocation, smaller packets use MCS 9, corresponding to 10 BRPs, and larger packets use MCS 6, corresponding to 23 BRPs. These values are exactly those discussed as examples in Sections IV-B and IV-C, and reported in Fig. 1. As already discussed, in this case the maximum number of vehicles increases from 200 in the Benchmark case to 282 in the Proposed one.

Only in few cases, the results with the two approaches are the same, depending on the specific settings. For example, with $d^* = 180$ m and adjacent allocation, the smaller packets use MCS 19, corresponding to 4 BRPs, whereas the larger packets use MCS 17, corresponding to 8 BRPs; choosing $r_s = 5$, all packets require two subchannels, with 10 subchannels per TTI, while selecting $r_s = 6$, smaller messages can use a single subchannel, but the apparent advantage is balanced by the number of subchannels reduced to 8.

It can also be noted that the results do not suggest a general preference for the adjacent or non-adjacent configuration. The results are in fact strictly related to the number of RBPs needed for the messages and the available sets $\mathcal{R}_A$ and $\mathcal{R}_N$. Actually, they overall provide similar performance and one of the two exceeds the other only in very specific cases.

The same results are shown in Fig. 3 in terms of percentage increase allowed by the Proposed approach for adjacent and non-adjacent allocations. As observable, the improvement mostly ranges between 10% and 30%, with few cases at 0% and a peak at more than 150%. It can also be observed that the difference varying the target distance is in general a little more stable with a non-adjacent allocation; this is due to the larger size of $\mathcal{R}_N$ compared to $\mathcal{R}_A$, which implies more granularity.

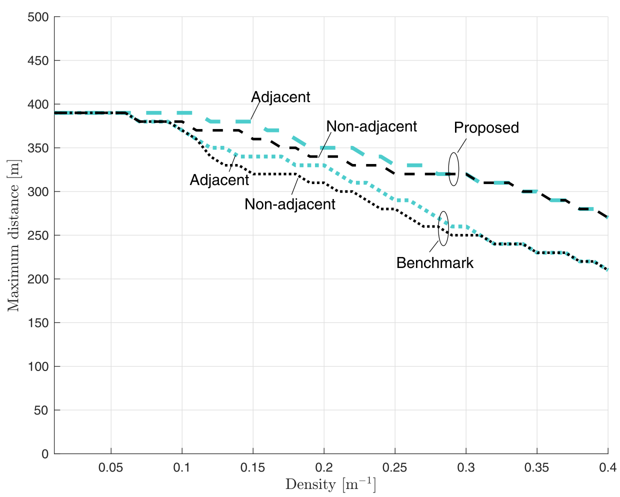

FIGURE 4. Max distance vs. density.

C. COVERAGE VS. VEHICLE DENSITY TRADE-OFF

Assuming a highway scenario, in Fig. 4, the maximum distance that allows a sufficient quality of service is obtained as a function of the vehicle density. More specifically, a 1-D approximation of the highway is assumed, similarly to many other related papers (e.g., [30]–[33]), with density of vehicles ρ. Given the maximum number of vehicles occupying different resources $\hat{\nu}$, we approximate the interference with the power received by the two nodes (one per direction) at a distance $\hat{\nu}/\rho$ from the source; in other words, we assume that the same resource of the interfered node is reused by the $\hat{\nu}^{\text{th}}$ nodes on both sides and that their position can be approximated as $\hat{\nu}$ times the average inter-vehicle distance, equal to $1/\rho$.[5] Then, the SINR is calculated for the generic node at the distance d as

$$\gamma(d, \hat{\nu}, \rho) = \frac{P_r(d)}{P_n + P_{I1}(d, \hat{\nu}, \rho) + P_{I2}(d, \hat{\nu}, \rho)} \quad (17)$$

where $P_r(d)$ is the power received at the distance d, P_n is the noise power, $P_{I1}(d, \rho)$ is the power received at the distance $(\hat{\nu}/\rho) - d$ (interferer located closer to the destination than to the source), and $P_{I2}(d, \rho)$ is the power received at distance $(\hat{\nu}/\rho) + d$ (interferer located closer to the source than to the destination).

Using (17) and given the density ρ, we define as the maximum distance $d_{\max}$ the maximum value at which the SINR is higher than the minimum value for both smaller and larger packets, assuming any possible combination of MCSs. In formulas,

$$d_{\max} = \max \Big\{ d \geq 0 : \exists m_S, m_L \in \mathcal{M} \text{ so that } \gamma(d, \hat{\nu}, \rho) > \underline{\gamma}(m_S, B_{TB_S}) \text{ AND } \gamma(d, \hat{\nu}, \rho) > \underline{\gamma}(m_L, B_{TB_L}) \Big\}. \quad (18)$$

In Fig. 4, the density ranges between 0 and 0.4 vehicles/m (to give a reference, a highway with 3+3 lanes begins to be congested with a density of 0.15/0.2 vehicles/m [34]). Looking at the curves, the Proposed approach provides an increase of about 10% of the maximum distance, an improvement which exceeds 30% for $\rho = 0.35$. The exception is given by small densities, where the interference is negligible and all the approaches, limited by noise, lead to the same $d_{\max}$. Note that the same curves can also be observed from the opposite point of view, i.e., by setting a maximum distance as target and deriving the limit on the acceptable density; setting $d_{\max} = 300$ m, for example, the supported density goes from 0.22/0.24 with the Benchmark approach (non-adjacent/adjacent) to 0.35 with the Proposed one, with an improvement of approximately 50%.

VI. CONCLUSION

With reference to LTE-V2X and the cooperative awareness service, which are planned as the basis for all safety applications in future vehicles connected via C-V2X, in this work we have addressed the optimization of the settings when the periodic messages are not all of the same size. This condition is indeed expected in practice and is prone to inefficiencies in the resource allocation process. We have thus placed attention on the constraints that are given by the specifications and defined a combinatorial optimization problem. As a result, we have also provided algorithms to solve the optimization and examples to evaluate the impact of the proposal. Our results show that a significant improvement can be granted, compared to an optimization based on the

[5] A distance $\hat{\nu}/\rho$ is also the average value for the $\hat{\nu}^{\text{th}}$ vehicle both if we assume an uniform distribution of nodes or a distribution that follows a Poisson point process, as done for example in [30]–[33].

larger packets, both in terms of system capacity, given a target range (i.e., at least 10% to 30% increase in the number of vehicles that can be allocated), or in terms of supported coverage, given a target density (i.e., 10% to 30% longer range).

APPENDIX

Hereafter, we calculate the number of RBPs per beacon and the maximum distance per each MCS $m \in \mathcal{M}$ that follow the given $B_{\rm TB}$, recalling that $\mathcal{M}$ is the set of all possible MCSs.

A. MODULATION ORDER AND RBPs PER BEACON

For each $m \in \mathcal{M}$, from [35, Table 8.6.1-1] we derive: 1) the modulation order, with the corresponding number of bits per symbol $b_{\rm sy}(m)$; and 2) the transport block size (TBS) index $I_{\rm TBS}(m)$.

$I_{\rm TBS}$ is in turn used together with $B_{\rm TB}$ to obtain the number of RBPs per beacon $r_{\rm TB}(m, B_{\rm TB})$ from [35, Table 7.1.7.2.1-1]. The same table also provides the total number of bits carried by the selected RBPs, which is denoted as $b_{\rm TBS}(m, B_{\rm TB})$.

B. MINIMUM SINR

With the values obtained, the number of data bits per second per Hz carried by the given MCS, denoted by $b_{\rm Hz}(m, B_{\rm TB})$, can be calculated as

$$b_{\rm Hz}(m, B_{\rm TB}) = \frac{b_{\rm TBS}(m, B_{\rm TB})}{t_{\rm slot}\ w_{\rm RB}\ r_{\rm TB}(m, B_{\rm TB})} \tag{19}$$

where $t_{\rm slot} = 0.5$ ms is the duration of the slot and $w_{\rm RB} = 180$ kHz is the bandwidth of an RBP.

By inverting the Shannon equation with a parametric loss of 60% due to implementation, as suggested by 3GPP in [36], hereafter expressed as $\phi = 0.6$, the minimum SINR can be obtained as

$$\underline{\gamma}(m, B_{\rm TB}) = 2^{\frac{b_{\rm Hz}(m, B_{\rm TB})}{1-\phi}} - 1. \tag{20}$$

C. MAXIMUM DISTANCE

The maximum distance allowed by an MCS with the given $B_{\rm TB}$ is calculated starting from $\underline{\gamma}$ and considering an interference-free signal and only the path-loss component of the propagation, i.e., averaging over large-scale and small-scale fading, as

$$d_{\max}(m, B_{\rm TB}) = L^{-1}\left(\frac{P_{\rm tx}\ G_{\rm t}\ G_{\rm r}}{\underline{\gamma}(m, B_{\rm TB})\ P_{\rm n}(m, B_{\rm TB})}\right) \tag{21}$$

where $L(d) \triangleq L_0 d^{\beta}$ is the path-loss function depending on the distance d, L_0 is the path-loss at 1 m, β is the loss exponent, $P_{\rm tx}$ is the transmitted power, $G_{\rm t}$ and $G_{\rm r}$ are the antenna gain at the transmitter and receiver, respectively, and $P_{\rm n}$ is the noise power. The noise power is calculated as $P_{\rm n}(m, B_{\rm TB}) = k\ T_0\ F_{\rm n}\ \ r_{\rm TB}(m, B_{\rm TB})\ w_{\rm RB}$, where k is the Boltzmann constant, $T_0 = 290$ K is the standard noise temperature, and $F_{\rm n}$ is the noise figure.

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