Pilot Placement for Power-Efficient Uplink Positioning in 5G Vehicular Networks

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***Abstract*—This paper studies the pilot placement for power-efficient uplink positioning within future fifth generation (5G) enhanced vehicle to everything (eV2X) networks. The optimal pilot allocation of multicarrier signals may help to fulfil the stringent requirements, in terms of vehicle position accuracy and latency, within vehicular applications, such as autonomous driving. Contiguous and non-contiguous pilot placements in the frequency domain are assessed, by considering the trade-off between minimum Cramér-Rao bound (CRB) and peak-to-average power ratio (PAPR), among other pilot design criteria. Contiguous placement of pilots with a high separation between subcarriers is a candidate pattern to fulfil the design criteria within future vehicular networks.**

***Index Terms*—5G, positioning, power efficient, pilot placement.**

I. INTRODUCTION

Fifth generation (5G) cellular networks are expected to support disruptive technologies, such as millimeter wave (mmWave), massive multiple-input multiple-output (MIMO), massive machine-type communications (mMTC) or enhanced vehicle-to-everything (eV2X) networks. The standardization of 5G has already been initiated by focusing on network designs able to provide ultra-high throughput, low latency, high reliability, and long communication range. In addition, high-accuracy positioning is expected to become essential in the near future (e.g. autonomous vehicles). As a result of the increasing interest, the positioning support is envisaged to be already incorporated in 5G in the coming Release 16.

The positioning methods of Long Term Evolution (LTE) technology can be considered as a baseline for 5G, since multicarrier orthogonal frequency-division multiplexing (OFDM) is currently one of the most solid candidates to be adopted in the physical layer of 5G. However, further study on positioning enhancements is necessary to fulfil the stringent accuracy and latency requirements of critical applications such as, for instance, autonomous driving. In this sense, the positioning performance of Global Navigation Satellite Systems (GNSS) can be enhanced with cellular-based relative and cooperative positioning, by using vehicle-to-vehicle (V2V) or vehicle-to-infrastructure (V2I) distance measurements, as proposed in [1]. These relative ranging measurements are expected to be estimated by means of pilot or reference signals. However, the current LTE standard in [2] does not specify any dedicated uplink or sidelink pilot for ranging or positioning. Although the sounding reference signal (SRS) can be re-used for uplink ranging, this pilot is not optimized for positioning, which may hinder the fulfilment of the high-accuracy requirement.

Since the sidelink and uplink signals are transmitted by the user or vehicle, both physical layers are constrained by the well-known problem of high peak-to-average power ratio (PAPR), which reduces the battery life time or increases the energy cost [3]. Thus, the pilot design for power-efficient uplink positioning (also applicable to the sidelink) is a key aspect to fulfil the potential requirements of future eV2X networks. The existing works on pilot design have focused on aspects such as improving channel estimation and synchronization at the receiver side, with the aim of maximizing the data rate [4], or minimizing PAPR at the transmitter side for reducing the penalty incurred by high peak-to-average modulations, such as OFDM in terms of power efficiency [3]. Additionally, the optimal power allocation in terms of capacity and ranging has been studied in [5], and the sparse pilot placement has been assessed in [6] for round-trip delay (RTD) ranging, which can be applied to cooperative positioning. In this work, we focus on designs that jointly optimize the synchronization (i.e., time-delay estimation) and PAPR, which to the best of the authors' knowledge, have not been considered so far. For this purpose, the pattern of the uplink LTE SRS is used as a baseline, and it is assessed with different pilot placements, by using the Cramér-Rao bound (CRB) for time-delay estimation and the PAPR, as the main metrics for the performance evaluation.

This paper is organised as follows. In Section II, the role of localization within the standardization of 5G eV2X networks is introduced. In Section III, the pilot design criteria is discussed, by considering the standard approach and the vehicular scenario. Then, the pilot placement is assessed as a trade-off between CRB and PAPR in Section IV. Finally, conclusions and future work are drawn in Section V.

II. LOCALIZATION FOR 5G EV2X NETWORKS

This section introduces the role of localization within 5G eV2X networks, and the interest to support vehicular positioning within the future standard. Then, the main challenges and considerations are discussed for positioning within 5G eV2X.

A. Current Standardization

The 3GPP consortium has identified in [7] new uses cases and requirements to be supported within future cellular networks. This includes high-accuracy positioning, in order to fulfil the localization requirements within critical communications, mMTC and eV2X communications. These potential requirements are a position accuracy below 1 meter for the 95% of the service area, and a latency around 10 ms [7]. Considering the high interest and the perspectives of the automotive industry, the main eV2X services identified within 5G are vehicle platooning, autonomous driving, extended sensors, and remote driving [8].

The current standardization process of eV2X is mainly focused on the sidelink communications, where the relative distance between vehicles is a key aspect to be considered and thus to be incorporated into the eV2X specification [9]. Although GNSS or differential GNSS are considered as a baseline location method, 5G is envisaged to support cellular-based positioning methods. In this sense, a new study item is proposed in [1] to assess the feasibility of LTE positioning methods in the context of 5G, including positioning enhancements of the LTE radio-interface, i.e., LTE Uu (downlink and uplink) and PC5 (sidelink).

B. Main Challenges

The main vehicular scenarios proposed for 5G are the highway deployment and the urban grid for connected cars [10]. In the highway scenario, the main requirements are based on reliability and availability under high speeds. The urban scenario has a high network load and a high density of users, and the service performance is assessed in terms of reliability, availability and latency. In addition, 5G is expected to support regulatory positioning requirements, as well as a range of position accuracy and latency levels. The 5G design should also target positioning methods with a reduced device cost, reduced device power consumption, and an efficient signalling over the air interface and in the network [10].

III. PILOT PLACEMENT FOR POWER EFFICIENCY AND POSITIONING PURPOSES

The objective of this section is to describe the criteria to design pilot signals for power-efficient uplink positioning within 5G eV2X networks. As a baseline, the LTE pilot schemes are assessed considering this criteria. Then, design considerations within vehicular networks are discussed.

A. Design Criteria

The design of pilot signals is driven by different requirements depending on the application, which can be summarized as follows:

1) Channel Estimation Accuracy: The channel estimation is typically used for demodulation and scheduling purposes. However, the introduction of pilot subcarriers reduces the overall capacity. In the frequency domain, the mean square error (MSE) of the channel estimation is optimized with equidistant and equipowered pilot sequences, as it is proven in [4]. The frequency spacing between pilot subcarriers is defined by the expected coherence bandwidth or channel delay spread.

2) Positioning Accuracy: The minimum achievable variance of the time-delay estimation with a pilot signal can be determined by the CRB. Considering an AWGN channel, the CRB is defined in [11] as

$$\operatorname{var}(\tau) \geq \mathrm{CRB}(\tau) = \frac{T^2}{8\pi^2 \cdot \mathrm{SNR} \cdot \sum\limits_{n\in\mathcal{N}} p_n^2 \cdot n^2}, \qquad (1)$$

where T is the OFDM symbol period, SNR is the signal-to-noise ratio, p_n^2 is the relative power weight of subcarrier n, and $\mathcal{N}$ is the subset of pilot subcarriers. As it can be noticed in (1), the CRB is driven by the power and allocation of the pilot subcarriers, and it is independent of the code sequence used. In this sense, the CRB decreases, i.e., the ranging accuracy improves, when most of the power is allocated to the pilot subcarriers at the edges of the band, or to an intermediate solution between edged and equipowered subcarriers when joint time-delay and channel estimation is sought [5].

3) Power Amplifier Efficiency: The time-domain OFDM signal is known to have large peak-to-average power variations, which leads to a saturation of the power amplifier at the transmitter. The inefficient operation of the power amplifier in the nonlinear region introduces distortions on the transmitted signal that degrade the bit error rate (BER) and thus, need to be reduced. The power amplifier efficiency can be assessed through the PAPR, which is defined as

$$\mathrm{PAPR}(x(t)) = \frac{\max\limits_{0\leq t<T} \left\{ |x(t)|^2 \right\}}{\mathrm{E}\left[|x(t)|^2 \right]}, \qquad (2)$$

where $x(t)$ is the OFDM signal over a period T, and $\mathrm{E}[\,\cdot\,]$ is the expectation operator. The PAPR depends on the power, allocation and phase of the active subcarriers. The constant envelope Zadoff-Chu sequences are shown to have a low PAPR, ideal autocorrelation and a low cross-correlation [12]. As it is discussed in [13], these sequences are the best candidate for a design with equipowered pilots.

4) Multiplexing: An efficient multiplexing scheme is necessary to cover a high-density of users. OFDM pilots can be efficiently multiplexed in time and frequency. But, the sparsity of pilots, which increases user multiplexing, is limited by the channel sounding capabilities. These pilot resources can also be re-allocated to different users by means of code sequences with a low multiple access interference (MAI). These multiplexing schemes can also be used to implement a multi-antenna transmission.

5) Scheduling: Pilot resources can be scheduled depending on the channel conditions and the inter-cell or inter-user interference [14, p.286]. Thus, the power and allocation of resources are also designed according to scheduling purposes. As an example, a distant user can concentrate the available power by transmitting only certain subcarriers (instead of the whole band), in order to improve the channel estimates over those subcarriers.

6) Signalling Overhead: The information required to allocate pilot resources and the feedback information from pilot measurements is defined as signalling overhead, and it reduces the data throughput. In case of a flexible pilot allocation, the signalling overhead increases. Thus, an uniform or pre-defined pilot design is preferred for throughput maximization.

B. LTE Pilot Schemes

The pilot or reference signals within the LTE standard are specified for the downlink, uplink and sidelink transmission in TS 36.211 [2]. These pilots can be classified between those designed for channel estimation or for positioning:

1) Sounding Pilots: These pilots are used for demodulation and channel estimation purposes, but they can also be re-used for positioning. For instance, the downlink synchronization signals and the CRS can be considered signals of opportunity for observed time-difference of arrival (OTDoA), and the SRS is the main pilot for uplink time-difference of arrival (UTDoA) measurements. Indeed, the base station (BS) tries to schedule the maximum SRS bandwidth during an UTDoA positioning occasion, and several SRS transmissions can be multiplexed with a certain interleaving factor, i.e., separation between pilot subcarriers. However, since these signals are not designed for positioning, they mainly suffer from the hearibility or near-far problem, where near and powerful transmissions mask far and weak transmissions, resulting in a degradation of the trilateration performance.

2) Positioning Pilots: The positioning reference signal (PRS) is the only dedicated pilot for positioning in LTE. The PRS is allocated in the time-frequency grid of the downlink with a semi stair-wise pattern. These pilot subcarriers are equipowered with pseudo-random quadrature phase-shift keying (QPSK) sequences. The PRS pattern is scheduled in consecutive subframes with a frequency reuse of six and a certain periodicity. Since the data transmission is not allocated in the PRS subframes, the hearibility problem is significantly reduced. However, certain BSs may not transmit at certain periods due the PRS muting scheme. The total number of BSs used for the OTDoA measurement is limited by the frequency reuse of six and the periodicity of the PRS occasions. Furthermore, a high density of positioning pilots considerably reduces the downlink throughput.

C. Design Considerations within Vehicular Networks

The key role of localization in vehicular networks results in the need to design a pilot signal for power-efficient positioning, especially for the uplink and sidelink. The eV2X scenario demands accurate and reliable positioning, but the potential pilot design is also constrained by a low PAPR, necessary to maintain the energy efficiency and reduced cost of the vehicle device. Since the vehicular scenario is a very dynamic environment with a medium to high density of vehicles, the design also needs to easily multiplex the pilot resources among vehicles with a fast response. Thus, the general guidelines to design the vehicular pilot signal are high bandwidth allocation, low PAPR and high multiple access.

IV. ANALYSIS ON THE TRADE-OFF BETWEEN CRB AND PAPR

The objective of this section is to shed light on the pilot placement for power efficiency and uplink positioning. For this purpose, a baseline pilot design, i.e., the LTE SRS, is considered. The subcarrier placement is left as a degree of freedom in order to analyse what the best placement should be used for both minimizing the CRB and the PAPR. This leads to a trade-off between CRB and PAPR, since both design criteria are at odds one with each other. As the vehicular scenario is dominated by line of sight (LoS), e.g. V2I models [11], additive white Gaussian noise (AWGN) is considered for the sake of simplicity of the simulations with a SNR equal to 5 dB for a maximum transmit power of a certain amplifier.

A. Baseline Pilot Signal

The LTE SRS is considered the baseline pilot signal for this study, due to its low PAPR and high multiplexing properties. It is directly mapped into the frequency domain based on a interleaved scheme with a spacing of two or four subcarriers. These pilot subcarriers are allocated in resource blocks (RBs), which are formed by 12 subcarriers and 7 symbols [2]. The SRS is only allocated in the last symbol of the subframe. For a short SRS allocation of 2 or 4 RB, an optimized QPSK sequence is used according to the standard. For longer SRS allocation than 4 RB, the SRS sequence is specified to be based on the Zadoff-Chu codes, which are polyphase sequences defined in [12]. The LTE standard uses 30 code bases, which can be multiplexed with 8 code shifts each one.

The SRS already fulfils part of the pilot design criteria defined in the previous section. First, the channel estimation accuracy is favoured by equispaced and equipowered pilot subcarriers. Second, a low PAPR is achieved by a contiguous allocation of RBs and the use of the Zadoff-Chu sequences (or optimized QPSK sequences), resulting in a reduced power amplifier complexity. Third, the interleaving allocation and the large base of code sequences allow a flexible scheduling and multiplexing of users. Finally, the signalling overhead can be maintained low due to the pre-defined pilot pattern.

Although the SRS is used to compute UTDoA measurements, this pilot signal is not optimized for positioning. Let us assess this aspect by evaluating the CRB and the PAPR of the SRS standard definition. The LTE specification defines the SRS sequences for each system bandwidth and active resource allocation. This results in a SRS sequence length defined in multiples of 2 RBs. The trade-off between CRB and PAPR for the standard SRS pilot placements is shown in Figure 1, by considering a system bandwidth of 20 MHz and the 240 possible code sequences (i.e., 30 Zadoff-Chu bases by 8 code shifts) for each possible resource allocation. The optimized QPSK and the extended Zadoff-Chu sequences provide a very low PAPR. However, the resulting PAPR varies from one code sequence to another, and it slightly increases with code length. The CRB also increases as function of the code length, because more RBs are allocated in the band and therefore more bandwidth is used. Thus, the larger the resource allocation in

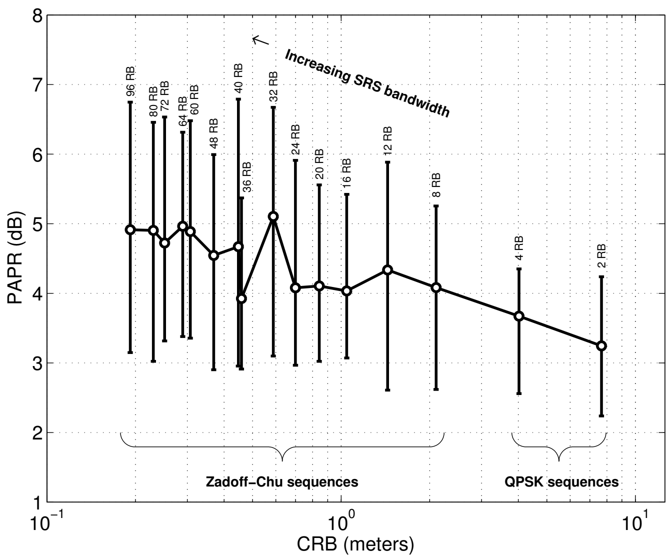


Fig. 1. Mean CRB and mean PAPR of the 240 code sequences for each LTE SRS resource allocation within a system bandwidth of 20 MHz, where the errorbar indicates minimum and maximum PAPR of the group of sequences.

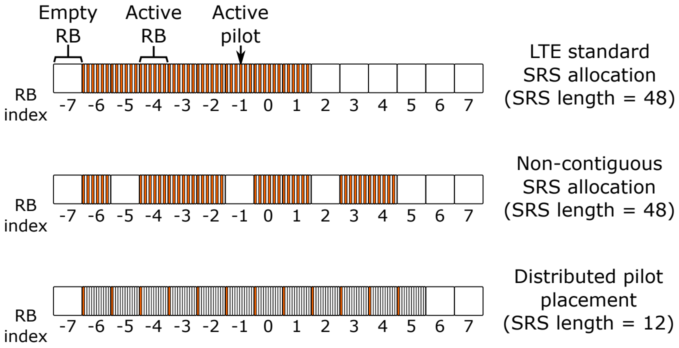


Fig. 2. Example pilot placements with 8 active RBs out of 15 available RBs.

RBs, the better the positioning accuracy, as it is recommended in the LTE UTDoA procedure. However, this considerably reduces the multiplexing capability.

B. Non-contiguous Resource Placement

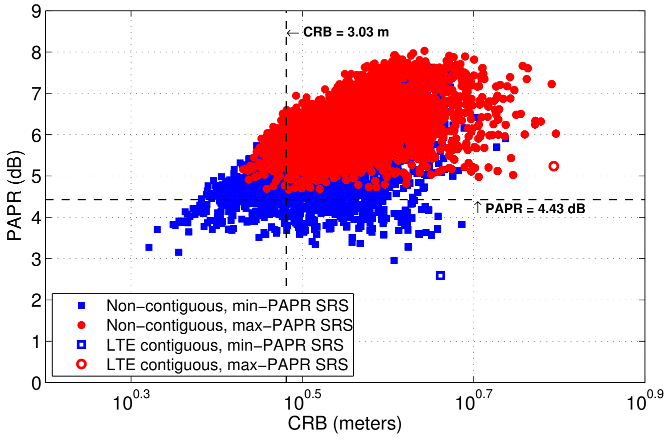
The non-contiguous allocation of the SRS within a certain available bandwidth is studied here. This implies a combinatorial problem, where all the possible combinations of active RBs are considered by discarding the possible index repetitions. For this assessment, the system bandwidth of 3 MHz is used, i.e., 15 available RBs, in order to alleviate the computational complexity of the combinatorial problem. Only 8 active RBs are considered, and the SRS is mapped with an interleaving factor of two subcarriers, the latter feature as specified in the standard. The same group of 240 Zadoff-Chu sequences are used in the same order for the different activation of RBs. An example of continguous and non-contiguous resource placement is shown in Figure 2.

At this point, let us consider those Zadoff-Chu codes that result in the minimum and maximum PAPR with a sequence length of 48 in Figure 1. These specific sequences are used with all the possible combinations of active RBs within 15 available RBs. The resulting PAPR of the contiguous (i.e., as specified in the LTE standard) and non-contiguous SRS placements is shown in Figure 3a. This result indicates that the contiguous allocation of RBs specified in the LTE standard (i.e. empty markers in Figure 1) tends to achieve a very low PAPR regardless of the code sequence. In this sense, the current LTE standard already uses an adequate pilot placement, in order to reduce the PAPR. However, the contiguous allocation is not optimal in terms of positioning, because it provides the worse CRB. The only way to improve the CRB for a contiguous allocation placement would be to occupy all the available bandwidth. In contrast, some non-contiguous placements are able to minimize the CRB while at the same time keeping a low enough PAPR. This is the case of the south-western most points in Figure 3a.

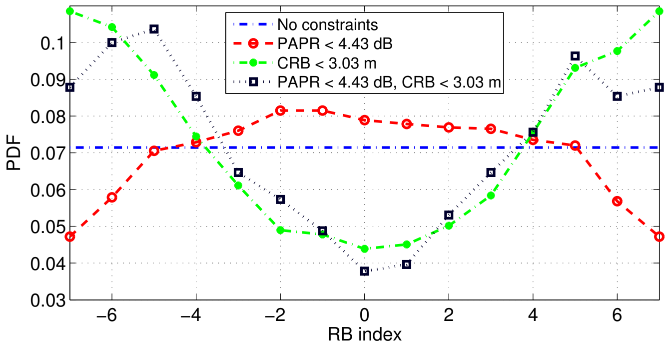
In order to further evaluate this trade-off, the probability density function (PDF) of the active RB placement for each possible combination is shown in Figure 3b, by considering the Zadoff-Chu sequence with minimum PAPR. The resulting PDF is uniform for every available RB, because all possible combinations of placements have been tested. However, if the PAPR is constrained to below 4.43 dB, which is the mean PAPR minus its standard deviation, there is a higher density of active RBs in the central part of the band than at the edges. If the CRB is constrained to below 3.03 meters, which is the mean CRB minus its standard deviation, the PDF of the resulting active RBs follows a similar trend to that for optimal ranging, with a parabolic distribution for the use of frequency resources. Finally, if both CRB and PAPR constraints are applied, the resulting PDF is still driven by the more dense allocation of RBs at the edge of the band, which means that the CRB dominates the PAPR constraint.

C. Distributed Pilot Placement

The maximization of the allocated bandwidth is critical to achieve high-accuracy positioning. However, given a limited number of active resources, the introduction of non-contiguous active RBs can degrade the PAPR. As solution to this trade-off, the interleaving factor can be increased, as it shown in Figure 2. In this sense, contiguous RBs can be allocated to occupy the maximum available bandwidth, while maintaining a good multiplexing capability. The impact of the interleaving factor on the PAPR is assessed by computing the complementary cumulative density function (CCDF) with the 240 Zadoff-Chu SRS codes, sequence length equal to 48, and a system bandwidth of 10 MHz. As it is shown in Figure 4, if the same code sequences are maintained, the resulting PAPR is independent on the spacing between active subcarriers. Thus, the same PAPR is obtained with a localized approach (one pilot every subcarrier) or any interleaving mapping. However, the CRB can be maximized with a high sparsity of pilot resources. This sparsity helps to increase the number of vehicles that can be scheduled and multiplexed within the same pilot symbol. In addition, the low delay spread of the



(a) Contiguous and non-contiguous SRS allocation



(b) PDF of active RB placement

Fig. 3. LTE standard contiguous placement and all possible non-contiguous placements for 8 active RBs out of 15 available RBs (i.e., system bandwidth of 3 MHz), by considering the standard Zadoff-Chu sequences with minimum and maximum PAPR from Figure 1.

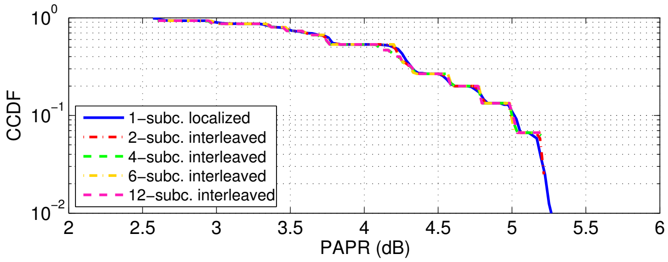


Fig. 4. CCDF of the PAPR for different interleaving factors, by using 240 SRS codes and the same sequence length equal to 48 within a system bandwidth of 10 MHz.

vehicular scenario allows a sparse allocation of equidistant pilots for channel sounding purposes. The pre-defined pattern also helps to reduce the signalling overhead.

Future work is aimed to further study the pilot placement within clusters, to assess the multiband or carrier aggregation approach. The periodicity between pilot symbols and their pilot placement is also of interest. In addition, the pilot design problem can consider obstructed- and non-LoS conditions within the CRB [15], or the channel reciprocity between uplink and downlink in time-division multiplexing (TDD).

V. CONCLUSION

This paper has studied the pilot placement within uplink scenarios dominated by line of sight (LoS), as in fifth generation (5G) vehicular networks. The pilot placement for power efficiency and positioning purposes can fulfil the stringent requirements for these vehicular applications. The Long Term Evolution (LTE) sounding reference signal (SRS) is considered as baseline design, which is based on equipowered and contiguous interleaved subcarriers. Then, contiguous and non-contiguous frequency placements are here studied. The contiguous placement with a high interleaving factor is a candidate design to achieve a high positioning accuracy and low peak-to-average power ratio (PAPR). Future work is aimed to further study clustering placement, symbol periodicity, and channel impairments and reciprocity within vehicular scenarios.

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