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Performance Analysis of 256-QAM Demodulation for 5G NR Sidelink

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Abstract. Higher order modulations are the key elements to the throughput and spectral efficiency increase, especially important for the limited bandwidth scenarios. In this paper, we present a detailed analysis of the 256-QAM signal demodulation performance for the novel sidelink (SL) mode of the 5G NR communication systems. The performance is frequency offset (CFO). It was shown that the CFO has critical impact on the system performance, along with channel mobility. The simple and effective CFO studied in the non-stationary, frequency selective channel in the presence of the carrier compensation algorithm based on the slot-by-slot time-domain signal processing is proposed and investigated. Obtained simulation results have shown the feasibility of the 256-QAM modulation in applications to the main 3GPP sidelink scenarios and parameters, with the proposed CFO compensation method applied even in the case of significant user mobility.

Keywords. 5G NR sidelink, SL, 256-QAM, demodulation, CFO compensation, Doppler effect

1. Introduction

Industry requests for direct communication between large numbers of devices without using base stations eventually lead to the development and implementation of the sidelink (SL) protocols within the framework of the LTE communication systems. Further development of these protocols continued within the next generation of the communication standards, the 5G NR specification. In Rel.16 of the 5G NR, the V2X (Vehicle-to-everything) capabilities based on the air interface were introduced for the first time. Among the new usage models, we should especially note remote driving scenarios in the rapidly changing environment with the high Doppler spread channels. Nevertheless, in most aspects, 5G NR SL in Rel.16 and Rel.17 follow the basic capabilities and options from LTE Rel.15. However, many basic communication elements and options may require additional performance analysis before being implemented in 5G NR SL for the new scenarios and requirements.

Currently, 256-QAM modulation has not yet been adopted for data transmission using the SL protocol. So, at the 3GPP TSG RAN4 (3rd Generation Partnership Project

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Technical Specification Group Radio Access Network) meeting, the possibility of using 256-QAM modulation in SL together with other modulations was discussed [1]. In particular in [2], it was proposed to introduce a test scenario for analyzing the performance of 256-QAM demodulation and to set requirements for it. The extension of the V2X service was defined as the main argument for the introduction of 256-QAM modulation in SL protocol. At the initial consideration stage, this proposal was declined, due to necessity to have relatively high SNR levels for successful 256-QAM demodulation, which may not be typical for V2X scenarios.

The main purpose of this paper is to investigate the performance of 256-QAM demodulation in SL framework based on the test scenario discussed and proposed as the baseline for analysis in [1]. The performance analysis is done by modeling the 5G NR SL communication system with the help of the link level simulator (LLS). During the initial analysis, the critical impact of carrier frequency offsets on the 256-QAM demodulation performance was proven. For this reason, we introduce a new approach for CFO compensation based on the slot-by-slot time-domain signal processing, which is more suitable for SL protocol. The paper discusses the use of an additional CFO compensation block for signal processing in the time domain and shows its effectiveness for a 3GPP test scenario of 256-QAM demodulation performance analysis, as well as for cases of significant user mobility, when the Doppler frequency becomes comparable with the carrier frequency offset.

2. Cyclic-prefix based CFO compensation

CFO is one of the major impairments for the orthogonal frequency-division multiplexing (OFDM) communication systems. Basically, CFO is the result of the frequency mismatch in the RF oscillators at the transmitter and receiver. The negative effect of CFO consists in the destruction of the orthogonality properties of the subcarriers and creating interference between them. The CFO impact on the OFDM performance has been known for a long time from the first IEEE 802.11a OFDM systems. Many different solutions and schemes for CFO compensation have been proposed and studied for more than 25 years [3][4][5][6][7][8][9][10][11]. In our paper, we will focus on the consideration of the additional CFO compensation block for slot-by-slot signal processing in the time domain, which includes a combination of two relatively simple CFO estimation algorithms. The structure of the OFDM communication system, including a CFO compensation block, is shown in Figure 1. Structure of the 5G NR sidelink communication system with the CFO compensation block. The first stage of the CFO compensation includes a rough evaluation/compensation of CFO based on cyclic-prefix (CP) correlation analysis. The second stage includes fine residual evaluation/compensation of CFO using standard pilot (demodulation reference) signals (DM-RS).

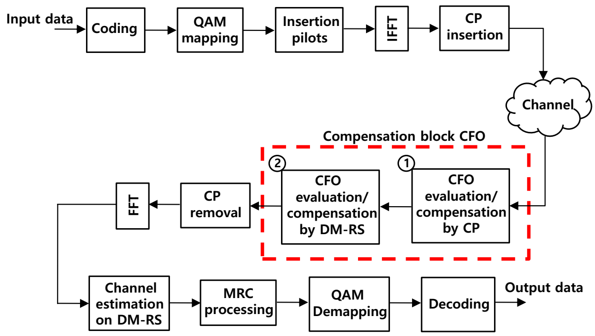

Figure 1. Structure of the 5G NR sidelink communication system with the CFO compensation block

The received signal model can be written as follows (Eq. (1)):

$$y[n] = \sum_{k=0}^{N_{Max_{delay}}} h[k]x[n-k]\, e^{j2\pi\Delta f\Delta t\, n} + w[n], \tag{1}$$

where $x[n]$ is the transmitted signal, k is the sum index, n is the sample index, $y[n]$ is the received signal, $h[k]$ are the channel model coefficients, Δf is the CFO value, Δt is the duration of one sample, $N_{Max_{delay}}$ is the number of samples corresponding to the maximum signal delay in multipath propagation, $w[n]$ are AWGN (Additive white Gaussian noise) samples. Rough evaluation is carried out using a correlation calculation unit (correlator) based on a cyclic prefix. The cyclic prefix is located at the beginning of each OFDM symbol and is a copy of the end of each symbol. Its main purpose is to decrease the inter-symbol interference created by the temporal dispersion of the transmission channel, but it can also be used to evaluate CFO. This is done by finding the phase difference between the cyclic prefix and the end of the symbol. The CFO evaluation using the CP-correlator for all available symbols in the frame can be written as follows (Eq.(2)):

$$\widehat{\Delta f}_{cp} = \frac{1}{2\pi} E\left\{\sum_{p=0}^{p-1} \arg\left\{\sum_{n=N_{Max_{delay}}}^{\frac{N_{CP}}{2}+12} y_p^*[n]y_p[n+N]\right\}\right\}, \tag{2}$$

$$y_p[n] = \sum_{k=0}^{N_{Max_{delay}}} h[k]x_p[n-k]e^{j2\pi(N_g p+n)\Delta f\Delta t} + w[n],$$

$$y_p[n+N] = \sum_{k=0}^{N_{Max_{delay}}} h[k]x_p[n+N-k]\, e^{j2\pi(N_g p+n+N)\Delta f\Delta t} + w[n],$$

where p is the symbol index, N is the symbol length without CP, $N_g = N + N_{cp}$ is the symbol length with CP, arg is the argument of a complex number, E is the averaging. As can be seen from Eq.(2), not all CP samples are used to evaluate CFO. This is due to two negative factors that are taken into account in the corresponding scenario for analyzing the performance of 256-QAM. The first of them is multipath propagation of the signal. Therefore, first CP samples and its replica samples at the end of the symbols are not included in the correlation window for evaluating CFO. The second factor is the synchronization error. This error is defined as timing offset and, for the sake of simplicity of the simulation, it is not modeled explicitly, but rather set to a fixed value. For this reason, the last CP samples and its similar samples at the end of the symbol are also not included in the correlation window when evaluating CFO. Figure 2. Selecting a correlation window for evaluating CFO by CP. shows an illustration of the OFDM symbol. In this figure, the area shaded in blue is the selected correlation window, taking into account the reasons indicated above.

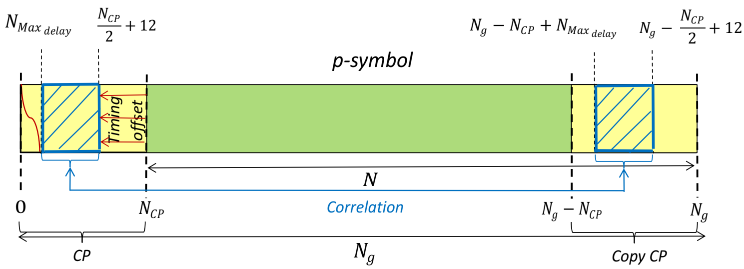

Figure 2. Selecting a correlation window for evaluating CFO by CP.

After the initial CFO evaluation using the CP-correlator, the first stage compensation is carried out in the time domain as shown in Eq.(3):

$$y_{comp_1}[n] = y[n]e^{-j2\pi\widehat{\Delta f_{CP}}\Delta t\, n} \tag{3}$$

The residual CFO is evaluated using PSSCH (Physical Sidelink Shared Channel) DM-RS (Demodulation Reference Signal) pilot signals in the frequency domain, but compensation is carried out also in the time domain (see Figure 1. Structure of the 5G NR sidelink communication system with the CFO compensation block). If there are two symbols for the PSSCH with the DM-RS pilot signals spaced in time, it is possible to evaluate the phase difference between these two symbols. Next, we can transfer to the frequency domain at the position of the symbols PSSCH DM-RS using FFT (fast Fourier transform). We can write down the residual CFO estimate as follows (Eq.(4)):

$$\widehat{\Delta f}_{DMRS} = \frac{E\{arg\{Y_1 Y_2^*\}\})}{2\pi\Delta T}, \tag{4}$$

where ΔT is the time duration between OFDM symbol centers with pilot PSSCH DM-RS, Y_1, Y_2 are demodulated received reference signals in the frequency domain on the first and second OFDM symbols with PSSCH DM-RS. The phase difference makes it possible to estimate precisely the average phase drift between two DMRS symbols. After the evaluation of the residual CFO, the second stage compensation is carried out as shown in (Eq.(5)):

$$y_{comp_2}[n] = y_{comp_1}[n]e^{-j2\pi\,\Delta\widehat{f_{DMRS}}\,\Delta t\, n}, \tag{5}$$

where y_{comp_2} are finally corrected signals in the time domain.

3. Simulation assumptions for SL evaluations

The main parameters of the used scenario were discussed at the 3GPP meeting [1], for analyzing the performance of 256-QAM demodulation, and are shown in Table 1. Main scenario parameters for performance analysis of 256-QAM demodulation in Sidelink. In general, the parameters in Table 1. Main scenario parameters for performance analysis of 256-QAM demodulation in Sidelink. converge with the existing test scenario for 64-QAM in [2], except for the MCS (Modulation Coding Scheme) value and the effective code rate. In the investigated scenario, MCS = 20 [12] and the data transmission channel is a multipath TDL-A (Tapped Delay Line) model, which is described in [13].

Table 1. Main scenario parameters for performance analysis of 256-QAM demodulation in Sidelink.

Parameters	Assumption
Carrier Frequency	6GHz
Bandwidth	20 MHz
Waveform	CP-OFDM
SCS	30 kHz
Resource blocks allocated	10 RBs
Channel Model	TDL-A, 30ns DS, ~30 km/h (Doppler f_D = 180 Hz)
Transmission scheme	1x2 Low, MRC
Timing offset	CP/2 - 12T_S
Frequency offset	600Hz
Modulation	256-QAM, MCS 20 from [12], Table 2
Coding	LDPC
PSSCH Allocation Size	732 REs
Number of DM-RS for PSSCH	120 REs
Transport Block Size of PSSCH	4608 bits
Effective code rate	0.79

The time-frequency structure of the SL subframe (one slot) consisting of 14 OFDM symbols is shown in Figure 3. Time-frequency structure of the SL frame.. As can be seen, in addition to the main PSSCH allocation, containing the data load, there are other channels, as well as standard special signals. They all perform their specific tasks. Similar functionality of these channels and signals can be found in [14]. It is also possible to find more detailed information in a number of review articles on sidelink [15] [16].

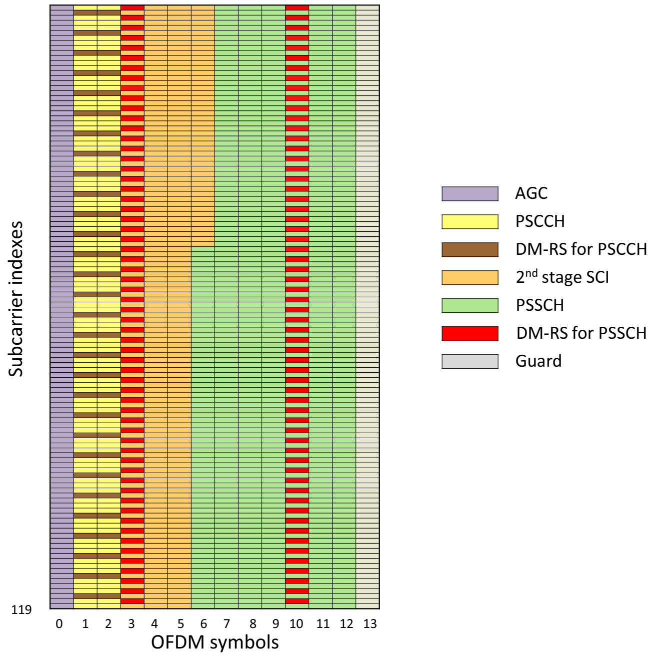

Figure 3. Time-frequency structure of the SL frame.

4. Simulation results

In this section, we present the simulation results obtained using the Matlab-based LLS for 5G NR sidelink. The LLS includes all the necessary elements of the sidelink communication system as shown in Figure 1. Structure of the 5G NR sidelink communication system with the CFO compensation block. In addition, LLS includes all relevant impairments: modeling carrier frequency offset, fixed timing offset and frequency selective offset, as well as time-variant channel with the Doppler spread modeling in accordance with Jakes approach.

Figure 4. Performance results of 256-QAM demodulation in sidelink. shows the 5G NR SL performance results for the 256-QAM modulation in the form of BLER (Block Error Rate) vs. SNR curves. As it can be seen from the presented results, the uncompensated CFO makes 256-QAM transmissions completely impossible (black curve, stationary case). Further, the results show the effectiveness of the CFO compensation block (presented in Figure 1. Structure of the 5G NR sidelink communication system with the CFO compensation block) depending on the channel mobility level in comparison with the ideal case (no CFO). The proposed CFO compensation block has proven to be sufficient for 256-QAM sidelink demodulation and has demonstrated a good efficiency for the cases of significant user mobility. For the main 3GPP scenario with user mobility of 30 km/h ($f_{doppler}$ = 180 Hz), the use of the developed CFO compensation block provides almost full compensation of the CFO and guarantees a BLER level below 10^{-1} with an SNR of ~ 24 dB. A more detailed study of this scenario has shown that using only a CP-compensator (the first stage of the CFO

compensation, see Figure 1. Structure of the 5G NR sidelink communication system with the CFO compensation block) is sufficient to obtain high performance results (see curves for 30 km/h user mobility in Figure 4. Performance results of 256-QAM demodulation in sidelink.). Nevertheless, additional compensation with the use of PSSCH DM-RS gives a gain of ~ 0.5 dB for BLER level of ~ 10^{-1} and about 1.0 dB for BLER level of ~ 10^{-2} .

However, it should be noted that the proposed method for the CFO compensation is based on the slot-by-slot time-domain signal processing, and therefore has several shortcomings. The first one is the necessity of data storage for each successive slot, and the second is its susceptibility to the inter-symbol interference in the case of the strong channel frequency selectivity. Consequently, the scheme may not work properly for the channels with the large delay spread. On the other hand, after the CFO evaluation and compensation block (see Figure 1. Structure of the 5G NR sidelink communication system with the CFO compensation block), the channel estimation procedure in the frequency domain is performed, followed by MRC (Maximum ratio combining) processing. This process can be regarded as another additional compensator of the residual CFO.

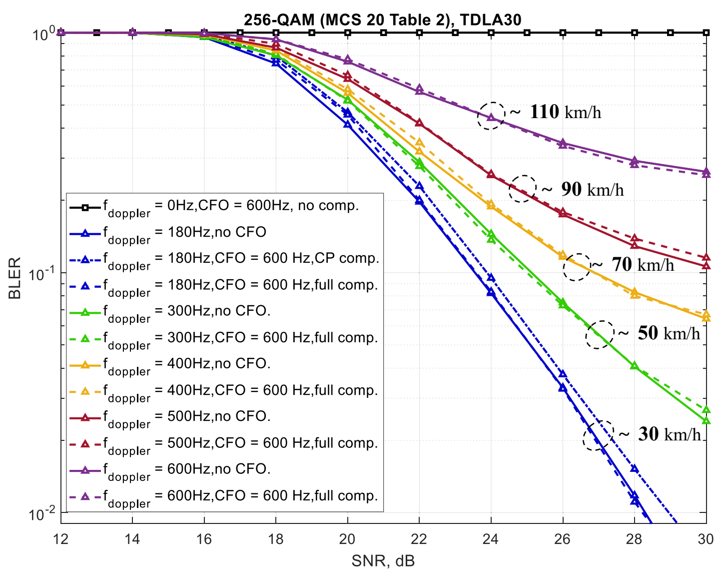

Figure 4. Performance results of 256-QAM demodulation in sidelink.

5. Summary

In this paper, we have shown the 5G NR SL performance results for the 256-QAM demodulation in sidelink mode for the baseline scenarios considered by 3GPP RAN4 meeting [1]. The main purpose of this analysis is to elaborate the requirements for 256-QAM modulation in RAN 4 specification. During the initial studies, the problem of the critical impact of CFO has been revealed. Normally, the CFO should be compensated during the initial acquisition process, on the base of primary and secondary synchronization signals [14]. However, for the purpose of developing the requirements for sidelink mode, we have considered the synchronization and data channels as independent entities. The proposed CFO compensation method based on the independent slot-by-slot time-domain signal processing has shown high efficiency for the cases of significant user mobility and provided an acceptable level of 5G NR SL performance results for the 256-QAM demodulation. Consequently, the discussion about 256-QAM modulation feasibility for the SL mode may be reconsidered for the new Rel.18 sidelink protocol based on the results obtained in this paper.

At the same time, the proposed method for the CFO compensation works properly only for mobile users at speeds up to 70 km/h (see Figure 4. Performance results of 256-QAM demodulation in sidelink.). However, this approach, based on the independent slot-by-slot time-domain signal processing, also may be extended on the Doppler spread compensation in time-varying channels. We consider this line of actions as the next step for further investigations.

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