Development and Experimental Validation of a 5G-NR Simulator Supporting Carrier Aggregation

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Abstract—This paper provides a comprehensive numerical and experimental analysis of 5G end-to-end systems resorting to the use of key features provided by MATLAB’s 5G toolbox. In this work, a 5G carrier fully complying with 3GPP requirements is generated and AWGN noise is added at baseband reception to study the impact of the different modulation formats on the symbol error rate (SER) and error vector magnitude (EVM). The developed simulator based on MATLAB’s 5G toolbox was then modified to incorporate the functionality of carrier aggregation. Finally, the signal generated with the simulator was loaded into an Arbitrary Waveform Generator (AWG) and propagated to an oscilloscope, first using a back-to-back electrical configuration and then using an optical link. The experimental 5G signal was received and processed by the developed MATLAB simulator, and then validated by direct comparison against theoretical and simulation results. The obtained results show that the developed end-to-end simulator is a powerful tool for the numerical and experimental analysis of high-capacity 5G transmission systems, enabling the embedded monitoring of SER and EVM.

Index Terms—5G-NR carrier, carrier aggregation, optical link

I. INTRODUCTION
In 5G - New Radio (NR), the Base Station (BS) and User Equipment (UE) can operate in different frequency ranges depending on radio frequency (RF) specifications such as sensitivity, out-of-band emissions, or network implementations. The spectrum is divided as follows [1], [2]:

| Frequency range type | Spectrum of frequency |
|----------------------|-----------------------|
| FR1                  | 410 MHz - 7125 MHz    |
| FR2                  | 24250 MHz - 52600 MHz |

The main goal of this work is generating 5G signals and measuring some key performance indicators, such as error vector magnitude (EVM) and symbol error rate (SER) with the maximum bandwidths defined by 3GPP for different frequency ranges specified in Table I. For frequency range 1 (FR1) the maximum BS channel bandwidth is 100 MHz and is defined as 273 physical resource blocks (PRB) with a subcarrier spacing (SCS) of 30kHz that will operate in the NR band n40 for the downlink (DL) in the frequency range 2300 MHz – 2400 MHz with time division duplex (TDD) as defined by 3GPP for the NR band n40 [2].

Before explaining the modules that make part of the simulator, it is necessary to introduce the concept of guardband (GB) and how to calculate the central frequency of the carriers that perform carrier aggregation. The relation between channel bandwidth and guardband can be observed in the figure below (Fig. 1).

![Channel bandwidth and transmission bandwidth for one carrier](image)

The guardband (in kHz), considering the maximum number of resource blocks for a 5G-NR carrier bandwidth (BW in kHz), can be calculated using the following expression [1]:

\[
GB = \frac{BW - N_{RB} \cdot 12 \cdot \Delta f - \Delta f}{2},
\]

where \(N_{RB}\) is the transmission bandwidth defined as the number of resource blocks (RB) and \(\Delta f\) is the SCS in kHz.

In the case of multi-carrier aggregation, we will perform intra-band contiguous carrier aggregation, as defined in Fig. 2. As we can observe in Fig. 2 the aggregated channel bandwidth \(BW_{Channel,CA}\) can be given by [2]:

\[
BW_{Channel,CA} = F_{edge,high} - F_{edge,low}
\]

The values of \(F_{edge,high}\) and \(F_{edge,low}\) can be calculated using the following equations [2]:

\[
F_{edge,high} = F_{C,low} - \frac{(N_{RB,low} \cdot 12 + 1) \cdot SCS_{low}}{2} + GB_{low}
\]

This work was partially supported by FEDER, through the CENTRO 2020 programme, projects ORCIP (CENTRO-01-0145-FEDER-022141) and SOCA (CENTRO-01-0145-FEDER-000010) and by FCT/MCTES through project FreeComm-B5G (UIDB/EEA/50008/2020). Fernando P. Guiomar acknowledges a fellowship from “la Caixa” Foundation (ID 100010434). The fellowship code is LCF/BQ/PR20/11770015.
OFDM Equalization
5G-NR Custom Waveform Generation
Synchronization
Propagation Channel
Results

\[ F_{\text{edge,low}} = F_{C,\text{high}} + \frac{\left( N_{RB,\text{high}} \cdot 12 - 1 \right) \cdot SC_{S,\text{high}} + GB_{\text{high}}}{2}, \quad (4) \]

where \( F_{C,\text{high}}, N_{RB,\text{low}}, SC_{S,\text{low}} \) and \( GB_{\text{low}} \) corresponds respectively to the central frequency, number of RBs, SCS and guardband of the lowest carrier aggregated and \( F_{C,\text{high}}, N_{RB,\text{high}}, SC_{S,\text{high}} \) and \( GB_{\text{high}} \) corresponds respectively to the central frequency, number of RBs, SCS and guardband of the highest carrier aggregated.

Considering that we are operating in NR n40 band, the channel raster will be equal to 100 kHz (table 5.4.2.3-1 [2]). So as defined in [2] the channel spacing between two consecutive aggregated carriers (\( \Delta F_c \) in MHz) will be given by:

\[ \Delta F_c = \frac{BW_{(1)} + BW_{(2)} - 2 \cdot GB_{(1)} - GB_{(2)}}{0.6} \cdot 0.3, \quad (5) \]

where \( BW_{(1)} \) and \( BW_{(2)} \) correspond respectively to the channel bandwidth of the two aggregated carriers in MHz, and \( GB_{(1)} \) and \( GB_{(2)} \) correspond respectively to the guardband associated with each of the two aggregated carriers also expressed in MHz units.

II. DEVELOPMENT OF THE SIMULATOR

A. Single-carrier simulator

Knowing that the objective of this paper was to create a 5G-NR simulator and measure the EVM and SER characteristics at the end of the system, numerically and experimentally, a function was created to generate 5G-NR carriers. The scripts provided by ‘5G NR Downlink Carrier Waveform Generation’ in 5G MATLAB Toolbox [3] were adapted to be able to control the generation of a 5G-NR carrier in terms of BS bandwidth, modulation format type for the physical downlink shared channel (PDSCH) signal, and the number of RB allocated for the same signal (signal under test). After this, it was necessary to create a script able to take these 5G-NR carriers and pass it over a additive white Gaussian noise (AWGN) channel with different values of signal-to-noise ratio (SNR).

To create a simulator able to take custom 5G-NR waveforms and measure EVM and SER characteristic over a AWGN channel with different SNR values, the scripts from ‘Test and Measurement’ provided by 5G MATLAB Toolbox [3] that already had a builtin function to measure the overall RMS EVM and the MAX EVM along with the subcarriers were modified and was added the capability to measure the SER of the PDSCH symbols, and display the constellation symbols of the same signal for a specific SER probability. The scheme of the work performed can be observed in Fig. 3.

In the figure above we can observe the scheme of the simulator developed. Based on this figure, the custom 5G-NR waveform is generated and in the next phase, the signal is upconverted and modulated to a specific frequency (depending on the operating band). After this, the waveform is demodulated to baseband and downconverted to the original sampling frequency. Then the waveform is filtered with a FIR filter (to ensure that all component of the waveform suffers the same delay from it) and it is added AWGN noise to the time domain signal. Then the waveform is filtered with a LPF filter and it is added AWGN noise to the time domain signal. In the end, after extracting the equalized PDSCH symbols, the RMS EVM of the overall waveform and the SER is computed.

B. Multi-carrier aggregation simulator

From the single-carrier simulator developed in section II-A, the simulator was adapted to be able to aggregate multiple 5G-NR carriers as specified in section I.

The 5G-NR waveforms are generated and modulated in different central frequencies, using equation 5, which guarantees
the guardband specifications by 3GPP (as in Fig. 2). After that, the two carriers are summed in the time domain and processed individually, after being isolated and filtered, as in the single-carrier simulator. In the end, we have two measurements for EVM and SER corresponding to the two 5G-NR carriers aggregated. The overall EVM and SER measurements will be the mean of the EVM and SER measurements of all 5G-NR carriers.

III. NUMERICAL VALIDATION

A. Simulator with a single-carrier 100 MHz BS bandwidth

![Fig. 4. Mean EVM of different modulation formats for different SNR values in a 100 MHz TDD configuration with an SCS of 30 kHz](image)

As defined in table 6.5.2.2-1 [2] the maximum average EVM depends on the modulation format. As we can observe in Fig. 4, after 32dB of SNR all modulation formats respect the 3GPP EVM requirements.

Also as we can see in Fig. 5, modulation formats with a higher number of symbols (more bits per symbol), such as 64-QAM and 256-QAM, are more affected by noise (because the average energy per symbol is the same for all QAM formats), and the experimental SER of these modulations moves further and further away from the theoretical SER as the number of symbols increases (due to penalties introduced by the OFDM demodulator).

B. Simulator with a multi-carrier aggregation scheme

Since the aggregated 5G-NR carriers on the simulator respect the guardband requirements by 3GPP, the overall carrier aggregated spectrum can be separated in individually 5G-NR carriers that will output results similar to the ones obtained in section III-A. The overall EVM and SER measurements will then be the mean of the EVM and SER of all 5G-NR carriers.

IV. EXPERIMENTAL VALIDATION

A. Experimental Setup

To replicate the system experimentally, the simulator developed in the sections above was incorporated in a script to generate a 5G-NR carrier, upsample and modulate it on a specific frequency (depending on the carrier bandwidth) and load it to an arbitrary waveform generator (AWG), Tektronix AWG700002, with 16 Gsa/s and ~7 GHz bandwidth. The carrier at the output of the AWG was then transmitted both over a coaxial cable and a fiber optic cable. After transmission, the signal samples were received by a real-time oscilloscope (Keysight DSOS804A) with 20 Gsa/s and 8 GHz bandwidth. Finally, the signal is inserted on the processing chain of the simulator reception side as in Fig. 3 to compute the EVM and SER measures associated with that transmission.

To receive on the oscilloscope the whole 5G-NR carrier generated in MATLAB, the number of samples received by the oscilloscope must be two times greater than the number of samples of the 5G-NR carrier upconverted with the sampling rate of the oscilloscope (this guarantees that we always receive the whole 5G waveform). Because of this, a function was created that given as input the number of RB, the channel bandwidth, sample frequency of the AWG and the oscilloscope outputs the the number of samples advised to be received on the oscilloscope.

To simulate the system experimentally, and prove the operation of the simulator developed, 5 MHz and 100 MHz channel bandwidth 5G-NR carriers, modulated on 50 MHz and 150 MHz (lowest IF tested to reduce the number of samples to be received by oscilloscope) respectively were used.

The channel used to study the 5G-NR simulator was an optical back-to-back (B2B) link observed in Fig. 6. The optical link was created using modified small form-factor pluggable (SFP) low-cost transceivers to perform analog transmission [4] with direct modulation of the laser (DML). It was also necessary to introduce a voltage optical attenuator (VOA) to optimize the optical power at the photodetector.

B. Experimental Results

In table II we can see the overall RMS EVM of the 5G-NR carrier transmitted for the two channels bandwidths. In Fig. 7 and 8 we can observe the RMS EVM measurement per subcarrier and the constellation PDSCH symbols for the
5G-NR carrier (with PDSCH signal modulated with QPSK) received on an optical link of Fig. 6.

For the 100 MHZ channel bandwidth 5G-NR carrier the scheme has the same as before. Fig. 9 and 10 show the RMS EVM measurement per subcarrier and the constellation PDSCH symbols for the 5G-NR carrier (with PDSCH signal modulated with QPSK) received on an optical link of Fig. 6.

Comparing the results obtain above we can see that the overall RMS EVM and RMS EVM per subcarrier are higher in the 100 MHz carrier bandwidth than in the 5 MHz carrier bandwidth. These results are expected since, as the bandwidth of the 5G-NR carrier increases, the losses introduced by the components that make part of the optical link will also increase (for example the SFP transceivers as demonstrated in [4]).

As we can observe in Fig. 10 the first RBs (approximately the first 125 RB) are affected by a higher penalty that the rest of the RB of the 5G-NR carrier. This extra penalty may be caused by the propagation channel. To compensate for this penalty we can apply techniques such as bit loading and power loading (in the firsts RBs) to the pre-transmitted 5G-NR carrier [5].

| Measurement Type | Configuration Type | 5 MHz RMS EVM [%] | 100 MHz RMS EVM [%] |
|------------------|--------------------|------------------|---------------------|
| Optical link     |                    | 14.1043          | 15.9533             |

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Fig. 6. Experimental setup for the validation of the developed 5G simulation package.

Fig. 7. PDSCH signal constellation symbols with 5 MHz carrier on an optical link

Fig. 8. EVM vs subcarrier on optical link with 5 MHz carrier

Fig. 9. PDSCH signal constellation symbols with 100 MHz carrier on an optical link

Fig. 10. EVM vs subcarrier on optical link with 100 MHz carrier
V. CONCLUSIONS

This work enables a way to perform a numerical and experimental analysis of the EVM and SER measures associated with the transmission of 5G-NR including carrier aggregation using a MATLAB-based simulator.

The obtained experimental results have shown that the developed simulator can reliably generate and process 5G-NR carriers with different bandwidths (5 MHz and 100 MHz have been demonstrated) that are fully compliant with 3GPP requirements, and provide valuable key performance indicators such as SER and EVM. The system has been validated both in the electrical B2B and with optical fiber transmission.

As future work, we intend to introduce techniques such as power and bit loading to pre-compensate individual RBs against the distortions and penalties introduced by the propagation channel. In addition to this, we intend to optimize the optical power values of the system in order to decrease the overall EVM. Finally, we intend to proceed to experimental testing, regarding the functionality of carrier aggregation and the transmission of 400 MHz channel bandwidth 5G-NR carriers.

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