WHITE PAPER

Testing 5G NR Devices with Standard Waveforms

MathWorks®

Introduction

The Fifth Generation New Radio (5G NR) standard is currently being defined by 3GPP, the group that defined the previous generation, known as LTE. Release 15 was launched in December 2017, and the initial version of Release 16 is being worked on at the time of publication. Two of the many features of 5G NR are support for a much larger bandwidth than LTE and carrier frequencies that can range up to 52.6 GHz (Table 1).

Frequency Range 1 (FR1)	Frequency Range 2 (FR2)
410–7125 MHz (*)	24,250–52,600 MHz

Table 1. Frequency ranges for 5G NR.

* FR1 is sometimes referred to as "sub-6 GHz," but the upper limit was increased from 6 GHz to 7.125 GHz in the June 2019 release of the standard (see [5] section 5.2).

These developments in the standard present engineers with new implementation challenges, as well as new testing challenges. It is important to assess the impact of the whole transmit and receive chain—including filtering, power amplifiers, clock and phase jitter, and antennas—on the signal quality, and doing so requires access to standard-compliant waveforms.

In this white paper, we review the types of standard waveforms available and generate a few examples of such waveforms. We also compute error vector magnitude (EVM), a measure of the quality of a waveform. Finally, we look at the impact on EVM of different impairments and compensating algorithms, including phase noise in the mmW region and filtering to reduce spectral leakage.

Standardized Waveforms

As part of the standardization process, 3GPP has defined reference waveforms of several types, which are used as the basis for tests such as throughput and EVM.

There are several types of reference waveforms:

- Test models (NR-TMs)
- Reference measurement channels (RMCs) and fixed reference channels (FRCs)

NR-TMs are downlink only, defined in [1] and [2], and used for measurements such as EVM, adjacent channel leakage ratio (ACLR), intermodulation, and dynamic range. These waveforms are relevant because they cover different types of modulation and different resource allocations (or spectrum occupancy).

RMCs and FRCs are defined in [3], [4], and [5] and cover both downlink and uplink. Those waveforms are used for receiver performance, maximum input level, and transmitter characteristics.

In this white paper, we generate NR-TM waveforms and perform EVM measurement with various waveforms and under various assumptions and levels of impairments.

Generating Waveforms

5G Toolbox™ provides access to 5G-compliant NR-TM waveforms, which you can use to test 5G devices. 5G Toolbox also lets you create many other types of waveforms, including RMCs, FRCs, or custom waveforms. In the rest of this paper, we focus on NR-TM waveforms.

Specifications

[1] section 4.9.2 and [2] section 4.9.2 define NR-TMs for FR1 and FR2, respectively. Table 2 presents an overview of those test model waveforms.

Test Model	Resource Allocation	Modulation	Example Usage
NR-FR1-TM1.1	Full band	Uniform QPSK	ACLR, intermodulation
NR-FR1-TM1.2	Full band	Boosted QPSK and deboosted QPSK	ACLR
NR-FR1-TM2	Single PRB	64QAM	EVM
NR-FR1-TM2a	Single PRB	256QAM	EVM
NR-FR1-TM3.1	Full band	Uniform 64QAM	EVM, dynamic range
NR-FR1-TM3.1a	Full band	Uniform 256QAM	EVM, dynamic range
NR-FR1-TM3.2	Full band	Deboosted 16QAM and boosted QPSK	EVM
NR-FR1-TM3.3	Full band	Deboosted QPSK and boosted 16QAM	EVM
NR-FR2-TM1.1	Full band	Uniform QPSK	ACLR, occupied bandwidth
NR-FR2-TM2	Single PRB	64QAM	EVM
NR-FR2-TM3.1	Full band	Uniform 64QAM	EVM, dynamic range

Table 2. NR-TMs for 5G NR.

The two examples below show how to generate NR-TMs with just a few parameters to select:

- TM name
- Desired bandwidth
- Subcarrier spacing
- Duplexing mode (FDD or TDD)

We first generate a single physical resource block (PRB) waveform, then full-band waveforms.

Single PRB Waveform

Let us select NR-FR2-TM2, which corresponds to single PRB allocation with 64QAM. The allocated PRB changes every slot, as specified in [2].

```
% Select the NR-TM or FRC waveform parameters
nrref   = NR-FR2-TM2    (...  ; % Model name and properties
bw      = 50MHz (FR1 & FR2)   ; % Channel bandwidth
scs     = 60kHz (FR1 & FR2)   ; % Subcarrier spacing
dm      = FDD                 ; % Duplexing mode
ncellid = 1                   ; % NCellID
sv      = V15.2.0             ; % TS 38.141-x version (NR-TM only)

% Run this entire section to generate the required waveform
Generate
```

Figure 1. Selecting parameters for an NR-FR2-TM2 waveform.

Clicking the Generate button generates a waveform compliant with TM specifications. Figure 2 shows the spectrum of the generated waveform with the settings shown in Figure 1.

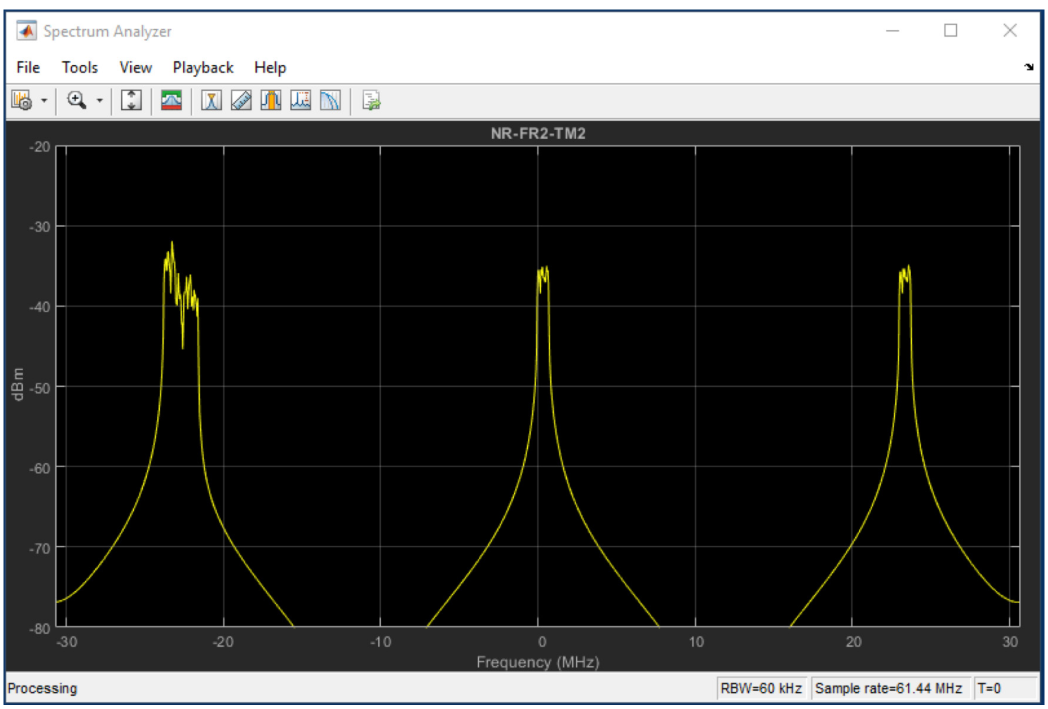

Figure 2. Spectrum of NR-FR2-TM2 waveform with 50 MHz bandwidth and 60 kHz subcarrier spacing.

The plot shows three peaks, one at each possible location of the data (PDSCH): lower edge, middle, and upper edge of the band. The peak at the lower edge includes energy associated with the control channel (PDCCH).

Figure 3 shows 4 ms worth of the resource grid before OFDM modulation; the x-axis represents the OFDM symbol number (i.e., time), and the y-axis represents the resource block number (i.e., frequency). One can clearly see the periodic switching of PDSCH resource allocation over time between the lower edge, middle, and upper edge of the band, as well as the PDCCH assignment at the lower edge.

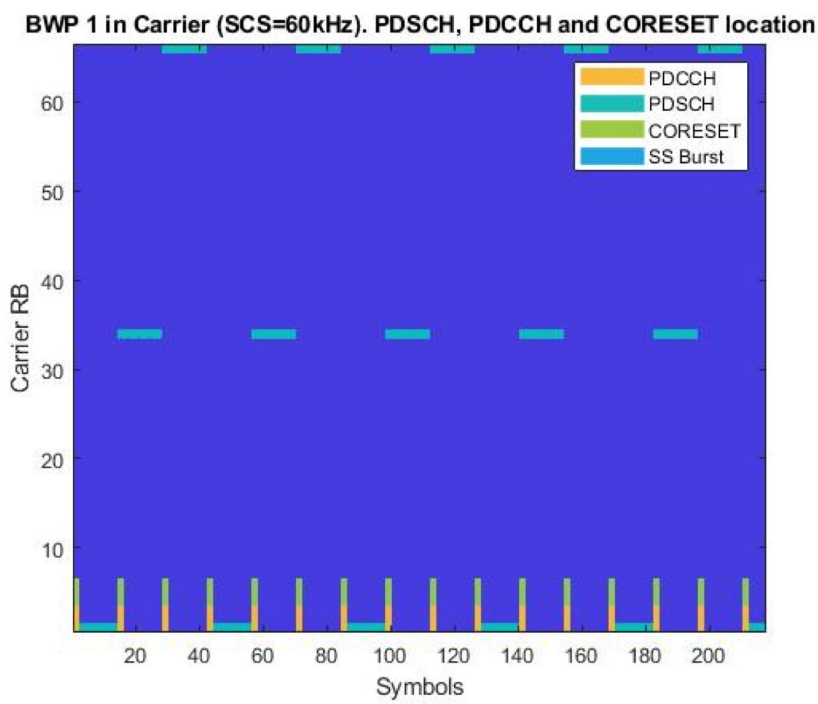

Figure 3. OFDM grid of NR-FR2-TM2 waveform with 50 MHz bandwidth and 60 kHz subcarrier spacing.

Full-Band Waveform

Next, we generate a full-band 256QAM waveform for FR1 with 100 MHz bandwidth:

```
% Select the NR-TM waveform parameters
nrtm = "NR-FR1-TM3.1a"; % NR-TM name and properties
bw   = "100MHz"; % Channel bandwidth
scs  = "30kHz"; % Subcarrier spacing
dm   = "FDD"; % Duplexing mode
```

Figure 4 shows the spectrum of the generated waveform. This waveform occupies most of the 100 MHz bandwidth, with a slight guard band on both sides.

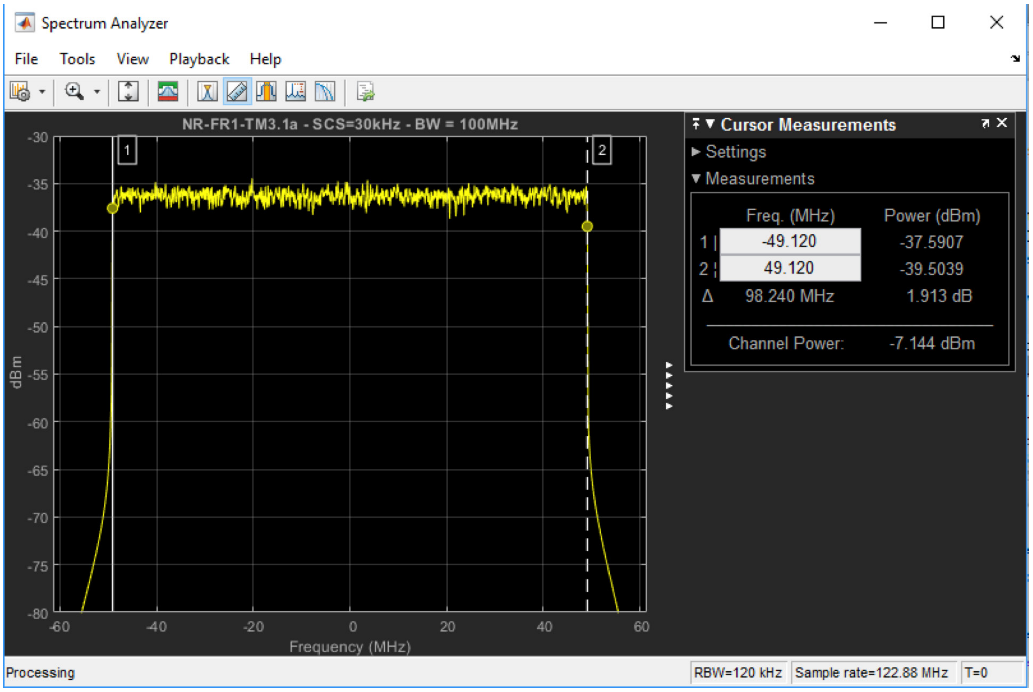

Figure 4. Spectrum of NR-FR1-TM3.1a waveform with 100 MHz bandwidth and 30 kHz subcarrier spacing.

Figure 5 shows the resource block allocation for PDSCH and PDCCH for this waveform. The PDSCH occupies all RBs except for part of the first three, which are reserved for the PDCCH.

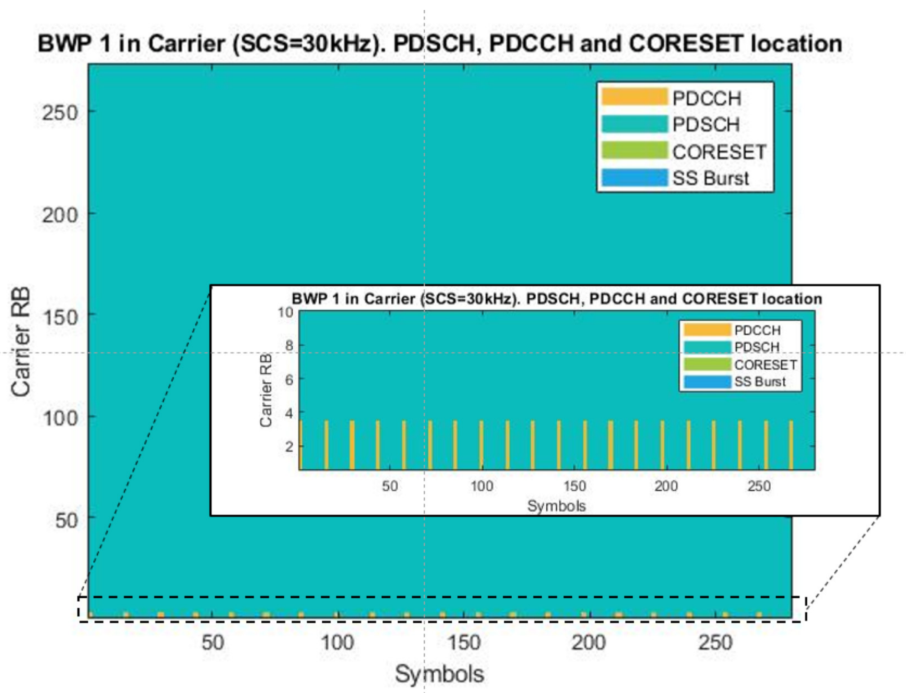

Figure 5. OFDM grid of NR-FR1-TM3.1a waveform with 100 MHz bandwidth and 30 kHz subcarrier spacing with a detail of the lower 10 resource blocks.

Spectral Characteristics

At this point, the waveform has not undergone any filtering and would not pass ACLR tests. You can use a digital filter to improve leakage into adjacent bands. MATLAB® offers many options for designing filters including single-rate and multirate filters and polyphase architectures.

Here we use a single-rate filter with a passband frequency at the band edge and a cutoff frequency set 5% higher than the passband:

```
%% Filter
fir = dsp.LowpassFilter();
fir.SampleRate = samplingrate;
transitionBand = 5;  % percent
% Bandwidth is product of number of subcarriers by SCS
SCS = tmwaveinfo.Info.SubcarrierSpacing;
BW = tmwaveinfo.Info.NSubcarriers * (SCS * 1e3);
fir.PassbandFrequency = BW/2;
fir.StopbandFrequency = (BW/2)*(1+transitionBand/100);
fir.StopbandAttenuation = 80; % dB

% Apply filter
txWaveform = step(fir,tmwaveform);
```

Figure 6 displays the magnitude of the filter response.

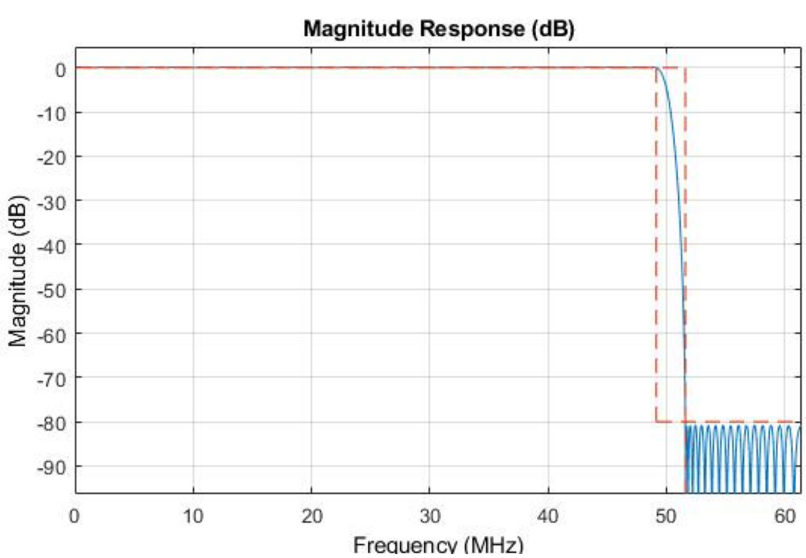

Figure 6. Magnitude of the filter response for the NR-FR1-TM3.1a waveform.

The filter meets the specified passband, transition band (5% of passband), and 80 dB stopband attenuation.

Figure 7 shows the spectrum of the original waveform (without filtering) and of the filtered waveform.

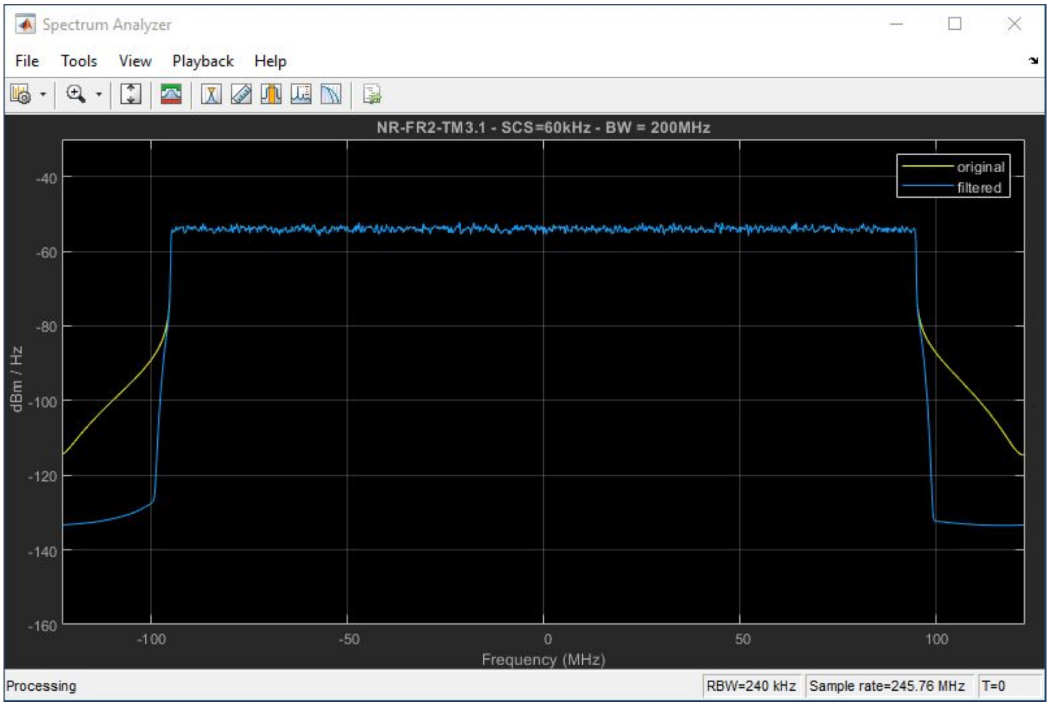

Figure 7. Spectrum of NR-FR1-TM3.1a waveform with and without filtering.

The spectrum of the filtered waveform has a good chance of meeting ACLR requirements.

EVM Measurement

Error vector magnitude is a measure of the difference between the reference waveform and the measured waveform. [3] and [4] section 6.4.2.1 for the user equipment (UE) and [5] section 6.5.2 for the gNodeB define minimum requirements for EVM.

[5] Annex C describes in detail how to measure EVM for FR2 waveforms. In addition to this procedure, [5] section 6.5.2.2 specifies that EVM measurement should skip the first two symbols of each slot. Table 3 shows the requirements for the downlink direction taken from [5].

Modulation Scheme for PDSCH	Required EVM (%)
QPSK	17.5
16QAM	12.5
64QAM	8
256QAM	3.5

Table 3. EVM requirements from TS 38.104 section 6.5.2.2.

Here, we want to measure the EVM of the NR-FR1-TM3.1a waveform we generated earlier. Processing includes synchronization, channel estimation, and equalization to recover the 256QAM constellation:

```
% Grid for current slot
currentGrid = rxGrid(:,NSlot*SymbolsPerSlot+(1:SymbolsPerSlot),:);
[estChannelGrid,noiseEst] = hChannelEstimatePDSCH(gnb,pdsch,currentGrid);

% Get PDSCH resource elements from the received grid
[pdschRx,pdschHest] = nrExtractResources(pdschIndices,currentGrid,estChannelGrid);

% Equalization: set noiseEst to 0 for zero-forcing equalization
noiseEst = 0;
[pdschEq,csi] = nrEqualizeMMSE(pdschRx,pdschHest,noiseEst);

% Decode PDSCH physical channel
[dlschLLRs,rxSymbols] = nrPDSCHDecode(pdschEq, ...
     pdsch.Modulation,gnb.NCellID,pdsch.RNTI,noiseEst);
```

Figure 8 shows the recovered 256QAM constellation after equalization.

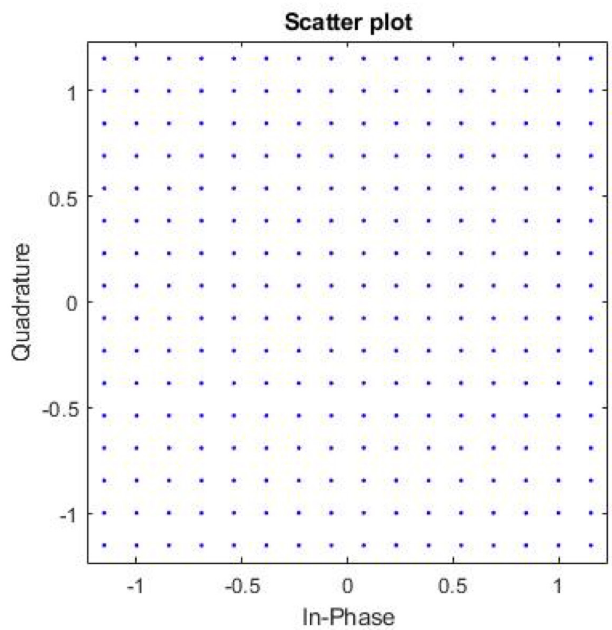

Figure 8. 256QAM constellation recovered in the receiver.

The EVM measured on the waveform without filtering is virtually 0%, or -272 dB. This is because the waveform is ideal, with no spectral limitation and no impairments, and uses floating-point values.

Adding the filter discussed above to the chain greatly decreases leakage into the adjacent band but, at the same time, introduces a little distortion, particularly at the edge of the band. The overall EVM is still an excellent -90.2 dB or close to 0%.

Figure 9 shows the EVM for each resource element in the last slot of the filtered waveform.

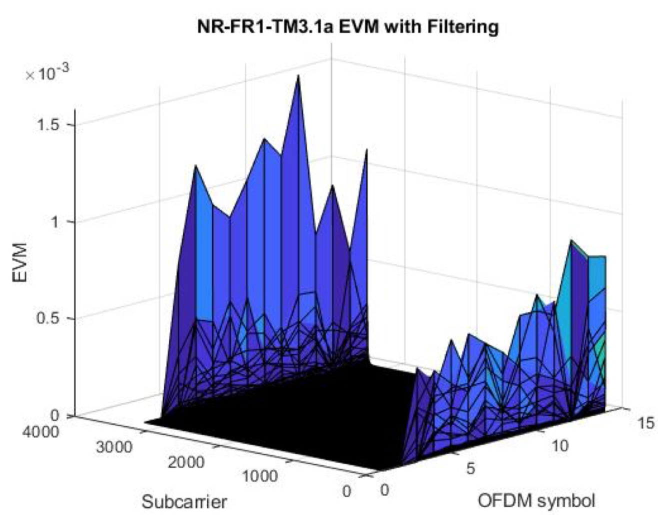

Figure 9. EVM of the filtered NR-FR1-TM3.1a waveform for each resource element in the last slot.

As can be readily seen, the EVM is maximum at the bottom and top of the subcarrier range. These are the areas next to the transition band—that is, at the edge of the passband. These areas represent the parts of the passband that experience the highest ripple.

The second takeaway is that good ACLR can be achieved with no significant impact on EVM.

Impairments: Phase Noise

At millimeter waves (24 GHz and up), phase noise can become a dominant issue in signal quality. Phase noise is generated by local oscillators and phase-locked loops (PLLs) that are part of the front end of a receiver chain.

3GPP TS 38.803 [6] offers examples of phase noise models for a receiver around 30, 45, and 70 GHz. Here we want to take the example of 30 GHz.

In this example we consider NR-FR2-TM3.1, a full-band 64QAM waveform for FR2, and specify the characteristics as shown in Table 4.

Waveform	Modulation	Subcarrier Spacing	Bandwidth
NR-FR2-TM3.1	64QAM	60 kHz	200 MHz

Table 4. Specified characteristics for the NR-FR2-TM3.1 waveform.

Here are the parameters to select to generate this waveform:

```
% Select the NR-TM waveform parameters
nrtm = "NR-FR2-TM3.1";  % NR-TM name and properties
bw   = "200MHz"; % Channel bandwidth
scs   = "60kHz"; % Subcarrier spacing
dm   = "FDD"; % Duplexing mode
```

The phase noise model in [6] section 6.1.10 is defined as follows:

$$PN(f_0) = PSD_0 \cdot \frac{\prod_{n=1}^{N} 1 + \left(\frac{f_0}{f_{z,n}}\right)^{\alpha_{z,n}}}{\prod_{m=1}^{M} 1 + \left(\frac{f_0}{f_{p,n}}\right)^{\alpha_{p,m}}}$$

Where $f_{z,n}$, $\alpha_{z,n}$, $f_{z,m}$, $\alpha_{z,m}$ are specified as follows:

n,m	$f_{z,n}$	$\alpha_{z,n}$	$f_{p,m}$	$\alpha_{p,m}$
1	3e3	2.37	1	3.3
2	550e3	2.7	1.6e6	3.3
3	280e6	2.53	30e6	1

and PSD_0 = 1585 (or 32dB).

This model translates into the phase noise profile shown in Figure 10.

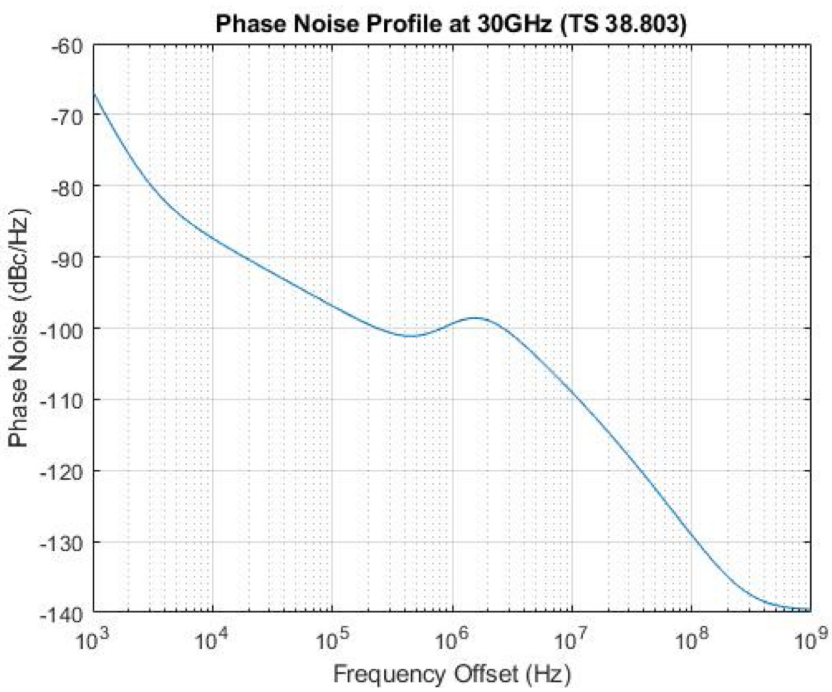

Figure 10. Model of phase noise according to 30 GHz example in 3GPP TS 38.803.

Communication System Toolbox™ includes a variety of models for RF impairments, including **comm.PhaseNoise** for phase noise.

Here, we model the phase noise with **comm.PhaseNoise** in the signal bandwidth, which is up to half the sampling rate. This model accepts a vector of frequency offset values, f, and the corresponding phase noise level in dBc/Hz, PN_dBc. We chose to define the phase noise at logarithmically spaced frequencies between 10 kHz and half the sampling rate.

```
%% Phase Noise Model
x = 4:0.11:log10(fir.SampleRate/2); % offset from 1e4Hz to fs/2
f = 10.^x;      % Frequency is logarithmically spaced
PN _ dBc = PNmodel(f);
pnoise = comm.PhaseNoise('FrequencyOffset',f,'Level',PN _ dBc,...
     'SampleRate',fir.SampleRate);
rxWaveform = pnoise(txWaveform);
```

When we include the phase noise model above, the EVM increases considerably to reach about -28 dB or 4%. Figure 11 shows the constellation of the demodulated waveform affected by phase noise.

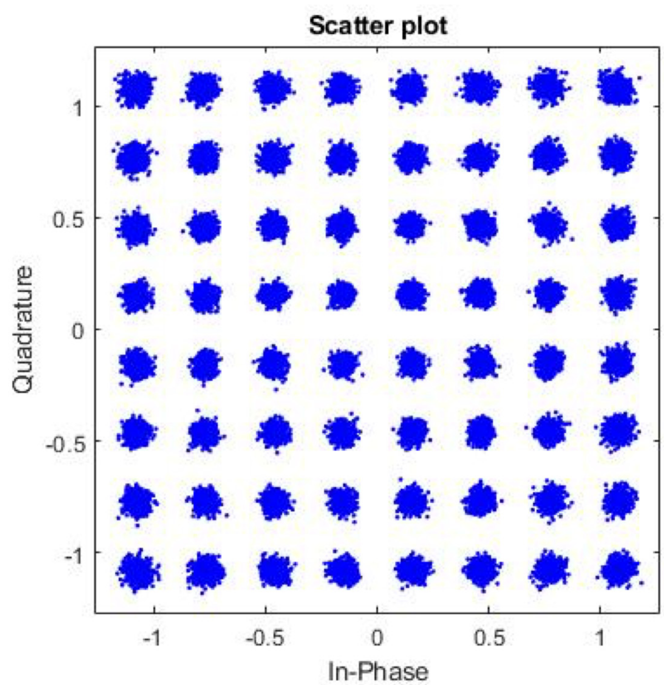

Figure 11. Constellation of NR-FR2-TM3.1 waveform corrupted by phase noise.

Figure 12 shows the EVM for each resource element in the last slot of the filtered waveform.

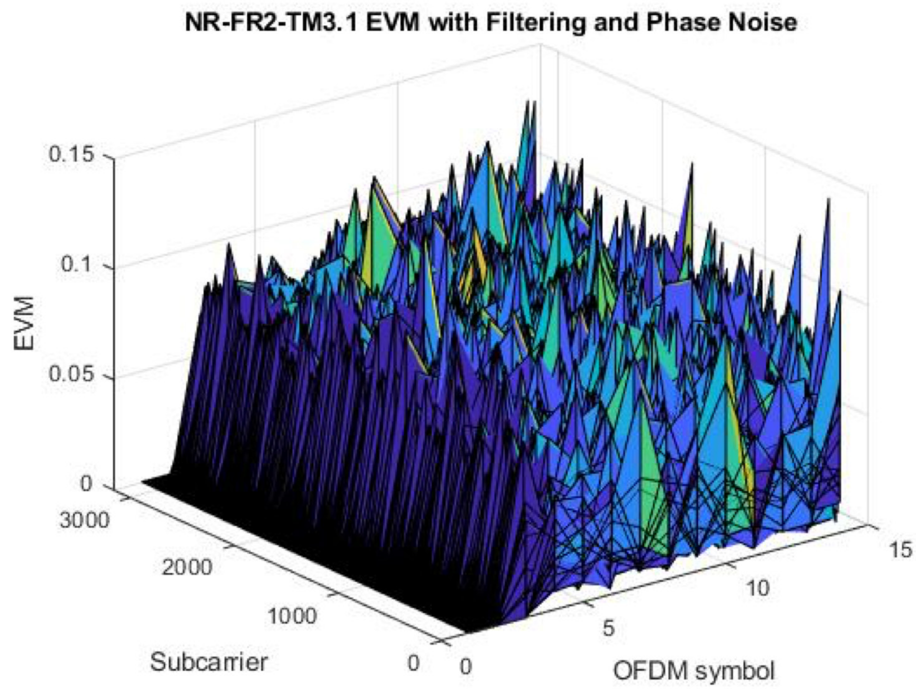

Figure 12. EVM of the NR-FR2-TM3.1 waveform corrupted by phase noise, for each resource element in the last slot.

As a reminder, 3GPP specifies a maximum of 8% or -21.93 dB EVM level for 64QAM, as per [5] section 6.5.2.2, as shown in Table 3. So, this phase noise model provides some margin for 64QAM modulation, but it may make 256QAM modulation difficult.

This example highlights two important points:

- Phase noise matters at high carrier frequencies. If not properly optimized, it can lead to severe degradations of the signal quality.
- Modeling the impact of phase noise on waveform quality is critical, and MATLAB lets you perform this analysis early in the design phase.

Other Impairments: Power Amplifiers and Design of DPD Algorithms

Phase noise, although critical, is not the only impairment to investigate when considering the transmission chain. Another key element is the power amplifier, where nonlinearity, frequency-dependent characteristics, and memory all play a role. To learn more about modeling power amplifiers and designing a digital predistortion (DPD) algorithm for them, see the example ***Power Amplifier Characterization with DPD for Reduced Signal Distortion.***

This example shows how to take measurement data from a lab; develop an equivalent behavioral model, which includes nonlinearity and memory effect; place this model in a larger transmission chain; and develop a DPD algorithm to linearize the overall chain.

Conclusion

In this white paper, we discussed the need for standard-compliant waveforms and how to generate them using 5G Toolbox. We then showed how to incorporate a filter in the chain for ACLR reduction and performed EVM measurement. Finally, we included phase noise from a mmWave model and observed how EVM was affected.

MATLAB and *5G Toolbox* enable you to investigate different waveforms, filters, and impairments such as phase noise and power amplifiers, and optimize your system while still at the conceptual phase.

References

[1] 3GPP TS 38.141-1 version 15.2.0, June 2019

[2] 3GPP TS 38.141-2 version 15.2.0, June 2019

[3] 3GPP TS 38.101-1 version 15.6.0, June 2019

[4] 3GPP TS 38.101-2 version 15.6.0, June 2019

[5] 3GPP TS 38.104 version 15.6.0, June 2019

[6] 3GPP TS 38.803 version 14.2.0, September 2017

Next Steps

Learn more about using MATLAB for 5G and 5G NR applications:

5G Explained - Video Series

5G Toolbox - Overview

5G Wireless Technology - Overview

5G New Radio Design with MATLAB - Ebook

Power Amplifier Characterization with DPD for Reduced Signal Distortion - Example