5G Waveform Evaluations
for mmWave Communication Using SystemVue

Introduction

Due to the potential availability of enormous channel bandwidths, the millimeter wave (mmWave) bands are currently being eyed for mobile radio communications. Larger channel bandwidths are critical to enabling the wireless industry to meet the increasing data rate and capacity demands of future wireless networks. One of the key issues in the radio interface design for mmWave communications is the selection of waveform. A key challenge; however, is that at high carrier frequencies, e.g. mmWave bands, transmitted and received signals can suffer from severe hardware impairments. Evaluating the performance of several state-of-the-art waveforms in the presence of hardware impairments is therefore of great importance to proper waveform design.

Mobile radio communication above 6 GHz, otherwise known as the mmWave frequency range, holds great promise these days. The key reason for its appeal is that it has a vast amount of spectrum available, especially when compared to the legacy sub-6 GHz bands in use today. Additionally, at mmWave frequencies, antennas are much smaller. Consequently, a large number of antennas can fit into a single mobile device, with beamforming techniques being used to combat hostile propagation channels. Because of these advantages, mmWave communication is today considered as one of the key components for the realization of 5G radio access technology, also termed New Radio (NR).

For mmWave communication, a fundamental issue is the waveform design. In recent years, a number of multi-carrier (MC) and single-carrier (SC) waveforms have been proposed for the 5G air-interface. The challenge when designing MC waveforms, is that the hardware used for building transceivers can have many imperfections; namely, oscillator phase noise and a nonlinear power amplifier (PA), which get more pronounced with increasing carrier frequencies. The design/evaluation of waveforms must therefore, take into account these hardware impairments, especially for mmWave communications.

Assessing Waveform Candidates

- Spectral efficiency
- Multiple-Input Multiple-Output (MIMO) Compatibility
- Peak-to-average-power-ratio (PAPR)
- Robustness against hardware impairments
- Robustness to channel time-selectivity and frequency-selectivity
- Time localization
- Frequency localization/out-of-band emissions
- Transceiver baseband complexity
This application note evaluates and compares the performance of various state-of-the-art waveforms in the presence of hardware impairments. To aid in this process, the performance evaluations were conducted under common simulation assumptions and using the SystemVue software environment from Keysight Technologies, Inc., for electronic system-level (ESL) design.

**Assessing Waveform Candidates**

Mobile radio communication above 6 GHz is characterized by large channel bandwidths, extreme data rate requirements, harsh propagation conditions, severe RF impairments, a massive number of antennas, and small-sized low-cost base stations. Several key performance indicators (KPIs) that are important for the assessment of waveforms are as follows:

- **Spectral efficiency.** Spectral efficiency is vital to meeting extreme data rate requirements. In general, spectral efficiency is more important at lower carrier frequencies than at very high frequencies, where large channel bandwidths are likely to be available for mobile communication.

- **Multiple-Input Multiple-Output (MIMO) Compatibility.** Massive MIMO is the driving technology in providing high spectral efficiency, via spatial multiplexing, and greater coverage, via beamforming. Beamforming will be instrumental in overcoming high propagation losses at mmWave frequencies.

- **Peak-to-average-power-ratio (PAPR).** A low PAPR is essential for power-efficient transmissions from devices (e.g., uplink). It is noteworthy that small, low-cost base stations are envisioned at high frequencies. Therefore, low PAPR is also important for downlink.

- **Robustness against hardware impairments.** Waveform robustness is critical, especially with phase noise and PA nonlinearities. Phase noise increases as a function of carrier frequency, while the impact of a nonlinear PA increases as a function of signal bandwidth.

- **Robustness to channel time-selectivity and frequency-selectivity.** Depending on the scenario—line-of-sight (LOS)/non-line-of-sight (NLOS)—beamforming algorithm and user mobility, the channel can have different combinations of high/low frequency selectivity and high/low time selectivity.

- **Time localization.** Time localization is important to enable efficient time-division-duplex (TDD) transmission and support low latency applications.

- **Frequency localization/out-of-band emissions.** Frequency localization is relevant to support the potential co-existence of different services by multiplexing different waveform numerologies in the frequency domain.

- **Transceiver baseband complexity.** Baseband complexity is very important to enabling efficient baseband processing at large bandwidths, especially from the receiver perspective.

For mmWave communication, the most important KPIs are robustness to hardware impairments, PAPR, time/frequency localization, compatibility with MIMO, and
computational complexity. Although spectral efficiency is always an important KPI to meeting high data rate requirements, it is more important at lower carrier frequencies where spectrum is scarce. Above 6-GHz communication, spectral efficiency is not a major performance indicator due to the large channel bandwidths envisioned at mmWave bands.

**Waveform Candidates**

Both MC (multi-carrier) and SC (single-carrier) waveforms have been proposed for the 5G air-interface. The MC candidates include Cyclic-Prefix (CP)-OFDM, Windowed (W)-OFDM, Pulse-shaped (P)-OFDM, Unique-Word (UW)-OFDM, Universal-Filtered (UF)-OFDM, and Filter-Bank Multi-Carrier (FBMC) with Offset Quadrature Amplitude Modulation (OQAM), while the SC candidates include DFT-spread (Discrete Fourier Transform-s)-OFDM, and Zero-Tail (ZT)-DFT-s-OFDM.

Due to its desirable features, the CP-OFDM waveform is currently used in LTE for downlink transmissions. These features include: robustness to frequency selective channel, easy integration with MIMO, very good time localization, and a low complexity baseband transceiver design. The main drawbacks of OFDM are high PAPR and poor localization in frequency.

The FBMC-OQAM waveform is based on filter-bank implementations where each subcarrier is filtered. FBMC is less localized in time, but well localized in frequency. The localization in both the time and frequency domains is controlled by the choice of prototype filters. The cons of the FBMC-OQAM waveform include its non-straightforward compatibility to MIMO techniques and increased complexity compared to OFDM.

In an UF-OFDM waveform, groups of adjacent subcarriers, which can be flexibly defined, are digitally passband filtered. The sub-band filtering with spectrally wider filters, as compared to FBMC, has the advantage of a shorter impulse response in the time domain, thus, making the symbol extension in the time domain comparable to the CP (cyclic prefix) of OFDM. Some of the key benefits of the UF-OFDM waveform are low out-of-band spectral emissions, and the ability to operate each sub-band with a different numerology to adapt dynamically to different deployment scenarios.

The W-OFDM waveform improves the frequency localization of OFDM by applying low complexity windowing or sub-band filtering, which enables smoother temporal transitions between successive OFDM symbols. This windowing or filtering can be employed at either the transmitter or the receiver, or at both the transmitter and receiver.

In the DFT-s-OFDM waveform, data is spread with DFT, followed by subcarrier mapping and Inverse Fast Fourier Transform (IFFT). Its main benefit is low PAPR. Other important advantages include low complexity, frequency domain equalization, and good time
localization. The cons of the DFT-s-OFDM waveform are poor localization in frequency and performance degradation in the high signal-to-noise ratio (SNR) region, as compared to OFDM in frequency selective channels.

A common framework for the synthesis of the various candidate waveforms is illustrated in Figure 1. Here, each waveform can be generated by selectively enabling or disabling certain blocks or operations. The synthesis blocks (operations) and the associated design parameters are summarized in Table 1. Note that the blocks necessary to generate the CP-OFDM signal are shown in white, whereas the extra blocks required for the generation of any of the other waveforms are highlighted in grey.

![Waveform Synthesis](image)

Figure 1. Waveform Synthesis: All waveforms can be synthesized by sequentially activating certain blocks in this diagram.

Table 1. Synthesis operation and design parameters.

<table>
<thead>
<tr>
<th>Waveforms (MC/SC)</th>
<th>Design parameters</th>
<th>Synthesis operations</th>
</tr>
</thead>
<tbody>
<tr>
<td>CP-OFDM (MC)</td>
<td>Sub-carrier spacing, FFT Size</td>
<td>A, B, D, G, K</td>
</tr>
<tr>
<td>W/P-OFDM (MC)</td>
<td>Sub-carrier spacing, FFT Size, CP length, window/pulse shape</td>
<td>A, B, D, G, H, K</td>
</tr>
<tr>
<td>UF-OFDM (MC)</td>
<td>Sub-carrier spacing, FFT Size, CP on/off, Subband Filters, Guard time</td>
<td>A, B, D, I, K</td>
</tr>
<tr>
<td>FBMC-OQAM (MC)</td>
<td>Sub-carrier spacing, FFT Size, Prototype filter, Overlapping factor</td>
<td>A, B, D, E, F, J, K</td>
</tr>
<tr>
<td>DFT-s-OFDM (SC)</td>
<td>Sub-carrier spacing, FFT Size, CP length, DFT block size</td>
<td>A, B, C, D, G, K</td>
</tr>
</tbody>
</table>

Table 1. Synthesis operation and design parameters.

**Hardware Impairment Models**

The hardware used for building transceivers can have many imperfections, and these imperfections get more pronounced with increasing carrier frequencies. Hardware impairments would cause distortion of the transmitted and received signal and lead to increased error vector magnitude (EVM) and/or reduced effective Signal to Interference and Noise Ratio (SINR). Further impacts of hardware impairments include increased
out-of-band (OOB) emission and interference to other links or users. Consequently, when designing or evaluating waveforms, hardware impairments must be taken into account. The following parts will briefly describe the modelling and the impact of oscillator phase noise and nonlinear PA.

**Phase noise**

Phase noise is typically caused by Local Oscillator (LO) instability. This means that the LO output spectrum is not an ideal Dirac impulse, but instead exhibits a skirt-like shape as shown in Figure 2. Because of phase noise, the received signal samples will have random time-varying phase errors. In an OFDM system, phase noise causes common phase error (CPE) and inter carrier interference (ICI), which results in degraded EVM performance.

![Figure 2. Power spectral density of the phase noise (low mode).](image)

Phase noise also causes leakage between adjacent channels, which is detrimental in near-to-far scenarios of a user equipment (UE) constellation in a cell. And, phase noise has adverse effects on interference cancellation schemes.

Generally, the phase-noise variance grows with the square of the carrier frequency. It is inversely proportional to the power consumption of the complete frequency generation (PLL, reference, etc.). This makes it an important effect in mmWave systems, especially those striving for low power consumption, as it may limit throughput. Careful selection of carrier bandwidth and sub-carrier spacing is therefore crucial, as is the design of the phase-tracking reference signal.
Phase noise can be compensated for using various approaches. For example, the CPE can easily be estimated (and corrected) in the frequency domain as the common phase rotation of the constellation, using scattered pilots. Intercarrier interference (ICI) may be modelled as additive noise, though not always Gaussian, and is usually hard to compensate. It requires denser pilots for phase noise and channel tracking, and can be computationally intensive. With relatively large subcarrier spacing, it may be sufficient to compensate the CPE only. This is implicitly done if the estimated channel transfer function, using the scattered pilots (which include the common phase rotation), is used for equalization.

Nonlinear Power Amplifier

Due to physical constraints, it is generally understood that the practical PA efficiency at mmWave frequencies is much less than that at centimeter-wave frequencies. As the bandwidth and modulation order are increased to achieve high data rates at mmWave bands, the PAPR of communication signals increases correspondingly. Therefore, it’s expected that mmWave PAs will likely work in the nonlinear region during transmission. Unless suitable PAPR-reduction techniques are deployed, this may further limit the power efficiency of the PA. However, since the PAPR of OFDM-signals tends to grow logarithmically, the PAPR issue is not considerably worse than in the sub-6 GHz case.

When signals with a large dynamic range go through a nonlinear PA, they suffer from nonlinearity effects, resulting in both in-band distortion and spectral regrowth. While in-band distortion increases the EVM of the transmitter signal, spectral regrowth causes adjacent channel interference. The power series model, or polynomial model, is widely used in modelling memoryless nonlinear PAs. The model is given by:

\[
y(t) = \sum_{k=0}^{K} c_{2k+1} |x(t)|^{2k} x(t) \quad (1)
\]

where \( K \) is the nonlinear order, \( y(t) \) is the output signal, \( x(t) \) is the input signal, and \( c_{2k+1} \) is the \((2k+1)\) th complex-valued polynomial coefficient. The coefficients \( c_{2k+1} \) can be calculated by using least squares estimation (LSE). The PA-related parameter settings are listed in Table 2.
### Table 2. Nonlinear PA parameter settings.

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Settings</th>
</tr>
</thead>
<tbody>
<tr>
<td>Nonlinear order K</td>
<td>5</td>
</tr>
<tr>
<td>Output 1-dB gain compression power</td>
<td>0.01 W</td>
</tr>
<tr>
<td>Output third-order intercept power</td>
<td>0.1 W</td>
</tr>
<tr>
<td>Saturation power</td>
<td>0.032 W</td>
</tr>
<tr>
<td>Gain compression at saturation</td>
<td>3 dB</td>
</tr>
</tbody>
</table>

**Performance Evaluations**

To better understand the impact of hardware impairments on the candidate waveforms (CP-OFDM, DFTS-OFDM, W/P-OFDM, UF-OFDM, FBMC-OQAM), their performance must be properly evaluated in the presence of the impairments. For the purposes of this discussion, link-level evaluations of the waveforms are performed using SystemVue software.

As an example, the end-to-end simulation chain for a OFDM waveform, which is composed of basic signal processing components, is illustrated in Figure 3. For a fair comparison between the different waveforms, the same reference simulation chain is used for each performance evaluation. Different waveform source generators and receivers are plugged into the reference simulation chain under common simulation assumptions (Table 3). For these evaluations, scattered pilot-based channel estimation was used, which also compensates for CPE.

![Figure 3. Example simulation chain with OFDM in SystemVue.](image-url)
In Figures 4 and 5, the BER and EVM performance of the waveforms under different hardware impairments is plotted. Notice that the EVM and BER performance of the considered waveforms are only slightly reduced in the presence of phase noise. Generally speaking, MC waveforms are sensitive to phase noise. However, with phase noise compensation and sufficiently large subcarrier spacing, these waveforms are robust to phase noise. In this case, scattered pilot-based channel estimation compensated for CPE. When nonlinearity in the PA is included the system, both the BER and EVM performance degrade as compared to the case on an idealistic linear PA. It is also interesting to note that there is no significant difference in the BER and EVM performance among the various candidate waveforms.
Figure 4. BER performance of different waveforms with/without hardware impairments.

Figure 5. EVM performance of different waveforms with/without hardware impairments.

Figure 6 shows the complementary cumulative distribution function (CCDF) of the PAPR of the different waveforms. The graph clearly shows that the PAPR performance of the FBMC-OQAM and W/P-OFDM waveforms is similar to that of CP-OFDM. The UF-OFDM waveform, on the other hand, has a slightly higher PAPR than the CP-OFDM waveform. When comparing it with a SC waveform (e.g., DFT-s-OFDM), it becomes obvious that a common drawback of MC waveforms is their high PAPR.
Figure 6. CCDF of PAPR of different waveforms.

Figure 7 shows the power spectral density (PSD) of different waveforms without any hardware impairments. The CP-OFDM and DFT-s-OFDM waveforms have much higher OOB power leakage than the other waveforms. Specifically, FBMC has the lowest OOB emission among all candidate MC waveforms. It is worth mentioning that the OOB emission of each waveform depends on the parameter setting (e.g., overlapping factor for FBMC, filter design for UF-OFDM, and windowing/pulse function for W/P-OFDM). By adjusting these parameters, it’s possible to balance the localization of a waveform in the time and frequency domains.

Figure 7. PSD of different waveforms without hardware impairments.
Figure 8 shows the PSD of different waveforms subject to phase noise. Compared with the results in Figure 7, the sharp spectrum roll-off provided by the FBMC-OQAM, W/P-OFDM, and UF-OFDM waveforms is significantly reduced when phase noise is included. It is still much lower; however, than that of the CP-OFDM and DFT-s-OFDM waveforms. When a nonlinear PA is further taken into account, the sharp spectrum roll-off promised by these waveforms is unlikely to be achieved (Figure 9). This is due to the fact that the PA nonlinearity leads to spectral regrowth. For low-power transmission (relatively higher power backoff), there can still be an OOB advantage over CP-OFDM.

From these comparisons, it is observed that the studied waveforms have similar EVM/BER performance with and without hardware impairments. The new waveforms (e.g., W/P-OFDM, FBMC, UF-OFDM) exhibit improved spectral confinement as compared to CP-OFDM and DFT-s-OFDM, but the improvement gets smaller when hardware impairments (e.g., phase noise and nonlinear PA) are taken into account. For nonlinear PA with high-power transmission, similar OOB emissions are observed for all waveforms.
Figure 9. PSD of different waveforms subject to nonlinear PA and high-power transmission.

Summary

The choice of which waveform to use for mmWave communication is important, as its design and performance evaluation. An important factor in this consideration is how it will be affected by hardware impairments such as phase noise and nonlinear PAs. After evaluating the performance of several 5G candidate waveforms in the presence of hardware impairments, it has been shown that all exhibit similar EVM/BER performance. The evaluation also revealed that with phase noise compensation and sufficiently large subcarrier spacing, MC waveforms can be robust to phase noise. Additionally, the spectral confinement (i.e., steep spectrum roll-off at OOB emissions) of OFDM signals can be improved through the use of filtering/windowing components extended to OFDM, but the improvement gets less obvious when hardware impairments are taken into account. In all cases, SystemVue provided an ideal tool for accurately evaluating waveform performance.

Acknowledgements

The work detailed in this application note is partly funded by the 5G PPP mmMAGIC project, a European Commission H2020 program under grant agreement No. 671650.

Learn more at: www.keysight.com

For more information on Keysight Technologies’ products, applications or services, please contact your local Keysight office. The complete list is available at: www.keysight.com/find/contactus