Solutions for Design and Evaluation of 5G Candidate Waveforms

Even while fourth generation (4G) cellular systems—LTE and LTE-Advanced—are in the midst of deployment, the move to fifth generation (5G) systems has already begun with a vision of “everything everywhere and always connected.” A key advantage of 5G over 4G will be its ability to offer super-fast (on the order of 10 Gbps), consistent and high-quality connectivity with very low latency (a few milliseconds at most) in support of new use cases and the billions of sensors that make up the Internet of Things (IoT). Just as critically, 5G networks are expected to feature significantly enhanced spectral efficiency and improved coverage.
These capabilities bode well for a society increasingly dependent on data-hungry applications for wireless devices like smartphones and tablets; just to name a few. By 2020, analysts predict there will be between 20 and 50 billion such devices in existence; ranging from devices connected with machine to machine (M2M) technology that transmit a few bytes of data per day to applications streaming multiple high-definition video channels. As these devices come into service, the effect will be undeniable—an explosion in demand for wireless data. The industry is looking to 5G to keep up with this demand by providing consumers both seamless 24/7 access to everything everywhere, and the ability to be always connected.

Problem

While early 5G research work has been going on for the last couple of years, bringing 5G from theory to reality in time for the 2020 data explosion will be a challenging task. The first step is formalizing its standardization. Even though there is a consistent definition of what the 5G vision is, the standardization work for 5G has not yet begun. Consequently, the challenges researchers face primarily stem from working on a technology without having a standard in place. 3GPP held its first 5G workshop in September 2015, but determining what 5G will look like won’t really happen until the middle of 2016. Commercial deployment is expected around 2020. In the meantime, the next step is for 5G research to be developed and deployed.

Future 5G wireless communication systems will have to handle a variety of traffic types such as mobile broadband and machine type communication. New multiple access schemes, waveforms and modulation formats are being researched to address the various use cases. Selecting the right waveform is one of the more critical decisions in 5G. There are many factors to consider when evaluating new waveform types, including such things as spectral efficiency, latency, computational complexity, energy efficiency, the adjacent channel performance for co-existence, and implementation costs. Selecting the right waveform is complicated by the fact that 5G is still very much in the research phase, and that means the requirements the waveform must meet may change. Never the less, design and evaluation of candidate 5G waveforms today is essential to jumpstarting 5G research, moving the 5G ecosystem forward and helping to accelerate the eventual deployment of 5G mobile wireless.
Solutions

Physical-layer waveforms have not yet been defined and, because there is no consensus on potential waveforms, several candidates are in the running: filter bank multi-carrier (FBMC), generalized frequency division multiplexing (GFDM), universal filtered multi-carrier (UFMC), filtered orthogonal frequency-division multiplexing (F-OFDM), and many more. F-OFDM and FBMC are widely considered by multiple researchers.

To better understand the differences between these two technologies, consider the block diagram in Figure 1. For a F-OFDM signal, the subcarrier data symbols \( S_k \) are filtered by a prototype filter \( P \) with a symbol time spacing defined by \( T \), and then multiplied into each subcarrier. The use of prototype filters with a rectangular impulse response, \( h(t) \), results in an undesirable magnitude response, which suffers from large side lobes in the frequency domain. To minimize this effect, the rectangular pulse can be replaced with new pulses that have a commonly used window function with soft transitions at the beginning and end of the symbols. Doing so lowers the side lobes, but it comes at the cost of a wider main lobe. Research is currently underway to find a design that uses a better window function (e.g., a Chebyshev-based design) and can eliminate this issue.

Like F-OFDM, FBMC is a well-known multicarrier technique in which data symbols are simultaneously transmitted over multiple frequency subcarriers. The main difference between the two is the choice of symbol time and prototype filters. In an FBMC system, for example, such as that shown in Figure 1, the data symbols are spaced at \( T/2 \) using time delays. When \( (k+n) \) is an even number, the phase shift is effectively zero degrees, while when \( (k+n) \) is an odd number, it is 90 degrees. One reason why 5G researchers have taken such interest in FBMC is that its use minimizes receiver complexity and it can handle both short burst transmission and Multiple Input Multiple Output (MIMO) channels.

As mentioned above, F-OFDM and FBMC are not the only waveform technologies being explored for 5G. Some of the other waveform technologies and the new techniques being utilized on them, which are also currently under investigation, are shown in Figure 2. A prime example is a raised cosine response that has been previously used for conventional OFDM systems. It meets the Nyquist criterion, which means that it has no inter-symbol interference, and its' pulse \( h(t) \) in applications is almost always orthogonal with respect to shifts by \( nT \). Now, a new method of data transmission known as Faster-Than-Nyquist (FTN) signaling is being revisited for 5G.

### Block diagram of OQAM/FBMC

<table>
<thead>
<tr>
<th>Q0(t)</th>
<th>Q1(t)</th>
<th>Q2(t)</th>
<th>Q3(t)</th>
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#### Transmit signal equation for filtered OFDM

\[
X(t) = \sum_n \sum_k S_k(n) P(t-nT)e^{j2\pi(k-n)T/T}
\]

#### Transmit signal equation for FBMC

\[
X(t) = \sum_n \sum_k S_k(n) P_k(t-nT/2)
\]

Figure 1. Shown here is a basic block diagram of F-OFDM and FBMC waveforms, along with the corresponding transmit signal equations for each technology.
With the FTN method, \( h(t) \) is no longer orthogonal with respect to the symbol time, and pulses occur faster, by a factor designated as \( \alpha \). The time–frequency grid in the top right corner of Figure 2 shows one symbol in each TF unit area that meets the Nyquist criterion. With the FTN, there is a higher symbol density in each TF area—an innovation that can transmit up to twice the number of bits as ordinary modulation schemes at the same bit energy and spectrum. As a result, required bandwidth is reduced, but at the expense of the loss of orthogonality between the carriers.

The FBMC waveform introduces a new approach to pulse-shape adaptation and a dynamic subcarrier spacing technique to adjust the energy spread and minimize the loss of energy. Essentially, the pulse shaping at each subcarrier is designed in such a way that the waveform’s out-of-band (OOB) emission become negligible. These advances make FBMC a much more powerful technique for multi-user asynchronous fragmented spectrum scenarios such as Web access or machine-to-machine (M2M) communication.

While the work being done to identify candidate 5G waveforms is essential, just as important is the ability to fully explore those candidates. Because 5G is evolving, the solution utilized for this task must be flexible enough to quickly adapt to the changing standard. And, it must be able support various 5G candidate waveforms for orthogonal and non-orthogonal multicarrier communication systems, including advanced MIMO and beamforming signal processing. Furthermore, to help engineers get a jumpstart on their 5G research, the solution should ideally provide both transmitter and reference receiver modeling examples that can be easily re-designed to achieve optimal performance for comparison of each of the candidate proposals.

Prime examples of solutions offering the flexibility and advanced functionality needed to quickly and effectively generate and evaluate 5G mobile communications waveforms are the Keysight Technologies, Inc. SystemVue Electronic System Level (ESL) design software with 5G Baseband Exploration Library and N7608B Signal Studio for Custom Modulation software. SystemVue is a

\[
\Delta F = \frac{1}{T}
\]

Non orthogonal sub-carriers

\[
\Delta F = \alpha / T, \quad \alpha < 1
\]

Pulse shape adaptation/ dynamic subcarrier spacing

\[
\Delta F = \alpha / T, \quad \alpha < 1
\]

Asynchronous fragmented spectrum

Figure 2. This diagram provide a closer look inside some of the new 5G waveform technologies.
system-level communications design environment that can be used to create 5G candidate waveforms (Figure 3). It brings together Physical Layer (PHY) baseband algorithmic modeling, accurate RF modeling, standards-based reference Intellectual Property (IP), and direct interaction with test equipment. Used early in the R&D lifecycle, it follows both the RF and baseband design paths into implementation, providing continuity for cross-domain verification.

Adding the 5G Baseband Exploration Library to the mix provides ready-to-use advanced digital signal processing blocks for 5G candidate waveform technologies, end-to-end physical layer transmit and receive simulation models, and signaling schemes for MIMO channels (Figure 4). It also enables reference waveform generation to verify RF circuit designs. Together, SystemVue and its 5G library provide design teams with a cost-effective and highly productive way to jumpstart their 5G technology research. Using these solutions, the teams can more easily explore, validate and integrate the latest PHY developments as they happen, reducing hundreds of thousands of dollars in research and development costs, as well as schedule and technology risks.

While SystemVue is used for 5G signal generation and more system-level tasks, Signal Studio for Custom Modulation enables...
fast and easy generation of custom FBMC, OFDM and IQ signals for component, transmitter and receiver test of 5G applications (Figure 5). An easy-to-use, parameterized graphical user interface accelerates the custom signal creation process at every stage.

Once the 5G test signals have been created, either using SystemVue or Signal Studio, it is combined with two pieces of hardware—a precision AWG and a vector signal generator with wideband I/Q inputs—which enables generation of wideband test signals with up to 2 GHz of modulation bandwidth at frequencies up to 44 GHz (and higher with upconverters) to test 5G candidate waveform within and beyond their limits.

Multicarrier Waveform Quality

Systems using multicarrier waveforms like FBMC and F-OFDM have a number of issues that can affect their waveform quality; namely, Peak-to-Average Power Ratio (PAPR) and RF impairments stemming from the nonlinearity in the RF chain. PAPR is defined as the ratio of maximum instantaneous power to average power. In multicarrier systems, inherently high PAPR can severely degrade the spectral performance of a communication system.

Figure 6 shows an example of a Complementary Cumulative Density Function (CCDF) curve, obtained using SystemVue, for an OFDM (red) and FBMC (blue) waveform, with and without PAPR reduced. More aggressive clipping can reduce the PAPR.
even farther; however, it also increases OOB spectral regrowth and distortion of the original signal. Ensuring the overall Error-Vector-Magnitude (EVM) does not exceed a specified limit is, therefore, critical.

The nonlinearity of an RF chain is another factor that can significantly impact the quality of a waveform. For a closer look, consider the nonlinear amplifier model shown in Figure 7. Here, the input power is being swept from -20 to 10 dBm, with a gain of 28.5 dB. Because the amplifier model exhibits multiple types of nonlinear behavior between the transmitter and receiver chain, the measurement is set to the 1-dB compression mode and the FBMC EVM measurement block is connected at the output of the amplifier. The resulting “my EVM vs swept input power” SystemVue graph shows that EVM rapidly increases as the output power approaches the compression point. The LO source and modulator block can also be used to simulate the effects of phase noise, IQ imbalance and other RF impairments.

A SystemVue workspace that contains this design, as well as all other designs discussed in the application note, is available for download at http://www.keysight.com/find/eesof-how-to-5g-waveforms. The workspace also includes an interactive test bench to help engineers better understand how to address both baseband and RF using a single simulation tool.

Evaluating 5G System Performance

When designing candidate 5G waveforms, evaluation of their performance with realistic RF impairments is essential. This can be accomplished by first modeling the RF behavior, and then performing an end-to-end link level simulation using SystemVue.

To effectively model a waveform’s RF behavior, it’s helpful to first have a good understanding of the basic concept. When multicarrier signals with high PAPR pass through a nonlinear device, they may suffer significant distortion. The 1-dB compression point is commonly used to specify nonlinearity within a transmitter. Standard RF metrics for receiver nonlinearity are different because they address a different problem. The receiver metrics for nonlinearity are called intercept points. The nonlinear relationship between input and output voltage can be approximated by the equation shown in Figure 7. The DC offset and higher order terms can be ignored for an architectural top-level simulation.

Also shown in Figure 7, the IQ modulator is represented by the cosine and sine of the RF carrier frequency, ω. Linear distortion introduced by the IQ modulator comes from the asymmetry between the mixers; something that is always present in the analog world. Asymmetry between the mixers can introduce gain imbalance in ‘a’ and quadrature error ‘θ.’ The quadrature error refers to the phase difference between the two local oscillator signals, aside from the inherent 90-degree difference. It accounts for phase noise and/or frequency offset.

Figure 7. Proper evaluation of 5G system performance requires the inclusion of RF impairments, such as nonlinear behavior and IQ modulator, which can distort waveform quality.
A set of FBMC transmitter modeling examples are shown in Figure 2. The examples are for a 20-MHz bandwidth FBMC signal with 128 subcarriers allocated. Here, QPSK data symbols are mapped into the FBMC transmitter block configured with a poly-phase-networked synthesis filter bank, and then up-converted to a 2-GHz frequency band.

Once the RF behavior of the waveform has been modeled, the next step is to evaluate its link level performance. Using the transmitter configuration for an FBMC system shown in Figure 1 as an example, the first step is to select the ideal time synchronization of the receiver model. Next, some of the nonlinear characteristics are put inside the RF channel model using the transmitter and receiver amplifier models. The transmitted and received bits are then logically connected to the inputs of the Bite-Error-Rate (BER) simulation model in the schematic. Finally, a simulation is run with one thousand transmit data frames. Two plots generated from the resulting simulation are shown in Figure 8.

The un-coded BER curve with the Additive white Gaussian noise (AWGN) channel in the left-most graph in Figure 8 shows that both FBMC and OFDM link-level performance are similar. However, the nonlinearity that exists between the transmitter and receiver chain results in a higher BER. The right-most graph of the coded BER with fading channel shows the coding gain performance of the Low Density Parity Check (LDPC) algorithm. Note that in the presence of nonlinearities without any PAPR reduction applied, the error correction for LDPC is still severe, much like the un-coded case.

Figure 8. These graphs show the results of an end-to-end link level simulation on the FBMC system in Figure 1.
Summary of Results

While 5G is primed to address the data explosion expected in 2020, getting to that point will be a long and arduous process. The technology is evolving and still very much in the early research and development stage. Moving this process forward will require the design of 5G waveforms and the ability to fully evaluate these waveforms. At the system level, SystemVue software and its 5G Baseband Exploration Library offer the ideal solution for this task. When those waveforms are needed for component, transmitter and receiver test of 5G applications, Signal Studio for Custom Modulation software is the optimal choice. With these solutions, design teams now have the tools they need to quickly move forward with their 5G research while the standard continues to evolve. Ultimately, that will mean accelerated deployment of future 5G systems.

The Power to Accelerate Wireless Design and Test

Keysight is a leader in wireless test, focused on the highest performance design and test of wireless devices and networks, with application-focused platforms optimized for existing and emerging standards. Adding to this optimal R&D and field support, Keysight allows engineers to better understand the intricacies of the continuously evolving wireless industry so they can accelerate development of products.

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- 5G Waveform Generation and Analysis Testbed, Reference Solution
- N5264A PNA-X Measurement Receiver for Antenna Test
- N9030A PXA Signal Analyzer, 3 Hz to 50 GHz
- N5183B MXG X-Series Microwave Analog Signal Generator, 9 kHz to 40 GHz
- M9703A AXIe 12-bit High-Speed Digitizer/Wideband Digital Receiver