Introduction

With its aggressive performance goals, the emerging 5G standard will almost certainly incorporate a combination of millimeter-wave (mmWave) frequencies, ultra-broad bandwidths and massive multiple-input/multiple-output (MIMO) methods. Although each of these adds difficulty to the design of transmitters and receivers, the most significant unknowns are in the over-the-air radio channels between user equipment (UE) and base station (BS). To fully characterize the channel, it is necessary to create mathematical models of channel performance and use them to define new air interface standards for 5G.

The successful deployment of mmWave-based systems requires a solid understanding of channel conditions. Currently, attention is being focused on radio-wave propagation at a variety of possible carrier frequencies above today’s densely populated spectrum in the region below 6 GHz. Detailed characterization of channel propagation is vital for the development of a reliable 5G wireless system design. A technique called channel sounding is necessary step towards understanding the channel and, thereby, enable the data rates, spectrum flexibility and ultra-broad bandwidth envisioned for 5G.

A variety of measurement methods are available, and each has strengths and weaknesses. Using previous research as a starting point, Keysight Technologies, Inc. has implemented a measurement system that leverages “best of” attributes while adding new contributions. The proposed measurement solution is based on commercial, off-the-shelf (COTS) hardware and software products, plus additional software tuned to accelerating 5G measurements with real-time data processing performed in on-board FPGAs. Keysight also provides tools to ensure system synchronization and calibration, which are essential to producing precise and repeatable results.

Specifically, the measurement system enables characterization of channel performance for the development of new channel models. As new models are defined, these can be simulated in Keysight’s SystemVue electronic system-level (ESL) software. This enables a skilled researcher to quickly implement a customized system and achieve excellent results.
Overview of 5G: Expectations and opportunities

The market outlook for 5G is based on a few aggressive projections: massive growth in demand for mobile data; exploding diversity of wireless applications; and massive growth in the number of connected devices. In addition, if present trends continue, it’s likely that there will be dramatic changes in end-user expectations for overall network performance and quality of service (QoS).

This future scenario promises important benefits for mobile users: amazingly fast connections; increasingly reliable connectivity; and dependably excellent QoS, even in a crowd. The net result is anytime, anywhere availability of the best possible user experience.

The associated technical requirements include numbers that are quite daunting when compared to present-day 4G systems:

- 100x increase in data rates
- 1000x increase in network capacity
- 100x network densification
- 100x improvement in energy efficiency
- 1 ms latency
- Five-nines reliability (99.999%)

Among these, pushing data rates 100x faster stands out because it simply isn’t possible in today’s crowded RF spectrum. This is driving the need to investigate mmWave frequencies; however, limited familiarity with radio-wave propagation in that part of the spectrum is driving the need to thoroughly investigate, model and understand the channel.

As a result, there are at least three opportunities to innovate in the hardware and software tools needed to support the development process: design; simulation and emulation; and calibration and validation.
Sketching the general solution

In any wireless communication architecture, the radio channel has a tremendous effect on system performance. This will be especially true in 5G at mmWave frequencies. With their very short wavelengths, mmWave signals are rapidly absorbed as they propagate through the atmosphere. Attenuation is especially high at the resonant frequencies of oxygen, water and carbon dioxide molecules.

To understand the radio channel, it is necessary to measure the channel, extract the key characteristics and develop a dependable model that can be used in emulation and simulation. Channel sounding is a measurement technique that mimics the operation of any wireless communication system. Referring to Figure 1, a transmitted signal travels through the air, is affected by channel conditions and then reaches the receiver. By applying signal processing in the receiver, a measurement system can extract the characteristics of the wireless channel at a frequency of interest.

![Diagram of wireless channel]

\[ R_{yy}(\tau) = E[x^*(t)y(t-\tau)] = h(t-\tau) \otimes R_x(\tau) = h(t-\tau) \otimes \delta(\tau) = h(t) \]

Figure 1. Applying matrix math and solving for \( h(t) \) provides an approximate mathematical model of the RF radio channel.

To create the desired mathematical model, a variety of channel parameters need to be estimated. Starting with the channel impulse response (CIR), which contains all the characteristics of the channel, important parameters include angle of arrival (AoA); angle of departure (AoD); Doppler shift; and power delay profile (PDP), which includes absolute path delay and path loss can be estimated. There are also essential statistical parameters and modeling elements: angular spread (AS) of AoA and AoD; power angular spectrum (PAS); Doppler spectrum; the correlation matrix; and the Rician K factor, which are related to fading. MIMO channels introduce spatial information and correlation information that presents more challenges in channel parameter estimations in AoA, AoD, AS, and PAS.
Channel Sounding for 5G

The technical choices for new 5G mmWave air interface designs create a baseline that sets the requirements of the measuring system:

– Ability to handle carrier frequencies ranging from 10 to 90 GHz and perhaps higher
– Ability to support bandwidths of 500 MHz, 1 GHz, 2 GHz and perhaps higher
– Capable of handling massive MIMO antenna configurations

These requirements lead to one umbrella challenge and five crucial technical challenges, as illustrated in Figure 2.

Figure 2. The five technical challenges affect the overall need to define the most effective approach and architecture for a channel sounding measurement system.

Starting at the top of the diagram, the overarching challenge is selecting the most effective approach and architecture for the channel sounding system. Moving through the triangles from left to right highlights the crucial technical issues that must be resolved:

– Finding RF and microwave (µW) test equipment that provides sufficient performance when used in concert with mmWave upconversion (signal generation) or downconversion (signal analysis).
– Providing the necessary bandwidth in signal generation, acquisition and analysis. This affects the necessary clock rates and bit depths (i.e., dynamic range and resolution) in the analog-to-digital converter (ADC) and digital-to-analog converter (DAC) technologies.¹
– Collecting and managing large quantities of data with storage to accommodate long-duration sounding measurements at high sampling rates and across many channels.²
– Getting adequate accuracy in parameter-estimation algorithms to handle the required path-delay resolution and angular resolution for MIMO estimations.
– Enabling accurate synchronization and calibration of all included measurement hardware, thereby ensuring precise and repeatable results.

¹. System performance must also be capable of handling the expected 5G Doppler frequencies, which will be higher than those seen in similar 3G and 4G scenarios.
². Total required capacity is the product of total measurement time, the sampling rate and the number of channels.
Comparing different sounding techniques

At least three different baseband processing approaches are commonly used to perform channel sounding: sliding correlator, swept frequency and wideband correlation. Among these the simplest to implement are the sliding-correlator and swept-frequency approaches. While effective at measuring propagation loss, neither are effective at measuring time-varying channels and both suffer from slow measurement speeds. In addition, the sliding correlator method provides only amplitude information.

In comparison, wideband correlation is more complex, but the fastest method because it measures the entire bandwidth, simultaneously enabling faster access to CIR data. The wideband correlation method also includes the phase information that is essential to the required vector measurements and analysis. As a result, wideband correlation stands apart from the two alternatives.

Assessing MIMO sounding methods

Many sounding systems incorporate single-input, single-output (SISO) measurements. MIMO is a key technology in 5G and must be included in the channel characterization. Specific to MIMO measurements, there are three common ways to transmit and receive the necessary signals: use switching on both the transmitter and receiver sides, use parallel transmitting and receiving or use switching at the transmitter and perform parallel receiving (Figure 3).1

While the all-parallel approach provides the fastest measurements, it introduces cross-interference between the various transmitting channels, potentially degrading the performance of sounding measurements. This problem does not affect the switched transmit/parallel receive or all-switched approaches.

Comparing these, switched transmission/parallel reception is much faster than the all-switched technique. With its speed advantage and freedom from cross-interference, the switched-transmit/parallel-receive method thus emerges as the better choice.

1. The fourth choice, parallel transmission and switched receiving, misses too much information on the receiving side to be effective.
Proposing a specific solution

Drawing from the preceding comparisons, Keysight’s preferred approach uses wideband correlation as the baseband sounding technique and switched-transmit/parallel-receive for assessing MIMO data capture. This provides three important technical advantages: fast measurement speed, MIMO sounding capability and excellent measurement performance (with minimal cross-channel interference).

Figure 4 illustrates the basic architecture. On the left, the transmitter side includes a single-channel wideband signal generator and mmWave switch. On the right, the receiver side provides parallel signal acquisition with a wideband multi-channel receiver that can be implemented using high-performance digitizers or wideband vector signal analyzers.

Figure 5 shows the next level of detail in the channel sounding system. The wideband signal generator includes a wideband arbitrary waveform generator (AWG) and mmWave vector signal generator (VSG). The AWG provides the in-phase and quadrature (I/Q) signals that modulate the output of the VSG, and the mmWave switch routes the VSG output to the transmit antennas in sequence. On the receiver side, a multi-channel downconverter translates the received signals into the IF bandwidth of the multi-channel digitizer.

Figure 5. To manage cost, maximize availability and ensure supportability, the proposed solution uses COTS instrumentation to implement the proposed architecture.
Sketching the hardware elements

Figure 6 illustrates the recommended test and measurement hardware elements. To ensure a consistent time base, each subsystem is connected to a 10 MHz rubidium frequency standard (e.g., a TaiFuTe HJ5418B rubidium clock).

Table 1 provides functional descriptions of the major hardware elements in both the transmitter and receiver subsystems. With these essential elements as a starting point, you can modify the test platform as needed to meet specific requirements: channel count, carrier frequency, analysis bandwidth, and so on. For more information about data storage and streaming, please see the sidebar.

Table 1. The transmitter and receiver subsystems use COTS hardware to implement the channel sounding system.

<table>
<thead>
<tr>
<th>Description</th>
<th>Function</th>
</tr>
</thead>
<tbody>
<tr>
<td>Transmitter subsystem</td>
<td></td>
</tr>
<tr>
<td>Vector signal generator</td>
<td>Provides wideband signal generation up to 44 GHz with +23 dBm output power to 20 GHz and +13 dBm @ 40 GHz with differential I/Q inputs. Differential external I/Q inputs support modulation bandwidths up to 2 GHz. Available upconverters enable translation above 44 GHz.</td>
</tr>
<tr>
<td>Arbitrary waveform generator</td>
<td>Two-channel AWG drives vector signal generator modulation inputs with baseband I/Q modulation signals at bandwidths up to 2 GHz</td>
</tr>
<tr>
<td>Solid-state switch</td>
<td>Provides sequential serial output through each of the transmit antennas</td>
</tr>
<tr>
<td>Receiver subsystem</td>
<td></td>
</tr>
<tr>
<td>PXIe quad downconverter</td>
<td>Connected to receiver antennas and performs phase-coherent translation of mmWave signals up to 50 GHz down to baseband for digitization</td>
</tr>
<tr>
<td>PXI hybrid amplifier/attenuator</td>
<td>Provides four channels of IF signal conditioning</td>
</tr>
<tr>
<td>AXIe 12-bit high-speed digitizer/</td>
<td>Makes high-speed, high-resolution, phase-coherent measurements on eight channels per module. On-module FPGA performs on-the-fly CIR calculations.</td>
</tr>
<tr>
<td>wideband digital receiver</td>
<td></td>
</tr>
<tr>
<td>AXIe 2-, 5- or 14-slot chassis</td>
<td>Houses the high-speed digitizer and AWG modules in transmitter and receiver chassis; also provides a foundation for systems with up to 16, 40 or 104 receiver channels, respectively</td>
</tr>
<tr>
<td>PXIe 18-slot chassis</td>
<td>Houses the downconverter and signal conditioning modules as well as the embedded controller. Has sufficient power to support four quad downconverters and four amplifier modules.</td>
</tr>
<tr>
<td>PXIe high-performance embedded</td>
<td>Resides in the PXIe chassis and controls the PXIe and AXIe chassis in the Rx subsystem</td>
</tr>
<tr>
<td>controller</td>
<td></td>
</tr>
<tr>
<td>MXG X-Series microwave analog</td>
<td>Ensures phase coherence by providing a low phase noise LO signal for the downconverters. High output power enables use of a splitter to feed multiple downconverters with one MXG</td>
</tr>
<tr>
<td>signal generator</td>
<td></td>
</tr>
<tr>
<td>Waveform generator with arb</td>
<td>Provides synchronization triggers</td>
</tr>
</tbody>
</table>

1. For complete information about model numbers and the necessary options, please see the 5G Channel Sounding Reference Solution brochure, Keysight publication 5992-0983EN.

Estimating data storage and streaming needs

Because sounding measurements can be quite long in duration, data reduction, data storage or streaming of raw I/Q or CIR data may be necessary. You can use the following equation to calculate the required data capacity:

\[ N_{\text{cap}} = T_s \times F_s \times N_{Rx} \]

- \( T_s \) is the total time for the sounding measurement
- \( F_s \) is the sampling rate
- \( N_{Rx} \) is number of channels that are receiving signals in parallel
- \( N_{\text{cap}} \) is the total captured data size in samples

In 5G channel sounding, \( F_s \) must be large to capture the ultra-broad bandwidth and \( N_{Rx} \) is large due to the use of massive MIMO configurations. As a simple example, consider a 1 GHz sample rate and eight receiver channels: the required capacity for a one-second measurement is 8 GSa (1 s x 1 GHz x 8 channels). If each sample contains four bytes—two for I data, two for Q data—then 32 GB of storage capacity is needed.
Outlining the essential software elements

Figure 7 shows a typical flow diagram of the data-analysis steps that are performed when characterizing new channels. It illustrates the relationships and data flows between the key elements, and modeling summarizes some of the major functions performed by each block.

Specific to channel sounding (Figure 7, upper left), the reference solution uses the Keysight quick-start toolkit. It includes tools for configuration and calibration that simplify and accelerate the complex channel sounding analysis process.

In terms of essential data collection, the FPGA built into the M9703A digitizers provide the real-time data processing necessary to correlate and calculate CIR data on the fly (Figure 7, upper left). This in-system data reduction makes data streaming and storage more manageable. The streaming requirements are determined by the size of the MIMO array, sample rate, and size of CIR data.

The resulting data also can be used for post-processing to estimate other channel parameters. For detailed post-processing analysis of acquired signals, the channel parameters can be extracted using different models in the SystemVue platform (Figure 7, upper right). The Keysight 89600 VSA software can also be used for signal demodulation and vector signal analysis. These tools enable you to explore virtually every facet of today’s most complex signals and, ultimately, use that understanding to create better channel models.

SystemVue can be configured to provide three essential capabilities: signal creation, parameter extraction and channel simulation. For example, the channel sounding signal itself is a crucial aspect of the system. Whether you already have a channel stimulus or want to experiment with new variations, SystemVue provides the necessary tools to create I/Q signals and download them to the AWG.

SystemVue can also perform custom channel-parameter extraction using the space-alternative generalized expectation-maximization (SAGE) algorithm (optional). Recent innovations have made the SAGE method more applicable to MIMO systems.

Once channel modeling is complete, you can use the SystemVue 5G baseband verification library (W1906EP) to perform link-level simulation of new channel models, including scaling schemes for MIMO channels (Figure 7, lower right). The integrated simulation environment enables you to investigate, implement and verify system behavior using hardware in the loop to verify and accelerate algorithms through real-time co-verification via FPGA.
Ensuring measurement accuracy

To achieve precise results, system synchronization and calibration are required. The channel sounding system must be capable of measuring and characterizing its own phase and amplitude impairments and compensating for the following issues:

- Inter-channel phase errors
- Antenna errors in amplitude and phase
- I/Q mismatch errors
- Spectral flatness errors

The reference solution includes calibrations that cover the following measurements:

- System impulse response
- I/Q imbalance
- Multi-channel magnitude and phase skew
- Power level
- Antenna calibration using antenna pattern data from user or antenna manufacturer

Proper synchronization of the transmitter and receiver subsystems ensures accurate results when measuring crucial parameters such as absolute delay. This is why the recommended configuration includes two 10 MHz rubidium clocks and a trigger source (e.g., 33511B waveform generator). Together, these initiate signal generation on the transmitter side and coordinate signal acquisition on the receiver side. The included software tools for I/O management simplify the level of instrument control needed to achieve the required timing and synchronization.

Channel parameter estimation

The various channel parameter estimation algorithms can be categorized to 3 types:

- Beamforming based
- Subspace based
- Maximum likelihood (ML) based algorithms

The beamforming based algorithms are simple with poor estimation performance. The subspace-based algorithms have good performance, but the maximum number of paths the algorithm can estimate is less than the number of receiving antennas, thus these algorithms cannot work well for more complex channel scenarios.

The ML based algorithm (e.g. SAGE) is well accepted and widely used due to its high estimation precision and its capability of joint parameter estimator for multiple channel parameters, what’s more, the maximum estimating path number is not limited by the number of antenna array elements.
Examining results from an example system

Figure 8 shows an example implementation of a system capable of 4x4 MIMO channel sounding. The cart on the left is the transmitter subsystem and that on the right is the receiver subsystem.

By implementing real-time correlation processing in the digitizer’s (M9703A) embedded FPGA, the resulting data compression enables storage into onboard memory. The captured CIR signals can be transferred in real time through the PCIe bus.

Figure 9 shows an example screen from the SystemVue 5G verification library that is used to specify instrument configuration for CIR data capture and post processing of channel parameter estimations. Using those tools and the pictured system produced the channel parameter estimation results shown in Figure 10.

Figure 8. This example implementation shows a 4x4 MIMO measurement at a 28 GHz carrier frequency and 1 GHz analysis bandwidth. It’s expandable to 8x8 MIMO up to 44 GHz with 1 GHz BW.

Figure 9. The SystemVue channel parameter-estimation allows for extraction of critical parameters such as path loss, path delay profile, AoD, and AoA.

Figure 10. The measurement shows channel impulse response and channel extraction for the multi-path channel.

As a final note, the example system can be extended to higher frequencies using mmWave upconverters and downconverters such as the Virginia Diodes, Inc. N9029AV15, which covers 50 to 75 GHz.1

1. Other frequency bands are available, depending on the application.
Conclusion

With its aggressive performance goals, the emerging 5G standard will incorporate a challenging combination of technologies. Although these present challenges are in the design of transmitters and receivers, one of the most significant unknowns is in the over-the-air radio channels at mmWave carriers. To fully characterize and understand these unknowns, it is necessary to create mathematical models and use them to define a new air interface standard.

Keysight’s reference solution uses wideband correlation as the baseband sounding technique and switched-transmit/parallel-receive for MIMO data capture. This provides three important advantages: fast measurement speed, MIMO sounding capability and excellent measurement performance.

Using COTS hardware and software elements plus application-specific tools, the reference solution enables fast and accurate characterization of channel performance for the development of new channel models. Once created, these new models can then be simulated in SystemVue and validated with hardware-in-the-loop verification of algorithms. This enables more exploration in less time, deeper understanding of the channel and, ultimately, a 5G ecosystem that provides the best possible user experience.

Related Information

- Brochure: 5G Channel Sounding Reference Solution, publication 5992-0983EN
- Brochure: SystemVue Electronic System-Level (ESL) Design Software, publication 5992-0106EN
- Data Sheet: W1906BEL 5G Baseband Exploration Library, publication 5992-0218EN
- Brochure: 89600 VSA Software, publication 5990-6553EN
- Brochure: Simplify Signal Creation with Signal Studio Software, publication 5989-6448EN
- Technical Overview: M9099 Waveform Creator Software, publication 5991-3153EN
- Data Sheet: E8267D PSG Vector Signal Generator, publication 5989-0697EN
- Data Sheet: MXG X-Series Signal Generator, publication 5991-3131EN
- Data Sheet: 33500B Series Waveform Generators, publication 5991-0692EN
- Data Sheet: M8190A Arbitrary Waveform Generator, publication 5990-7516EN
- Technical Overview: 85331B/85332B Solid State Switches, publication 5989-4960EN
- Data Sheet: M9362AD01 PXIe Quad Downconverter, publication 5990-6624EN
- Data Sheet: M9352A PXI Hybrid Amplifier/Attenuator, publication 5990-9964EN
- Data Sheet: M9703A AXIe High-Speed Digitizer/Wideband Digital Receiver, publication 5990-8507EN
- Data Sheet: M9502A and M9505A AXIe Chassis, publication 5990-6584EN
- Data Sheet: M9514A and M9521A AXIe 14-Slot Chassis and System Module, publication 5991-3908EN
- Data Sheet: M9037A PXIe Embedded Controller, publication 5991-3661EN
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