How Can Distributed Architecture Help mmWave Network Analysis?

The Growing Need for Millimeter Wave Technology

In a world of interconnection, the need to transmit more information faster is driving designers to millimeter-wave (mmwave) frequencies, 30 to 300 GHz. This range is named for the 1 mm to 10 mm wavelengths at these frequencies. Microwaves can carry up to about 1 Gbit/s, but millimeter waves offer transmission rates of 10 Gbit/s or higher. This creates opportunities in many consumer and research markets.

One of the most prominent applications of mmwave technology is 5G, the next generation of wireless communication. Currently, more and more devices are demanding data within the limited cellular bands at or below 6 GHz. 5G aims to take advantage of the availability of mmwave frequencies to accommodate the growing number of Internet of Things (IoT) devices. One of the ways it will do this is by replacing large centralized cellular towers with smaller hot spots, called “cells.” A tower can only support a limited number of devices, so increasing the number of cells will relieve cellular traffic.
Another potential use of mmwave technology is WiGig. The Wireless Gigabit Alliance (WiGig) is working to add multi-gigabit speeds to WiFi devices using the 60 GHz frequency band. WiGig devices have the standard 2.4 and 5 GHz bands as well as an additional 60 GHz band that can be used with other nearby WiGig devices. The 60 GHz band offers transmission rates up to 7 Gbit/s over focused beams that will not interfere with each other.

Millimeter-wave technology also offers very low latency. This is crucial for applications like automotive radar, where every fraction of a second counts. Lane assistance, adaptive cruise control, emergency braking, and many other features all rely on high frequency radar. These radars traditionally operated around the 24 GHz band, but by 2022 the 24 GHz band will be completely phased out and replaced with a 77 to 81 GHz band. The wide bandwidth and small wavelength will allow much higher resolution and accuracy than the lower frequency radar. This accuracy is critical as cars are becoming increasingly autonomous.

Mmwave also has a very strong presence in the aerospace and defense industry. Millimeter imaging stations for airport screening operate at 35 to 325 GHz. Higher frequencies and bandwidths are needed to get the best resolution to determine potential threats. Secure radar communications are being moved from crowded lower frequency bands up into the mmwave range.

All of these applications present unique challenges in their testing and application. Error sources such as cable losses, connector repeatability, and phase shifts that might have been mostly negligible at radio frequencies are amplified at higher frequencies. High-end vector network analyzers typically have maximum frequencies of 67 GHz, so many of these applications require testing beyond the limits of most hardware. However, there are now ways to increase the frequency range of VNAs.
mmWave Vector Network Analysis – A Distributed Architecture

Keysight has leveraged decades of test and measurement experience to create a mmwave frequency extension for vector network analyzers. This distributed system is optimized for making accurate measurements and helping you face the challenges of mmwave measurements.

The measurement solution for mmwave network analysis is a distributed system composed of a vector network analyzer (VNA), a test set controller, and frequency extenders.

A distributed system is made up of separate components that communicate together to act as one system. The frequency extenders interface with the device under test (DUT) and are the only pieces of the system that operate at mmwave frequencies. This allows us to test mmwave devices without having to completely rebuild VNAs to handle higher frequencies.

Each piece of the distributed configuration brings measurement advantages. As described in the next section, small frequency extenders bring the measurement to the device to minimize cable errors. The test set controller is the interface between the VNA and the frequency extenders. It contains switches and amplifiers that allow the VNA to make continuous sweeps across the entire frequency range of interest. Without the test set controller, the VNA cannot continuously sweep over large frequency ranges.

Keysight’s distributed solution is based on the N5295AX03 modular frequency extension. The N5295AX03 can be added to an existing compatible network analyzer (PNA or PNA-X with a maximum frequency of 26.5 GHz or higher), reducing the cost of test by upgrading instead of replacing. The frequency extenders connect to the N5292A test set controller, which interfaces with the test set of the VNA. This gives the VNA a new maximum frequency of 120 GHz so it can test modern mmwave devices.
Avoiding errors for mmWave measurements

A distributed system also addresses two big sources of error in high frequency measurements: cable losses and temperature instability.

Cable loss

There is a relationship between frequency and cable loss, as shown in Figure 1. Cable losses at mmwave frequencies can have a significant impact on measurements. Even a very good cable will lose 1.1 to 1.5 dB over 8 cm at 110 GHz and higher, so a measurement with 0.5 meter cables can lose 9 dB between the DUT and the instrument. This makes it important to minimize cable length and bring the measurement to the device. External frequency extenders can get much closer to devices than a VNA and its test set, mitigating a few dB of cable losses.

![Figure 1: Cable Losses.](image)

Shorter cables also reduce cable movement and provide more accurate phase control. At a wavelength of 2.7 mm it only takes a 1.35 mm movement in the measurement plane to cause a 180° phase shift.
Temperature stability

Temperature stability is crucial for systems that will be running for many hours. As temperature increases it agitates more charge carriers, resulting in thermal noise. The power in dBm of this thermal noise is given by:

\[ P_{dBm} = 10 \log_{10}(k \times T \times B \times 1000) \]

Where \( k \) is the Boltzmann constant in J/K, \( T \) is temperature in K, and \( B \) is the measurement bandwidth in Hz. We can see in this equation that the power of the thermal noise increases with temperature. This thermal noise, along with thermal expansion of cable connectors, leads to drift errors in measurement as temperature increases. Drift errors are due to changes in the system after calibration. Figure 2 shows 1 port match measurements made with two systems that have been running for 8 hours. The N5291A (blue) is a mmwave system that contains N529AX03 frequency extenders. The other system (red) is a different mmwave system that relies on another frequency extension solution. The N5295AX03 is much better at minimizing drift uncertainty, especially at higher frequencies. They key to this is temperature regulation.

The N5295AX03 was designed with temperature regulation in mind. The modules are small enough to get close to the device but not so small that external temperature control is required. Convection cooling keeps the modules at a consistent temperature during measurement, which minimizes drift. The modules have magnitude stability of less than 0.015 dB and phase stability of less than 0.15° over a 24-hour period. This is comparable to the stability of a full-size PNA-X network analyzer.

![Figure 2: Drift impact on calibrated measurements.](image)
The distributed architecture of this system allows you to bring the measurement to your device, which minimizes cable losses, phase errors, and temperature drift. These advantages help you make accurate and fully traceable measurements.

System implementation

Figure 3a shows a high level block diagram of how the mmwave test architecture is arranged. We can see what this setup might actually look like in Figure 3b.

Let’s dig a little deeper into each block.
Vector Network Analyzer

In this type of system, the vector network analyzer is the measurement and computation engine. A versatile VNA is essential for testing monolithic microwave integrated circuits (MMICs), which contain many components that operate in different frequency ranges. The single-connection, multiple-measurement (SCMM) architecture of the PNA-X allows you to make measurements such as S-parameters, noise figure, gain compression, THD, IMD, and spectrum analysis - all from one connection.

Figure 4: SCMM on a PNA-X.

The N5295AX03 is compatible with the PNA and PNA-X network analyzers listed in Table 1 and Table 2. These VNAs have the frequency range needed to drive the N5295AX03 and measure the output. They are also compatible with the test set required for interfacing with the N5295AX03.

Table 1: Supported PNA configurations

<table>
<thead>
<tr>
<th>Publication/Option</th>
<th>Description</th>
<th>Low Frequency Extension</th>
</tr>
</thead>
<tbody>
<tr>
<td>N5222B-201</td>
<td>26.5 GHz 2-port PNA with configurable test set option</td>
<td>Option 205 ³</td>
</tr>
<tr>
<td>N5222B-401</td>
<td>26.5 GHz 4-port PNA with configurable test set option</td>
<td>N/A</td>
</tr>
<tr>
<td>N5224B-201</td>
<td>43.5 GHz 2-port PNA with configurable test set option</td>
<td>N/A</td>
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<tr>
<td>N5224B-401</td>
<td>43.5 GHz 4-port PNA with configurable test set option</td>
<td>N/A</td>
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<td>N5225B-201</td>
<td>50 GHz 2-port PNA with configurable test set option</td>
<td>N/A</td>
</tr>
<tr>
<td>N5225B-401</td>
<td>50 GHz 4-port PNA with configurable test set option</td>
<td>N/A</td>
</tr>
<tr>
<td>N5227B-201</td>
<td>67 GHz 2-port PNA with configurable test set option</td>
<td>Option 205 ³</td>
</tr>
<tr>
<td>N5227B-401</td>
<td>67 GHz 4-port PNA with configurable test set option</td>
<td>N/A</td>
</tr>
</tbody>
</table>

1. All hardware options listed are the minimum required hardware options.
2. All PNA models listed require Option 020.
3. Option 205 allows the millimeter wave system to have a start frequency of 900 Hz.
Table 2: Supported PNA-X configurations

<table>
<thead>
<tr>
<th>Publication/Option</th>
<th>Description</th>
<th>Low Frequency Extension</th>
</tr>
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<tbody>
<tr>
<td>N5242B-201</td>
<td>26.5 GHz 2-port PNA with configurable test set option</td>
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<td>N5242B-401</td>
<td>26.5 GHz 4-port PNA with configurable test set option</td>
<td>Option 425 3</td>
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<tr>
<td>N5244B-201</td>
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<td>N5244B-401</td>
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<td>N5245B-201</td>
<td>50 GHz 4-port PNA with configurable test set option</td>
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<tr>
<td>N5247B-201</td>
<td>67 GHz 2-port PNA with configurable test set option</td>
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<tr>
<td>N5247B-201</td>
<td>67 GHz 4-port PNA with configurable test set option</td>
<td>Option 425 3</td>
</tr>
</tbody>
</table>

1. All hardware options listed are the minimum required hardware options.
2. All PNA models listed require Option 020.
3. Option 425 allows the millimeter wave system to have a start frequency of 900 Hz.

Frequency extenders

The frequency extenders up-convert the 26.5 GHz output from the test set to test devices at millimeter-wave frequencies. The block diagram of the N5295AX03 frequency extender in Figure 5 shows the conversion circuitry. There are three multiplier chains available, which can mix the RF input to produce frequencies as high as 120 GHz. This frequency is well within the millimeter range and provides accurate characterization of cutting-edge millimeter-wave devices.

Figure 5: N5295AX03 frequency extender block diagram.
Active devices, such as transistors and amplifiers, require a DC bias for operation. A bias tee combines AC and DC signals so active devices can simultaneously be biased and tested. Figure 6 is a simplified equivalent circuit of a bias tee. The inductor and capacitor prevent the DC and RF sources from interfering with each other. N5295AX03 frequency extenders have a bias tee built-in, allowing them to be as close to the DUT as possible. This helps minimize long ground loops. Ground loops occur when there is more than one path to ground and can introduce unwanted interference, especially if the loop is long. A DC bias can provide a ground path so keeping it close to the DUT minimizes ground loop interference.

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![Bias tee equivalent circuit.](image)

The output from the frequency extender to the DUT is a 1 mm broadband coupler. The coupler has high directivity, meaning it is very good at separating signals moving in opposite directions. In this case, it separates the reference signal going to the DUT and the test signal coming from the DUT. The reference and test signals are sampled by a broadband Gilbert cell mixer. Gilbert cell mixers cancel out unwanted mixing products to produce a very clean output. The mixer converts the reference and test signals to the network analyzer’s IF so they can be analyzed by the instrument.
Test Set Controller

The test set controller is the interface between the frequency extender modules and the VNA. The test set controller allows you to make broadband sweeps across the entire frequency range of the frequency extenders. Without a test set controller a VNA is limited to banded measurements. Banded measurements divide the full frequency range into smaller bands that are swept individually. This is useful for looking at DUT responses at particular frequencies, but a broadband sweep is preferable for a complete characterization of the DUT.

Figure 7: N5292A test set controller.

The test set controller amplifies the network analyzer’s local oscillator (LO) signal to drive the frequency extenders’ mixers across their entire frequency range. The controllers also error correct and condition the frequency extender output to be at the IF of the VNA. The controller simplifies the measurement setup by providing RF, LO, and intermediate frequency (IF) signals to the frequency extenders over a single cable. This allows all measurement configuration to be done on the VNA’s interface without having to adjust hardware.

Low frequency extension

The minimum frequency supported on the PNA and PNA-X is 10 MHz. If you need to go to lower frequencies, you can use a low frequency extension (LFE) for network analyzers, like Keysight VNA Option 205/425 that extends the minimum frequency down to 900 Hz. As shown in Figure 8, the LFE contains a separate source and receiver designed for low frequencies. Low frequency testing enables more accurate device models by giving a more complete picture of device behavior. The frequency extender module includes an input for the LFE, making its total range 900 Hz to 120 GHz.
Conclusion – A Distributed Architecture Makes Better mmWave Measurements

The growing application space of mmwave applications calls for systems that can accurately characterize devices at mmwave frequencies. Keysight’s distributed architecture approach allows vector network analyzers to keep up with this trend and make accurate, repeatable measurements up to 120 GHz.

To learn more about Keysight’s mmwave solution for vector network analysis, please visit the product page. You can also find more information about mmwave characterization in the Millimeter-wave Component Characterization webcast.

Learn more at: www.keysight.com

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