APPLICATION NOTE

5 Practical Hints for Better Millimeter-Wave Signal Analysis

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Mainstream Millimeter Wave

Just a decade ago it might have been hard to believe, but millimeter-frequency applications above 50 GHz are going mainstream. Wireless HD, 802.11ad wireless networking, 5G cellular, early 6G and automotive radar are high-profile examples of an important trend, supported by remarkable advances in semiconductor technology.

What industry trends are driving the move to millimeter wave frequencies? One of the key technology drivers is the high cost of lower-frequency spectrum. The more modest cost of wide chunks of contiguous spectrum at higher frequencies has economic appeal. Also, there is a public benefit to shifting existing traffic to higher frequencies to free up lower-frequency spectrum whenever possible.

Millimeter-wave products are becoming economically viable. Affordable retail prices are available for Wireless HD. Radar options are available on an increasing number of cars. Bringing this technology to the mass market at the price points required for largescale adoption poses tremendous challenges in design and manufacturing.

The economic potential is large, the opportunities are relatively near-term, and the technological challenges are just the kind of thing RF engineers can get excited about. Whether your focus is on design or test, there is plenty of difficult work ahead in the pursuit of practical ways to fully utilize the potential capacity of the centimeter and millimeter bands.

Engineering is inherently challenging at microwave and millimeter frequencies. As RF engineers have moved to millimeter-wave frequencies and wider bandwidths, they must tackle the problem of increased noise that goes along with the wider bandwidths and increased data rates of microwave and millimeter bands. This noise reduces signal-to-noise-ratio (SNR) and eventually blunts channel capacity gains, as shown in Figure 1.

The wide bandwidths available at millimeter-wave frequencies promise dramatic gains in channel capacity. Unfortunately, these bandwidths gather up more noise, and that limits real-world capacity and spectral efficiency.

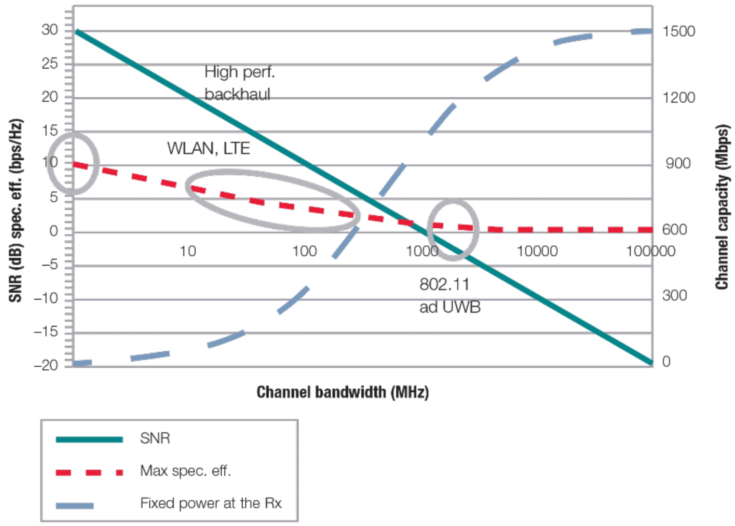

Figure 1. Comparing the maximum spectral efficiency of different channel bandwidths. The S-shaped curve shows how spectral capacity and channel efficiency returns diminish as bandwidths get very wide. Source: Keysight.com

Also shown in Figure 1 are the spectral efficiency and channel bandwidth where existing services operate. This is where RF engineers have already turned theory into practical reality. It is the landscape of tradeoffs you will optimize as millimeter technologies become widespread.

Testing at millimeter-wave frequencies

Testing at millimeter-wave frequencies is a nontrivial endeavor, requiring care and attention. Many things that can be ignored at lower frequencies really begin to matter. Accuracy and dynamic range are already declining as frequency increases, and you don't want to give up anything you don't have to in terms of accuracy, repeatability or connection loss. Because the measurement solutions you buy—including signal analyzers, signal generators and associated equipment—are more expensive, you want to extract all available performance and preserve all the margin you can.

Whether you have made many measurements at millimeter frequencies or not, you may be following developments in this area. Given the expansion of wireless and other applications to higher frequencies and wider bandwidths, there is no shortage of coverage. Getting accurate, reliable measurements at millimeter frequencies will certainly challenge you to hone your skills and pay close attention to factors that you treat more casually at RF or even microwave.

Given the march to higher frequencies and wider bandwidths, these four hints for optimizing millimeter-wave signal analysis are more important than ever.

- Hint 1: connector savers make a difference
- Hint 2: external mixing or direct frequency coverage—which is the best choice for you?
- Hint 3: calibration is key
- Hint 4: correct torque for millimeter connections is easy and important
- Hint 5: when to use coax and when to use waveguide

Hint 1: connector savers make a difference

Look at the front panel of many millimeter-frequency signal generators and analyzers. Instead of the usual female connector—Type-N, 3.5 mm, 2.4 mm, etc.—you'll often find a male connector with a large-diameter knurled flange that enables finger-tightened connections (Figure 2).

Because most cable assemblies use a male connector at each end, there must be a good reason for this departure from the norm. Indeed, that's the case, and the reasons can be summarized with the words "connector saver." Two examples are in Figure 3.

Figure 2. While the typical front-panel connector is female, the gender is often reversed for equipment covering millimeter frequencies (30 GHz to 300 GHz). The male connector offers some degree of protection from several types of damage. Source: Keysight.com

Figure 3. "Connector savers" are coaxial adapters placed between instrument front-panel connectors and cables or DUTs. They can be easily replaced if they are damaged or become worn.
Source: Keysight.com

Even connector savers, a good practice recommended here, add the effects of one more electrical and mechanical interface. As always, it's a matter of optimizing tradeoffs.

One approach to mastering the connection tradeoffs is to eliminate some adapters by using cables different from the usual male-at-each-end custom. Cables can take the place of connector savers and streamline test connections, especially when you'll be removing them infrequently. Also, consider cable length and quality carefully. Good cables can be expensive but may be the most cost-effective way to improve accuracy and repeatability.

Two more benefits of connector savers are captured with the words "expendable" and "replaceable." Millimeter connectors are inevitably small and somewhat delicate, and replacing an instrument's front-panel connector is an expensive operation. What's more, recalibration is often required, and that can take an instrument out of service for the calibration period.

In situations that require frequent connection changes, it makes sense to keep a sacrificial adapter semi-permanently attached to the front panel of the instrument. When the adapter gets damaged or worn, it can be easily replaced at modest expense. Relatively speaking, even the most expensive metrology-grade adapter costs less than an instrument repair and recalibration.

Front-panel connectors are subject to several kinds of damage and wear. The use of the male connector and a connector saver helps in several ways. First, the male connector tends to encourage the use of a connector saver. An operator not trained in the proper use and care of connectors cannot connect most cables (again, male at both ends) directly to the front panel and is therefore less likely to cause accidental damage. Second, the male connector is generally more physically robust than the female. The most common type of damage is destruction of the female collet by a center conductor that is either misaligned or the wrong size. A male front-panel connector focuses the damage on the less-expensive part.

As a final point, this gender choice tends to dramatically reduce the number of connection cycles for the instrument connector itself. Even with careful operation, wear and damage are inevitable and it's better to focus the wear and risk on expendable parts.

Q: How do you determine the gender of connectors with varying configurations of outer shells?

A: The gender is determined by the center-most conductor of a connector, regardless of the position of the outer nuts, threaded barrels or bayonet hardware.

Q: What is the purpose of the flats machined into the barrels of the connector savers?

A: The flats machined into the barrels of the connector savers pictured above are not just for torque wrenches. They also allow use of a common open-ended wrench to avoid connector rotation when nuts are tightened. Connector rotation should be avoided because of the wear it causes, es specially with delicate millimeter hardware.

Q: Are these standard adapters the only adapters available?

A: No, they are not the only adapters available. Some instruments use custom adapters that can function as connector savers rather than the standard adapters described above. These custom adapters are a user-replaceable part of a front-panel connector set and may offer a choice of connector types at the user end. This approach may provide a shorter physical connection and some improvement in mechanical robustness due to the compact configuration. However, the special adapter may be a disadvantage if it is damaged in its connector-saver role and a replacement is not readily available.

Summary

Coaxial adapters functioning as connector savers are a practical accessory for mitigating wear and damage to more delicate input connectors.

Hint 2: external mixing or direct frequency coverage—which is the best choice for you?

External mixing has long been a practical and economical way to make millimeter frequency measurements. Signal analyzers such as the N9041B UXA X-Series signal analyzer bring the performance and convenience of a single-instrument solution with continuous direct coverage from 2 Hz to 110 GHz. And now, the N9042B UXA X-Series signal analyzer with the V3050A Signal Analyzer Frequency Extender offers an additional configuration with price and performance options to consider.

External mixing

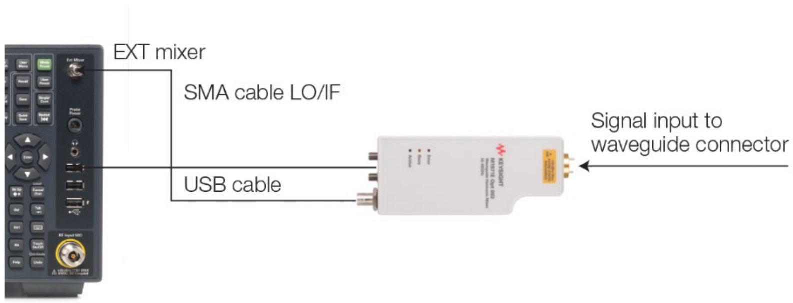

Figure 4. The first practical millimeter measurements were made with external mixers (left). Source: Keysight.com

External mixing effectively moves the analyzer's first mixer outside of the analyzer itself. The analyzer supplies a LO drive signal to the mixer and receives—sometimes through the same cable—a downconverted IF signal to process and display. This provides a lower-cost solution, where analyzers with lower frequency coverage handle millimeter signals through a direct waveguide input.

In use, this setup is more complicated than a one-box solution, but innovations such as smart mixers with USB plug-and-play make the connection and calibration process more convenient. An external mixer can be a kind of "remote test head," extending the analyzer's input closer to the DUT and simplifying waveguide connections or the location of an antenna for connector-less measurements.

The drawbacks of external mixers include:

- They are banded, which limits frequency coverage.
- They lack input conditioning such as filters, attenuators, and preamps.
- Their effective measurement bandwidth is limited by the IF bandwidth of the host analyzer, a problem for the very wideband signals used so often at millimeter frequencies.
- They often require some sort of signal-identification process to separate the undesirable mixer products that appear as false or alias signals in the analyzer display. Signal identification is straightforward with narrowband signals but can be impractical with very wide ones.

Signal analyzer with frequency extender

Figure 5. The N9042B UXA with the V3050A Signal Analyzer Frequency Extender offers simpler setup but preserves the “remote test head” element of the measurement setup. Source: Keysight.com

With a price point just above the external mixer option, the use of the N9042B UXA X-Series signal analyzer with the V3050A Signal Analyzer Frequency Extender eliminates the more complicated external mixer setup and uses the V3050A as the “remote test head” to move the measurement plane to the device under test.

With the V3050A Signal Analyzer Frequency Extenders:

- Continuous coverage 50 GHz to 110 GHz (or 2 Hz to 110 GHz) when paired with N9042B UXA.
- Hardware preselected to reduce images.
- Utilizes full analysis bandwidth available in N9042B UXA.

Signal analyzer with continuous, direct frequency coverage

Figure 6. Signal analyzers with direct coverage to the millimeter bands, such as the N9041B UXA X-Series Signal Analyzer shown here, are becoming more common. Source: Keysight.com

Millimeter signal analyzers offer a measurement solution that is better in almost all respects, although is considerably more expensive. They provide direct, continuous coverage and calibrated results. Their filters and processing eliminate the need for signal identification, and their input conditioning makes it easier to optimize for sensitivity or dynamic range.

With the N9041B UXA:

- Continuous frequency coverage 2 Hz to 110 GHz.
- Hardware preselected to 50GHz: software preselected to 110 GHz to reduce images.
- Utilizes full analysis bandwidth available in N9041B UXA.

Summary

Budget and test setup considerations will play a key role in determining the best choice among the options available today.

Hint 3: calibration is key

Regardless of the physical configuration of the test setup, magnitude and phase errors introduced by cables and fixtures impact results in a significant way at these frequencies. For example, path loss can be multiple dB per meter rather than the tenths of a dB encountered at lower frequencies. Unless this is accounted for, designs are overburdened with the additional constraints.

One option is to purchase additional test equipment and write custom software to calibrate out the effect of the test cables and fixtures, but this is costly and time consuming.

The U9361 RCal Receiver Calibrator series seamlessly moves the measurement plane from the input of the signal analyzer to the output of the device under test. Simply connect the RCal module to a Keysight X-Series signal analyzer via USB. Insert the RCal module at the DUT reference plane. The combined pair will execute a series of measurements used to calculate correction factors, referenced to the RCal's point of connection. The correction factors can be applied to all measurements that follow.

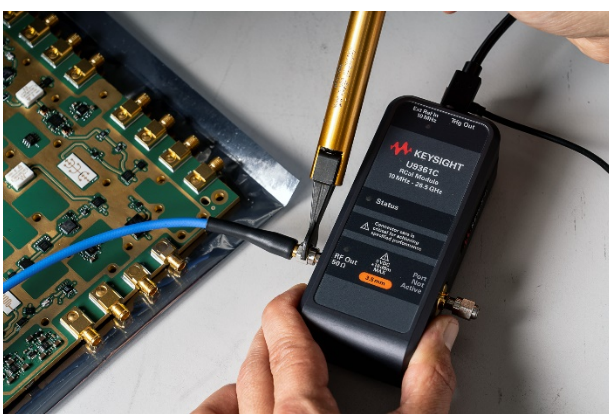

Figure 7. The U9361 Series RCal Receiver Calibrator effectively moves the reference plane to the DUT to improve your test Rx system accuracy by an order of magnitude. Source: Keysight.com

Summary

At millimeter wave frequencies path loss can be significant and correcting for it is critical to making accurate measurements.

Hint 4: correct torque for millimeter connections is easy and important

Connector torque can be important and helpful at high frequencies. Applying consistent torque points to use of a torque wrench and avoiding damage means paying attention to its limiting function.

Consistent torque places a consistent stress on the nut and the rest of the connector structure. This has three important benefits:

- Consistent mechanical alignment and axial positioning of connector elements ensures the best connector performance (e.g., return loss) and repeatability.
- Sufficient strain reduces the possibility that the connection will be loosened by vibration, thermal changes or external mechanical action such as bending or twisting.
- Proper torqueing avoids connector damage from deformation due to excessive tightening.

The first and third benefits are often difficult to discern. Suboptimal connector performance can be a hard problem to isolate and connector distortion or damage from excessive tightening may be invisible to the eye.

The second benefit is something a bit easier to see. After using your fingers and thinking you've got a connector tight enough, you later discover that it's loose. Maybe the connector was bumped, or maybe something more subtle happened: thermal cycles or cable motion reduced the strain from fingertip-tightened "too low" to zero.

Proper torque

Proper connector torque is simple for the vast majority of microwave and millimeter connections we use because there are only two torque values needed to cover SMA through 1.85 mm (70 GHz). SMA connectors should be torqued to 56 Newton-cm or 5 inch-pounds and all the rest—3.5, 2.92, 2.4 and 1.85 mm—should be tightened to 90 N-cm or 8 in-lbs. Guidance for 1 mm input connectors varies from 4 inch-pounds to 10 inch-pounds, so consult the manufacturer's recommendations before you begin.

What if you are mating an SMA connector with one of the other compatible precision connectors, 3.5 or 2.92 mm? Should you use the SMA torque value or the precisionconnector value? The answer is to follow the value for the male connector. Thus, if the SMA connector is male gender, then you should use the SMA torque value.

Torque wrenches

The power of wrenches must be used carefully because you can't feel forces through them the way you do with your fingers. The potential for over-straining something is also greater when multiple or longer adapters are used or when devices are connected directly without cables that relieve bending stress. The diagram below describes one example: "wrench-lift stress."

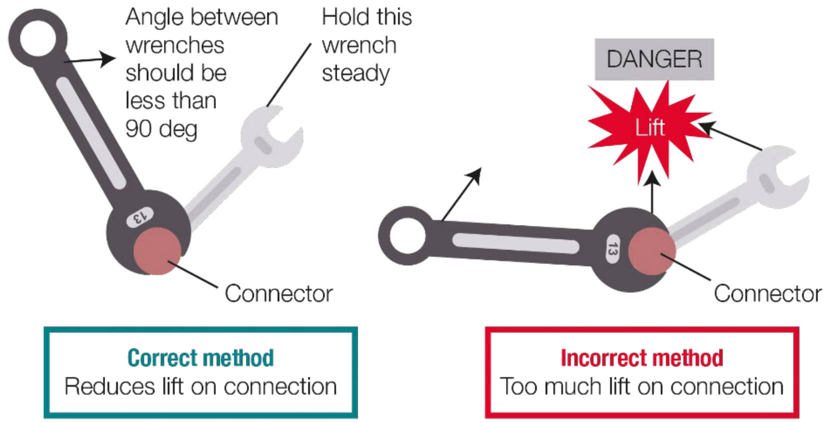

Figure 8. Using the appropriate wrenches to tighten or loosen connectors is good practice but they can cause wrench-lift stress and bend connectors if used the wrong way. Maintaining a small angle between the two wrenches during assembly and disassembly will avoid the problem. Source: Keysight.com

The second wrench is typically a simple open-ended one, but it also has an important job to do. By preventing rotation of the connector mating surfaces while they are in contact, it reduces a major source of connector wear and damage.

Summary

While connector torque and rotation aren't the only sources of problems such as connector damage and poor performance, they are very important considerations.

Hint 5: when to use coax and when to use waveguide

Most RF engineers frequently use coaxial cables and connectors. Coaxial cables and connectors are now readily available at frequencies to 110 GHz and at first glance they may seem so much easier and simpler than waveguide. Whether or not you use waveguide frequently, it is useful to understand the choices and tradeoffs.

It's perhaps no surprise that there are both electrical and mechanical factors involved in the connection decision. Especially in the millimeter frequency range and above, electrical and mechanical characteristics do an intricate dance. Understanding how they intertwine is essential to making better measurements.

Coaxial connections

Coaxial connections are flexible and convenient. Direct wiring, in its coaxial incarnation, is the obvious choice wherever it can do the job acceptably well. The advances of the past several decades in connectors, cables and manufacturing techniques have provided a wide range of choices at reasonable cost. Coax is available at different price/performance points from metrology-grade to productionquality, and flexibility varies from extreme to semi-rigid. While the cost is significant, especially for precision coaxial hardware, it is generally less expensive than waveguide.

Coax can be a simple and efficient solution when device connections require some kind of power or bias, such as probing and component test. A single cable can perform multiple functions, and the technique of frequency multiplexing can allow coax to carry multiple signals, including signals moving in different directions. For example, Keysight's waveguide harmonic mixers use a single coaxial connection to carry an LO signal from a signal analyzer to an external mixer and to carry the IF output of the mixer back to the analyzer.

Waveguide

Loss is an important reason waveguide may be chosen over coax. Power considerations, both low and high, are often the reasons engineers trade away the flexibility and convenience of coax. In most cases, the loss in waveguide at microwave and millimeter frequencies is significantly less than that for coax, and the difference increases at higher frequencies.

For signal analysis, this lower loss translates to increased sensitivity and potentially better accuracy. Because analyzer sensitivity generally declines with increasing frequency and increasing band or harmonic numbers, the lower loss of waveguide can make a critical difference in some measurements. Also, because available power is increasingly precious and expensive at higher frequencies, the typical cost increment of waveguide may be lessened.

On the subject of power, the lower loss in waveguide comes with high powerhandling capability. As occurs with small signals, the benefit increases with increasing frequency.

Coax	Waveguide
Advantages	
Flexible	Low loss
Wide frequency range	High power handling ability
Easy to change routing	Mechanically durable
Light weight	
Can carry DC bias	
Can carry multiple signals	
Can be less expensive	
Good match for component measurements	
Disadvantages	
Lossy, increasing with frequency	Inflexible
Can be delicate	May need customer construction (expensive)
Limited power handling	Time delays for constructions and reconfiguration
	Frequency range ≤ 1 octave
	Transitions needed to connect to analyzers and other coaxial elements

Figure 9. Comparing the benefits of coaxial and waveguide connections for microwave and millimeter frequency applications. Source: Keysight.com

Summary

As you can see from the summary above, other coax/waveguide tradeoffs may factor in your decision of which connection to use.

Conclusion

Sensitivity is an essential aspect for millimeter frequency measurements. Power is hard to come by at these frequencies, and the wide bandwidths used can gather substantial noise, limiting SNR. Optimizing the displayed average noise level (DANL) of your signal analyzer, along with careful connections, should yield excellent spurious and emissions measurements.

Millimeter measurements, especially wideband ones, will continue to be demanding, but the tools are in place to handle them as they become a bigger part of your engineering efforts. Whether you choose external mixing, a signal analyzer with frequency extender or a single-box signal analyzer with continuous, direct frequency coverage, understanding what measurements you need to make is a key part of the process.

Adapters and connectors mentioned in this note can be found on www.keysight.com.

Additional Resources

- Data Sheet: UXA X-Series Signal Analyzer, Multi-Touch, N9041B, publication 5992-1822EN
- Configuration Guide: UXA X-Series Signal Analyzer, Multi-Touch, N9041B, publication 5992-2112EN
- Data Sheet: N9042B UXA X-Series Signal Analyzer, publication 3121-1037.EN
- Configuration Guide: N9042B UXA X-Series Signal Analyzer, publication 3121-1036.EN
- Product: U9361 RCal receiver calibrator for improved receiver test system accuracy by 10X
- Brochure: Signal Analysis Solutions Catalog, publication 7120-1206.EN

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