Light Report

The Essential Role of Testing and Validation in Private Network Deployment

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Introduction

How significant will 5G Private Networking be for developing business operations over the next few years? Very significant, according to a recent survey[1] of senior executives from 1,000 industrial organizations. 30% said they were at the piloting stage or beyond, and 40% expected to roll out 5G at scale at a single site within the next two years.

The benefits that 5G private networking offers are set to grow increasingly vital across a range of sectors and applications, as IoT and edge computing become more central to business operations over the next few years. Yet deploying 5G private networks raises new challenges to ensure the anticipated performance is achieved. Network coverage, connectivity, stability, security. These and other essential parameters must operate as expected in order for connected devices – such as autonomous robots in smart warehouses – to work effectively.

Keysight Technologies, with its extensive testing, measurement and certification capabilities, has established a three-stage testing and validation process for 5G private networks. These stages can be implemented independently or in combination to dramatically speed up and cut the costs of deployment.

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1 Accelerating the 5G Industrial Revolution. Capgemini Research 2021

Why private networks?

The business case for employing a private cellular network is compelling. A recent report on 4G/5G private networking published by Beecham Research – 4G/5G Private Networking: New Choices for IoT Deployment – highlights the fact that this development is enabling new choices for IoT deployment. Moreover, IoT in business operations has the proven ability to boost operational efficiency, improve product and service performance, and enhance operational agility. The overall result is a significant uplift to a company's competitive offer and its bottom line. Therefore the ability to own and manage a mission-critical resource, the network that transports IoT operational information and intelligence efficiently and securely, is a logical next step in enterprise-wide IoT deployment.

There are many benefits that private networks offer for businesses. These are some of the main ones:

- Local coverage, both indoors and outdoors, designed to meet on-site needs
- High level of network security, with data remaining on-site
- Sufficient network capacity for requirements at all times
- Local management control over network traffic and use, including seamless integration with enterprise IT/OT
- Very high network reliability
- Predictable and ensured low latency – data control
- High data rates and high density devices

These are diverse benefits – some are more important than others for a particular installation. How do you ensure that the private network being implemented will deliver the performance required for the business? How do you ensure that the IoT solution will be successful?

At the same time, as illustrated in **Figure 1**, there are 15 key application groups where 5G private networks are currently being used or planned. Each group has multiple applications, and these coincide with many IoT applications that are moving to real time operation with edge processing. The purpose of this is to move from monitoring to control, by introducing automation. The leading sector for this is Industrial/ Manufacturing, but others such as Hospitals, Oil & Gas, Mining and Ports/ Airports are not far behind.

The majority of these operate on large sites – some like Ports are very large – and others like Industrial/ Manufacturing sites are often highly complex, with many different activities operating at the same time. With "wireless" being by far the major form of communication, there is ample opportunity for mutual interference, security issues and other challenges. These need to be identified up front – before they are discovered post deployment when they could take a lot more time and resources to fix.
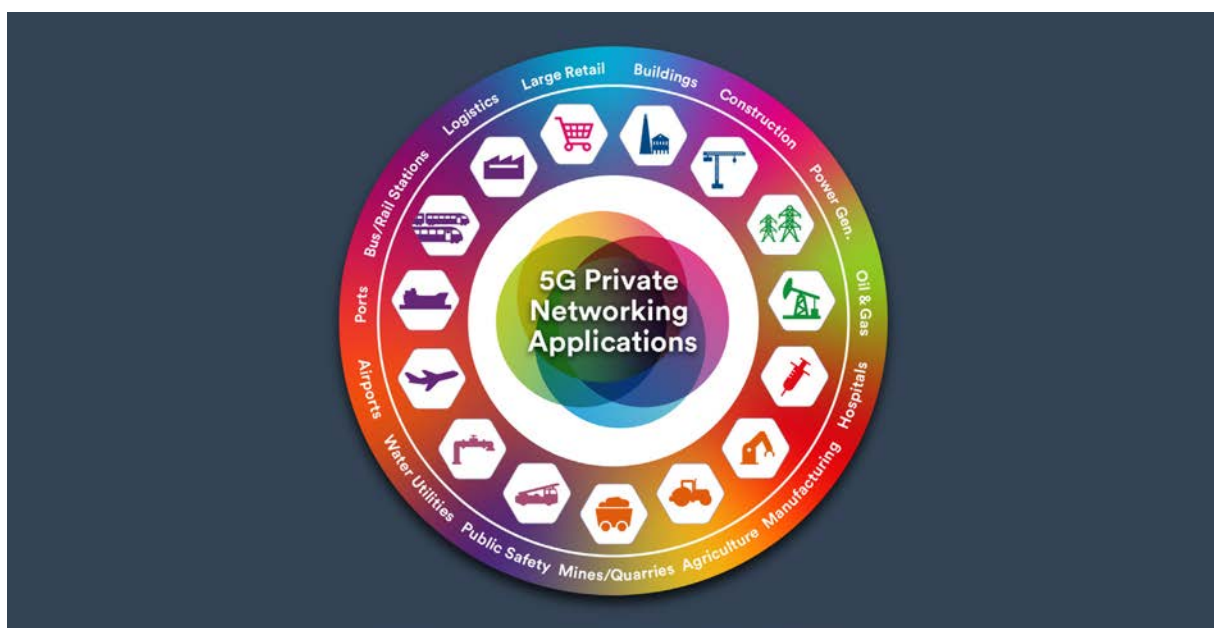

Figure 1: Most popular 5G private networking application groups
(Source: Beecham Research)

Succeeding with IoT

IoT solutions have evolved into an increasingly complex mix of computing and communications technologies, which introduces a number of interrelated issues that impact all players in the value chain – device and hardware manufacturers, systems integrators and solution providers, service providers, application and software developers.

The biggest issue is failure to perform, for example not enabling the requisite performance and meeting the business objectives. This is a topic that Beecham Research investigated in an earlier report – Why IoT Projects Fail. This showed that, in a survey of senior executives as illustrated in **Figure 2**, 58% of IoT projects were considered either mostly or fully unsuccessful by their companies. A further 30% considered them to be mostly – but not fully – successful, with only 12% considering them to be fully successful.

The report details and quantifies the key reasons why deployments continue to fail. They include business challenges as well as various technical concerns arising from IoT's complex mix of communications and computing technologies.

Findings included issues when companies went from prototypes to large scale systems, and the fact that often there is not enough early-stage testing and extensive field trials are needed to work out where failures can arise.

Cutting testing short is a common fault in conventional IT projects as well as IoT. Extensive testing and validation are increasingly vital for the success of private network design, implementation, and operation. Keysight has the requisite product portfolio of test solutions that facilitate private network infrastructure creation, implementation, and operation across all stages of the network lifecycle. In addition the company has extensive experience in the global communications ecosystem.
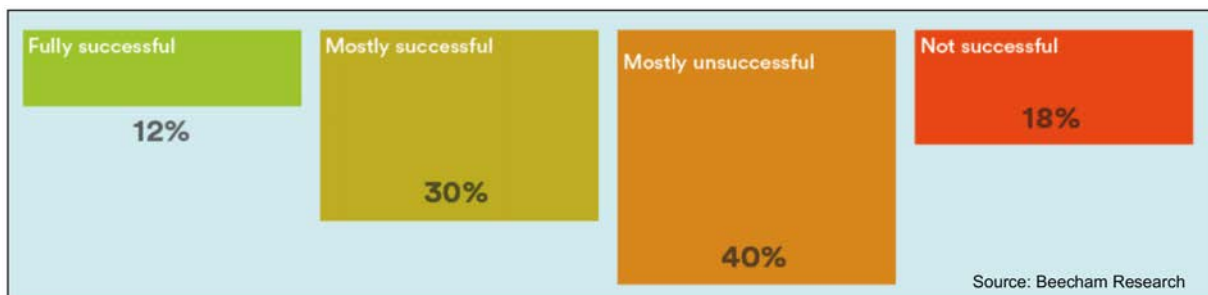

Figure 2: How successful was your IoT project?
(Source: Beecham Research)

Testing and validating private network performance

As noted earlier, Keysight's testing and validation process broadly divides into three stages: Build, Deploy and Run. These stages can be implemented independently or in combination.

Build comprises research, development, validation and certification of the private network infrastructure. It includes the validation and conformance of the IoT devices as well as the radio access network (RAN) and other network infrastructure.

Deploy covers the design, deployment and optimization as well as facilitating site acceptance of the network.

Run comprises monitoring, securing, optimizing and assuring the network.

Each stage divides into sub-sets that utilise specific test products that address specific tasks. There are eight to choose from for Build, with the first task typically being Industrial Device Design, Validation, and Certification. For Deploy there are six to choose from, with the first typically being Pre-Deployment Solutions. And for Run there are three to choose from, with the first typically being End-to-End Performance Assurance for Guaranteed SLAs, Predictive Analytics, and Diagnostics.

Detailing the test products for all seventeen sub-sets and tasks they address is beyond the scope of this report. However in order to illustrate the depth and breadth of the company's portfolio, some of the test products that are used for each of the first tasks in Build, Deploy and Run are outlined below.

For Industrial Device Design, Validation, and Certification (Build) they are:

• 5G wireless test platform
• Outdoor 5G NR drive test solution
• Wireless network analyser

For Pre-deployment (Deploy) they are:

• Handheld RF and microwave analysers
• Open RAN architect solutions
• Plug & play interoperability testing in the lab

For End-to-End Performance Assurance for Guaranteed SLAs, Predictive Analytics, and Diagnostics (Run) they are:

• Nemo autonomous probe
• Active network monitoring, core network solutions (QoS validation)
• Cloud Peak (MEC NFV1 performance testing).

Four key steps

Step 1.

Validation and Conformance of Industrial Devices. Designing a 5G private network starts prior to designing and installing a real network. The process begins with the design, validation, and conformance testing of industrial devices. Mostly intended for Industry 4.0 applications, 5G private network devices create new challenges. Connected devices are also becoming increasingly complex. Future robotic arms, for example, will embed multiple devices to increase position accuracy and versatility. In addition to devices, radio access networks and core equipment require validation for functionality, performance, reliability, and interoperability. The equipment also needs to comply with industry standards, as well as security and TSN / 5G integration requirements.

Step 2.

Network Design and Planning starts the network side of the lifecycle with the design and installation of a real network. Key aspects that need to be considered are:
- site surveying, radio planning, and spectrum clearance including interference and jamming identification
- deployment model, slicing, and isolation
- multi-access edge computing (MEC) design
- overprovisioning and optimization.

Spectrum clearance is an important focus area during the design and planning stage to prepare for the network rollout. Ensuring RAN performance requires verifying the spectrum and identifying potential sources of interference. Possible sources include local electrical / plant equipment, strong signals from local emitters, and defective equipment (**Figure 3**). In addition, the potential sources of frequency jamming must be identified and sources that jam the legal spectrum eliminated.
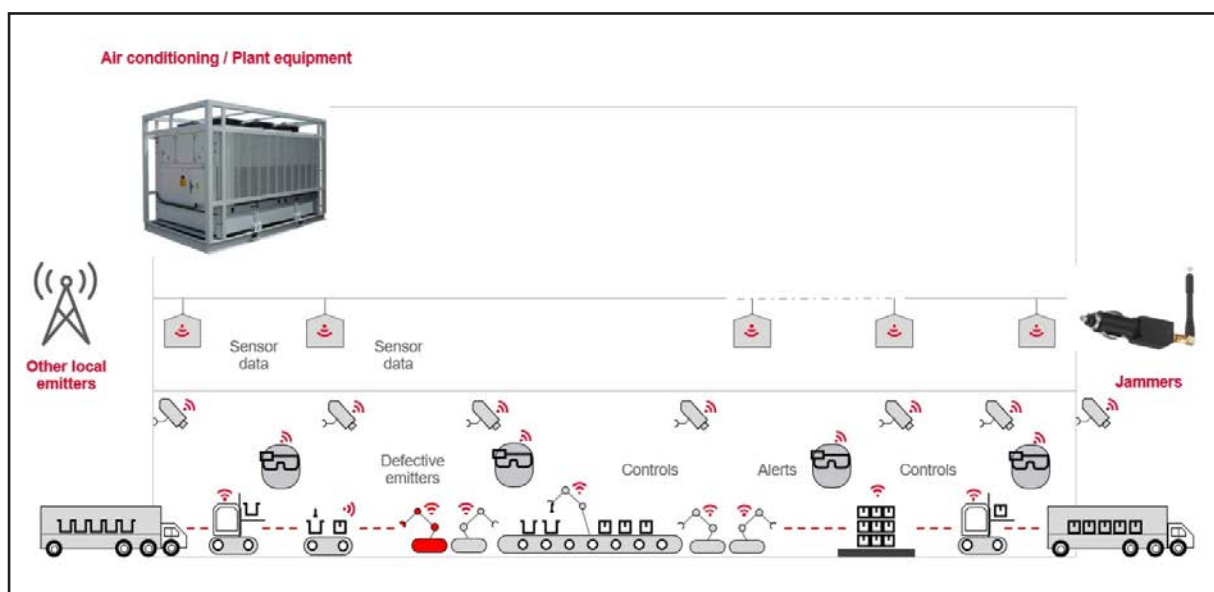

Figure 3:
Potential sources of interference in a factory.
Source: Keysight

Step 3.

Network Deployment involves acceptance and performance testing, which helps validate the network installation. Acceptance testing spans the RAN or O-RAN, 5G core, MEC, and end-to-end network. Site acceptance testing for the RAN includes functional testing for connectivity and conformance to the standards; performance testing for coverage, speed, latency, and other quality of service (QoS) aspects.

For the core network, testing covers functional testing for connectivity and standards conformance; performance testing for coverage, speed, latency, positioning, and other QoS aspects; and availability, reliability, and stability testing. End-to-end testing includes interoperability testing; functional testing for connectivity and standards conformance; performance testing for coverage, speed, latency, and other QoS aspects; availability, reliability, and stability testing; and security testing.

Step 4.

Network Operations and Optimization. This is the last phase of the 5G private network lifecycle. Network monitoring is particularly important for both critical and non-critical communications, as well as interference and jamming.

Network and cloud performance should be understood and security assurance performed. While security is a key area of focus during the operations phase of a 5G private network, particularly for industrial applications, ensuring data security is a much broader concern that requires an end-to-end lifecycle strategy. This strategy starts during the design of the industrial devices that will run on the network and extends to the operation of the network itself (**Figure 4**).
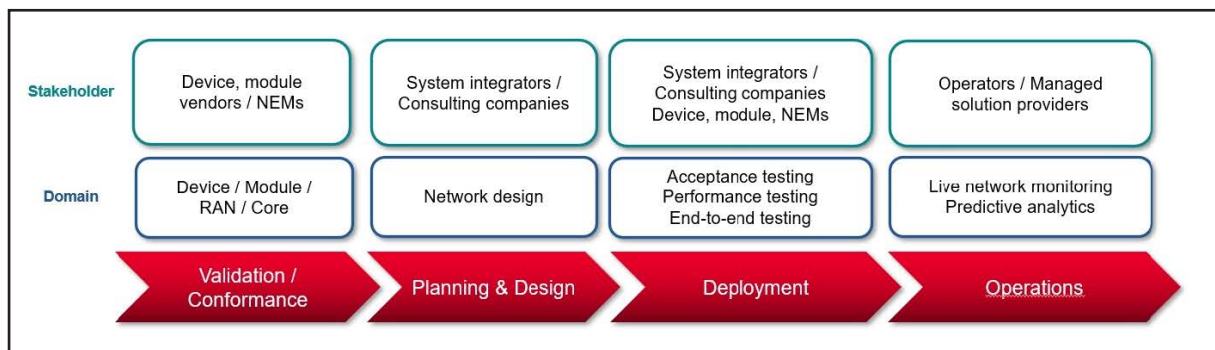

Figure 4:
Complete 5G private network lifecycle
Source: Keysight

Full lifecycle strategy

5G private networks offer significant benefits to manufacturers, but they also present many challenges. Successful deployment starts much earlier than the network design and planning stage, with the development of industrial devices and network elements. A full lifecycle strategy should be adopted.

You then need to decide how you will install the private network using one of the deployment models in Figure 5. The private network can be an isolated network that shares no resources with the public network, a hybrid network that shares some resources with the public network (RAN only or RAN and control plane) or using a 5G standalone slice from a public operator.
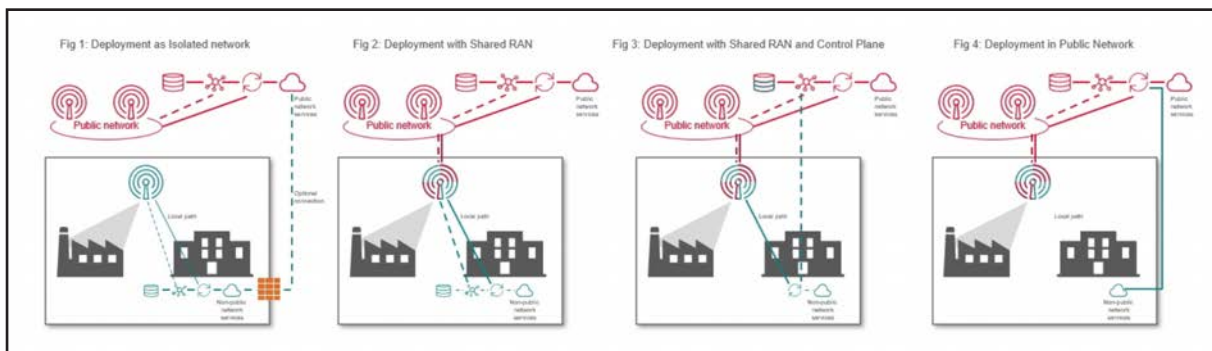

Figure 5:
Deployment options for industrial 5G networks
(Source: 5G-ACIA).

To avoid congestion at peak loads it might be necessary to overprovision the network. Avoiding network congestion also requires designing the mobile edge cloud data center with peak workloads in mind for computing, network, and storage needs. A 5G private network can employ a dedicated and isolated standalone setup, or a public wireless service provider. Each option offers different levels of security and has specific service and network management needs.

** For further details on these steps, see Keysight's white paper 5G Private Networks for Industry 4.0 Part 2.

Example case: AI-LINK

Based in China, AI-LINK, provides industrial internet of things (IIoT) solutions, built on 5G and cloud edge computing technology platforms. In order to accelerate 5G private network deployments for large-scale smart warehouse applications, AI-LINK selected Keysight's 5G test tools for end-to-end performance validation of cloud-native 5G radio access network (RAN) equipment in a digital twin laboratory environment.

AI-LINK chose Keysight's user equipment (UE) emulation solution (UeSIM) and LoadCore, a cloud-native 5G core (5GC) network test solution, to simulate a large number of industrial mobile devices designed for deployment in 5G private networks. Keysight's solutions enabled AI-LINK to verify the function and performance of 5G RAN equipment prior to deployment in smart warehouses.

In particular, AI-LINK used Keysight's 5G test solutions to simulate and stress test the behavior of autonomous guided vehicles (AGVs) used in smart warehouses. Using Keysight's UeSIM and LoadCore UE emulation solutions, AI-LINK could verify the interoperability of the protocol domain and the radio frequency domain. End-to-end verification of the 5G private network in a laboratory environment enabled AI-LINK to quickly, efficiently and securely resolve complex connectivity issues that may occur in large-scale industrial scenarios. As a result, AI-LINK can accelerate deployments of 5G private networks.

Conclusions

5G private networks bring significant benefits yet deployment involves significant challenges, for example ensuring optimum network coverage, connectivity, and stability. Various deployment options, stringent requirements, and the need for control, data, and spectrum security make implementing a 5G private network a complex task. Overcoming the challenges requires a holistic view of the network lifecycle from design validation to operations.

About Keysight Technologies

Keysight delivers advanced design and validation solutions that help accelerate innovation to connect and secure the world. Keysight's dedication to speed and precision extends to software-driven insights and analytics that bring tomorrow's technology products to market faster across the development lifecycle, in design simulation, prototype validation, automated software testing, manufacturing analysis, and network performance optimization and visibility in enterprise, service provider and cloud environments. Customers span the worldwide communications and industrial ecosystems, aerospace and defense, automotive, energy, semiconductor and general electronics markets. Keysight generated revenues of $4.9B in fiscal year 2021. For more information about Keysight Technologies (NYSE: KEYS), visit **www.keysight.com**.

Optimize Signal Quality In 5G Private Network Base Stations

With the rapid evolution of cellular communication systems, there is a growing need for higher operating frequencies and wider bandwidths to support next-generation wireless standards. The Internet of Things (IoT), autonomous vehicles, wireless broadband, interruption-free video, and the fourth industrial revolution will all benefit from 5G.

Over the next decade, thousands of companies will likely deploy private cellular networks. Enterprises can harness the advantages of 5G private networks for businesses with support from the Third Generation Partnership Project (3GPP) standards, and more. In order to provide comprehensive coverage of 5G new radio (NR) private network, 5G NR measurement applications running on a signal analyzer should be able to measure and interpret transmitter tests. Some key tests include output power, output power dynamics, transmit ON / OFF power, transmit signal quality, unwanted emissions, and transmitter intermodulation. Therefore, it is essential to select testing devices that can provide robust performance, and ensure that the base station transmitters in the network perform to standards.

To characterize and test millimeter-wave (mmWave) products' true performance, designers and manufacturers need to address testing challenges that make the signal quality more susceptible to impairments. Error vector magnitude (EVM) measurement offers powerful insight into the performance of a digital communication base station transmitter and is one of the primary metrics to assess the quality of the transmitted signal.

This white paper will discuss the EVM measurement as a key component of transmit signal quality in 5G private network base stations, the testing challenges that mmWave poses, and the Keysight solutions that address these challenges.

This white paper offers insight on the following topics:

- Characterizing mmWave signal quality with EVM

- Overcoming challenges in testing at high frequencies and wide bandwidths

- Optimizing EVM measurements

The Main Use Cases for 5G NR

In fact, Rel-16 includes several capabilities designed specifically for industrial environments, such as the ability to replace Ethernet, Wi-Fi, and LTE networks. 5G is well-suited for industrial environments. The three main use cases for 5G NR are enhanced mobile broadband (eMBB), massive machine-to-machine communications (mMTC), and ultra-reliable low-latency communications (URLLC).

eMBB

When discussing 5G eMBB, we are referring to the target peak and average data rates, capacity, and coverage of 5G compared to conventional mobile broadband. It specifies a 5G design with downlink (DL) speeds of up to 20 gigabits per second (Gbps) and uplink (UL) speeds of 10 Gbps.

mMTC

The mMTC network can support 5G IoT solutions with billions of sensors and connected devices, as well as devices with low data rates / low bandwidth that require longer battery life. This category also includes high-bandwidth / high data rate devices.

URLLC

Applications in the URLLC segment require fail-safe communication; these applications include autonomous vehicles, smart transportation networks, and the industrial internet. Rel-16 also includes time-sensitive networking (TSN), a vital feature for the coexistence of ethernet and 5G networks in factories and other areas where private networks are prevalent. Rel-16 also includes support for unlicensed spectrum which could help 5G deployments in the private sector.

The Rise of 5G Private Networks

In the coming years, the wireless communications segment will expand significantly as 5G private networks come into existence. This includes taking advantage of higher frequency and wider bandwidth applications.

5G NR operates in two frequency ranges (FR): FR1 operates in the sub-6 GHz band and FR2 in the mmWave band. The maximum channel bandwidth goes up to 100 MHz for FR1 and 400 MHz for FR2. The mmWave spectrum is faster and has lower latency. In addition, its signals are easier to contain inside buildings, so they are less likely to interfere with macro mobile networks. However, testing is complicated due to the range of frequencies, bandwidths, and deployment modes that devices and networks support. In conjunction with 5G NR, private base stations (BS) can support connectivity for different spectrum bands (sub-GHz, 1 to 6 GHz, or mmWave). The 5G base station products must pass all of the test requirements prior to their release. Otherwise, the products are not 3GPP-compatible or appropriate to implement in a network.

Testing Challenges

3GPP defines the radio frequency (RF) conformance test methods and requirements for NR base stations in the technical specifications. TS 38.141-1 (conducted conformance testing) and TS 38.141-2 (radiated conformance testing) specify the radio frequency conformance test methods and requirements for NR base stations in both FR1 and FR2. Chapter 6 of these specifications lays out the requirements for transmission tests for the base station transmitters (Tx).

You can define four types of base station configurations according to 3GPP, depending on the conducted or radiated type of the test. Type 1-C refers to the NR base station operating at FR1 with requirements defined at individual antenna connectors. Type 1-H refers to the NR base station operating at FR1 with requirements defined at individual transceiver array boundary (TAB) connectors, and over-the-air (OTA) requirements defined at the radiated interface boundary (RIB). Type 1-O and Type 2-O refer to NR base stations operating at FR1 or FR2 with a requirement set consisting only of OTA defined at the RIB. In general, the main difference between conducted and radiated tests is the radiated tests for BS types 1-H, 1-O, and 2-O.

At mmWave frequencies and wider bandwidths, the signal quality is more susceptible to impairments. To characterize and test the true performance of mmWave products, designers and manufacturers need to address testing challenges in these situations. An EVM measurement can offer powerful insight into the performance of a digital communication base station transmitter and can detect any flaw affecting the magnitude and phase trajectory of a signal, regardless of the modulation format. In 3GPP standards, EVM measurement is one of the primary metrics to assess the quality of the base station transmitted signal from the base station.

1. Characterizing mmWave Signal Quality: EVM

EVM is the most common metric for evaluating modulation quality in digital communications. The error vector is the vector difference between the I-Q reference signal and the measured signal at a given time. The error vector is a complex quantity with a magnitude and phase component.

EVM is the root mean square (RMS) of the error vector over time at the instant of the symbol clock transition. You can normalize EVM either by the amplitude of the outermost symbol or by the square root of the average symbol power. EVM measurement is sensitive to any signal impairment affecting the magnitude and phase trajectory of a signal for any digital modulation format. Therefore, EVM is an ideal tool for diagnosing problems in the baseband, the IF, or the RF sections of a communication system. In Figure 1, you can see the calculation of the error vector as a vector difference between an ideal reference signal and a measured signal at a given time.
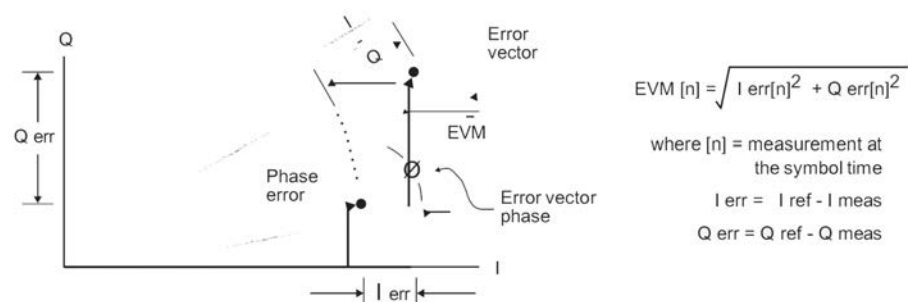

$$EVM\,[n] = \sqrt{I\,err[n]^2 + Q\,err[n]^2}$$

where [n] = measurement at the symbol time

$$I\,err = I\,ref - I\,meas$$

$$Q\,err = Q\,ref - Q\,meas$$

Figure 1: **Calculation of EVM**

Signal Quality

Many factors influence the quality of a signal, including the baseband signal processing, modulation, filtering, and up-conversion. At mmWave frequencies and wide bandwidths, signal impairments can pose more of a problem. Orthogonal properties in orthogonal frequency-division multiplexing (OFDM) systems prevent interference between overlapping carriers. However, impairments such as in-phase and quadrature (I-Q) impairments, phase noise, linear compression (AM to AM), and nonlinear compression (AM to PM), as well as frequency errors distort the modulated signal.

Phase noise poses one of the greatest challenges to mmWave OFDM systems, since each subcarrier interferes with the other, resulting in impaired demodulation. To avoid these impacts on design performance, device designers need to overcome the physical challenges present in wide bandwidth and mmWave signals. Measurement and characterization of signal quality require test solutions with better performance than the device under test (DUT) without introducing new issues. You can see some examples of I-Q modulation impairments that cause constellation symbols to deviate from their defined locations in Figure 2. These deviations provide information about the nature of the impairments based on the type and intensity of deviations.

These factors combine into a single plot by considering the EVM contribution to each impairment as well as the output power. For example, you can achieve an EVM bathtub curve for a system based on its operating level. On low operating power levels, noise performance dominates the EVM performance and on high operating levels, non-linearity is dominant. Typically, you can define the lowest EVM level for a system by the aggregation of all the error sources, including phase noise.
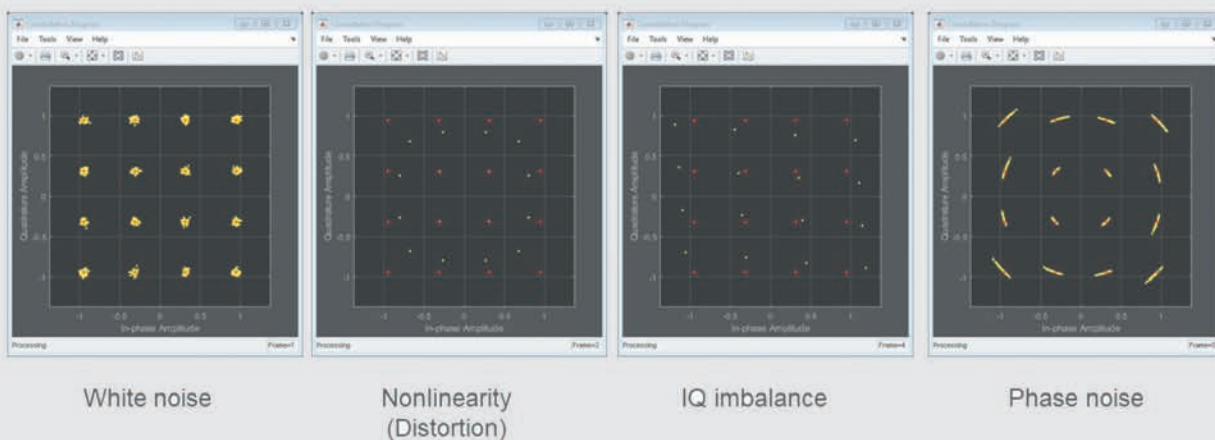

| White noise | Nonlinearity (Distortion) | IQ imbalance | Phase noise |

Figure 2: **Examples of I-Q modulation impairments that cause deviation for constellation symbols**

EVM measurements during conformance testing verify that modulation quality is within the limits specified by the minimum requirements. Antenna connectors and TAB connectors must meet the minimum requirements when testing one at a time or in parallel. You must repeat tests for all antenna connectors and TAB connectors.

EVM for NR carriers of different modulation schemes on physical data shared channel (PDSCH) must be less than the limits appearing in Table 1. It is necessary to perform EVM measurements for all bandwidths on all allocated resource blocks and downlink slots within 10 ms measurement periods.

Modulation scheme for PDSCH	Required EVM (%)
QPSK	18.5 %
16QAM	13.5 %
64QAM	9 %
256QAM	4.5 %

Table 1: **EVM requirements for BS type 1-C and BS type 1-H**

OTA modulation quality requirement for radiated conformance testing is a directional requirement at the RIB that one needs to ensure is within OTA coverage range. The purpose of the test is to ensure that OTA modulation quality is within the minimum requirements.

The EVM of each NR carrier for BS types 1-O and 2-O must not exceed the limits in Table 2 for different modulation schemes on PDSCH. For NR, for all bandwidths, you need to perform the EVM measurement for each NR carrier over all allocated resource blocks and downlink slots within 10 ms measurement periods.

Modulation scheme for PDSCH	Required EVM (%)
QPSK	18.5 %
16QAM	13.5 %
64QAM	9 %
256QAM	4.5 %

Table 2: **EVM requirements for BS type 1-O and BS type 2-O**

2. Challenges in Testing at High Frequencies and Wide Bandwidths

Excessive path loss poses a major challenge in mmWave frequencies. The components of mmWave devices are compact and highly integrated with no places to probe. In contrast to traditional cable tests, this situation results in the need for radiated tests, or OTA tests. But OTA tests present their own set of challenges including path loss.

Confronting Path Loss

It is possible to perform OTA tests for either the near-field or far-field. While near-field measurements may be appropriate for some applications, 5G cellular communication requires far-field assumptions. The far-field distance and path loss associated with radiated waves increase with frequency due to the nature of the waves. The characteristics of these signals change as they propagate from antenna arrays and become more developed (Figure 3). With an LTE 15 cm device operating at 2 GHz frequency, for example, the far-field region begins at 0.3 meters and has a 28 dB path loss. However, for a 5G NR device of the same size operating at 28 GHz, the far-field region starts at 4.2 meters and the path loss is 73 dB. So when you increase the frequency, the path loss increases.
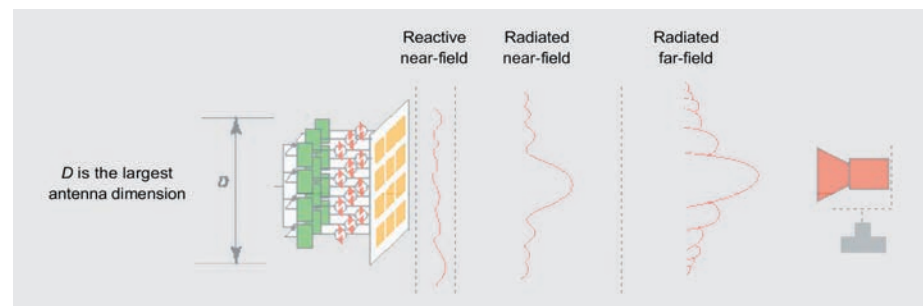

Figure 3: **Beam properties at different distances from the antenna array**

You can get a better idea of path loss by looking at Table 3 below. The greater the path loss and the larger the distance between the DUT and the probe antenna, the more challenging the test will be. For an antenna size of 10 cm, the path loss difference between 2 GHz and 28 GHz can be up to 45 dB. The difference between 2 GHz and 43 GHz is 53 dB (Table 3).

Size (cm)	2 GHz Distance | Path loss	28 GHz Distance | Path loss	43 GHz Distance | Path loss
10	13 cm | 21 dB	187 cm | 66 dB	287 cm | 74 dB
15	30 cm | 28 dB	420 cm | 73 dB	640 cm | 81 dB
20	53 cm | 33 dB	740 cm | 78 dB	114 cm | 86 dB

Table 3: **An estimate of far-field distance and path loss for different radiating apertures**

Due to the excess path loss, getting accurate OTA measurements is challenging using mmWave devices. Because of the excessive path loss between instruments and DUTs, signal analysis measurement becomes more challenging due to the low signal-to-noise ratio (SNR). Low SNR degrades base station transmitter measurements, such as EVM and adjacent channel leakage ratios (ACLR), and misrepresents the performance of the DUTs. Additionally, analyzing wide bandwidth signals at mmWave frequencies involves overcoming the effects of frequency response, which degrades the quality of the signal further. Therefore, 5G private networks require engineers to rethink their design and testing processes.

Measurement Uncertainties

In addition, wideband noise complicates mmWave testing which adds to measurement uncertainties and complexity. With mmWave, you will be able to achieve higher frequency; wider bandwidth; lower latency; higher data throughput, resolution and accuracy; and higher-order modulation schemes for faster data rates. However, mmWave also introduces more noise. In other words, to achieve greater sensitivity at a receiver, a transmit signal must compete with the channel's noise floor.

Using the Shannon-Hartley theorem, we can gain insight into the maximum transmission rate over a communication channel with noise within a certain bandwidth. Increased bandwidth increases the rate of the signal transmission over a channel with a bandwidth of B to reach the receiver, but it also introduces more noise into the signal analyzer. The upshot is that greater bandwidth reduces the SNR and makes achieving accurate mmWave measurements more difficult. Consequently, mmWave devices and components require careful evaluation.

$$C = B \log_2(1 + S/N)$$

Where C is the channel capacity in bits per second (bit/s), B is the signal bandwidth in Hz, S is the average received power over the bandwidth in watts, and N is the average power of the noise over the bandwidth in watts.

Frequency Responses

Testing mmWave also faces the challenge of frequency responses. A test system's cables, connectors, switches, and fixtures can impact frequency response in the path between the signal analyzer and the DUT. These responses consist of different frequencies and include amplitude and phase errors which degrade measurement accuracy. When you test 5G NR FR2 signals with a wider bandwidth and higher frequency, the frequency response becomes worse.

Because the primary objective of a test system is to characterize a DUT, you need to extend the measurement accuracy from a signal analyzer's input port (reference plane), to the DUT's test port (test plane). Then you must ensure that the system isolates the DUT's measured results from the effects of other test segments.

Figure 4 shows a 64 QAM modulation signal at a 100 MHz symbol rate and carrier frequency at 10 GHz measured by a signal analyzer at the DUT's input port. Test system components contribute to frequency responses, including phase and amplitude responses which affect modulation quality. Due to these frequency responses, the I-Q constellation (upper left) on the left panel is chaotic, and it is not possible to demodulate the signal. Therefore, you need to minimize these frequency responses to improve the accuracy of the measurement between the test plane and the reference plane. Minimizing the frequency responses will help you produce more accurate measurements (see Figure 4, right panel).
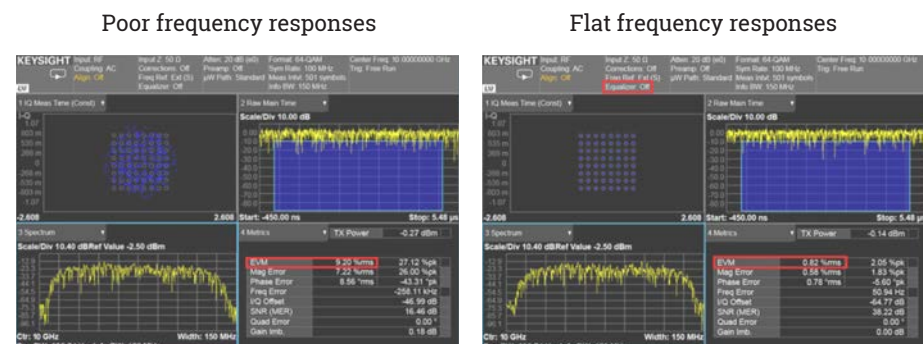
Poor frequency responses   Flat frequency responses

Figure 4: **An example of the impact of frequency responses on the EVM**

3.   Tips for Optimizing EVM Measurements

A signal analyzer can incorporate attenuation at high-power levels or use a pre-amplifier at low-power levels in order to measure the variety of input signals. In general, signal analyzers provide several RF signal paths, such as a default path, a microwave pre-selector bypass, a low-noise path, and a full-bypass path to reduce noise, and therefore, improve sensitivity and SNR. Full bypass reduces path loss, signal fidelity, and measurement sensitivity while avoiding multiple switches in the low-band switch circuitry and bypassing the microwave pre-selectors. MmWave full bypass paths have up to 10 dB less loss, improve SNR, and enable you to produce more accurate EVM measurements.

Getting to Higher Frequency Safely

Wireless standards specify transmitter measurements at maximum output power. The first mixer of a signal analyzer attenuates the input power level to protect the analyzer from input signal distortion. The input signal level can appear below the mixer's optimal level in certain scenarios, such as OTA tests and testing systems with huge insertion losses. Integrated pre-amplifiers can provide a lower noise figure, but they have a lower intermodulation distortion-to-noise-floor dynamic range. It is important to find the right input mixer level that balances distortion performance with noise sensitivity. A higher input mixer level can improve SNR, whereas a lower input mixer level can reduce distortion.

It is also very important to keep the path loss between the DUT and signal analyzer as low as possible when building a mmWave test system. Using an external mixer can minimize path loss by enabling you to move the test port close to the DUT, thereby shortening the mmWave signal path and enhancing SNR. However, due to the fact that there is no pre-selector at the front of the mixer, strong out-of-band signals can cause some unwanted images to appear in the band of interest, thus reducing measurement accuracy.

External Frequency Extender

On Keysight's V3050A advanced external frequency extender, a pre-selector and a RF switch combine to provide swept power spectrum between 2 Hz and 110 GHz that is unbanded and pre-selected. As a result, the V3050A solution features excellent sensitivity and the deepest dynamic range (Figure 5).
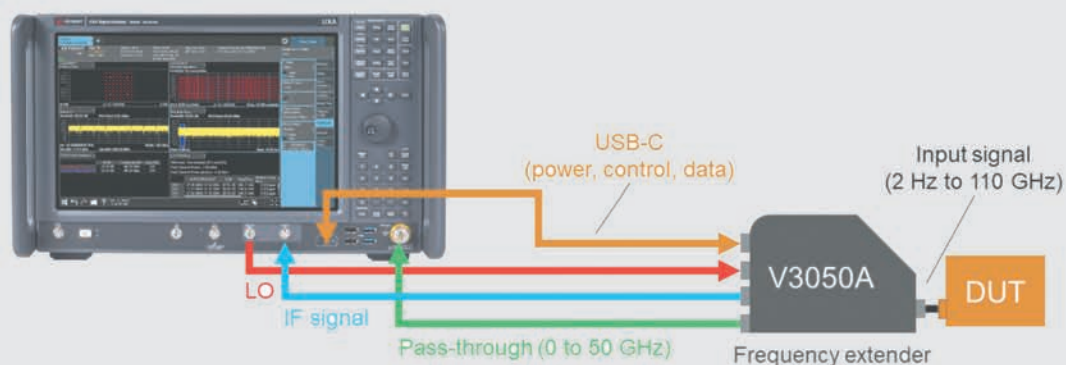

Figure 5: **Extending frequency range using Keysight's V3050A frequency extender**

The phase noise performance of a signal analyzer can also affect EVM measurements. In 5G NR, data transmit in parallel using OFDM, a modulation scheme that uses many closely spaced orthogonal subcarrier signals, each with a different modulation scheme. If the local oscillator (LO) of a signal analyzer has poor phase noise, the subcarrier with phase noise interferes with other subcarriers, lowering modulation quality. There are several methods for phase noise optimization with signal analyzers including best close- in, best wide-offset, and fast tuning. Signal analysis for modulation analysis requires not only consideration of the phase noise profile of the signal analyzer, but also its operating frequency, bandwidth, and subcarrier spacing.

A signal analyzer's specifications are usually valid up to the instrument's input connectors, where the instrument sets the reference plane. It is important to take into account the impact of the components outside the test instrument in the path between the instrument and the DUT. These components can contribute to the degraded measurement accuracy of systems by adding to frequency responses. RF engineers should look for new and better ways to minimize frequency response errors in wide bandwidths and high frequencies such as mmWaves and beyond.

The Keysight U9361 RCal receiver calibrator operates by moving the reference plane to the DUT to calibrate the system. Data automatically transfer from the memory to the signal analyzer and the analyzer detects it easily. By using this setup, you can reduce the effort and complexity of calibrating your test receiver system up to 110 GHz.

4. Keysight's Signal Analysis Solutions

A low-noise amplifier (LNA) at the front-end of the signal analyzer reduces the system noise figure with, or without the internal preamplifier to optimize the mixer's input level (Figure 6). Both of Keysight's N9042B UXA X-Series and N9032B PXA X-Series signal analyzers feature integrated LNA and preamplifiers for various test scenarios. The two- stage gain optimizes the measurements at low input levels to reduce the noise and provide the best performance, while balancing noise and distortion. N9032B is an ideal solution for FR1 applications, and N9042B covers frequency ranges for both FR1 and FR2 applications.
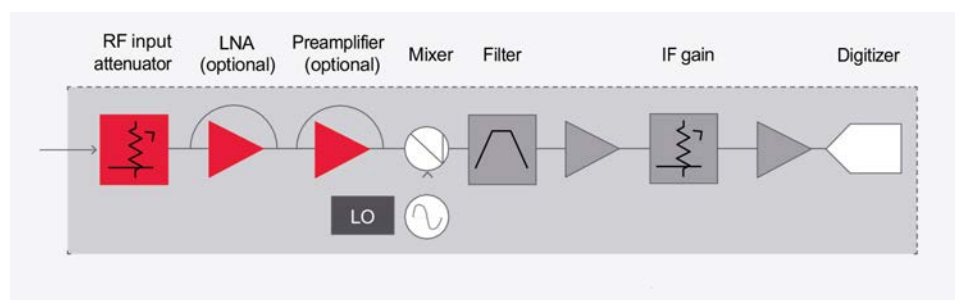

Figure 6: **Optimizing the input mixer level with the LNA and preamplifier**

Figure 7 shows an example of the noise floor of a signal analyzer ranging from 2 Hz to 50 GHz. Turning the preamplifier on lowers the noise floor by around 20 dB. By switching on both the preamplifier and LNA, you will be able to lower the noise floor even further.

Figure 7: **An example of reduced noise floor using a preamplifier and LNA, in N90442B UXA X-Series signal analyzer**

Figure 8 shows an example of 5G demodulation where the input power is -40 dBm and below the signal analyzer's best mixer input level. Here, the attenuator is set to 0 dB, and the signal path is a full bypass. Even after minimizing all path losses for the signal analyzer, the EVM does not perform as expected. Turning the LNA on (right) improves the EVM significantly, enabling it to go from 5.75% to 1.99%.
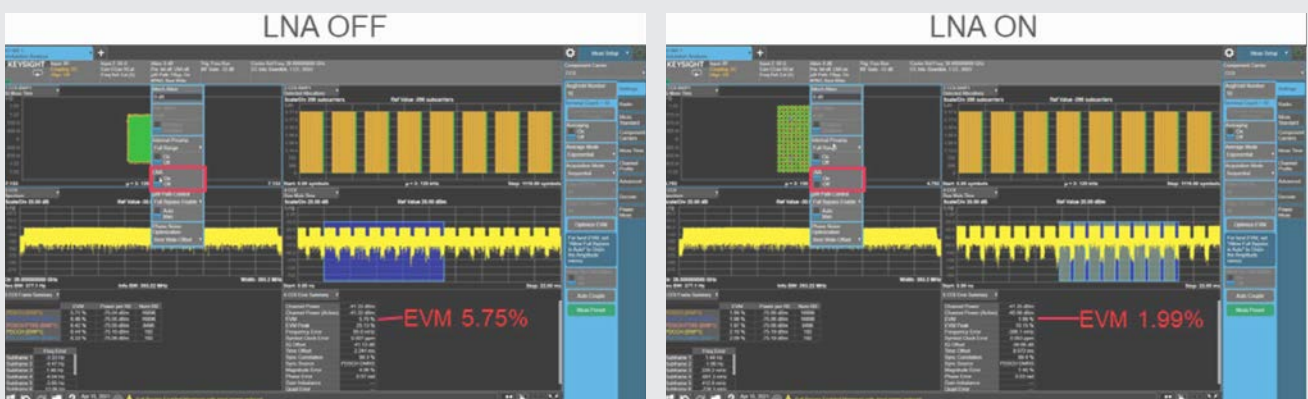

Figure 8: **Using LNA in N9042B UXA X-Series signal analyzer to achieve better EVM measurement results**

Keysight's N9042B UXA X-Series signal analyzer offers wide analysis bandwidth and deepest dynamic range for complex mmWave analysis in 5G private network applications. In mmWave frequencies, signal quality is more susceptible to distortion, phase noise, and modulation errors. The N9042B UXA X-Series signal analyzer and the frequency extender enable new levels of performance for high frequency measurements, including covering the current 5G NR FR1 and FR2 bands and beyond, up to 110 GHz.

An entirely new front-end design provides low noise performance and high dynamic range. The design also addresses applications in base station transmitter tests, such as EVM and other modulation quality tests while continuing to perform low-level measurements on unknown signals. The N9042B supports the PathWave X-Series family of multi-touch applications, as well as the PathWave vector signal analysis (89600 VSA) software. A new CPU performs compute-intensive measurements, such as demodulation and EVM, up to 40% faster than prior analyzers.

Similarly, Keysight's N9032B PXA X-Series signal analyzer delivers the widest analysis bandwidth in its class, as well as unparalleled performance to meet your requirements for lower frequency wide bandwidth analysis. The N9032B offers up to 2 GHz of bandwidth, or four times more bandwidth for all frequencies of 8.4, 13.6, and 26.5 GHz. The N9032B analyzer features the same LNA and preamplifier as the UXA family and offers optimal displayed average noise level (DANL), EVM residuals, and sensitivity in its class.

Using Keysight's U9361 RCal calibrator, you can compensate for path losses and improve accuracy by an order of magnitude. With the N9032B, you get all the functionality of a 6U-high signal analyzer, but in a compact 4U-high package. As a result of its compact design, it is easy to replace legacy rack-mounted spectrum analyzers to save space. The front-end LNA improves DANL for N9032B by 3-7 dB, compared to the N9030B and N9040B. Figure 9 shows a comparison between the new N9042B and the previous N9040B UXA, as well as the new N9032B and the previous N9030B PXA.
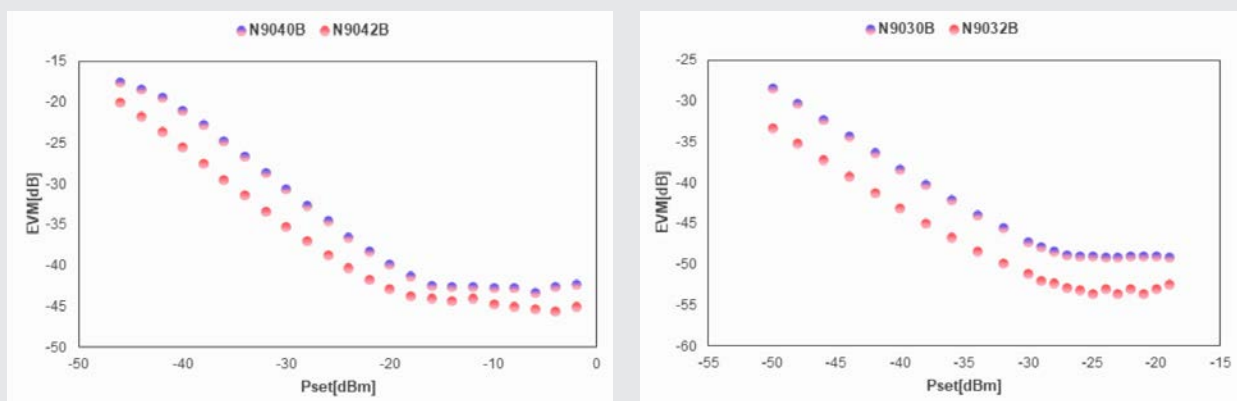

Figure 9: **A comparison between the new N9042B and the previous N9040B UXA (left), and the new N9032B and the previous N9030B PXA (right)**

There are a variety of options to meet any 5G private network requirement with Keysight's signal analyzer portfolio. Using the N9032B and N9042B, you can perform the most accurate signal analysis for FR1 and FR2 applications. In addition, RCal receiver calibrator, the VXG Signal Generator, and Keysight's industry-leading measurement software applications offer a comprehensive solution for your 5G private network base station transmitter conformance with a wide range of compliance regulations.

	Signal analyzer						Signal generator		
	UXA			PXA		MXA	PSG-D	VXG	
	N9042B	N9041B	N9040B	N9032B	N9030B	N9021B	E8267D	M9384B	M9383B 4
Max. frequency	110 GHz	110 GHz	50 GHz	26.5 GHz	50 GHz	50 GHz	44 GHz	44 GHz	44 GHz
Max. bandwidth	4 GHz	1 GHz (9.6 GHz 1)	1 GHz (1.2 GHz 1)	2 GHz	510 MHz (0.9 GHz 1)	510 MHz (0.9 GHz 1)	80 MHz (2 GHz 2)	2 GHz 3 (4 GHz 2)	2 GHz (4 GHz 2)
Phase noise at 10 GHz, 10 kHz offset	-126 dBc/Hz	-126 dBc/Hz	-126 dBc/Hz	-126 dBc/Hz	-124 dBc/Hz	-121 dBc/Hz	-129 dBc/Hz	-127 dBc/Hz	-127 dBc/Hz

Table 4. **Keysight's 5G NR waveform generation and analysis solutions — hardware**

1. Support maximum analysis bandwidth with wide IF output option and an external digitizer.
2. Get up to 4 GHz of RF bandwidth with wideband external differential I/Q inputs.
3. Get up to 4 GHz of RF bandwidth with dual-channel bonding.
4. Modular form factor.

	Application software	Description
Signal generation	N7631APPC / N7631EMBC	PathWave Signal Generation for 5G NR
	N7630APPC / N7630EMBC	PathWave Signal Generation for Pre-5G
	N7608APPC / N7608EMBC	PathWave Signal Generation for Custom OFDM
Signal analysis	N9085EM0E	5G NR Measurement Application
	N9054EM1E	Vector Modulation Analysis Custom OFDM Application
	89601BHNC	5G NR modulation analysis

Table 5. **Keysight's 5G NR waveform generation and analysis solutions — software**

For more information visit Keysight's X-Series signal analyzers or check out:
• Three Best Practices for Optimizing EVM Measurements for Wideband Signals
• Tackling Millimeter-Wave Signal Analysis Challenges
• Four Tips for 5G New Radio Signal Analysis
• 5G & Beyond For Dummies®, Keysight Technologies Special Edition
• Keysight Technologies Vector Signal Analysis Basics

Learn more at: **www.keysight.com**