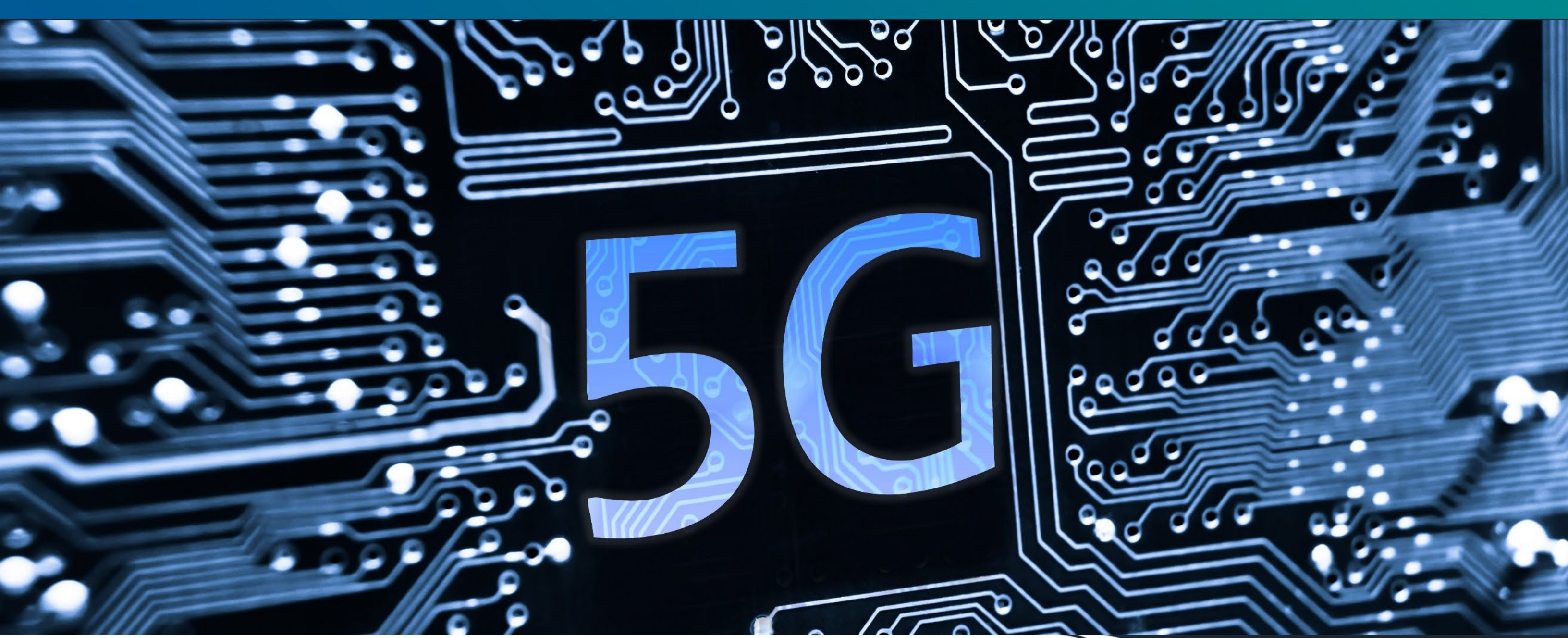


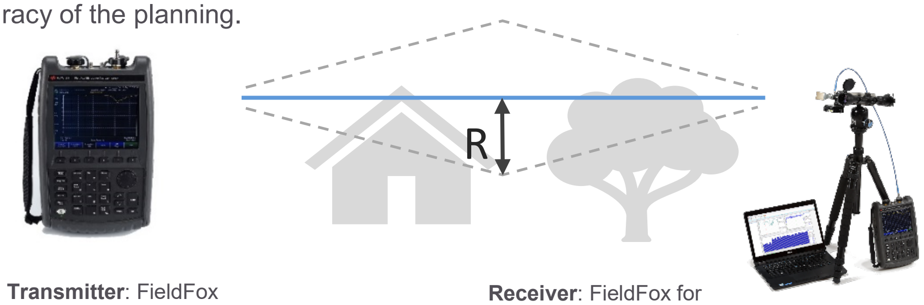
WHITE PAPER

Field Testing in 5G NR

mmWave Challenge in 5G NR

5G NR deployments are planned predominantly on the 3.5 GHz range and the 28-29 GHz range. Both frequency ranges are new to the cellular network industry. Particularly the mm-wave frequencies (>28 GHz) have different propagation characteristics compared to the lower frequencies traditionally used in cellular networks. mmWave signal blockage is much higher compared to lower frequencies. On the other hand, the higher frequencies are highly reflective compared to lower frequencies, providing alternative angles of arrival in case of line of sight blockage.

The free space loss of signals of different frequencies is well understood, but measurements will be needed to understand the pathloss in different real-life environments. This information in turn is needed in link budget calculation and signal propagation model tuning. Link budget is the key input for estimating the 5G NR RAN CAPEX investments as it directly impacts the number of 5G NR base stations needed in an area. Propagation models are used in the radio network planning tool and the models need to be tuned for the characteristics of the new frequency ranges to improve the accuracy of the planning.



Transmitter: FieldFox with preamplifier for 5G NR signal transmission

Receiver: FieldFox for reception and Nemo Outdoor for logging measurement data and location for post-processing

Figure 1. Pathloss measurement setup for 5G NR using Keysight's FieldFox portable spectrum analyzer.

KEYSIGHT TECHNOLOGIES

Pathloss measurements can be done with a continuous wave (CW) test transmitter and receiver capable of measuring the RSSI on the selected frequency. When setting up the measurement system, it is crucial to make sure that the measurement dynamics of the setup reaches the same maximum pathloss as what is expected in a real network. Otherwise cell edge scenarios, which are the most interesting test scenarios, cannot be measured. Keysight's FieldFox portable spectrum analyzer can be used as a receiver and transmitter in pathloss measurements as illustrated in Figure 1. With two FieldFox devices, antennas, and LNA amplifiers, one can measure the pathloss on the full dynamic range of the expected pathloss in real 5G NR networks. FieldFox supports the full 5G NR spectrum range from sub 6 GHz to mmWave without additional down converters.

Massive MIMO and Beamforming – What Does It Mean and How Can I Measure It?

Massive MIMO (mMIMO) and beamforming are buzzwords widely used in the telecom industry when referring to 5G NR and the latest advancements of LTE, but the definitions of mMIMO and beamforming are vague. The challenge is that MIMO comes in many different variants, some of them having been is use already for years in legacy LTE networks. Also, the mathematical theory behind the MIMO and mMIMO is very complex. Typically, only the two extremes, overly simplified and scientific, mathematically expressed descriptions, are available for mMIMO.

MU-MIMO

To understand how mMIMO works, we must first investigate how Multi User MIMO (MU-MIMO) works and what it means. In legacy LTE, the term MIMO usually refers to Single User MIMO (SU-MIMO). In SU-MIMO, both the base station and the UE have multiple antenna ports and antennas, and multiple data streams are transmitted simultaneously to the UE using the same time-frequency resources, doubling (2x2 MIMO), or quadrupling (4x4 MIMO) the peak throughput of a single user.

In MU-MIMO, the base station sends multiple data streams, one per UE, using the same time-frequency resources. Hence, MU-MIMO increases the total cell throughput, i.e. cell capacity. The base station has multiple antenna ports, as many as there are UEs receiving data simultaneously, and one antenna port is needed in each UE.

It should be noted that SU-MIMO and MU-MIMO can be used simultaneously. For example, if a base station has eight antenna ports, and there are four UEs, each with two antenna ports, transferring data simultaneously, the base station could set up 2x2 SU-MIMO transfers to all four UEs simultaneously with MU-MIMO. In other words, a total of eight streams of data, all sent at the same time, using the same time-frequency resources.

Beamforming – Principle of Operation

Terms beamforming and mMIMO are sometimes used interchangeably. One way to put it is that beamforming is used in mMIMO, or beamforming is a subset of mMIMO. In general, beamforming uses multiple antennas to control the direction of a wavefront by appropriately weighting the magnitude and phase of individual antenna signals in an array of multiple antennas. That is, the same signal is sent from multiple antennas that have sufficient space between them (at least ½ wavelength).

In any given location, the receiver will thus receive multiple copies of the same signal. Since the signals are sent from different antennas, each copy of the signal has traveled a different distance and will arrive at the receiver at a different phase. Depending on the location of the receiver, the signals may be in opposite phases, destructively averaging each other out, or constructively summing up if the different copies are at the same phase, or anything in between. The constructively summed up case would be the in-beam direction. By adjusting the phase (delay) and magnitude of each signal component, the direction of the beam can be steered.

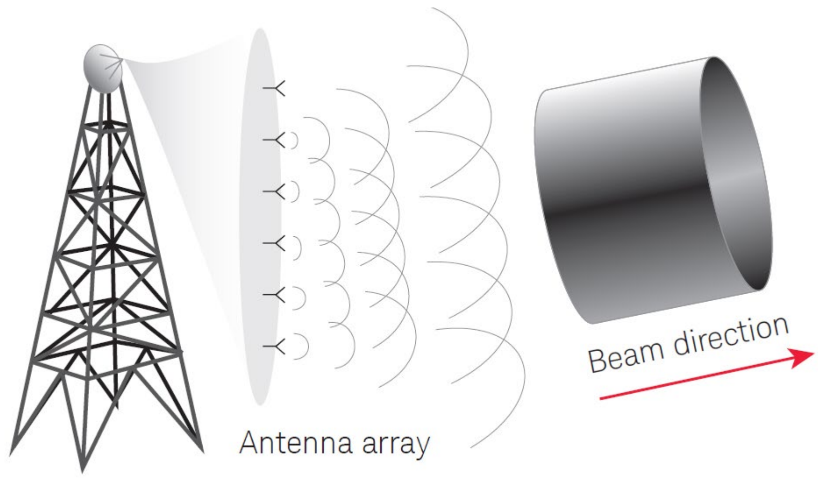


Figure 2. Creating directional beams by varying the phase (delay) and amplitude of each antenna transmission.

Beamforming is further divided into subcategories as explained in the following chapters.

Digital Beamforming (a.k.a. Baseband Beamforming or Precoding)

The signal is pre-coded (amplitude and phase modifications) in baseband processing before RF transmission. Multiple beams (one per each user) can be formed simultaneously from the same set of antenna elements. In the context of LTE/5G NR, MU-MIMO equals to digital beamforming. Digital beamforming (MU-MIMO) is used in LTE Advanced Pro (transmission modes 7, 8, and 9) and in 5G NR. Multiple TRX chains, one per each simultaneous MU-MIMO user, are needed in the base station. Digital beamforming improves the cell capacity as the same PRBs (frequency-time resources) can be used to transmit data simultaneously for multiple users.

Analog Beamforming

The signal phases of individual antenna signals are adjusted in the RF domain. Analog beamforming impacts the radiation pattern and gain of the antenna array, thus improving coverage. Unlike in digital beamforming, only one beam per a set of antenna elements can be formed. The antenna gain boost provided by analog beamforming overcomes partly the impact of high pathloss in mmWave. Therefore, analog beamforming is considered mandatory for the mmWave frequency range in 5G NR.

Hybrid Beamforming

Hybrid beamforming combines analog beamforming and digital beamforming. It is expected that mmWave gNB (5G NR base station) implementations will use some form of hybrid beamforming. One approach is to use analog beamforming for coarse beamforming, and inside the analog beam use a digital beamforming scheme as appropriate, either MU-MIMO or SU-MIMO.

Massive MIMO

Above we have discussed what MU-MIMO means and how beamforming works. Massive MIMO (mMIMO) is another term yet to be explained. The most commonly seen definition is that mMIMO is a system where the number of antennas exceeds the number of users. In practice, massive means there are 32 or more logical antenna ports in the base station. It is expected that NEMs will start with a maximum of 64 logical antenna ports in 5G NR.

It is important to differentiate the physical antenna elements from the logical antenna ports. Typically, there would be more physical antenna elements than there are logical antenna ports. For each logical antenna port, there is one TRXU unit in the base station, and there can be as many simultaneous MU-MIMO beams as there are TRXUs/logical antenna ports.

If only one physical antenna is used per simultaneous user, the performance of MU-MIMO is poor because of the fast fading experienced by the downlink radio channel of each UE. Fast fading makes accurate channel state estimation difficult and decreases the potential capacity gain as one or more of the simultaneously scheduled UEs are in a fading dip on any given time and not able to receive data. Transmitting the data stream of each UE via multiple physical antennas removes the fast fading similarly to traditional diversity transmission. In the context of MU-MIMO and mMIMO, this is referred to as channel hardening. Therefore, the massive number of antennas improves MU-MIMO performance and makes it feasible for real-life network implementations.

Figure 3 illustrates how mMIMO works in practice. An antenna array of 50 omni elements, with ½ wavelength distance between the antenna elements is used. The 50 elements are used to transmit four distinct streams, one stream for each UE. All four streams are transmitted using the same physical resource blocks, i.e. the same time-frequency resources. The data streams do not interfere with each other because each of them has a distinct radiation pattern, where the signal strength in the direction of the target UE is optimized, and in the directions of the other UEs (victim UEs) the signal strength is minimized. In the academic discussion, beamforming is sometimes referred to as null-steering, which becomes apparent when looking at Figure 3. In addition to steering the beam towards the target UE, it is equally important to make sure that all the other UEs are sitting in the nulls of the radiation pattern.

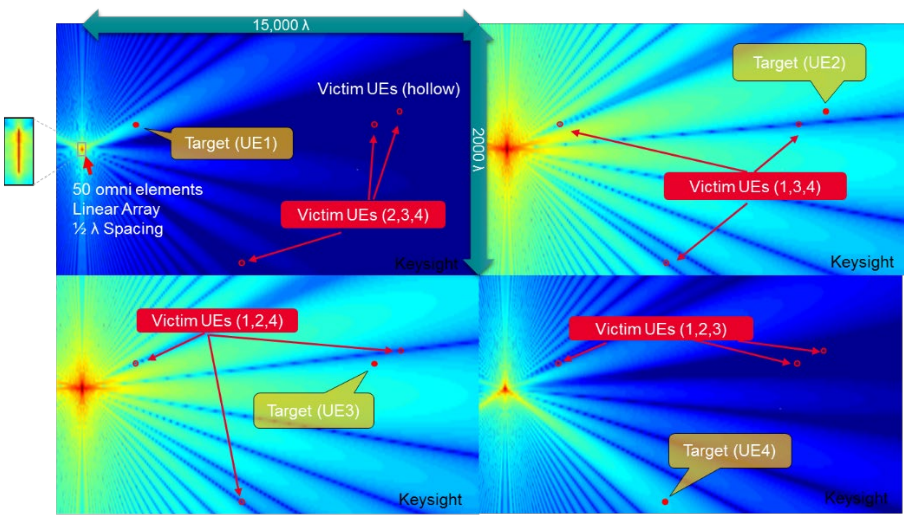


Figure 3. Signal radiation patterns of simulated MU-MIMO transmissions to four UEs in free-space.

In MU-MIMO/mMIMO, the base station applies distinct precoding for the data stream of each UE where the location of the UE, as well as the locations of all the other UEs, are taken into account to optimize the signal for the target UE and at the same time minimize interference to the other UEs. To do this, the base station needs to know how the downlink radio channel looks like for each of the UEs.

In TDD systems, the uplink and downlink channels are reciprocal as they are on the same frequency, and hence, the base station can estimate the downlink radio channel by measuring the uplink radio channel from the sounding reference signal (SRS) that the UEs are sending uplink.

In FDD systems, downlink and uplink channels are on different frequencies and, hence, are not reciprocal. For the base station to know how the radio channel looks like for downlink, each UE needs to measure the channel state information (CSI) from downlink reference channels and report it back to the base station.

Beam-Based Coverage Measurements in 5G NR

The basic concepts of network coverage measurements are different in 5G NR compared to LTE. In 5G NR, the coverage is beam-based, not cell-based. Also, there is no cell-level reference channel from where the coverage of the cell could be measured. Instead, each cell has one or multiple synchronization signal block (SSB) beams (see Figure 4). The maximum number of SSB beams per cell is between 4 and 64, depending on the frequency range. SSB beams are static, or semi-static, always pointing to same direction. They form a grid of beams covering the whole cell area. The UE searches for and measures the beams, maintaining a set of candidate beams. The candidate set of beams may contain beams from multiple cells. The metrics measured are SS-RSRP, SS-RSRQ, and SS-SINR for each beam. Physical cell ID (PCI) and beam ID are the identifications separating beams from each other. In field measurements, these metrics can be collected both with scanning receivers and test UEs. Hence, SSB beams show up as a kind of new layer of mini-cells inside each cell in field measurements.

As can be seen from Figure 4, the different SSB beams of a cell are transmitted at different times. Therefore, there is no intra-cell interference among the SSB beams, and at least scanning receivers should be able to detect also extremely weak SSB beams, even in the presence of a dominant, strong beam from the same cell. In general, the amount of reference signals in the air will increase. As an example, let us imagine a place of poor dominance in an LTE network, where a scanner or a test UE detects reference signals from six different cells. If it were a 5G NR network, the device could see, for example, six beams of each six cells, in total 36 reference signals. Provided of course that the scanner or test UE is fast enough to catch all these signals. The performance of UEs as well as scanners is yet to be seen both in the spec sheets and in practice.

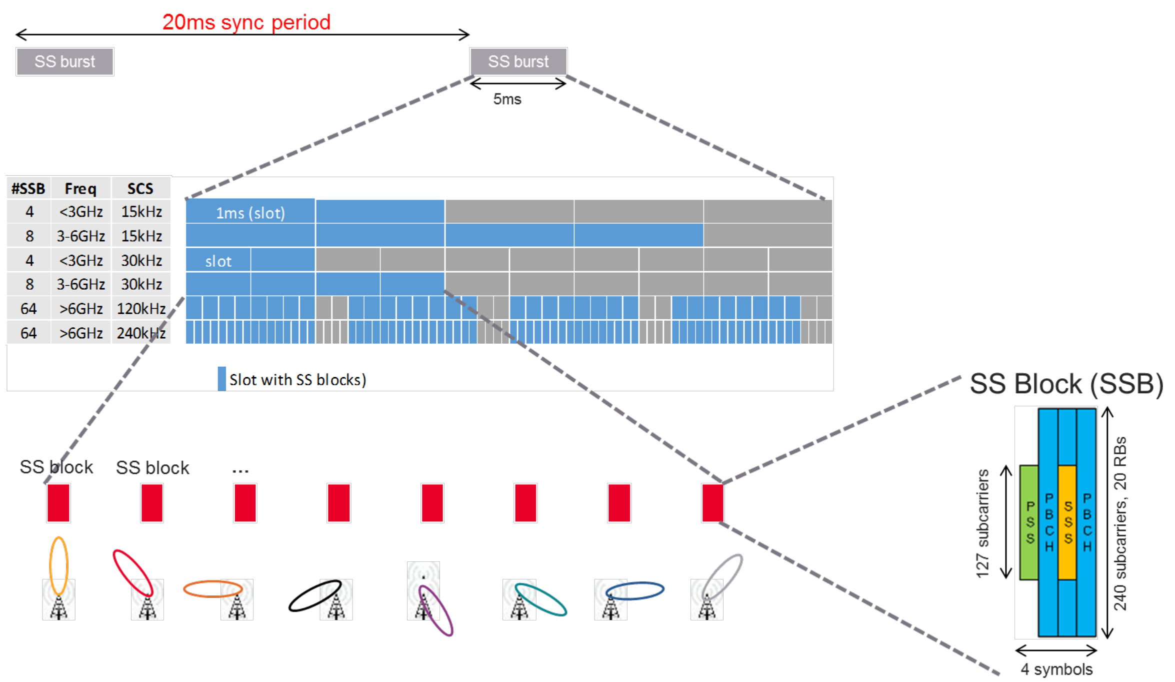


Figure 4. Grid of SSB beams in 5G NR.

It must be kept in mind that 5G NR can operate without beamforming, in which case there would be one SSB beam covering the whole cell area, and all the coverage testing methodology would default back to as in LTE as SSB beam equals to a cell in that case.

How to Test the Capacity Gain of Massive MIMO

As discussed earlier, Massive MIMO is a cell capacity feature for sub 6 GHz 5G NR. The gain is achieved only when multiple UEs are generating downlink traffic simultaneously. There are many variables impacting the real-life gain provided by the mMIMO.

The spatial distribution of cell users has a big impact. Ideally, the UEs should be scattered across the cell area. If all users are packed in the same location, for example around the same table in a cafeteria, it becomes impossible to isolate the users to different beams that do not overlap. The minimum horizontal and vertical spatial separation between UEs may differ depending on the number of physical antenna elements in the gNB antenna panel in the horizontal and vertical dimensions. The signal-to-noise-ratio of each user as well as the multipath propagation profile impact the achievable performance. The scheduling decisions as well as whether MU-MIMO is to be used or not, are made every 1 ms slot by the gNB.

The gNB scheduling and link adaptation algorithms are proprietary, not defined in 3GPP. Hence it is an area where the network equipment manufacturers can differentiate from each other. The performance of the mMIMO has a major impact on the system capacity of the 5G NR network. Hence, it is in the best interest of operators to verify the field performance of massive MIMO implementations as part of the vendor selection and network acceptance processes.

At Keysight Nemo Wireless Solutions, we have hands-on experience on the LTE massive MIMO field verification. The principles of mMIMO operation are the same in LTE and 5G NR. Therefore, the test system and methodology developed and tested for LTE mMIMO verification can be reused for 5G NR.

When testing the capacity gain of mMIMO, there need to be multiple test UEs distributed in the cell area, each performing active bulk data transfer testing against a test server simultaneously. As part of the test setup, it is important to ensure that the core network and backend server have sufficient bandwidth, so that the radio interface is the only bandwidth bottleneck during the test. Multi-threaded data downloads can be used in the tests to remove sub-optimal impacts of the TCP flow control. The different scenarios to be tested may include UEs close to each other to test the threshold for spatial separation where mMIMO can still provide gain, vertical distribution of UEs (one in each floor of a high-rise building), horizontal distribution of UEs, line-of-sight UEs vs non-line-of-sight UEs with rich multipath propagation environment, cell edge vs cell center, moving UEs, or any combination of the above.

Keysight's measurement solution consists of field test units with form factors ranging from a single smartphone with special test FW/SW to PC-controlled chassis housing multiple test UEs, and Nemo Cloud, the centralized cloud-based control SW for the field units. Nemo Cloud is the key for orchestrating the tests. The data transfer test of each UE can be centrally controlled from Nemo Cloud, and the status and location of the test UEs can also be monitored in real time from Nemo Cloud.

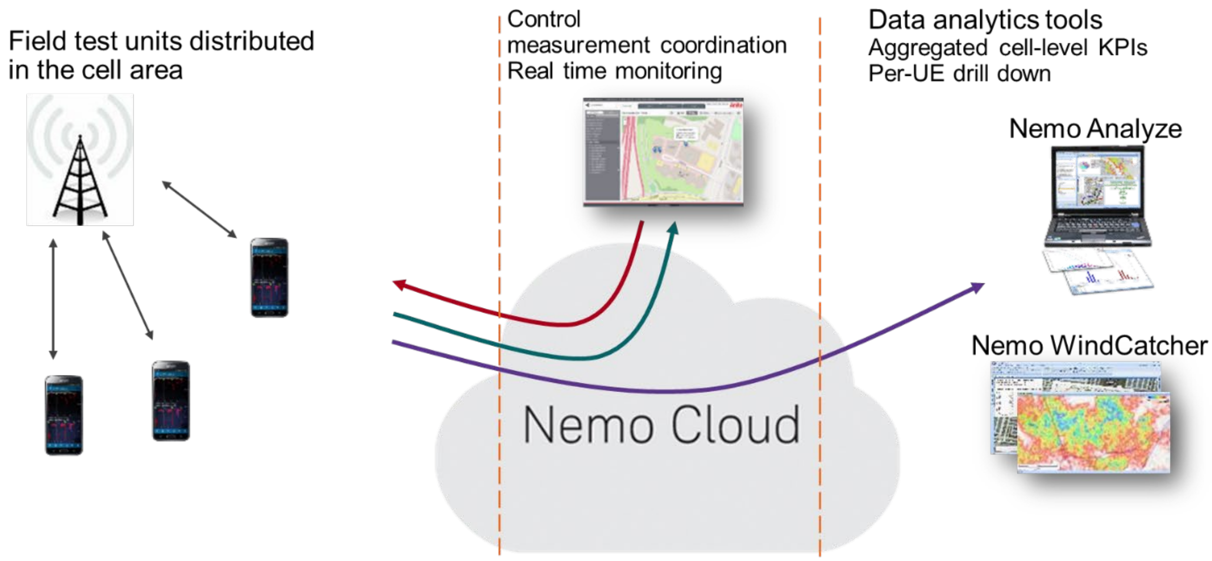


Figure 5. Keysight's 5G NR ready testing solution for LTE mMIMO.

With Keysight's data analytics tools, Nemo Analyze and Nemo WindCatcher, the data collected by each UE can be processed and visualized. Cell level KPIs are also automatically calculated, the most important being the total cell throughput, instantaneous time series view, as well as statistical view.

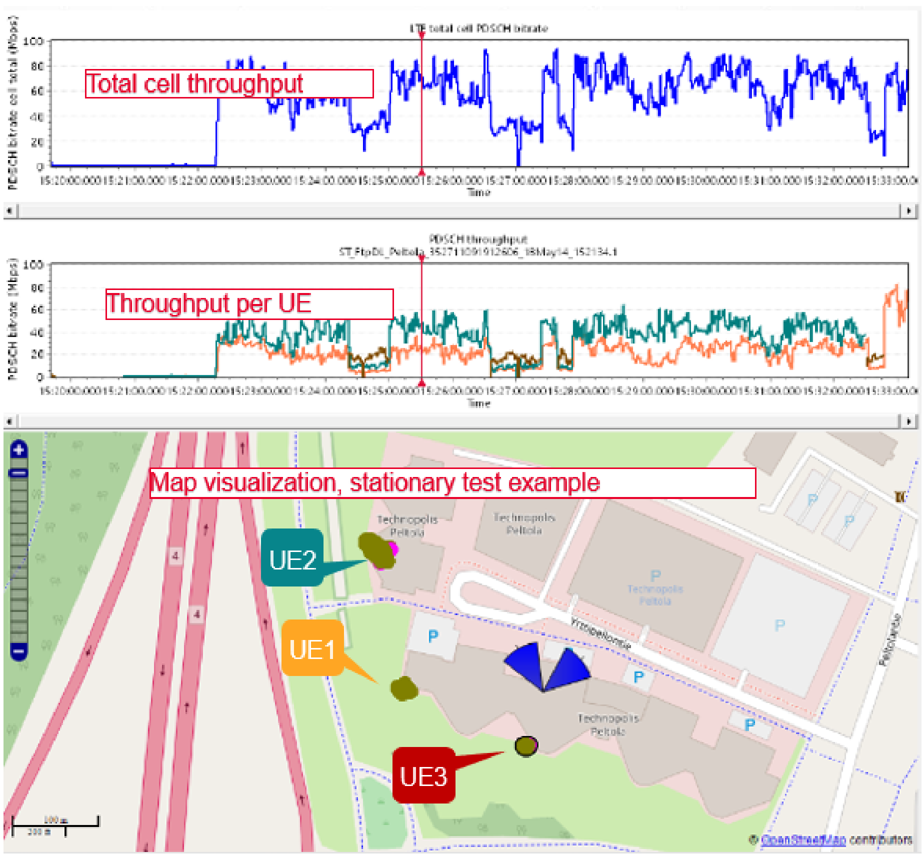


Figure 6. View from the post-processing tool, mMIMO test case.

Scanner-Based vs UE-Based Field Measurements

Both scanners and test UEs will be available for field testing in 5G NR. In legacy technologies, scanners were best suited for coverage measurements because they can measure all cells from all networks in one go. A UE is always tied to one operator and does not necessarily measure all technologies or even all carriers as it is limited by the neighbor list definitions in the network. This is valid reasoning also in 5G NR. Scanners will be able to measure the SSB beams, which is the basic coverage measure of the 5G NR network.

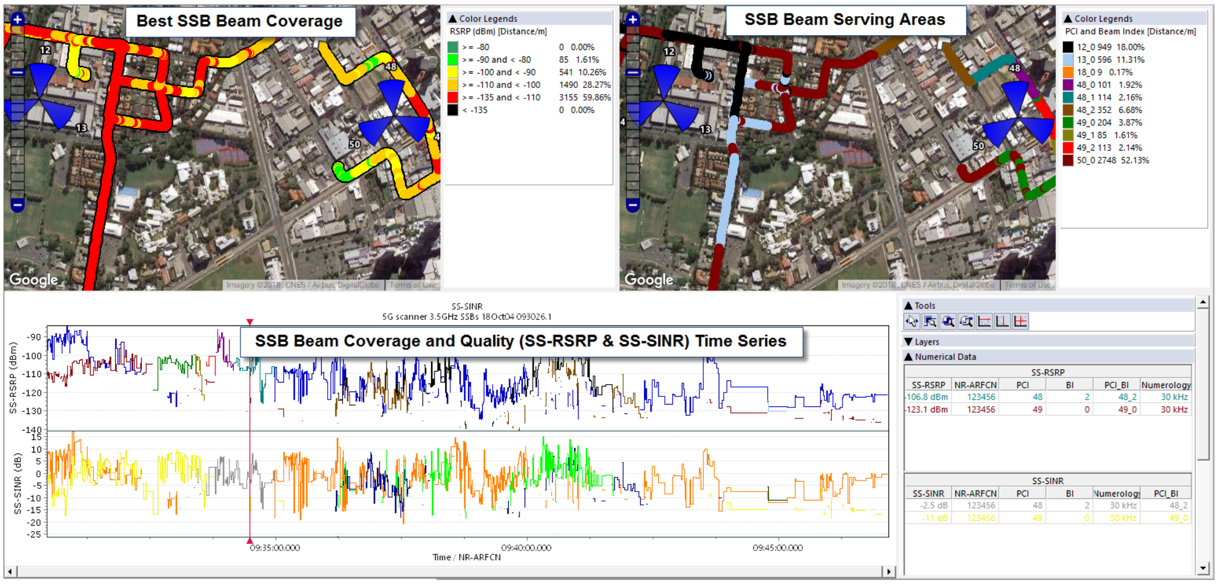


Figure 7. Example of Nemo Outdoor 5G NR scanner measurements. Coverage and quality metrics, namely SS-RSRP, SS-SINR, are reported per each SSB reference beam of a cell.

However, there are a few differences in using scanners in 5G NR compared to legacy technologies. In WCDMA and LTE networks, scanners can read the full system information including global cell ID, MNC, MCC, and other useful network parameters. In 5G NR, only the bare minimum system information is broadcasted in the common PBCH channel that is part of the SSB block. This is to avoid common, always on cell-level transfer and to minimize the energy consumption of the network. The rest of the system information is sent to the UE on-demand at the time a connection is established. This means that 5G NR scanners cannot read the full system information from the cells they are scanning.

Another thing to consider is that the scanner antennas are different from real devices. This has been a consideration already in LTE along with the MIMO antennas and will be more so in 5G NR. With the first CPE devices being introduced, coarse beamforming is being implemented also in the device end. Hence antenna gain as well as MIMO performance will become even more dependent on the devices at hand. However, there will always be a need for device agnostic coverage measurements that focus on the performance of the network, and scanner continues to provide the best solution for that use case.

Figure 8 illustrates the steps of a UE accessing the network in 5G NR. SSB beams (PSS, SSS, and PBCH) are the only signals common to the cell and always in the air in 5G NR. CSI-RS is a UE-specific reference signal, and PDSCH is the traffic channel for downlink. Both CSI-RS and PDSCH are beamformed. When a UE is moving in the cell, the UE-specific beams are adjusted to follow the UE based on the CSI feedback collected from the radio channel. SSB beams, on the other hand, remain static, and the UE performs beam switching between the SSB beams, similarly to handovers between cells performed in legacy technologies. It should be noted that initial implementations will not necessarily utilize all the beamforming features as defined here. For example, the UE-specific traffic channels may be initially transmitted using the same beam (precoding) as the reference beams.

Going back on what can be measured with a scanner and with a UE, a scanner can only see the SSB beams (cell-wide part of Figure 8) whereas all the channels, signals, and beams of Figure 8 are visible for the test UE.

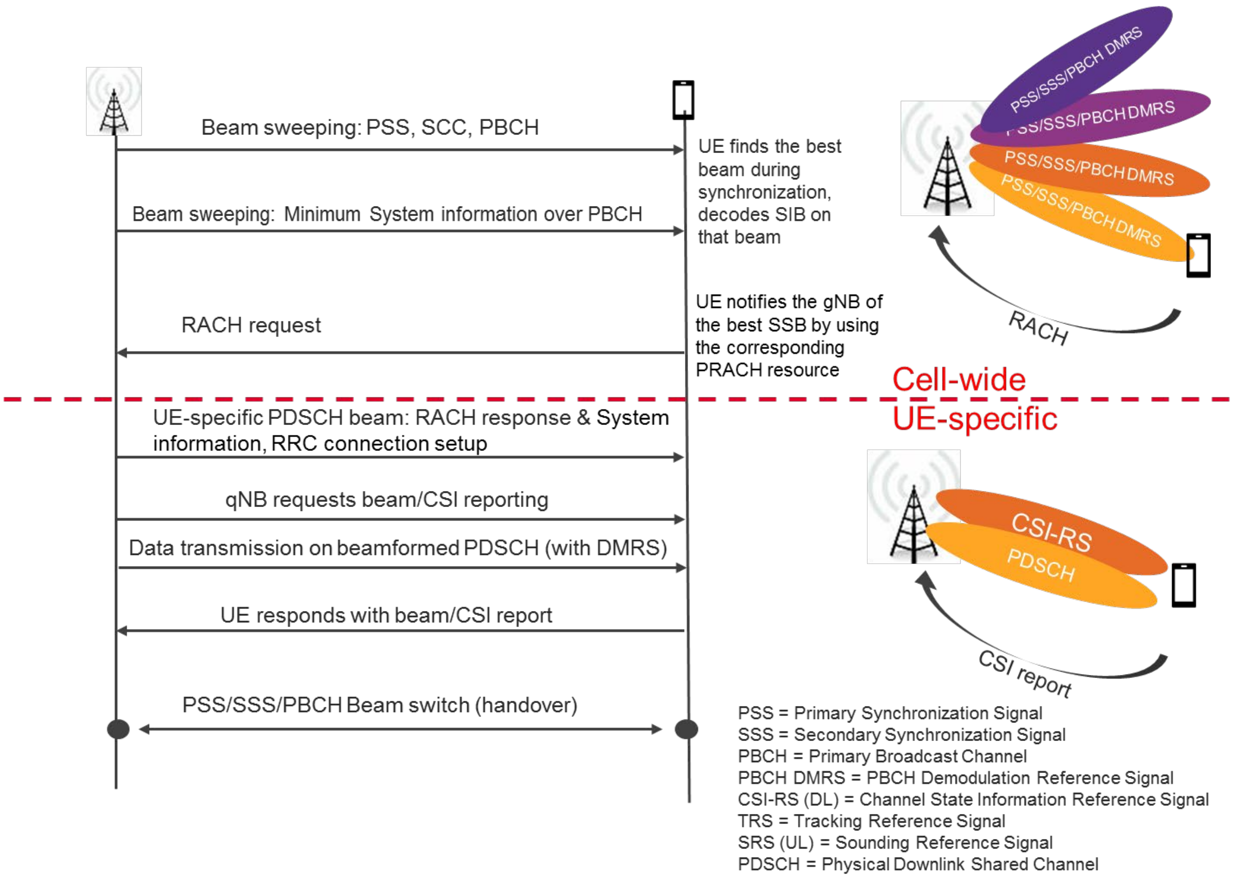


Figure 8. UE access process, reference beams and UE-specific beams in FDD, one CSI-RS mode.

Channel state information (CSI) measurements can be performed in different ways depending on the network configuration and TDD/FDD mode, as illustrated in Figure 9. CSI information includes channel quality indicator (CQI), rank indicator (RI), codebook index (precoding weights as suggested by UE), and CRI, the ID of the strongest CSI-RS beam as seen by the UE in case of multiple CSI-RS beams. The FDD cases provide more visibility from the field measurement perspective as the CSI information is measured by the UE from CSI-RS and this information will then be available also in the diagnostics data of the test UE.

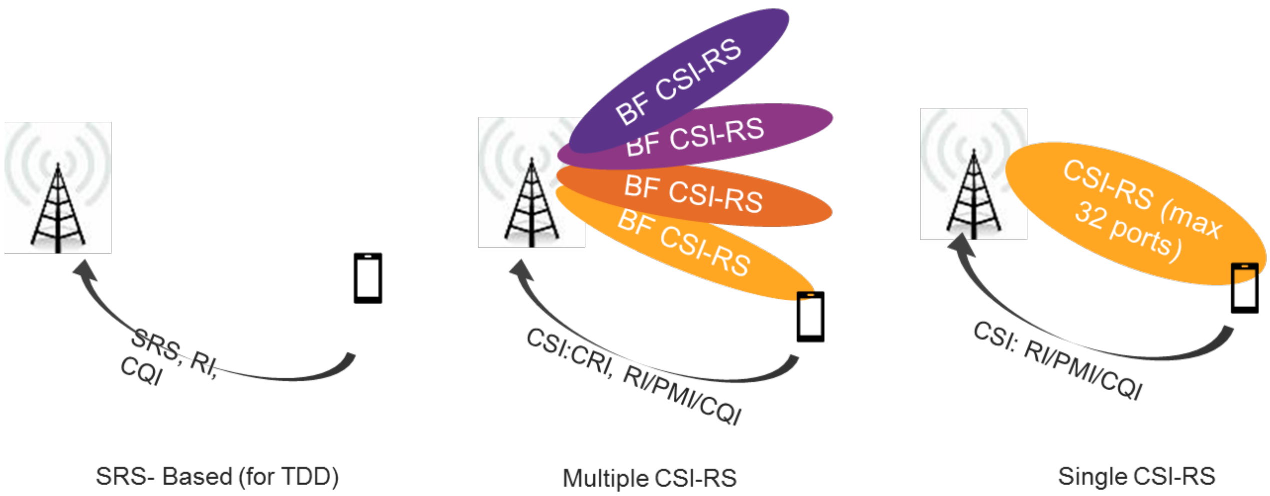


Figure 9. Different channel state information (CSI) achievement methods enabled by 3GPP specifications.

QoE Measurements in 5G NR

As with legacy technologies, the only way to accurately assess quality of experience (QoE) in 5G NR is via active tests conducted at the device end, as Figure 10 clearly illustrates. The three important, measurable KPIs related to the QoE of any type of transaction, accessibility, retainability, and time-to-content, are only visible and measurable at the device end, and are best measured by active tests using real over-the-top (OTT) applications.

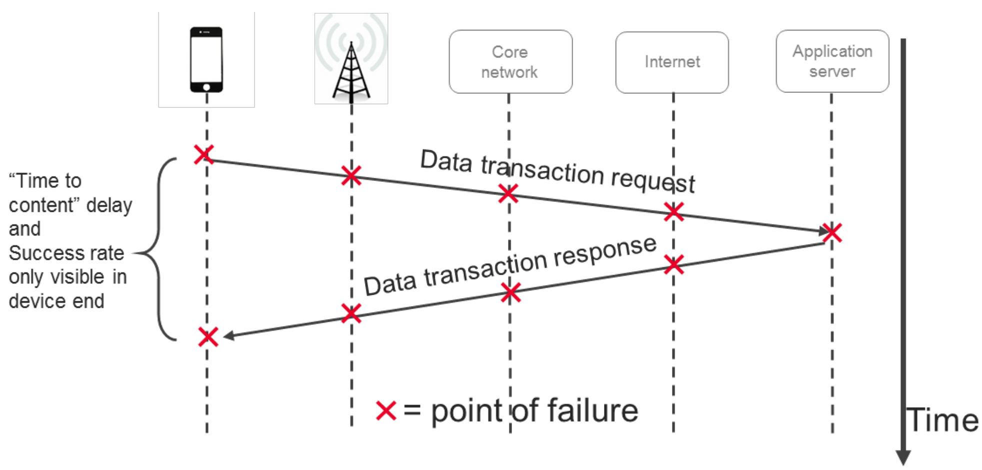


Figure 10. Transaction flow of an end-user.

Network slicing is a new concept in 5G NR for both core network and RAN. Network slicing allows multiple virtual networks to be created on top of a common shared physical infrastructure. A single physical network will be sliced into multiple virtual networks that can support different radio access networks (RANs), or different service types running across a single RAN. Network slicing replaces the QoS profiles used in LTE and UMTS. One big difference to the legacy technologies is that the type of application is to be automatically detected by the network. This means that the network can apply different QoS settings for different OTT applications. For example, the network could detect a WhatsApp call to be a VoIP service and relay the traffic on a network slice that is optimized for low latency, guaranteed low bitrate traffic. Network slicing impacts the low-level numerology of RAN, including subcarrier spacing and slot duration.

This means that a 5G NR network with network slicing operates differently depending on the application being used by the subscriber. Therefore, active QoE testing using real OTT applications will be increasingly important in 5G NR. Making bulk data transfers using FTP or speedtest.net will not give an accurate picture of the true QoE. Keysight Nemo Wireless Solutions has years of experience on QoS/QoE measurements. We have the capability to assess the QoE and translate the user experience into measurable KPIs. We perform true end-to-end verification using real chat, video, and social media applications popular in the consumer space. YouTube, Netflix, WhatsApp, to name a few. We will use this capability for the quality assessment in 5G NR.

New Way of QoE Measurements

We have a new, unique test protocol that can be used to quickly and scientifically test the latency and peak throughput of the connection, including root cause analysis that will automatically indicate where the bottleneck of the connection is: device end, last mile (RAN), core, or backend server. This will speed up the field verification of the 5G NR mobile broadband use case. The new test scheme also provides QoS prediction on a mean opinion score (MOS) scale for different application types, including VoIP, streaming video, live TV, and web browsing. This allows us to quickly check the end-to-end 5G NR performance of different types of applications without having to check the QoE app by app.

Summary

5G NR network coverage measurements will be beam-based instead of cell-based. This will change the methodology of coverage KPI calculation. The amount of reference signals in the air is increasing as there will be multiple reference beams per cell, posing more stringent performance requirements for scanning receivers and test UEs.

Both test UEs and scanners will be needed for 5G NR field verification. A scanner is a good tool for SSB reference beam coverage measurements, but UE-based active field testing is needed for the verification of the rest of the functionalities, including traffic channel beams, QoS/QoE, mobility, and LTE interoperability. Keysight is working with all major scanner vendors and UE/chipset vendors to provide field test solutions for 5G NR.

mMIMO capacity gain is dependent on the network equipment implementation of the antenna panels as well as the gNB scheduler algorithms. Field verification of mMIMO performance is important as a part of the vendor selection process as well as network acceptance. The test setup is complex, involving multiple test UEs distributed in the cell area with coordinated bulk data transfer stress tests. Keysight has a mMIMO test solution, powered by Nemo Cloud, proven in LTE Advanced Pro mMIMO testing.

QoE testing in 5G NR will get more complicated because of network slicing. It is expected that networks will have the ability to detect the traffic type and relay data streams from different applications to different QoS settings (slices). This means testing with speedtest.net or FTP bulk data transfer will not reflect the true service quality as seen by an OTT app. At Keysight we have years of experience on QoS/QoE measurements and, hence, we will be able to address the 5G NR QoE measurement challenge and translate the user experience into measurable KPIs.

Read more about Nemo measurement solutions at www.keysight.com/find/nemo.