The Challenge of the First Commercial 5G Service Deployment

The 3rd Generation Partnership Project (3GPP) published its very first 5G specification in December 2017. It includes non-standalone (NSA) mode using the LTE core and radio networks, while preparing a full-scale rollout of NR stand-alone deployments. The main scenario for NSA mode is the widely considered LTE-NR Dual Connectivity (DC), in which user data can be exchanged between a mobile device and a NR base station along with LTE connectivity.

Figure 1: 5G NR Deployment Scenario and UE Architecture.
The first 5G standard non-standalone deployment configuration offers throughput
and latency advantages that can be achieved with the existing 4G network coverage.
However, it requires more complex hardware implementations to allow simultaneous
connections with both LTE and NR networks, which will increase costs, especially
for user equipment (UE).

While the expectations for 5G seem to be growing in the news every month,
Keysight is actively working to resolve many technical issues with 5G product
developers. The purpose of this paper is to share some of the common technical
challenges being addressed. This includes the technical challenges related to co-
existence issues in LTE-NR DC that come from a combination of intermodulation
products at different sub-6 GHz frequency bands. A second major challenge is the
implementation of susceptible mmWave components into the mobile devices.

4G and 5G Global Spectrum Landscape

Spectrum availability is a key input in the readiness and ability to win the global 5G race.
South Korea, Germany, Australia, the United Kingdom, Romania and the U.S. have
already announced plans for 5G auctions this year. Looking at the specific 5G spectrum
bands, they are focused on mid band (3.3 GHz ~ 4.2 GHz) for longer distance service
and high band (24.25 GHz ~ 29.5 GHz) for faster data speeds.

While the 5G frequency auction is one of the main issues for global operators, initial
service will be anchored in existing 4G core networks. It will aggregate multiple bands in
sub-6 GHz and add a new one at 28 GHz. Some of the band combinations will create
unavoidable levels of intermodulation (IMD) power in specific bands. Bands with harmful
IMD may lose spectrum efficiency and operators will face numerous service quality
issues. For this reason, it is critical to understand IMD effects related to 4G and 5G
co-existence.

The current release of the 3GPP specification defines different frequency ranges (FR).
The designator, FR1, supports frequencies between 0.45 GHz and 6 GHz. FR2 covers
operating bands between 24.25 GHz and 52.6 GHz. The FR2 mmWave frequency is a
new area for most of the mobile device design engineers. mmWave has many technical
challenges such as large loss, wide bandwidth, and limited instrument accessibility.
These must all be addressed in the early design phase.
Increased RF Front-End (RFFE) Complexity

Fundamentally, sub-6 GHz 5G and 4G RFFE requirements look the same. Sharing the RF path in a typical RF architecture is an obvious design concept to reduce cost and PCB area using the same componentry. However, there are differences between 5G NR and 4G LTE that need to be taken care of in the RF design.

**Increased bandwidth:** 5G NR has a maximum channel bandwidth up to 100 MHz and wide spectrum allocated in new bands. For example, the n77 NR band has a 900 MHz wide frequency range from 3.3 GHz to 4.2 GHz. This is too wide to be supported by a single component. For example, the power amp requires a much wider effective bandwidth controlled by biasing and supply feeding circuits to ensure linear performance while mitigating memory effects. The filter also needs to cover this broad frequency range, which will require the adoption of new ceramic technology in addition to conventional SAW/BAW filter design approaches.

**Waveform:** The uplink carrier will use both CP-OFDM and DFT-S-OFDM waveforms. There will be a PAPR (Peak to Average Power Ratio) difference on the uplink signal compared to LTE.

**Multi-band and multi-RAT:** Over 1000 band combinations are now supported for LTE and the new 5G band will increase this number dramatically. With these multi-band requirements, the intermodulation issues are more significant and will be extremely difficult to troubleshoot. In cell communication systems, IMD can create interference which will reduce receiver sensitivity or even inhibit communication completely. This is the main concern in various carrier aggregation(CA) scenarios from an eNb for 4G. Engineers for most of the component vendors are spending significant amounts of time simulating and testing to address these IMD issues.

Creating thousands of test cases to support increasing LTE frequency bands, defining various CA scenario and calculating IMDs and harmonics with different combination of aggressor bands and victim bands - all requires a large amount of simulation and test time. It usually starts by designing circuits for the LNA, filter and other components using a circuit simulator and extracting S-parameters. The results are then imported into the communication system simulator for the IMD analysis, where thousands of test cases are run to find the optimized component parameters. This is normally conducted by creating a special script for the automated simulation, an approach that has worked well for 4G RFFEs.
Now let’s consider an approach for a 5G RFFE which supports DC (dual connectivity) frequency bands, including the new 3.5 GHz band. When you consider the increased number of band combinations of LTE and NR, with a much wider bandwidth, the current methodology will need to be re-visited and validated. Experienced 4G component development engineers have a high level of confidence that their product spec will meet the system level performance metrics (throughput greater than 95% as defined in the 3GPP standard) when they are integrated into a system. However, for the 5G DC cases, RF engineers will need to do more research to achieve the required performance at the system level.

Sub-6 GHz Dual-connectivity IMD Case Study

Figure 2 shows a behavioral model of a DC enabled RFFE. From the top right, there are two uplink transmitters configured at band 3 and band n78 with maximum output power with 20 MHz bandwidth. These two modulated signals will create intermodulation distortion signals going through the non-linear power amplifier. At the top left of the schematic, one downlink source signal is assigned at band 3 with a victim frequency and receive power set to −95 dBm to make a worst scenario. These two signals combine and feed into the primary receiver path. Which is then filtered and down converted to a 210 MHz IF frequency.

1. b3 DL source
   - At victim frequency
   - Receive power at −95 dBm

2. Transmit IMD signals jump into the receiver

3. Non-linear PA creates IMDs

4. Simultaneous UL Tx:
   - b3 UL at 1740 MHz
   - n78 UL at 3575 MHz

5. IF frequency
   - At 210 MHz

Figure 2: 5G NR RF Front-End Behavioral Model for Dual Connectivity (Keysight SystemVue).
The simulation results in Figure 3a indicate that there are many IMD signals with different order and power levels created. The most significant IMD lands on band 3 downlink's receive frequency 1835 MHz. Figure 3b shows the simulation that also analyzed the path measurement at the LNA output. By turning on and off the b3 and n78 transmitters, each NDCP (noise and desired channel power) is displayed in the red and blue trace, with total IMD power colored in green. You may notice that the IMD power contributed to most of the NDCP power and it cannot be separated easily from the wanted b3 downlink receive signal. As a result, the receiver sensitivity is degraded and the throughput performance is reduced as shown in figure 3c.

Figure 3a: Intermodulation and harmonic analysis with two modulated signals at 1740 MHz and 3575 MHz.
After thousands of similar simulation case studies for co-existence issues, 3GPP has defined the problematic band combinations in TS38.306 - User Equipment (UE) radio access capabilities. In some 3GPP standard documents you may now find an indication “Single Uplink Allowed”, which means the UE may not be capable of supporting simultaneous dual uplink operation due to possible intermodulation interference to its own downlink band. Other than that, the UE is mandated to operate in dual uplink mode.
**mmWave Components for Mobile Devices**

Compared to sub-6 GHz, mmWave front-ends require substantial antenna and beamforming gain to overcome lossy propagation loss. Figure 4 shows that the architecture is drastically different than sub-6 GHz. The mmWave front-end will have a large conducted path loss associated with the high frequency and therefore the trace length between antenna element and active circuitry will have very low tolerances.

On the other hand, with the increase in frequency comes a proportional reduction of the wavelength. The antenna array size is now getting small enough to be integrated into the same package that contains the active transceiver circuits operating at mmWave. This entirely integrated package must support all required phase shifting, path switching and amplification to drive each antenna array elements properly.

With this kind of new architecture, RF engineers must design mmWave component circuits and characterize their models to capture the fluctuation of the individual device. Then, the component level design will be verified for system level performance evaluation.

Figure 4: Beamforming RFIC with Split-IF architecture including antennas, phase shifter, variable gain control, filters and frequency conversion components (behavioral model by Keysight SystemVue).
Once the circuit and system level design is completed, the next step is the verification and test of the prototype hardware. As explained earlier, the mmWave RFFE and phased array antenna will normally be integrated in the package, with very limited access for the measurement instruments. This is one of the most challenging tasks for all 5G mmWave device developers, especially user equipment (UE). The limitation of physical access has brought the requirement of radiated measurement also known as Over-the-Air (OTA) test.
Over-the-Air (OTA) Simulation

3GPP defined an Over-the-Air (OTA) test standard for 4G and is aggressively working to establish a radiated performance specification for 5G. The configuration of an OTA test system consists of a base station emulator, reference antennas, and a DUT position controller in an anechoic chamber. The test system is controlled with a complex integration of software and hardware. An OTA test system helps engineers perform antenna measurements, RF parametric, function and protocol testing. However, once they face an error from the measurement, they struggle to finding the error’s root cause. This debugging task might be the last step of a mmWave device design before they return to the initial design stage for the review.
Let’s say the EVM (error vector magnitude) measurement value in the OTA test result is not the maximum at the beam peak direction, but at the other location. What would be your next step to solve the problem? Being able to run a simulation in your OTA environment would help you find out. By modeling the individual building blocks for the OTA, you could divide the key function blocks and better perform a root cause analysis. Figure 6 shows an OTA analysis example.

Figure 6: Software simulation based OTA analysis (Keysight SystemVue).

a. NNR source configuration
   - Uplink, Downlink
   - Numerology
   - Frame structure

b. Power setup
   - Measurement reference channel
     \[ \text{EPRE}_{\text{dBm}} = \text{NDensity}_{\text{dBm}} \cdot \text{Hz} + 10^{\log_{10}(15e3/2^N\text{Numerology})} + \text{SINR} \]
   - \( \text{SignalPower}_{\text{dBm}} = \text{EPRE}_{\text{dBm}} + 10^{\log_{10}(\text{PDSCH}_\text{RBNumRBs} \cdot 12)} \)

c. Beamforming RFIC
   - Define beam angle
   - Generate weight vector

d. OTA configuration
   - DUT antenna
   - Probe antennas
   - Distance and polarization
   - Element rotation

e. NR reference receiver
   - Frame synchronization
   - Channel estimation and equalization
   - Demodulation and decoding

f. EVM measurement
   - Error vector magnitude
   - EVM vs direction pattern

g. Power measurement
   - Signal power calculation
   - EIRP pattern

h. Plotting
   - 3D beam pattern
   - Beam measurement
Description of the models:

a. The NR reference baseband source may be used to configure the uplink, downlink, flexible numerology, frame structure, modulation and coding scheme. It generates a baseband complex IQ signal in the output.

b. Converting the baseband signal to an RF envelope format. Each of the image and real signal paths are band pass filtered, modulated, and upconverted to a 28 GHz carrier frequency. Specific transmit output power is applied using EPRE calculation equation.

c. A non-linear power amplifier represents the general transmitter RF behavior.

d. A vector analysis model can provide most of the RF parametric tests and can be connected to any test point within the schematic.

e. The beamforming RFIC model includes phase shifter, variable gain and splitter.

f. Generating beam weight vector to set transmit beam direction. It behaves like a beamforming controller.

g. Beam pattern display measurement (Beam shape in 3D, Direction, Power).

h. Configuring DUT and probe antennas specification, distance, polarization, position.

i. RF receiver model including noise floor specification change.

j. Beam power measurement and EIRP calculation.

k. The NR reference baseband receiver provides demodulated and decoded output symbols and bits. The output symbols may be used for EVM measurements.

The building blocks used in the simulation provide great flexibility to model various components in an OTA system. They are reference baseband modem IP compliant with the 3GPP standard. They can be used for RF behavioral models with non-linear characteristics, antenna patterns, beam controllers, of the chamber, create a 3GPP mmWave channel model, and even virtual instruments. These amazing reference models can be used for your own specific test scenario combinations.
Conclusion

The abundance of new frequency band configurations in the sub-6GHz LTE-NR dual connectivity, combined with non-instrument-accessible mmWave mobile devices, makes it increasingly difficult for design and verification engineers to develop their commercial 5G devices.

More devices are being integrated into packages that will need different types of design and simulation tools. Modern EDA tools are needed from the component level implementation all the way through to system level performance verification.

Keysight’s circuit simulator (ADS) and communication system simulator (SystemVue) solves these cross-domain engineering issues from the component level characterization to the system level evaluation. It is essential not only for the design verification but also for making your R&D workflow more efficient.

5G’s complexity will continue to increase. Finding effective solutions will be one of the greatest challenges for wireless technology experts. Become a part of our 5G collaboration program for your system design and verification. We are looking forward to welcoming you on-board for your 5G journey.

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