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Introduction

5G is rapidly approaching, bringing with it the promise of powerful new use cases that will require a flexible technology that can deliver ultra-reliable low latency (uRLLC), massive machine-type communications (mMTC), and much faster data rates with enhanced Mobile Broadband (eMBB). As mobile operators fast-track their 5G deployment plans, chipset and device manufacturers must also accelerate their development activities, including determining how best to test 5G data throughput most effectively. This application note provides detailed information on the technical issues they face and the solutions Keysight provides.

This application note focuses on the eMBB use case, which is targeted in the Verizon’s 5G Technical Forum (“5G TF”) specification as well as in phase 1 of the 3GPP 5G New Radio (NR) specifications.

The definition of the eMBB use case has been accelerated in 3GPP because it has major industry demand. 3GPP has agreed to the early completion of the non-standalone (NSA) 5G NR mode for the eMBB use case. In non-standalone mode, the connection is anchored in LTE while 5G NR carriers are used to boost data-rates and reduce latency. Data rates of up to 20Gbps (downlink) and 10Gbps (uplink) are on the horizon for early network rollouts in the next few years.

This application note describes the new challenges of testing high data rates and provides a solution to these challenges using Keysight’s 5G Protocol R&D Toolset.
eMBB Use Case

The enhanced Mobile Broadband use case of 5G brings new and powerful capabilities to support high-speed data rates, improved connectivity and system capacity. High data rates and greater capacity are critical in order to use virtual reality (VR) and augmented reality (AR) applications, which include new video formats with increased resolutions (8K+) and higher frame rates (HFR). For interactive AR and VR applications, low latency is an additional key requirement. With the number of users increasing and simultaneously consuming or sharing premium content, 4G networks will struggle from a capacity point of view and the improved capacity of a 5G network will be needed.

To achieve the higher data rates, improved connectivity and higher capacity required for eMBB, in addition to using sub-6 GHz frequencies, 5G is also being deployed in a high-frequency, millimeter wave spectrum, which has significantly greater bandwidths. LTE operates at frequencies up to 6 GHz, whereas millimeter wave frequencies of up to 100 GHz are under consideration for 5G. The 5G TF specifications that cover 28 GHz and 39 GHz are also being considered by other operators.

At higher frequencies, propagation and penetration losses are higher, which is why beam-forming techniques are used to increase the signal level received by a device. The improved signal quality helps overcome the high path loss and improves connectivity to cell-edge users. Beamforming achieves a stronger signal-to-noise ratio by providing high gain in specific spatial directions.

This brings about new testing challenges as new procedures for beamforming are being introduced in the 5G TF and 3GPP 5G NR specifications. There are also changes in the physical layer including the frame structure, new reference signals as well as scheduling and transmission modes to support the eMBB use case.

The following section explains the new frame structure and the concept of beamforming introduced in the 5G TF and 3GPP 5G NR specifications to achieve high data rates, improved connectivity and higher system capacity. The later sections describe how to use Keysight’s 5G Protocol R&D Toolset to configure and test data throughput.
Physical Layer Characteristics And Data Throughput

The following table compares the physical layer characteristics in LTE, 5G TF specifications and 3GPP 5G NR specifications. Red indicates a change from LTE.

Note: The 3GPP 5G NR specifications are currently under discussion and therefore may change.

<table>
<thead>
<tr>
<th>Table 1: Comparison of LTE, 5G TF and 3GPP 5G NR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Characteristic</td>
</tr>
<tr>
<td>Frame structure</td>
</tr>
<tr>
<td>Radio frame</td>
</tr>
<tr>
<td>Subframes in a frame</td>
</tr>
<tr>
<td>Slots in a frame</td>
</tr>
<tr>
<td>Resource blocks</td>
</tr>
<tr>
<td>Frequency domain</td>
</tr>
<tr>
<td>Carrier aggregation</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
</tr>
<tr>
<td>Carrier bandwidth</td>
</tr>
<tr>
<td>Frequency bands</td>
</tr>
<tr>
<td>Beamforming</td>
</tr>
<tr>
<td>Modulation</td>
</tr>
<tr>
<td>MIMO</td>
</tr>
<tr>
<td>Channel coding scheme</td>
</tr>
</tbody>
</table>

As can be seen from Table 1, the 5G TF frame structure parameters such as subcarrier spacing and carrier bandwidth are fixed compared to 3GPP 5G NR where the values are scalable to accommodate a wider range of use cases. As mentioned above, 5G TF targets the eMBB use case. Higher subcarrier spacing, carrier bandwidth, and use of higher frequencies all contribute to a higher data rate and improved connectivity compared to LTE.
Radio Frame Structure

The radio frame size in LTE and 5G TF is the same at 10 ms. In LTE, each frame contains 10 subframes and 20 slots, compared with 50 subframes and 100 slots in 5G TF. This means that 5G TF slots (0.1 ms) are shorter than LTE slots.

A resource block is the smallest entity that can be assigned to a device. Both LTE and 5G resource blocks consist of one slot in the time domain and 12 subcarriers in the frequency domain. LTE has a typical subcarrier spacing of 15 kHz, compared to 75 kHz in 5G TF.

The maximum carrier bandwidth in LTE is 20 MHz, compared to 100 MHz in 5G TF if 100 resource blocks are being used. The higher 5G TF and 5G bandwidth results in higher data rates and improved network capacity.

The 5G TF specifications support the use of carrier aggregation in downlink and uplink using a maximum of eight component carriers. If carrier aggregation is used, the bandwidth would be 8 x 100 MHz = 800 MHz.
## Throughput Calculation

The throughput rate is calculated using Transport Block Size (TBS), which is the number of bits transmitted in one subframe every Transmit Time Interval (TTI). TBS is dependent on the number of resource blocks allocated to the UE as well as the modulation and coding scheme (MCS) used. In the 5G TF specifications, the highest modulation and coding scheme is 64 QAM. According to table 8.1.5.2.1-1 in [2], the highest transport block size is 66392 bits. This results in a throughput rate of 663.92 Mbps per component carrier. If eight component carriers are being used, the throughput will be 663.92 Mbps x 8 = 5.3 Gbps per UE.

### Table 2. Example data throughput calculations.

<table>
<thead>
<tr>
<th>Specifications</th>
<th>Modulation and coding scheme</th>
<th>Transmit time interval</th>
<th>Transport block size</th>
<th>Data throughput per CC</th>
<th>Component carriers</th>
<th>Total data throughput</th>
</tr>
</thead>
<tbody>
<tr>
<td>5G TF 64 QAM</td>
<td>64 QAM (6 bits per symbol)</td>
<td>0.2 ms</td>
<td>66392 bits</td>
<td>663.92 Mbps</td>
<td>8</td>
<td>5.3 Gbps</td>
</tr>
</tbody>
</table>
Beamforming

Beamforming is necessary in order to avoid transmission losses when using millimeter wave frequencies. Beamforming combines signals from multiple antenna elements in an antenna array, so that the combined signal level increases when several signal phases align (constructive interference). The signals from each antenna element are transmitted with a slightly different phase (delay) to produce a narrow beam directed towards the receiver, see figure 2.

Figure 2. Creating directional beams by varying the time and phase of the transmission of each antenna.

In 5G TF, beamforming is used for reference signals, broadcast control channels and data channels, whereas in LTE beamforming is used for data channels only.

When testing data throughput, the following steps are required for a device to connect to a network cell and send/receive data:

- Cell search to acquire time and frequency synchronisation with a cell
- Beam acquisition followed by Random Access Procedure
- Attach procedure

New procedures for beamforming have been defined in the 5G TF specifications. The implementation of beamforming is still being discussed in 3GPP NR. The below procedures for beamforming are defined in the 5G TF specifications. Each procedure is described briefly. For more detailed information, please refer to [2].

- Beam acquisition and tracking
- Beam refinement
- Beam feedback
- Beam switch
Beam acquisition and tracking

For a UE to send and receive data, it must first connect to the network by acquiring a beam. The 5GNB (5G Node B) periodically transmits beams at different angles by transmitting BRS (Beam Reference Signal). This is known as beam sweeping, see figure 3. When the UE identifies the strongest beam, it starts a Random Access Procedure, using timing and angular information, to connect to the beam. When the UE has connected to a beam, data transfer can take place on the UE-specific (dedicated) beam.

![Figure 3. Beam sweeping and acquisition.](image)

The number of beams transmitted and the periodicity of beam sweeping is determined by the beam reference signal (BRS) transmission period. There are four different transmission periods defined in [2]. The longer the transmission period the more beams are generated. Each generated beam has a Beam Index (BI) and each UE is allocated a BI, however multiple UEs can have the same BI.

Table 3: Calculating total beam indices using beam reference signal (BRS) configuration and transmission period

<table>
<thead>
<tr>
<th>BRS configuration</th>
<th>BRS transmission period</th>
<th>Symbols in BRS transmission period (Nsym)</th>
<th>Antenna ports (P)</th>
<th>Number of beam indices (Nsym x P)</th>
</tr>
</thead>
<tbody>
<tr>
<td>00</td>
<td>1 slot &lt;5 ms</td>
<td>7</td>
<td>8</td>
<td>56</td>
</tr>
<tr>
<td>01</td>
<td>1 subframe = 5 ms</td>
<td>14</td>
<td>8</td>
<td>112</td>
</tr>
<tr>
<td>10</td>
<td>2 subframes = 10 ms</td>
<td>28</td>
<td>8</td>
<td>224</td>
</tr>
<tr>
<td>11</td>
<td>4 subframes = 20 ms</td>
<td>56</td>
<td>8</td>
<td>448</td>
</tr>
</tbody>
</table>

As can be seen from the table, the higher the transmission period the more beam indices are generated, which means that there can be an increased number of angular beam directions or increased number of beams in certain angular directions. For more information about beam reference signals, see section 6.7.4 in [1].
**Beam refinement**

In the beam acquisition procedure, the best direction for the 5GNB to transmit and the UE to receive is determined. In the beam refinement procedure, the wider beam (direction) is narrowed down (refined) by the 5GNB transmitting narrower beams only in the direction determined in the beam acquisition procedure. This means the best angular direction for the 5GNB to transmit and the UE to receive is refined to a finer granularity. The narrower beam is identified by Refinement Reference Signal Resource Index (BRRS-ID).

Beam refinement can only be done in dedicated mode when the UE has already acquired a BI using BRS and is done by the network sending BRRS (Beam Refinement Reference Signal). Transmission of a BRRS triggered by the network sending a DCI or by the UE requesting the network to send BRRS using SR (Scheduling Request). For further information, please refer to [2].

**Beam feedback**

5G UEs return the following beam measurement information back to the 5GNB.

**Beam state information (BSI)**

The UE maintains a candidate beam set of four beams; for each beam the UE reports the Beam State Information (BSI). BSI is based on measurements of BRS, and the reported parameters are Beam Index (BI) and Beam Reference Signal Received Power (BRSRP).

The UE can report BSI on either xPUCCH or xPUSCH. When reporting BSI on xPUCCH, the UE reports BSI for the beam with the highest BRSRP in the candidate beam set. When reporting BSI on xPUSCH, the UE reports BSIs for one, two or four beams (determined by the 2-bit BSI request from the 5GNB) with the highest BRSRP in the candidate beam set.
Beam refinement information (BRI)

The UE also reports Beam Refinement Information (BRI). This is based on the Beam Refinement Reference Signal (BRRS) measurements, and the reported parameters are Beam Refinement Reference Signal Resource Index (BRRS-RI) and Beam Refinement Reference Signal Received Power (BRRS-RP).

Figure 5. Beam refinement.

BRRS measurements are initiated by 5GNB using DCI (Downlink Control Information) and sent using xPUCCH or xPUSCH, for more information refer to [2].
Beam switch

The beam switching procedure is used by the serving cell to change the serving beam of the UE. This can be done in two ways:

Beam switch using BRS

Beam switch is the process of changing the serving beam for the UE. There are two procedures for beam change: DCI-based and MAC-CE based.

In the DCI-based procedure, the 5GNB initiates the procedure by setting the field ‘beam_switch_indication’ to 1 in the DCI. The UE will switch to the serving beam with the highest reported BRSRP as reported in the BSI report.

In the MAC-CE-based procedure, the 5GNB transmits a MAC-CE control element containing a BI to the UE. Upon receiving the MAC-CE control element, the UE switches the serving beam to match the beam specified in the MAC-CE control element. For more information, see section 8.3.4 in [2].

Beam switch using BRRS

As for beam switch using BRS, there are two procedures for beam change: DCI-based and MAC-CE based.

In the DCI-based procedure, 5GNB triggers BRI reporting using DCI. The UE reports up to four beams. Based on the BRI report, 5GNB initiates a beam switch procedure by setting the field ‘beam_switch_indication’ to 1 in the DCI.

In the MAC-CE-based procedure, 5GNB transmits a MAC-CE control element containing a BRRS-RI to the UE. Upon reception of the MAC-CE control element the UE switches the serving beam to match the beam specified in the MAC-CE control element. For more information, see section 8.4.4 in [2].
Testing eMBB Using Keysight’s 5G Protocol R&D Toolset

Figure 6 shows Keysight’s 5G test system setup. The test system consists of a 5G network emulator, UXM 5G, which is connected and controlled by a test system PC on which the Keysight 5G Protocol R&D Toolset is installed. The UE is connected to the test system using a millimeter wave connection, which will need to support the high frequencies required for data throughput testing of eMBB. Due to the high-frequency test challenges associated with incorporating antenna connectors in chipsets and handsets, data throughput testing must be done Over-The-Air (OTA).

The 5G network emulator simulates the layer 1 (PHY), layer 2 (MAC/RLC/PDCP) and layer 3 (RRC/NAS).

Figure 6 5G test system.

All Keysight software applications including the 5G Protocol R&D Toolset support the existing 5G TF specifications and are designed to support other specifications in the future, such as 3GPP 5G NR and early carrier acceptance test specifications.

The 5G Protocol R&D Toolset provides an easy-to-use graphical interface where you can create, edit, configure and run tests, which are also known as scripts. This is done by dragging and dropping script elements into an editor after which the script elements can be configured, see figure 7. Keysight also provides a number of sample scripts which can be loaded into the editor and then modified, see figure 8. As you can see there are script elements for activating, deactivating and reconfiguring 5G cells, inserting RRC and NAS messages, and inserting user prompts and verdicts.

Using Keysight 5G Protocol R&D Toolset you can create a test for data throughput by loading a script and configuring script elements. Examples of parameters that can be configured are power levels for synchronisation and reference signals, beamforming parameters, and resource blocks to be used for transmitting and receiving control information and data.
Figure 7. Drag and drop script elements onto scripting pane.

Figure 8. 5G Protocol R&D Toolset with sample script loaded.
Creating And Running A Data Throughput Script

The following section describes the steps required to create and configure a data throughput test using Keysight’s 5G Protocol R&D Toolset.

Creating a data throughput script

Below are the steps to create a data throughput script as shown in figure 9.

- Using File → New create a new script. Script Information and SIM details will automatically be inserted. These can be used to describe the test and include SIM Information.
- Drag and drop the Activate 5G Cell script element into the editor.
- Drag and drop 5G Dynamic Control Point into the editor. As you can see, this script element appears twice in the script in figure 9.

Alternatively, a sample script could be loaded into the editor.

The following script elements need to be configured.

- Activate 5G Cell
- 5G Dynamic Control Point

Figure 9. Data throughput script.
Activate 5G cell

Activate 5G Cell allows you to configure cell parameters such as band, ARFCN, power levels, RACH parameters and Beam configuration, see figure 10. Using the System Information tab, you can configure the BRS transmission period, see figure 11. The values you configure in the Activate 5G Cell script element are initial values that can be modified later on in the script using Dynamic Control Point (DCP). The cell configuration parameters can be loaded and saved and used later for another test.

Figure 10: Cell Information Dialog.

Figure 11: Configuration of BRS Transmission period in the MIB.
Dynamic control point

The Dynamic Control Point enables the network emulator state-machine to behave like a live network until a certain exit condition has been met. This exit condition could be:

- The device sending a particular message, for example, Attach Complete.
- The user performing some actions, for example, sending data for data throughput testing.
- End of a configured guard timer.

For the data throughput script in figure 9, there is one DCP with the exit condition ‘Attach Complete’ and another one with the exit condition ‘User action’. Hence, during script execution, the script will pause at the first DCP and after Attach Complete is received from the UE, it will continue. At the second DCP, the script will pause again and this time the user can perform an action, for example change lower layer parameters such as power levels, BRS transmission period or send/receive data for data throughput testing. This is done using L1/L2 configuration, which is launched form the 5G Protocol R&D Toolset at the point where the script has progressed to a DCP. For a DCP with the exit condition User Action, the user decides when to exit the DCP.

![Dynamic Control Point](image)

Figure 12. Configuration of a Dynamic Control Point.

Running The Data Throughput Script

During script execution, you can perform certain user actions at a DCP. This is done using L1/L2 Configuration. figure 13 shows the process.

1. The user loads a data throughput script and runs it using the green ‘Run script’ button as shown in figure 14.

2. At a DCP, the script pauses and the user can modify lower layer parameters and/or send data in L1/L2 Configuration. The parameters that have been configured in L1/L2 configuration can be saved and reused for another script. The section ‘Using L1/L2 Configuration’ shows important parameters to configure for a data throughput test.

3. Once lower layer parameters have been modified, you can configure the number of data packets to send in L1/L2 Configuration, see figure 15. This will initiate a data transfer.
Run script in 5G Protocol R&D Toolset

Figure 13. Interactive process for developing scripts.

Figure 14. Panel for starting and stopping a script.

Figure 15. Panel for configuring the number of data packets to send.
During test execution, the user interface shows an integrated Real Time Trace (RTT) that displays the progress of the test with layer 3 protocol messages being sent and received, see figure 16. The RTT log is saved at the end of the test execution to a log file directory where all files associated with the test case run are saved in one place. For more information on log files, refer to the section on ‘Analysing Results.’

Figure 16. Real Time Trace.

**Using the L1/L2 configuration**

During a script run, at a Dynamic Control Point, you can modify the parameters using the L1/L2 Configuration application. The following are some of the parameters that can be configured:

- Scheduling of subframes for the connected cell, which includes which subframes to use for UL and DL control information as well which subframes to use for UL and DL data, see figure 17.
- Layer 2 parameters, which include frequency, beam reference signal transmit power (BRSTP) BRS transmission period, xSIB Default Config and xPBCH Tx Periodicity, see figure 18. For more information refer to [3].

When applying the parameter values in L1/L2 Configuration, the values set initially in the Activate Cell script element are overridden.

Figure 17. Configuring subframe patterns.

Figure 18. Configuring frequency, BRSTP and BRS Transmission Period.
Analysing Results

To ensure rapid development of devices, Keysight provides detailed logs and log analysis tools to help you diagnose issues with your device quickly, reliably and efficiently.

Each script run generates the following log files:
- Log File (.alf)
- Real Time Trace (.rtt)

Log file

The .alf file can be opened with Keysight Log Viewer, which is Keysight’s primary tool for analysing protocol logs. The Keysight Log Viewer application provides powerful message decoding, enhanced search facilities and rapid navigation tools to find records of interest, see figure 19. Bookmarks can be added to facilitate troubleshooting and the whole log or specific parts of the log can be exported. Keysight Log Viewer includes a KPI viewer where KPIs are displayed graphically. For data throughput, typical KPIs would include graphs of data rates at different layers (PHY/MAC/RLC/PDCP and application layer), Channel Quality Information (CQI), MCS, BLER (Block Error Rate) and ACK/NACKs vs time. It is important to measure the quality of the signal as that would affect data throughput. KPIs like BSI and BRI are significant in order to check that the UE has selected the strongest beam as reported by the network. Test reports including the KPI graphs can be generated in different formats.
Real time trace

The Real Time Trace (.rtt) file is a copy of the real time trace displayed during runtime and is saved as a text file. It logs timestamp, cells, the direction of a message as well as layer 3 messages (RRC and NAS). It is also possible to view the hexstring of the messages by double-clicking on a message.

In addition to the log files, many other files used for debugging as well as a copy of the script that was executed are stored in the results directory. All the files can be zipped and sent to Keysight Customer Support for additional analysis.
Summary

5G implementation and testing have many challenges. New concepts of beamforming and millimeter wave are being implemented to maximize the capabilities of available GHz spectrum. Testing using high frequencies requires the test setup to include additional hardware to support these frequencies, and OTA testing is necessary.

Achieving 5 Gbps and higher data rates in the short term is an exciting prospect. The Industry is looking for test platforms that can offer the ability to test these data rates without the need to program complex tests, thus saving considerable time and effort.

Keysight’s 5G Protocol R&D Toolset provides an easy-to-use solution to test eMBB, a key 5G driver. It is the first in a series of 5G Keysight network emulator solutions to be launched.

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   Available at www.3gpp.org/DynaReport/38802.htm
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