Keysight Technologies

*Bluetooth®* 5 Technology Fundamentals and Critical Test Parameters

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**Bluetooth 5**

<table>
<thead>
<tr>
<th>Feature</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>2x speed</td>
<td>2 Mbps</td>
</tr>
<tr>
<td>4x range</td>
<td>300 meters</td>
</tr>
<tr>
<td>8x broadcasting data</td>
<td>255 bytes</td>
</tr>
<tr>
<td>Improved coexistence</td>
<td></td>
</tr>
</tbody>
</table>
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Bluetooth technology has been around for close to 20 years and gone through five generations. V1.0 was meant for cable replacement with low data rate. V2.0 was enhanced with a faster data rate. V3.0 introduced the high speed mode of 24 Mbps. The versions up to V3.0 are known as Bluetooth Classic.

In Bluetooth 4.0, Bluetooth Low Energy was introduced with a data rate of 260 kbps. It was optimized for low power devices so that it can run for a long period with small current consumption.

Bluetooth 4.2, was specifically enhanced to target IoT applications. It included IPv6 support for IP connection to the end node. It also added better security and a 10x packet capacity increase for improved throughput.

Bluetooth 5 was announced in 2016, and several improvements were made for the low-energy features to improve IoT applications. It has the benefits of 2x speed and 4x range improvement compared to the previous low-energy standard (V4.0). The longer range is achieved through channel coding with the tradeoff of lower data rate. In previous versions, no channel coding was included. Bluetooth 5 also increases the data broadcasting capacity by 8x.
Major New Features of Bluetooth 5

There are many exciting new features in Bluetooth 5.

8x broadcasting message capacity: The increase in broadcasting message capacity allows Bluetooth devices to send larger data to other devices without being paired. Bluetooth 5 device will be more ‘location-aware’ so that users can enjoy extra navigational features. For example, a user can easily find his or her way around a shopping mall.

2x the speed and 4x the range: The Bluetooth 5 headset will probably work for the entire home now. Imagine your headset working if you leave your home office to grab lunch at the kitchen. Bluetooth 5 could be the backup for a WLAN connection at home. The range is improved by a factor of four in Bluetooth 5, so theoretically you could be up to 300 meters away from your Bluetooth 5 speaker and still beam a song to it. However, the exact distance is limited to the hardware you are using. The speed will be twice as fast as Bluetooth 4.2 LE. But you are not likely to get up to this speed in real world applications. It will still be a significant speed improvement from Bluetooth 4.2.

Improved interference immunity or coexistence: Bluetooth 5 has been enhanced with a physical layer that helps avoid interference with nearby wireless devices. A slot availability mask can detect and prevent interference on neighboring bands. This helps to improve coexistence and interoperability in a crowded spectrum environment.

More power efficient: With so many new features released in Bluetooth 5, one may think that the device will consume more power. The reality is that data rate or bandwidth can be decreased to achieve up to 4x the range while maintaining similar power requirements as Bluetooth 4.2.

Backward compatibility: All the major enhancements in Bluetooth 5 are on the low-energy features that are optimized for IoT applications. Nothing has changed on the Bluetooth Classic side. Bluetooth 5 will maintain a mandatory low-energy mode that is backward compatible with the low-energy version of Bluetooth 4.2, but to enjoy the added features of Bluetooth 5, new radio chip is required.

As you can see, the enhancements of Bluetooth 5 are focusing on increasing the functionality of Bluetooth for IoT applications. It will improve IoT experience and allow easy connections across a wide range of connected devices, including wearables, connected healthcare devices, and smart city sensors.
PHY layers of Bluetooth 5

In Bluetooth 5, three physical layers (PHY) are defined using different modulation schemes, coding schemes and data rates (See Table 1).

LE 1M is a mandatory mode, and it is backward compatible with the low-energy version of Bluetooth 4.2. There are two more PHYs that increase the data rate to 2 Mbps or extend the coverage range with channel coding schemes.

<table>
<thead>
<tr>
<th>PHY</th>
<th>Modulation scheme</th>
<th>Coding scheme</th>
<th>Data rate</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Access Header</td>
<td>Payload</td>
<td></td>
</tr>
<tr>
<td>LE 1M</td>
<td>1 M Symbols / second</td>
<td>Uncoded</td>
<td>Uncoded</td>
</tr>
<tr>
<td>LE 2M</td>
<td>2 M Symbols / second</td>
<td>Uncoded</td>
<td>Uncoded</td>
</tr>
<tr>
<td>LE Coded</td>
<td>1 M Symbols / second</td>
<td>S = 8</td>
<td>S = 8</td>
</tr>
<tr>
<td></td>
<td></td>
<td>S = 2</td>
<td></td>
</tr>
</tbody>
</table>

Table 1. Bluetooth 5 physical layers

Standard-based Bluetooth Low Energy RF PHY Test Cases

The Bluetooth specifications are developed and licensed by the Bluetooth Special Interest Group (SIG). The Bluetooth Test Specifications document forms the basis of conformance tests for Bluetooth devices. It allows high probability of air interface interoperability between different manufacturers’ devices. Tables 2 and 3 show the list of RF physical layer test cases for Bluetooth 4.0, 4.2, and 5. These tests are repeated for various Bluetooth physical layers.

Transmitter tests (TP/TRM-LE/CA/BV-xx-C)

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>LE 1M</th>
<th>LE 2M</th>
<th>LE 1M, SMI</th>
<th>LE 2M, SMI</th>
<th>LE coded S=8</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output power</td>
<td>Verifies the maximum peak and average power emitted from the device</td>
<td>01</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>In-band emissions</td>
<td>Verifies that the in-band spectral emissions are within limits at normal operating conditions</td>
<td>03</td>
<td>08</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Modulation characteristics</td>
<td>Verifies that the modulation characteristics of the transmitted signal are correct</td>
<td>05</td>
<td>10</td>
<td>09</td>
<td>11</td>
<td>13</td>
</tr>
<tr>
<td>Carrier frequency offset and drift</td>
<td>Verifies that the carrier frequency offset and carrier drift of the transmitted signal are within specified limits at normal operating conditions</td>
<td>06</td>
<td>12</td>
<td></td>
<td></td>
<td>14</td>
</tr>
</tbody>
</table>

Table 2. Transmitter tests map to the different Bluetooth Low Energy physical layers. The numbers in the table indicate the test case numbers as listed in the Bluetooth Test Specification document.
### Receiver tests (TP/RCV-LE/CA/BV-xx-C)

<table>
<thead>
<tr>
<th>Test</th>
<th>Description</th>
<th>LE 1M</th>
<th>LE 2M, SMI</th>
<th>LE 2M, SMI</th>
<th>LE coded S=2, SMI</th>
<th>LE Code S=8, SMI</th>
<th>LE coded S=8, SMI</th>
</tr>
</thead>
<tbody>
<tr>
<td>Receiver sensitivity</td>
<td>Verifies that the receiver sensitivity is within limits for non-ideal signals at normal operating condition.</td>
<td>01</td>
<td>08</td>
<td>14</td>
<td>20</td>
<td>26</td>
<td>27</td>
</tr>
<tr>
<td>C/I and Receiver Selectivity Performance</td>
<td>Verifies the receiver’s performance in presence of co-/adjacent channel interference, and mirror image rejection performance</td>
<td>03</td>
<td>09</td>
<td>15</td>
<td>21</td>
<td>28</td>
<td>29</td>
</tr>
<tr>
<td>Blocking Performance</td>
<td>Verifies that the receiver performs satisfactorily in the presence of interference sources operating outside the 2400 – 2483.5 MHz band.</td>
<td>04</td>
<td>10</td>
<td>16</td>
<td>22</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Intermodulation Performance</td>
<td>Verifies that the receiver intermodulation performance is satisfactory</td>
<td>05</td>
<td>11</td>
<td>17</td>
<td>23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Maximum input signal level</td>
<td>Verifies that the receiver can demodulate a wanted signal at high signal input levels</td>
<td>06</td>
<td>12</td>
<td>18</td>
<td>24</td>
<td></td>
<td></td>
</tr>
<tr>
<td>PER Report Integrity</td>
<td>Verifies that the DUT PER report mechanism reports the correct number of received packets to the tester</td>
<td>07</td>
<td>13</td>
<td>19</td>
<td>25</td>
<td>30</td>
<td>31</td>
</tr>
</tbody>
</table>

Table 3. Receiver tests map to the different Bluetooth Low Energy physical layers. The numbers in the table indicate the test case numbers as listed in the Bluetooth Test Specification document.
Key changes for Bluetooth LE Devices RF Testing

<table>
<thead>
<tr>
<th>Predefined test mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Bluetooth SIG made non-link test mode mandatory.</td>
</tr>
<tr>
<td>- Non-link based test verifies the functionality of the device hardware only.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Simplified and optimized test cases</th>
</tr>
</thead>
<tbody>
<tr>
<td>- Bluetooth SIG defined non-ideal packet (dirty packet) with frequency drift for</td>
</tr>
<tr>
<td>receiver sensitivity test.</td>
</tr>
<tr>
<td>- Bluetooth SIG added a PER test (as opposed to Classic BER test).</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Predefined test packets</th>
</tr>
</thead>
<tbody>
<tr>
<td>- For the first time with Bluetooth LE, Bluetooth SIG fully defines test packets in</td>
</tr>
<tr>
<td>the Test Specification Document.</td>
</tr>
<tr>
<td>- Depending on the test, the packet payload content may vary.</td>
</tr>
</tbody>
</table>

The first difference is that Non-Link test mode is pre-defined and made mandatory. Traditionally, Bluetooth SIG gave manufacturers the option to test their devices with either Link or Non-Link mode. However, with the adoption of Bluetooth LE, one of the goals has been to create very low-cost technologies for applications in a variety of new market segments. Consistent with this goal, Bluetooth SIG decided to make testing of Bluetooth low energy devices with Non-Link mode mandatory.

Another difference is a simplified test case using predefined non-ideal packets, also known as dirty packets. The Bluetooth SIG defines the Bluetooth LE RF physical layer test cases, to ensure interoperability among all Bluetooth LE devices, as well as to verify the basic performance of Bluetooth LE devices. Bluetooth LE RF physical layer test cases are derived from the classic Bluetooth RF test cases. However, the introduction of Non-Link test mode and several other changes further simplifies RF test cases. Some of these changes include the relaxation of some RF physical specs, such as blocking resolution, and reducing the number of test cases, such as removing the regulatory tests.

The last major difference between Bluetooth LE test specifications and Bluetooth test specifications are the predefined test packets. It is also the first time the Bluetooth SIG has defined the test packets, so every manufacturer’s test packet follows the same guidelines, enhancing the interoperability of Bluetooth LE devices.
**Bluetooth signal generation and signal analysis solutions**

Keysight offers *Bluetooth* signal generation and signal analysis solutions that can cover all *Bluetooth* test cases all the way up to *Bluetooth* 5.

The Keysight N9081C *Bluetooth* measurement application runs inside a Keysight X-Series signal analyzer, and covers measurements that you need during the product validation process. It has one-button self-tests with pass/fail results that simplify the test setup and data analysis.

It can perform transmit analysis measurements, adjacent channel power and output spectrum measurements, enhanced data rate in-band spurious emissions measurements, and low energy in-band emission measurements. It can also monitor the RF spectrum.

The Keysight N7606B Signal Studio for *Bluetooth* is a flexible signal creation program that reduces the time you spend on signal creation and simulation. You can easily create *Bluetooth* standard compliant signals for component, transmitter, or receiver testing.
**Bluetooth LE Transmitter Measurements**

In the Bluetooth transmit analysis, you may have multiple test items to deal with such as peak power, average power, modulation characteristics, frequency drift, and others. The N9081C Bluetooth measurement app provides you with one-button measurements that have pass/fail metrics as per the latest standard.

You can also choose several views of the measurement results. In Figure 3, the current measurement view is the RF spectrum of a Bluetooth LE signal. You can switch to other types of views in the N9081C Bluetooth Application.
Figure 4 is the RF envelope view, which shows the power vs time trace of the Bluetooth signal. This view also displays other parameters such as the packet type, as well as how long and what type of payload is being measured.

Figure 5. Demodulation waveform view of Bluetooth LE 1M signal
Figure 5 is the demodulation waveform view. When the input signal is Bluetooth basic or low energy, the modulation is GFSK, and the demodulation waveform shows the demodulated signal as a frequency vs time trace.

If the input signal is Bluetooth EDR, the modulation is DQPSK/D8PSK and the analyzer will show a constellation view.

The N9081C can also display results summary table (Figure 6) that includes the test items, maximum, minimum, and average measurements results, as well as test limits. All measurement results in the summary table can be programmatically extracted or exported using the front panel on the analyzer for post-processing.
The most frequently-used measurement display is the quad-view, which provides a combination view of RF spectrum, RF envelope, demodulation waveform, and results summary table.

Figure 7. Quad-view display of Bluetooth 5 PHY (LE 1M) using N9081C Bluetooth measurement application running in the Keysight N9000B CXA Signal Analyzer.
**Bluetooth LE in-band emission test**

The in-band emissions test is another frequently tested item for Bluetooth LE. It verifies that the level of unwanted signals from the transmitter does not exceed the specified limits. This test is performed for both EDR and LE transmitters. For EDR transmitters, there should be no emissions exceeding 26 dB below the maximum transmitted power beyond 500 kHz away from the carrier.

![Bluetooth LE in-band emission test](image)

For Bluetooth LE transmitters, as shown on the screen in Figure 8, there should be no emission greater than -20 dBm at a frequency offset of 2 MHz and no emission greater than -30 dBm at a frequency offset of 3 MHz. You can see that this particular signal is well within the limit lines and passes the in-band test.

To perform Low Energy In-Band Spurious Emission tests, the DUT transmits LE test packets with maximum payload size and PRBS9 as the payload. The tester acquires the signal from the DUT using a 1-MHz frequency span, an RBW of 100 kHz, and a VBW of 300 kHz. The acquisition center frequency is set to 2.401 GHz + N MHz, with N initially set to zero. As the test progresses, N is incremented by 1 MHz until the whole regulatory range is covered.
**Bluetooth 5 LE coded for long range**

In Bluetooth 5, LE Coded scheme is added to quadruple the transmission range while maintaining low power consumption. With this added feature, Bluetooth is no longer just a protocol for personal area networks. It can also provide the good indoor and outdoor coverage needed for IoT applications.

In the coded scheme, two lower data rates are supported with $S = 8$ (125 kbps) and $S = 2$ (500 kbps). This coded scheme improves the link budget by 12 dB using Forward Error Correction (FEC) without increasing the output power and therefore achieving up to 4x range improvement. These lower data rates are sufficient for most IoT applications.

![Figure 9. Transmitter measurements of Bluetooth LE coded scheme](image)

The Keysight N9081C enables the analysis and demodulation of any of the Bluetooth 5 physical layers. Figure 9 shows the quad-view display of Bluetooth LE Coded scheme.
**Bluetooth LE Receiver Measurements**

For receiver tests, typical measurements include bit-error-rate (BER), block-error-rate (BLER), packet-error-rate (PER), and frame error rate (FER). These are required for the performance verification and functional test of the receivers during RF/baseband integration and system verification. The Keysight N7606B Signal Studio for Bluetooth signal creation enables you to create fully channel-coded signals for Bluetooth 5, such as signals with 2 MSa/s symbol rate for higher data rate and channel coding of S = 2 or 8 for Bluetooth long range. The software enables users to generate the three different PHYs of Bluetooth 5.

![Image of Keysight Signal Studio for Bluetooth](image)

Figure 10. Keysight Signal Studio for Bluetooth enables user to generate Bluetooth Basic Rate, Enhanced Rate, and Low Energy RF signals.
This software can generate signals for dirty transmitter measurements. By default, dirty transmitter is off. The dirty transmitter specification table is defined by Bluetooth SIG. You can see the frequency offset, modulation index, and symbol timing error as defined in the Bluetooth specifications.
Figure 12. Dirty transmitter setup using N7606B
Summary

The Bluetooth tests involve step-by-step manual setup of multiple parameters to generate waveforms with specific payloads, and often involve multiple iterations in the measurement process. One way to save time is to use test equipment with one-button, standard-compliant measurement software that provide pass-fail metrics per the standard, such as the Bluetooth embedded application offered on Keysight signal analyzers. In this case, the steps are performed automatically and measurement readings are compared with the standard specifications. Measurement results are displayed with minimal setup and external processing, saving significant time and effort.

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