APPLICATION NOTE

Bluetooth® 5 Technology Fundamentals and Critical Test Parameters

Insights for a Successful Deployment

Bluetooth® 5

2x speed 2 Mbps	4x range 300 meters	8x broadcasting data 255 bytes	Improved coexistence

KEYSIGHT TECHNOLOGIES

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Bluetooth® Standard Evolutions

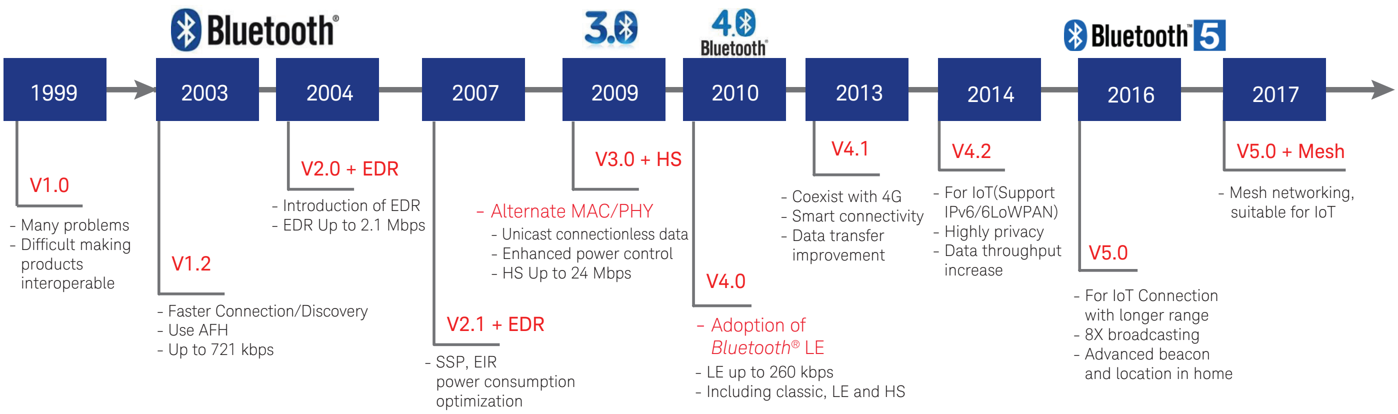

Figure 1. *Bluetooth*® standard evolutions

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 (LE) 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, better security, and a 10x packet capacity increase for improved throughput.

Bluetooth® 5 was announced in 2016, and it included several 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.

Various *Bluetooth*® versions have been around for many years, and it continues to evolve and grow.

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.

Mesh networking: In July 2017, the *Bluetooth*® SIG released an independent extension of the *Bluetooth*® Core Specification called *Bluetooth*® Mesh. Put together with other enhancements, adding mesh networking to *Bluetooth*® 5 capabilities makes it a potential for industrial IoT applications. With mesh networking, all the devices in the network can communicate with each other, as opposed to a star-type topology, where devices need to be connected to the central hub. This makes the size and area of mesh network virtually unlimited, like a large connected sensor network.

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, smart city sensors, and industrial applications.

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.

PHY	Modulation Scheme	Coding Scheme		Data Rate
		Access Header	Payload	
LE 1M	1 M Symbols / s	Uncoded	Uncoded	1 Mbps
LE 2M	2 M Symbols / s	Uncoded	Uncoded	2 Mbps
LE Coded	1 M Symbols / s	S = 8	S = 8 S = 2	125 kbps 500 kbps

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. The following two tables show the 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)

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

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.

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Receiver tests (TP/RCV-LE/CA/BV-xx-C)

Test	Verifies	LE 1M	LE 2M	LE 1M, SMI	LE 2M, SMI	LE coded S=2	LE Code S=8	LE coded S=2, SMI	LE coded S=8, SMI
Receiver sensitivity	Receiver sensitivity is within limits for non-ideal signals at normal operating condition	01	08	14	20	26	27	32	33
C/I and Receiver Selectivity Performance	Receiver's performance in presence of co-/adjacent channel interference, and mirror image rejection performance	03	09	15	21	28	29	34	35
Blocking Performance	Receiver performs satisfactorily in the presence of interference sources operating outside the 2400 – 2483.5 MHz band	04	10	16	22				
Intermodulation Performance	Receiver intermodulation performance is satisfactory	05	11	17	23				
Maximum input signal level	Receiver can demodulate a wanted signal at high signal input levels	06	12	18	24				
PER Report Integrity	The DUT PER report mechanism reports the correct number of received packets to the tester	07	13	19	25	30	31	36	37

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.

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Key changes for *Bluetooth*® LE Devices RF Testing

Predefined test mode	- *Bluetooth*® SIG made non-link test mode mandatory. - Non-link based test verifies the functionality of the device hardware only
Simplified and optimized test cases	- *Bluetooth*® SIG defined non-ideal packet (dirty packet) with frequency drift for receiver sensitivity test. - *Bluetooth*® SIG added a PER test (as opposed to Classic BER test).
Predefined test packets	- For the first time with *Bluetooth*® LE, *Bluetooth*® SIG fully defines test packets in the Test Specification Document. - Depending on the test, the packet payload content may vary.

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.

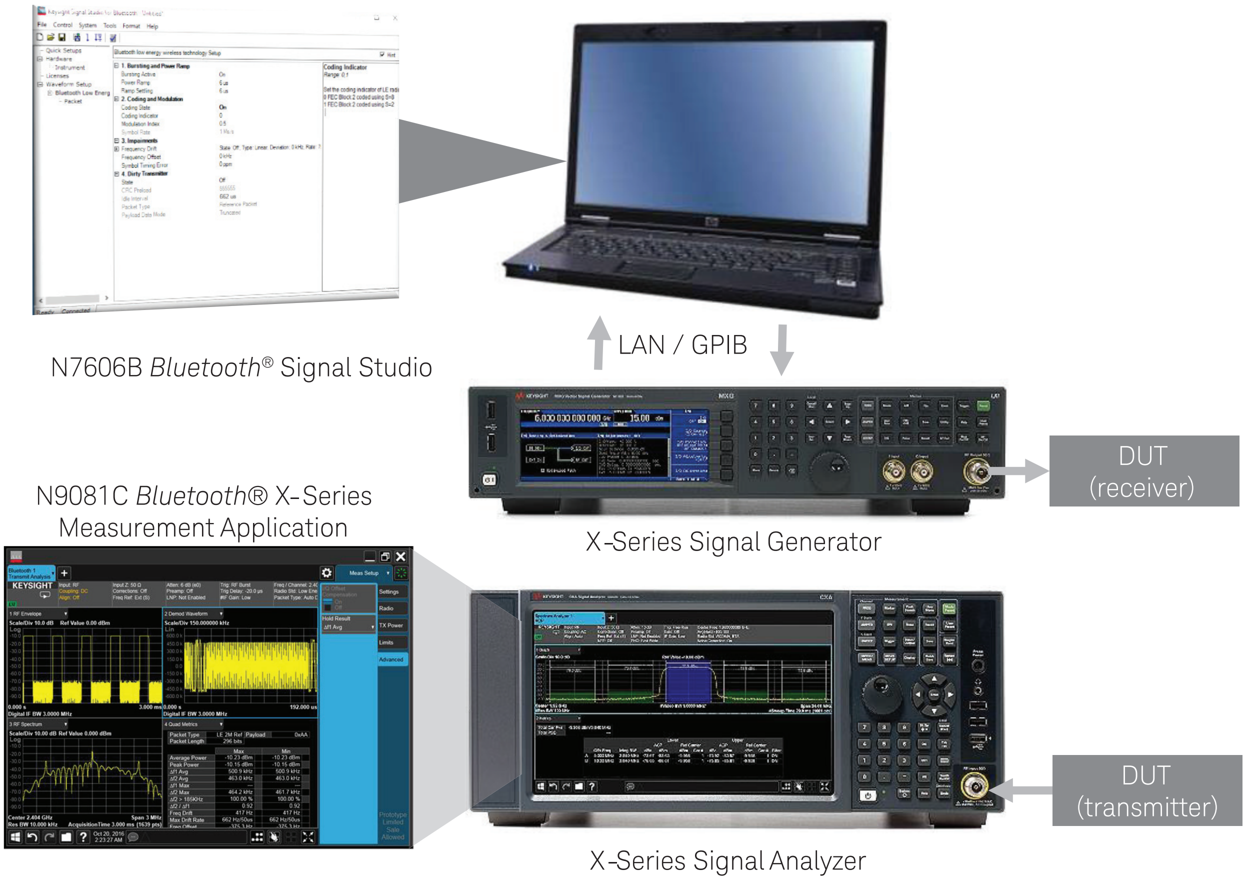

Figure 2. Keysight *Bluetooth*® signal generation and signal analysis solutions

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

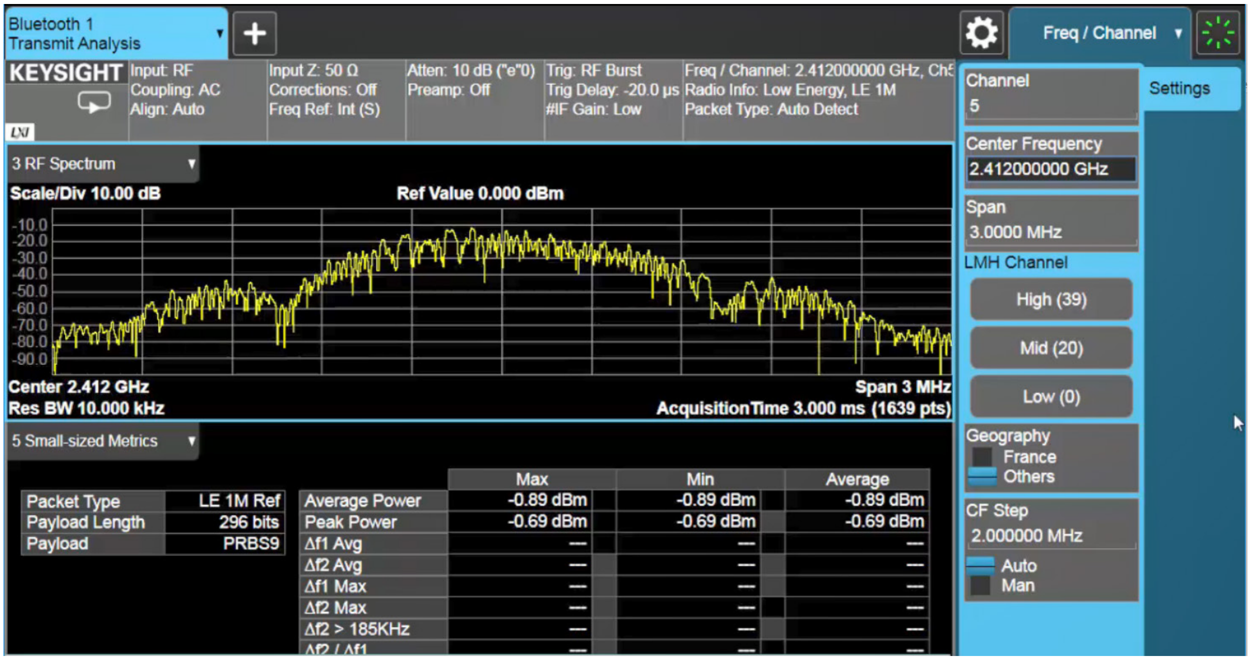

Figure 3. Transmitter measurement of *Bluetooth*® 5 PHY LE 1M using a Keysight CXA signal analyzer and N9081C *Bluetooth*® measurement application

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.

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Figure 4. RF envelope view of *Bluetooth*® LE 1M signal

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.

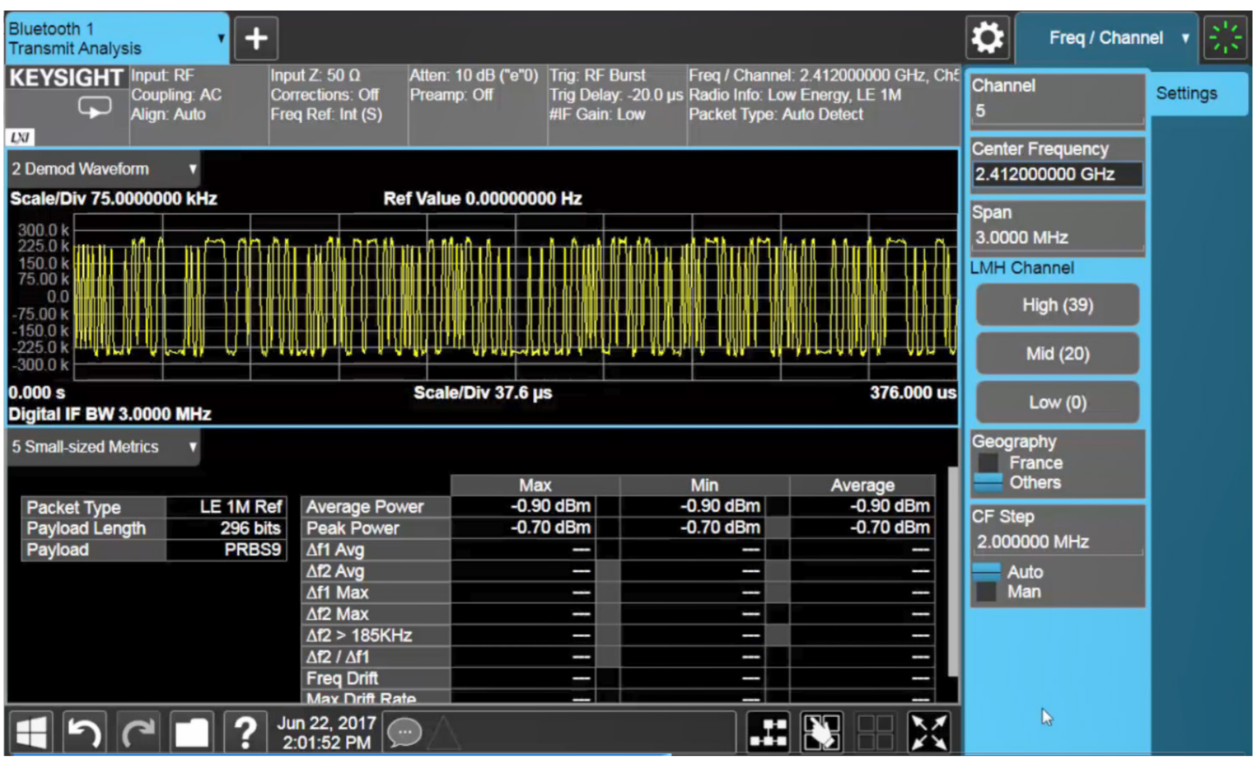

Figure 5. Demodulation waveform view of *Bluetooth*® LE 1M signal

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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.

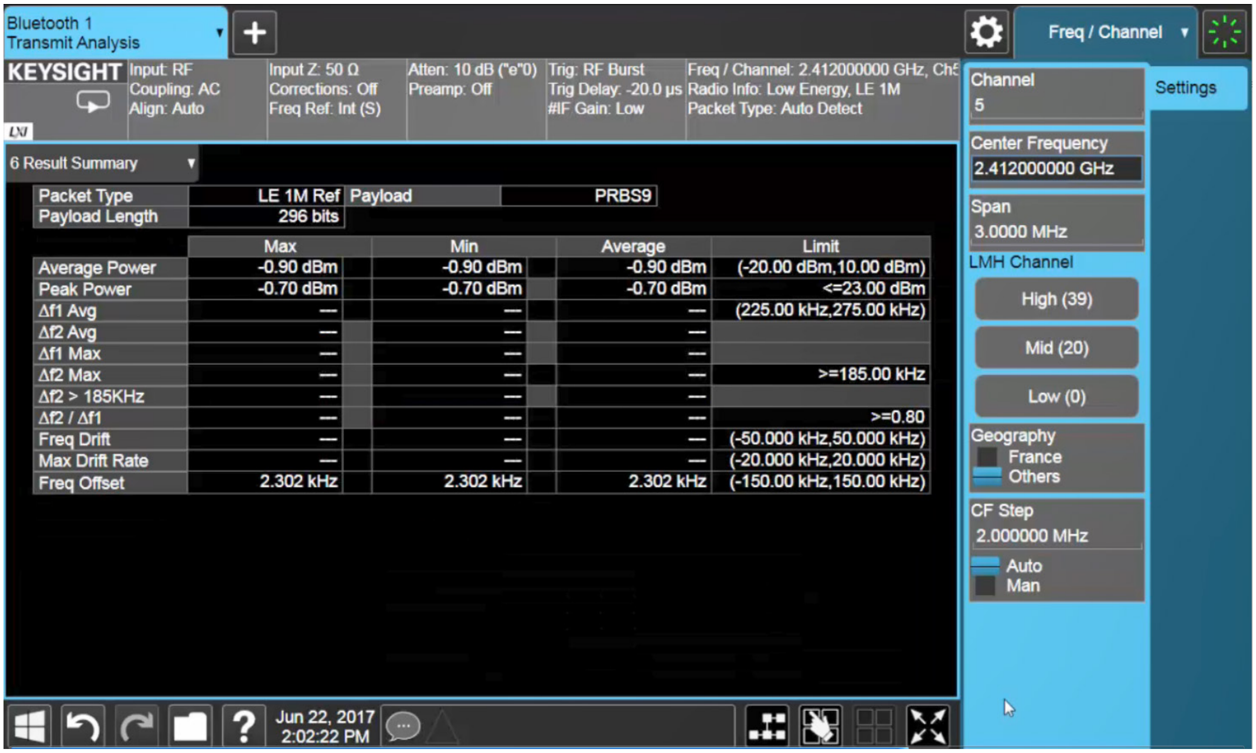

Figure 6. Results summary table of Keysight N9081C *Bluetooth*® measurement application

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.

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

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.

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.

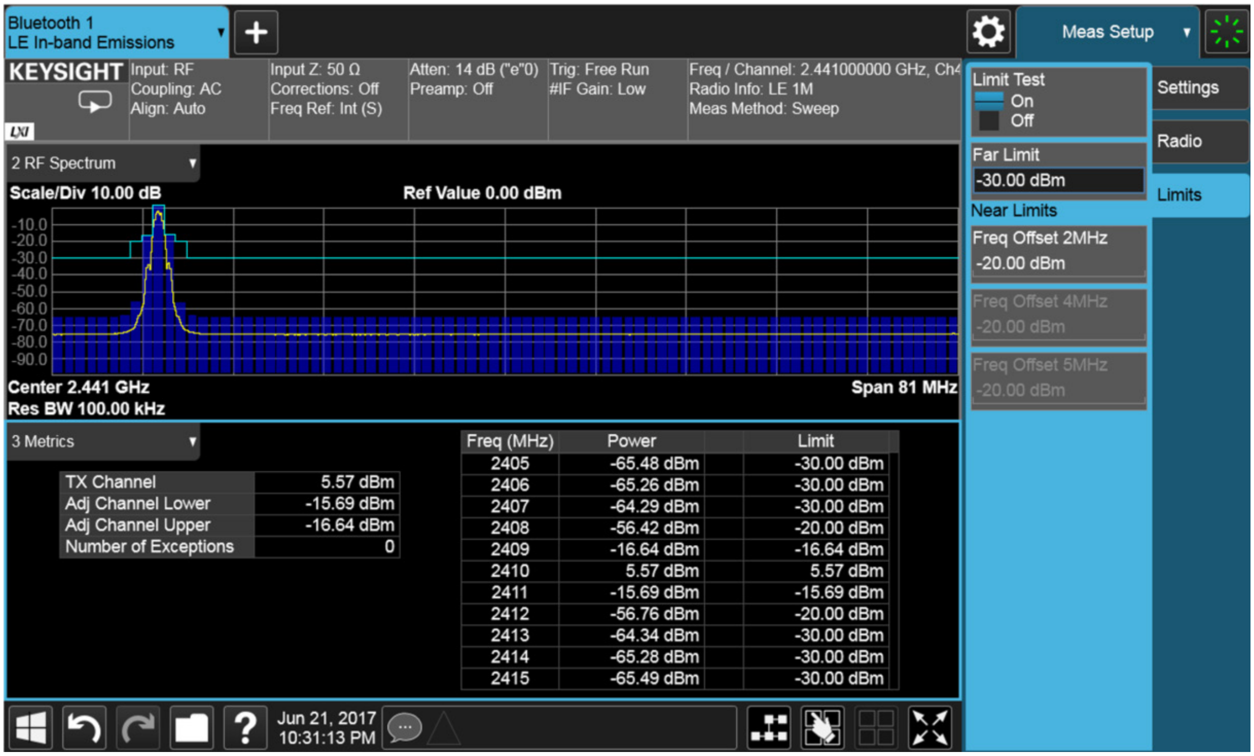

Figure 8. *Bluetooth*® LE in-band emission test

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.

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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.

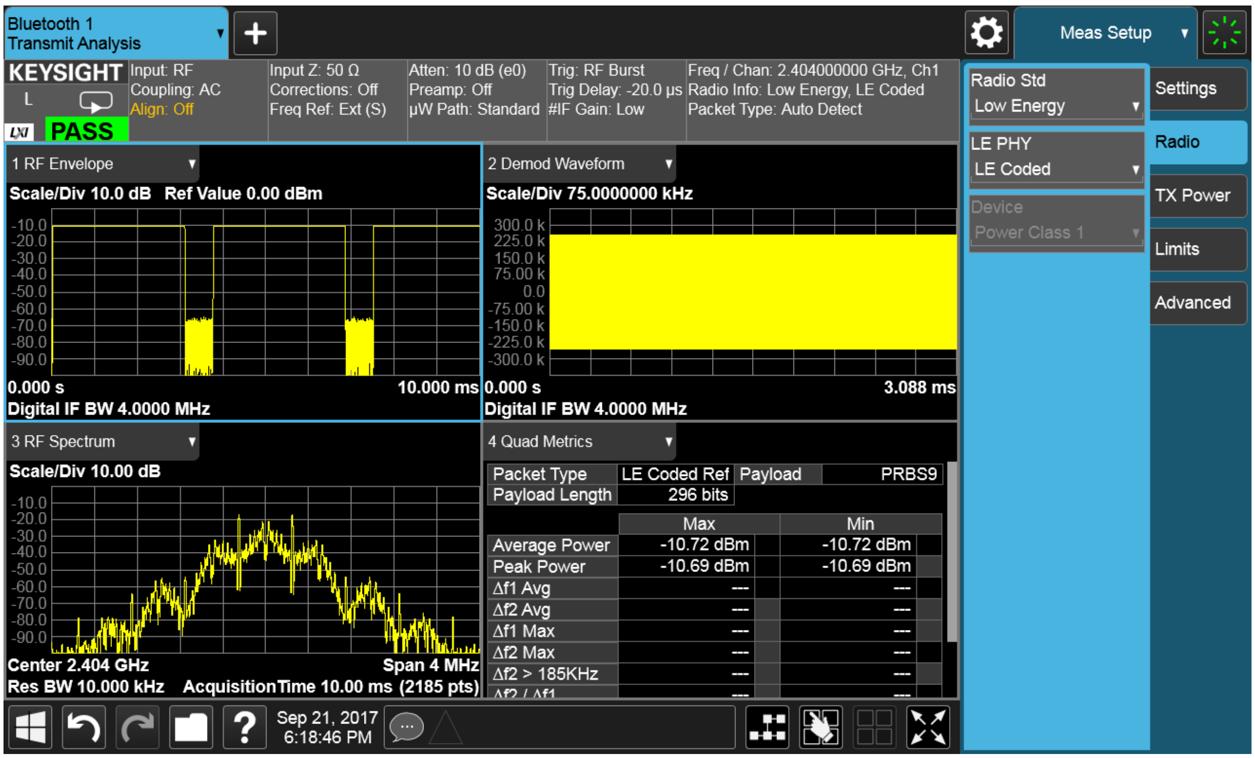

Figure 9. Transmitter measurements of *Bluetooth*® LE coded scheme

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.

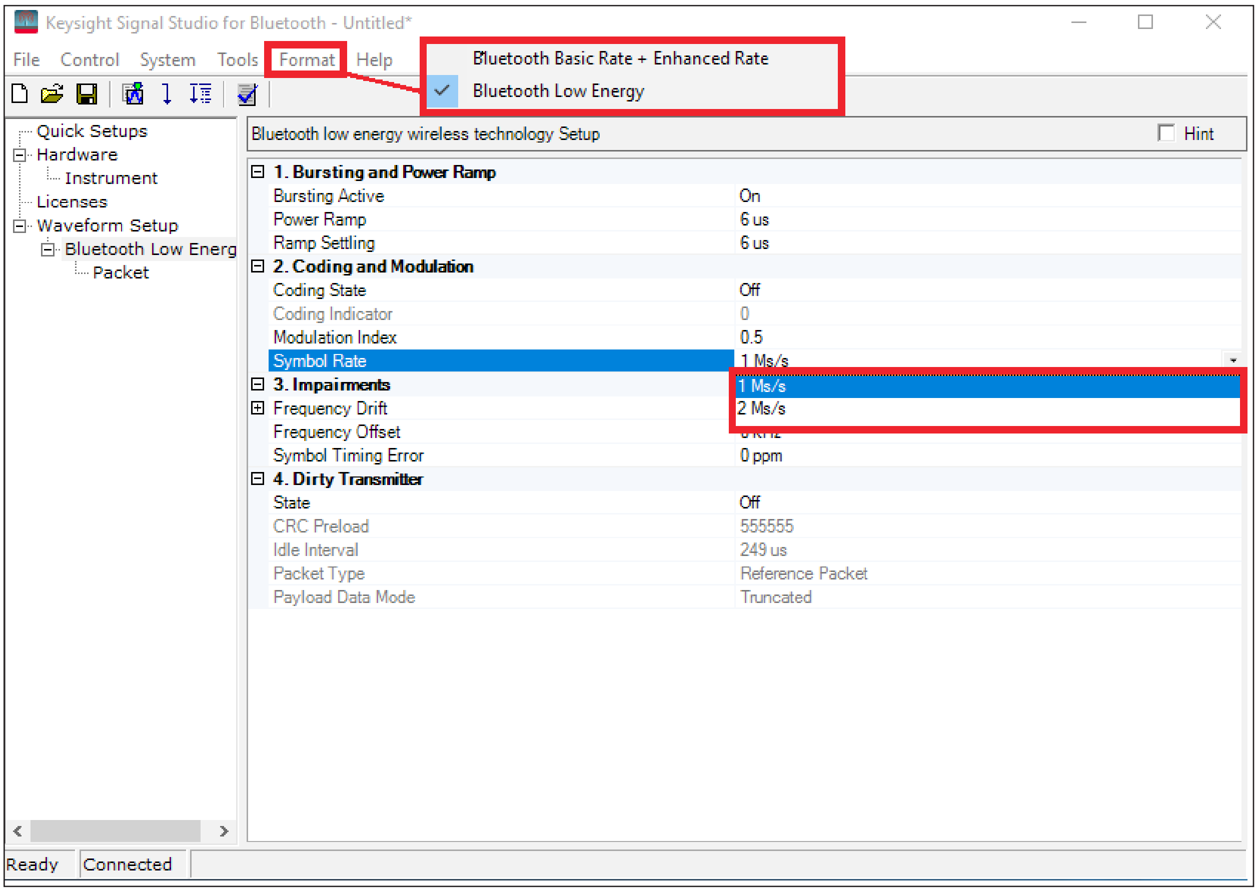

Figure 10. Keysight Signal Studio for *Bluetooth*® enables user to generate *Bluetooth*® Basic Rate, Enhanced Rate, and Low Energy RF signals.

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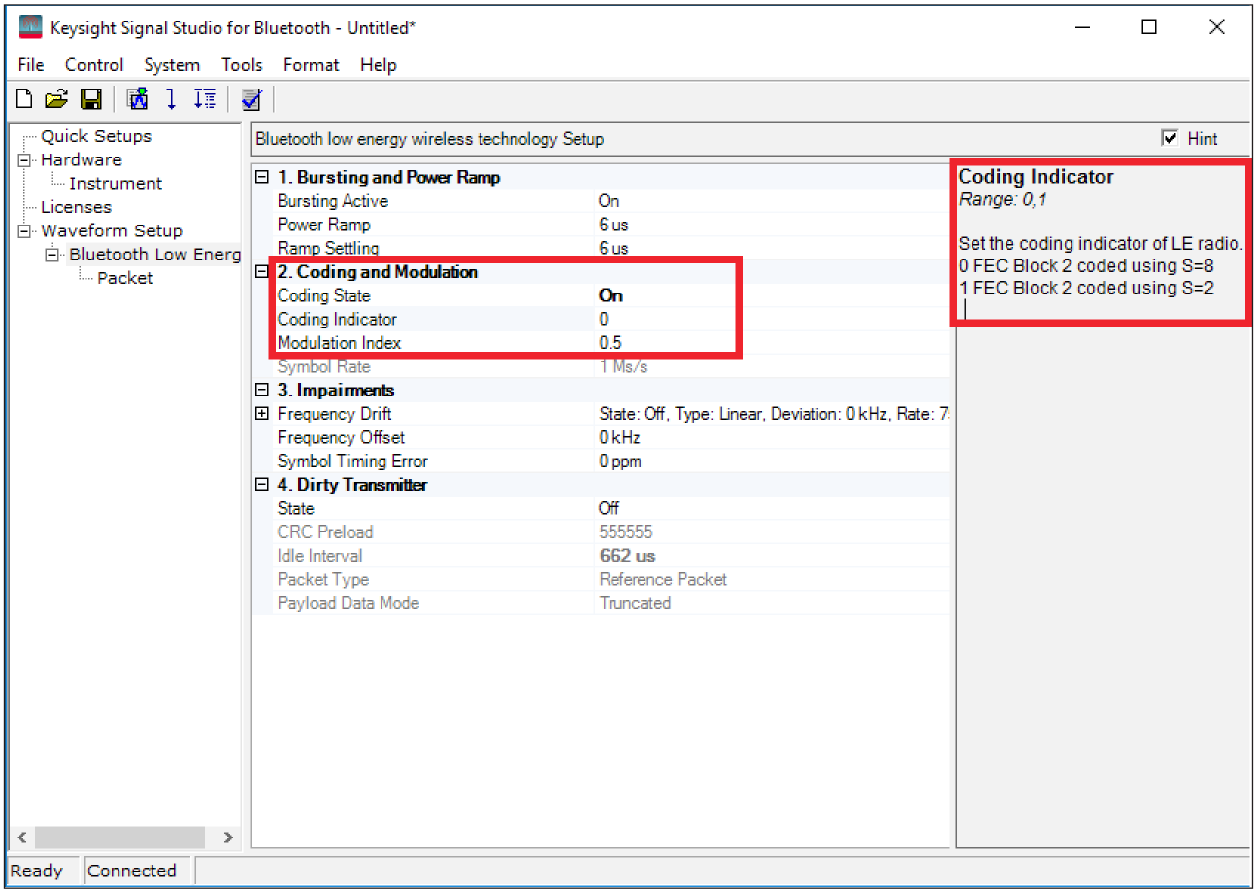

Figure 11. *Bluetooth*® LE Coding Scheme setup using N7606B

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.

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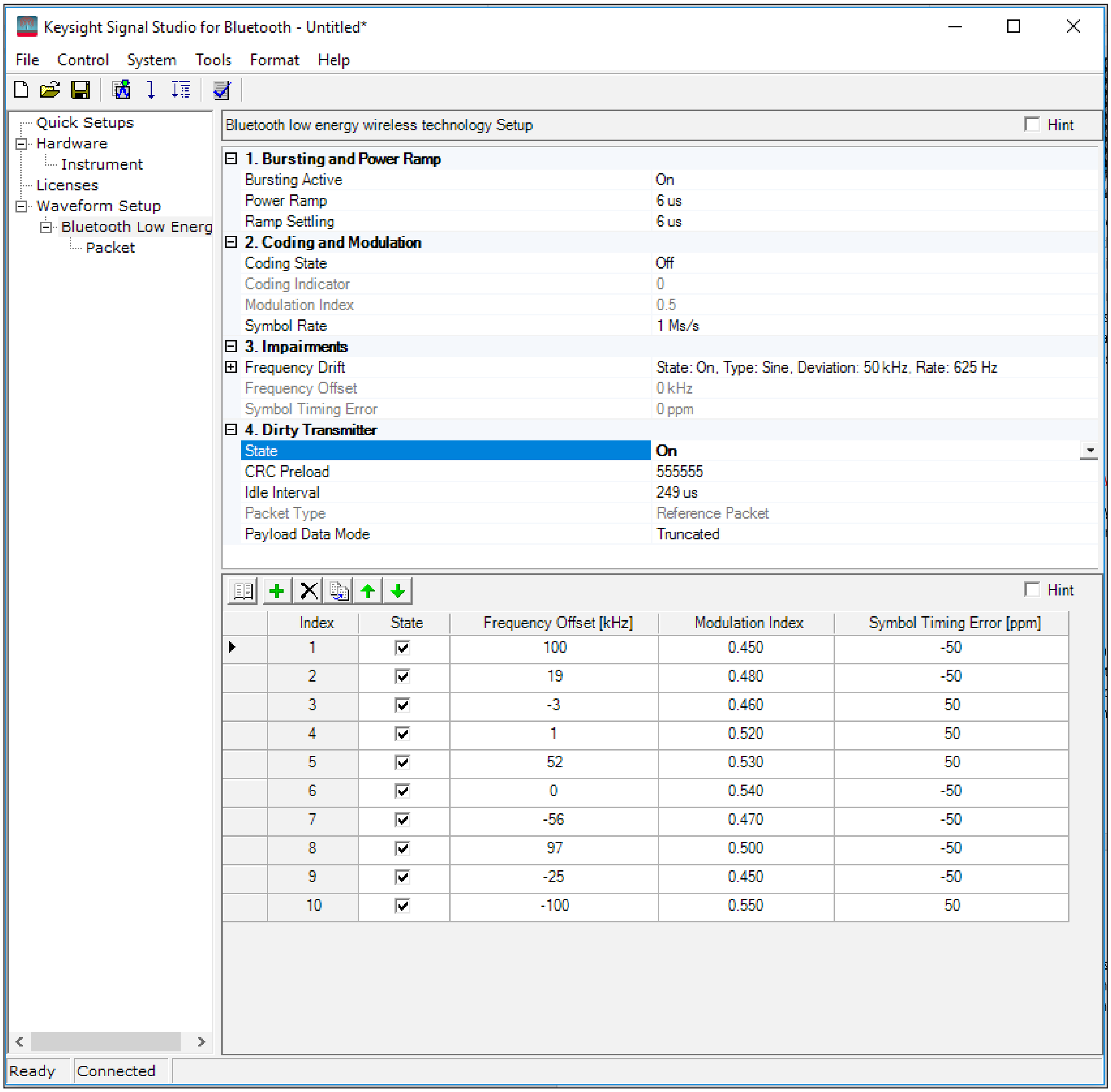

Figure 12. Dirty transmitter setup using N7606B

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Bluetooth® LE and *Bluetooth*® 5 Signaling Functional Test

Alternatively, to perform functional test on *Bluetooth*® LE devices, the X8711A IoT device functional test solution (shown in Figure 13) is a cost-effective, over-the-air signaling test solution that allows users to test IoT devices in actual operation mode.

With this solution, you can:

- Complete transmit (Tx) power and receiver (Rx) Packet Error Rate (PER) test in seconds.
- Perform the transmit (Tx) power measurement in normal operation mode.
- Perform the PER test via the bi-directional interrogation method of the device under test (DUT).
- Perform sensitivity test using PER as an indicator and adjusting the downlink power (from the X8711A to the DUT) power while maintaining good signaling conditions to the X8711A's receiver. This ensures that packet errors are generated by the DUT and not the X8711A.
- Easily perform *Bluetooth* LE® 4.2 and *Bluetooth*® 5 signaling power measurements with the Keysight measurement suites software, as shown in Figures 14-15. The software includes essential test steps for functional testing.

Figure 13. X8711A IoT device functional test solution

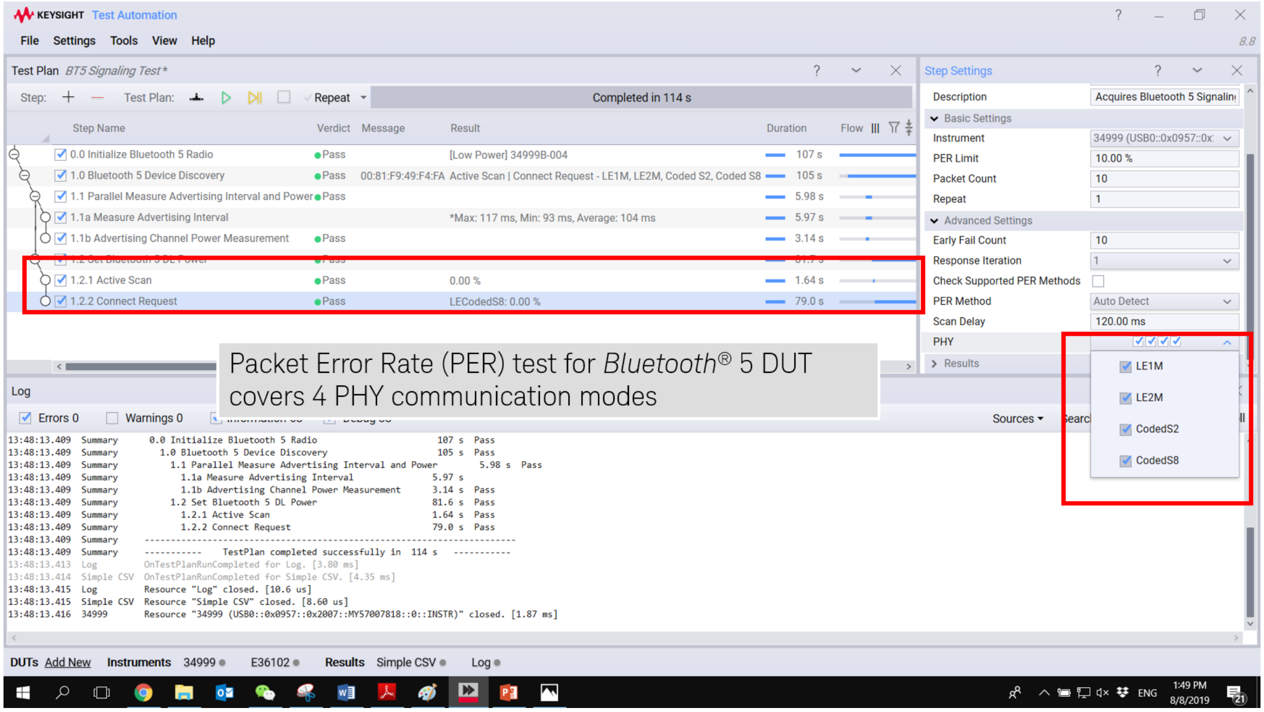

Figure 14. PER measurement using the X8711A *Bluetooth*® 5 Signaling Measurement Suite

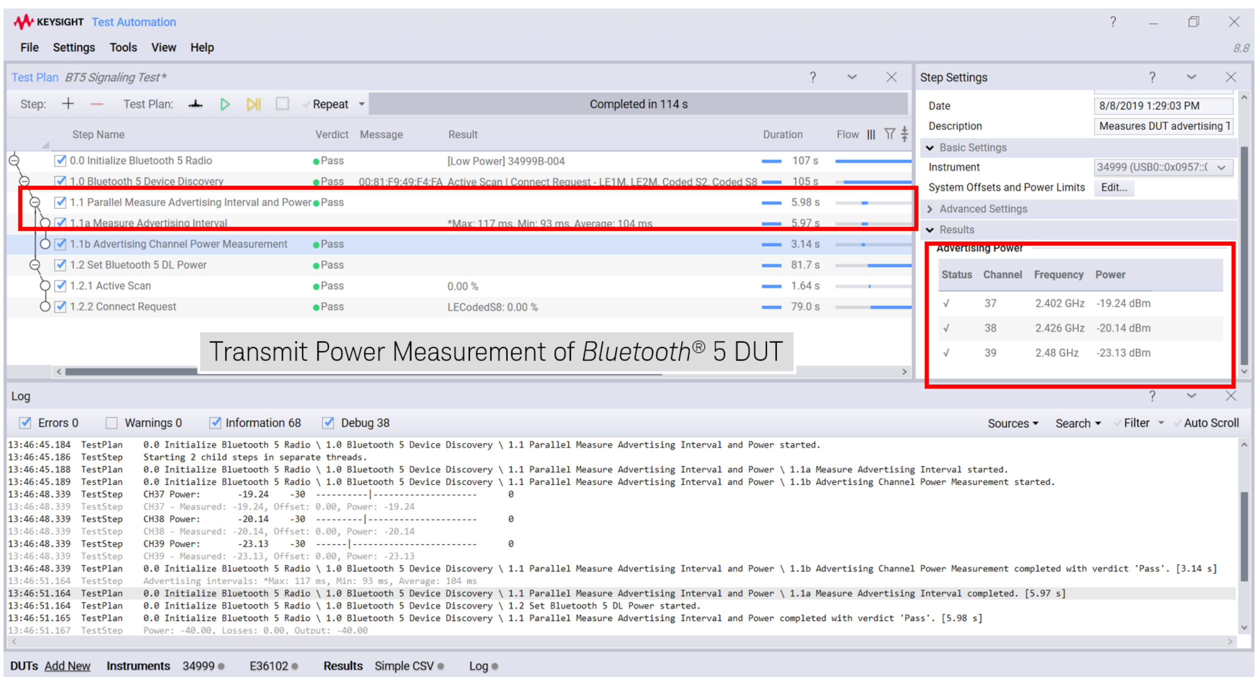

Figure 15. Transmit power measurement using the X8711A *Bluetooth*® 5 Signaling Measurement Suite

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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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