MKW40Z PHY Test Using Direct Test Mode

1. Introduction

This document describes the Bluetooth® Low-Energy (BLE) PHY tests using the Direct Test Mode (DTM) on MKW40Z. MKW40Z supports the DTM through the UART interface. The setup uses an external PHY tester with BLE PHY test capability to perform the tests.

Contents

2. Direct Test Mode (DTM)

Use the DTM to control the BLE DUT and to provide a report back to the tester. MKW40Z supports these DTM test commands with a specific DTM software driver:

Table 1. DTM test commands and events

RF test command/event	HCI command/event	2-wire UART command/event
LE_TRANSMITTER_TEST	LE Transmitter Test command	LE Transmitter Test
LE_RECEIVER_TEST	LE Receiver Test command	LE Receiver Test
LE_TEST_END	LE Test End command	LE Test End
LE_STATUS	Command Complete event	LE Test Status
LE_PACKET_REPORT	Command Complete event	LE Packet Report

For more information about the DTM, see *Bluetooth Core Specification 4.1, Vol 6, Part F: Direct Test Mode*.

3. Test Setup

3.1. Hardware setup

Requirements:

- PC
- R & S® CBT Bluetooth tester
- FRDM-KW40Z board
- RS232 cable
- RS232 to TTL converter
- 3-wire connectors
- RF cable

Figure 1 shows the hardware setup of the PHY testing using the KW40Z DTM. The R & S CBT Bluetooth Tester (referred to as CBT) is used. A level shifter is required to interface between the CBT RS-232 and the MKW40Z UART, and to properly translate the voltage levels. The Linear Technology LTC2804 RS-232 transceivers are used. The RF port of the KW40Z is connected to the CBT RF port using the RF cable for PHY testing.
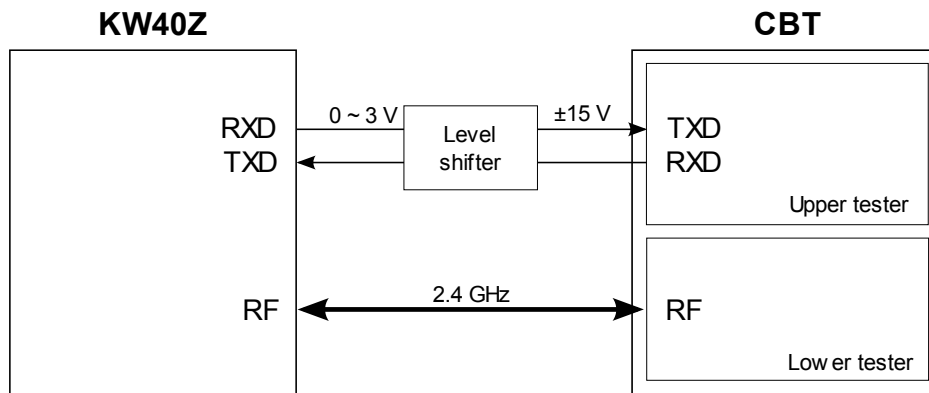
Figure 1. Hardware setup diagram

Configure the FRDM board to use the SMA connector by populating the capacitor C40 and depopulating the capacitor C34.

Connect one end of the RF cable to the SMA connector on the KW40Z and the other end to the SMA connector located on the front panel of the CBT.

Connect the 3-wire level-shifter connectors to the UART RX, TX, and GND pins on the KW40Z, respectively. The corresponding pins for the UART RX, TX, and GND on the KW40Z board are highlighted in the following figure. Depending on the hardware configuration of the level shifter used, the UART connection between the KW40Z and the level shifter is straight or crossed over.

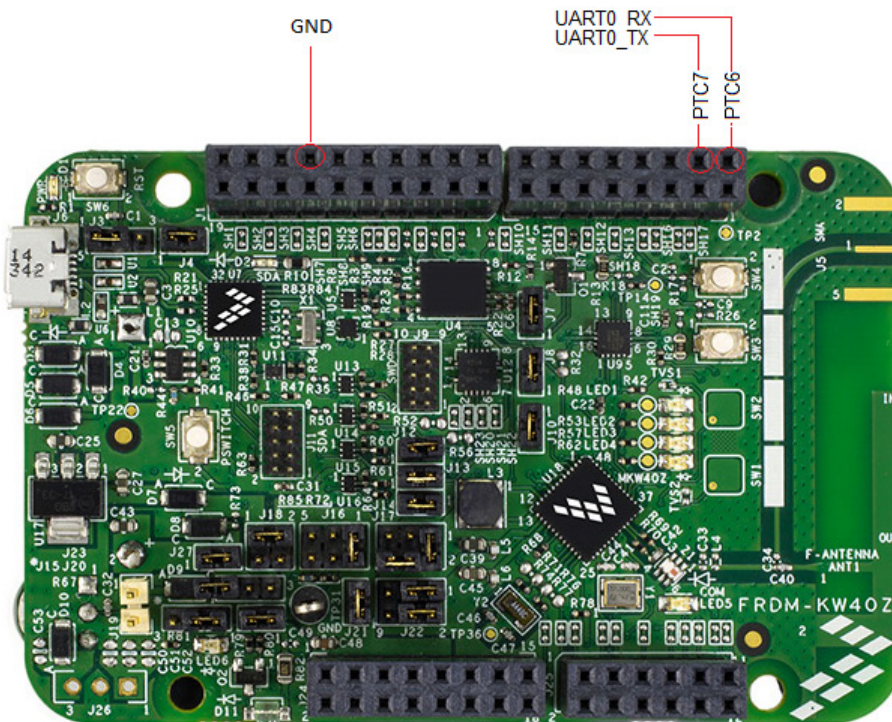Connect the CBT to the level shifter using the RS232 cable.

Figure 2. KW40Z UART0 and GND pins

3.2. Software setup

A sample embedded code is provided to properly set up the KW40Z in the DTM mode with the UART module enabled. In the code, UART0 is routed to PTC6 and PTC7. IAR Embedded Workbench® IDE is required to build the embedded application. See the release notes contained in the Kinetis KW40Z Connectivity Software package for the required IAR IDE version (*/ConnSw/BLE_Release_Notes.pdf*).

3.2.1. Setup procedure

- Download and install Kinetis KW40Z Connectivity Software from www.nxp.com/frdm-kw40z.
- Navigate to the "Downloads" tab and scroll down to "Protocol Stacks" to find the installer link "Kinetis KW40Z Connectivity Software" (REV 1.0.1 at the time this document was released).
- Click on the link and download the installer software (*KW40Z_Connectivity_Software.exe*), as shown in the following figure.
- Run the installer.

Figure 3. KW40Z Connectivity Software link

3.2.1.1. Compile and program the board

- Navigate to *../ConnSw/examples/Bluetooth/hci_app/frdmkw40z/bare_metal/build/iar* and open the workspace file *hci_app.eww*.
- Navigate to *../ConnSw/boards/frdmkw40z* and open the *board.h* file. Check that the BOARD_UART_CONFIG macro is defined as BOARD_USE_DEBUG_UART:
  ```
  #ifndef BOARD_UART_CONFIG
  #define BOARD_UART_CONFIG BOARD_USE_DEBUG_UART
  #endif
  ```
- Compile and program the board.

4. PHY Tests

Perform the following tests using the hardware and software setup described in the previous sections.

4.1. RX PER test

The PER (Packet Error Rate) test measures the BLE receiver quality.

4.1.1. Introduction

The PER tests are based on counting the number of packets received by the DUT out of a series of consecutive LE test packets transmitted by the tester. The test is performed with the frequency hopping disabled.

The PER is defined as:

$$PER = \left(1 - \frac{N_{recv}}{N_{trans}}\right) \cdot 100\%$$
$$N_{recv} = Number\ of\ packets\ received\ by\ the\ EUT\ passing\ CRC$$
$$N_{trans} = Total\ number\ of\ packets\ transmitted\ by\ the\ tester$$

Eqn. 1

4.1.2. Setup

- On the CBT, press the "MENU SELECT" button in the top row.
- Select "Bluetooth LE"—"Receiver Quality," and press the "ENTER" button.
- On the CBT, please select "Connect. Control" in the upper right corner (Figure 5). A new window appears. In this window, you can enable the test mode and modify various parameters to suit various test configurations. Make sure the "Connection" tab is selected (in the bottom left corner of the display).
- Select "Enable Test Mode" if it is not enabled already (Figure 4). The CBT returns to the previous screen.
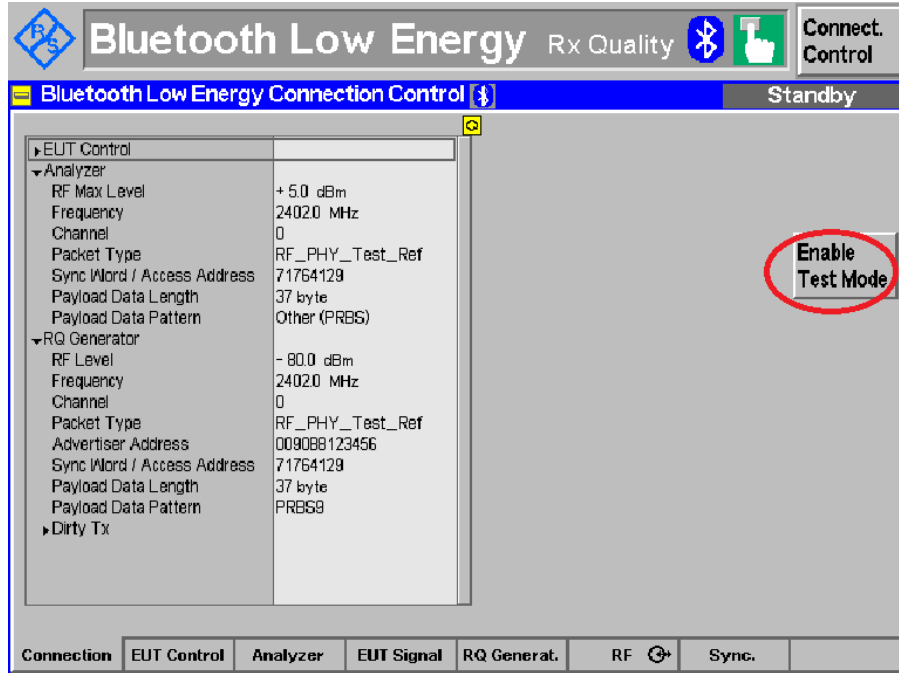- Select "PER" to start the PER test (Figure 5).

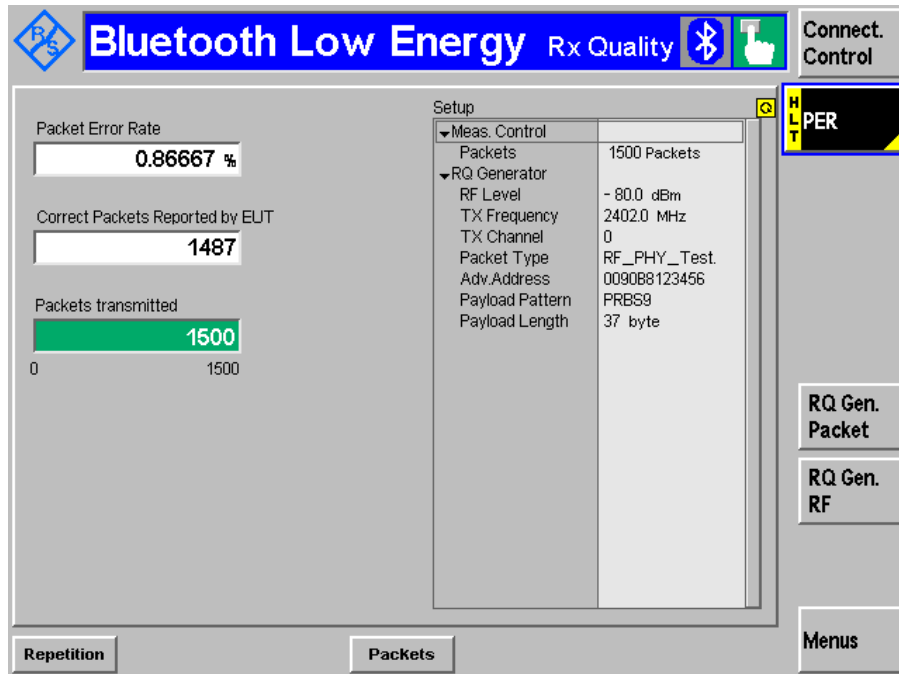**Figure 4. "Connect. Control" menu—test mode disabled**

Figure 5. "Receiver Quality" window—starting the PER test

4.1.3. Interpreting results and expected outcome

All measured values must fulfill these conditions:

- The PER must be higher than 30.8 % for a minimum of 1500 packets transmitted by the tester if the DUT's MAX_RX_LENGTH is 37 bytes.
- The PER must be higher than the value calculated according to the formula specified in Eqn. 1 for a minimum of 1500 packets transmitted by the tester if the DUT's MAX_RX_LENGTH is greater than 37 bytes.

The PER may vary significantly according to the RF level (especially for lower dBm values for the RF level).

4.1.4. Changing parameter values

To change the number of packets, follow these steps:

- Select the "PER" tab (if it is not selected already).
- Select "Packets" in the bottom middle part of the window.
- Enter the desired number of packets using the numerical keyboard on the "DATA" panel or the control wheel on the "VARIATION" panel of the CBT.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner near the display).

To change the RF level, payload data length/pattern, TX channel/frequency, and packet type, follow these steps:

- Enter the "Bluetooth Low Energy Connection Control" section (if not done already) by selecting "Connect. Control".
- Select the "RQ Generat." tab.
- Modify the desired field by selecting it and using the numerical keyboard on the "DATA" panel or the control wheel on the "VARIATION" panel of the CBT.
- Press the "ENTER" button and then the "Escape" button each time you modify a field.

4.2. TX output power test

4.2.1. Introduction

The TX output power test measures the output power of the BLE transmitter.

4.2.2. Setup

- On the CBT, press the "MENU SELECT" button in the top row.
- Select "Bluetooth LE"—"Power" and press the "ENTER" button.
- On the CBT, select "Connect. Control" in the upper right corner (Figure 1). A new window appears. In this window, you can enable the test mode and modify various parameters to suit various test configurations. Make sure the "Connection" tab is selected (it is located in the bottom left corner of the display).
- Select "Enable Test Mode" if it is not enabled already (Figure 4).
- Select "Power" and then press the "ON/OFF" button to start and stop the TX power test.
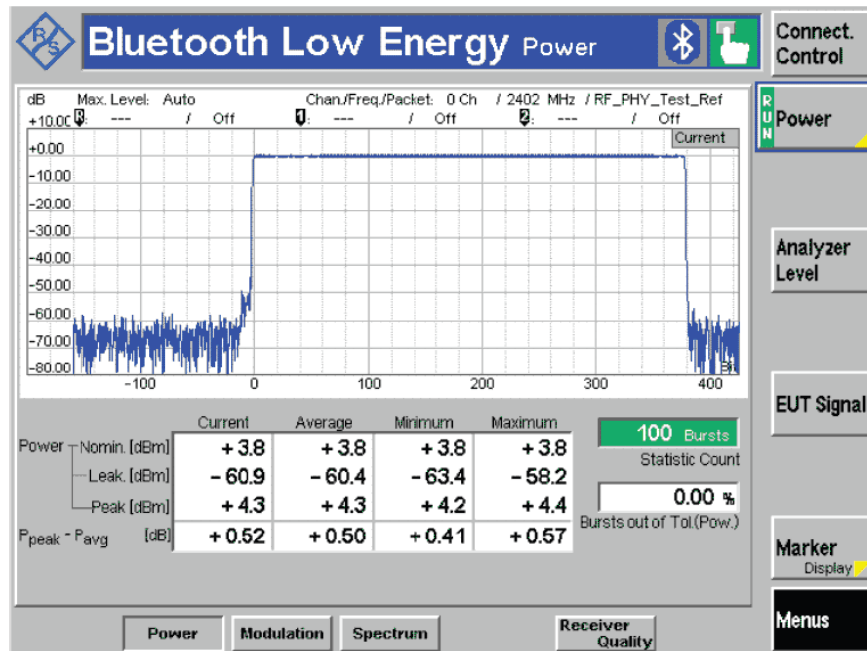

Figure 6. Starting the TX output power test

4.2.3. Interpreting results and expected outcome

All measured values must fulfill these conditions:

$$-20\ dBm \leq P_{avg} \leq +10\ dBm$$
$$P_{peak} - P_{avg} \leq +3 dBm$$

NOTE

The P$_{avg}$ values are found in the "Power – Nomin.[dBm]" row in Figure 6.
The P$_{peak}$ values are found in the "Power – P$_{peak}$ [dBm]" row in Figure 6.

4.2.4. Changing parameter values

To change the statistic count, follow these steps (this option determines the number of samples used):

- Make sure the "Power" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Statistic Count".
- Enter the desired statistics count using the numerical keyboard on the "DATA" panel or using the control wheel on the "VARIATION" panel of the CBT.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner near the display).

To change the display mode, follow these steps (use this option to view the graph according to the current value or the minimum, average, or maximum value over a certain time frame):

- Make sure the "Power" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Display Mode".
- Select the desired display mode using the control wheel on the "VARIATION" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner near the display).

To change the RF level, payload data length/pattern, TX channel/frequency, and packet type, follow these steps:

- Enter the "Bluetooth Low Energy Connection Control" section (if not already there) by selecting "Connect. Control".
- Select the "RQ Generat." tab.
- Modify the desired fields by selecting them and using the numerical keyboard on the "DATA" panel or the control wheel on the "VARIATION" panel of the CBT.
- Press "Enter" and then "Escape" each time you modify a field.

4.3. TX modulation test

4.3.1. Introduction

The TX modulation test measures the BLE transmitter signal quality.

4.3.2. Setup

- On the CBT, press the "MENU SELECT" button in the top row.
- Select "Bluetooth LE"—"Modulation", and press the "ENTER" button.
- On the CBT, select "Connect. Control" in the upper right corner (Figure 6). A new window appears. In this window, you can enable the test mode and modify various parameters to suit various test configurations. Make sure the "Connection" tab is selected (it is located in the bottom left corner on the display).
- Select "Enable Test Mode" if it is not enabled already (Figure 4).
- Select "Modulation", and press the "ON/OFF" button to start the TX modulation test.
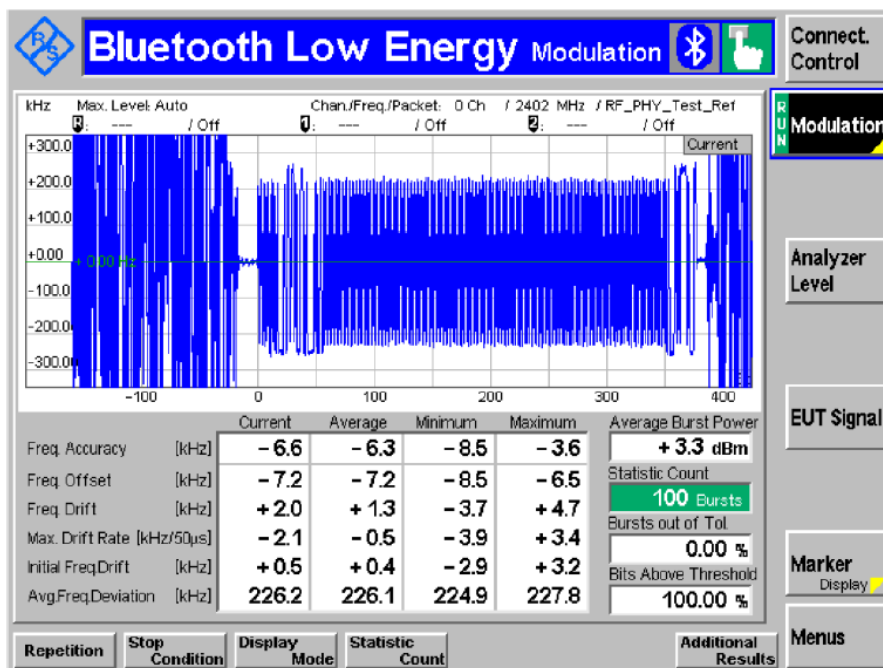

Figure 7. Starting the TX modulation test—mandatory results view
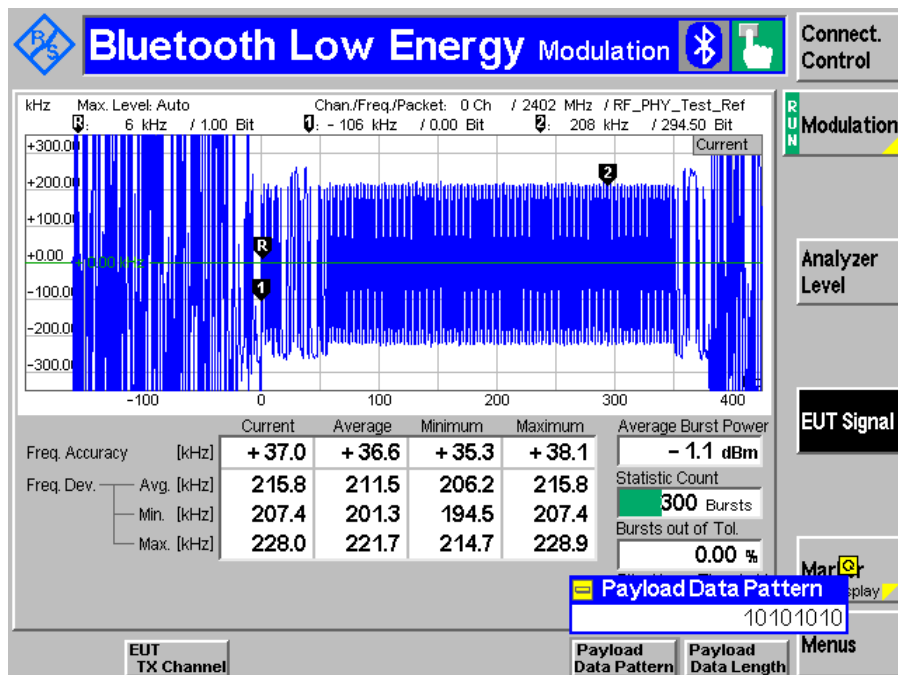
4.3.3. Interpreting results and expected outcome

Figure 8. Frequency deviation and accuracy characteristics for payload data pattern 10101010— additional results view
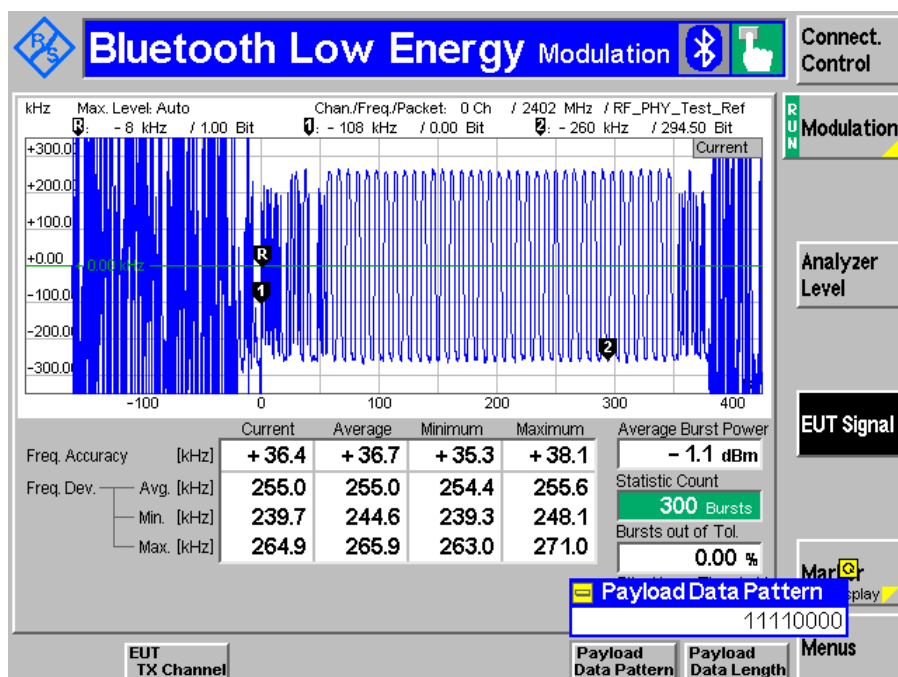

Figure 9. Frequency deviation and accuracy characteristics for payload data pattern 11110000— additional results view

4.3.3.1. Frequency deviation

According to the R & S CBT operation manual, the frequency deviation is first calculated over the whole packet payload without the border bits. Each bit is oversampled four times. This yields the measurement curve in the graphical display. To obtain the scalar results *Freq. Dev. Avg. /Max. /Min.*, the whole payload is divided into adjacent segments with a length of eight bits and the average frequency *favg* on each of these segments is calculated. The next steps depend on the payload pattern type:

- For the 10101010 pattern, the maximum frequency deviation from *favg* is calculated for each *i* bit within the segment.
- For the 11110000 pattern, the average frequency deviation from *favg* is calculated for bits 2, 3, 6, and 7 of the segment.

All measured values must fulfill these conditions at the low, medium, and high frequencies:

$$225\ kHz \le \Delta f1_{avg} \le 275\ kHz$$

At least 99.9% of all *Δf2max* frequency values recorded over 10 LE test packets must be greater than 185 kHz.

The ratio of the two frequency deviations corresponding to the two payload types (10101010 and 11110000, respectively) must be:

$$\Delta f2_{avg}/\Delta f1_{avg} \ge 0.8$$

Where:

- *Δf1avg* is the average frequency deviation for the data payload pattern 11110000 (Figure 9 – "Freq. Dev. – Avg. [kHz], Average" column).
- *Δf2avg* is the average frequency deviation for the data payload pattern 10101010 (Figure 8 – "Freq. Dev. – Avg. [kHz], Average" column).
- *Δf2max* is the average frequency deviation for the data payload pattern 10101010 (Figure 8 – "Freq. Dev. – Max. [kHz], Average" column)

From the values in Figure 8 and Figure 9, it can be seen that:

- *Δf1avg* = 255.0 kHz, which is included in the interval of [225.0 ; 275.0] kHz. This implies that the test number 1 passed.
- *Δf2avg / Δf1avg* = 0.82, which is greater than 0.8. This implies that the test number 2 passed.
- *Δf2min* = 214.7 kHz (Figure 8 – "Freq. Dev. – Min. [kHz], Minimum" column), which is the absolute minimum value for each bit in every instantaneous capture and is greater than 185 kHz. This implies that every *Δf2max* instantaneous value is greater than 185 kHz, which implies that test number 3 passed.

4.3.3.2. Frequency drift

According to the R & S CBT operation manual, the frequency drift is calculated as a difference between the measured frequency at the start of the packet (the value used to calculate the frequency accuracy) and the frequency in the payload (in kHz).

To obtain the latter, the payload is grouped into 10-bit groups and the maximum of the individual frequency drifts is calculated as:

$$Freq\ Drift = Max_n\ |f(t_0) - f(t_n)| * sgn(f(t_0 - f(t_n)),$$
$$n \geq 2,$$
$$t_n = the\ time\ at\ the\ 10-bit\ groups,$$
$$t_0 = the\ time\ at\ the\ start\ of\ the\ packet$$

The first bit and the last bit of the payload are not considered.

For the test to pass, the frequency drift for *n > 1* must be smaller than 50 kHz:

$$Max_n\ |f_n - f_0| \leq 50\ kHz$$

4.3.3.3. Initial frequency drift

The initial frequency drift must be smaller than 20 kHz:

$$|f_1 - f_0| \leq 20\ kHz$$

4.3.3.4. Maximum frequency drift rate

According to the R & S CBT operation manual, the maximum frequency drift rate is calculated as a maximum of the drift rate anywhere within the packet payload. The drift rate is a function of time; it is an estimate for the first derivative of the frequency drift with respect to time. In practice, the maximum drift rate is calculated from the measured frequency *f* in the burst:

$$Max\ Drift\ Rate = Max_n \frac{|f_n - f_{n-5}|}{t_n - t_{n-5}} * sgn(f(t_0 - f(t_n)),$$
$$t_n - t_{n-5} = 50\mu s,$$
$$n \geq 6,$$
$$t_n = the\ time\ at\ the\ 10-bit\ groups,$$
$$t_0 = the\ time\ at\ the\ start\ of\ the\ packet$$

The first bit and the last bit of the payload are not considered; the same is valid for the incomplete 10-bit groups at the end of the payload (spare bits). This implies that the payload length must be at least 62 bits, otherwise the maximum drift rate measurement result is invalid.

For the test to pass, this inequality must be valid:

$$Max_n \frac{|f_n - f_{n-5}|}{t_n - t_{n-5}} \leq \frac{20kHz}{50\mu s}$$
$$t_n - t_{n-5} = 50\mu s$$

4.3.3.5. Frequency accuracy

Frequency accuracy is the difference between the RF carrier frequency measured over the packet preamble and the nominal Bluetooth channel frequency. The preamble is a constant 4-bit pattern at the beginning of the packet, preceding the information bits. To obtain the measured frequency, make an integration of the four bits from the center, the first bit in the preamble to the center, and the first bit following the preamble.

For the test to pass, this inequality must be valid:

$$|f_n - f_{TX}| \le 150 \ kHz \ ,$$
$$f_n = RF \ carrier \ frequency \ measured \ over \ the \ packet \ preamble \ ,$$
$$f_{TX} = nominal \ BLE \ channel \ freq$$

4.3.4. Changing parameter values

To change the statistic count, follow these steps (this option determines the number of samples used):

- Make sure the "Modulation" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Statistic Count".
- Enter the desired statistics count using the numerical keyboard on the "DATA" panel or the control wheel on the "VARIATION" panel of the CBT.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the display mode, follow these steps (use this option to view the graph according to the current value or the minimum, average, or maximum value over a certain time frame):

- Make sure the "Modulation" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Display Mode".
- Select the desired display mode using the control wheel on the "VARIATION" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the EUT TX channel, follow these steps:

- Make sure the "EUT Signal" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "EUT TX Channel".
- Use the control wheel on the "VARIATION" panel of the CBT to select the desired channel.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the payload data pattern:

- Make sure the "EUT Signal" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Payload Data Pattern".
- Use the control wheel on the "VARIATION" panel of the CBT to select the desired data payload pattern.

- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the payload data length:

- Make sure the "EUT Signal" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Payload Data Length".
- Use the control wheel on the "VARIATION" panel of the CBT to select the desired data payload length.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

4.4. TX Adjacent Channel Power (ACP) test

4.4.1. Introduction

The TX ACP test measures the signal strength at the adjacent channels.

4.4.2. Setup

- On the CBT, press the "MENU SELECT" button in the top row.
- Select "Bluetooth LE"—"Spectrum", and press the "ENTER" button.
- On the CBT, select "Connect. Control" in the upper right corner (Figure 7). A new window appears. In this window, you can enable the test mode and modify various parameters to suit various test configurations. Make sure the "Connection" tab is selected (in the bottom left corner of the display).
- Select "Enable Test Mode" if not already enabled.
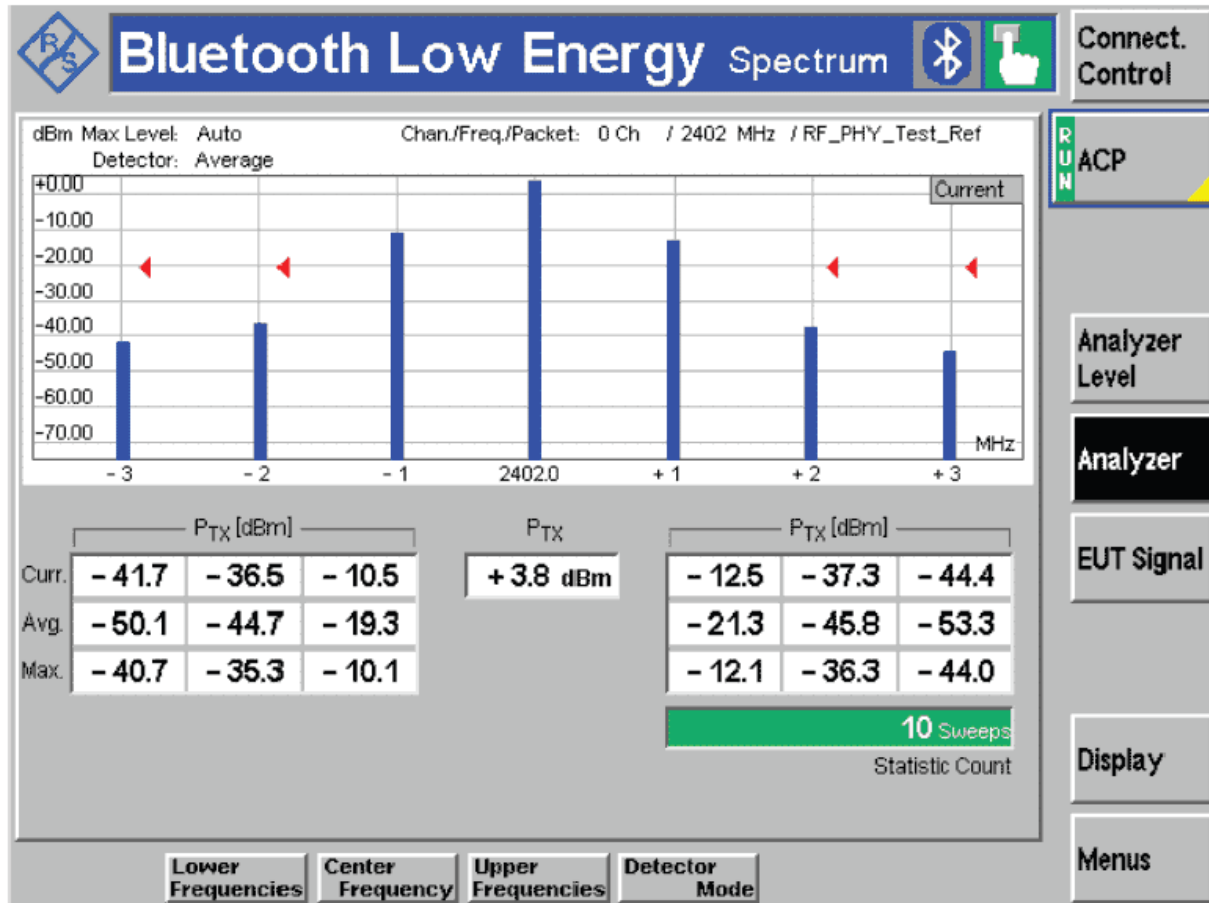- Select "ACP," and then press the "ON/OFF" button to start the TX ACP test.

Figure 10. Starting the TX ACP test

4.4.3. Interpreting results and expected outcome

All measured values must fulfill these conditions:

$$P_{TX} \leq -20\ dBm\ for\ (f_{TX} \pm 2\ MHz),$$
$$P_{TX} \leq -20\ dBm\ for\ (f_{TX} \pm [3+n]\ MHz),$$
$$where\ n = 0, 1, 2, ...$$

For each operating frequency, up to three bands of 1 MHz width (as defined in the measurement) can be exempted from the requirements. The excepted values must comply with an absolute value of $P_{TX} \leq -20$ dBm.

4.4.4. Changing parameter values

To change the statistic count, follow these steps (this option determines the number of samples used):

- Make sure the "ACP" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Statistic Count".

- Enter the desired statistics count using the numerical keyboard on the "DATA" panel or the control wheel on the "VARIATION" panel of the CBT.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the display mode, follow these steps (use this option to view the graph according to the current value or the minimum, average, or maximum value over a certain time frame):

- Make sure the "ACP" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Display Mode".
- Select the desired display mode using the control wheel on the "VARIATION" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the detector mode, follow these steps (use this option to switch between the "Average", "Peak", and "RMS" modes):

- Make sure the "Analyzer" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Detector mode".
- Use the control wheel on the "VARIATION" panel of the CBT to select the desired mode. The display is automatically updated according to this setting.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the lower frequencies, follow these steps:

- Make sure the "Analyzer" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Lower Frequencies".
- There are three frequencies lower than the center frequency that you can choose from. Use the arrows on the "VARIATION" panel of the CBT to select the desired box.
- Use the control wheel on the "VARIATION" panel of the CBT to select the desired frequency value inside the respective box.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the center frequency, follow these steps:

- Make sure the "Analyzer" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Center Frequencies".
- Use the control wheel on the "VARIATION" panel of the CBT to select the desired frequency value.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the upper frequencies, follow these steps:

- Make sure the "Analyzer" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Upper Frequencies".

- There are three possible frequencies greater than the center frequency that you can choose from. Please use the arrows on the "VARIATION" panel of the CBT to select the desired box.
- Use the control wheel on the "VARIATION" panel of the CBT to select the desired frequency value inside the respective box.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the EUT TX channel, follow these steps:

- Make sure the "EUT Signal" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "EUT TX Channel".
- Use the control wheel on the "VARIATION" panel of the CBT to select the desired channel.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the payload data pattern, follow these steps:

- Make sure the "EUT Signal" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Payload Data Pattern".
- Use the control wheel on the "VARIATION" panel of the CBT to select the desired data payload pattern.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

To change the payload data length, follow these steps:

- Make sure the "EUT Signal" button is highlighted in black. If it is not, select it.
- From the bottom menu, select "Payload Data Length".
- Use the control wheel on the "VARIATION" panel of the CBT to select the desired data payload length.
- Press the "ENTER" button on the "DATA" panel of the CBT.
- Press the "ESCAPE" button (it is located in the bottom right corner, near the display).

5. R & S CBT Bluetooth Tester

The R & S CBT Bluetooth Tester is used in the test.

- Model #: CBT-1153.9000.35
- Software version: CBT V5.70
- Front module: FMR7
- RF board: 1153.9700.02, 05.00
- Digital board: 1153.9500.02, 04.01
- DDC module: 1100.2300.03, 05.00
- Audio CBT-B41: 1170.3435.02, 01.09
- Bluetooth extension: 1153.9622.02, 02.02

6. Revision History

The following table summarizes the changes done to this document since the last release.

Table 2.   Revision history

Revision number	Date	Substantive changes
0	09/2015	Initial release.
1	03/2016	Clarified, added and corrected instructions and figures for creating the general hardware setup and software setup in Section 3, "Test Setup". Clarified the instructions for configuring the devices for each test case in Section 4, "PHY Tests". Added a section about the expected outcome for each PHY test, which contains the mathematical explanations of various parameters, how they are calculated, their accepted range, and the correlations between the parameters presented by the CBT and the ones from the PHY Test document. Added a section with the instructions for changing the parameter values for each PHY test. Added figures to Section 4, "PHY Tests" to clarify the differences between various settings and parameter displays for each test case.

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