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frontline TLF3000

Sapphire User Manual V2.0

An RF tester for the *Bluetooth*® 5 LE standard, compatible with TLF3000.

March 23, 2018

1 Contents

2   Overview.

TLF3000 is a wideband, ultra-high dynamic range 2.4 GHz software-defined receiver, signal analyzer and signal generator. It captures and analyzes the entire 2402-2480 MHz band simultaneously. It can also generate arbitrary waveforms occupying the band 2395-2485 MHz with a maximum peak level of 0 dBm. Additionally, it includes a CW signal generator covering 25MHz to 6GHz with an output level of -50 dBm to -28 dBm

Sapphire is a *Bluetooth*® 5 LE application for the *TLF3000* software-defined receiver, signal analyzer and signal generator. The Sapphire application can:

1. Perform all phy level tests as specified in Bluetooth Low Energy RF Phy Test Specification (with minor restrictions). Testing beyond the limits of the specification is also supported.
2. Act as a signal generator, creating all necessary signals for receiver testing including signals outside the specification as well as supplemental data for AoA/AoD testing. Signals as weak as -120 dBm can be generated for testing long range modes.
3. Act as a signal analyzer, performing transmitter tests on conducted or off-air signals without knowledge of the payload format or hopping sequence. Test coverage includes AoA/AoD supplemental data.
4. Generate advertising or scan request packets to provoke activity from items on a production line and analyze the captured packets.

The application has been honed for speed. The ability to perform in-band emission tests over the entire 2.4 GHz band in just a few milliseconds is particularly impressive. This is possible due to *TLF3000* unique parallel architecture.

A key feature of the unit is its ability to perform C/I, receiver selectivity and intermodulation tests without the need for additional test equipment. This is possible due to *TLF3000* ultra-linear wideband signal generator. This permits both wanted and interfering signals to be generated through the same signal path. The high linearity and low noise floor ensure that there is ample dynamic range to encompass both the wanted and interfering signals. Furthermore, high fidelity filtering of the interfering signals ensures that they are correctly bandlimited and that unwanted sidebands are not responsible for test failures; this is frequently overlooked when external test equipment is used to provide these signals. The single signal path also removes the need for time consuming and laborious calibration of signal combiners as well as eliminating the need to ensure that the injected interfering and wanted signals do not generate intermodulation products before arriving at the DUT.

Unique to *TLF3000* is a 25 MHz to 6 GHz signal generator. This enables the majority of the receiver blocking performance to be explored prior to committing the DUT for formal inspection at a test house with its associated costs.

The Sapphire application is highly parameterised, permitting it to be configured for different scenarios. For example:

1. The unit will function with arbitrary access addresses, allowing multiple devices to be tested simultaneously without cross-talk.
2. The unit may be controlled directly from a host machine via USB or Ethernet, or operated stand-alone with digital IO used to start, stop and report test results.
3. The DUT may be controlled directly from the unit or via a common host platform.

3 Control.

3.1 Overview

Sapphire can be controlled in three ways:

Control method	Interface		
	USB	Ethernet	Digital IO
Native language	✓	✓	
Sapphire GUI	✓	✓	
Standalone			✓

Table 1: Methods of Controlling Sapphire

3.2 Native language

The *TLF3000* supervisor program and Sapphire application can be controlled via a simple native language. The native language provides a convenient means of controlling Sapphire for high level host languages, such as Python. The native language exposes all the features supported by Sapphire.

The native language relies on three control channels:

1. *Command Control channel*. Transfers commands from the host to Sapphire.
2. *Command Response channel*. Contains the response from Sapphire for the command issued on the Command Control channel. There is one response for every command issued.
3. *Data channel*. Transfers asynchronous data from Sapphire to the host.

If a USB interface is used, then these three channels map to three USB endpoints. If an Ethernet interface is used, then the first two channels map to one TCP/IP socket whilst the data channel maps to a second TCP/IP socket.

It is possible to utilise both the USB and Ethernet interfaces simultaneously.

3.3 Sapphire GUI

A GUI is shipped with the Sapphire application. This permits the application to be controlled via a host running Windows, Linux or OS X. The GUI connects to the *TLF3000* either over USB or Ethernet. The GUI exposes the majority of the Sapphire functionality.

The GUI may also be used to generate test script files in a format which can be used by native language programs.

3.4 Standalone

By placing the Sapphire image on a USB memory stick and attaching it to the *TLF3000* USB port, it is possible to run Sapphire without the need for a host computer. In this mode of operation, the test script to be executed is contained on the USB memory stick. Control of Sapphire is accomplished by toggling digital IO and pass/fail results are communicated back by Sapphire setting digital IO.

4   Operating Modes.

4.1   Overview

Sapphire has five operating modes:

Mode	DUT control	Test control	Tx Test	Rx Test
Phy layer	Serial	Script	✓	✓
Signal generator	None	User		✓
Signal analyzer	None	User	✓	
Advertise/Scan	None	Signalling	✓	✓
Standalone	Serial	Digital IO	✓	✓

Table 2: Sapphire operating modes overview.

4.2   Phy layer tester

The phy layer mode executes tests in accordance with the Bluetooth 5 LE RF Phy Test Specification. The tests to be performed are entered into a script which is then executed by Sapphire. The DUT is automatically controlled by Sapphire via a serial interface.

All tests are fully parameterised, permitting exploration of margin against the Bluetooth 5 specification or datasheet figures.

4.3   Signal Generator

The signal generator mode permits manual control over all the signal sources used in the Bluetooth 5 LE RF Phy Test Specification. Any combination of the following signals can be generated simultaneously:

1.   Packetized LE test signal
2.   GFSK modulated interferer signal
3.   In-band CW signal
4.   Out-of-band CW signal.

All signal sources are fully parameterised.

4.4   Signal Analyzer

The signal analyzer mode monitors all 40 LE channel simultaneously. Any packets which match a specified access address are captured and analyzed in accordance with the Bluetooth 5 LE RF Phy Test Specification. Tests include the in-band emissions test, which can be completed in as little as 2.5 ms.

If the captured packet is not a standard test packet, then an 'off-air' mode can be selected which performs accurate approximations to the standard Bluetooth 5 LE RF tests but which is agnostic to the packet payload. This permits RF test to be performed on live links.

The signal analyzer mode also permits the capture of raw IQ data.

4.5   Advertise/Scan

The advertise/scan mode permits RF testing of devices when there is no access to either HCI or direct test mode. In this mode of operation, the DUT is provoked by Sapphire issuing advertising or scan request packets. The sensitivity of the DUT can be deduced from the signal level required to provoke a response, whilst the transmitter quality is ascertained by analysing the packets sent by the DUT.

4.6 Standalone

The standalone mode permits Sapphire to be run without a USB or Ethernet connection. In this mode of operation, the Sapphire image and test script are held on a memory stick which is attached to the USB port of the *TLF3000*. The supervisor program on the *TLF3000* will automatically launch the Sapphire application which will then execute the test script held on the memory stick. Control of the Sapphire application and signalling of pass/fail are accomplished by the use of digital IO.

5 Launching the Sapphire GUI.

In order to communicate with the *TLF3000* unit, it is necessary to attach it to a host computer via USB or Ethernet (or both). An Ethernet connection is only possible if the host computer and *TLF3000* unit reside on the same subnet. The *TLF3000* IP address can be changed by connecting it to a host computer via USB and using the *Application Loader*.

To launch the Sapphire GUI it is first necessary to run *Application Loader*. This should result in the following screen being displayed:
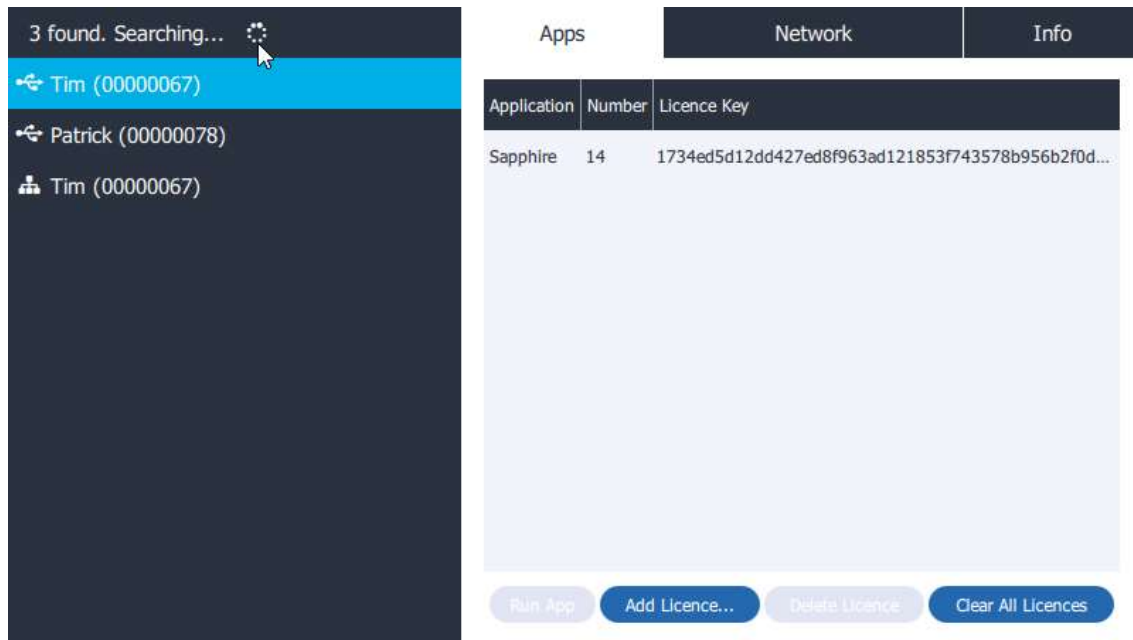
Figure 1: Application Loader main screen.

This screen indicates that the following *TLF3000* devices have been discovered:

1. Serial number 00000067 connected via USB (highlighted)
2. Serial number 00000078 connected via USB
3. Serial number 00000067 connected via Ethernet (this device is shown twice)

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The right hand side of the window has three tabs:

1. *Apps*. Shows which applications are licensed to run on this unit. It also permits the loading of new licence keys.
2. *Network*. Shows the current network settings and permits these to be modified.
3. *Info*. Provides more information about the unit and permits the unit's friendly name to be modified. It also provides a means of updating the firmware on the unit.

To launch the Sapphire application open the "*Apps*" tab and then either:

1. Double click on the Sapphire application
2. Highlight the Sapphire application and then click the "*Run App*" button.

On launching the application, the searching cursor should stall, the fan on the *TLF3000* unit will start to spin and after a few seconds the Sapphire GUI will load.

6   Anatomy of the Sapphire GUI.

6.1   Overview

The Sapphire GUI is composed of the following elements:

1. A tool bar along the top of the window
2. A monitor panel to the right of the window
3. A status bar at the bottom of the window
4. Mode tabs located immediately underneath the tool bar
5. A mode control panel to the left of the window
6. A graphics area
7. A scripting/tabular results area below the graphics area
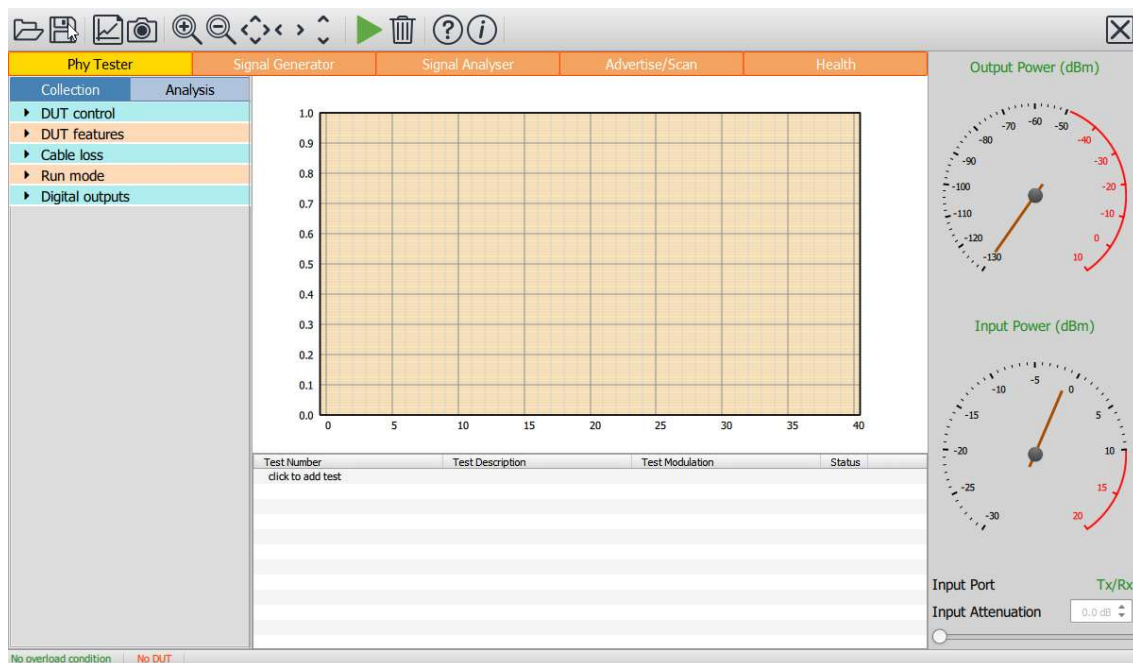
Figure 2: Sapphire GUI

6.2   Toolbar

The toolbar contains the following elements:

6.3   Open and save

Opens and loads a settings file. Settings are saved individually for each mode of operation. The appropriate settings file is automatically selected on the basis of the current mode tab.

Saves the settings or results. Settings are saved individually for each mode of operation. The choice as to whether settings or results are saved is determined by the file extension which is selected. This tool can also be used to save test scripts in the format required by the native programming language.

6.4   Screen capture

Saves the current graphics area as an image file. A variety of image file formats are supported.

Takes a screen shot of the GUI and saves as an image file. A variety of image file formats are supported.

6.4.1   Zooming

Activates the cross-hair cursor which permits zooming within in the graphics area. Depress the left mouse button whilst dragging the cursor to select the area to be displayed. Clicking the right mouse button within the graphics area will give a list of additional zoom options.

Zooms out within the graphics area. Clicking the right mouse button within the graphics area will give a list of additional zoom options.

Pans within the graphics area. Hold down the left mouse button and drag to pan anywhere within the graphics display.

Pans along the x-axis within the graphics area. Hold down the left mouse button and drag horizontally. This is particularly useful for examining long waveforms.

Pans along the y-axis within the graphics area. Hold down the left mouse button and drag vertically.

6.4.2   Run and clear

Causes the currently selected mode to run. NOTE: the signal generator will not output energy until this is clicked.

Stops the currently selected mode running. A running operation will automatically be aborted if a different mode of operation is selected.

Clears the current results history. Not applicable in signal generator mode.

6.4.3   Help

Displays the online documentation in a pop-up window.

Displays version information.

6.4.4   Exit

6.5   Monitor panel

6.5.1   Overview

The purpose of the monitor panel is to permit the user to quickly ascertain whether:

1. There is RF energy being emitted from the unit
2. There is RF energy being received by the unit

Whenever the unit or DUT appears to be unable to receive, the monitor panel should always be the first item to examine. Many problems can be quickly resolved with the information that it displays.

The monitor panel also determines which RF port is being used and provides manual control of the receiver front-end attenuation (not accessible in phy tester mode).

6.5.2   Output power

The output power gauge shows the energy being emitted by the *TLF3000*. The gauge is only approximate and should not be used for accurate measurements.

The red arc indicates the overload region. If an overload does occur, this will be evident by the 'Output Power (dBm)' label turning red and a warning message being displayed in the status bar.

The output power gauge only shows the energy being emitted within the 2.4 GHz ISM band. Energy from the out-of-band CW blocker is not included, even if its frequency lies within the 2.4 GHz ISM band.

6.5.3   Input power

The input power gauge shows the energy incident on the selected *TLF3000* input port. The gauge is only approximate and should not be used for accurate measurements.

The red arc indicates the overload region. If an overload does occur, this will be evident by the 'Input Power (dBm)' label turning red and a warning message being displayed in the status bar. It may be possible to remove a receiver overload condition by:

1. Adding additional receiver front-end attenuation using the control at the bottom of the monitor panel (not accessible in phy tester mode)
2. Swapping to the 'Tx/Rx' RF port to the 'Monitor In' RF port is being used. It is also necessary to indicate which RF port is being used by setting the switch at the bottom of the monitor panel.

The input power gauge only shows energy within the 2.4 GHz ISM band. F-bar filters at the front of the receiver chain ensure other energy is eliminated and cannot block the receiver.

6.5.4 Input port

The input port switch selects which of the two RF input ports will be used:

1. The 'Monitor In' port is suitable for off-air monitoring and has a noise figure of 6 dB. In benign environments no additional receiver front-end attenuation should be required. However, in environments with strong Wi-Fi activity, it may be necessary to add receiver front-end attenuation to prevent overload conditions.
2. The 'Tx/Rx' port is suitable for conducted measurements. If the DUT is capable of outputting more than +10 dBm, it may be necessary to add receiver front-end attenuation to prevent overloading the receiver.

6.5.5 Input attenuation

These controls are used to select the receiver front-end attenuation. The attenuation may be adjusted by:

1. Moving the slider
2. Using the up/down arrows on the spin box
3. Typing a numeric value into the spin box text area

The available attenuation range is 0 to 31.5 dB in steps of 0.5 dB.

6.6 Status bar

6.6.1 Overview

The status bar at the bottom of the window is divided into three areas:

1. Overload indicator
2. DUT connection status
3. Error message text

6.6.2 Overload indicator

The overload indicator will turn red when an overload condition occurs on either the transmit output or the selected receiver input port. The text of the message will indicate where the overload condition is occurring.

6.6.3 DUT connection status

The DUT connection status message indicates whether the Sapphire application believes it currently has communication with a DUT via a serial interface.

6.6.4 Error message text

The error message text reflects the last error detected by the Sapphire application running on the *TLF3000* unit. This message is cleared when either the 'Run' or 'Clear' buttons are pressed, or when a different operating mode is selected.

6.7 Mode tabs

The operating mode is selected by the tabs immediately underneath the tool bar. The following operating modes can be selected:

1. Phy tester
2. Signal generator
3. Signal analyzer
4. Advertise/Scan

In addition, it is possible to display a page showing the health of the *TLF3000* unit.

Whenever a new mode of operation is selected, any currently running tests are aborted.

6.8   Mode control panel

For each operating mode, a mode control panel is displayed to the left of the window. This panel allows the user to define the parameters for the current operating mode. The contents of the mode control panel are mode-specific.

In the case of the phy tester, signal analyzer and advertise/scan modes, the mode control panel is divided into two tabs:

1. *Collection*. This tab contains parameters which determine what data will be collected and how it will be collected.
2. *Analysis*. This tab contains parameters which determine how results from the collected data will be displayed.

6.9   Graphics area

For the phy tester, signal analyzer and advertise/scan modes of operation, a graphical representation of the results are displayed in the graphics area. Which results are displayed and how they are displayed are determined by the settings in the "Analysis" tab on the mode control panel.

For the signal generator mode, the graphics area provides a visual indication of which signals have been programmed. Note that the graphics area only shows what has been programmed; to make the programmed signals appear at the transmitter port, the 'Play' button within the tool bar must be activated.

6.10 Scripting/tabular results area

In the phy tester mode, the region below the graphics area is used for constructing and displaying test scripts. This area also indicates whether the tests have been run, and if so, whether they passed or failed.

In the signal analyzer and advertise/scan modes, the region below the graphics is used to display tabular results. Which results are displayed is determined by settings on the 'Analysis' tab in the mode control panel. The results tables also contain test limits which can be adjusted by the user. Tests that fail the limits are highlighted. The contents of the graphics display area can also be controlled by highlighting rows within the results table.

The scripting/tabular results area is not used in signal generator mode.

7 Signal Generator Mode.

7.1 Overview

The signal generator is able to produce any combination of the following signals:

1. Packetized LE test signal
2. GFSK modulated interferer signal
3. In-band CW signal
4. Out-of-band CW signal.

The mode control panel on the left hand side of the screen lists the signals which can be generated. The switch to the left of the signal name programs the signal on or off. Although a signal may be programmed on, *no output is generated from the unit until the 'Play' button in the tool bar is activated*.

The top graph in the graphics window shows a symbolic representation of signals generated within the 2.4 GHz ISM band. The graphics assume a resolution bandwidth of 100 kHz, hence the displayed levels for modulated signals will be slightly lower than their programmed levels. The LE channels are emphasised by alternating colour bars. Advertising channels are further highlighted.

The bottom graph in the graphics window shows a symbolic representation of the signals generated between DC and 6 GHz. The graphics assume a resolution bandwidth greater than modulation bandwidth, hence all signals appear at their programmed levels.
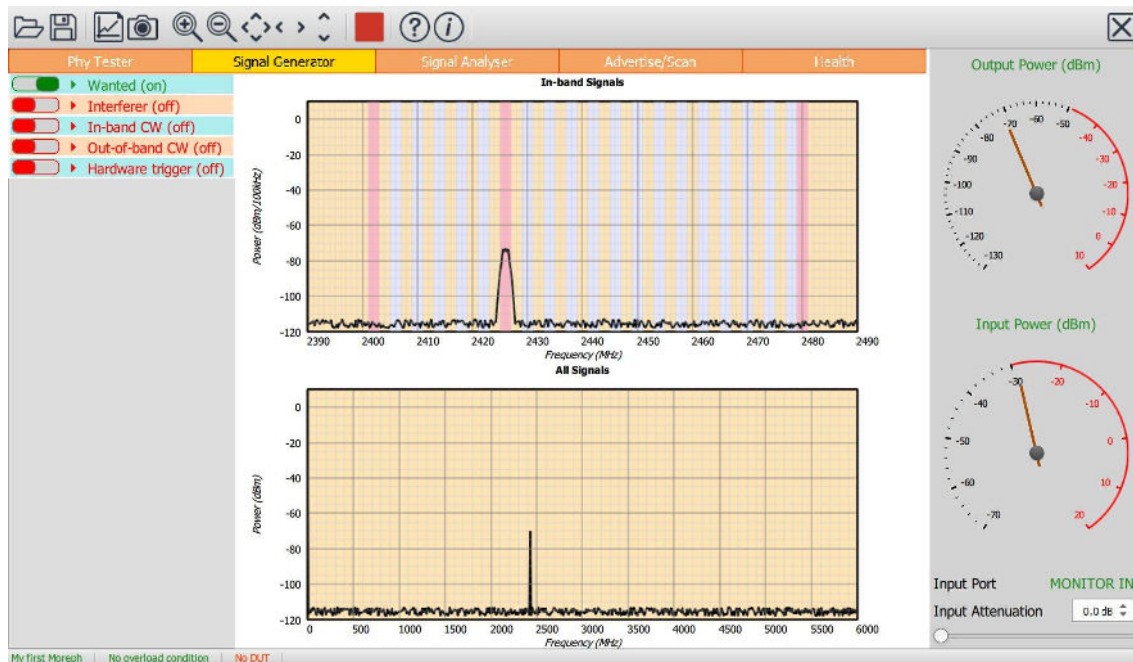
Figure 3: Sapphire GUI in signal generator mode.

7.2 RF connections

The signal generator output is on the Tx/Rx port.

7.3 Programming the packetized LE signal

7.3.1 Overview

Many of the parameters governing the packetized LE signal are programmable, however, the access address is fixed at the test address of `0x71764129`. If greater flexibility in defining a packetized LE signal is required, then the user should use Tanzanite, a LE Traffic Generator application compatible with *TLF3000*.

To turn the packetized LE signal on or off, toggle the switch to the left of the 'Wanted' text.

To program the packetized LE signal, expand the 'Wanted' signal menu by clicking on it:
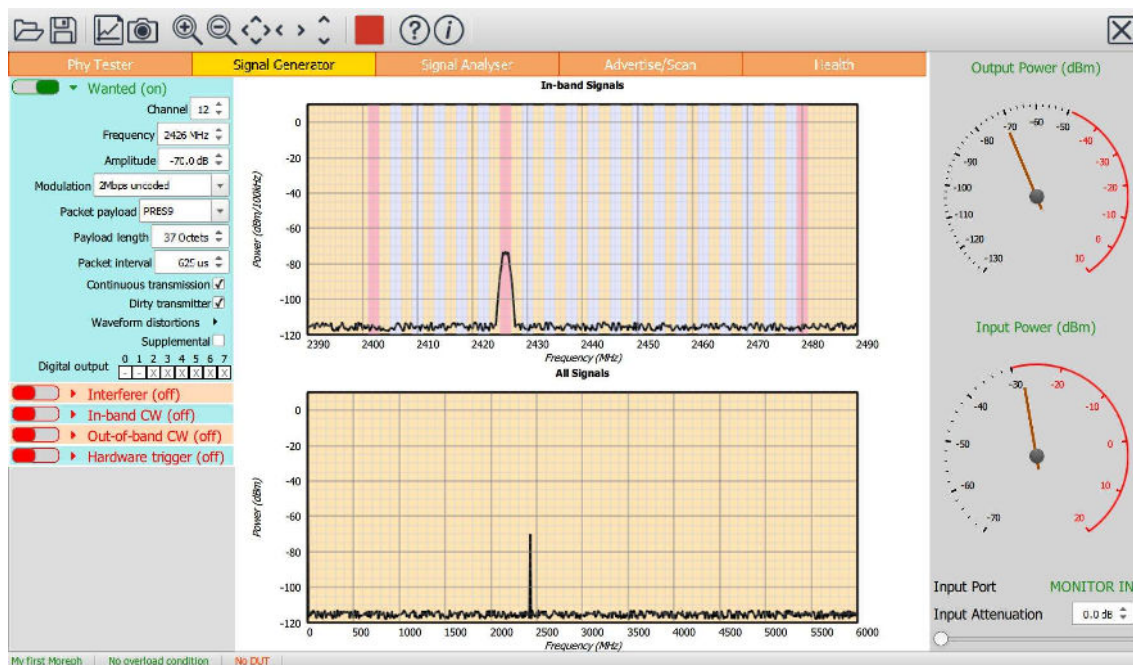
Figure 4: Programming the packetized LE signal.

7.3.2 Carrier frequency

The frequency of the carrier can be set to anyone of the 40 LE channels either by:

1. Using the channel number spin box
2. Using the frequency spin box

As with all spin boxes, adjustment can be performed either by using the up/down arrows or by entering a numeric value into the text field.

7.3.3 Amplitude

The amplitude of the wanted signal can be adjusted from -120 dBm to 0 dBm. The total combined output power of the unit within the 2.4 GHz ISM band is 0 dBm. Therefore, if other signals are active, the maximum output power for the wanted signal will be reduced to maintain the peak output power within the 0dBm limit.

7.3.4   Modulation

The modulation may be set to anyone of the Bluetooth 5 LE RF phys:

1. 2 Mbps, GFSK
2. 1 Mbps, GFSK
3. 500 kbps, s=2 spreading, GFSK
4. 125 kbps, s=8 spreading, GFSK

The 1 Mbps, 500 kbps & 125 kbps signals are all bandlimited to 2 MHz, whilst the 2 Mbps signals are bandlimited to 4 MHz.

Each packet has a power ramp time of 2 µs followed by 2 µs of unmodulated carrier prior to the preamble. At the end of each packet there is a further 2 µs of unmodulated carrier prior to a 2 µs ramp down. These parameters are in full compliance with the *Bluetooth 5 LE RF PHY Test Specification*.

Modulation index, carrier offset, drift, drift rate and symbol timing can all be adjusted by enabling the dirty transmitter mode.

If the modulation scheme is changed to or from 2 Mbps, then the packet interval may be automatically updated.

7.3.5   Payload

The packet payload can be set to any one of the following (least significant bit first):

1. PRBS9 sequence, as defined in the Direct Test Mode section of the Bluetooth 5 Core Specification
2. `11110000` repeated
3. `10101010` repeated
4. `11111111` repeated
5. `00000000` repeated
6. `00001111` repeated
7. `01010101` repeated
8. PRBS15 sequence, as defined in the Direct Test Mode section of the Bluetooth 5 Core Specification

The choice of payload also defines the first octet of the packet header:

b_7 b_6 b_5 b_4 b_3 b_2 b_1 b_0	Payload
0 0 0 0 0 0 0 0	**PRBS9**
0 0 0 0 0 0 0 1	11110000
0 0 0 0 0 0 1 0	10101010
0 0 0 0 0 0 1 1	**PRBS15**
0 0 0 0 0 1 0 0	11111111
0 0 0 0 0 1 0 1	00000000
0 0 0 0 0 1 1 0	00001111
0 0 0 0 0 1 1 1	01010101

Table 3: Choice of payload defining first octet of the packet header.

If other payloads are required, then the user should use Tanzanite, a Bluetooth LE traffic generator application compatible with *TLF3000*.

7.3.6 Payload Length

The payload length can be adjusted between 0 and 255 octets. Altering the payload length may result in the packet interval changing. If the packet length exceeds the packet interval, then the packet interval will be rounded up to the next multiple of 625 μs.

7.3.7 Packet Interval

The minimum packet interval is dependent on both the payload length and the modulation scheme. For a 2 Mbps packet with no payload, the minimum packet interval is 74 μs. The maximum packet interval is 100 ms.

The packet interval may change automatically if either the payload length or the modulation scheme is changed. If this occurs, then the packet interval will be set the lowest multiple of 625 μs which encompasses the entire packet.

7.3.8 Packet count

The signal generator can be set to transmit LE packets continuously or a finite number of packets can be specified. The specification of a finite number of packets is useful if it is desired to measure the PER on a receiving DUT.

No packets are transmitted from the unit until either:

1. The 'Run' button in the tool bar is pressed
2. The 'Run' button in the tool bar is pressed and the signal generator is triggered by toggling lines on its digital interface

If a finite number of packets have been specified, then the signal generator will continue to run even after the all the packets have been transmitted. To generate another sequence of packets it is necessary to either:

1. Stop the signal generator by activating the 'Stop' button in the tool bar and then restarting the signal generator using the 'Run' button
2. Toggling digital lines to stop the generator and then toggling digital lines to restart the signal generator

The minimum number of packets which can be set is 1. If not in continuous mode, the maximum number of packets which can be sent is 63500.

7.3.9 Dirty transmitter

7.3.9.1 Overview

By selecting dirty transmitter mode, it is possible to control:

1. Modulation index
2. Carrier offset
3. Carrier drift magnitude
4. Carrier drift rate
5. Symbol timing error

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The carrier drift is applied in accordance with the Bluetooth 5 LE RF Phy Test Specification:

1. The carrier drift at the start of each packet is zero
2. The carrier drift follows a sinusoidal variation whose frequency is determined by the drift rate parameter
3. The magnitude of the sinusoidal variation is determined by the drift magnitude parameter
4. Successive packets have the sign of the carrier drift reversed

The GUI holds two different sets of waveform distortions. One set is applied to 2 Mbps modulated waveforms whilst the other set is applied to 1 Mbps, 500 kbps & 125 kbps modulated waveforms.

Clicking on the 'Waveform distortions' button will pop-up the dirty transmitter dialog which displays the waveform distortion table which is currently in use:

Figure 5: Dirty transmitter dialogue box displaying the waveform distortion table currently in use.

The transmitted signal is divided into groups of 50 packets. The first 50 packets are transmitted using the distortions defined in the first row of the waveform distortion table, the second 50 packets are transmitted using the distortions defined in the second row of the waveform distortion table, etc. Once all the rows in the waveform distortion table have been exhausted, the first row is reused.

Each individual distortion specified in the waveform distortion table can be adjusted using the associated spin box, either by using the up/down arrows or by entering a numeric value into the text field. The parameters can be varied over the following ranges:

Parameter	2 Mbps	1 Mbps, 500 kbps & 125 kbps
Carrier offset	±500 kHz	±250kHz
Modulation index	0.4 to 0.6	0.4 to 0.6
Drift magnitude	±150 kHz	±78 kHz
Drift rate	0 to 2440 Hz	0 to 2440 Hz
Symbol timing error	±100 ppm	100 ppm

Table 4. Ranges over which the transmit distortions may be varied.

7.3.9.2 ~~Editing the waveform distortion table~~

A row in the table can be selected by left or right clicking on the packet group number in the first column. Once a row in the packet group table has been selected, an edit menu can be popped-up by right clicking anywhere in the selected row.

The edit row permits the following operation to be performed:

1. *Copy*. The contents of the selected row are copied into the waveform distortion clipboard
2. *Paste*. The contents of the waveform distortion clipboard are copied into the selected row (this option is only available if the waveform distortion clipboard is not empty)
3. *Remove*. The selected row is deleted from the waveform distortion table.
4. *Clear All*. The entire waveform distortion table is deleted. Once the table has been cleared, a new entry can be inserted by clicking immediately underneath the table header.
5. *Insert above*. A new entry is inserted above the selected row. The new entry has no distortions and a modulation index of 0.5.
6. *Insert below*. A new entry is inserted below the selected row. The new entry has no distortions and a modulation index of 0.5.
7. *Duplicate*. The selected row is duplicated.

A new row can be inserted at the end of the waveform distortion table by clicking immediately below the last row. The new entry has no distortions and a modulation index of 0.5.

7.3.9.3 ~~Waveform distortion buttons~~

The buttons along the bottom of the dirty transmitter dialog perform the following functions:

1. *Reset*. The contents of the waveform distortion table are reset to the values they held when the dirty transmitter dialog was popped up and all edits are discarded.
2. *Restore defaults*. The contents of the waveform distortion table are reset to the values specified in the Bluetooth 5 LE RF Phy Test Specification.
3. *Apply*. The current contents of the waveform distortion table will be used for all future transmissions and the dirty transmitter dialog is closed.
4. *Cancel*. Any edits to the waveform distortion table are discarded and the dirty transmission dialog is closed. All future transmissions will use the waveform distortions which were present prior to the dirty transmitter dialog being popped-up.
5. *Open*. The waveform distortion table will be loaded from an XML file.
6. Save. The currently displayed waveform distortion table will be saved to an XML file.

7.3.10 Supplemental

7.3.10.1 Overview

If "Supplemental" is selected then a supplemental will be added to the end of the packet. For AoD operation, the supplemental phase is modulated to simulate the switching between antennas. It is possible to control:

1. Supplemental length
2. AoA or AoD mode
3. Length of switching slots
4. Antenna switching pattern
5. Number of antenna
6. Antenna phases (as seen by the DUT)

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Abrupt switching between the transmit antenna would result in large sidebands being imposed on the wanted signal. The Sapphire application avoids the introduction of sidebands of modulating the amplitude of the signal during the switching slots as well as the phase. As a consequence, a 1 Mbps signal with supplemental remains within a 2 MHz bandwidth, whilst a 2 Mbps signal with supplemental remains within a 4 MHz bandwidth. The Sapphire application is able to perform 180° phase shifts between successive transmit antenna whilst maintaining these bandwidths.

Clicking on the "Antenna phases" button will pop-up the antenna phases dialog which displays current supplemental definition. The dialog includes a graph showing how the transmitter phase will be modulated over the length of the supplemental.
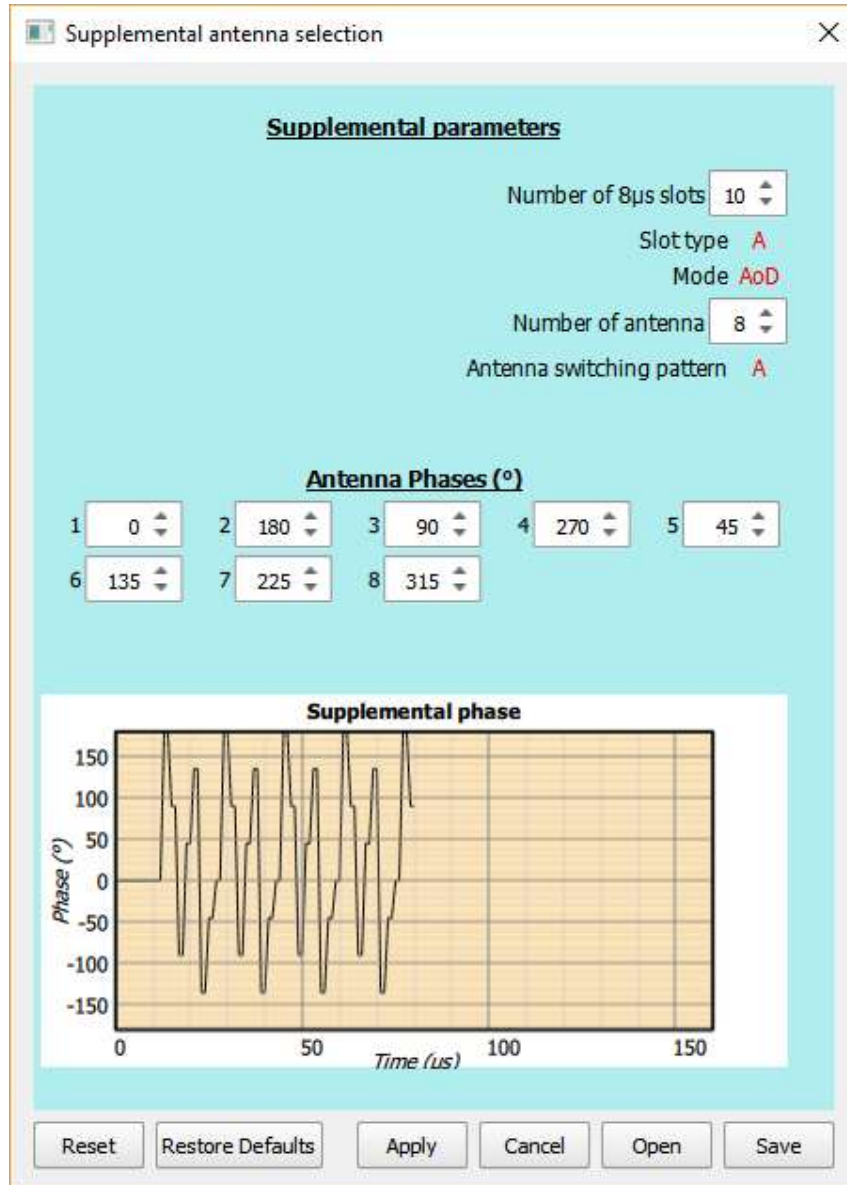
Figure 6: Supplemental Antenna Selection

7.3.10.2 ~~Setting supplemental parameters~~

The length of the supplemental is defined by a spin box showing the length in 8 μs slots. The minimum length is 2 x 8 μs slots (guard interval + reference interval + switching/sampling slots) and the maximum length is 20 x 8 μs slots.

The slot type can be toggled between 'A' and 'B' by clicking on the displayed slot type. Type 'A' slots are 1 μs long (i.e. 1 μs switch and 1 μs sample) whilst type 'B' are 2 μs long (i.e. 2 μs switch and 2 μs sample).

The mode of operation can be set to either AoA or AoD. Switching between modes is achieved by clicking on the displayed mode. If AoA is selected, then the phase of the supplemental is not modulated and the only relevant parameter is the supplemental length. In this instance all other parameters in the dialog are hidden.

In AoD mode the number of transmit antenna can be selected using a spin box. The minimum number permissible is 2 and the maximum 63. If the number of sampling slots is less than the number of antenna, then not all antennas will be used.

The antenna switching pattern can be toggled between 'A' and 'B' by clicking on the displayed pattern. Antenna switching pattern 'A' corresponds to the sequence:

```
1 2 3 4 . . . 1 2 3 4 . . . 1 2 3 4 . . .
```

Whilst antenna switching pattern 'B' corresponds to the sequence:

```
1 2 3 4 . . n-4 n-3 n-2 n-1 n n-1 n-2 n-3 n-4 . . 4 3 2 1 2 3 4 . .
```

7.3.10.3 ~~Setting antenna phases~~

A spin box is displayed for each antenna phase. The antenna phases are entered in units of degrees. Any value from -360° to +360° can be entered.

For short supplemental lengths or large numbers of transmit antenna, there may be more transmit antenna than sampling slots. In this instance not all the transmit antenna may be used.

7.3.10.4 ~~Antenna phase dialog buttons~~

The buttons along the bottom of the antenna phases dialog perform the following functions:

1. *Reset.* All supplemental parameters and antenna phases are reset to the values they held when the antenna phases dialog was popped up and all edits are discarded.
2. *Restore defaults.* The supplemental parameters and antenna phases are reset to RF Creations default values.
3. *Apply.* The current supplemental parameters and antenna phases will be used for all future transmissions and the antenna phases dialog is closed.
4. *Cancel.* Any edits to the supplemental parameters or antenna phases are discarded and the antenna phases dialog is closed. All future transmissions will use the supplemental parameters and antenna phases which were present prior to the antenna phases dialog being popped-up.
5. *Open.* The supplemental parameters and antenna phases will be loaded from an XML file.
   Save. The currently displayed supplemental parameters and antenna phases will be saved to an XML file.

7.3.11 Digital output

To enable other test equipment to be synchronised with Sapphire's transmissions, it is possible to toggle digital output lines when a packet is being transmitted. The selected lines will be low between transmissions and go high during the transmission.

The *TLF3000* unit has 8 digital output lines. Lines 2 to 7 are available for signalling packet transmission. Lines are selected by toggling 'X' to '1' in the appropriate box.

If a digital output line is specified as monitoring both wanted signal transmissions and modulated interferer transmissions, then the state of the line is the logical OR of the two signals.

The IO voltage for the lines may be either:

1. An internal 3.3 V generated supply
2. An external supply in the range 0.8 V to 3.6 V

The selection of the IO voltage is performed under 'Hardware trigger'

7.4 Programming the GFSK modulated interferer signal

7.4.1 Overview

Sapphire can generated a GFSK modulated interferer signal. This signal is required to perform receiver C/I and intermodulation tests.

To turn the modulated interferer signal on or off, toggle the switch to the left of the 'Interferer' text.

To program the modulated interferer signal, expand the 'Interferer' signal menu by clicking on it:
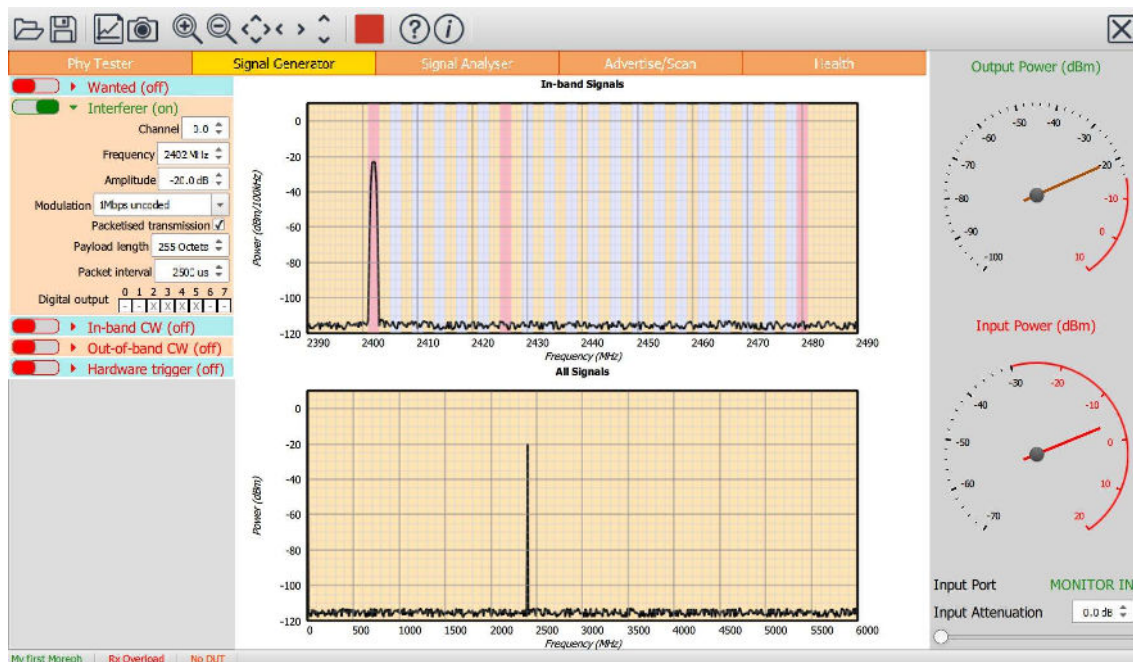
Figure 7: Programming the modulated interferer signal.

7.4.2 Carrier frequency

The frequency of the carrier can be set by:

1. Using the channel number spin box
2. Using the frequency spin box

As with all spin boxes, adjustment can be performed either by using the up/down arrows or by entering a numeric value into the text field.

If 1 Mbps, 500 kbps or 125 kbps modulation is selected, then the carrier frequency can be set to any integer MHz between 2395 MHz and 2485 MHz inclusive. Odd MHz frequencies do not coincide with LE channels, so are donated by LE channels plus 0.5. Channel numbers are extended beyond the range 0 to 40 to encompass frequencies outside the range 2402 to 2480 MHz.

If 2 Mbps modulation is selected, then the carrier frequency can be set to any value between 2396 MHz and 2486 MHz inclusive, in steps of 2 MHz. Channel numbers are extended beyond the range 0 to 40 to encompass frequencies outside the range 2402 to 2480 MHz.

If the receiver intermodulation tests are being performed on channels near the band edges, then the required frequency for the modulated interferer signal may fall outside the 2402-2480 MHz band. For large values of the frequency separation parameter 'n' (as defined in the Bluetooth 5 LE RF Phy Test Specification), the required frequency may also fall outside the 2395MHz to 2485MHz range supported by the Sapphire application. Under these circumstances it will not be possible to perform the intermodulation test. This is one of two areas where the test coverage of the Sapphire application is not compliant with the Bluetooth 5 LE RF Phy Test Specification. However, the intermodulation test has to be performed with the interfering signals both above and below the wanted signal. The Sapphire application can always perform the test cases where the interferer signals lie within the 2.4 GHz band. When the interfering signals lie outside the 2.4 GHz band, it is highly likely that they will suffer some attenuation from the receiver's front-end filtering. Therefore it is unlikely that a device will pass the intermodulation test when the interfering signals lie within the 2.4 GHz band, but fail when the interfering signals lie outside the 2.4 GHz band.

7.4.3 Amplitude

The amplitude of the modulated interferer signal can be adjusted from -120 dBm to 0 dBm. The total combined output power of the unit within the 2.4 GHz ISM band is 0 dBm. Therefore, if other signals are active, the maximum output power for the modulated interferer signal will be reduced to maintain the peak output power within the 0 dBm limit.

7.4.4 Modulation

The modulation may be set to anyone of the Bluetooth 5 LE RF phys:

1. 2 Mbps, GFSK
2. 1 Mbps, GFSK
3. 500 kbps, s=2 spreading, GFSK
4. 125 kbps, s=8 spreading, GFSK

The 1 Mbps, 500 kbps & 125 kbps signals are all bandlimited to 2 MHz, whilst the 2 Mbps signals are bandlimited to 4 MHz. The suppression of sidebands outside the band limit is extremely high. This is essential to ensure that the wanted signal is not being swamped by sidebands from the modulated interfering signal during C/I tests.

If the modulation is changed to 2 Mbps, then the carrier frequency will automatically be altered if it is not a multiple of 2 MHz.

No transmitter distortions are applied to the modulated interfering signal. To apply transmitter distortions to the interfering signal, use Tanzanite, the *TLF3000* Bluetooth LE traffic generator application.

7.4.5   Packetisation

The modulated interferer signal can either be continuous or packetised. The Bluetooth 5 LE RF Phy Test Specification stipulates that the signal should be continuous. However, the use of a packetised signals can often reveal issues with IP2 performance in low-IF receiver architectures.

To turn the interferer from continuous to packetized, tick the "*Packetised transmission*" checkbox. Once this box is checked, the user will have the ability to enter payload length and the packet interval for the packetized transmission. The payload length can be in the range 0 to 255 bytes. The payload always contains a PRBS sequence. The packet interval is the time between the start of one packet and the start of the subsequent packet. Intervals of up to 100ms can be entered. The minimum interval which can be entered is determined by the payload length.

7.4.6   Digital output

To enable other test equipment to be synchronised with Sapphire's transmissions, it is possible to toggle digital output lines when the modulated interferer signal is being transmitted. The selected lines will be low prior to transmission and go high during the transmission.

The *TLF3000* unit has 8 digital output lines. Lines 2 to 7 are available for signalling modulated interferer transmission. Lines are selected by toggling 'X' to '1' in the appropriate box.

If a digital output line is specified as monitoring both wanted signal transmissions and modulated interferer transmissions, then the state of the line is the logical OR of the two signals.

The IO voltage for the lines may be either:

1.   An internal 3.3 V generated supply
2.   An external supply in the range 0.8 V to 3.6 V

The selection of the IO voltage is performed under 'Hardware trigger'

7.5   Programming the in-band CW signal

7.5.1   Overview

Sapphire can generate an in-band (i.e. 2395 MHz to 2485 MHz) CW interferer signal. This signal is required to perform receiver intermodulation tests.

To turn the in-band CW interferer signal on or off, toggle the switch to the left of the 'In-band CW' text.

To program the in-band CW interferer signal, expand the 'In-band CW' signal menu by clicking on it:

Figure 8: Programming the in-band CW interferer signal.

7.5.2 Frequency

The frequency of the in-band CW interferer signal can be set by:

1. Using the channel number spin box
2. Using the frequency spin box

As with all spin boxes, adjustment can be performed either by using the up/down arrows or by entering a numeric value into the text field.

The frequency can be set to any integer MHz between 2395 MHz and 2485 MHz inclusive. Odd MHz frequencies do not coincide with LE channels, so are donated by LE channels plus 0.5. Channel numbers are extended beyond the range 0 to 40 to encompass frequencies outside the range 2402 to 2480 MHz.

7.5.3 Amplitude

The amplitude of the in-band CW interferer signal can be adjusted from -120 dBm to 0 dBm. The total combined output power of the unit within the 2.4 GHz ISM band is 0 dBm. Therefore, if other signals are active, the maximum output power for the in-band CW interferer signal will be reduced to maintain the peak output power within the 0dBm limit.

7.6 Programming the out-of-band CW signal

Sapphire can generate an out-of-band CW interferer signal. This signal is required to perform receiver blocking tests.

To turn the out-of-band CW interferer signal on or off, toggle the switch to the left of the 'Out-of-band CW' text.

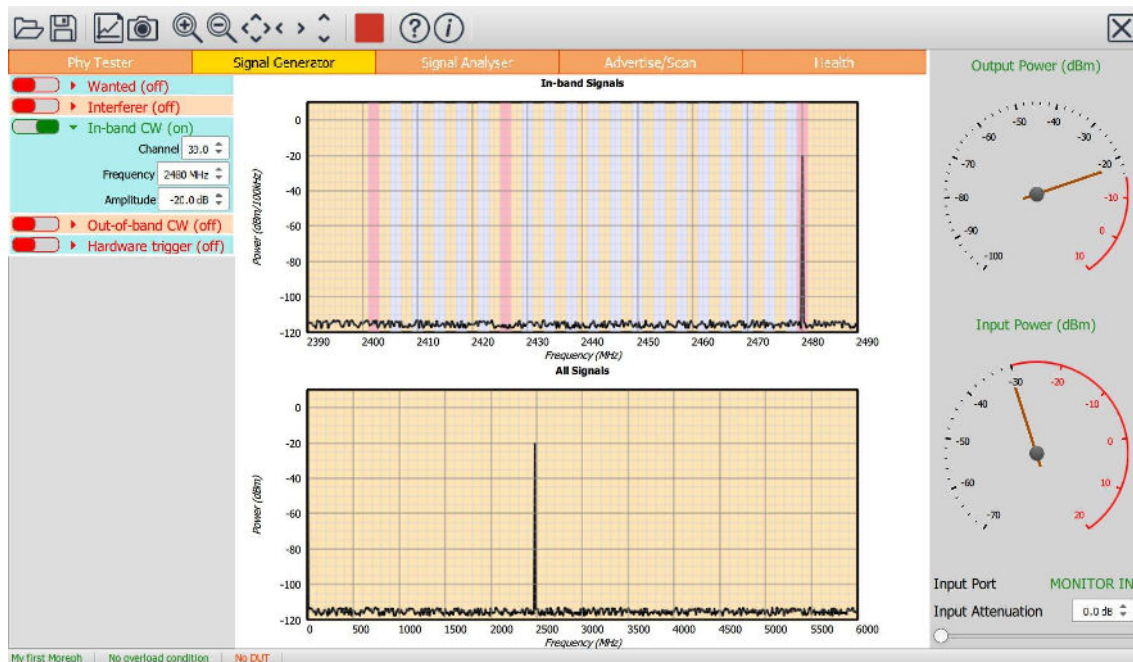To program the out-of-band CW interferer signal, expand the 'Out-of-band CW' signal menu by clicking on it:
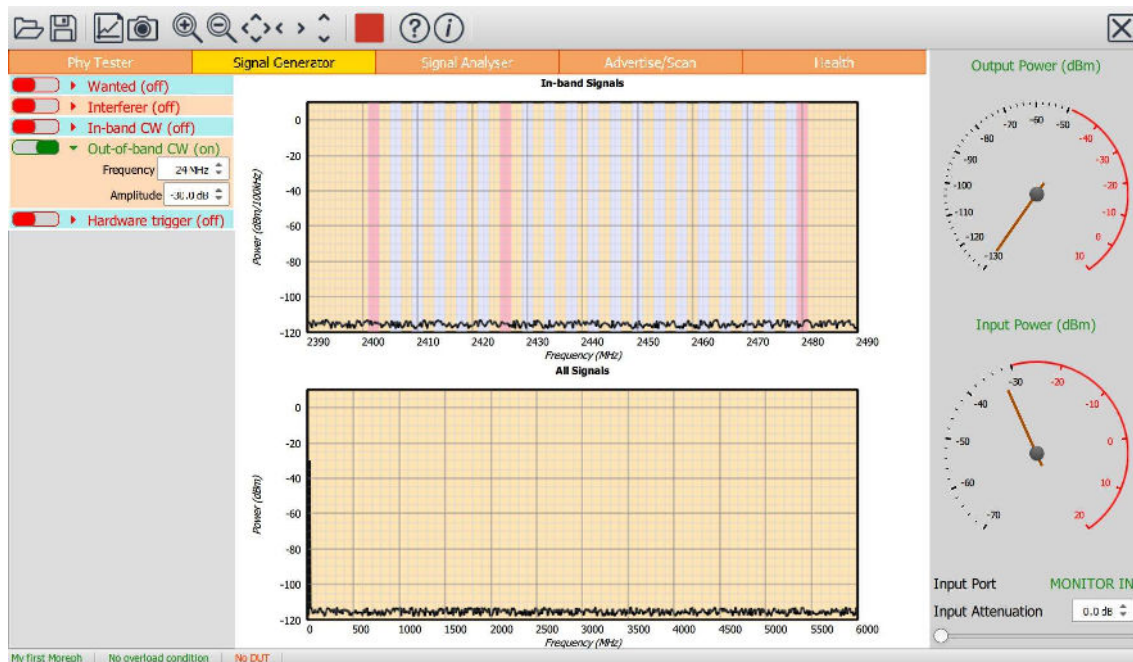
Figure 9: Programming the out-of-band CW interferer signal.

7.6.1   Frequency

The frequency of the out-of-band CW interferer signal can be set by using the frequency spin box. The frequency can be set to any integer MHz between 24 MHz and 6 GHz.

The Bluetooth 5 LE RF Phy Test Specification requires that the blocker frequency be swept from 30 MHz to 12.75 GHz. The Sapphire application cannot provide the blocker frequencies above 6 GHz. The 6 GHz upper limit does encompass the second harmonic of the 2.4 GHz band, therefore it is unlikely that a device which passes the blocking test below 6 GHz will fail above 6 GHz. However, this one of the two areas where the test coverage of the Sapphire application does not meet the full Bluetooth 5 LE RF Phy Test Specification.

7.6.2   Amplitude

The amplitude of the out-of-band CW interferer signal can be adjusted from -50 dBm to -28 dBm.

The amplitude of the out-of-band CW interferer signal does not impact the maximum amplitude of the in-band signals. The energy of the out-of-band CW interferer signal is excluded from the power indicated by the 'Output power' gauge in the monitor panel.

7.7   Hardware trigger

7.7.1   Overview

The signal generator output can be started or stopped by toggling the 'Play' button on the toolbar. It is also possible to start or stop the signal generator by toggling digital input lines. This feature is useful if the signal generator must be synchronised with other test equipment.

To enable control of the signal generator from the digital input lines, toggle the switch to the left of the 'Hardware trigger' text.

To program the hardware trigger feature, expand the 'Hardware trigger' menu by clicking on it:
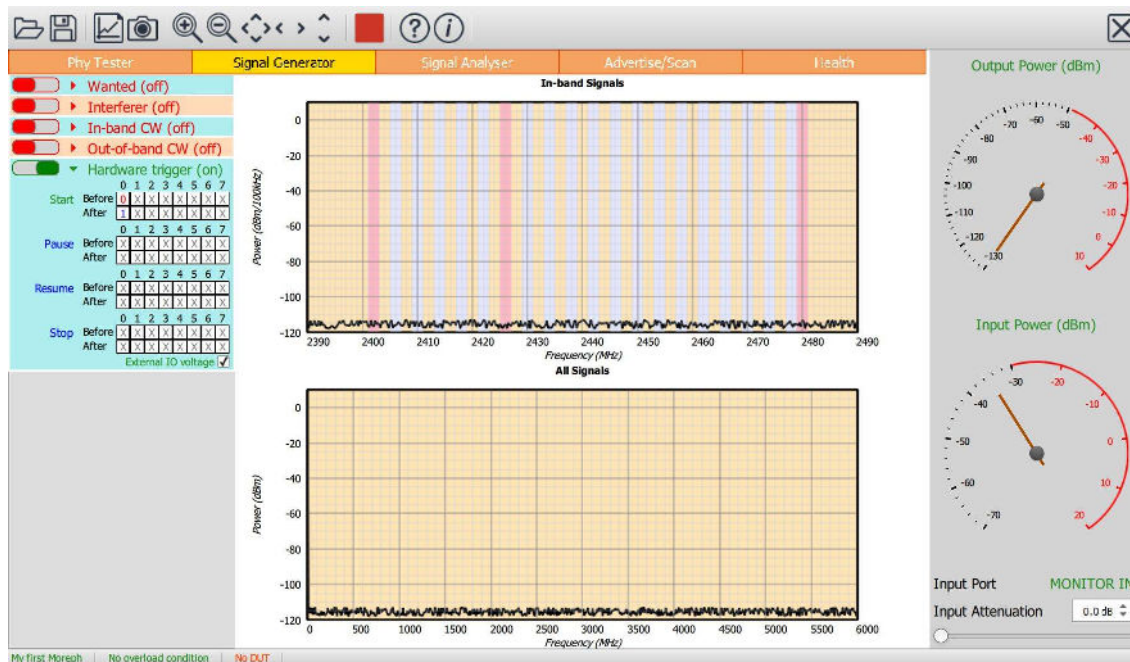
Figure 10: Programming the hardware trigger feature.

7.7.2 Starting the signal generator via digital input lines

The hardware trigger menu contains an item labelled 'Start', to the right of which is a table of two rows and 8 columns. Each column in the table represents a digital input line. The top row in the table indicates the state the digital input lines must be in prior to the signal generator starting. The bottom row in the table indicates the state the digital input lines must be in after the signal generator has started. A '0' indicates the corresponding line must be low, a '1' indicates the line must be high and an 'X' indicates 'don't care'. If the digital input lines transition from a state which matches the 'before' row to a state which matches the 'after' row and the signal generator was in the stopped state, then the signal generator will be started.

When the digital signal generator is started, all the selected signals are turned on. The signal generator will then start to issue the specified number of LE packets, if the 'Wanted' signal has been selected.

7.7.3 Pausing the signal generator via digital input lines

The hardware trigger menu contains an item labelled 'Pause', to the right of which is a table of two rows and 8 columns. Each column in the table represents a digital input line. The top row in the table indicates the state the digital input lines must be in prior to the signal generator pausing. The bottom row in the table indicates the state the digital input lines must be in after the signal generator has paused. A '0' indicates the corresponding line must be low, a '1' indicates the line must be high and an 'X' indicates 'don't care'. If the digital input lines transition from a state which matches the 'before' row to a state which matches the 'after' row and the signal generator was in the running state, then the signal generator will be paused.

When the digital signal generator is paused, all the selected signals are turned off. If the 'Wanted' signal has been selected, then the number of LE packets already transmitted is remembered.

7.7.4 Resuming the signal generator via digital input lines

The hardware trigger menu contains an item labelled 'Resume', to the right of which is a table of two rows and 8 columns. Each column in the table represents a digital input line. The top row in the table indicates the state the

digital input lines must be in prior to the signal generator resuming. The bottom row in the table indicates the state the digital input lines must be in after the signal generator has resumed. A '0' indicates the corresponding line must be low, a '1' indicates the line must be high and an 'X' indicates 'don't care'. If the digital input lines transition from a state which matches the 'before' row to a state which matches the 'after' row and the signal generator was in the paused state, then the signal generator will resume operation..

When the digital signal generator resumes operation, all the selected signals are turned on. If the 'Wanted' signal has been selected, then the signal generator will start transmitting the number of packetized LE signals which were remaining when the previous 'Pause' was issued.

7.7.5   Stopping the signal generator via digital input lines

The hardware trigger menu contains an item labelled 'Stop', to the right of which is a table of two rows and 8 columns. Each column in the table represents a digital input line. The top row in the table indicates the state the digital input lines must be in prior to the signal generator stopping. The bottom row in the table indicates the state the digital input lines must be in after the signal generator has stopped. A '0' indicates the corresponding line must be low, a '1' indicates the line must be high and an 'X' indicates 'don't care'. If the digital input lines transition from a state which matches the 'before' row to a state which matches the 'after' row then the signal generator will stop, irrespective of the state it was previously in.

When the digital signal generator is stopped, all the selected signals are turned off. If the 'Wanted' signal has been selected, then the number of LE packets transmitted is reset to zero.

7.7.6   Saving and restoring settings

The current collection, analysis and limit settings can be saved by clicking the 'Save' button on the toolbar. Select the 'Signal generator settings (*.sgs)' file type to save the current settings.

An existing signal generator settings file (*.sgs) can be opened using the 'Open' button on the toolbar.

The signal generator settings file (*.sgs) is an XML file. It is not recommended that this file be edited manually. If it needs to be modified, open it from the signal generator, modify the required parameters and re-save.

8 Signal Analyzer Mode.

8.1 Overview

In signal analyzer mode, the Sapphire application is able to analyze incoming signals against the Bluetooth 5 LE RF Phy Specification. The application is able to analyze both conducted and off-air signals. The analysis can be performed on LE test packets or can be payload agnostic. All 40 LE channels are monitored simultaneously, as are all four of the LE RF phys defined in Bluetooth 5. Hence there is no requirement to program the signal analyzer to look on a specified channel or to look for a specified phy. The signal analyzer accumulates results separately for each channel, modulation scheme and packet length. This permits the results to be filtered and displayed in a number of different ways.

The left hand mode control panel is divided into two separate tabs:

1. *Collection*. This tabs contains the parameters which define which signals will be collected and processed.
2. *Analysis*. This tabs contains the parameters which define how the captured results will be displayed.

The central graphics area is used to plot the results in a manner defined by the parameters under the analysis tab.

Below the analysis tab is a results table which displays statistics of the test quantities defined in the Bluetooth 5 LE RF Phy Test Specification. These results are filtered by the parameters set under the 'Analysis' tab in the mode control panel. *If no results are displayed this may be because the analysis filter settings are inconsistent with the packet being received.*

The receiver port and front-end attenuation are set using the controls in the monitor panel on the right hand side of the window.

Data collection is started/stopped by toggling the 'Play' button in the toolbar.

The 'Clear' button in the toolbar will discard all results which have been collected.

Figure 11: Sapphire GUI signal analyzer mode.

8.2 RF connections

The signal analyzer can monitor signals on either the 'Tx/Rx' port or the 'Monitor In' port. See section 8.3.9 on setting the RF input port.

8.3 Programming data collection

8.3.1 Overview

The data to be collected is determined the settings of the parameters under the 'Collection' tab of the mode control panel on the left hand side of the window.

It is possible to select:

1. Which Bluetooth 5 LE test quantities are to be measured
2. Which Bluetooth 5 LE phys are of interest
3. Which RF channels are of interest
4. Which packet lengths are of interest
5. The access address of the packets to be analyzed
6. Whether the packets to be analyzed are whitened
7. A minimum RSSI for collected packets
8. When the data analysis should terminate

8.3.2 Programming the measurements to be performed

Sapphire divides the Bluetooth LE RF phy transmitter test measurements into five groups:

1. Power measurements, which includes:
   a. P_{avg}
   b. $Pk - P_{avg}$
2. Modulation characteristics, which includes:
   a. $\Delta F1max$
   b. $\Delta F1avg$
   c. $\Delta F2max$
   d. $\Delta F2avg$
   e. $\Delta F2avg / \Delta F1avg$
   f. $\Delta F2max\,99.9\%$
3. Drift and carrier offset measurements, which includes:
   a. F_0
   b. F_n
   c. $|F_1 - F_0|$ or $|F_3 - F_0|$ for 125 kbps
   d. $|F_0 - F_n|$
   e. $|F_n - F_{n-5}|$ or $|F_n - F_{n-3}|$ for 125 kbps
4. In-band emissions, which includes:
   a. $F_{tx}\pm\,2MHz$ or $F_{tx}\pm(4,5)MHz$ for 2 Mbps
   b. $F_{tx}\pm\,(3+n)MHz$ or $F_{tx}\pm(6+n)MHz$ for 2 Mbps
   c. Number of exceptions
   d. Maximum exception
5. AoA/AoD

Each of these groups of measurements can be individually selected under the 'Collect' menu of the 'Collection' tab.

If the 'waveform' item is selected, then raw IQ data for the last packet analyzed is also saved. The raw IQ data is 32x oversampled, as per the Bluetooth 5 LE RF Phy Test Specification. Although it is possible to alter the oversampling ratio using the native language, this is currently not supported in the Sapphire GUI. If the 'waveform' item is selected, the volume of data which needs to be transferred to the host is large. This may have an impact on the rate at which packets can be analyzed. If it is important to analyze packets as fast as possible, then it is advisable to disable collection of raw IQ data.

The Bluetooth 5 LE RF Phy Test Specification requires the use of test packets. These packets have the 0x71764129 access address, a predefined header and one of 8 possible payloads. To enable less restrictive testing, Sapphire supports an 'Off-air' analysis mode. The 'Off-air' analysis mode is header and payload agnostic, but still provides good approximations to the quantities defined in the Bluetooth 5 LE RF Phy Test Specification. The 'Off-air' mode also performs analyzes of the packet's preamble, access address, header, payload and CRC. Any LE packet can be analyzed in the 'Off-air' mode. The 'Off-air' mode does impose a greater processing load on the *TLF3000* unit.

Results for the "Off-air" mode are held separately from those of the conventional test packet mode. **If both off-air and conventional test packet results have been collected, make sure that analysis tab 'Off-air' mode has been set accordingly to ensure the anticipated results are displayed.**

Figure 12: Sapphire GUI signal analyzer mode.

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8.3.3   Programming which RF Phys to collect

The 'Modulation' menu permits selection of which RF Phys are to be collected and processed. One or more of the following can be selected:

a.   2 Mbps, GFSK

b.   1 Mbps, GFSK

c.   500 kbps, s=2 spreading, GFSK

d.   125 kbps, s=8 spreading, GFSK

The results for each RF Phy are accumulated separately.
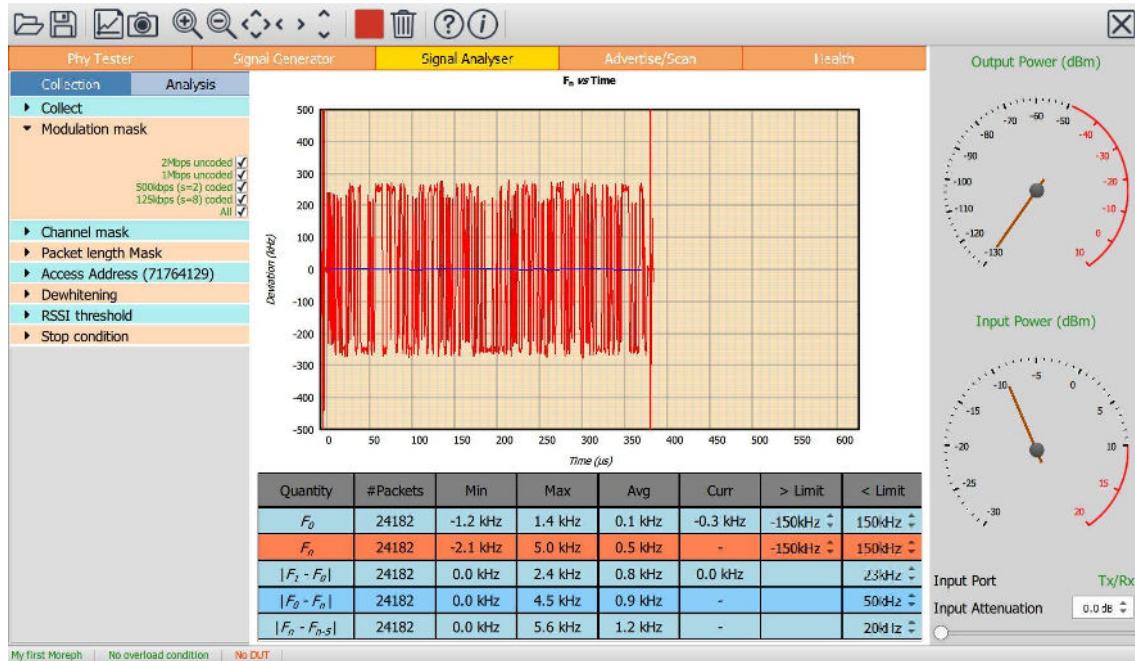
Figure 13: Programming which RF phys to collect.

8.3.4 Programming which RF channels to collect

The 'Channel' menu permits the RF channels on which data is to be collected and processed to be defined. *Note: these are RF channel numbers, not LE channel indices.*

The required RF channels can be selected by either:

1. Ticking the individual channel boxes
2. Using the quick channel group selection buttons:
    a. Clear all
    b. Select all
    c. Primary advertising
    d. Data/Secondary advertising
3. Entering a textual description

The textual description must be of the form:

$a_{start}:a_{step}: a_{stop}, b_{start}: b_{step}: b_{stop}, ...$

This implies that all channels from a_{start} to a_{stop} in steps of a_{step} will be selected, plus all channels from b_{start} to b_{stop} in steps of b_{step}, etc.

If a_{step} is unity, then $a_{start}:a_{step}: a_{stop}$ can be abbreviated to $a_{start}: a_{stop}$.

If a_{step} is equal to a_{stop} then $a_{start}:a_{step}: a_{stop}$ can be abbreviated to a_{start}.

Figure 14: Programming which RF channels to collect.

8.3.5 Programming which packet lengths to collect

The 'Packet length' menu permits the LE packet lengths for which data is to be collected and processed to be defined.

Due to memory restrictions, individual packet lengths cannot be specified. Instead, the range of possible packet lengths is divided up into 32 groups, each group spanning 8 contiguous packet lengths.

The required packet lengths are selected by ticking the corresponding boxes. If all packet lengths are of interest, then clicking the 'All' box at the bottom of the menu will select all packet length groups.
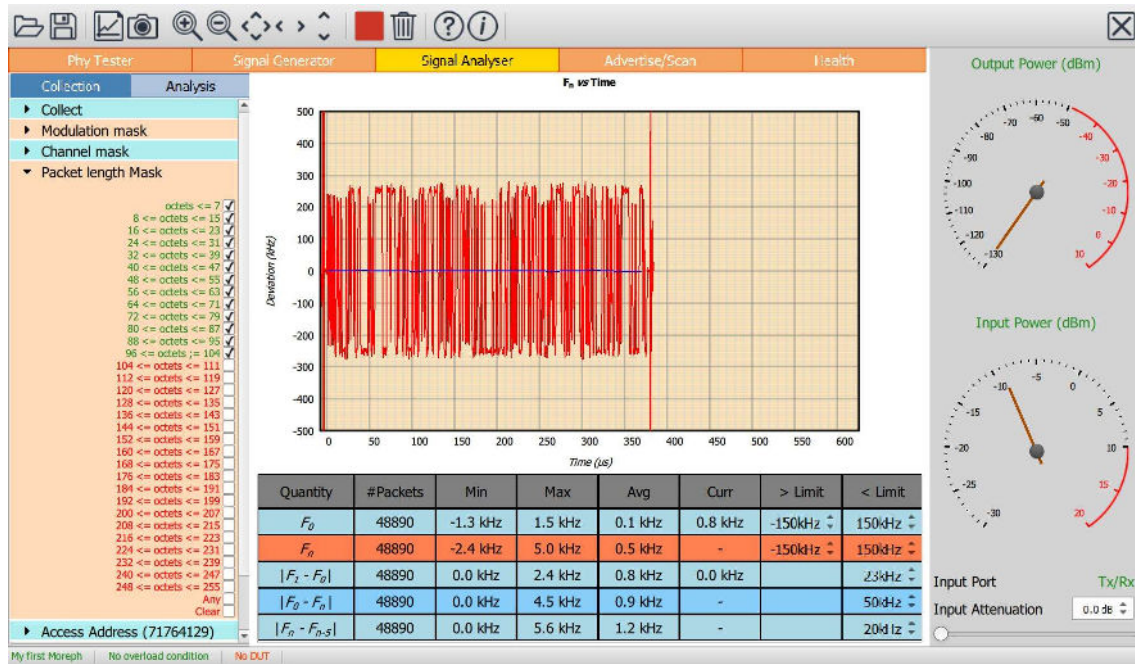
Figure 15: Programming which packet lengths to collect.

8.3.6 Programming which access address to collect

Sapphire's signal analyzer will only collect and process packets with a specified access address. The access address to use is defined under the 'Access Address' menu.

Changing the access address can be useful under the following circumstances:

1. When it is necessary to collect and analyze off-air packets
2. When multiple test units are running simultaneously on a production line or characterisation rig and it is desired to minimise cross-interference

Note that Sapphire completely decouples the use of the test access address ($0x71764129$) from the contents of the packet. Sapphire can analyze any packet with the test access address, or can analyze test packet with access addresses other than the test access address.

The access address menu allows direct selection of either the advertising access address of the test access address through check boxes. It is also possible to enter an arbitrary access address by directly editing the text field at the bottom of the menu. Sapphire does not make any checks between the arbitrary access address entered by the user and the constraints on access addresses set out in the Bluetooth 5 Core Specification.

Figure 16: Programming which access address to collect.

8.3.7 Programming de-whitening of the packet

The Bluetooth 5 RF Phy Test Specification uses un-whitened test packets with the test access address (0x71764129). However, if it is desired to analyze packets off-air, it is likely that these will have had whitening applied. It is therefore necessary to inform the Sapphire data collection whether to expect whitened or un-whitened packets.

The selection of whether to process the packets as whitened or un-whitened is done via the single checkbox under the 'Dewhitening' menu.
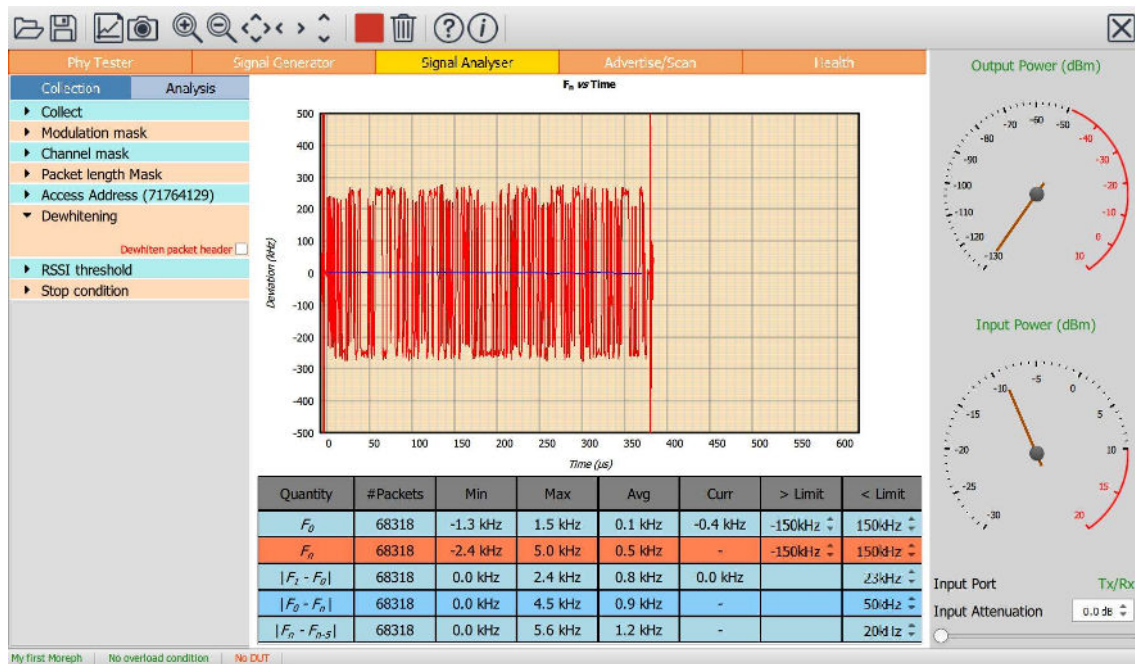
Figure 17: Programming de-whitening of the packet.

8.3.8   Programming the RSSI threshold

The signal analyser will attempt to capture all signals with the specified access address provided they satisfy both the selected channel and packet length criteria. Without any further selectivity, the *TLF3000* is more than capable of capturing signals from distant devices as well as the device under test. To help filter out unwanted devices, an RSSI threshold can be set. Only those packets with signal strengths above the RSSI threshold will be captured and analysed. The RSSI threshold can be set in the range -120dBm to +20dBm. The lower limit effectively disables the RSSI threshold.
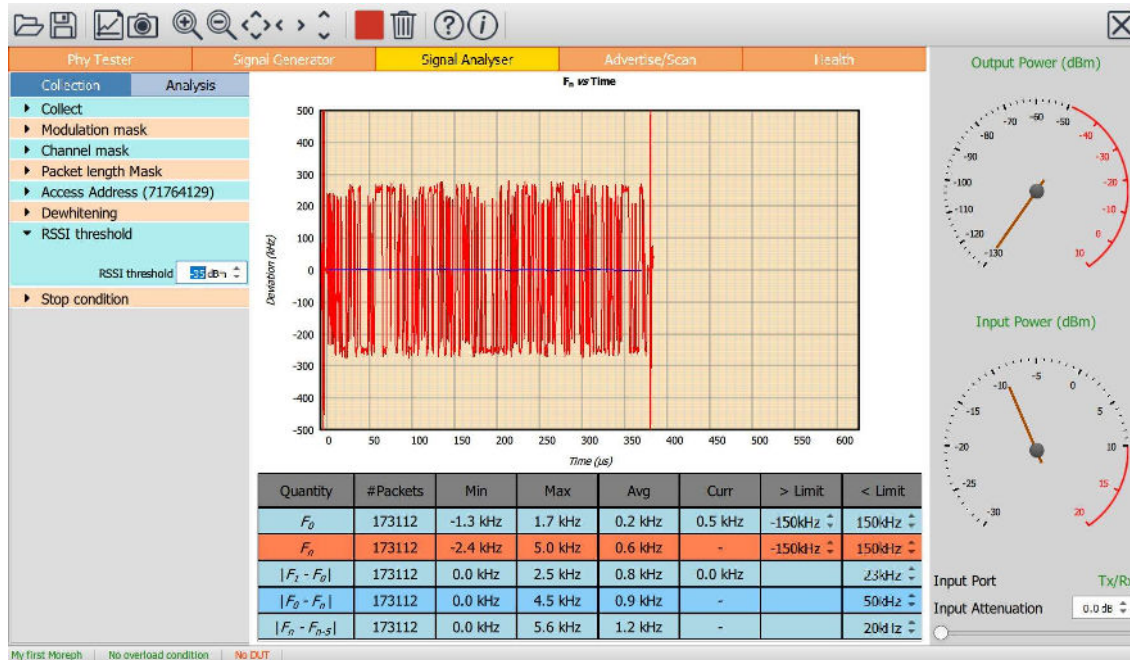
Figure 18: Programming the RSSI threshold

8.3.9   Programming the termination criterion

Once the signal analyzer has been started by toggling the 'Play' button in the toolbar, it will continue to collect, process and display data until either:

1. The 'Stop' button in the toolbar is toggled
2. The stop condition has been set to 'Stop on test failure' and a test limit is failed

The 'Stop on test failure' condition is set by the single checkbox under the 'Stop condition' menu.

The test limits are shown in the results table. The penultimate column of the results table displays the lower limit and the final column the upper limit. They can be altered by changing the values in the spin boxes, either by using the up/down arrows or by entering numeric text directly.

Some limit values are shared between different modulation schemes whilst others are specific to a modulation scheme. The table below shows whether limits values are shared or are specific for each test category and modulation scheme:

Test	Modulation			
	2 Mbps	1 Mbps	500 kbps	125 kbps
Power	Shared	Shared	Shared	Shared
Modulation	2Mbps specific	Shared	Shared	125 kbps specific
Drift & carrier offset	Shared	Shared	LR specific	LR specific
In-band emissions	2 Mbps specific	Shared	Shared	Shared

Table 4: Table expressing whether limits values are shared or specific for each test category and modulation scheme.

The limit values shown in the results table apply to the modulation scheme currently selected in the 'Modulation' menu under the 'Analysis' tab.

When a limit fail is detected, and the stop condition has been set to 'Stop on test failure', then the GUI will automatically alter its graphics and tabular display to reflect the quantity that failed. It is possible that a rogue packet will fail more than one test limit, so the data displayed may only partially reflect the reason why the packet failed.

If waveform collection has been enabled under the 'Collect' menu, then the IQ data displayed refers to the packet which failed. This provides an invaluable mechanism for catching rogue packets, particularly when monitoring links off-air, and then determining where in the packet the problem occurred.

Figure 19: Programming the termination criterion.

8.3.10 Selecting the RF input port

The signal analyzer can monitor signals on either the 'Monitor In' RF port or the 'Tx/Rx' RF port. The selection of which port is used is made clicking the port displayed towards the bottom of the monitor panel.

The Monitor In port is designed for monitoring signals off-air. The Tx/Rx port is designed for conducted measurements.

If the monitor panel shows a lack of RF input energy, check that the DUT is connected to the same RF port as selected by the label at the bottom of the monitor panel.

8.3.11 Adjusting the RF frontend attenuation

The RF frontend attenuation is set via either:

1. The slider at the bottom of the monitor panel
2. The spin box at the bottom of the monitor panel

The RF frontend attenuation can be set between 0 and 31.5 dB in steps of 0.5 dB.

To set the RF attenuation, the 'Input Power' gauge on the monitor panel must be examined. This shows both the current input signal level (the position of the needle) and the point at which saturation of the *TLF3000* receiver will occur (the red arc). The RF attenuation should be adjusted such that the input signal level is just below the saturation level.

If too little attenuation is applied, then there is a danger that the *TLF3000* receiver will be overloaded. An overload condition on the receiver is indicated by:

1. The needle on the 'Input Power' gauge on the monitor panel entering the region of the red arc (the input power measurement is only approximate so this is only a rough guide)
2. The title of the 'Input Power' gauge on the monitor panel turning red
3. The text 'Rx overload' appearing in red within the status bar at the bottom of the window

If too much attenuation is applied, then the test results may become unreliable. In order to calculate the frequency deviation within a packet, an FM demodulation process is employed. The quality of the output of the FM demodulation process is critically dependent on the signal-to-noise ratio of the signal at the input to the demodulator. If too much attenuation is applied, then the signal to be analyzed will be pushed down towards the *TLF3000* receiver noise floor and the accuracy of the test results will be compromised.

8.4 Controlling data analysis and presentation

8.4.1 Overview

The Sapphire application accumulates results independently for each:

1. LE RF phy
2. LE RF channel
3. Packet length group

In addition, results are accumulated separately for the 'Off-air' mode. The 'Analysis' tab in the mode control panel determines how these results are filtered and displayed. *If no results are displayed, then it is possible that the current analysis filter does not correspond to any of the packets which have been collected.*

The 'Measurement' menu under the 'Analysis' tab determines which group of measurements will be displayed.

The displayed results are filtered according to the settings of the 'Modulation', 'Channel' and 'Packet length' menus.

The graphics area shows a plot of one of the test quantities. This may be selected either through the 'Plot' menu or by highlighting a row in the results table. The 'Plot' menu also defines the format of the plot.

The results table shows the filtered results for the selected measurement group. It also contains the test limits.

8.4.2   Selecting the measurement group to display

Sapphire divides the Bluetooth LE RF phy transmitter test measurements into five groups:

1. Power measurements, which includes:
   a. *Pavg*
   b. *Pk - Pavg*
2. Modulation characteristics, which includes:
   a. *ΔF1max*
   b. *ΔF1avg*
   c. *ΔF2max*
   d. *ΔF2avg*
   e. *ΔF2avg / ΔF1avg*
   f. *ΔF2max 99.9%*
3. Drift and carrier offset measurements, which includes:
   a. *Fo*
   b. *Fn*
   c. *|F1 – F0 | or |F3 – Fo | for 125 kbps*
   d. *|F0 – Fn |*
   e. *|Fn – Fn-5 | or |Fn – Fn-3 | for 125 kbps*
4. In-band emissions, which includes:
   a. *Ftx± 2MHz or Ftx±(4,5)MHz for 2 Mbps*
   b. *Ftx± (3+n)MHz or Ftx±(6+n)MHz for 2 Mbps*
   c. *Number of exceptions*
   d. *Maximum exception*
5. AoA/AoD

The Sapphire GUI displays the results from just one of these measurement groups at any one time. The selection of which measurement group to display is accomplished through the 'Measurement' menu under the 'Analysis' tab.

The Sapphire application stores results separately for the 'Off-air' mode. The 'Off-air' check box in the 'Measurement' menu is used to select results which were collected in the 'Off-air' mode.

If no results are displayed, then it is possible that no packets have been received or that the analysis measurement group selected is incompatible with the choice of collection measurement group(s).

Figure 20:: Selecting the measurement group to display.

8.4.3 Filtering the displayed results by RF phy

The displayed results are filtered by the RF phy. Only the results from one RF phy can be displayed at any one time. This restriction is due to the fact that different test limits are applicable to the different RF phys.

The RF phy filter is accessible from the 'Modulation' menu under the 'Analysis' tab. There is a separate checkbox for each RF phy.
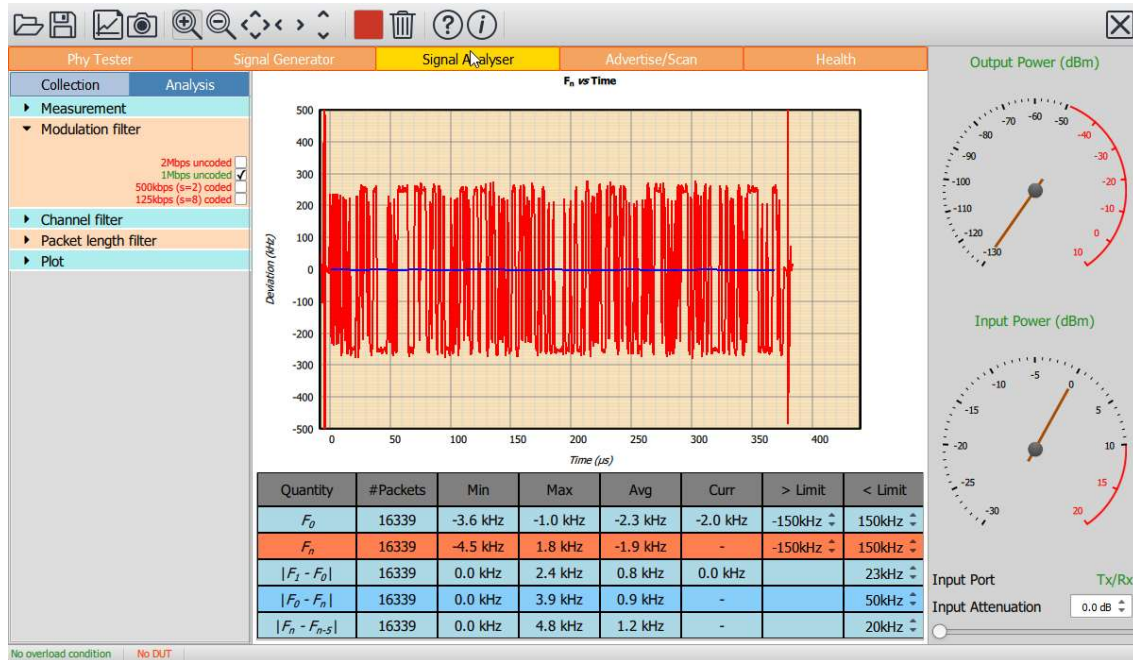
Figure 21: Filtering displayed results by RF phy.

8.4.4 Filtering the displayed results by RF channel

The displayed results can be filtered by RF channel number. This facility may be useful when monitoring a live link and it is suspected that there is a problem with packet transfer on a particular RF channel. It also provides a simple means of comparing test results on different RF channels.

The RF channels used to filter the results are selected via the 'Channel' menu under the 'Analysis' tab. *Note that the filtering is by RF channel number and not LE channel index.*

The required RF channels can be selected by either:

1. Ticking the individual channel boxes
2. Using the quick channel group selection buttons:
   a. Clear all
   b. Select all
   c. Primary advertising
   d. Data/Secondary advertising
3. Entering a textual description

The textual description must be of the form:

a_{start}:a_{step}: a_{stop}, b_{start}: b_{step}: b_{stop}, …

This implies that all channels from a_{start} to a_{stop} in steps of a_{step} will be selected, plus all channels from b_{start} to b_{stop} in steps of b_{step}, etc.

If a_{step} is unity, then $a_{start}\!:\!a_{step}\!:\!a_{stop}$ can be abbreviated to $a_{start}\!:\!a_{stop}$.

If a_{step} is equal to a_{stop} then $a_{start}\!:\!a_{step}\!:\!a_{stop}$ can be abbreviated to a_{start}.

Figure 22:: Filtering displayed results by RF channel.

8.4.5 Filtering the displayed results by packet length

The displayed results can be filtered by packet length. This provides a simple facility for monitoring transmitter quality as a function of packet length.

Due to memory restrictions, individual packet lengths cannot be specified. Instead, the range of possible packet lengths is divided up into 32 groups, each group spanning 8 contiguous packet lengths.

The packet length filtering is specified via the 'Packet length' menu under the 'Analysis' tab. The required packet lengths are selected by ticking the corresponding boxes. If all packet lengths are of interest, then clicking the 'All' box at the bottom of the menu will select all packet length groups.

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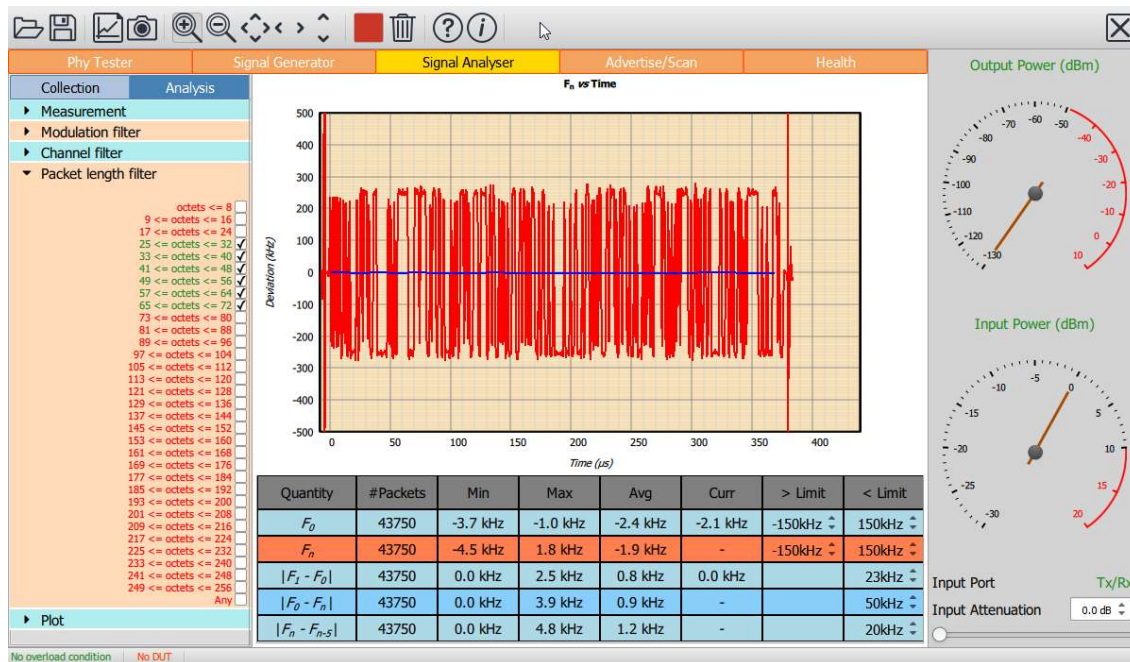
Figure 23: Filtering displayed result by packet length.

8.4.6   Understanding the results table

The results table contains a summary of the results obtained from the selected measurement group when filtered by the selected RF phy, RF channel and packet length.

The first column in the table contains the quantities defined in the Bluetooth 5 LE RF Test Specification which are members of the currently selected measurement group.

The second column in the table contains the number of packets which have contributed to the results for each measured quantity.

The third and fourth columns contain the minimum and maximum values which have been observed for each measured quantity.

The fifth column contains the average value of the measured quantity overall packets. If the units of the measured quantity are dBm or dB, then the average is the average of the dB values, not an average of the powers or linear ratios.

If the measured quantity is a scalar quantity, i.e. it has a single value per packet, then the last measured value is displayed in the sixth column.

For scalar quantities with test limits, the lower limit is contained in column seven and the upper limit in column eight.

Quantity	#Packets	Min	Max	Avg	Curr	> Limit	< Limit
ΔF_{1max}	557204	478.2 kHz	530.6 kHz	504.6 kHz	-		
ΔF_{1avg}	557204	500.9 kHz	502.6 kHz	499.8 kHz	501.5 kHz	450kHz ↕	550kHz ↕
ΔF_{2max}	557204	413.0 kHz	499.8 kHz	458.4 kHz	-		
ΔF_{2avg}	557204	455.5 kHz	458.5 kHz	459.9 kHz	456.3 kHz		
$\Delta F_{2avg}/\Delta F_{1avg}$	557204	0.907	0.914	0.907	0.910	0.80 ↕	
ΔF_{2max} 99.9%	557203	409.6 kHz	409.6 kHz	411.6 kHz	409.6 kHz	370kHz ↕	

Figure 24: The results table.

When the selected filters include more than one RF channel or packet length group, then the displayed values of minimum, maximum and average are the minimum, maximum and average overall packets which satisfy the selected filtering parameters.

If no measurement is available, then the symbol '-' is used to fill the corresponding table cell.

If a cell exceeds one of its test limits, then that cell is highlighted in red.

It is possible to select a row in the table by clicking on it. Once a row has been selected, the corresponding quantity will be plotted in the graphics areas. The format of the plot is controlled by the 'Plot' menu under the 'Analysis' tab.

8.4.7   Controlling the graphical data

8.4.7.1   Overview

The graphical data being displayed is controlled by the 'Plot' menu under the 'Analysis' tab. The left hand combo box lists all the quantities which are measured for the current measurement group (which is selected under the 'Measurement' menu of the 'Analysis' tab). These are the same quantities as displayed in the first column of the results table. The quantity to be plotted can be selected either through the combo box or by highlighting the appropriate row in the results table.

The right had combo box under the 'Plot' menu determines how the measured quantity is to be plotted. Options may include:

1. vs channel
2. vs RF phy
3. vs packet length group
4. as a histogram
5. vs time (not available for in-band emission measurements)
6. vs frequency (only available for in-band emission measurements)

The screen update period can also be altered via the 'Plot' menu.

8.4.7.2   vs channel

The quantity to be plotted is shown as a function of the RF channel number. For each RF channel the following quantities are displayed:

1. minimum observed value (bottom of pink bar)
2. average value (junction of red and pink bars)

3. maximum observed value (top of red bar)
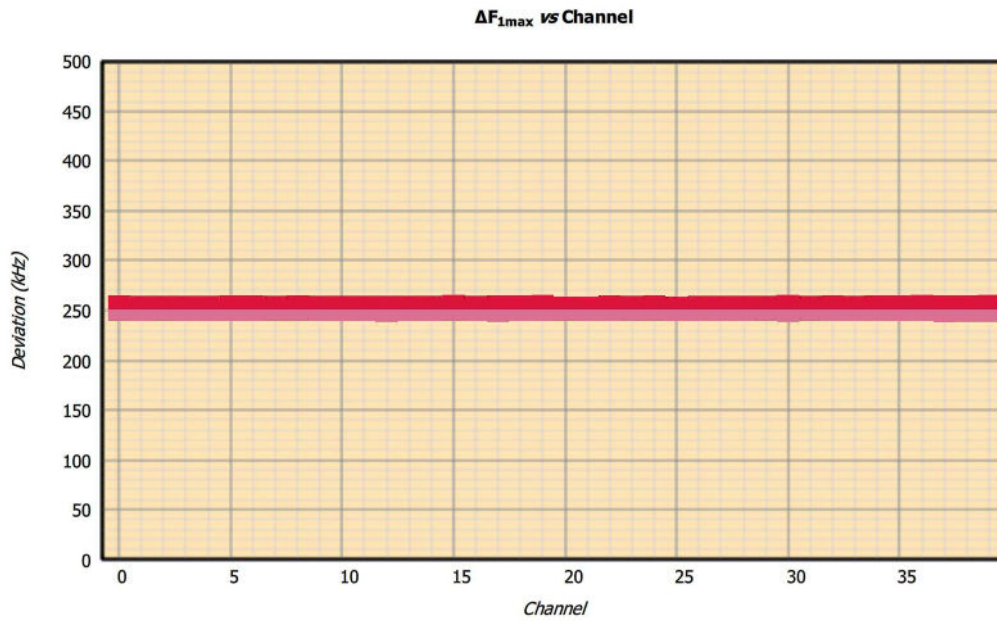
Figure 25: Results vs channel

8.4.7.3 ▰▰▰▰

The quantity to be plotted is shown as a function of the RF phy. For each RF phy the following quantities are displayed:

1. minimum observed value (bottom of pink bar)
2. average value (junction of red and pink bars)
3. maximum observed value (top of red bar)
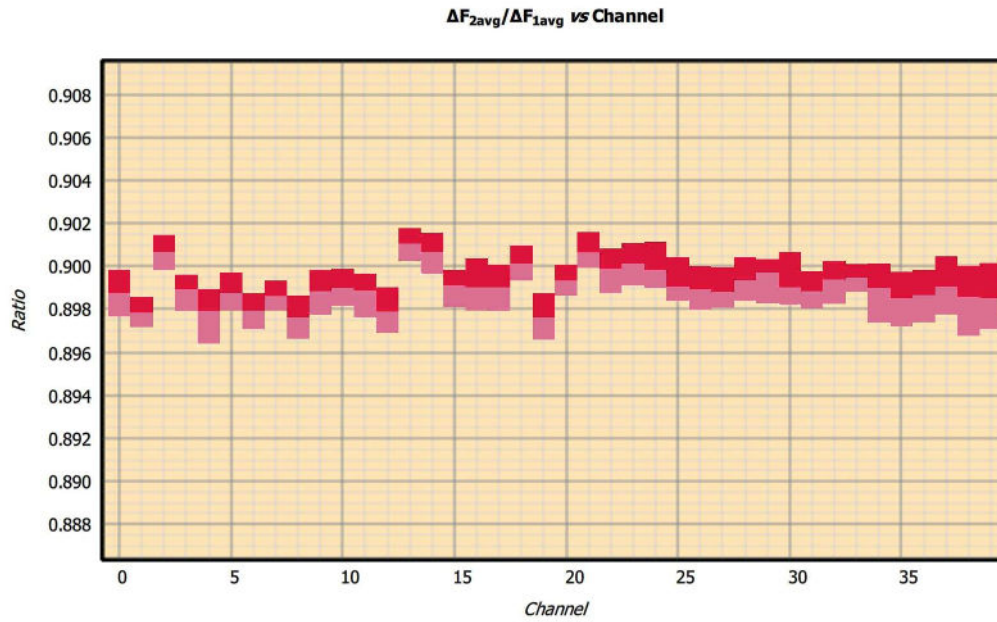
Figure 26: Results vs RF phy.

8.4.7.4 ~~packet-length-Group~~

The quantity to be plotted is shown as a function of the packet length group. For each packet length group the following quantities are displayed:

1. minimum observed value (bottom of pink bar)
2. average value (junction of red and pink bars)
3. maximum observed value (top of red bar)
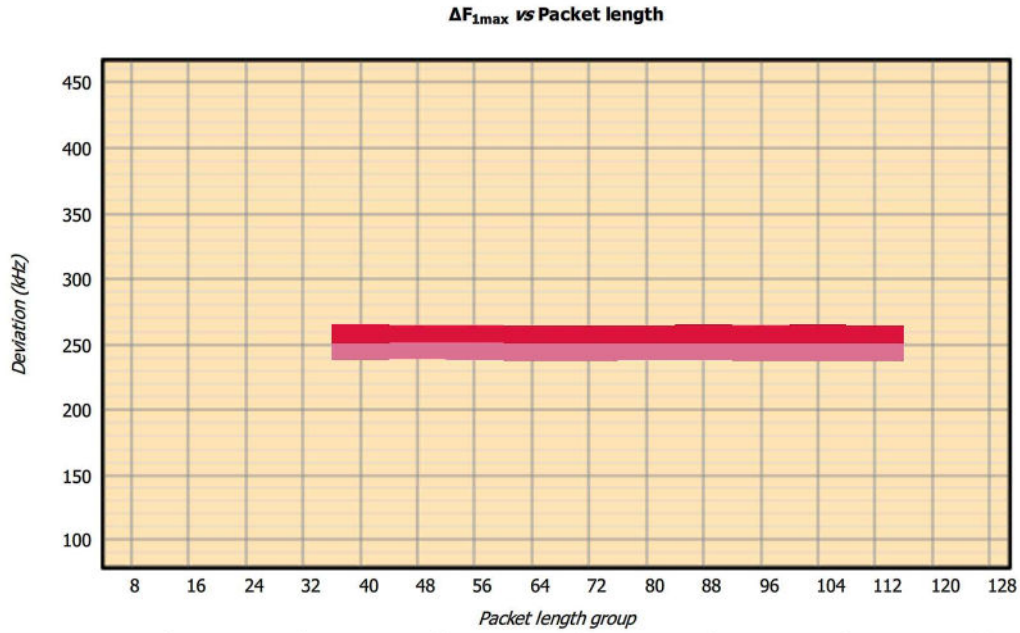
Quantity	#Packets	Min	Max	Avg	Curr	> Limit	< Limit
ΔF_{1max}	4441	237.5 kHz	265.8 kHz	251.1 kHz	-		
ΔF_{1avg}	4441	250.8 kHz	251.6 kHz	251.1 kHz	251.0 kHz	225kHz $\updownarrow$	275kHz $\updownarrow$
ΔF_{2max}	4441	204.4 kHz	247.8 kHz	225.7 kHz	-		
ΔF_{2avg}	4441	225.0 kHz	226.5 kHz	225.7 kHz	225.1 kHz		
$\Delta F_{2avg}/\Delta F_{1avg}$	4441	0.896	0.902	0.899	0.898	0.80 $\updownarrow$	
ΔF_{2max} 99.9%	4400	204.6 kHz	209.5 kHz	207.1 kHz	207.0 kHz	185kHz $\updownarrow$	

Figure 27: Results vs packet length group.

8.4.7.5 ~~Histogram~~

A histogram of the plotted quantity is displayed.
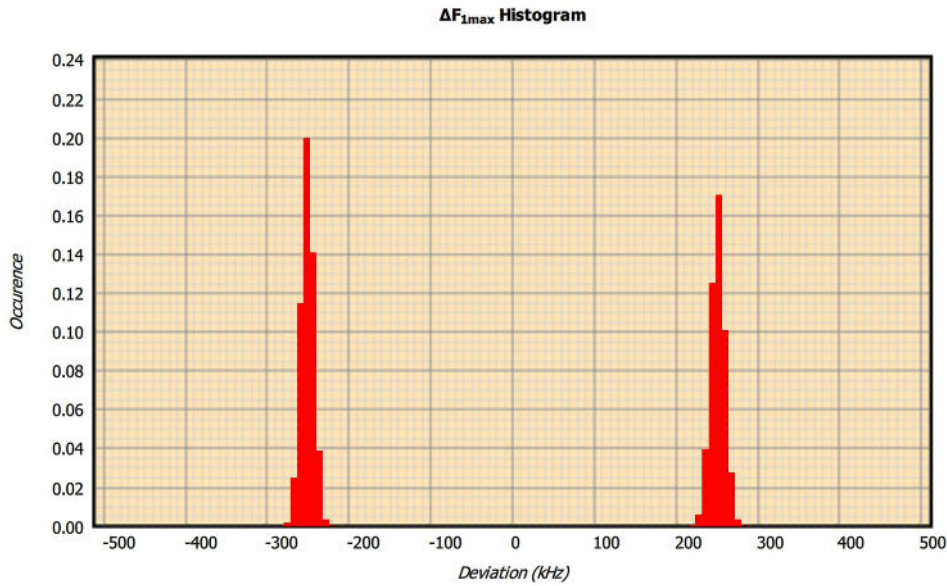
Figure 28: Results plotted as a histogram.

8.4.7.6 ~~Outline~~

This option is not available for in-band emission tests.

The measured quantity is shown by the blue lines on the plot. The plot corresponds to the value(s) obtained from the last packet on which the selected quantity was measurable. If waveform collection has been enabled ('Collect' tab, 'Measurement' menu) then either the frequency deviation or the packet power will also be displayed in red. ~~The waveform data will not be displayed if the quantity selected is measured on the last analyzed packet.~~
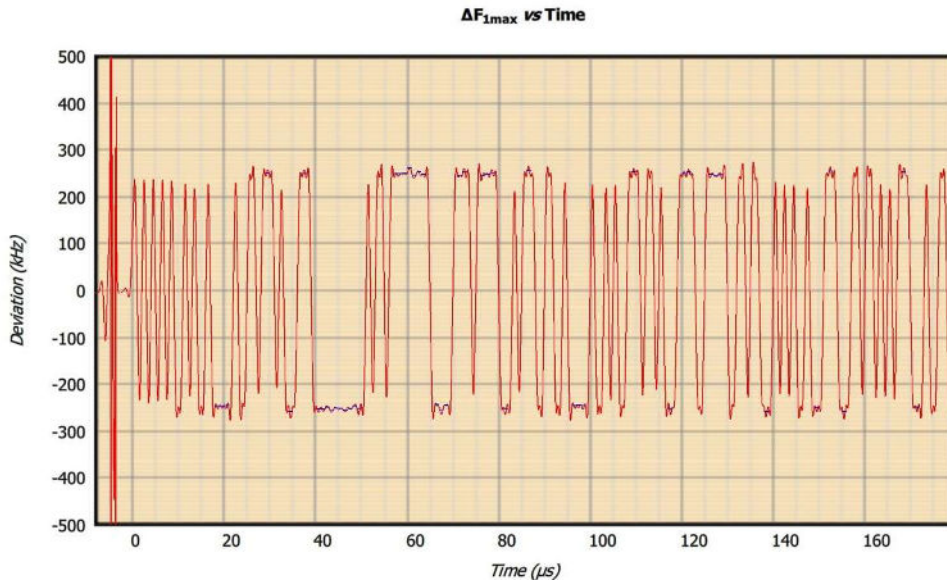
Figure 29: vs time.

8.4.7.7 ~~vs frequency~~

This option is only available for in-band emission tests.

When the vs frequency option is selected for in-band emission tests, additional options become available:

1. Plotting of the in-band emission results for every MHz in the 2.4 GHz ISM band (1 MHz spectrum)
2. Plotting of the 100 kHz resolution measurements which were summed to yield the in-band emission results at every 1 MHz (100 kHz spectrum)

For each spectrum it is possible to plot:

1. Current in-band emission results (orange line)
2. Maximum in-band emission results (red line)
3. Minimum in-band emission results (green line)

Figure 30: In-band emissions vs frequency.

8.4.8 ~~Screen update period~~

The 'Plot' menu contains a slider which can be used to alter the rate at which the results table and graphics are updated.

The fastest update period possible is around 50 ms, typically limited by the host screen refresh rate. However, if substantial processing is required by Sapphire – for example, the transfer of raw IQ data at 32x oversampling for a 256 byte 125 kbps packet – then the specified update rate may not be achievable.

The slowest update rate is 2 seconds. This gives the user time to assimilate the displayed results and waveform data before the next update.

8.5   Adjusting test limits

The test limits are shown in the results table. The penultimate column of the results table displays the lower limit and the final column the upper limit. They can be altered by changing the values in the spin boxes, either by using the up/down arrows or by entering numeric text directly.

Some limit values are shared between different modulation schemes whilst others are specific to a modulation scheme. The table below shows whether limit values are shared or are specific for each test category and modulation scheme:

Test	Modulation			
	2 Mbps	1 Mbps	500 kbps	125 kbps
Power	Shared	Shared	Shared	Shared
Modulation	2 Mbps specific	Shared	Shared	125 kbps specific
Drift & carrier offset	Shared	Shared	LR specific	LR specific
In-band emissions	2 Mbps specific	Shared	Shared	Shared

Table 5: Table showing whether limit values are shared or are specific for each test category and modulation scheme.

The limit values shown in the results table apply to the modulation scheme currently selected in the 'Modulation' menu under the 'Analysis' tab.

8.6   Saving and restoring settings

The current collection, analysis and limit settings can be saved by clicking the 'Save' button on the toolbar. Select the 'Signal analysis settings (*.sas)' file type to save the current settings.

An existing signal analysis settings file (*.sas) can be opened using the 'Open' button on the toolbar.

The signal analysis settings file (*.sas) is an XML file. It is not recommended that this file be edited manually. If it needs to be modified, open it from the signal analyzer, modify the required parameters and re-save.

8.7   Saving current results table and graphics

The current graph and results table can be saved as an image by clicking the "Graph" button on the toolbar. The range of possible graphics formats includes:

1. Windows bitmap files (*.bmp)
2. Joint photographic expert group files (*.jpg)
3. Portable network graphics files (*.png)
4. Portable bitmap files (*.pbm)
5. Portable graymap files (*.pgm)
6. Portable pixmap files (*.ppm)
7. X11 bitmap files (*.xbm)
8. X11 pixmap files (*.xpm)

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8.3 Instrumentation and quantities
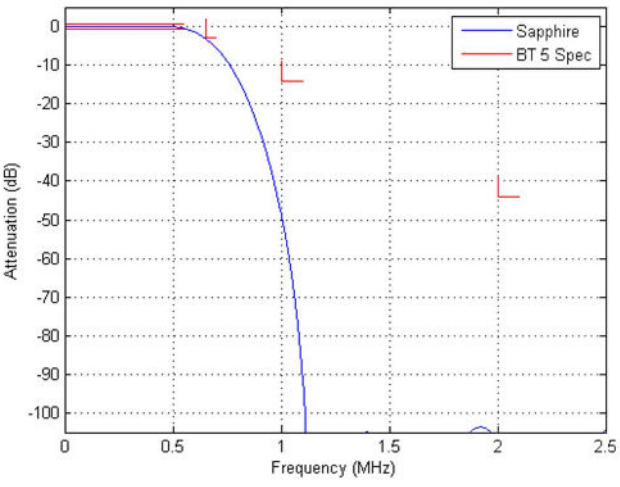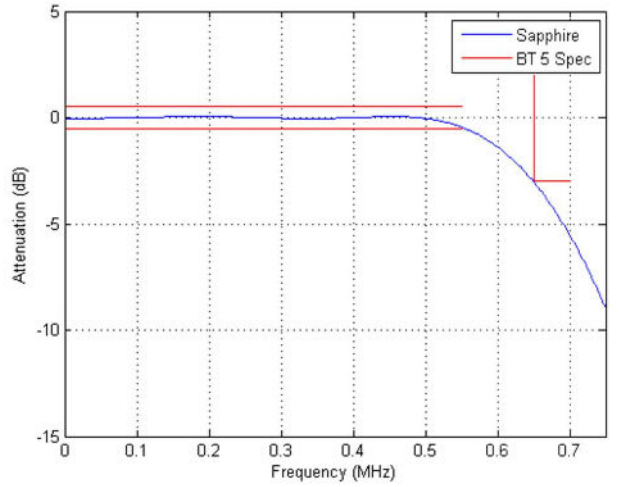
8.3.1 Power measurements

Bluetooth LE Phy test Specification	Sapphire
Output power tests are only specified for 1Mbps packets	Output power tests are available for all Bluetooth 5 RF phys
Tests should be performed on a spectrum analyzer with a 3MHz RBW	Tests are performed using the same filters as specified for the modulation and drift tests
P_{avg} should be measured over at least the central 60% of the packet	P_{avg} is measured over the central 7/8ths of the packet

Table 6: Power measurements compared between Bluetooth test specification and Sapphire.

8.3.2 Modulation measurements

Bluetooth LE Phy test Specification	Sapphire
Modulation tests are only specified for 2 Mbps, 1 Mbps & 125 kbps	Modulation tests are available for all Bluetooth 5 RF phys
Oversampling rate at least 32x	Oversampling rate 32x
Filter shape for 1 Mbps & 125 kbps should be at least: ±650 kHz @ -3 dB ±1 MHz @ -14 dB ±2 MHz @ -44 dB	
Filter for 1 Mbps & 125 kbps to have less than 0.5 dB peak-to-peak ripple between ±550 kHz	

Filter shape for 2 Mbps should be at least: ±1.3 MHz @ -3 dB ±2 MHz @ -14 dB ±4 MHz @ -44 dB	
Filter for 2 Mbps to have less than 0.5 dB peak-to-peak ripple between ±1.1 MHz	
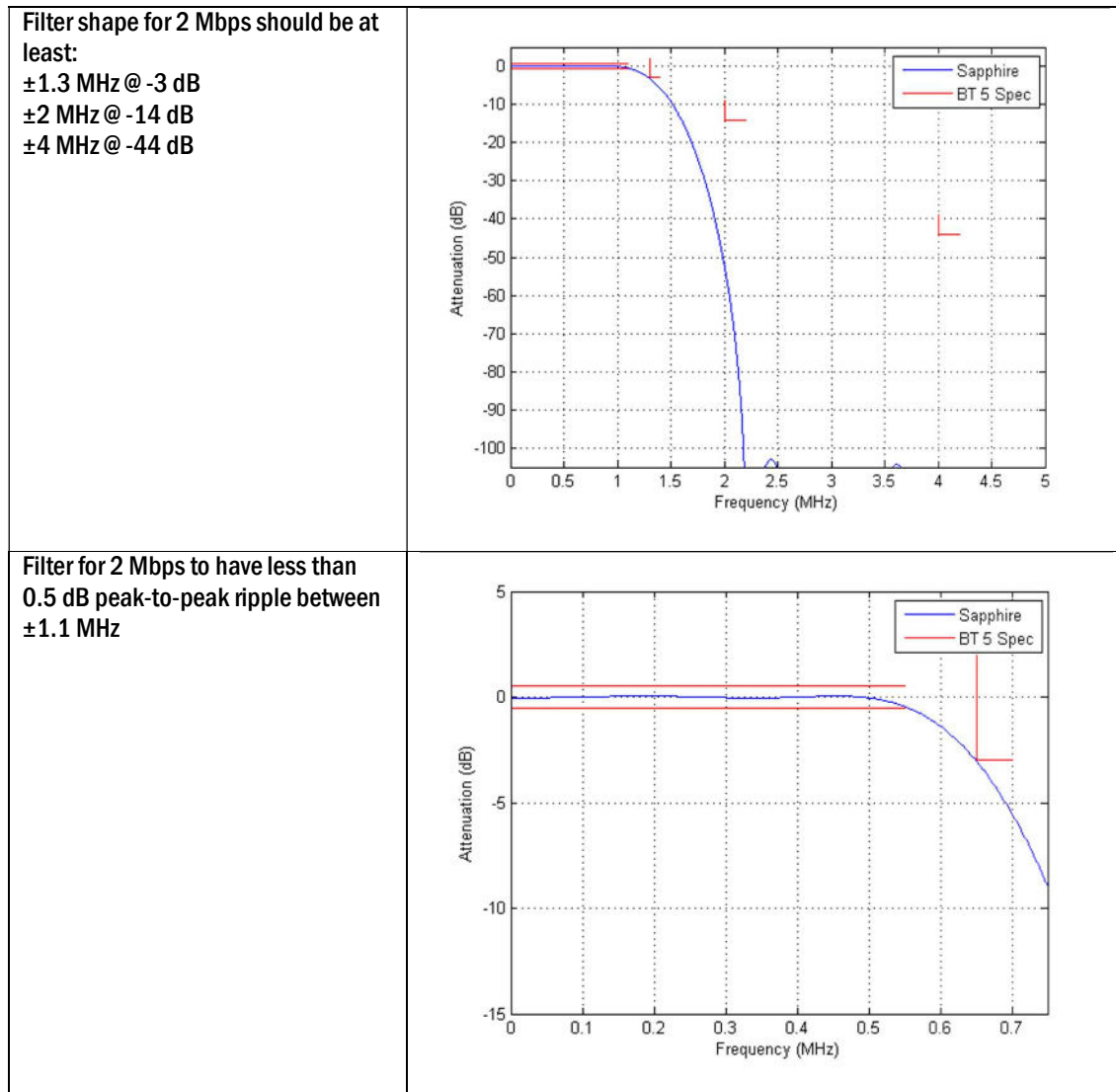
Table 7: Modulation measurements compared between Bluetooth test specification and Sapphire.

The $\Delta F2_{avg} / \Delta F1_{avg}$ current entry in the results table shows the ratio of $\Delta F2_{avg}$ for the last packet on which this quantity could be calculated to $\Delta F1_{avg}$ for the last packet on which this quantity could be calculated, with the restriction that both packets had the same RF phy, RF channel and lay in the same packet length group. The maximum, minimum and average values of $\Delta F2_{avg} / \Delta F1_{avg}$ are updated whenever a new value of $\Delta F2_{avg} / \Delta F1_{avg}$ can be calculated.

The $\Delta F2_{max}99\%$ current entry in the results table shows the frequency corresponding to the 99.9 percentile for all $\Delta F2$ measurements made over all packets collected. The maximum, minimum and average values are updated at the end of each packet. The $\Delta F2_{max}\ 99\%$ value will only be displayed once at least 100 $\Delta F2$ measurements have been made.

8.2.3 Drift and carrier offset measurements

Bluetooth RF-PHY Test Specification	Sapphire
Drift and carrier offset tests are only specified for 2Mbps, 1Mbps & 125kbps	Drift and carrier offset tests are available for all Bluetooth 5 RF phys
Specifications for measurement filters	See filters defined for modulation measurements.

Table 8: Drift and carrier offset measurements compared between Bluetooth test specification and Sapphire.

8.2.4 In-band emission measurements
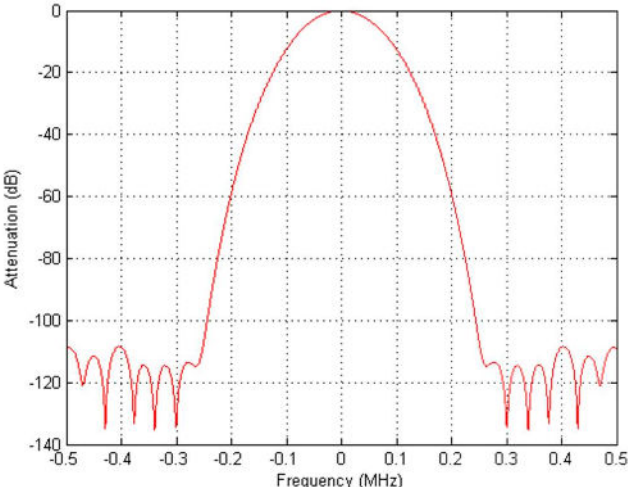
Bluetooth RF PHY test Specification	Sapphire
Modulation tests are only specified for 2 Mbps & 1 Mbps	Modulation tests are available for all Bluetooth 5 RF phys
RBW of 100 kHz	Accurate Gaussian response with 3 dB bandwidth of 100 kHz
Average detector Sweep time of 100 ms	Assuming 400 points per sweep for a spectrum analyzer typical of the period when the Bluetooth specification was first written, this gives an averaging time of 2.5 ms per point
Maximum hold over 10 sweeps	Maximum hold starts prior to the packet power ramp up and continues until the end of the packet power ramp down or 2.5 ms, whichever is longer.

Table 9: In-band emission measurements compared between Bluetooth test specification and Sapphire.

The maximum exception row in the results table will only indicate exceptions that exceed the -20 dBm absolute limit.

9 Phy Tester Mode.

9.1   Overview

In phy tester mode, the Sapphire application directly controls the DUT and executes an editable test script which define which of the Bluetooth 5 LE RF Phy Test Specification tests are to be performed.

Communication to the DUT is via one of the following protocols:

1. Direct test mode (2-wire)
2. H4
3. H5 (3-wire)
4. BCSP

The application is capable of running all of the Bluetooth 5 LE RF Phy Test Specification tests, with the following caveats:

1. Blocking tests cannot be performed above 6 GHz. The Bluetooth 5 LE RF Phy Test Specification states that blocking frequencies up to 12.75 GHz should be used. Since this limit includes the second harmonic of the 2.4 GHz ISM band, it is unlikely that a DUT which passes at frequencies below 6 GHz will fail at frequencies above 6 GHz.
2. The CW blocker has a relatively high harmonic content. A notch filter is used to reduce the harmonic content falling within the 2.4 GHz ISM band. However, care should be exercised to ensure that blocking failures are not due to harmonics of the blocker landing on the wanted signal. Such care should always be exercised with blocking tests, irrespective of the test equipment being used.
3. Some intermodulation tests require the interferers to be placed a significant distance outside the 2.4 GHz ISM band. The *TLF3000* unit is not always capable of generating these interferers. However, the Bluetooth 5 LE RF Phy Test Specification requires that the intermodulation test be performed with the interferers both above and below the wanted signal. The *TLF3000* unit can always generate the interferer signals for the case where they lie within the 2.4 GHz ISM band. When they are switched to lie outside the 2.4 GHz band they will become attenuated by the frontend filtering of the DUT. It is therefore unlikely that a DUT will pass the intermodulation test with the interfering signal inside the 2.4 GHz ISM band, but fail when the interfering signals are placed outside the 2.4 GHz ISM band.

The Sapphire application allows the Bluetooth 5 LE RF Phy Test Specification tests to be expanded to include:

1. Testing on different RF channels
2. Testing with different packet lengths
3. Testing over a different number of packets
4. Testing with a different wanted signal level or over a sweep of wanted signal levels
5. Testing with different interferer signal levels or over a sweep of interferer signal levels
6. Testing with different blocker frequencies

Test termination criteria can be set allowing PER searches to be performed.

9.2   Communicating with the DUT

9.2.1   Overview

Sapphire supports communications with the DUT over a serial interface. The control of this interface is governed by the settings in the 'DUT control' menu under the 'Collection' tab.

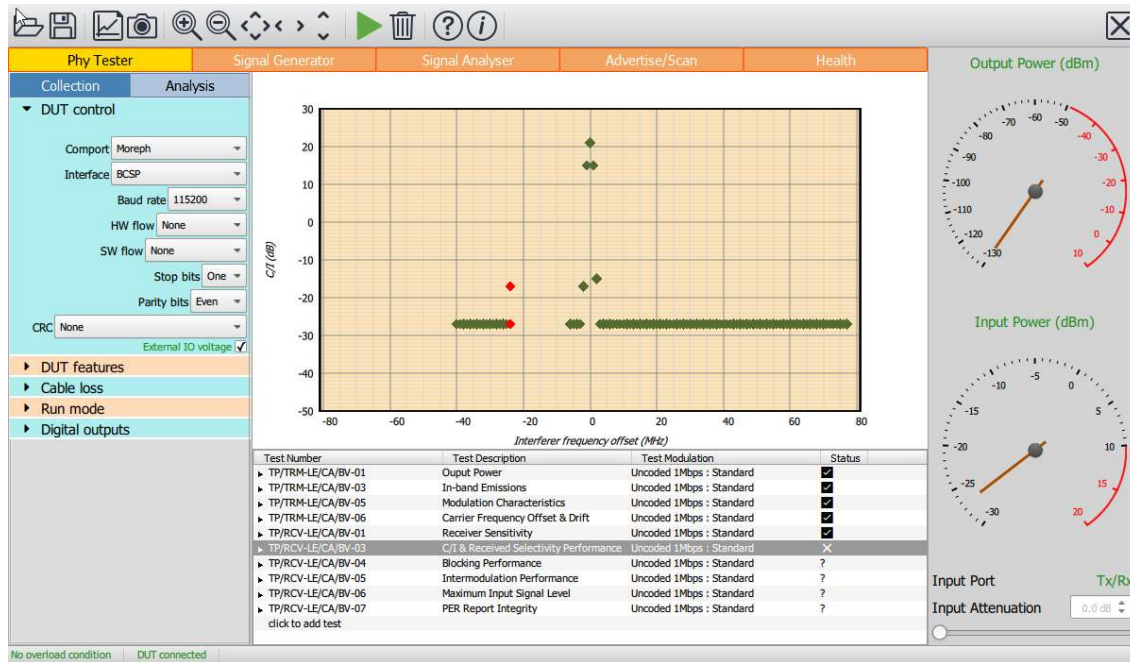The status bar indicates whether the Sapphire application currently believes it has communications with a DUT.

Figure 31: Communicating with the DUT.

9.2.2 Hardware connections

The serial interface connection can be either

1. via the digital IO connector on the rear of the *TLF3000* unit
2. via a comport accessible from the host

The pinout of the digital IO connector on the rear of the *TLF3000* unit is:

Pin	Signal	Direction
1	Vio	Input/Output
2	Vio	Input/Output
9	RTS	Output
10	TX	Output
17	CTS	Input
18	RX	Input
19	Gnd	-
20	Gnd	-

Table 10: Pinout of the digital IO connector on the rear of TLF3000.

Vio is the voltage level which is used for signalling. This can either be supplied by the *TLF3000* unit or the DUT. If it is supplied by the *TLF3000* unit, then it is fixed at 3.3 V. If it is supplied by the DUT, then it must be in the range 0.8 V to 3.6 V. Whether Vio is supplied by the *TLF3000* unit or the DUT is determined by the setting of the 'External IO voltage' checkbox in the 'DUT control' menu under the 'Collection' tab. It is essential that this checkbox is set to the correct state prior to the DUT being attached.

9.2.3 Protocol settings

All protocol settings are contained in the 'DUT control' menu under the 'Collection' tab.

The DUT may be communicated with using any one of the following protocols:

1. Direct test mode (also known as 2-wire mode)
2. H4
3. H5 (also known as 3-wire mode)
4. BCSP (a Qualcomm/CSR proprietary mode)

The protocol is selected from the 'Interface' combo box. Selecting the protocol will automatically set appropriate defaults for all other serial link parameters.

Other link parameters which may be set are:

1. Baud rate. Supported baud rates are 50, 75, 110, 134, 150, 300, 600, 1200, 1800, 2400, 9600, 19200, 38400, 57600, 115200 and 230400. An automatic baud rate detection features is also supported. Additional baud rates can be added on request.
2. Hardware handshaking
3. Software flow control (not supported for H5 or BCSP)
4. Number of stop bits
5. Parity bits
6. CRC (H5 and BCSP only, not yet supported)

9.3   DUT supported features

In order for Sapphire to determine which tests are applicable to the DUT, it is necessary to establish which features the DUT supports. The DUT supported features can be entered in the 'DUT type' menu of the 'Collection' tab.

Parameters which are required are:

1. The role of the DUT. This may be one of:
    a. Central
    b. Peripheral
    c. Broadcaster
    d. Observer
   This information is required to ascertain whether the DUT has both a transmitter and receiver and which channels these operate on.
2. Support for advertising extensions
3. Support for data length extensions
4. Maximum supported octets in an advertising packet. Permissible range is 37 to 255. This is only required if advertising extensions are supported.
5. Maximum supported octets in a receive packet. Permissible range is 27 to 251. This is only required if data length extensions are supported and advertising extensions are not supported.
6. Maximum supported receive time. Minimum permissible value is 328µs. This is only required if data length extensions are supported and advertising extensions are not supported.
7. Maximum supported octets in a transmit packet. Permissible values are 27 to 251. This is only required if data length extensions are supported.
8. Maximum supported transmit time. Minimum permissible value is 328 µs. This is only required if data length extensions are supported.
9. Support for 2 Mbps phy.

10. Support for long range (coded) phys.

11. Support for stable modulation index.

12. Support for angle of arrival processing.

13. Support for angle of departure processing.

At the bottom of the 'DUT type' menu is a button labelled 'Query DUT'. This can be used to request the supported features information be obtained directly from the DUT over the serial link. It also provides a simple means to establish that communications with the DUT are working. Although the majority of the supported features information can be obtained from the DUT using the query button, it may not be possible to ascertain the DUT role.
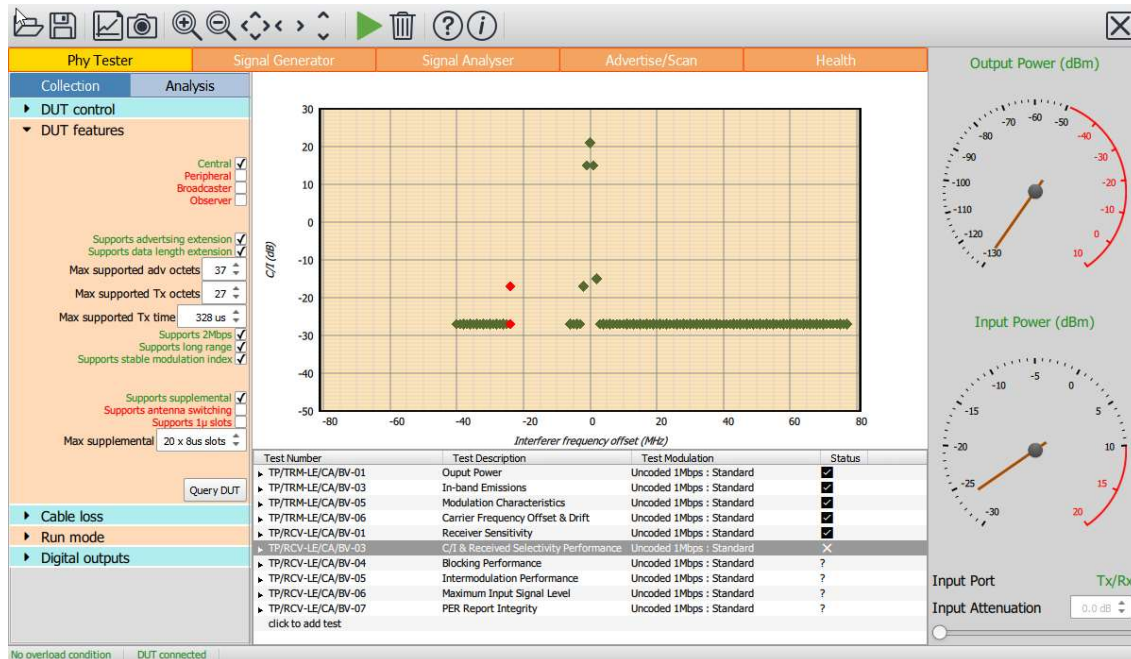
Figure 32: DUT supported features.

9.4　RF connections

For phy layer testing the DUT is connected to the Tx/Rx RF port.

Sapphire needs an estimate of the cable loss between the Tx/Rx port and the DUT at 2.4 GHz. This is necessary to compensate for receiver power levels and to adjust transmitter output levels. The cable loss is entered under the 'Cable loss' menu of the 'Collection' tab. The value can be entered either by using the slider or the spin box. Permissible values are between 0 dB and 5 dB.

The cable loss value is also used to compensate the blocker level. Since the cable loss value is only applicable at 2.4 GHz and the blocker frequency can be anywhere from 24 MHz to 6 GHz, the compensation is extremely rough. However, given the accuracy of the blocker signal level and the relatively low levels of cable attenuation, this is not normally an issue.

Figure 33: Entering the cable loss value.

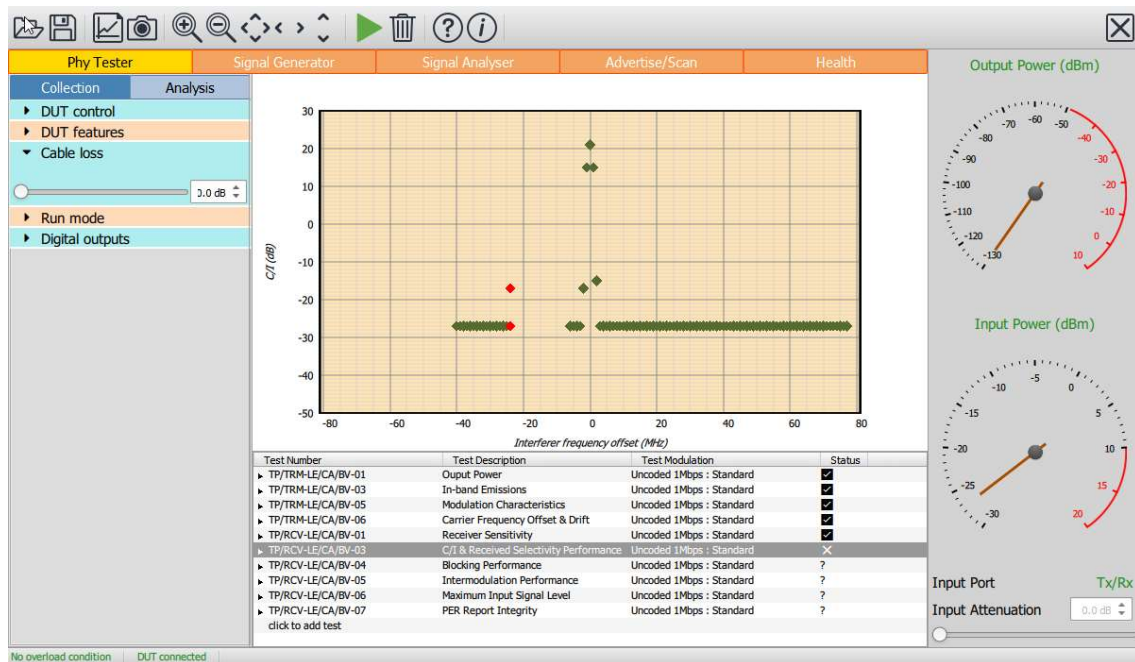## 9.5   Run modes and termination criteria

The operation of the phy layer tester can be modified by using the options available in the 'Run mode' menu under the 'Collection' tab. Available options are:

1. *Only test against limits.* When performing receiver tests a number of packets are sent to the DUT and then the DUT queried to determine how many arrived uncorrupted. The test limit is typically around 30% PER. In many cases it is not necessary to send the full number of packets to determine whether the 30% PER test limit will be exceeded or passed. If 'Only test against limits' is checked, Sapphire will attempt to minimise test time by only sending the minimum number of packets required to determine whether the test will pass. However, in doing so, the accuracy to which the true PER can be determined is compromised.

2. *Run to completion.* If the run to completion option is checked, then Sapphire will always perform all the tests which have been specified. If this option is not checked, then Sapphire will terminate execution of the test script as soon as a test failure is detected. An exception to this rule is when PER searches are being performed, either by sweeping the level of the wanted signal or the interfering signals. In these instances as soon as the test fails Sapphire will move to the next test item.

3. *Reorder tests.* There is a small time advantage in performing all the transmitter tests first followed by the receiver tests. If reorder tests is checked, then Sapphire will perform transmitter tests followed by receiver tests. If it is not checked, the Sapphire will perform the tests in the order that they appear in the test script.

4. *Loop tests.* If loop test is checked, then once the test script is exhausted it will be re-run. This facility is useful for tracking down errors which occur infrequently.

5. *Show table.* If selected then a window will pop-up at the end of the test run providing a summary of the test results. The contents of this window can also be saved to file by pressing the file save button in the toolbar and then selecting .html as the file type.
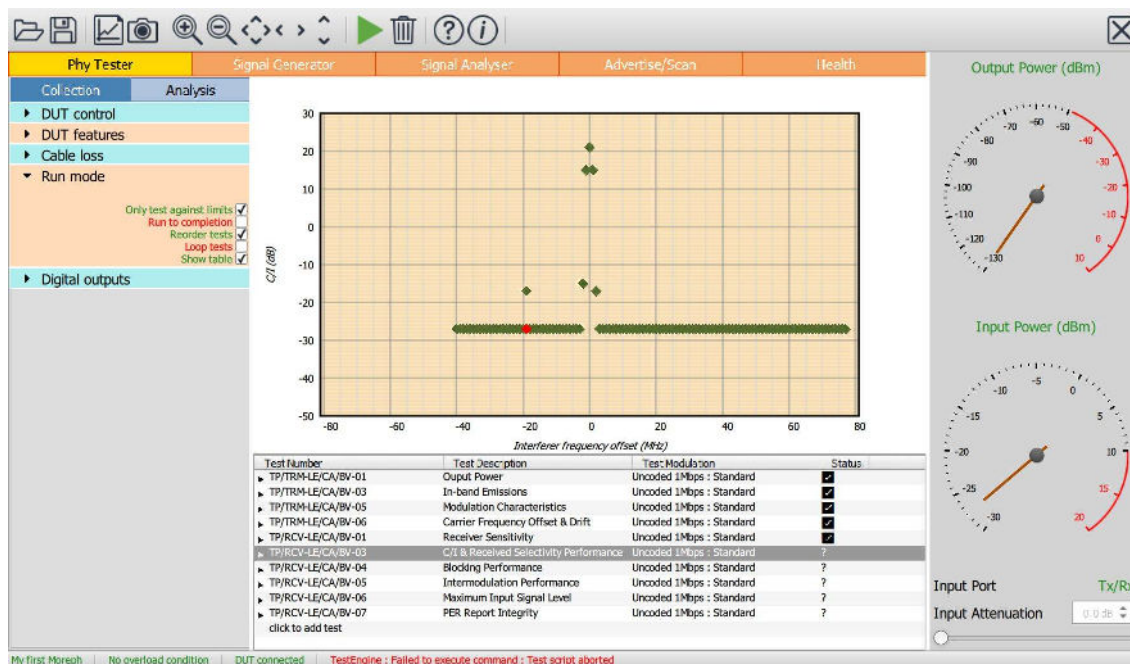

Figure 34. Run modes and termination criteria.

9.5.1 Monitoring activity on the digital IO connector

It is possible to monitor the activity of the phy layer tester via the digital IO connector on the rear panel of the *TLF3000* unit. The settings in the 'Digital outputs' menu under the 'Collection' tab control the state of the output lines. Two options are available:

1. *Running*. Sets the state of the output lines to indicate when the phy layer tester is running.
2. *Pass*. Sets the state of the output lines to indicate pass or fail when the phy layer tester terminates.

For each option there are 8 boxes denoting the how the 8 output lines should be configured. The contents of each box can be toggled by clicking on it. The four possible states for each box are:

State	Meaning
0	Set line low when condition is true
1	Set line high when condition is true
X	Ignore this line
-	Line not available for this function

Table 11: Possible states of the output lines.

The voltage level of the lines will be determined by the setting of 'External IO voltage' in the 'DUT control' menu.
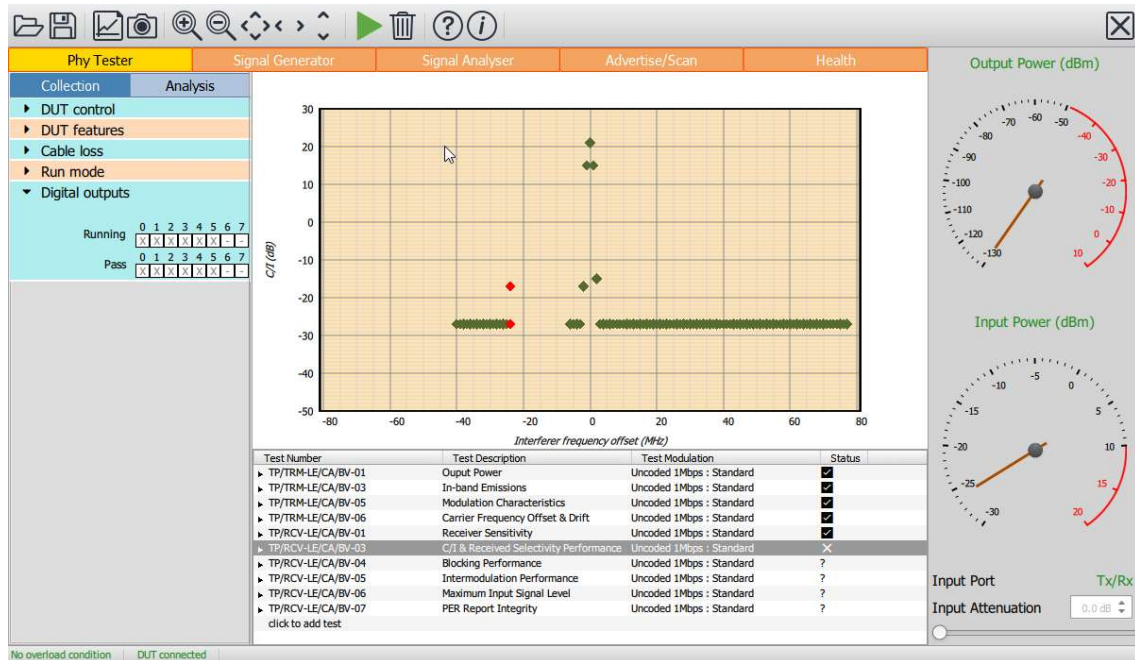

Figure 35: Monitoring activity on the digital IO connector.

9.6   Building a test script

9.6.1   Overview

The test script will be displayed at the bottom of the window below the graphics area. On entering the phy layer tester the script will be empty. To commence building a test script, click on 'click to add test'. This will open up a pop-up window where the test contents can be defined.

9.6.2   Test definition window

The pop-up test definition window permits any one of the Bluetooth 5 LE RF Phy Test Specification tests to be selected. Various parameters for each test can also be modified.

The test definition window consists of:

1. A yellow bar containing drop down menus which can be used to select the test to be performed.
2. A list of expandable menus which can be used to alter parameters defining the test.
3. A 'Restore Defaults' button which can be used to reset the test parameters to the values defined in the Bluetooth 5 LE RF Test Specification.
4. An 'Apply' button which will add a new test to the end of the test script or save the edits to an existing test.
5. A 'Cancel' button which will discard all information which has been entered into the test definition window. If a new test was being created, then it will be discarded. If an existing test was being edited, then the edits will be discarded.
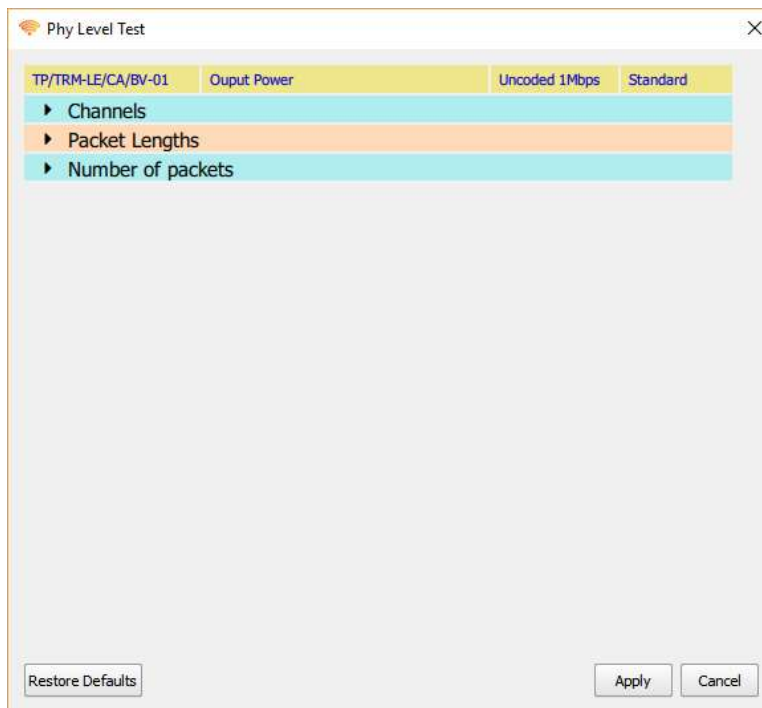
Figure 36: Test definition window.

9.6.3 Selecting the test type

The test type is selected by using the drop down menus in the yellow bar at the top of the test definition pop-up window.

If the test number if known, then it may be selected directly by using the left hand drop down menu. The number and type of tests which are displayed in the menu will be dependent on what features the DUT supports. It is therefore essential to ensure that the DUT properties are set correctly prior to creating a test script.

If the test number is not known, then the second drop down menu may be used to select the test by its name.

Figure 37: Selecting the test type if the test number is not known.

Having selected a test by its name, it may be necessary to refine the test selection by specifying the modulation scheme using the two remaining menus:
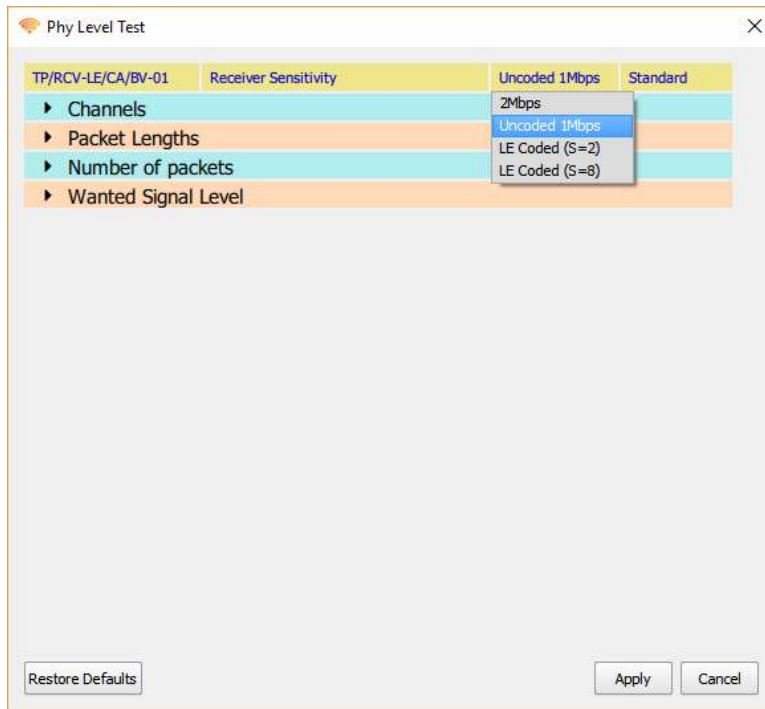
Figure 38: Refining the test selection by specifying the modulation scheme, 1.
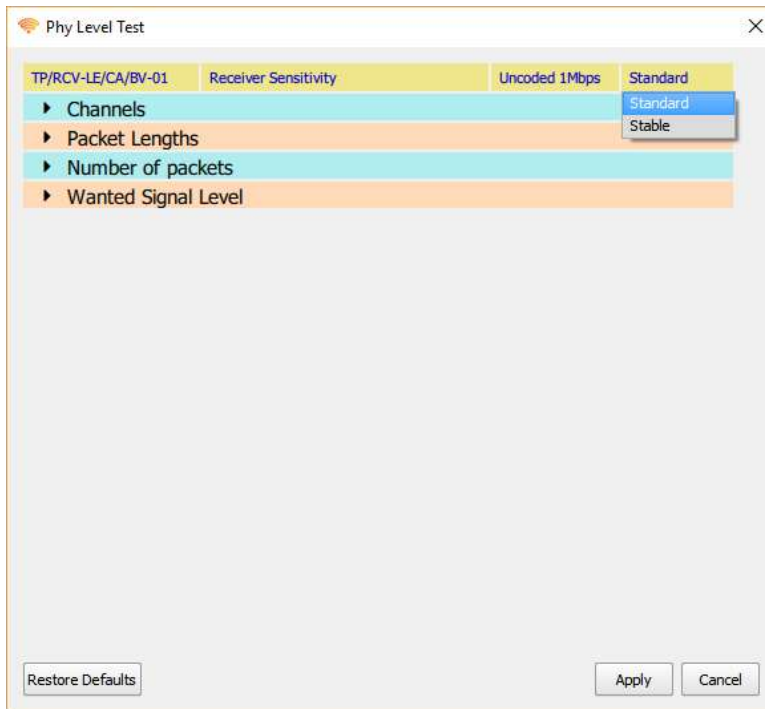
Figure 39: Refining the test selection by specifying the modulation scheme, 2.

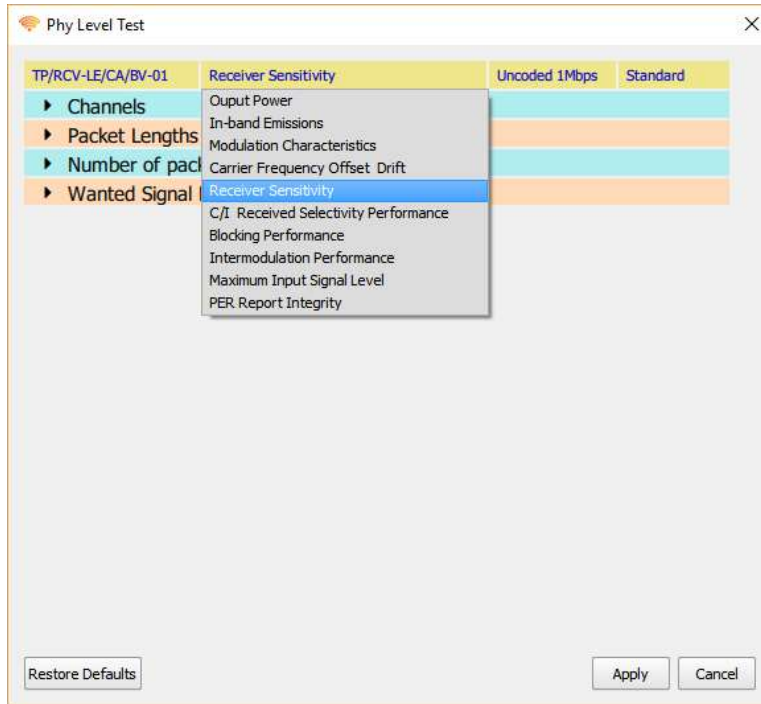### 9.6.4   Selecting which channels are tested

To select which RF channels the test is to be performed on, expand the 'Channels' menu.

The RF channels can be selected by clicking on the checkboxes.

Groups of RF channels can be selected using the toggle buttons at the bottom left:

1. *Clear all.* All RF channels will be deselected.
2. *Select all.* All RF channels which are supported by the DUT will be selected.
3. *Primary advertising.* The primary advertising channels will be selected.
4. *Data/Secondary advertising.* The data and secondary advertising channels supported by the DUT will be selected.
5. *Specification channels.* The RF channels defined for the test in Bluetooth LE RF Phy Test Specification will be selected.

It is also possible to select the RF channels by entering text into the text field at the bottom of the menu. The required format for the text is described in section 8.6.12.

Figure 40: Selecting which channels are tested.

9.6.5   Selecting which packet lengths are tested

To select which packet lengths the test is to be performed on, expand the 'Packet Lengths' menu.

The wanted packet lengths can be selected by clicking on the checkboxes.

Groups of packet lengths can be selected using the toggle buttons at the bottom left:

1. *Clear all.* All packet lengths will be deselected.
2. *Select all.* All packet lengths which are supported by the DUT will be selected.
3. *Specification.* The packet lengths specified for the test in Bluetooth LE RF Phy Test Specification will be selected.

It is also possible to select the packet lengths to be used by entering text into the text field at the bottom of the menu. The required format for the text is described in section 8.6.12.

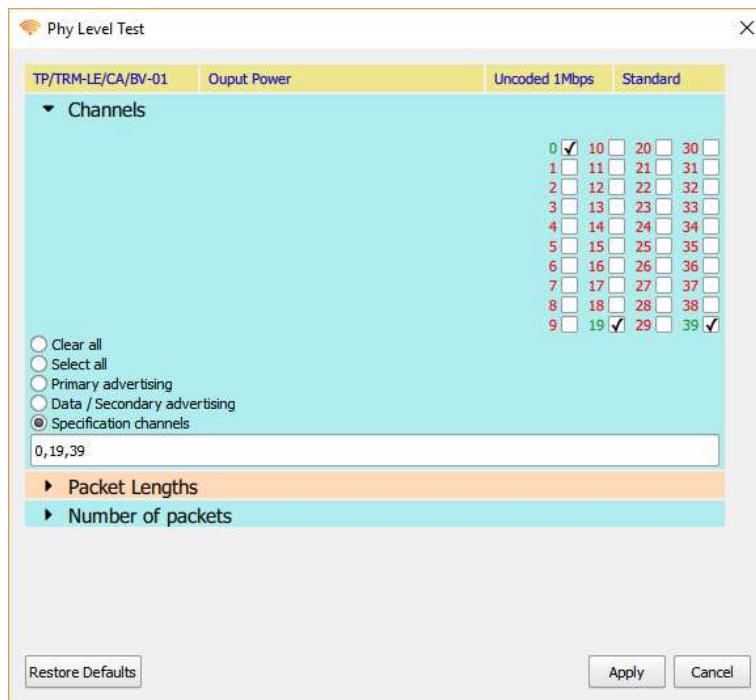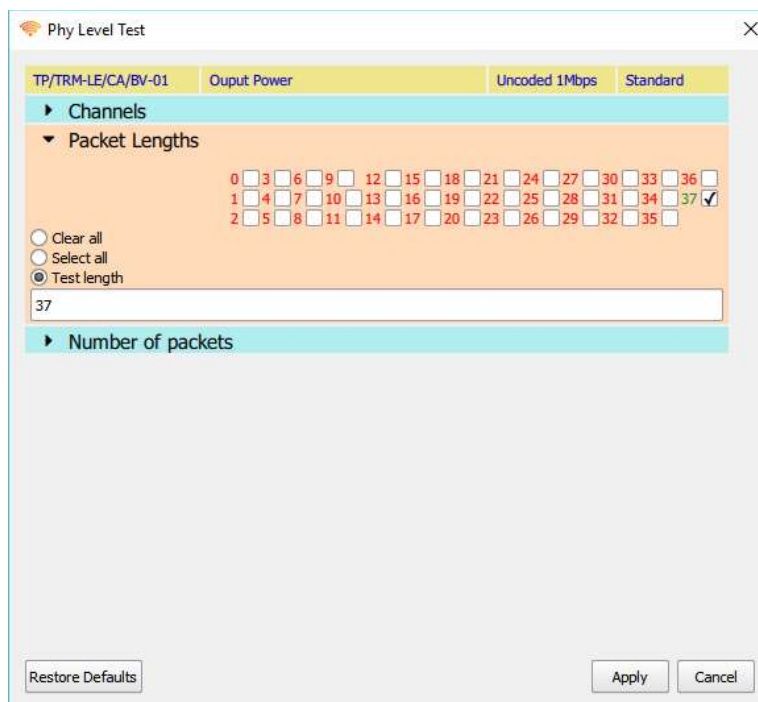*Figure 41: Selecting which packet lengths are tested.*

9.6.6   Selecting how many packets are used in the test

To select how many packets are used in the test, expand the 'Number of packets' menu.

If the 'Specification' checkbox is ticked, then the number of packets as defined in the Bluetooth 5 LE RF Test Specification will be used. This value will be shown in the spin box. The spin box will not be editable whilst the 'Specification' checkbox is ticked.

If the 'Specification' checkbox is cleared, then the number of packets can be entered into the spin box, either by using the up/down arrows or by entering a numeric value directly into the text field.

When performing 'quick look' receiver tests, it is frequently useful to reduce the number of packets from the 1500 specified in the Bluetooth 5 LE RF Phy Test Specification. By using a reduced number of packets, it becomes possible to explore a greater range of other parameters.
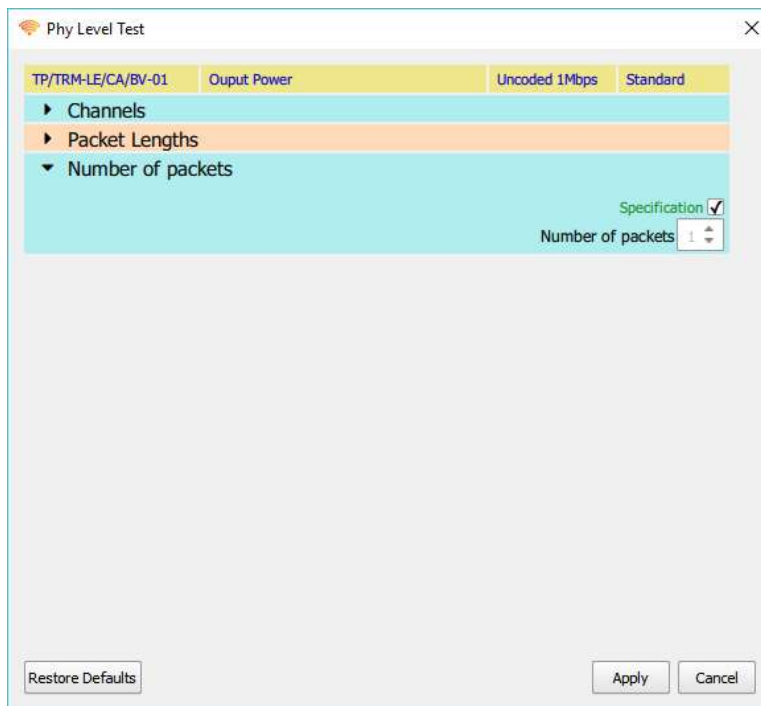
Figure 42: Selecting how many packets are used in the test.

9.6.7   Selecting the wanted signal level for receiver tests

To select the wanted signal level to be used for receiver tests, expand the 'Wanted Signal Level' menu.

If the 'Specification' checkbox is ticked, then the wanted signal level as defined in the Bluetooth 5 LE RF Test Specification will be used. This value will be shown in the spin box. The spin box will not be editable whilst the 'Specification' checkbox is ticked. The wanted signal level will also be shown on the signal level gauge at the bottom of the menu.
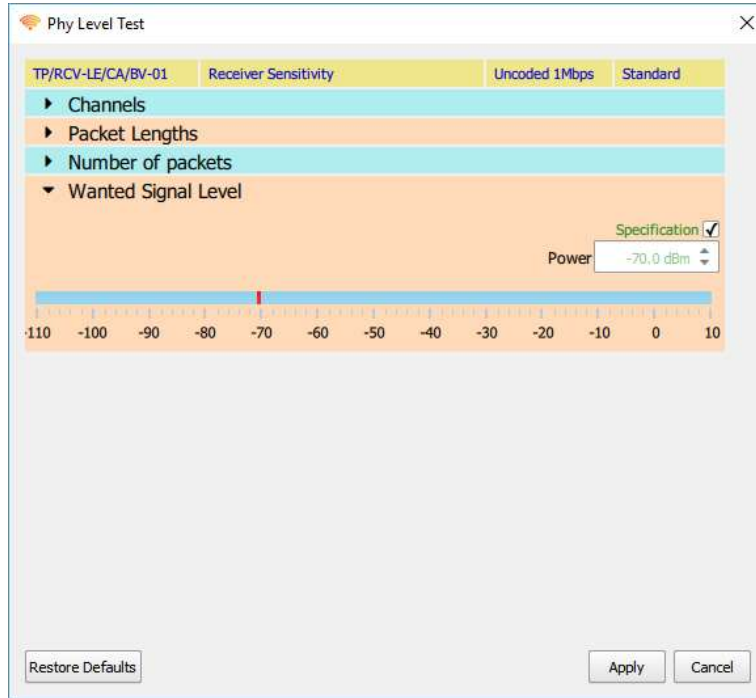
Figure 43: Wanted signal levels shown at the bottom of the menu.

If the 'Specification' checkbox is cleared, then the wanted signal level can be entered into the spin box, either by using the up/down arrows or by entering a numeric value directly into the text field. If the cursor is placed directly over the red bar in the signal level gauge, then a '+' will appear adjacent to the cursor. By holding down the left mouse button it is then possible to drag the red bar to set the wanted signal level. Wanted signal levels must be in the range -110 dBm to +5 dBm. The resolution of the wanted signal level is 0.1 dBm.
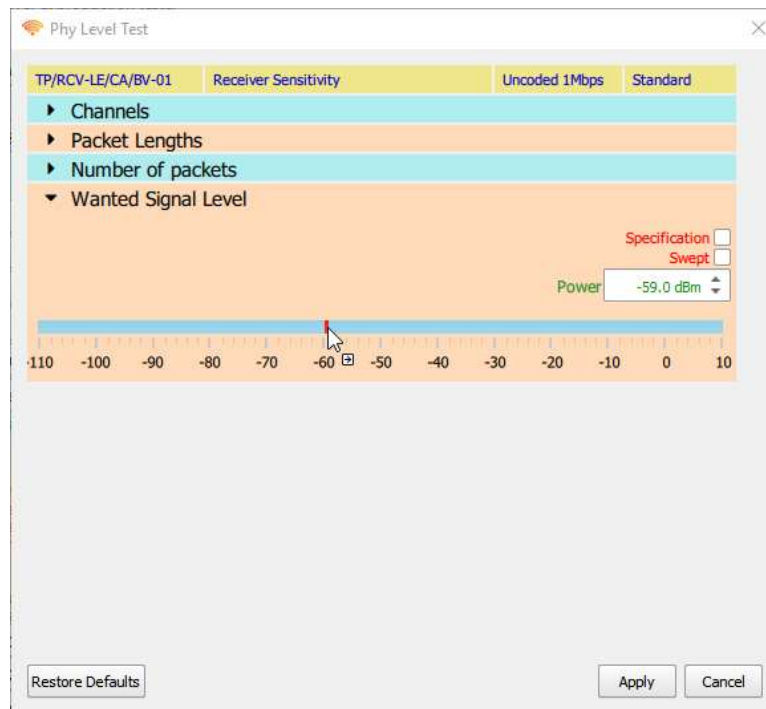
Figure 44: Setting the wanted signal level.

If it is desired to sweep the wanted signal level over a range of values, for example, to perform a PER search, then tick the 'Swept' checkbox. *If interfering signals have been programmed to have swept levels, then it is not possible to sweep the wanted signal level.*

The wanted signal level power sweep is defined by the numbers displayed in the three spin boxes:

1. *Maximum Power*. This indicates the power level at which the sweep will start. The sweep will be from the maximum wanted signal power towards the minimum wanted signal power. The maximum power cannot be above +5 dBm and must be greater than or equal to the minimum power. The resolution of the maximum power is 0.1dBm.
2. *Power Step*. This is the step size that the sweep will take from the maximum power towards the minimum power. The step size cannot be less than 0.5 dB. The resolution of the step size is 0.1dB.
3. *Minimum Power*. This indicates where the power sweep should terminate. The last wanted signal power to be test will be greater than or equal to the minimum power. The minimum power cannot be below -110 dBm and must be less than or equal to the maximum power. The resolution of the minimum power is 0.1 dBm.

If maximum input signal level tests are being performed, the direction of the sweep is reversed and the roles of maximum power and minimum power are swapped.

The red bar in the signal level gauge indicates the range selected by the maximum and minimum powers. This entire range may not be explored during the sweep since the actually values tested are dependent on the selection of the step size.

If the cursor is placed over one of the limits of the red bar, then it will change to a double headed cursor. It is then possible to hold down the left mouse button and drag the edge of the red bar to adjust either the minimum or maximum power.

If the cursor is placed over the body of the red bar, then a '+' will appear adjacent to the cursor. It is then possible to hold down the left mouse button and drag the entire sweep range up or down the gauge.

Figure 45: Setting a wanted signal level range.

9.6.8 Configuring C/I receiver tests

9.6.8.1 Overview

In order to perform C/I receiver tests, it is necessary for Sapphire to know where the image frequencies of the DUT receiver lie. The location of the image frequencies alter the level of the interfering signal which must be generated.

The C/I receiver tests can take a long time to perform. Frequently it is only a few offsets of the interferer signal from the wanted signal that are interest. It is possible to individually select which interferer offset frequencies are used.

Most LE devices will greatly exceed the Bluetooth 5 LE RF Phy Specification C/I test. Sapphire therefore contains the ability to adjust the interferer signal level as well as the ability to sweep it over a range of values.

9.6.8.2 Specifying the DUT Image frequencies

To set the DUT image frequency, expand the 'C/I Image Frequency' menu.

The spin box labelled 'Image frequency' determines the offset of the DUT's image frequency. The image frequency can be set to any value from 0 MHz to 100 MHz in steps of 1 MHz. The step size is limited to a resolution of 1 MHz

to be compatible with the resolution of the interfering signal offset. Sapphire implicitly assumes that the image frequency offset is the same for all LE RF channels.

For each of the LE RF channels it is possible to specify whether high-side or low-side mixing is employed by the DUT. With high-side mixing the image will appear above the wanted signal, whilst with low-side mixing the image will appear below the wanted signal. The choice between high- and low-side mixing can be made by:

1. Toggling the individual checkboxes for each LE RF channel
2. Using the toggle buttons are the bottom left of the window:
   a. 'All channels low-side mix' will set low-side mix for all LE RF channels
   b. 'All channels high-side mix' will set high-side mix for all LE RF channels
3. By entering a text string into the text field at the bottom of the window. The format of this text string is defined in section 8.6.12.
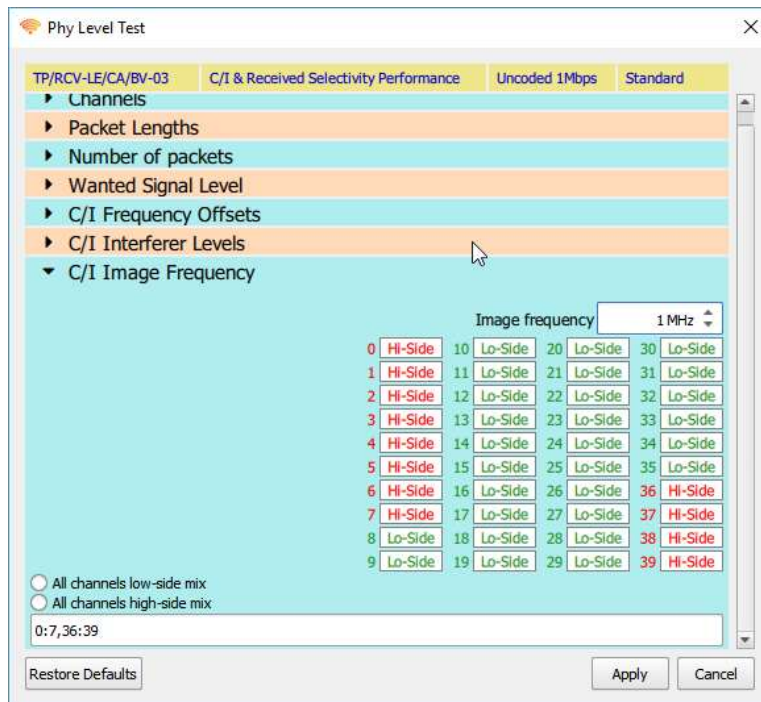
Figure 46: Specifying DUT image frequencies.

9.6.8.3 ~~Selecting the C/I receiver test offset frequencies~~

To select which offsets of the interferer from the wanted signal are to be explored, expand the 'C/I Frequency Offsets' menu.

The interfering signal can be placed up to 81 MHz from the wanted signal with a resolution of 1 MHz. If the interferer signal is placed outside the range 2395 MHz to 2485 MHz then the test will be silently ignored.

The C/I interferer signal frequency offsets can be set by:

1. Individually ticking the checkboxes for each frequency offset
2. Using the toggle buttons located at the bottom left of the window:
   a. *Clear All.* Removes all C/I interferer offset frequencies
   b. *Select All.* Ticks all C/I interferer offset frequencies
   c. *Force symmetry.* Ensures that the interferer frequency offsets that lie below the wanted signal are an image of the interferer frequency offsets that lies above the wanted signal.
3. Entering a text string directly into the text field at the bottom of the window. The format for this text string is described in section 8.6.12.

Positive C/I frequency offsets correspond to the interferer being at a higher frequency than the wanted signal. Negative C/I frequency offsets correspond to the interferer being at a lower frequency that the wanted signal.
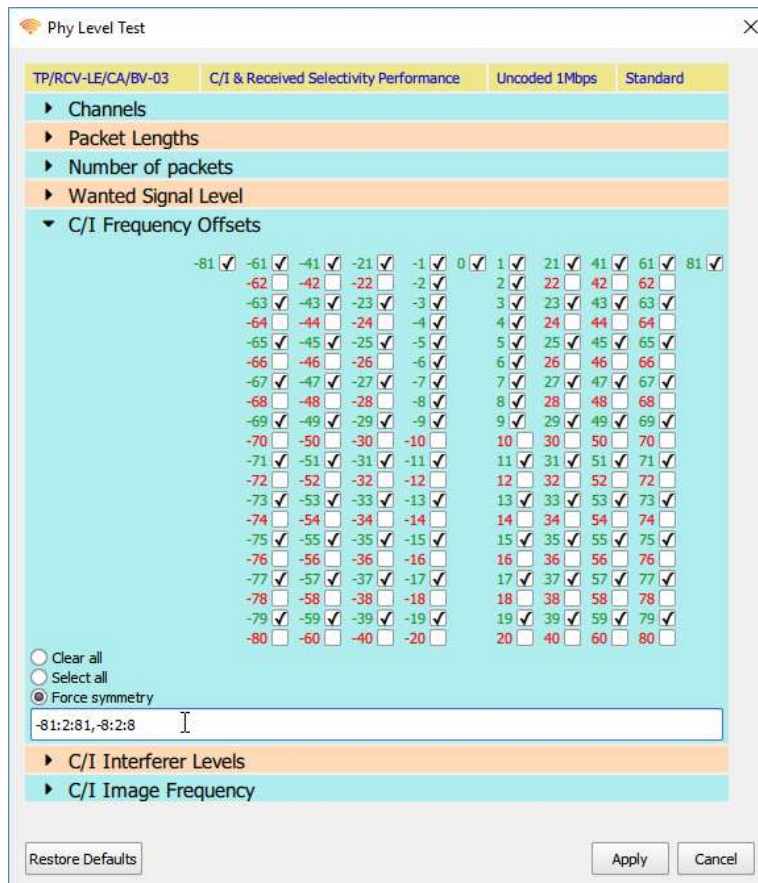
Figure 47: Selecting the C/I receiver test offset frequencies.

9.6.8.4 ~~Selecting the interferer signal levels for C/I receiver tests~~

To select the interferer signal levels to be used in the C/I receiver tests, expand the 'C/I Interferer Levels' menu.

At the top of the window is graphical display of the C/I levels which have been selected. This has been provided so that the plausibility of the selected parameters can be seen at a glance.

Below the graphical display, the C/I levels are shown in a tabular form, similar to that of the Bluetooth 5 LE RF Phy Test Specification.

Below the table is a 'Specification' checkbox. If this check box is ticked, then the C/I values in the table and displayed on the graph are those defined in the Bluetooth 5 LE RF Phy Test Specification. The spin boxes within the table are disabled when the 'Specification' checkbox is ticked.
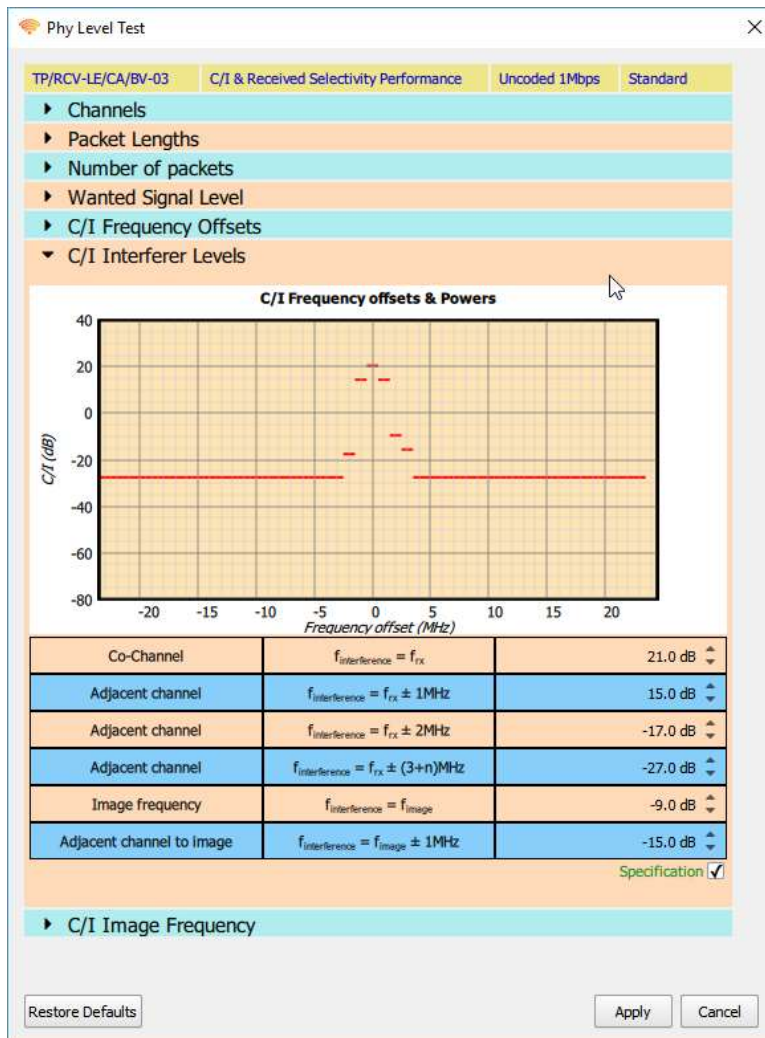
Figure 48: Interferer signal level for C/I receiver tests.

To enable the C/I levels to be adjusted, the 'Specification' checkbox must be cleared. Once the checkbox has been cleared, the following controls are accessible:

1. The individual spin boxes in the last column of the table can be used to adjust the C/I values. Each value can be adjusted from -80 dB to +40 dB with a resolution of 0.1 dB.
2. An offset can be applied to all the C/I levels in the table by using the 'Offset' spin box below the table. The offset can be varied from -80 dB to +20 dB. However, many offsets may results in signals levels which cannot be generated by the TLF3000 unit. When Sapphire encounters signal levels which cannot be generated the test is ignored and execution moves to the next test.
3. The offset to be applied to all the C/I levels in the table is also shown by the red bar in the gauge at the bottom of the window. It is possible to adjust the offset by clicking on the gauge. Alternatively, if the cursor is placed over the red bar, then a '+' symbol will appear adjacent to the cursor. It is then possible to hold down the left mouse button and drag the red bar.
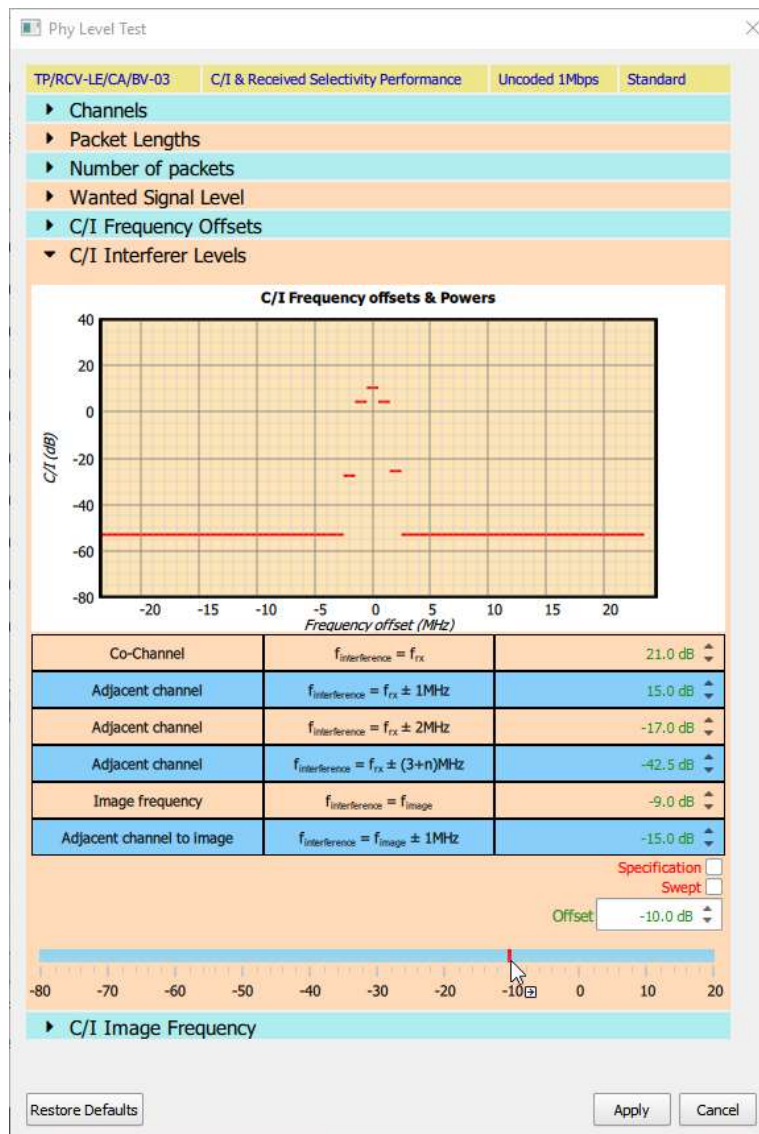
Figure 49: Changing the signal level for C/I receiver tests.

If it is desired to perform the C/I receiver tests over a range of interfering signal levels, then the 'Swept' checkbox must be ticked. *It is only possible to sweep the interferer signal level if the wanted signal is not being swept.*

The sweep of interferer levels is accomplished by applying a swept offset to all the values in the C/I table. It is not possible to specify individual sweeps for each row of the table. If this facility is required, then multiple C/I tests should be placed in the test script, each test configured to execute one row in the C/I table.

The offset level sweep is defined by the numbers displayed in the three spin boxes:

1. *Maximum Offset*. This indicates the offset at which the sweep will start. The sweep will always be from the maximum C/I towards the minimum C/I. The maximum offset cannot be above +20 dB and must be greater than or equal to the minimum offset. The resolution of the offset is 0.1 dB.
2. *Offset Step*. This is the step size that the sweep will take from the maximum C/I towards the minimum C/I. The step size cannot be less than 0.5 dB. The resolution of the step size is 0.1dB.
3. *Minimum Offset*. This indicates where the C/I sweep should terminate. The last interferer signal level to be tested will be greater than or equal to the signal level defined by this offset. The minimum offset cannot be below -80 dB and must be less than or equal to the maximum offset. The resolution of the minimum offset is 0.1 dB.

The red bar in the signal level gauge indicates the range selected by the maximum and minimum offsets. This entire range may not be explored during the sweep since the actually values tested are dependent on the selection of the step size.

If the cursor is placed over one of the limits of the red bar, then it will change to a double headed cursor. It is then possible to hold down the left mouse button and drag the edge of the red bar to adjust either the minimum or maximum offset.

If the cursor is placed over the body of the red bar, then a '+' will appear adjacent to the cursor. It is then possible to hold down the left mouse button and drag the entire sweep range up or down the gauge.

Figure 50: Selecting a range of signal levels for C/I receiver tests.

9.6.9 Configuring blocker receiver tests

To configure the blocker frequencies and levels to be used in the blocker receiver tests, expand the 'Blocker' menu.

At the top of the window is graphical display of the blocker levels which have been selected. This has been provided so that the plausibility of the selected parameters can be seen at a glance.

Below the graphical display, the blocker levels are shown in a tabular form, similar to that of the Bluetooth 5 LE RF Phy Test Specification. The range of blocker frequencies is subdivided into a number of segments, each segment occupy one row of the table. The second column shows the frequency at the start of the segment, the third column the step size that will be used to move the blocker through the segment and the fourth column denotes the end of the segment. The final column specifies the blocker level to be used for the segment.

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Below the table is a 'Specification' checkbox. If this check box is ticked, then the blocker frequencies and levels in the table and displayed on the graph are those defined in the Bluetooth 5 LE RF Phy Test Specification. Editing of the table is disabled when the 'Specification' checkbox is ticked.
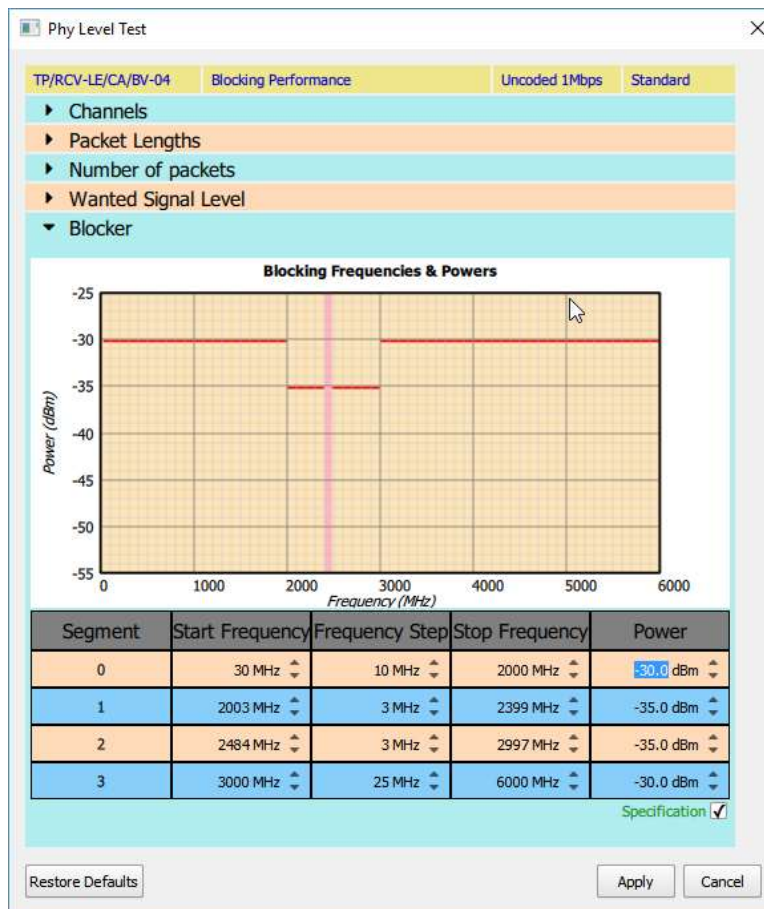
Figure 51: Blocker frequencies and levels.

To enable the blocker levels to be adjusted, the 'Specification' checkbox must be cleared. Once the checkbox has been cleared, the following controls are accessible:

1. The individual spin boxes in the last column of the table can be used to adjust the blocker values. Each value can be adjusted from -55 dBm to -25 dBm with a resolution of 0.1 dB.
2. An offset can be applied to all the blocker levels in the table by using the 'Offset' spin box below the table. The offset can be varied from -40 dB to +20 dB. However, many offsets may results in blocker levels which cannot be generated by the *TLF3000* unit. When Sapphire encounters signal levels which cannot be generated the test is ignored and execution moves to the next test.

The offset to be applied to all the blocker levels in the table is also shown by the red bar in the gauge at the bottom of the window. It is possible to adjust the offset by clicking on the gauge. Alternatively, if the cursor is placed over the red bar, then a '+' symbol will appear adjacent to the cursor. It is then possible to hold down the left mouse button and drag the red bar.
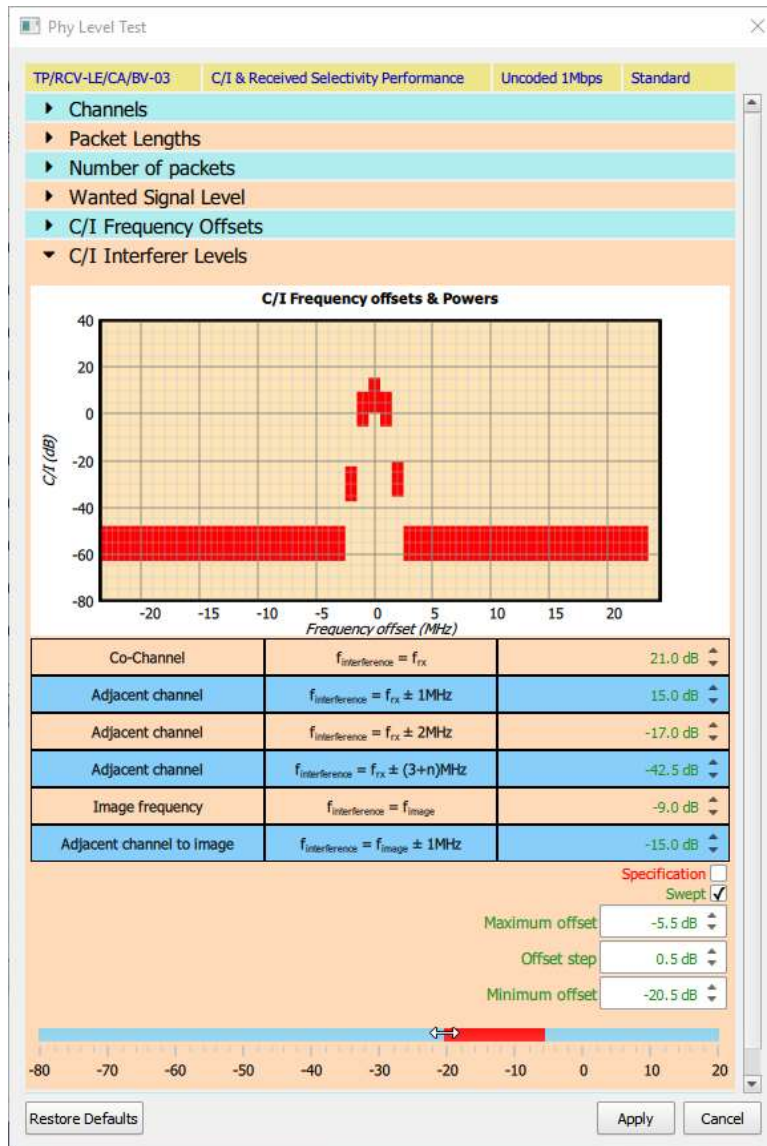
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Clearing the 'Specification' checkbox also permits the blocker frequencies to be adjusted. The start, step and stop frequencies within the table can now be adjusted using the associated spin box. The segments within the table are always held in order of increasing frequency. The minimum start frequency is 24 MHz for the first segment or 1 MHz above the stop frequency of the previous segment. The maximum stop frequency is 6 GHz for the last segment or 1 MHz below the start frequency of the subsequent segment. Step sizes can be varied from 1 MHz to 1 GHz. The resolution of all blocker frequency parameters is 1 MHz.

It is also possible to remove or add blocker frequency segments. To do so, highlight a frequency segment by clicking on the segment number in the first column. If the right mouse button is held down then a pop-up menu will appear with the following options:

1. *Delete*. The highlighted row will be deleted.
2. *Insert above*. A new frequency segment will be inserted above the highlighted segment.
3. *Insert below*. A new frequency segment will be inserted below the highlighted segment.
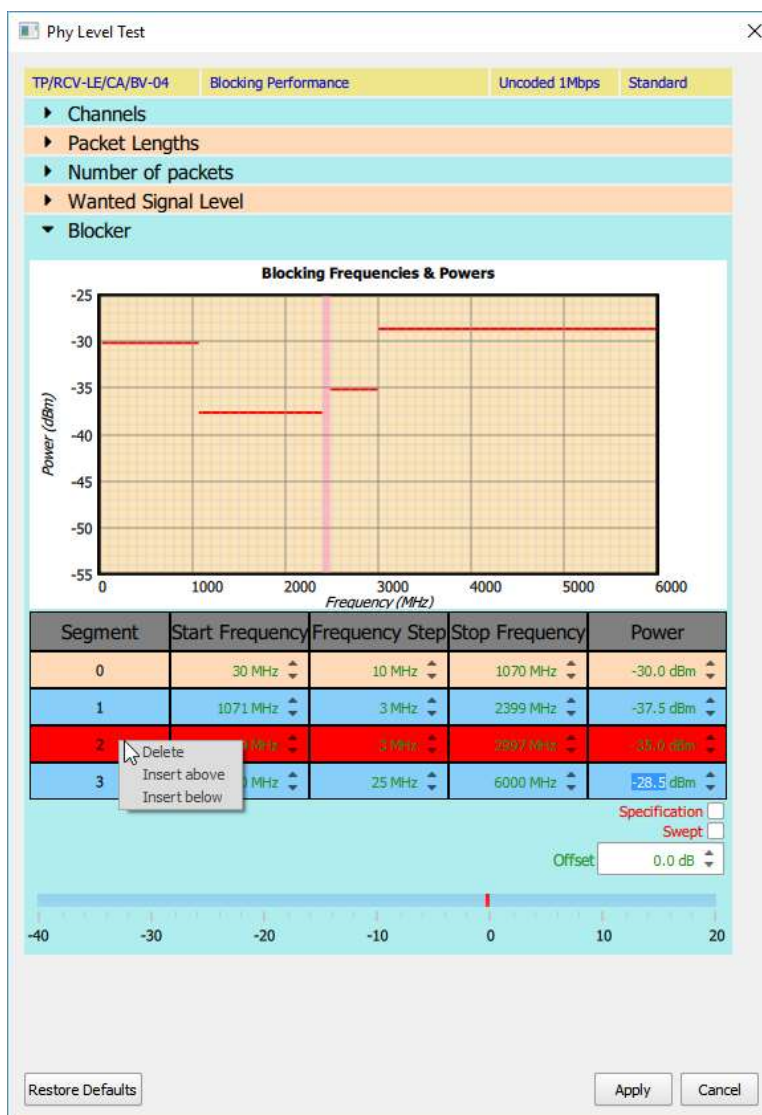

Figure 52: Removing or adding blocker frequencies and levels.

If it is desired to perform the blocker receiver tests over a range of blocker signal levels, then the 'Swept' checkbox must be ticked. *It is only possible to sweep the blocker signal level if the wanted signal is not being swept.*

The sweep of blocker levels is accomplished by applying a swept offset to all the values in the blocker table. It is not possible to specify individual sweeps for each frequency segment of the table. If this facility is required, then multiple blocker tests should be placed in the test script, each test configured to execute one frequency segment.

The offset level sweep is defined by the numbers displayed in the three spin boxes:

1. *Minimum Offset*. This indicates the offset at which the sweep will start. The sweep will always be from minimum blocker level to maximum blocker level. The minimum offset cannot be below -40 dB and must be less than or equal to the maximum offset. The resolution of the offset is 0.1 dB.
2. *Offset Step*. This is the step size that the sweep will take from the minimum blocker level to the maximum blocker level. The step size cannot be less than 0.5 dB. The resolution of the step size is 0.1 dB.
3. *Maximum Offset*. This indicates where the blocker sweep should terminate. The last blocker level to be tested will be less than or equal to the signal level defined by this offset. The maximum offset cannot be above +20 dB and must be greater than or equal to the minimum offset. The resolution of the minimum offset is 0.1 dB.

The red bar in the signal level gauge indicates the range selected by the maximum and minimum offsets. This entire range may not be explored during the sweep since the actually values tested are dependent on the selection of the step size.

If the cursor is placed over one of the limits of the red bar, then it will change to a double headed cursor. It is then possible to hold down the left mouse button and drag the edge of the red bar to adjust either the minimum or maximum offset.

If the cursor is placed over the body of the red bar, then a '+' will appear adjacent to the cursor. It is then possible to hold down the left mouse button and drag the entire sweep range up or down the gauge.
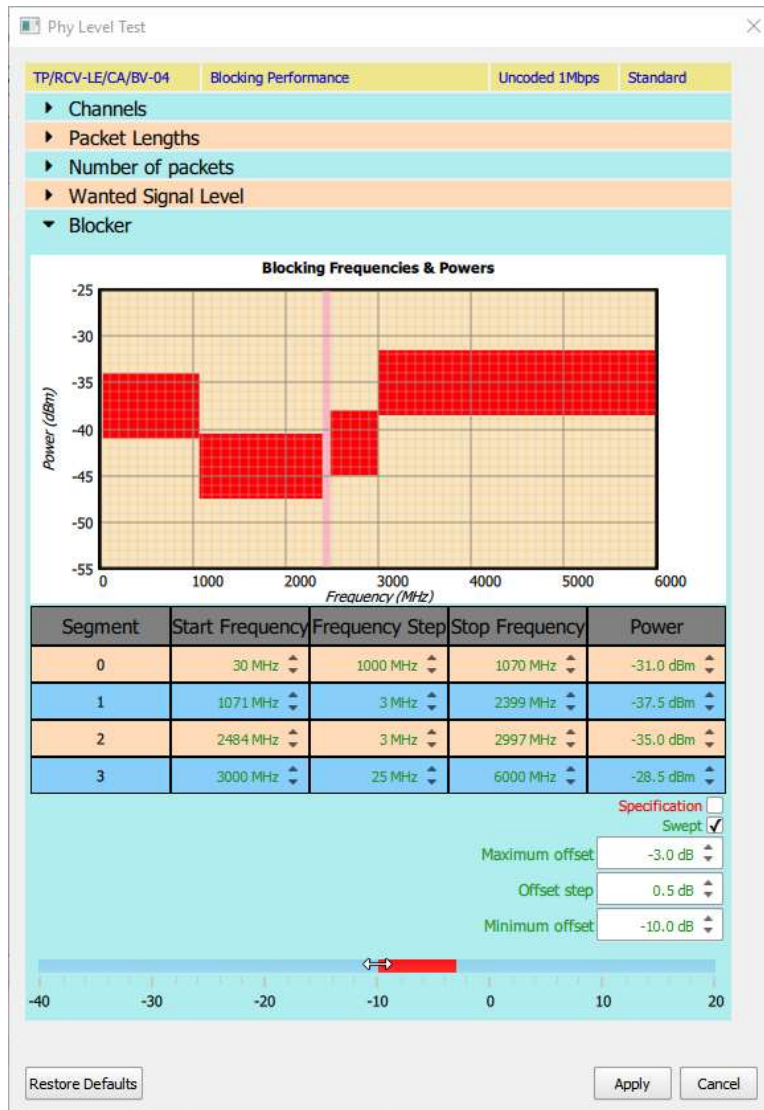
Figure 53: Selecting a range of blocker frequencies and levels.

9.6.10 Configuring receiver intermodulation tests

To configure the parameters to be used in the receiver intermodulation tests, expand the 'Intermodulation Spacings and Levels' menu.

At the top of the window is graphical display of the interferer levels and frequencies which have been selected. This has been provided so that the plausibility of the selected parameters can be seen at a glance. The graph is constructed as follows:

1. Wide bars are used to indicate continuously modulated interferer signals
2. Narrow bars are used to indicate CW interferers
3. The bars are colour coded as:
    a. Green: interferer spacing N = 3
    b. Blue: interferer spacing N = 4
    c. Red: interferer spacing N = 5
4. The interferer frequencies are shown below the wanted signal. The test will be performed for the interferer frequencies both below and above the wanted signal.

Below the graphical display are a series of checkboxes to select the frequency offsets of the interfering signals. The frequencies of the interfering signals are related by:

$$F_{wanted} = 2\,F_{cw} - F_{modulated}$$

and:

$$|\,F_{modulated} - F_{CW}|\ = N$$

where: F_{wanted} is the frequency of the wanted signal

$F_{modulated}$ is the frequency of the continuously modulated interfering signal

F_{CW} is the frequency of the CW interfering signal

N is the parameter selected by the checkboxes

The Bluetooth 5 LE RF Phy Test Specification does not provide a default value for the parameter N. Sapphire adopts the default value of 3.

The interferer signal levels are displayed in a spin box and a signal gauge at the bottom of the window. The CW interferer and the continuously modulated interferer are always constrained to have the same signal level.

Below the checkboxes which select the parameter N is a 'Specification' checkbox. If this check box is ticked, then the interferer signal levels are those defined in the Bluetooth 5 LE RF Phy Test Specification.
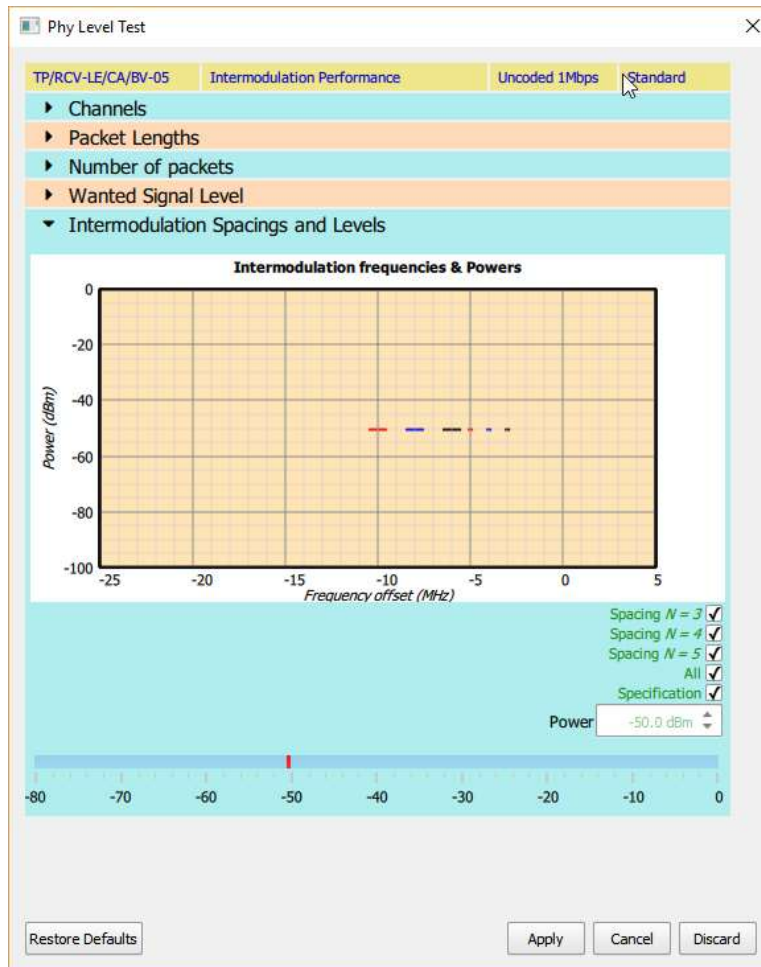
Figure 54: Entering interferer signal levels.

If the 'Specification' checkbox is cleared, then the interferer signal levels can be entered into the spin box, either by using the up/down arrows or by entering a numeric value directly into the text field. If the cursor is placed directly over the red bar in the signal level gauge, then a '+' will appear adjacent to the cursor. By holding down the left mouse button it is then possible to drag the red bar to set the interferer signal levels. Interferer signal levels must be in the range -80 dBm to 0 dBm. The resolution of the interferer signal levels is 0.1 dBm.
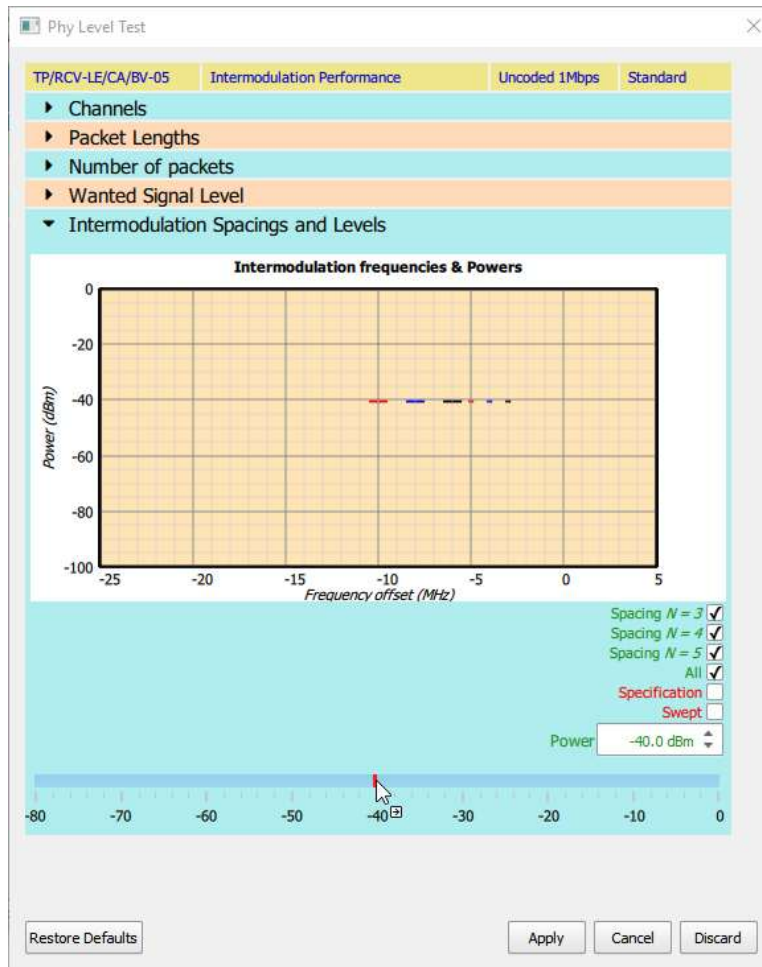
Figure 55: Selecting interferer signal levels over a range of values.

If it is desired to sweep the interferer signal levels over a range of values then tick the 'Swept' checkbox. **If wanted signal has been programmed to have swept levels, then it is not possible to sweep the interferer signal levels.**

The interferer signal level power sweep is defined by the numbers displayed in the three spin boxes:

1. *Minimum Power*. This indicates the power level at which the sweep will start. The sweep will always be from the minimum interferer signal power towards the maximum interferer signal power. The minimum power cannot be below -80 dBm and must be less than or equal to the maximum power. The resolution of the minimum power is 0.1 dBm.
2. *Power Step*. This is the step size that the sweep will take from the minimum power towards the maximum power. The step size cannot be less than 0.5 dB. The resolution of the step size is 0.1 dB.
3. *Maximum Power*. This indicates where the power sweep should terminate. The last interferer signal power to be test will be less than or equal to the maximum power. The maximum power cannot be above 0dBm and must be greater than or equal to the minimum power. The resolution of the maximum power is 0.1 dBm.

The red bar in the signal level gauge indicates the range selected by the maximum and minimum powers. This entire range may not be explored during the sweep since the actually values tested are dependent on the selection of the step size.

If the cursor is placed over one of the limits of the red bar, then it will change to a double headed cursor. It is then possible to hold down the left mouse button and drag the edge of the red bar to adjust either the minimum or maximum power.

If the cursor is placed over the body of the red bar, then a '+' will appear adjacent to the cursor. It is then possible to hold down the left mouse button and drag the entire sweep range up or down the gauge.

9.6.11 Configuring the receiver PER report integrity tests

When running the receiver PER report integrity tests it is possible to configure the number of integrity checks to perform. To access this parameter, expand the 'Integrity Count' menu.

If the 'Specification' check box is ticked, then 3 integrity checks will be performed as defined in the Bluetooth 5 LE RF Phy Test Specification.

If the 'Specification' check box is cleared, then the spin box displaying the number of integrity checks becomes enabled. The number of integrity checks can be changed to any number between 1 and 100 inclusive.
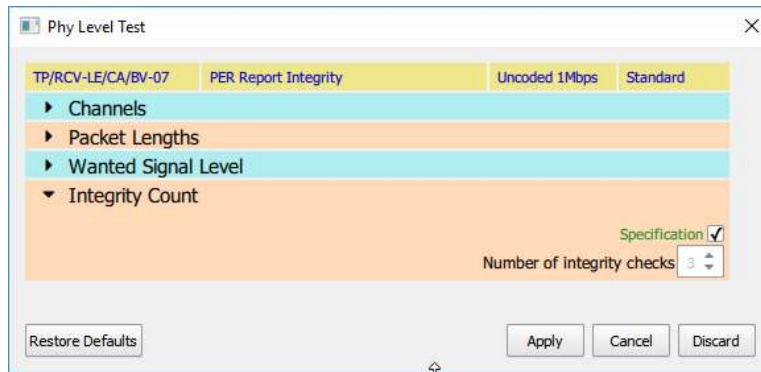
Figure 56: Configuring the receiver PER report integrity tests.

9.6.12 Textual input of test parameters

Many of the menus for configuring the test parameters permit the input of text strings to define ranges of parameter values. These textual descriptions must be of the form:

a_{start}:a_{step}: a_{stop}, b_{start}: b_{step}: b_{stop}, ...

This implies that all values from a_{start} to a_{stop} in steps of a_{step} will be selected, plu sall values from b_{start} to b_{stop} in steps of b_{step}, etc.

If a_{step} is unity, then a_{start}:a_{step}: a_{stop} can be abbreviated to a_{start}: a_{stop}.

If a_{step} is equal to a_{stop} then a_{start}:a_{step}: a_{stop} can be abbreviated to a_{start}.

9.7   Test duplication

Running any of the modulation characteristics tests will automatically generate results for the corresponding carrier offset and drift tests. This occurs since the packets the DUT must transmit for the carrier offset and drift tests are a subset of those required for the modulation characteristic tests. Furthermore, the test channels used for modulation characteristic measurements are the same as those required for carrier offset and drift

measurements. It is therefore unnecessary to explicitly include the carrier offset and drift tests within the test script if the corresponding modulation characteristics test are present.

Running any of the in-band emission tests will automatically generate results for the corresponding output power tests. This occurs since the packet types used in the two tests are identical. However, the test channels for in-band emission tests are not always the same as those for output power tests. Where there is overlap in the test channels, the overlapping channels can be excluded from the output power tests if the corresponding in-band emissions tests are included in the test script.

9.8   Test script window

The test script displayed at the bottom of the window underneath the graphics area. Each row in the table represents one test in the test script. The columns in the table contain:

1. Column 1 contains the test script number as defined in the Bluetooth LE RF Phy Test Specification
2. Column 2 contains the test script title, providing a textual description of the test
3. Column 3 indicates the modulation scheme which will be used for the test
4. Column 4 indicates the test status:
    a.   '?' indicates that the test has not been run and no results are available
    b.   ▸ indicates that the test is currently being run
    c.   '✓' indicates that the test has been run and the test limits have been passed
    d.   '✗' indicates that the test has been run and at least one test limit has failed

When a test is running it is highlighted in the test script window.

By clicking on a test number the test entry will be expanded to show the parameters defining the test configuration.

Tests can be added to the test script by clicking on the 'click to add test' text at the bottom of the test script. To edit a test, double click the entry in the test script. To delete a test, double click on the entry and then select 'Discard' in the test definition pop-up window.
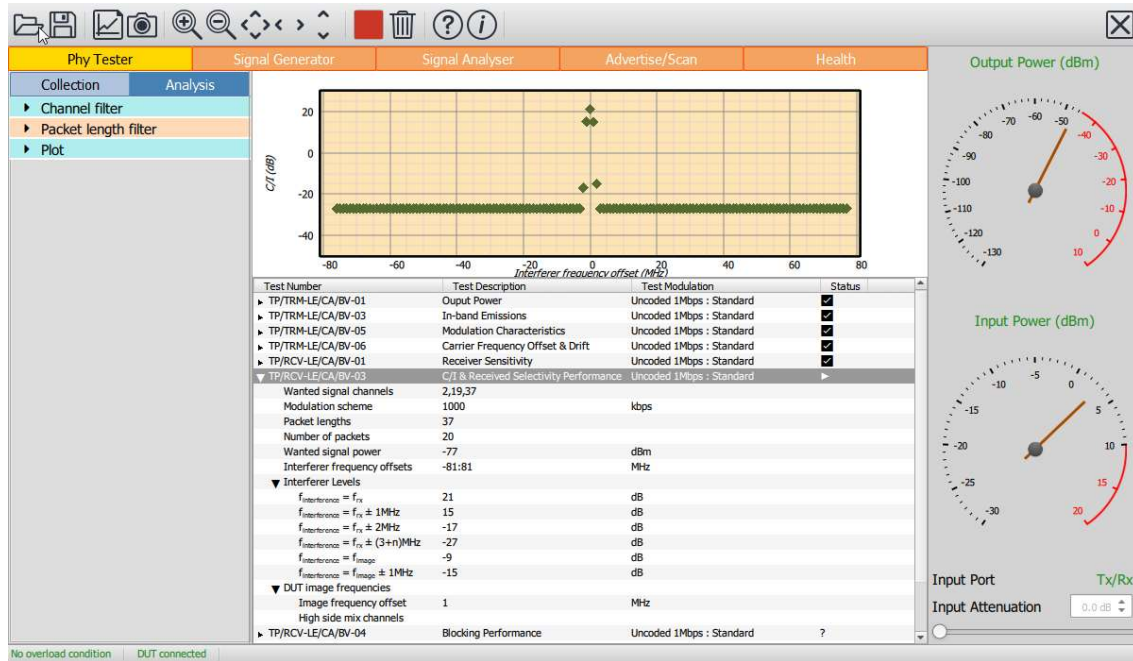
Figure 57: The test script window.

9.9 Saving and recalling test scripts

The current test script can be saved by clicking the 'Save' button in the toolbar. The test script can be saved in two formats:

1. Test script file (*.tsf). This is an XML file containing the test script. These files can be read back into the Sapphire GUI. Test script files should never be edited manually. To edit a test script file, read it back into the Sapphire GUI, edit it and then save it again. This format also contains all the settings contained in the 'Collection' and 'Analysis' tabs.

2. Text file (*.txt). This an ASCII text file representation of the test script. The format of this file is that used by the Sapphire native programming language.

To recall a test script, click the 'Open' button in the toolbar and filter by test script files (*.tsf).

9.10 Running a test script

In order to run a test script the following steps must be taken:

1. Sapphire must be told how to communicate with the DUT by setting the parameters in the 'DUT control' menu under the 'Collection' tab. If a test script is loaded from a test script file, then these parameters will be read in from the file.
2. Sapphire must be informed which features the DUT supports by setting the parameter in the 'DUT type' menu under the 'Collection' tab. If a test script is loaded from a test script file, then these parameters will be read in from the file.
3. The cable loss between the *TLF3000* unit and the DUT must be entered in the 'Cable loss' menu under the 'Control' tab. If a test script is loaded from a test script file, then these parameters will be read in from the file.
4. The termination criteria must be set in the 'Run mode' menu under the 'Control' tab. If a test script is loaded from a test script file, then these parameters will be read in from the file.
5. A test script must either be entered manually (see section 9.6) or loaded from a file using the 'Open' button in the toolbar.
6. The DUT must be physically connected to the *TLF3000* unit by:
   a. RF cable connected to the Tx/Rx port
   b. Serial cable connected to the digital IO port (or to the host computer if the serial communications is to be via the host)
   c. If appropriate, an IO voltage may also be connected to the digital IO port

Once these steps have been taken, the test script can be executed by pressing the 'Play' button in the toolbar.

While the test script is executing the GUI will display the following:

1. The test currently being run will be highlighted in the test script panel
2. The status of the test being run will change from '?' to ' ▶ '
3. The graphics window will plot one of the quantities being tested

After each test in the test script terminates, its displayed status will change to either:

1. '✓' to indicate that all test limits associated with test passed
2. '✗' to indicate that one or more the test limits associated with the test failed

When the test script terminates execution the 'Stop' button in the toolbar will revert to the 'Play' button. If appropriate, an error message will be displayed in the status indicating why the test script terminated.

If the test script terminates due to a test limit failure, then the graphics window will plot quantity which failed.

9.11 Viewing the results

9.11.1 Overview

Once a test script has be run, the results can be view using the controls under the 'Analysis' tab.

The results which are plotted in the graphics area can be filtered by:

1. RF channel number
2. Packet length

9.11.2 Filtering by RF channel number

To filter the displayed results by RF channel number, expand the 'Channels' menu under the 'Analysis' tab. The required RF channels can be selected by:

1. Ticking the individual channel checkboxes
2. Using the toggle buttons at the bottom left of the window:
   a. *Clear all*. All RF channels will be deselected.
   b. *Select all*. All RF channels which are supported by the DUT will be selected.
   c. Primary *advertising*. The primary advertising channels will be selected.
   d. *Data/*Secondary *advertising*. The data and secondary advertising channels supported by the DUT will be selected.
   e. *Specification channels*. The RF channels defined for the test in Bluetooth LE RF Phy Test Specification will be selected.
3. Entering a text string in the text field at the bottom of the window. The required format of the text string is described in section 8.6.12.

If the quantity to be displayed is to be plotted against RF channel number, the RF channel filter settings are ignored.

Figure 58: Filtering by RF channel number.

9.11.3 Filtering by packet length

To filter the displayed results by packet length, expand the 'Packet length' menu under the 'Analysis' tab. The required packet lengths can be selected by:

1. Ticking the individual packet length checkboxes
2. Using the toggle buttons at the bottom left of the window:
   a. *Clear all*. All packet lengths will be deselected.
   b. *Select all*. All packet lengths which are supported by the DUT will be selected.
   c. *Specification*. The packet lengths specified for the test in Bluetooth LE RF Phy Test Specification will be selected.
3. Entering a text string in the text field at the bottom of the window. The required format of the text string is described in section 8.6.12.

If the quantity to be displayed is to be plotted against packet length, the packet length filter settings are ignored.
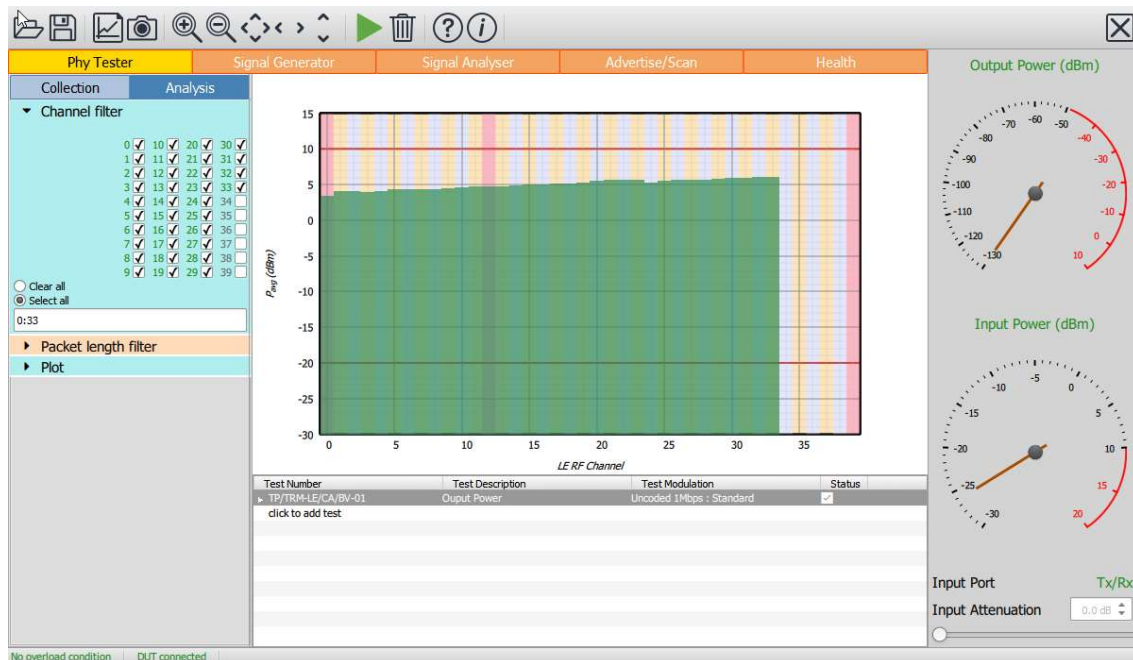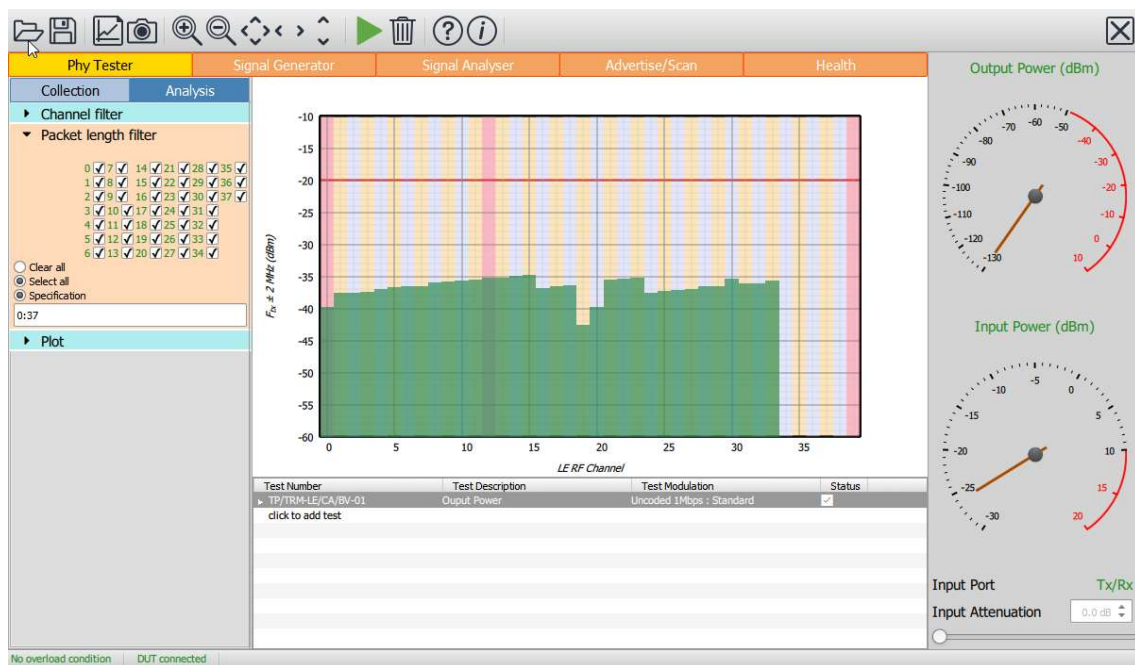

Figure 59: Filtering by packet length.

9.11.4 Selecting the quantity to be plotted

To select which test results are to be plotted, highlight the associated test in the test script window by clicking it.

To change the contents of the graphics area, expand the 'Plot' menu under the 'Analysis' tab. The left hand combo box determines the quantity to be plotted on the y-axis and the right hand combo box the quantity to be plotted on the x-axis.

9.11.4.1 Transmitter tests

For transmitter tests, the quantity plotted on the y-axis can be anyone of the quantities against which a test limit is applied in the Bluetooth 5 LE RF Phy Test Specification:

1. Power measurements:
   a. *Pavg*
   b. *Pk - Pavg*
2. Modulation characteristics:
   a. *$\Delta F1avg$*
   b. *$\Delta F2avg / \Delta F1avg$*
   c. *$\Delta F2max\ 99.9\%$*
3. Drift and carrier offset measurements:
   a. *Fo*
   b. *Fn*
   c. $| F_1 - F_0 |$ or $| F_3 - F_0 |$ for 125 kbps
   d. $| F_0 - F_n |$
   e. $| F_n - F_{n-5} |$ or $| F_n - F_{n-3} |$ for 125 kbps
4. In-band emissions:
   a. *$F_{tx}\pm 2MHz$* or *$F_{tx}\pm(4,5)MHz$* for 2 Mbps
   b. *$F_{tx}\pm (3+n)MHz$* or *$F_{tx}\pm(6+n)MHz$* for 2 Mbps
   c. Number of exceptions
   d. Maximum exception

The selected quantity may be plotted against:

1. RF channel number
2. Packet length

The selected quantity is plotted in the graphics area as a series of green bars. The associated test limits are plotted as red lines.
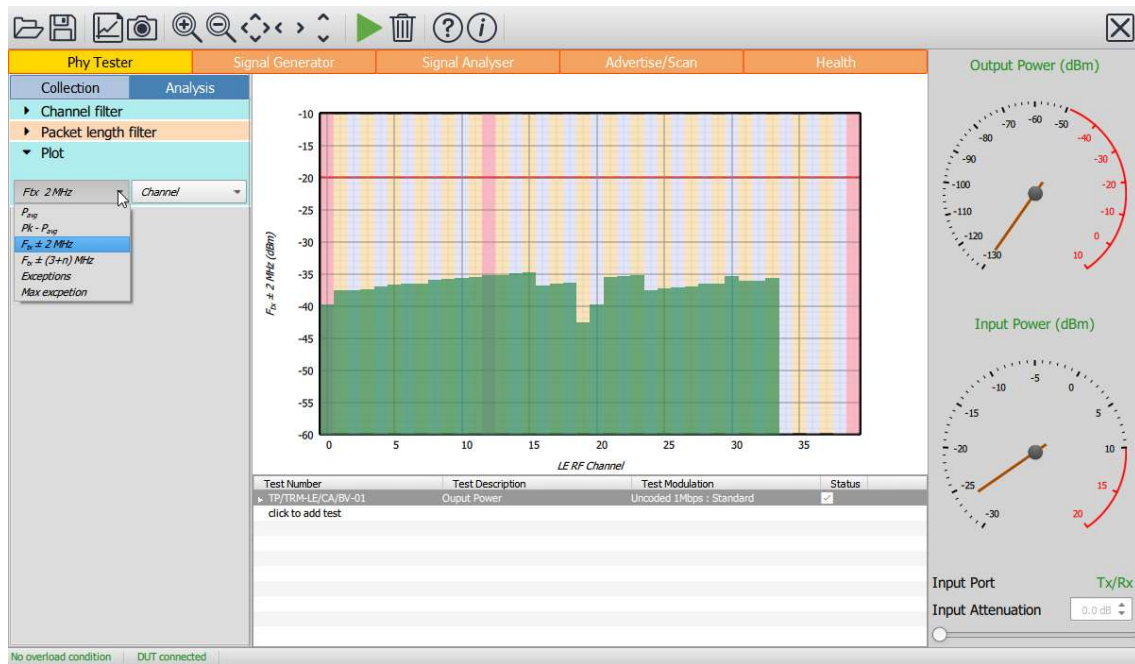
Figure 60: Transmitter tests.

9.11.4.2 ~~Receiver sensitivity, maximum input signal and PER report integrity tests~~

The y-axis can be selected to be either:

1.   Wanted signal level
2.   Log$_{10}$(PER)

If the y-axis is selected to be wanted signal level, then the x-axis can be either:

1.   RF channel number
2.   Packet length

If the y-axis is selected to be Log$_{10}$(PER) then the x-axis is wanted signal level and a classical PER curve is displayed.

The results are plotted as a series of diamonds which are colour coded red for fail and green for pass. Test limits are not displayed since these are functions of the packet length and so may not be the same for all the displayed points.
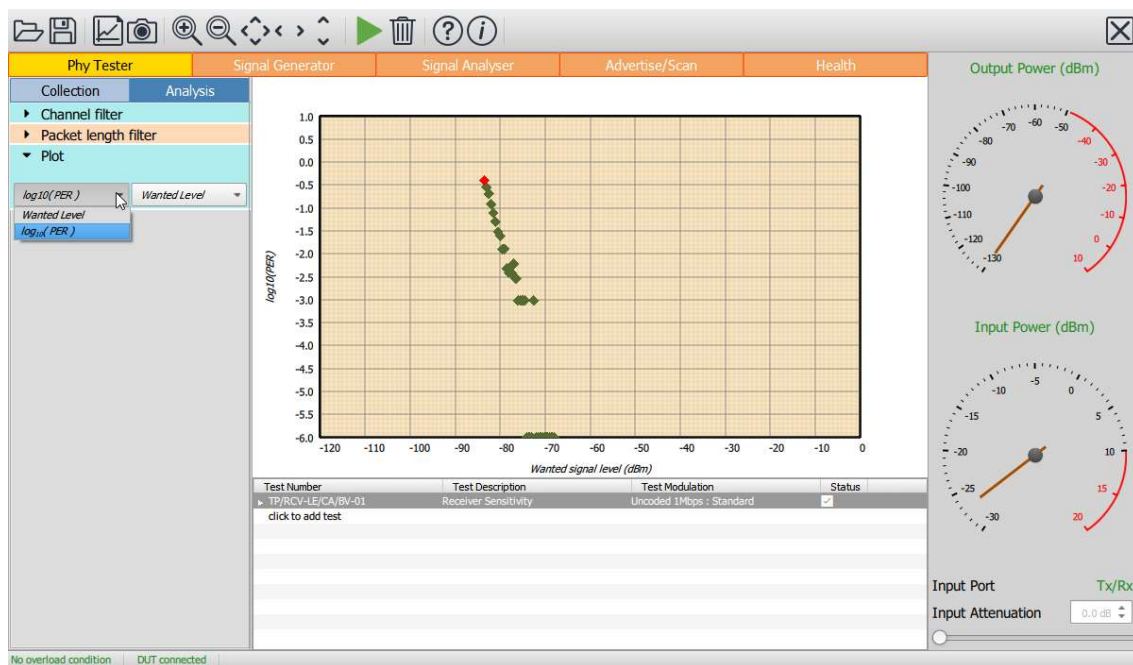
Figure 61: Receiver sensitivity, maximum input signal and PER report integrity tests

9.11.4.3 ~~Analysis Mode~~

For receiver C/I tests, the x-axis is always the offset of the interferer from the wanted signal. The y-axis may be selected to be one of the following:

1. C/I level
2. Wanted signal level
3. Interferer signal level

Results are plotted as diamonds which are colour coded red for failure and green for pass.. Test limits are not displayed since these are functions of the packet length and so may not be the same for all the displayed points.
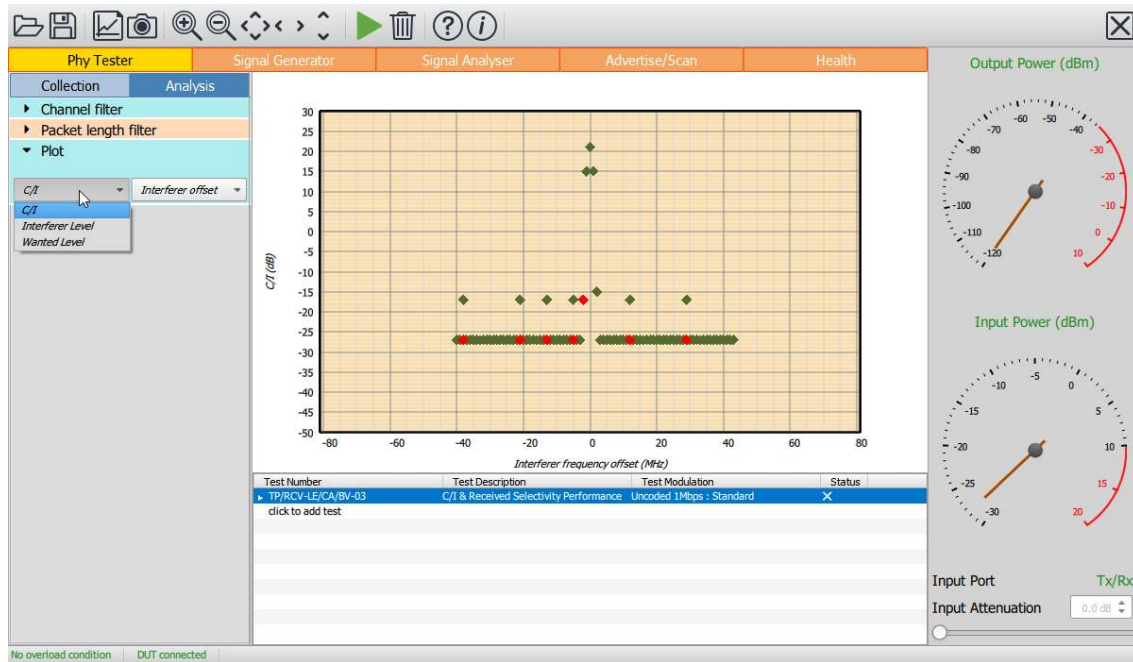
Figure 62: Receiver C/I tests.

9.11.5 Receiver blocking tests

For receiver blocking tests, the x-axis is always the blocker frequency. The y-axis may be selected to be one of the following:

1. Blocker level
2. Wanted signal level

Results are plotted as diamonds which are colour coded red for failure and green for pass. Test limits are not displayed since these are functions of the packet length and so may not be the same for all the displayed points.
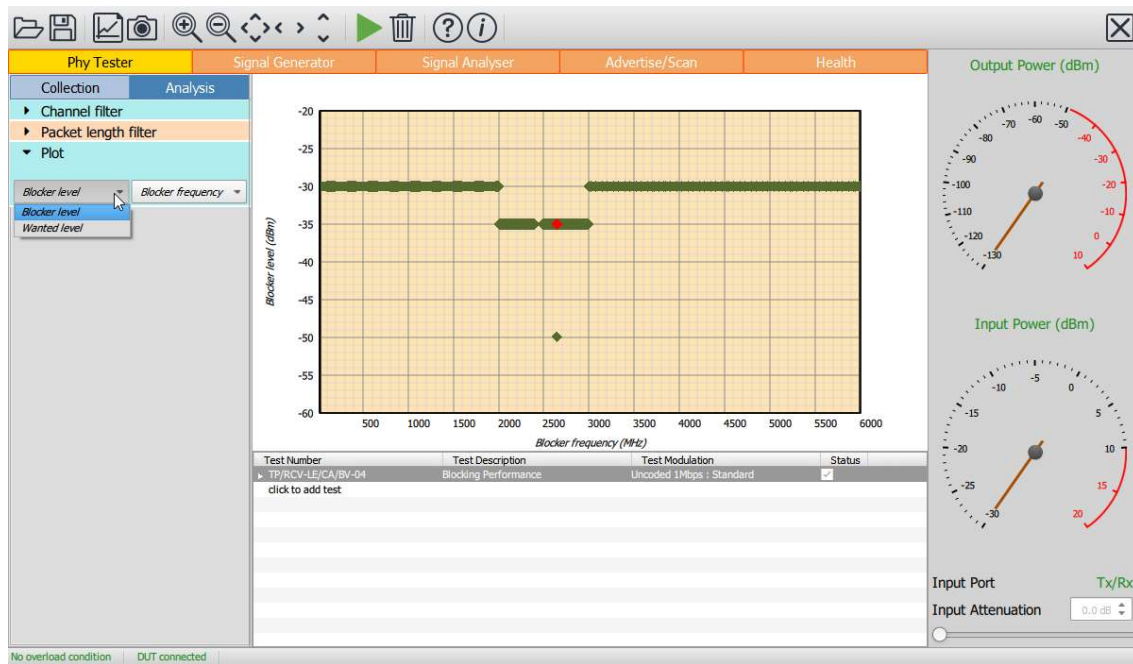
Figure 63: Receiver blocking tests.

9.11.6 Receiver intermodulation tests

The y-axis can be selected to be either:

1. Wanted signal level
2. Interferer signal level
3. $Log_{10}(PER)$

If the y-axis is either wanted signal level or interferer signal level, the x-axis will be RF channel number.

If the y-axis is selected to be $Log_{10}(PER)$ then the x-axis is wanted signal level and a classical PER curve is displayed against either the wanted signal level or the interferer signal level.

Results are plotted as diamonds which are colour coded red for failure and green for pass. Test limits are not displayed since these are functions of the packet length and so may not be the same for all the displayed points.
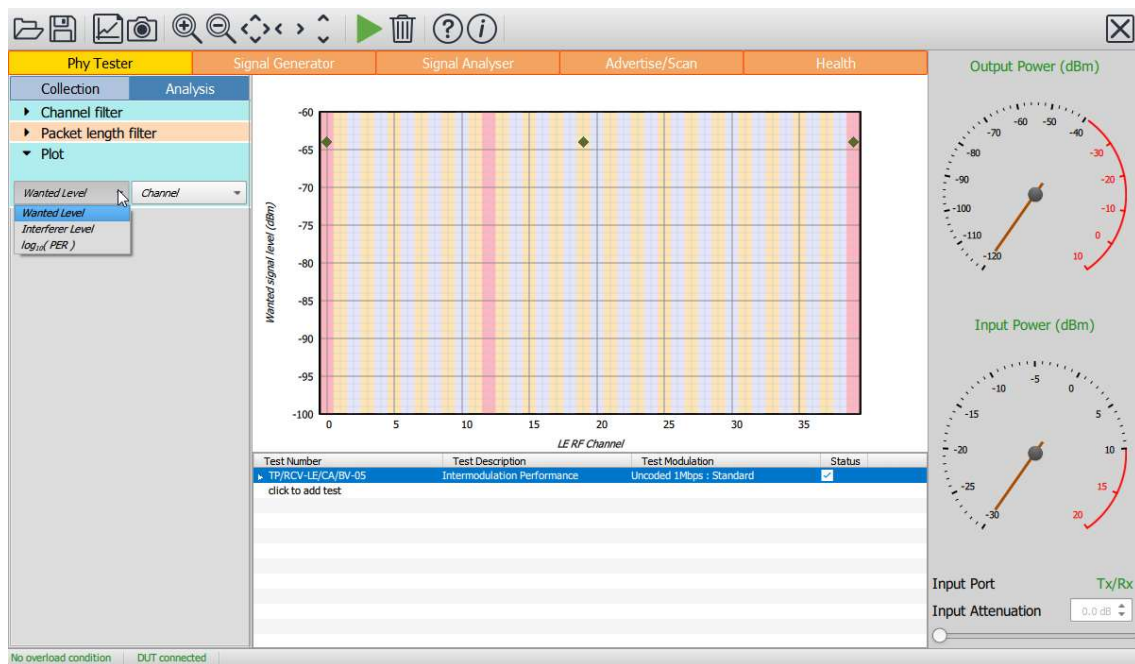

Figure 64: Receiver intermodulation tests.

9.12 Saving results

The test script results can be saved by clicking the 'Save' button on the toolbar. The format of the results file depends on the file type selected to save the current test script results. The results can be saved in the following formats:

1. xml: permitting the results to be read by a range of other applications
2. txt: a simple asci text file
3. csv: permitting the results to be read by spreadsheets
4. html: for viewing the results in a web browser or for inclusion in a test report

The current graph can also be saved as an image by clicking the 'Graph' button on the toolbar. The range of possible graphics formats includes:

1. Windows bitmap files (*.bmp)
2. Joint photographic expert group files (*.jpg)
3. Portable network graphics files (*.png)
4. Portable bitmap files (*.pbm)
5. Portable graymap files (*.pgm)
6. Portable pixmap files (*.ppm)
7. X11 bitmap files (*.xbm)
8. X11 pixmap files (*.xpm)

9.13 List of supported tests

Test number	Test description	Phy	Limitations
TP/TRM-LE/CA/BV-01-C	Output power	Uncoded, 1 Mbps	
TP/TRM-LE/CA/BV-03-C	In-band emissions	Uncoded, 1 Mbps	
TP/TRM-LE/CA/BV-05-C	Modulation characteristics	Uncoded, 1 Mbps	
TP/TRM-LE/CA/BV-06-C	Carrier frequency offset & drift	Uncoded, 1 Mbps	
TP/TRM-LE/CA/BV-08-C	In-band emissions	2 Mbps	
TP/TRM-LE/CA/BV-09-C	Modulation characteristics	Stable, uncoded, 1 Mbps	
TP/TRM-LE/CA/BV-10-C	Modulation characteristics	2 Mbps	
TP/TRM-LE/CA/BV-11-C	Modulation characteristics	Stable, 2 Mbps	
TP/TRM-LE/CA/BV-12-C	Carrier frequency offset & drift	2 Mbps	
TP/TRM-LE/CA/BV-13-C	Modulation characteristics	LE Coded, S=8	
TP/TRM-LE/CA/BV-14-C	Carrier frequency offset & drift	LE Coded, S=8	
TP/RCV-LE/CA/BV-01-C	Receiver sensitivity	Uncoded, 1 Mbps	
TP/RCV-LE/CA/BV-03-C	C/I & receiver selectivity	Uncoded, 1 Mbps	
TP/RCV-LE/CA/BV-04-C	Blocking	Uncoded, 1 Mbps	See (a)
TP/RCV-LE/CA/BV-05-C	Intermodulation	Uncoded, 1 Mbps	See (b)
TP/RCV-LE/CA/BV-06-C	Maximum input signal	Uncoded, 1 Mbps	
TP/RCV-LE/CA/BV-07-C	PER report integrity	Uncoded, 1 Mbps	
TP/RCV-LE/CA/BV-08-C	Receiver sensitivity	2 Mbps	
TP/RCV-LE/CA/BV-09-C	C/I & receiver selectivity	2 Mbps	
TP/RCV-LE/CA/BV-10-C	Blocking	2 Mbps	See (a)
TP/RCV-LE/CA/BV-11-C	Intermodulation	2 Mbps	See (b)
TP/RCV-LE/CA/BV-12-C	Maximum input signal	2 Mbps	
TP/RCV-LE/CA/BV-13-C	PER report integrity	2 Mbps	
TP/RCV-LE/CA/BV-14-C	Receiver sensitivity	Stable, uncoded, 1 Mbps	
TP/RCV-LE/CA/BV-15-C	C/I & receiver selectivity	Stable, uncoded, 1 Mbps	
TP/RCV-LE/CA/BV-16-C	Blocking	Stable, uncoded, 1 Mbps	See (a)
TP/RCV-LE/CA/BV-17-C	Intermodulation	Stable, uncoded, 1 Mbps	See (b)
TP/RCV-LE/CA/BV-18-C	Maximum input signal	Stable, uncoded, 1 Mbps	
TP/RCV-LE/CA/BV-19-C	PER report integrity	Stable, uncoded, 1 Mbps	
TP/RCV-LE/CA/BV-20-C	Receiver sensitivity	Stable, 2 Mbps	
TP/RCV-LE/CA/BV-21-C	C/I & receiver selectivity	Stable, 2 Mbps	
TP/RCV-LE/CA/BV-22-C	Blocking	Stable, 2 Mbps	See (a)
TP/RCV-LE/CA/BV-23-C	Intermodulation	Stable, 2 Mbps	See (b)
TP/RCV-LE/CA/BV-24-C	Maximum input signal	Stable, 2 Mbps	
TP/RCV-LE/CA/BV-25-C	PER report integrity	Stable, 2 Mbps	
TP/RCV-LE/CA/BV-26-C	Receiver sensitivity	LE coded, S=2	
TP/RCV-LE/CA/BV-27-C	Receiver sensitivity	LE coded, S=8	
TP/RCV-LE/CA/BV-28-C	C/I & receiver selectivity	LE coded, S=2	
TP/RCV-LE/CA/BV-29-C	C/I & receiver selectivity	LE coded, S=8	
TP/RCV-LE/CA/BV-30-C	PER report integrity	LE coded, S=2	
TP/RCV-LE/CA/BV-31-C	PER report integrity	LE coded, S=8	
TP/RCV-LE/CA/BV-32-C	Receiver sensitivity	Stable, LE coded, S=2	
TP/RCV-LE/CA/BV-33-C	Receiver sensitivity	Stable, LE coded, S=8	
TP/RCV-LE/CA/BV-34-C	C/I & receiver selectivity	Stable, LE coded, S=2	
TP/RCV-LE/CA/BV-35-C	C/I & receiver selectivity	Stable, LE coded, S=8	
TP/RCV-LE/CA/BV-36-C	PER report integrity	Stable, LE coded, S=2	
TP/RCV-LE/CA/BV-37-C	PER report integrity	Stable, LE coded, S=8	

Table 12: Supported tests.

Limitations:

(a) Blocking tests are limited to the range 25 MHz to 6 GHz. The Bluetooth test specification has an upper limit of 12.75 GHz. The supported range does include the 2nd harmonic of the 2.4 GHz band. If the blocking test passes at the 2nd harmonic, then it is highly likely to pass for higher test frequencies.

The blocking source used in the *TLF3000* has significant harmonic content. Some internal filtering of the source is applied to attenuate harmonics falling within the 2.4 GHz band. If blocking failures do occur, then further testing may be required to ascertain whether these are due to the fundamental of the blocker or one of its harmonics.

(b) The specification states that the intermodulation tests should be performed with the interfering signals both on the low side and the high side of the wanted signal. Under some circumstances, when the wanted signal is close to the band edge, this can lead to the interfering signals being placed outside the *TLF3000* signal generator bandwidth of 2395 MHz to 2485 MHz. When these circumstances arise, the test will only be performed with the interfering signals positioned closer to the band centre.

The requirement to perform intermodulation tests with the signals both above and below the wanted signal is somewhat perverse. If the wanted signal is at the band edge and the interfering signals are positioned outside the band, then the interfering signals will be attenuated by frontend filtering and the intermodulation performance of the device improved. Hence the inability of *TLF3000* to test this scenario is considered somewhat academic.

10 Advertise/Scan mode.

10.1 Overview

The advertise/scan mode permits restricted testing of devices for which no test interface is available, for example, devices assembled into final products on a production line. In the advertise/scan mode, normal LE packets are used to provoke a response from the DUT so that receiver performance can be checked and transmission quality verified.

There are two modes of operation:

1. *Advertise.* In this mode of operation the Sapphire application sends out pre-defined advertising packets at a specified signal level and waits for scan or connection requests from the device under test.
2. *Scan.* In this mode the DUT advertises and the Sapphire application sends out scan requests at a specified signal level to trigger a response from the DUT.

In advertise/scan mode an approximation to the following Bluetooth LE RF Phy Test Specification tests can be performed:

1. All transmitter tests, including in-band emissions
2. Receiver sensitivity

In principle, the *TLF3000* unit is capable to performing an approximation to all of the receiver tests defined in the Bluetooth LE RF Phy Test Specification whilst in advertise/scan mode, however, these are not currently implemented.

In advertise/scan mode the left hand mode control panel is divided into two separate tabs:

1. *Collection*. This tabs contains the parameters which define how the DUT will be provoked into transmission and how the captured data will be processed.
2. *Analysis*. This tabs contains the parameters which define how the captured results will be displayed.

The central graphics area is used to plot the results in a manner defined by the parameters under the analysis tab.

Below the analysis tab is a results table which displays statistics of the test quantities defined in the Bluetooth 5 LE RF Phy Test Specification. These results are filtered by the parameters set under the 'Analysis' tab in the mode control panel. *If no results are displayed this may be because the analysis filter settings are inconsistent with the packets being received.*

The receiver port and front-end attenuation are set using the controls in the monitor panel on the right hand side of the window.

Testing is started/stopped by toggling the 'Play' button in the toolbar.

The 'Clear' button in the toolbar will discard all results which have been collected.
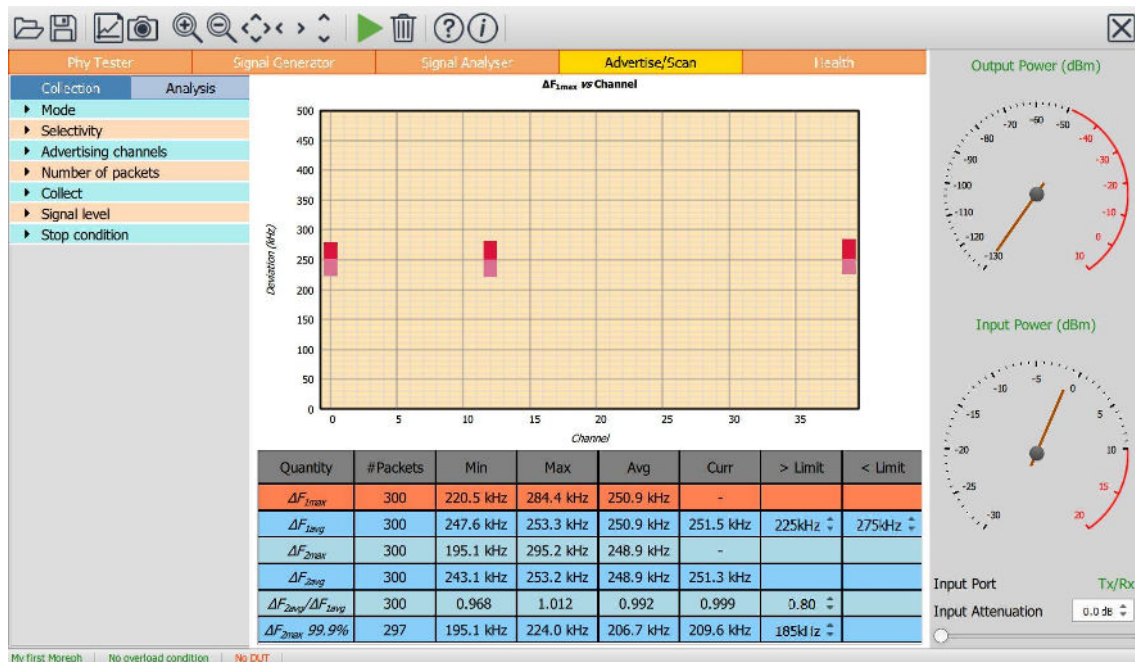
Figure 65: Sapphire advertiser/scan mode.

10.2 RF connections

The advertise/scan mode transmits the advertising and scan request packets on the 'Tx/Rx' port. It can receive and analyze signals on either the 'Tx/Rx' port or the 'Monitor In' port. See section 10.3.9 for settings the RF input port.

10.3   Programming the advertise/scan mode

10.3.1 Overview

To program the advertise/scan mode, then following parameters need to be set:

1. Whether the Sapphire should be run as an advertiser or scanner
2. The contents of the advertising packets or scan request packets
3. Parameters Sapphire should check prior to processing a packet from the DUT
4. Which advertising channel(s) to use
5. The number of packets to be sent
6. The transmitter measurements which are to be made
7. The range of signal levels Sapphire should transmit at
8. The termination criteria for the test

All of these parameters are accessible from the 'Collection' tab of the mode control panel.

10.3.2 Programming the advertise/scan packets

The programming of the advertising or scan request packets is done via the 'Mode' menu under the 'Collection' tab.

The choice between advertising and scanning is made through the 'Tester mode' combo box.

If advertising is selected, then the packet PDU type must also be selected. Options for the packet PDU are:

1. ADV_IND, connectable and scannable undirected advertising events
2. ADV_DIRECT_IND, connectable directed advertising events
3. ADV_SCAN_IND, scannable undirected advertising events

If scanning is selected, then the packet PDU type is set to SCAN_REQ.

Further parameters may be required to define the advertising or scan request packets:

10.3.2.1

Controls the setting of bit 5 in the packet header. This indicates which channel selection algorithm is supported. Options are:

1. 0 : algorithm #1)
2. 1 : algorithm #2)

The value is set by clicking the green text to toggle the value.

10.3.2.2

Controls the setting of bit 6 in the packet header. This indicates the nature of the AdvA field for advertising packets and the ScanA field for scan request packets. Options are:

1. 0 : the address is public
2. 1 : the address is random

The value is set by clicking the green text to toggle the value.

10.3.2.3

Controls the setting of bit 7 in the packet header. This indicates the nature of the TargetA field for the ADV_DIRECT_IND advertising packets. Options are:

1. 0 : the address is public
2. 1 : the address is random

The value is set by clicking the green text to toggle the value.

10.3.2.4

Sets the AdvA field in the advertising packet. Hex values may be entered directly by editing the green text.

10.3.2.5

Sets the TargetA field in the ADV_DIRECT_IND packet PDU. Hex values may be entered directly by editing the green text.

10.3.2.6

Sets the ScanA field in the scan request packet. Hex values may be entered directly by editing the green text.

10.3.2.7

Sets the length of the AdvData field in the advertising packet PDU. Valid values are between 0 and 31 inclusive. The value is set using the associated spin box.

10.3.2.8 AdvData

Sets the contents of the AdvData field in the advertising packet PDU. Hex values may be entered directly by editing the green text.

Figure 66: Programming advertising packets

10.3.3 Programming the checks to be performed on received packets

The programming of the checks to be performed on received packets is done via the 'Mode' menu under the 'Selectivity' tab. Only those packets which pass all the selected criteria will be analysed. All other packets will be discarded and will not contribute to the displayed statistics.

10.3.3.1 RSSI threshold

Only those packets with a signal strength greater than the RSSI threshold will be analysed. This applies to both advertise and scan modes. This helps the Sapphire application distinguish between packets from the device under test and more distant devices. The RSSI threshold can be set in the range -120dBm to +20dBm. The lower limit effectively disables the RSSI threshold.

10.3.3.2 Check InitA / ScanA

This option is only applicable to advertise mode. When the Sapphire application receives a connection request or scan request from t can check the corresponding InitA or ScanA address to ensure that it is from the DUT and not some other device. The 48bit address can be typed into the *InitA / ScanA address* field the *InitA / ScanA* field can be toggled to indicate whether the address is public or random.

10.3.3.3 Check AdvA address

This option is only applicable in scan mode. When the Sapphire application receives an advertising packet it can check the corresponding AdvA address to ensure that it is from the DUT and not some other device. The 48bit address can be typed in the *AdvA address* field and the *AdvA* field can be toggled to indicate whether the address is public or random.

10.3.3.4 Analyse SCAN_REQ

This option is only applicable in advertise mode. In order for the Sapphire application to analyse SCAN_REQ packets this field must be checked. Sapphire

10.3.3.5 Analyse CONNECT_IND

This option is only applicable in advertise mode. In order for the application to analyse CONNECT_IND packets this field must be checked.

10.3.3.6 Respond to ADV_IND packets

This option is only applicable in scan mode. In order for the Sapphire application to issue a scan request in respond to an ADV_IND packet this field must be checked.

10.3.3.7 Respond to ADV_SCAN_IND packets

This option is only applicable in scan mode. In order for the Sapphire application to issue a scan request in respond to an ADV_SCAN_IND packet this field must be checked.

TELEDYNE LECROY
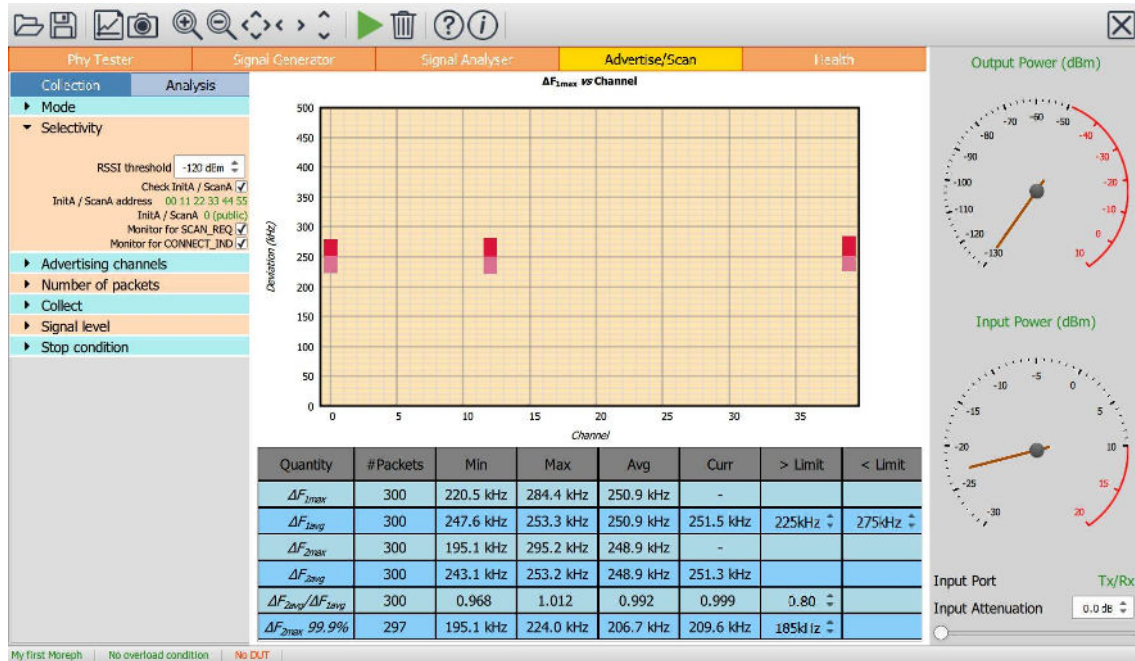
Figure 67: Programming selectivity in advertise mode

Figure 68: Programming selectivity in scan mode

10.3.4 Programming the advertising channels to use

The Sapphire application is capable of listening on 40 LE channels simultaneously as well as transmitting on all 3 primary advertising channels simultaneously. The capability alleviates the need for Sapphire to cycle round to the correct advertising channel before provoking a response from the DUT.

The choice of which primary advertising channels to use is made via the 'Channels' menu under the 'Collection' tab. The required channels are selected by ticking the appropriate checkboxes.

The *Concurrent analysis checkbox* determines whether the Sapphire application will analyse/transmit on all selected channels simultaneously or whether it will cycle around the channels in ascending order. If concurrent analysis is selected, then there is a danger that not all channels will get equal test coverage. However, concurrent analysis will generally result in far faster testing.

Figure 69: Programming the advertising channels to use.

10.3.5 Programming the number of packets to transmit

The number of packets to be transmitted can be set by expanding the 'Number of packets' menu. If the 'Continuous transmission' checkbox is ticked, then test will continue until the 'Stop' button in the toolbar is clicked, otherwise the number of packets specified in the 'Packet count' spin box will be transmitted. The packet count can be set to any value between 1 and 65535, inclusive.

In advertising mode, the packet count is the number of advertising packets which are transmitted. If multiple transmission signal levels have been defined, then this number of advertising packets is transmitted at each signal level.

In scan mode, the packet count is the number of scan request packets which are transmitted. If multiple transmission signal levels have been defined, this is the number of scan request packets transmitted at each signal level.

If concurrent analysis has been selected, then number of packets represents the total number of packets which will be transmitted/analysed over all selected channels. If concurrent analysis has not been selected then number of packets represents the number of packets which will be transmitted/analysed on each selected channel.
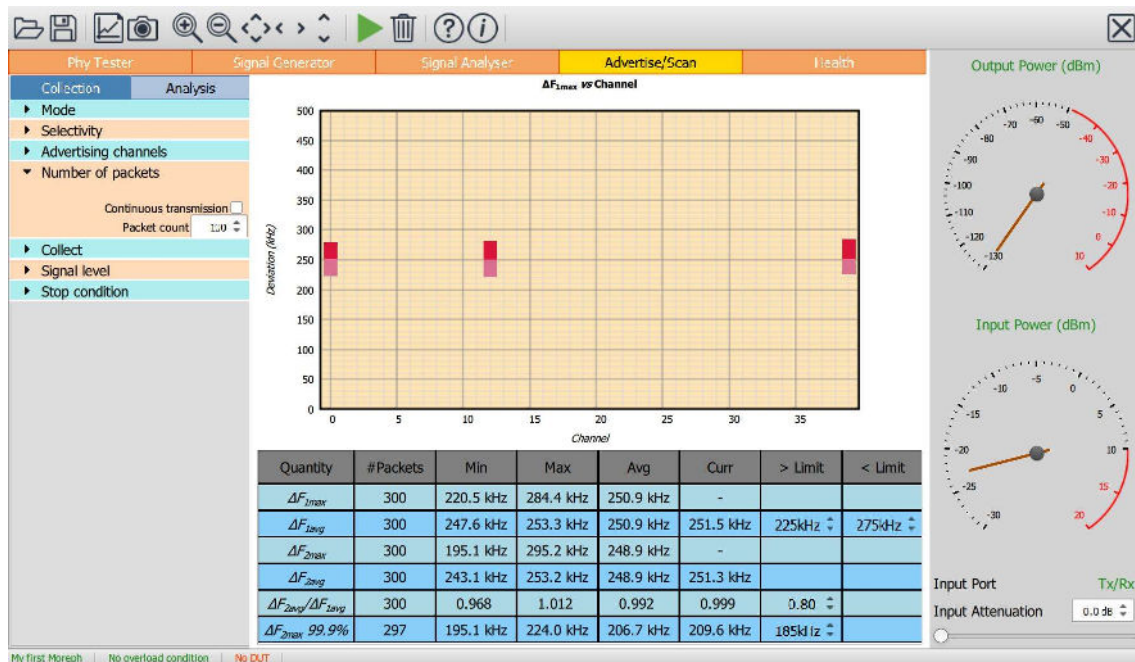
Figure 70: Programming the number of packets to transmit.

10.3.6 Programming the transmitter measurements to be performed

Sapphire divides the Bluetooth LE RF phy transmitter test measurements into five groups:

1. Power measurements, which includes:
    a. *Pavg*
    b. *Pk - Pavg*
2. Modulation characteristics, which includes:
    a. $\Delta F1max$
    b. $\Delta F1avg$
    c. $\Delta F2max$
    d. $\Delta F2avg$
    e. $\Delta F2avg / \Delta F1avg$
    f. $\Delta F2max\ 99.9\%$
3. Drift and carrier offset measurements, which includes:
    a. F_0
    b. F_n
    c. $|\,F_1 - F_0\,|$ or $|\,F_3 - F_0\,|$ for 125 kbps
    d. $|\,F_0 - F_n\,|$
    e. $|\,F_n - F_{n-5}\,|$ or $|\,F_n - F_{n-3}\,|$ for 125 kbps
4. In-band emissions, which includes:
    a. $F_{tx}\pm\ 2MHz$ or $F_{tx}\pm(4,5)MHz$ for 2 Mbps
    b. $F_{tx}\pm\ (3+n)MHz$ or $F_{tx}\pm(6+n)MHz$ for 2 Mbps
    c. Number of exceptions
    d. Maximum exception
5. AoA/AoD

Each of these groups of measurements can be individually selected under the 'Collect' menu of the 'Collection' tab.

If the 'waveform' item is selected, then raw IQ data for the last packet analyzed is also saved. The raw IQ data is 32x oversampled, as per the Bluetooth 5 LE RF Phy Test Specification. Although it is possible to alter the oversampling ratio using the native language, this is currently not supported in the Sapphire GUI. If the 'waveform' item is selected, the volume of data which needs to be transferred to the host is large. This may have an impact on the rate at which packets can be analyzed. If it is important to analyze packets as fast as possible, then it is advisable to disable collection of raw IQ data.

TELEDYNE LECROY

Figure 71: Programming the transmitter measurements to be performed.

10.3.7 Programming the packet transmission levels

The advertising and scan request packet transmission levels can be set by expanding the 'Signal level' menu.

The signal level can be entered into the spin box, either by using the up/down arrows or by entering a numeric value directly into the text field. If the cursor is placed directly over the red bar in the signal level gauge, then a '+' will appear adjacent to the cursor. By holding down the left mouse button it is then possible to drag the red bar to set the signal level. Signal levels must be in the range -100 dBm to 0 dBm. The resolution of the signal level is 0.1 dBm.
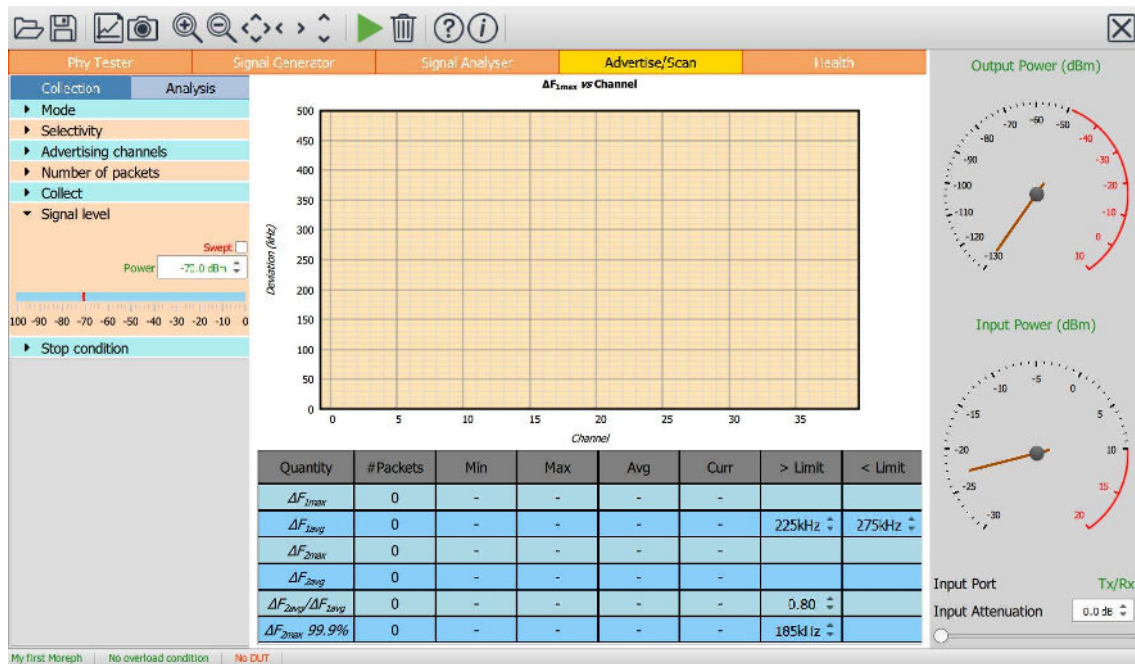
Figure 72: Programming the packet transmission levels.

If the user desires to sweep the signal level over a range of values – for example, to determine the sensitivity of the DUT receiver – then tick the 'Swept' checkbox.

The signal level power sweep is defined by the numbers displayed in the three spin boxes:

1. *Maximum Power*. This indicates the power level at which the sweep will start. The sweep will always be from the maximum signal power towards the minimum signal power. The maximum power cannot be above 0 dBm and must be greater than or equal to the minimum power. The resolution of the maximum power is 0.1 dBm.
2. *Power Step*. This is the step size that the sweep will take from the maximum power towards the minimum power. The step size cannot be less than 0.5 dB. The resolution of the step size is 0.1 dB.
3. *Minimum Power*. This indicates where the power sweep should terminate. The last signal power to be test will be greater than or equal to the minimum power. The minimum power cannot be below -100 dBm and must be less than or equal to the maximum power. The resolution of the minimum power is 0.1 dBm.

The red bar in the signal level gauge indicates the range selected by the maximum and minimum powers. This entire range may not be explored during the sweep since the actually values tested are dependent on the selection of the step size.

If the cursor is placed over one of the limits of the red bar, then it will change to a double headed cursor. It is then possible to hold down the left mouse button and drag the edge of the red bar to adjust either the minimum or maximum power.

If the cursor is placed over the body of the red bar, then a '+' will appear adjacent to the cursor. It is then possible to hold down the left mouse button and drag the entire sweep range up or down the gauge.

In advertise/scan mode a maximum of 32 different signal levels may be specified in the sweep. The power step size will automatically be adjusted to restrict the number of signal levels to 32.
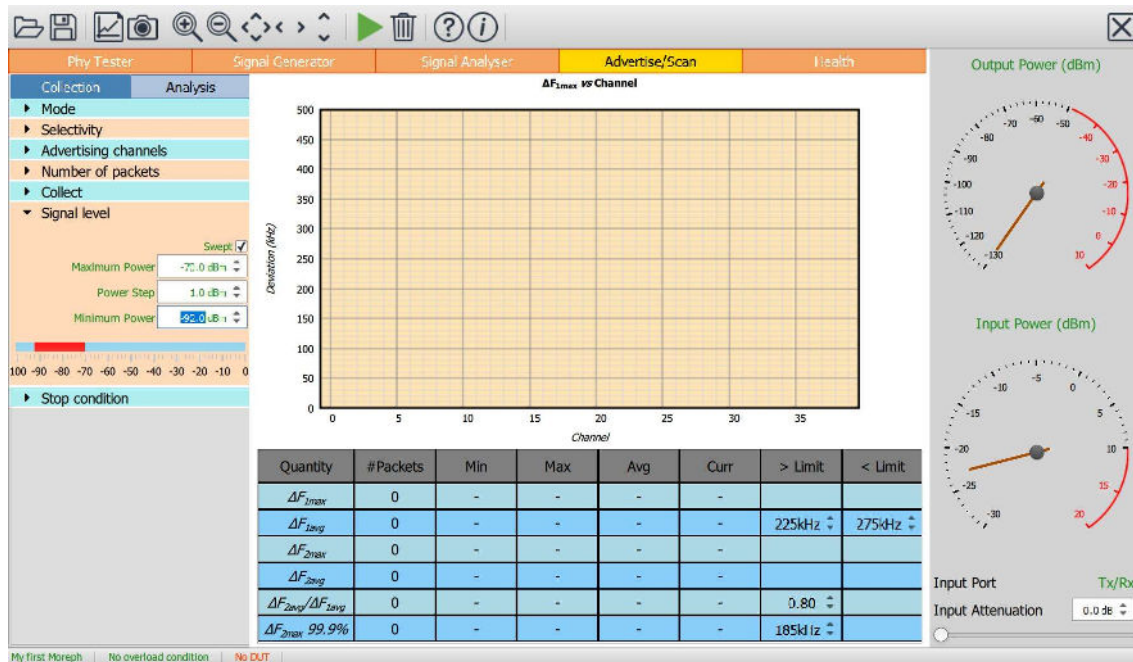
Figure 73: Programming a range of packet transmission levels.

10.3.8 Programming the termination criterion

The test termination criterion is set under the 'Stop condition' menu. Two basic termination criteria are possible:

1. The advertise/scan tester runs until the specified number of packets have been sent at each of the selected signal levels/channels.
2. The advertise/scan tester runs until a test limit failure is detected

The 'Stop on limit failure' checkbox selects which of these two termination criteria is used.

In the scan mode of operation it is also possible to specify a timeout. This specifies how long the Sapphire application should wait on each of the selected power levels/channels for the specified number advertising packets to be received and the associated scan requests issued. This parameter needs to be consistent with the advertiser's beacon period and the specified number of packets.
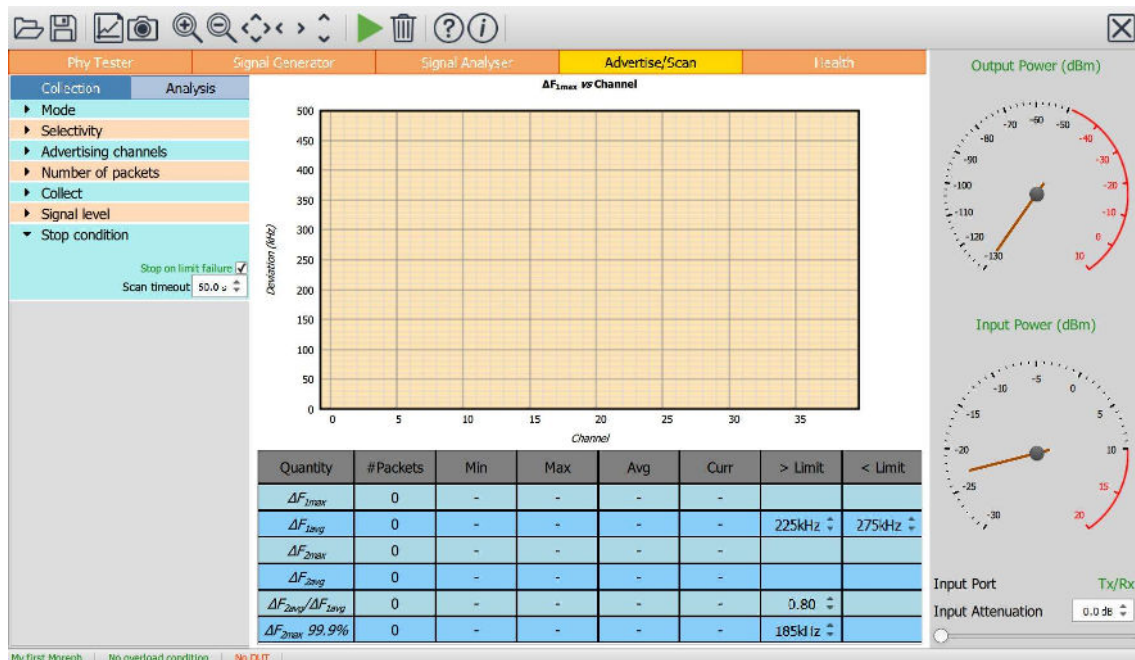
Figure 74: Programming the termination criterion.

10.3.9 Programming the test limits

The test limits are shown in the results table. The penultimate column of the results table displays the lower limit and the final column the upper limit. They can be altered by changing the values in the spin boxes, either by using the up/down arrows or by entering numeric text directly.

10.3.10   Setting the RF input port

In advertise/scan mode signals can be received and analyzed on either the 'Monitor In' RF port or the 'Tx/Rx' RF port. The selection of which port is used is made clicking the port displayed towards the bottom of the monitor panel.

The Monitor In port is designed for monitoring signals off-air. The Tx/Rx port is designed for conducted measurements.

If the monitor panel shows a lack of RF input energy, check that the DUT is connected to the same RF port as selected by the label at the bottom of the monitor panel.

10.3.11   Adjusting the RF frontend attenuation

The RF frontend attenuation is set via either:

1. The slider at the bottom of the monitor panel
2. The spin box at the bottom of the monitor panel

The RF frontend attenuation can be set between 0 and 31.5 dB in steps of 0.5 dB.

To set the RF attenuation, the 'Input Power' gauge on the monitor panel must be examined. This shows both the current input signal level (the position of the needle) and the point at which saturation of the *TLF3000* receiver will occur (the red arc). The RF attenuation should be adjusted such that the input signal level is just below the saturation level.

If too little attenuation is applied, then there is a danger that the *TLF3000* receiver will be overloaded. An overload condition on the receiver is indicated by:

1. The needle on the 'Input Power' gauge on the monitor panel entering the region of the red arc (the input power measurement is only approximate so this is only a rough guide)
2. The title of the 'Input Power' gauge on the monitor panel turning red
3. The text 'Rx overload' appearing in red within the status bar at the bottom of the window

If too much attenuation is applied, then the test results may become unreliable. In order to calculate the frequency deviation within a packet, an FM demodulation process is employed. The quality of the output of the FM demodulation process is critically dependent on the signal-to-noise ration of the signal at the input to the demodulator. If too much attenuation is applied, then the signal be analyzed will be pushed down towards the *TLF3000* receiver noise floor and the accuracy of the test results will be compromised.

10.4 Controlling data analysis and presentation

10.4.1 Overview

The Sapphire application accumulates results independently for each:

1. LE RF advertising channel
2. Signal transmission level of the advertising or scan request packets

The 'Measurement' menu under the 'Analysis' tab determines which group of measurements will be displayed.

The displayed results are filtered according to the settings of the 'Channel' and 'Power' menus.

The graphics area shows a plot of one of the test quantities. This may be selected either through the 'Plot' menu or by highlighting a row in the results table. The 'Plot' menu also defines the format of the plot.

The results table shows the filtered results for the selected measurement group. It also contains the test limits.

10.4.2 Selecting the measurement group to display

Sapphire divides the Bluetooth LE RF phy transmitter test measurements into five groups:

1. Power measurements, which includes:
   a. *Pavg*
   b. *Pk - Pavg*
2. Modulation characteristics, which includes:
   a. *$\Delta F1max$*
   b. *$\Delta F1avg$*
   c. *$\Delta F2max$*
   d. *$\Delta F2avg$*
   e. *$\Delta F2avg / \Delta F1avg$*
   f. *$\Delta F2max\ 99.9\%$*
3. Drift and carrier offset measurements, which includes:
   a. *F_0*
   b. *F_n*
   c. *$| F_1 - F_0 |$ or $| F_3 - F_0 |$ for 125 kbps*
   d. *$| F_0 - F_n |$*
   e. *$| F_n - F_{n-5} |$ or $| F_n - F_{n-3} |$ for 125 kbps*
4. In-band emissions, which includes:
   a. *$F_{tx}\pm 2MHz$ or $F_{tx}\pm(4,5)MHz$ for 2 Mbps*
   b. *$F_{tx}\pm (3+n)MHz$ or $F_{tx}\pm(6+n)MHz$ for 2 Mbps*
   c. Number of exceptions
   d. Maximum exception
5. Received packet count / Packet error rate. If advertise mode is selected, then the number of received packets is accumulated. If scan mode is selected, then the packet error rate is accumulated. It is not possible to calculate a PER in advertise mode since there is no means of knowing which advertising packets were correctly received.

The Sapphire GUI displays the results from just one of these measurement groups at any one time. The selection of which measurement group to display is accomplished through the 'Measurement' menu under the 'Analysis' tab.

If no results are displayed, then it is possible that no packets have been received or that the analysis measurement group selected is incompatible with the choice of collection measurement group(s).

Figure 75: Selecting the measurement group to display.

10.4.3 Filtering the displayed results by RF advertising channel

The displayed results can be filtered by RF advertising channel number. The RF advertising channels used to filter the results are selected via the 'Channel' menu under the 'Analysis' tab.

The required RF advertising channels can be selected by either:

1. Ticking the individual channel boxes
2. Using the quick channel group selection buttons:
   a. *Clear all*
   b. *Select all*
3. Entering a textual description (see section 9.6.12 for the format)
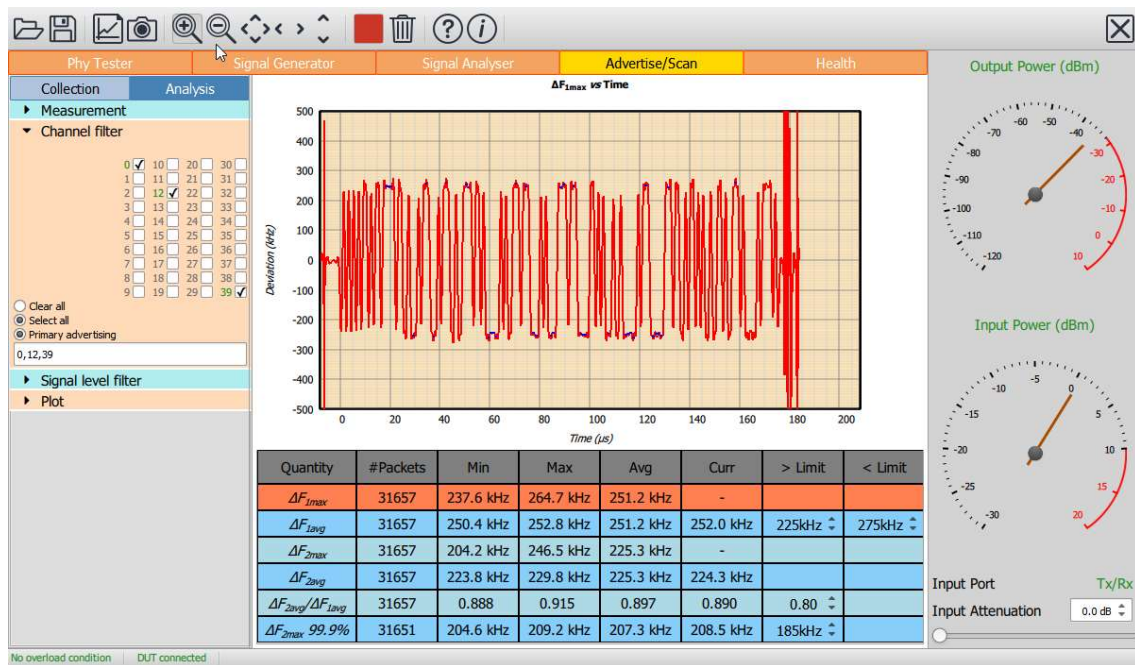
Figure 76: Filtering the displayed results by RF advertising channel.

10.4.4 Filtering the displayed results by signal transmission level

The displayed results can be filtered by the transmission level of the advertising or scan request packets. Up to 32 different signal transmission levels may be defined.

The signal transmission level filtering is specified via the 'Power' menu under the 'Analysis' tab. The required signal transmission levels are selected by ticking the corresponding boxes. If all signal transmission levels are of interest, then clicking the 'All' box at the bottom of the menu will select all signal transmission levels.

Figure 77: Filtering the displayed results by signal transmission level.

10.4.5 Understanding the results table

The results table contains a summary of the results obtained from the selected measurement group when filtered by the selected RF advertising channels and signal transmission levels.

The first column in the table contains the quantities defined in the Bluetooth 5 LE RF Test Specification which are members of the currently selected measurement group.

The second column in the table contains the number of packets which have contributed to the results for each measured quantity.

The third and fourth columns contain the minimum and maximum values which have been observed for each measured quantity.

The fifth column contains the average value of the measured quantity overall packets. If the units of the measured quantity are dBm or dB, then the average is the average of the dB values, not an average of the powers or linear ratios.

If the measured quantity is a scalar quantity, i.e. it has a single value per packet, then the last measured value is displayed in the sixth column.

For scalar quantities with test limits, the lower limit is contained in column seven and the upper limit in column eight.

Quantity	#Packets	Min	Max	Avg	Curr	> Limit	< Limit
ΔF_{1max}	7066	238.9 kHz	263.6 kHz	250.9 kHz	-		
ΔF_{1avg}	7066	250.2 kHz	251.6 kHz	250.9 kHz	251.0 kHz	225kHz ↕	275kHz ↕
ΔF_{2max}	7066	204.2 kHz	242.5 kHz	225.0 kHz	-		
ΔF_{2avg}	7066	223.6 kHz	226.5 kHz	225.0 kHz	225.3 kHz		
$\Delta F_{2avg}/\Delta F_{1avg}$	7066	0.891	0.903	0.897	0.898	0.80 ↕	
ΔF_{2max} 99.9%	7064	205.6 kHz	207.2 kHz	206.6 kHz	206.6 kHz	185kHz ↕	

Figure 78: Results table obtained from the selected measurement group when filtered by the selected RF advertising channels and signal transmission levels.

When the selected filters include more than one RF advertising channel or signal transmission level, then the displayed values of minimum, maximum and average are the minimum, maximum and average overall packets which satisfy the selected filtering parameters.

If no measurement is available, then the symbol '-' is used to fill the corresponding table cell.

If a cell exceeds one its test limits, then that cell is highlighted in red.

It is possible to select a row in the table by clicking on it. Once a row has been selected, the corresponding quantity will be plotted in the graphics areas. The format of the plot is controlled by the 'Plot' menu under the 'Analysis' tab.

10.4.6 Controlling the Graphical data

10.4.6.1 Overview

The graphical data which is displayed in controlled by the 'Plot' menu under the 'Analysis' tab. The left hand combo box lists all the quantities which are measured for the current measurement group (which is selected under the 'Measurement' menu of the 'Analysis' tab). These are the same quantities as displayed in the first column of the results table. The quantity to be plotted can be selected either through the combo box or by highlighting the appropriate row in the results table.

The right had combo box under the 'Plot' menu determines how the measured quantity is to be plotted. Options may include:

1. vs RF advertising channel
2. vs signal transmission level (only available for number of received packets)
3. as a histogram
4. vs time (not available for in-band emission measurements)
5. vs frequency (only available for in-band emission measurements)

The screen update period can also be altered via the 'Plot' menu.

10.4.6.2 ~~plot advertising channel~~

The quantity to be plotted is shown as a function of the RF advertising channel number. For each RF advertising channel three bars are drawn at channel to indicate:

1. minimum observed value (bottom of pink bar)
2. average value (junction of red and pink bars)
3. maximum observed value (top of red bar)

Quantity	#Packets	Min	Max	Avg	Curr	> Limit	< Limit
ΔF_{1max}	50533	237.3 kHz	264.7 kHz	251.2 kHz	-		
ΔF_{1avg}	50533	250.2 kHz	252.8 kHz	251.2 kHz	251.1 kHz	225kHz	275kHz
ΔF_{2max}	50533	204.2 kHz	246.5 kHz	225.3 kHz	-		
ΔF_{2avg}	50533	223.5 kHz	230.4 kHz	225.3 kHz	225.6 kHz		
$\Delta F_{2avg}/\Delta F_{1avg}$	50533	0.888	0.918	0.897	0.892	0.80	
ΔF_{2max} 99.9%	50527	204.6 kHz	209.2 kHz	207.3 kHz	208.5 kHz	185kHz	
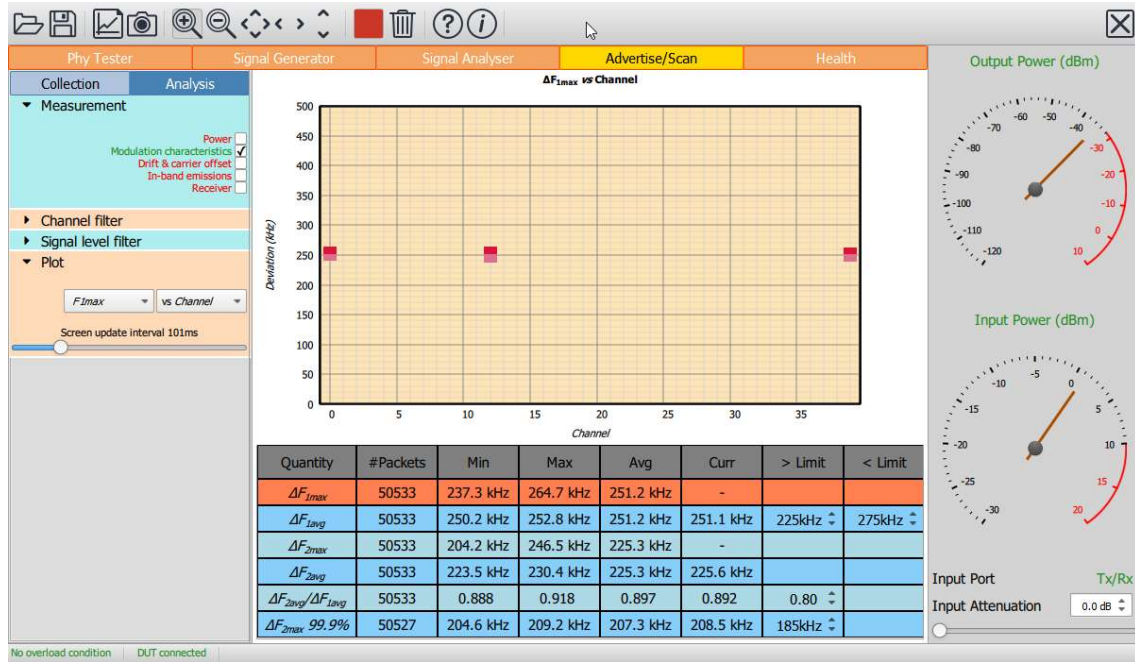
Figure 79: Results vs RF advertising channel.

10.4.6.3 ~~per...~~

This option is only available for number of received packets.

The number of received packets is shown as a function of the transmission signal level.

Number of rxed packets *vs* Advertiser power

Quantity	#Packets	Min	Max	Avg	Curr	> Limit	< Limit
Rxed pkts	3481	-	-	-	277.0		
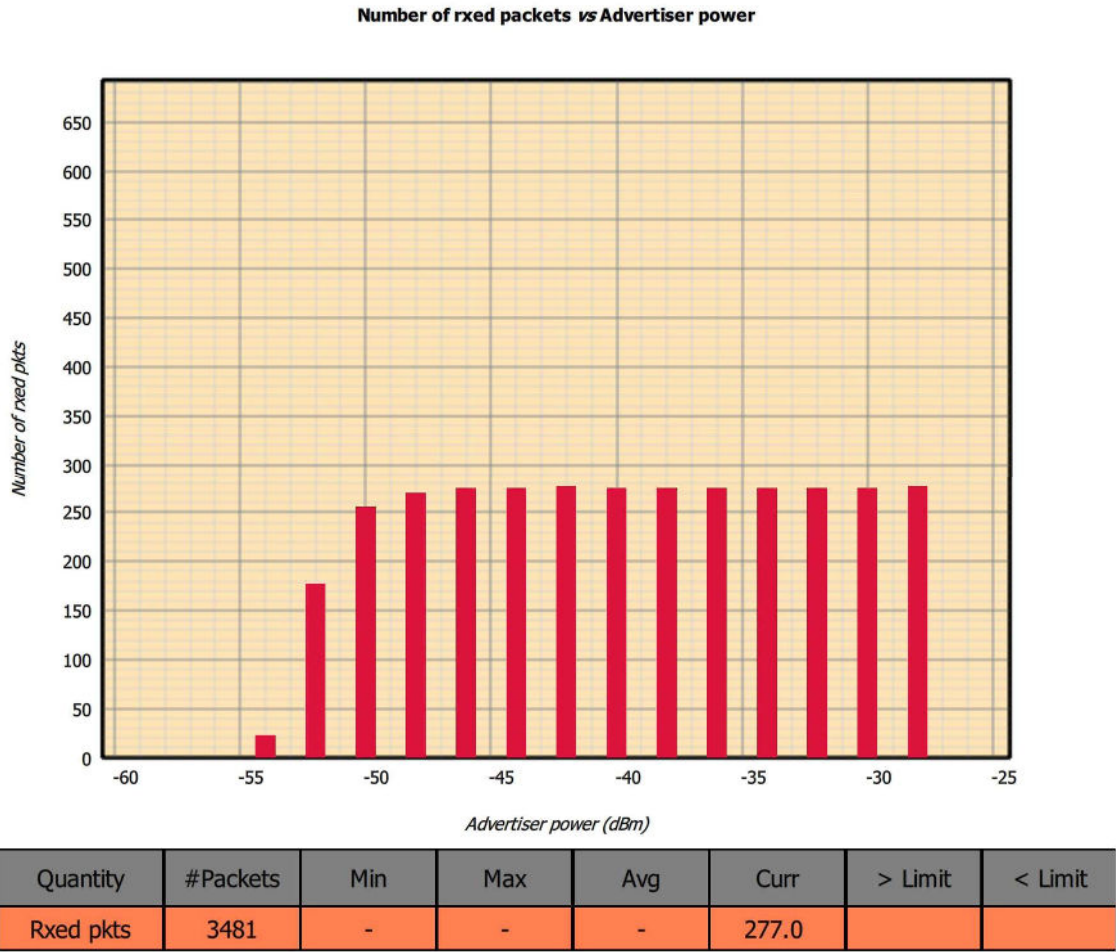
Figure 80: Results vs transmission level.

10.4.6.4 ~~Histogram~~

A histogram of the plotted quantity is displayed.

ΔF₂ₘₐₓ Histogram

Figure 81: Results as a histogram.

10.4.6.5 ████

This option is not available for in-band emission tests.

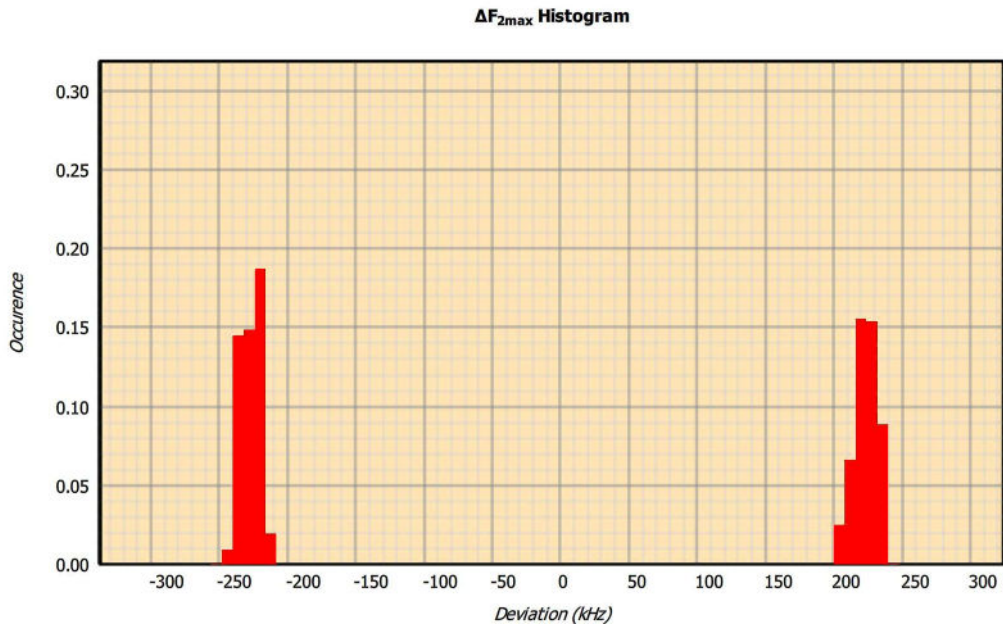The measured quantity is shown by the blue lines on the plot. The plot corresponds to the value(s) obtained from the last packet on which the selected quantity was measurable. If waveform collection has been enabled ('Collect' tab, 'Measurement' menu) then either the frequency deviation or the packet power will also be displayed in red. *The waveform data will only be displayed if the quantity to be plotted was measurable on the last received packet.*
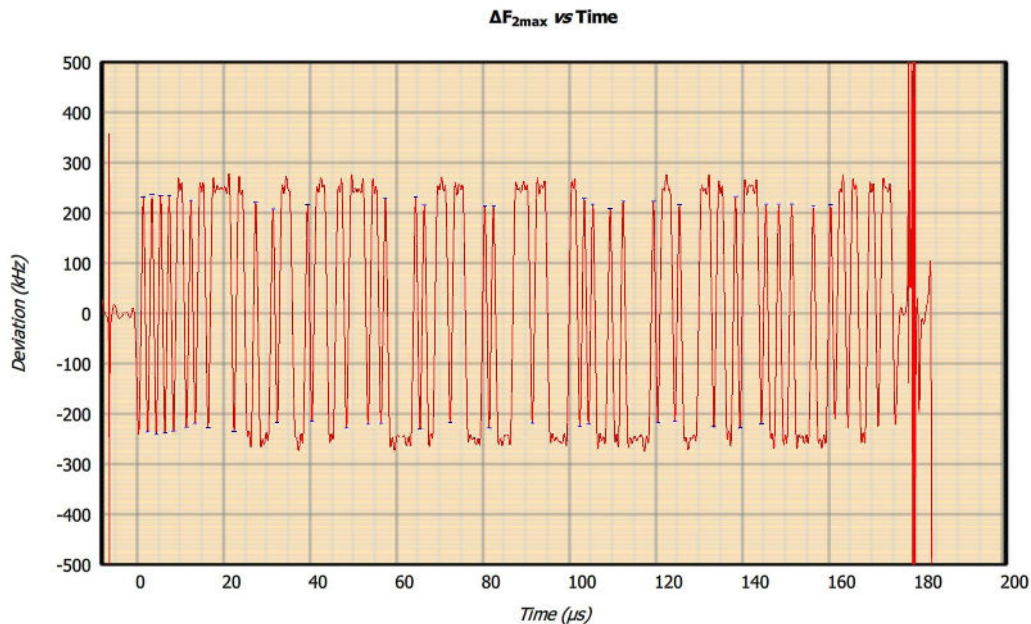
Figure 82: Results vs time.

10.4.6.6 ████

This option is only available for in-band emission tests.

When the vs frequency option is selected for in-band emission tests, additional options become available:

1. Plotting of the in-band emission results for every MHz in the 2.4 GHz ISM band (1 MHz spectrum)
2. Plotting of the 100 kHz resolution measurements which were summed to yield the in-band emission results at every 1 MHz (100 kHz spectrum)

For each spectrum it is possible to plot:

1. Current in-band emission results (orange line)
2. Maximum in-band emission results (red line)
3. Minimum in-band emission results (green line)

10.4.7 Screen update period

The 'Plot' menu contains a slider which can be used to alter the rate at which the results table and graphics are updated.

The fastest update period possible is around 50 ms, typically limited by the host screen refresh rate. However, if substantial processing is required by Sapphire, for example, the transfer of raw IQ data at 32x oversampling, then the specified update rate may not be achievable.

The slowest update rate is 2 seconds. This gives the user time to assimilate the displayed results and waveform data before the next update.

10.5 Saving and restoring settings

The current collection, analysis and limit settings can be saved by clicking the 'Save' button on the toolbar. Select the 'Advertise/scan settings (*.aas)' file type to save the current settings.

An existing advertise/scan settings file (*.aas) can be opened using the 'Open' button on the toolbar.

The advertise/scam settings file (*.aas) is an XML file. It is not recommended that this file be edited manually. If it needs to be modified, open it from the advertise/scan mode, modify the required parameters and re-save.

10.6 Saving current results table and graphics

The current results can be saved by clicking the 'Save' button on the toolbar. The format of the results file depends on the file type selected to save the current results. The results can be saved in the following formats:

1. xml: permitting the results to be read by a range of other applications
2. txt: a simple asci text file
3. csv: permitting the results to be read by spreadsheets
4. html: for viewing the results in a web browser or for inclusion in a test report

The current graph and results table can be saved as an image by clicking the "Graph" button on the toolbar. The range of possible graphics formats includes:

1. Windows bitmap files (*.bmp)
2. Joint photographic expert group files (*.jpg)
3. Portable network graphics files (*.png)
4. Portable bitmap files (*.pbm)
5. Portable graymap files (*.pgm)
6. Portable pixmap files (*.ppm)
7. X11 bitmap files (*.xbm)
8. X11 pixmap files (*.xpm)

11 Standalone Mode

11.1 Overview

The standalone mode permits Sapphire to be run without a USB or Ethernet connection. In this mode of operation, the Sapphire image and test script are held on a memory stick which is attached to the USB port of the *TLF3000*. The supervisor program on the *TLF3000* will automatically launch the Sapphire application which will then execute the test script held on the memory stick. Control of the Sapphire application and signalling of pass/fail are accomplished by the use of digital IO.

11.2 Connectivity

The DUT serial interface should be connected to the digital IO connector on the rear of the *TLF3000* unit. The relevant lines are:

Pin	Name	Direction	Special function
1	Vio	I/O	Max 500 mA from internal 3.3 V supply.
2	Vio	I/O	External voltage range 0.8 V to 3.6 V.
9	GPI #6	I	UART RTS
10	GPI #7	I	UART Rx
17	GPO#6	O	UART CTS
18	GPO#7	O	UART Tx
19	Gnd	-	
20	Gnd	-	

The IO voltage for digital interface can be either from the *TLF3000* unit or from the DUT. If the IO voltage is from the *TLF3000* unit, then it is fixed at 3.3 V. If the DUT supplies the IO voltage, then it must be in the range 0.8 V to 3.6 V. The choice of which unit supplies the IO voltage is defined in the Sapphire.sta file.

For standalone testing the DUT is connected to the Tx/Rx RF port.

Sapphire needs an estimate of the cable loss between the Tx/Rx port and the DUT at 2.4 GHz. This is necessary to compensate for receiver power levels and to adjust transmitter output levels. The cable loss is defined in the Sapphire.sta file. Permissible values are between 0 dB and 5 dB.

The cable loss value is also used to compensate the blocker level. Since the cable loss value is only applicable at 2.4 GHz and the blocker frequency can be anywhere from 24 MHz to 6 GHz, the compensation is extremely rough. However, given the accuracy of the blocker signal level and the relatively low levels of cable attenuation, this is not normally an issue.

The memory stick containing the Sapphire image and test script file is attached to the *TLF3000* unit via a USB on-the-go adapter. The memory stick can be attached either before or after the *TLF3000* unit has booted.

11.3 Memory stick contents

The memory must have a FAT32 file system. If an error log is required, then the memory stick must be write enabled.

The top level folder of the memory stick must contain the following two files:

1. *Moreph30.rfcapp*. This file contains the Sapphire application image.
   Sapphire.sta. This is the test script file.

Both these files can be generated from the Sapphire GUI.

11.3.1 Generating the Moreph30.rfcapp file

The Moreph30.rfcapp file can be generated by clicking the save file toolbar button and selecting file type "Application binary (*.rfcapp)". Enter the name "Moreph30" and save the file to the top level folder of the memory stick.

11.3.2 Generating the Sapphire.sta file

A working version of the Sapphire.sta file can be generated from Phy Tester Mode. The GUI should be used to enter:

1. All DUT serial interface communication parameters. DUT control via the host is not supported in standalone mode.
2. All DUT supported features.
3. Cable loss
4. Phy test script

Once all this information has been entered, the Sapphire.sta file can be generated by clicking on the toolbar save button and selecting file type "Standalone files (*.sta). Enter the name "Sapphire" and save to the top level folder of the memory stick.

The run mode parameters entered in the GUI are not transferred to the Sapphire.sta file. In standalone mode the run mode is always set to:

1. Only test against limits
2. Do not run to completion
3. Reorder tests
4. No looping of test script

11.3.3 Standalone test script file format

An example standalone test script file is:

```
H4,115200,1,0,1,NONE              // DUT communications
CENTRAL,0,0,37,27,27,328,328     // DUT properties
0                                 // Cable loss
1                                 // Vio source
0,0,1                             // Control, status & pass lines
TRM1,{37},{0:39},{1}             // Test 1
TRM5,{37},{0:39},{10}            // Test 2
RCV1,{37},{0,19,39},{100},{-70},,,,,
```

The test script if composed of the following lines:

1. DUT communications. The parameters on this line are:
    a. Communications protocol (DTM, H4, H5 or BCSP)
    b. Baud rate.
    c. Hardware flow control (0 = off, 1 = on)
    d. Software flow control (0 = off, 1 = on)
    e. Stop bits (1 or 2)
    f. Parity (NONE, EVEN or ODD)
2. DUT role and supported features. The parameters on this line are:
    a. DUT role (CENTRAL, PERIPHERAL, BROADCASTER or OBSERVER)
    b. Supports advertising extensions
    c. Supports data length extensions
    d. Maximum number of advertising octets
    e. Maximum number of receive payload octets
    f. Maximum number of transmit payload octets
    g. Maximum receive packet length in µs
    h. Maximum transmit packet length in µs
3. Cable loss in dBm
4. Digital IO voltage source (0 = internal 3.3 V, 1 = external)
5. Digital IO lines for control and status. The parameters on this line are:
6. Digital input line to be used for control
7. Digital output line to signify status
8. Digital output line to signify pass/fail

The remaining lines in the test script file define the tests to be performed. The format of these lines is covered in the Sapphire Programmer's Manual.

11.4 Control

Control of the standalone Sapphire application is performed using three digital IO lines:

1. Control. This is an input to the *TLF3000* unit. A transition on the line from '0' to '1' will cause Sapphire to attempt to run the test script.
2. Status. This is an output from the *TLF3000* unit. When this line is high, the Sapphire application is idle. When this line is low, the Sapphire application is executing the test script.
3. Pass/Fail. This is an output from the *TLF3000* unit. The status of this line is only valid when the status line is low. If this line is high, then the DUT passed the last execution of the test script. If this line is low, then the DUT failed the last execution of then test script.

12 Native Language Programming

Native language programming is described in the *TLF3000* User's Manual and the Sapphire Programmer's Manual.

In order to run the Sapphire application from the native programming language it is necessary to have:

1. A copy of the Sapphire application binary (.rfcapp)
2. The number of bytes in the Sapphire application binary
3. The CRC for the Sapphire application binary

All three of these can be obtained from the Sapphire GUI using the following procedure:

1. Click the save file button in the toolbar
2. Select file type "Application binary (*.rfcapp)"
3. Select a file name and save the Sapphire application
4. Note the number of bytes and CRC for the application from the pop-up dialog box