Tests of Bluetooth Low Energy 5.1 Indoor Navigation - Direction Finding

Application Note

Products:

- R&S®CMW500
- R&S®CMW270
- R&S®CMW290
- R&S®OSP
- R&S®CMWrun

Bluetooth Low Energy (BLE) 5.1 has introduced Angle of Arrival (AoA) and Angle of Departure (AoD) to enrich the direction finding (DF) feature. This application note gives the guidance of how to perform the BLE 5.1 DF RF tests according to the latest RF test specification of BT 5.1 [1] by using the Rohde & Schwarz test solutions.

Note:

Please find the most up-to-date document on our homepage

http://www.rohde-schwarz.com/appnote/GFM327.

ROHDE&SCHWARZ

Application Note

Yong Shi

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1 Introduction

Wireless connections between different electronic devices, e.g. mobile phones, computers, are getting easier thank the Bluetooth (BT) technology. By adopting BT technology, media contents, files etc. can then be exchanged between BT capable devices in a so called Personal Area Network (PAN), wireless audio streaming is one of the most popular applications utilizing the BT technology.

The Bluetooth technology started in 1998 which was collaborated technically by 5 companies (Ericsson, IBM, Intel, Nokia and Toshiba) who initially founded the Bluetooth Special Interest Group known as Bluetooth SIG. With the first official rollout of the BT 1.0 specification in 1999, BT technology has evolved over the last two decades, and continues to do so. R&S® is an active member in the Bluetooth SIG since 1999.

Bluetooth SIG defined two flavors of BT technologies, namely BT Classic (Basic Rate (BR)/Enhanced Data Rate (EDR)) and BLE (Bluetooth Low Energy). Both BT flavors are not compatible with each other. For a comparison between BT Classic and BLE technology, please refer to [3] .

BLE products are getting more and more market momentum since its first introduction back in 2010. It was firstly specified as BT4.0 aiming at low power consumption and low cost devices which is suitable particularly for Internet of Things (IoT) applications. BT5.0 announced in 2016 was another milestone with respect to the enriched capabilities in contrast to BT4.0, including four times the range, twice the speed and eight times increase in data broadcasting capability. In January 2019, BT SIG released the BT5.1 or BLE 5.1 standard with more improvements for BLE, like:

- Direction Finding (DF) - Angle of Arrival (AoA)/Angle of Departure (AoD)
- General Attribute Profile (GATT) Caching
- Periodic Advertising Sync Transfer
- Control Length Extension
- Advertising Channel Index Changes
- Minor Functional Enhancements batch 1

Location Service using BT technology is in fact not a new terminology. But the applied methodology is altered. Legacy BT proximity solutions are based on distance estimation using RSSI measurement and trilateration to determine the location of the device. However, this positioning method can only meet the meter level accuracy which does not offer certain satisfaction to some applications. Market demands of even high performance positioning service drive BLE5.1 to release the new positioning approach, a so called Direction Finding (DF) by utilizing Angle of Arrival (AoA)/Angle of Departure (AoD) technique that largely improves the indoor positioning accuracy down to centimeter level.

In this application note, we will be focusing on how to verify the physical layer of BLE 5.1 DF including AoA/AoD according to BT 5.1 RF test specification RF-PHY.TS.p15 dated on Jan.7th, 2020 [1] with the following structure

Chapter 2 outlines the AoA and AoD principle and their use cases, as well as some basic terminologies

Chapter 3 shows the R&S test solutions for the AoA and AoD physical layer verification and associated system requirements

Chapter 4 describes in details about the BLE 5.1 DF RF Testing according to the BT 5.1 RF test specification [1] in both manual mode and automatic mode by utilizing R&S®CMWrun test automation tool

The following abbreviations are used in this application note for Rohde & Schwarz test equipment:

- The R&S®CMW500/ R&S®CMW290/ R&S®CMW270 wideband radio communication tester is referred to as CMW
- The R&S®CMW100 wideband radio communication tester is referred to as CMW100
- The R&S®CMWrun Sequencer Software Tool is referred to as CMWrun
- The R&S®OSP Open Switch and Control Platform is referred to as OSP

2 Technical Backgrounds

2.1 Direction Finding

2.1.1 Angle of Arrival (AoA)

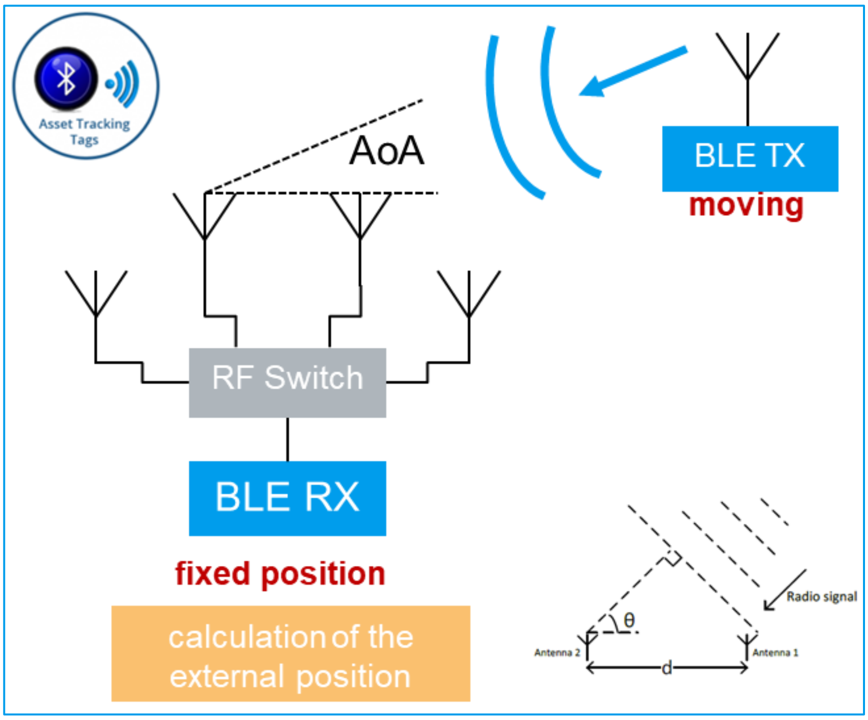


Fig. 2-1: Principle of Angle of Arrival (AoA)

Angle of Arrival (AoA) is a positioning method based on antenna array technique.

As depicted in Fig. 2-1, the transmitter, a tracked device or a moving object, sends a beacon signal using a single antenna. The transmitted plain wave signal travels across the receiver (a static object at fixed position) which is equipped with multiple antennas arranged in an antenna array (minimum two antenna elements). At the receiver side, it observes the received signal phase difference by calculating the IQ samples from the received RF signal while switching the current active antenna by RF switch sequentially. Details of the antenna switching is followed in Chapter 2.2. The phase difference at different antenna element is caused simply due to the fact that each of the antenna element in the array has the different distance to the transmitter. AoA uses the difference of phase incident on the receiver antenna array to calculate the AoA of the transmitted signal.

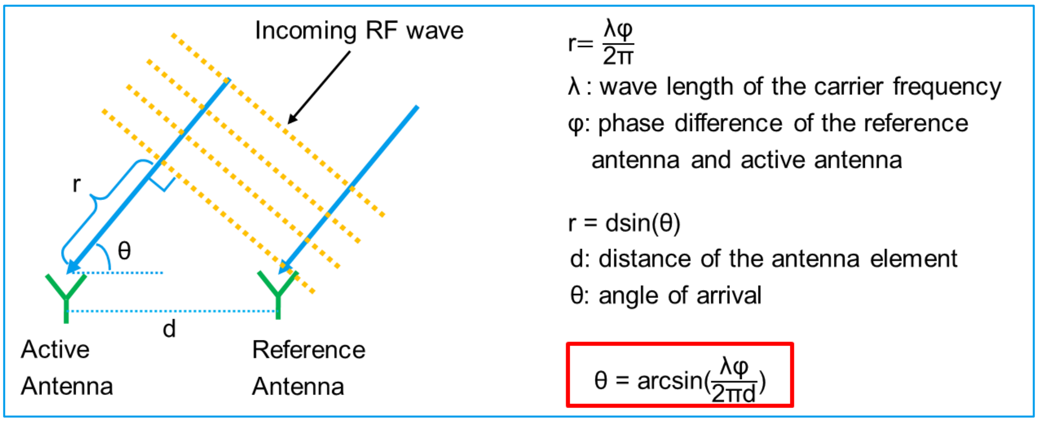


Fig. 2-2: Calculation of Angle of Arrival (AoA) θ

Fig. 2-2 illustrates the AoA θ calculation. By knowing the phase difference φ between the active antenna and reference antenna which is calculated from the IQ sample pairs captured on the RF signal, as well as the distance of both antenna elements d, together with the wavelength of the carrier frequency λ, the AoA angle $\theta = \arcsin(\frac{\lambda\varphi}{2\pi d})$ is determined.

The maximum distance d between two adjacent antenna elements should be λ/2, where λ is the wavelength of the carrier frequency. By applying the formula λ=c/f , where c is the speed of light $3x10^8$ m/s, f is the carrier frequency, the BLE operated in frequency range of 2.4 GHz has wavelength λ=12.5 cm. Therefore, the distance between the adjacent antennas of BLE device should be maximum 6.25 cm.

Asset tracking, Point of Interest (PoI) are typical applications of AoA.

2.1.2 Angle of Departure (AoD)

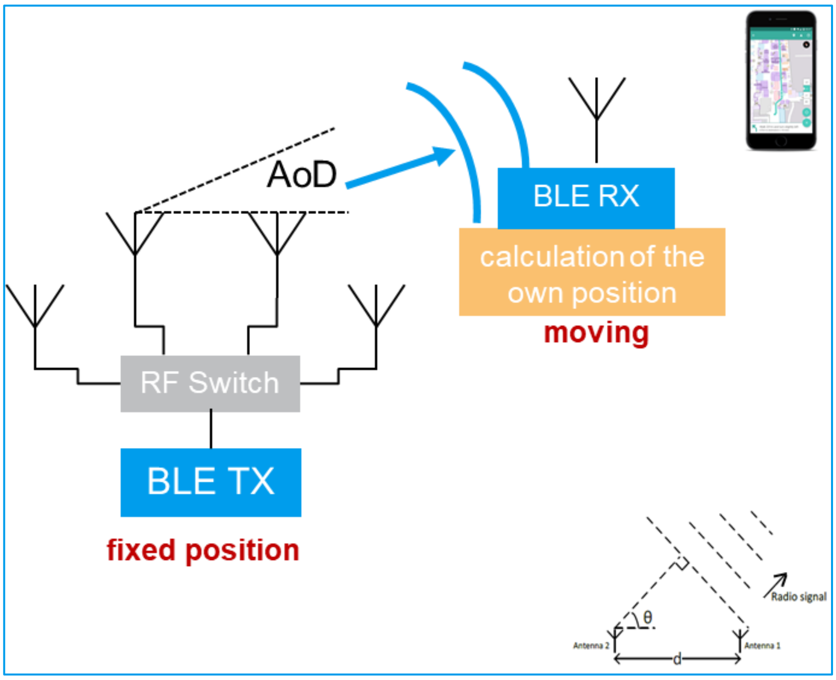


Fig. 2-3: Principle of Angle of Departure (AoD)

Angle of Departure (AoD) uses the similar technique as AoA to determine the position, however, the device role is now swapped in AoD scenario. In Fig. 2-3, the principle of AoD is depicted.The transmitter (a static object at fixed position) is now using multiple antennas arranged in an array to transmit beacon. The active antenna of the antenna array is switched according to the predefined antenna switching pattern. The receiver, a BLE mobile device, uses a single antenna to capture the RF packets and calculate them into IQ samples upon reception of the beacon. Based on the IQ samples, the phase difference of incident beacon from different antenna element can be calculated, thus the AoD is determined in turn. The estimated position accuracy is expected to be around 50 cm.

A typical use case of AoD is, for an instance, wayfinding etc.

2.2 Some Basic Bluetooth Low Energy Terminologies

2.2.1 Radio Access Scheme

Time Division Duplex (TDD) scheme is adopted by the BLE specification as the radio access.

2.2.2 Bluetooth LE Physical Layers

In BLE, three physical layers are specified, with the name in short, LE 1M, LE 2M and LE coded.

LE 1M was introduced early in BT4 with the symbol rate of 1 Msymbols/s and is the mandatory physical layer for BLE. In BLE5.0, two new optional physical layers, namely LE 2M and LE coded are added in addition. All BT SIG specified BLE PHY layers are summarized in Table 2-1.

PHY	Bluetooth LE	Modulation scheme (GFSK) gross data rate	Coding		Net data rate
			Access header	Pay-load	
LE 1M	Mandatory	Nominal Frequency Deviation 250 kHz 1 Msymbols/s	Uncoded		1 Mbit/s
LE 2M	Optional	Nominal Frequency Deviation 500 kHz 2 Msymbols/s	Uncoded		2 Mbit/s
LE coded	Optional	Nominal Frequency Deviation 250 kHz 1 Msymbols/s	S = 8	S = 2 S = 8	500 kbit/s 125 kbit/s

Table 2-1: Bluetooth Low Energy Physical Layers

LE 2M allows the PHY to operate at 2 Mbit/s that doubles the data rate comparing to LE 1M. Both LE 1M and LE 2M belong to so called LE uncoded PHY where no Forward Error Correction (FEC) coding is applied. Whereas the LE coded PHY extends the range to the factor of 2 and 4 via FEC S=2 and S=8 coding scheme, respectively, where S stands for the number of the symbols per bit.

Direction finding (DF) only adopts LE 1M and LE 2M, i.e. uncoded PHYs. Therefore, coded PHY is out of the scope of this application note.

Like legacy BT technology, BLE is operated in 2.4 GHz ISM Band (2400 MHz-2483.5 MHz) as well. It ranges from 2400 MHz to 2480 MHz and divides the whole frequency band into 40 channels (channel 0-39) with 2 MHz channel bandwidth each. The majority of the RF tests for DF are required to be performed at the lowest, middle and highest frequency, i.e. channel 0 (2402 MHz), 19 (2440 MHz) and 39 (2480 MHz) respectively.

2.2.3 Modulation

BLE applies Gaussian Frequency Shift Key (GFSK) modulation scheme with 0.5 standard modulation index to minimize the transceiver complexity.

Frequency deviation for LE 1M and LE coded is ±250 kHz, while ±500 kHz for LE 2M.

For all three BLE PHY layers described in Chapter 2.2.2, an optional stable modulation index (SMI) between 0.495 and 0.505 is available, which increases the link budget by 3 dB approximately.

2.2.4 Direct Test Mode

BT SIG specified a mandatory test method for Transmitter and Receiver compliance testing using a so called Direct Test Mode (DTM). This method applies to both legacy BLE and BLE 5.1

DTM is used to control the DUT and provide the test report to the tester, e.g. CMW. By communicating directly with the device physical layer through the Host Control Interface (HCI) or 2-wire UART interface, e.g. setting the test frequency, packet length and data pattern, without commanding those settings via the entire protocol stack, the test time is minimized in turn.

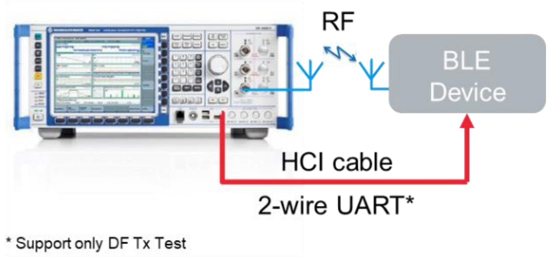


Fig. 2-4: Direct Test Mode - test with control cable via HCI or 2-wire UART interface

Fig. 2-4 indicates the DTM types which can be utilized for the DUT physical layer verification. As per BLE core specification [2], there are 2 ways of communications defined:

- HCI (Host Control Interface) for DUTs with accessible HCI interface
- 2 wire UART interface for DUTs with non-accessible HCI interface

For those DUTs with accessible HCI interface, there are two possible hardware interfaces which allow the HCI communication, namely, either USB connection or RS232 connection via an USB-RS232 adaptor.

Comm Protocol	HW Interface	Transmitter	Receiver
HCI	USB	Supported	Supported
	USB to RS232 adapter	Supported	Supported
2-wire UART	USB to RS232 adapter	Supported	Partially Supported[1)]

1) 2-wire UART is not applicable for Direction Finding Receiver Test

Table 2-2: DTM support on CMW

Table 2-2 shows the DTM support on CMW. Depending on the DUT, the hardware interface either USB direct or RS232 via USB-RS232 can be applied for both transmitter and receiver verification of a BLE DF DUT.

For details about the DTM, refer to [2]

In [5] describes in greater details about how the DTM connection between DUT and CMW is established. It includes the guidance of the installation and handling of the necessary driver that enables the DTM. This is a prerequisite for the BLE RF measurements.

2.2.5 BLE 5.1 DF Test Packet

This chapter is informative to help understand the BLE 5.1 DF test packet.

BLE 5.1 DF test packet format for LE uncoded PHY shown in Fig. 2-5 is used for physical layer conformance testing under DTM. Be noted that the real BLE packet differs slightly to the test packet. For this application note, we only focus on the LE uncoded PHY test packet.

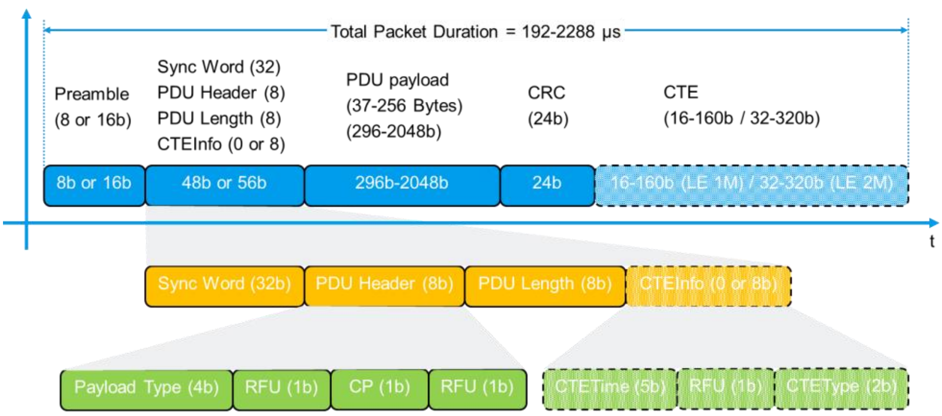


Fig. 2-5: BLE 5.1 DF Test packet format for LE uncoded PHY (source: BT5.1 core spec [2]), dotted part is optional portion of the packet)

Preamble (8 or 16 bits)

A transmitted fixed bit sequence for the receiver to perform frequency synchronization, symbol time estimation and Automatic Gain Control (AGC) training. Depending on the BLE 5.1 DF physical layer, 2 different preamble sequences are defined:

8 bits for LE 1M PHY: ‘10101010’ in transmission order

16 bits for LE 2M PHY: ‘1010101010101010’ in transmission order

Sync Word (32 bits)

A sequence with good auto correlation property allows the packet synchronization.

'10010100100000100110111010001110' in transmission order

Payload Type (4 bits)

This field defines the payload bit sequence in the PDU payload portion of the packet.

In the following table, only payload types relevant to the BLE compliant tests are listed.

Payload Type	Description	Use Cases
0000	PRBS9 sequence '11111111100000111101…' (in transmission order)	Used for wanted signal payload content for each transmission, e.g. Transmitter power and ACP measurements and for Receiver tests
0001	Repeated '11110000' (in transmission order) sequence	Used for verify the frequency deviation and the Gaussian filter properties of the transmitter modulator
0010	Repeated '10101010' (in transmission order) sequence	Used for verify the frequency deviation and the Gaussian filter properties of the transmitter modulator

PDU Length (8 bits)

Specifies the PDU payload length in Bytes.

PDU payload (296-2048 bits)

PDU payload filled by the bit sequence defined by the Payload Type with the length given by PDU length

CRC (24 bits)

24-bit CRC is calculated over the PDU. Constant Tone Extension (CTE) part is not included in CRC calculation.

All CTE relevant fields are explained in Chapter 2.2.6.

2.2.6 Constant Tone Extension for BLE 5.1 DF

BLE 5.1 introduced Constant Tone Extension (CTE) as an optional bit sequence that is contained in the BLE packet. CTE can be used for determining the relative direction of a received radio signal, i.e. Direction Finding purpose.

The CTE shall only be presented on the LE uncoded PHYs, i.e. LE 1M and LE 2M, and is not included in CRC or MIC calculations.

The presence of the optional CTE part in the packet is indicated by the CTEInfo Present (CP) flag. As long as the CTE is presented, CTETime, CTEType and CTE fields are required to be included in the test packet consequently.

Hereafter, it describes the list of CTE relevant fields in the BLE 5.1 test packet shown in Fig. 2-5 and their configurations.

CTEInfo Present (CP) (1 bit)

Important flag to indicate the presence of the CTE in the test packet

CP	Description
0	no CTEInfo field is present and there is no Constant Tone Extension in the test packet
1	the CTEInfo field is present and the test packet includes a Constant Tone Extension

CTEInfo (optional) (8 bits)

8 bits CTEInfo consists of CTETime (5 bits), RFU (1 bit) and CTEType (2 bits)

CTEInfo		
CTETime (5 bits)	RFU (1 bit)	CTEType (2 bits)

CTETime **(optional) (5 bits)**

CTETime field defines the length of the CTE in 8 µs unit.

As per BLE 5.1 specification, the time duration of the entire CTE part is between 16 µs and 160 µs. Therefore, the value of the CTETime field here shall be taken between 2 and 20 units which reflects the 16 µs and 160 µs CTE duration, respectively. All other values are reserved for future use.

CTEType (optional) (2 bits)

CTEType field defines the type of the CTE and the duration of the switching slots.

CTEType Value	Description
0	AoA Constant Tone Extension
1	AoD Constant Tone Extension with 1 µs slots
2	AoD Constant Tone Extension with 2 µs slots
3	Reserved for future use

Constant tone extension (CTE) (optional) (16-320 bits)

The CTE contents are a constantly modulated series of "1"s and no whitening applied. It has 16-160 bits when operating at 1 Msym/s modulation or 32-320 bits when operating at 2 Msym/s modulation.

The CTE has two types, namely AoA and AoD CTE whose structure are shown in Fig. 2-6 and Fig. 2-7, respectively. Except AoA transmit CTE, the other CTEs follow the same structure. It starts with the first 4 µs guard period, followed by the 8 µs reference period, and then a sequence of alternating switch slots and sample slots with each 1 µs or 2 µs long are configured by the host. 2 µs long switch and sample period is mandatory as per BLE 5.1 specification.

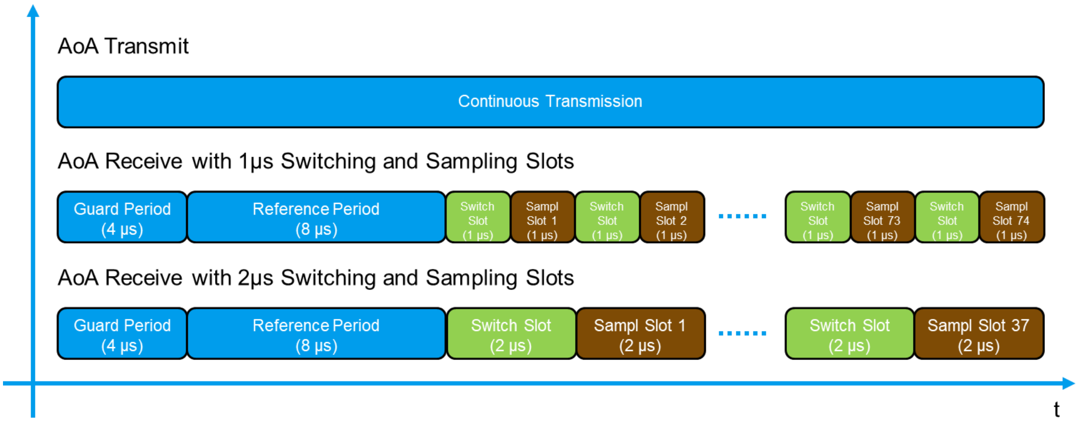


Fig. 2-6: AoA CTE Structure

Fig. 2-6 shows AoA CTE structure. When AoA CTE is transmitted, it is transmitted in a continuous way without having the antenna switched. Upon receiving AoA CTE, the receiver shall perform antenna switching at the rate and pattern defined by the host, either with 1 µs or 2 µs switch and sampling slot duration.

The switch slots in the CTE structure defines the time periods when the switching of the antenna array element will take place. Its time duration is configurable between 1 µs and 2 µs, so as for the IQ sampling time slot duration. In section 2.2.7, the antenna switch pattern is explained. The RF packets are captured in the sampling slot as well as in the reference period, details are explained in section 2.2.8.

The maximum number of available switch and sampling slots differs due to the slot duration being configured. Recall that the entire maximum CTE time length is 160 µs, after the first 12 µs (4 µs guard period + 8 µs reference period) being deducted, the CTE time length which is allowed for switch and sampling remains 148 µs. Thus, 74 switch and sampling slot pairs can be utilized in case 1 µs switch and sampling slot is configured. Correspondingly, 37 switch and sampling slot pairs in case of 2 µs configuration.

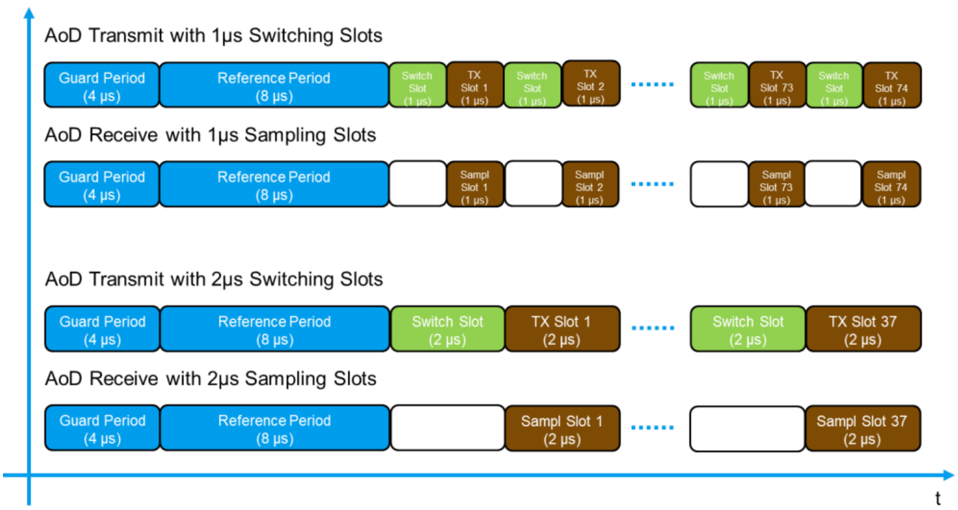


Fig. 2-7: AoD CTE Structure

Fig. 2-7 illustrates the AoD CTE structure. In case AoD CTE is transmitted, the transmitter shall perform antenna switching in contrast to AoA case, and followed by AoD beacon sending in the TX slot. While receiving AoD CTE, the receiver does not need to switch antenna, only the RF sampling is required. The maximum number of the switch and sampling slots has the same definition as for AoA.

2.2.7 Antenna Switching

A BLE 5.1 DF device that supports antenna array to receive the CTE packet (AoA method) or transmit CTE packet (AoD method) needs to switch between two or more antennas. The antenna switching pattern should be configured by its host.

In Table 2-3, mandatory antenna switching pattern between reference antenna and non-reference antenna associated with the number of antennas is specified by BLE 5.1 [2]. The first antenna A0 in the switching pattern shall be used during the reference period of the CTE. The antenna switching pattern is cycled over until the end of the CTE portion.

Number of Antenna	Antenna Switching Pattern
2	A0, A1, A0, A0, A0, A1, A0, A0, A0, A1, …
3	A0, A1, A0, A0, A0, A2, A0, A0, A0, A1, …
4	A0, A1, A0, A0, A0, A2, A0, A0, A0, A3, A0, A0, …

Table 2-3: Antenna Test Switching Pattern (A0=Reference Antenna, A1...3=Non-reference Antenna)

The following Table 2-4 and Table 2-5 show two examples of antenna switching pattern in the real use case.

#of Ant	Ref Period	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7	Slot 8	Slot 9	Slot 10	Slot 11	…	Slot 73	Slot 74
2	A0	A1	A0	A0									…	A1	A0
3	A0	A1	A0	A0	A0	A2	A0						…	A1	A0
4	A0	A1	A0	A0	A0	A2	A0	A0	A0	A3	A0	A0	…	A1	A0

Table 2-4: Example of Antenna Switching Pattern with 1µs switching slot duration and 20 units CTE length (74 sample slots in total)

#of Ant	Ref Period	Slot 1	Slot 2	Slot 3	Slot 4	Slot 5	Slot 6	Slot 7	Slot 8	Slot 9	Slot 10	Slot 11	…	Slot 36	Slot 37
2	A0	A1	A0	A0									…	A0	A1
3	A0	A1	A0	A0	A0	A2	A0						…	A0	A2
4	A0	A1	A0	A0	A0	A2	A0	A0	A0	A3	A0	A0	…	A0	A1

Table 2-5: Example of Antenna Switching Pattern with 2µs switching slot duration and 20 units CTE length (37 sample slots in total)

The test switching pattern is not allowed to be changed on the CMW.

2.2.8 RF sampling

The AoA or AoD receiver shall perform RF sampling upon receiving the packet containing CTE. The IQ calculation upon RF sample signal reception of DF is then performed on the CTE portion of the packet yet the 4 µs guard period portion at the beginning of the CTE is excluded during the procedure.

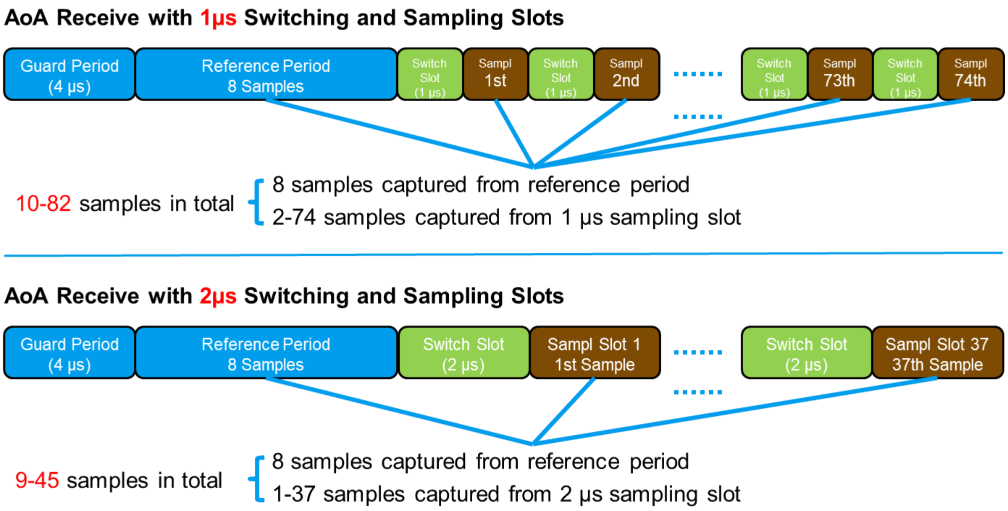


Fig. 2-8: AoA Receiver RF Sampling

In both AoA and AoD cases, the receiver shall take an RF sample each microsecond during the 8 µs reference period and one sample pair from each sample slot. The amount of samples captured in AoA receiver case are shown in Fig. 2-8. That generates 10 to 82 samples in 1 µs slot structure and 9 to 45 samples in 2 µs slot structure correspondingly. The same sampling concept applies to AoD receiver as well.

3 System Requirement

An overview of the available BLE 5.1 DF RF test solutions and required hardware/software configurations are included in this chapter.

3.1 Overview of the Test Solutions

In general, there are recommended four R&S test solutions listed in Table 3-1 to cover the test needs in different product lifecycle, starting from R&D design, pre-conformance, conformance, way up to production and service for the BLE 5.1 DF testing.

Setup No.	Direction Finding System Setup		Recommended for	Required HW
1	Manual Tests		R&D design	CMW270/290/500
2	Automatic Tests	Partially automated tests incl. test report	R&D design, pre-conformance tests, service (quality tests)	CMW270/290/500 + CMWrun
3	Automatic Tests	Full automated tests incl. test report	R&D design,pre-conformance tests, service (quality tests) and conformance (test houses)	CMW270/290/500 + CMWrun + OSP
4	Tx/Rx Tests		Production	CMW100*

Table 3-1: Overview of R&S® Test Solutions for BLE 5.1 DF Testing

*Note: Production test solution is out of the scope in this application note.

Setup 1 - Manual Test

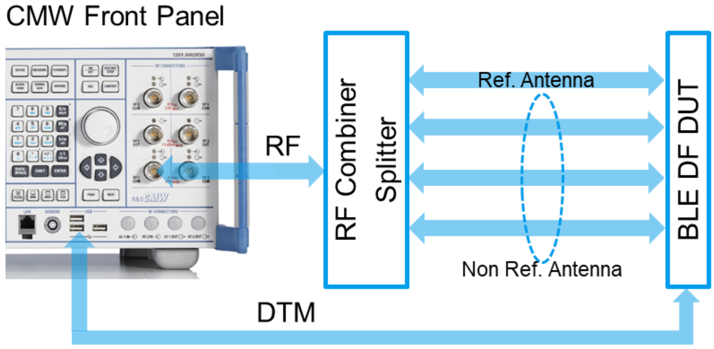


Fig. 3-1: Manual Test Setup

The manual setup (setup 1) shown in Fig. 3-1 is a simple one and suitable for the initial verification during the R&D design phase. All the measurements described in Chapter 4 are based on this setup.

Setup 2 - Partially Automated Test with CMWrun but without OSP

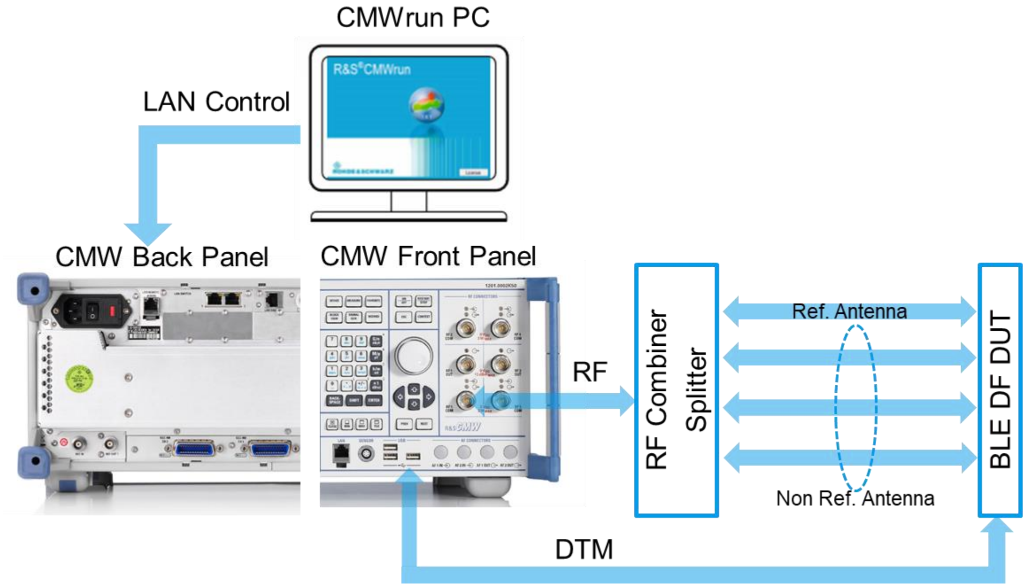


Fig. 3-2: Automation Test Setup with CMWrun (without OSP)

The partially automation test setup (setup 2) shown in Fig. 3-2 is a simplified solution in contrast to automation test setup 3 with the CMWrun support. This setup does not include RF switching unit OSP. With this solution, the majority of the BLE 5.1 DF Tests can be performed automatically except the four test cases, i.e. AoD TX Antenna Switching Integrity RF-PHY/TRM/ASI/BV-05, (06, 07, 08)-C, which still require the manual intervention to switch the antenna ports.

Setup 3 - Full Automated Test with CMWrun and OSP

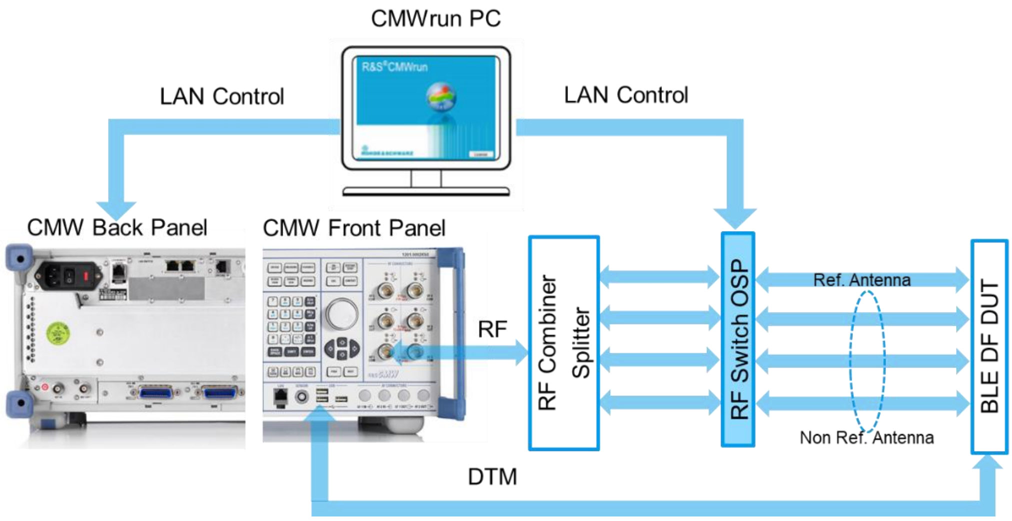


Fig. 3-3: Automation Test Setup with CMWrun and OSP

The full automated test setup (setup 3) shown in Fig. 3-3 supports the full test automation thanks the CMWrun and OSP. The biggest advantage of using the OSP in the setup lies in the fact that the user does not need to switch the antenna manually while performing the antenna switching integrity test case explained later in Chapter 4.3.1.2. Therefore, with this setup the complete 23 BLE 5.1 DF test cases can be performed full automatically. This requires CMWrun version greater than 1.9.9.

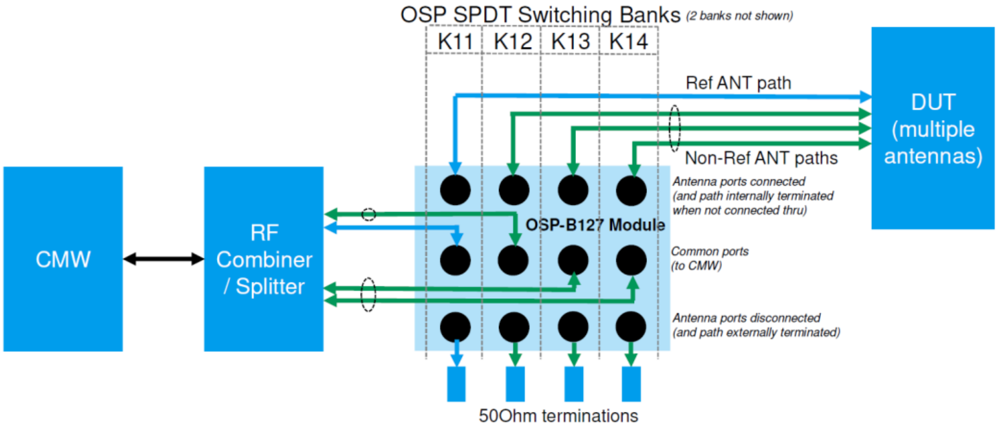


Fig. 3-4: Block Diagram of Cabling with OSP

In Fig. 3-4, it illustrates more in details about the cabling on OSP with one reference antenna and three more non-reference antennas.

3.2 Hardware and Software Requirements

CMW

Fig. 3-5: Communication Radio Tester CMW500/CMW290/CMW270

In the Table 3-2 below, an example configuration for CMW270 including a second channel for interferer measurements for BLE measurements up to Bluetooth Rel. 5.1 and the sequencer tool CMWrun is listed. This serves as a recommendation for the minimum system configuration.

Order-No.	Option	Description
1201.0002K75	CMW270	Wireless Connectivity Tester
1208.8909.06	CMW-PS275	CMW270 Basic Assembly (mainframe), 70Mhz to 3.3GHz (sel.)
1202.4701.09	CMW-S100H	Measurement unit advanced including Baseband Generator
1202.4801.03	CMW-S550N	Baseband Interconnection, flexible link, H550N (sel.)
1202.5008.09	CMW-S570H	RF Converter (TRX160),
1202.5108.03	CMW-S590D	RF Frontend, advanced functionality, H590A (sel.)
1201.0102.05	CMW-S600D	CMW270 Frontpanel With Display/Keypad, H600D (sel.)
1202.4201.20	CMW-S052S	Solid State Drive (SSD),
1208.7954.10	CMW-B500I	Signaling Unit advanced
1202.8659.03	CMW-B570H	Extra RF Converter
1202.7000.09	CMW-B660H	Option Carrier
1202.7100.09	CMW-B661H	Ethernet SW
1208.7319.02	CMW-PK364	6 GHz Flat Rate, up to 4 TRXs (SL)
1203.4205.02	CMW-KT057	Wireless Connectivity, CMWrun sequencer software tool (SL)
1203.9307.02	CMW-KM611	Bluetooth LE R 4.2 TX measurement
1211.1101.02	CMW-KM721	Bluetooth LE R5.0 TX measurement
1211.4023.02	CMW-KM722	Bluetooth LE R5.1 TX measurement
1207.8805.02	CMW-KS611	Bluetooth LE R4.2 DTM and RX measurements
1211.1124.02	CMW-KS721	Bluetooth LE R5.0 DTM and RX measurements
1211.4000.02	CMW-KS722	Bluetooth LE R5.1 DF DTM and RX Measurements

Table 3-2: Example CMW configuration for BLE DF

Minimum Software Requirements

Software	Version
CMW Base	3.7.120 or higher
CMW Bluetooth Signaling	3.7.70 or higher
CMWrun	1.9.8 or higher
CMWrun with OSP support	1.9.9 or higher

Table 3-3: Software Requirements for the BL DF Testing on CMW

OSP

Fig. 3-6: Active Switching Unit OSP

The R&S OSP220 with OSP-B127 module (<10GHz) is recommended as the active switching unit featuring:

- 6 x SPDT Solid State Relays (of which up to a maximum of four will be used)
- Control over LAN / GPIB using SCPI remote commands
- Internally terminates the unused ports

In Table 3-4, the required OSP hardware options are listed.

Option	Order-No	Description
OSP220	1528.3105K02	Open switch and control platform 2HU (without touchscreen)
OSP220	1528.3105.02	Open switch and control platform 2RU (without touchscreen)
OSP-B127	1505.4728.02	OSP module: 6 x SPDT, SSR, term 9 KHz to 10 GHz

Table 3-4: OSP configuration

Splitter/Combiner

Fig. 3-7: A cost effective alternative Splitter/Combiner

4-Way-0 degree Passive Combiner/Splitter is recommended. For example, Minicircuits ZX10-4A-27-S+ as shown in Fig. 3-7

https://www.minicircuits.com/WebStore/dashboard.html?model=ZX10-4A-27-S%2B

Key parameters:

- Lower Freq.: < 2.4GHz; Upper Freq. > 2500 GHz
- Insertion loss 6dB (theoretical) + < 1.5dB overhead
- Port Isolation > 15dB ideally
- Phase imbalance < 10deg ideally
- Amplitude imbalance < 0.8 dB ideally

Please be noted, any unused ports must be 50R terminated

Due to the limitation of the supported bandwidth, the above mentioned splitter cannot be used for interference tests.

4 Bluetooth LE Direction Finding RF Measurements

In contrast to BLE 5.0, BLE 5.1 introduced the additional RF tests and new IQ analysis requirements in the following sections.

Transmitter Tests

- Output Power with CTE (4.2.1.1)
- Carrier frequency offset and drift with CTE (4.2.1.2)
- Tx Power Stability, AoD Transmitter (4.3.1.1)
- Antenna switching integrity, AoD Transmitter (4.3.1.2)

Receiver Tests

- IQ Samples Coherency, AoA Receiver (4.2.2.1)
- IQ Samples Dynamic Range, AoA Receiver (4.2.2.2)
- IQ Samples Coherency, AoD Receiver (4.3.2.1)
- IQ Samples Dynamic Range, AoD Receiver (4.3.2.2)

There are all together 23 RF tests defined by BLE 5.1 test specification [1] for the DF as shown in Table 4-1.

RF-PHY 5.1 Test cases- Direction Finding

Description		1 Ms/s PHY		2 Ms/s PHY	
Output Power	TRM/BV-	15		-	
Carrier Frequency Offset and Drift with CTE	TRM/BV-	16		17	
		2us Slot	1us Slot	2us Slot	1us Slot
TX Power Stability; AoD Transmitter	TRM/PS/BV-	01	02	03	04
Antenna Switching Integrity; AoD Transmitter	TRM/ASI/BV-	05	06	07	08
IQ Samples Coherency; AoD Receiver	RCV/IQC/BV-	01	02	03	04
IQ Samples Coherency; AoA Receiver	RCV/IQC/BV-	05	-	06	-
IQ Samples Dynamic Range; AoD Receiver	RCV/IQDR/BV-	07	08	09	10
IQ Samples Dynamic Range; AoA Receiver	RCV/IQDR/BV-	11	-	12	-

Continuous transmission (Output Power; Carrier Frequency Offset and Drift with CTE)

- Direction Finding only supported for uncoded PHY's LE1M and LE2M
- Test case numbering relates to the BT SIG RF PHY Test Specification numbering
- 2us slot size mandatory, 1us slot size optional
- AoA Tx test cases only defined for 1us slot switching time

Table 4-1: Overview of BLE DF related RF conformance test cases

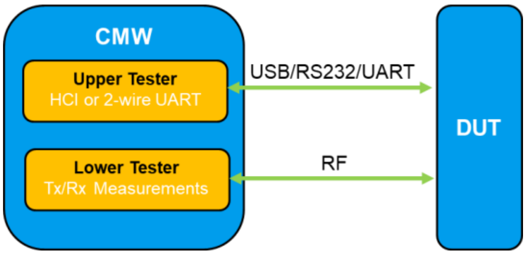


Fig. 4-1: CMW integrates Upper Tester and Lower Tester in one-box

Upper and lower tester concept specified by the BLE specification [2] requires the upper tester to manage the DTM connection to/from DUT, whereas the lower tester to perform the transmitter and receiver measurements. As an all-in-one tester shown in Fig. 4-1, CMW provides the BLE DF test solution with combined upper and lower tester functionality.

4.1 Preparation

4.1.1 Path Loss Calibration

Before the RF measurements is performed, a path loss calibration is required. The calibration procedure determines the path loss between the signal source and the input port of the DUT. CMW RF transmission power level applied in the subsequent test cases is then compensated by the path loss value.

Low	Middle	High
2402 MHz	2440 MHz	2480 MHz

Table 4-2: Frequencies for Testing of BLE DF

The path loss is frequency dependent. Table 4-2 gives the BLE DF RF specified tests frequencies. Therefore, the calibration needs to be conducted on these three carrier frequencies individually.

4.1.1.1 Calibration

In this chapter, a generic way of determining the path loss using CMW integrated General Purpose RF (GPRF) signal generator and GPRF measurement function is described.

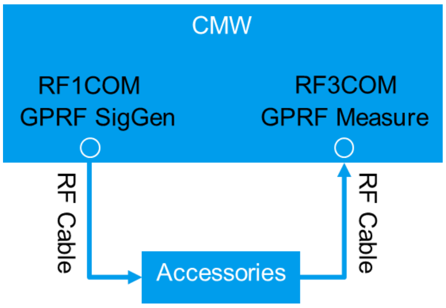


Fig. 4-2: Path Calibration Cabling

Setup the calibration environment with RF cables and the required accessories, as shown in Fig. 4-2. The accessories comprise Splitter/Combiner and/or OSP depends on the used test setup given in Chapter 3.1. The signal source is from RF1COM port and signal sink is on RF3COM port.

1. Launch CMW GPRF signal generator by pressing the "Signal Gen" hard key on the CMW front panel
2. Choose "Generator 1" to open the General Purpose RF Generator window

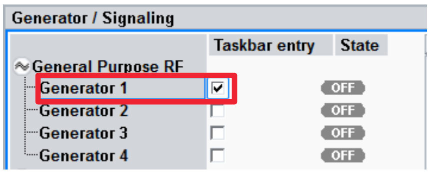


Fig. 4-3: Select GPRF Signal Generator

3. Launch CMW GPRF Measurement by pressing the "Measurement" hard key on the CMW front panel
4. Choose "General Purpose RF measurement" to open General Purpose RF Measurement window

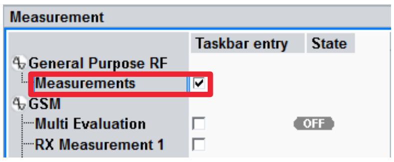


Fig. 4-4: Select GPRF Signal Measurement

5. Configure the RF signal routing properly on CMW. Press "RF Settings">"RF Routing" in GPRF measurement window to make sure the Connector "RF3COM" in RF Routing is set, see Fig. 4-5.

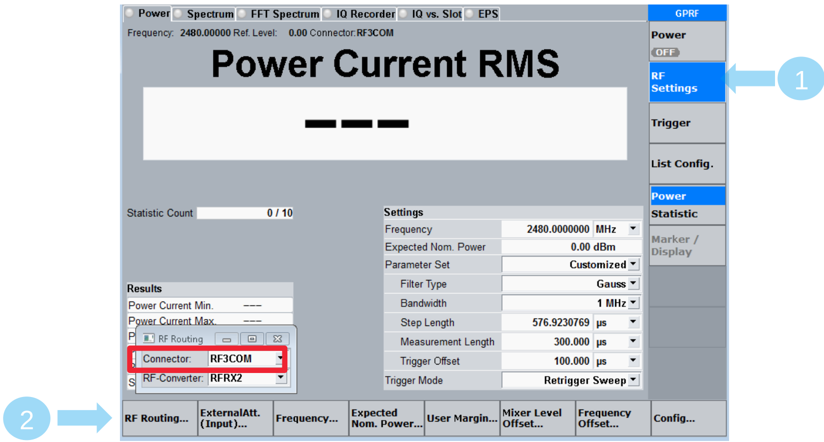


Fig. 4-5: Configure the RF Routing for RF measurement

6. In Generator window, set the "Frequency" that is under calibration, e.g. 2402 MHz, and the "Level" (default value is -30 dBm). See Fig. 4-6

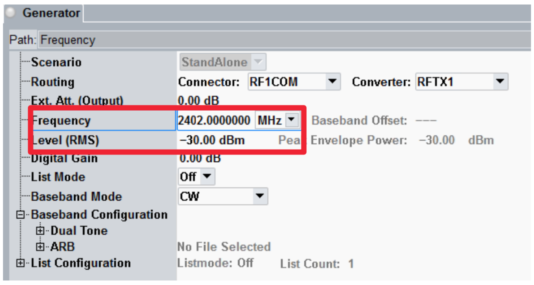


Fig. 4-6: Set Signal Frequency and Power Level in Signal Generator

7. Switch on the Generator followed by starting the measurement on the GPRF measurement side

8. In GPRF measurement window, set the same "Frequency" that is under calibration as on the GPRF Generator side, e.g. 2402 MHz

9. Read out the measured power level, e.g. -33.378 dBm, See Fig. 4-7

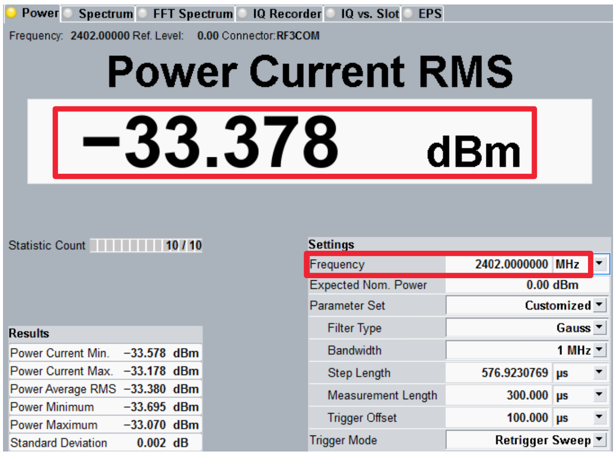


Fig. 4-7: Measure the Signal Power Level

10. Calculate the difference of the power level between the level at the generator side and the measured one. The difference is the path loss (PL) value at the calibrated frequency. So in our example here PL = (-33.378 dBm) - (-30 dBm) = -3.378 dB at 2402 MHz.

11. Repeat the above step 7-10 to calibrate path loss at Mid (2440 MHz) and High (2480 MHz) frequency

4.1.1.2 Create the Frequency Dependent Correction Table for Reference Antenna

In order to compensate the path loss for the RF test at the given test frequency by the CMW automatically, creating a Frequency Dependent Correction (FDC) Table on CMW is highly recommended. Path loss compensation by applying the values from the FDC table is a global setting on CMW which means that the signal output power level being compensated applies globally to all the launched applications, e.g. BLE, LTE etc. on CMW. Here is the procedure of the FDC table creation.

1. Press "Setup" hard key on the left side of the CMW front panel

2. Goto section "Misc" and click on "Freq.Dep.Corr.Tab …" (Frequency Dependent Correction Table). See Fig. 4-8

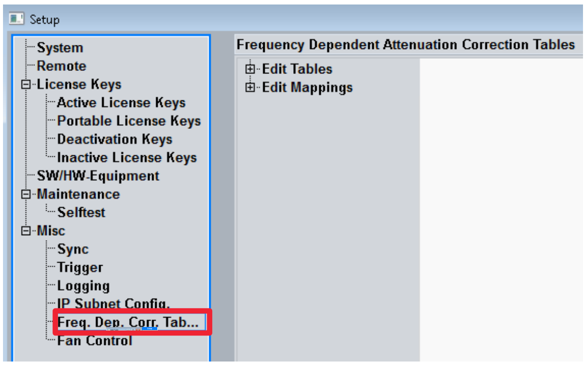


Fig. 4-8: Start Creating the Frequency Dependent Correction Table in CMW Global Setup Menu

3. Press the softkey "Add Table …" on the right side and give a table name, e.g. BLE DF under "Instrument 1". See Fig. 4-9

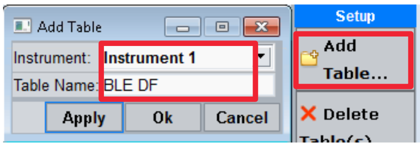


Fig. 4-9: Enter Frequency Dependent Correction (FDC) Table Name

4. Press the softkey "Add Entries …" on the right side and enter frequency and its pass loss value obtained by the procedure described in Chapter 4.1.1.1 in the Attenuation field, then press button "Ok" (save the entry and close the window) or "Apply" (only save the entry). See Fig. 4-10

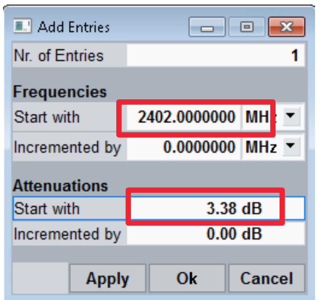
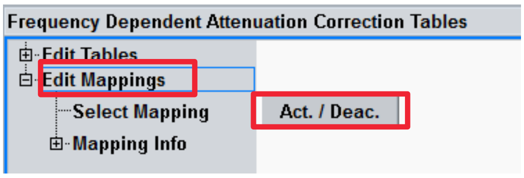


Fig. 4-10: Add entries in Frequency Dependent Correction (FDC) Table

5. Mapping the FDC Table to RF port and activate the FDC. Press "Act./Deac." button and configure TX and RX path in the "Edit Mappings" section, select the FDC table created in the previous steps. Save and close the window by pressing "Ok" or save the entry only by pressing "Apply" button. See Fig. 4-11



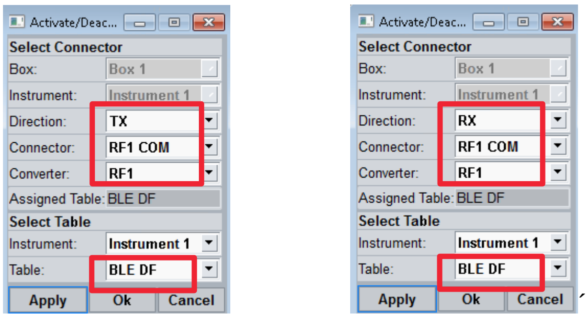


Fig. 4-11: Frequency Dependent Correction Table mapping

After all the above steps are done for all three frequencies, an FDC Table as shown in Fig. 4-12 is created. With the attenuation values in this table, the path loss is automatically compensated at the corresponding frequency and associated RF connector.

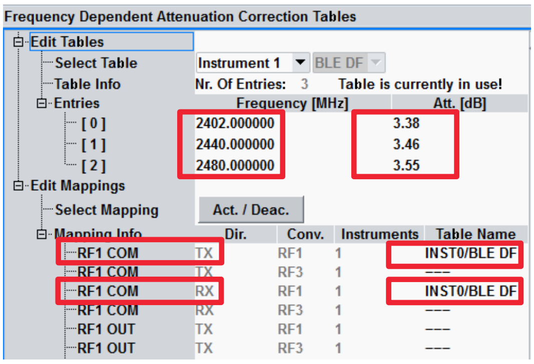


Fig. 4-12: Example Frequency Dependent Correction (FDC) Table

4.1.1.3 Measure the power offset between Reference Antenna and Non-reference Antennas.

For some BLE RF tests, there need multiple BLE DUT antennas to be connected to a Splitter/Combiner or optionally with OSP as illustrated in Fig. 4-13.

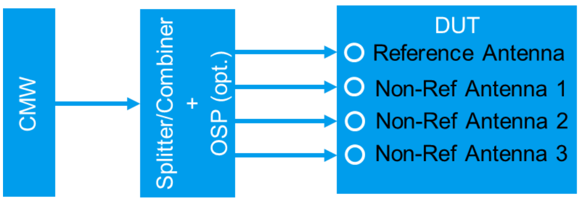


Fig. 4-13: Block Diagram of Multi Antenna Setup

The path loss compensation utilizing the FDC table described in the section 4.1.1.2 is relevant for reference antenna. For the other antennas, the path loss offset to the reference antenna needs to be measured and entered in the CMW BLE application as described in the following steps:

1. Measure the path loss on the non-reference antenna 1 while all other antenna ports are terminated with 50Ω terminator. The path loss determination method should follow the procedure described in section 4.1.1.1. Note down the measured

path loss value and calculate the difference to the reference antenna, thus the path loss offset value on antenna 1 is obtained.

2. Repeat the above step 1, to obtain the path loss offset of non-reference antenna 2 and antenna 3.

3. Enter the offset values as shown in Fig. 4-14. The menu entry can be opened via Bluetooth Rx measurement page "IQ Coherency" or "IQ Dynamic Range" in the Bluetooth Application on CMW, press "RF settings", and then "External Attenuation …" where the offset values can be entered for both Input Attenuation and Output Attenuation. This is only possible when CMW hardware option CMW-S100H (MUA) is installed.

ATTENTION:

If old CMW hardware option CMW-S100B (BB Meas) is installed, then the offset setting shown in Fig. 4-14 is not available on CMW. The user needs to ensure that the path loss offset between each non-reference path and reference path is less than 0.5 dB. For example, by utilizing the RF cables with same length.

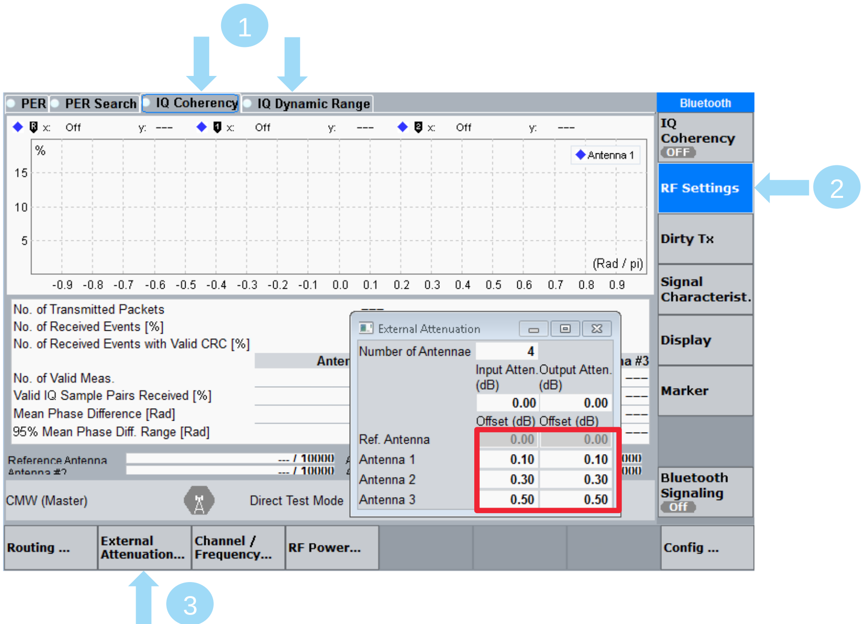


Fig. 4-14: Enter the attenuation offsets of the Non-reference antennas on CMW with hardware option MUA (CMW-S100H)

4.1.2 Enable Direct Test Mode (DTM)

As explained in Chapter 2.2.4, all BLE DF RF tests are conducted in the DTM. To enable the DTM, following steps needs to be performed beforehand. Details can refer to [5]

Assign USB driver to DUT

- Install the BLE USB driver delivered together with the CMW BT firmware
- Detecting the DUT in the Device Manager of the Windows
- Assign the right USB driver to DUT

Configure and Activate the Hardware Interface (USB or USB-RS232 adapter)

Depending on the selected hardware interface, either USB or USB to RS232 adapter is used. The details of the activation procedure and configurations are well described in [5]

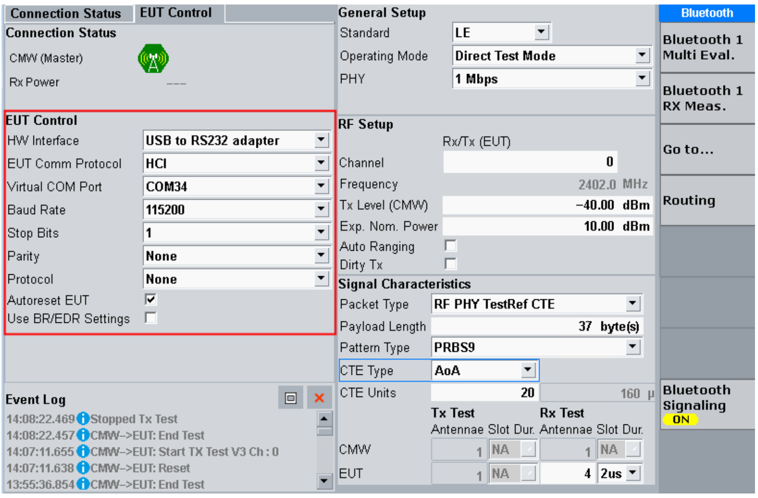


Fig. 4-15: DUT Control configurations on CMW (USB to RS232 adapter)

Fig. 4-15 shows the DUT control setting page in case USB to RS232 adapter is utilized.

4.1.3 General Configurations on CMW

For all the BLE DF transmitter and receiver tests, a certain parameter settings have to be configured on the CMW main configuration window as shown in Fig. 4-16.

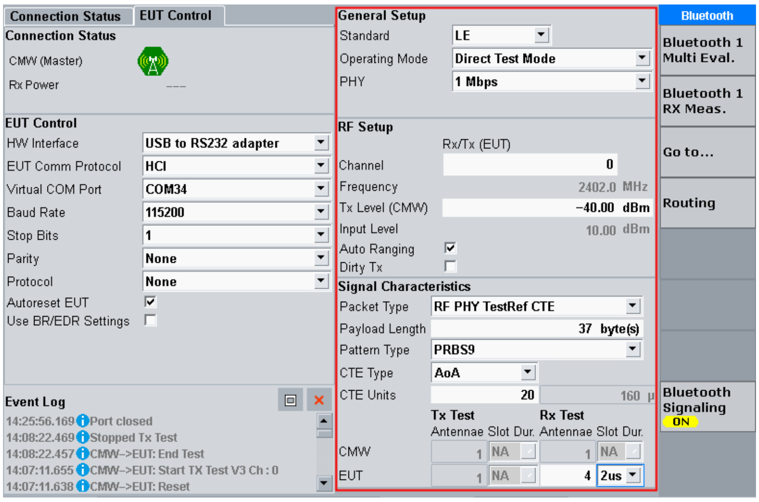


Fig. 4-16: CMW BLE DF General Configuration

The summary of general settings can be found in Table 4-3.

Conf. Field	Setting	Remark
Standard	LE	valid for all test cases
Operating Mode	Direct Test Mode	valid for all test cases
PHY	1 Mbps | 2 Mbps	test case dependent
Channel	0 (low) | 19 (middle) | 39 (high)	test case dependent
Tx Level (CMW)	-40 dBm (default)	test case dependent, unless otherwise stated, default value is applied
Auto Ranging	Enable	valid for all test cases
Dirty Tx	Disable	valid for all test cases
Packet Type	RF PHY TestRef CTE	valid for all test cases
Payload Length	<0..255 bytes>	DUT dependent
Pattern Type	ALL0: 00000000 ALL1: 11111111 P11: 10101010 (default) P44: 11110000 PRBS9: pseudo-random bit sequences of a length of 9 bits (transmission of identical packet series)	test case dependent, unless otherwise stated, default value is applied
CTE Type	AoA | AoD	test case dependent
CTE Units	<2..20>	DUT dependent
Number of Antennae	<2..4>	DUT dependent
Slot Duration (CMW)	1 µs | 2 µs	test case dependent
Slot Duration (EUT)	1 µs | 2 µs	test case dependent

Table 4-3: General CMW settings for BLE DF Testing

Some remarks to Table 4-3:

- For those settings marked as "test case dependent", they are explicitly listed in section "CMW Settings" of each test case described in Chapter 4.2 and 4.3.
- DUT dependent settings need to be configured individually in accordance with the DUT capability.

4.2 AoA Measurements

4.2.1 Transmitter Measurements

General

The goal of AoA transmitter tests is to verify the correct transmission of CTE. The DUT does continuous transmission of BLE packet and does not do any switching or sampling.

CMW, the lower tester, receives the test packet using a single antenna.

The AoA transmitter tests consist of:

- Output Power with CTE
- Carrier frequency offset and drift with CTE

Checks if it is modulated correctly, not whitened, all 1s etc.

Checks if the CTE bit and SuppInfo are set correctly in the packet

Setup

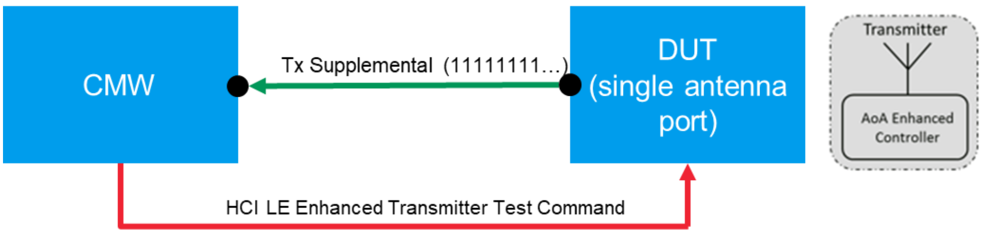


Fig. 4-17: Test Setup for AoA Transmitter Tests (Output Power with Constant Tone Extension (CTE) and Carrier frequency offset and drift with CTE)

4.2.1.1 Output Power with Constant Tone Extension (Test Spec Chapter 4.4.12, RF-PHY/TRM/BV-15-C)

Test Purpose

Test verifies the maximum peak and average power in the complete packet when transmitting with CTE.

CMW Settings

Conf. Field	Setting*
PHY	1 Mbps
Channel	0 (low)
Pattern Type	PRBS9
CTE Type	AoA
Slot Duration (EUT)	2 µs

* Refer to Table 4-3 for the rest of the CMW settings

Execute Test

- Switch on **Bluetooth Signaling**
- Goto **Bluetooth Multi Evaluation**
- Switch on **Multi Evaluation**
- Select **Power vs. Time** view

Pass Criteria

- -20 dBm ≤ PAVG ≤ +20 dBm (PVAG = Average Power)
- PPK ≤ (PAVG + 3 dB); (PPK = Peak Power)

Example result in Fig. 4-18 shows PAVG = -1.67 dBm, PPK = -1.15 dBm, PPK-PVAG = 0.52 dB< 3 dB, so the result verdict is pass

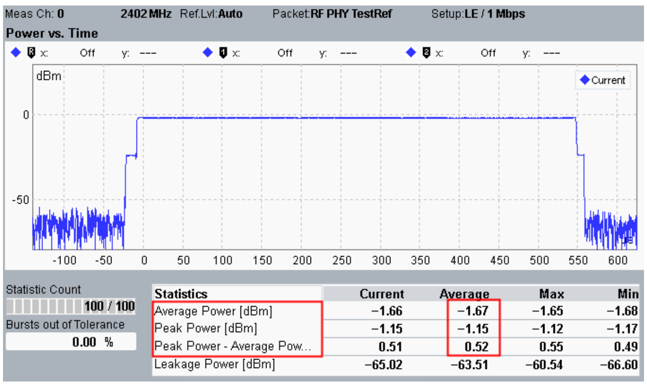


Fig. 4-18: Example result of TC RF-PHY/TRM/BV-15-C

4.2.1.2 Carrier frequency offset and drift with CTE (Test Spec Chapter 4.4.13, RF-PHY/TRM/BV-16-C) (Test Spec Chapter 4.4.14, RF-PHY/TRM/BV-17-C)

Test Purpose

Test verifies that the carrier frequency offset and carrier drift of the CTE portion in a transmitted signal is within specified limits.

CMW Settings

Conf. Field	Setting*
PHY	1 Mbps (for TC16) | 2 Mbps (for TC17)
Channel	0 (low)
Pattern Type	P44: 11110000
CTE Type	AoA
Slot Duration (EUT)	2 µs

* Refer to Table 4-3 for the rest of the CMW settings

Execute Test

- Switch on **Bluetooth Signaling**
- Goto **Bluetooth Multi Evaluation**
- Switch on **Multi Evaluation**
- Select **TX Measurement Modulation**
- Choose **Display** button
- At bottom of the display, toggle to **CTE Results**

Pass Criteria

- CTE Frequency Offset

The maximum CTE Frequency Offset measured over every 16 µs starting from the reference portion of the CTE should be within the range of f_{TX}±150 kHz

$$f_{TX} - 150\text{ kHz} \le f_{si} \le f_{TX} + 150\text{ kHz},$$

where

f_{TX} is the nominal expected center frequency TX

$f_{si} = f3_{maxi} - \Delta f1_{avg}$, i=1..k

$\Delta f1_{avg}$ is the calculated average frequency deviation used as a reference for the CTE average frequency offset measurement

$f3_{maxi}$ is measured across 16 µs

- CTE Frequency Drift

This is the change in carrier frequency drift across a 48 µs period

LE1M: $|f_{si} – f_{si-3}| \leq$ 19.2 kHz, where i=4…k

LE2M: $|f_{si} – f_{si-3}| \leq$ 13.6 kHz, where i=4…k

- CTE Initial Frequency Drift

$|f_{s1} – f_{p}| \leq$ 19.2 kHz

f_p is the average carrier frequency at the end of the payload, see the f_p calculation in [1].

The CTE initial frequency drift is measured between the end of the payload and the beginning of the CTE portion. See packet format in Fig. 2-5

- CTE Maximum Drift Rate

$|f_{si} – f_{0}| \leq$ 50 kHz, where i=1,2,3,4…k

CTE frequency drift is the CTE frequency offset relative to the initial carrier frequency f_0 which is measured within the preamble portion of the test packet, see packet format in Fig. 2-5

The maximum drift rate is the maximum calculated drift.

Fig. 4-19 shows example test results, where the pass criteria are all fulfilled as follows:

-150 kHz < CTE Frequency Offset = -1.4 kHz < 150 kHz

CTE Frequency Drift = 0 $\leq$ 19.2 kHz (LE1M case)

CTE Initial Frequency Drift = -0.8 $\leq$ 19.2 kHz

CTE Maximum Drift Rate = 0 $\leq$ 50 kHz

Meas Ch: **0** **2402 MHz** Ref.Lvl: **Auto** Packet: **RF PHY TestRef** Setup: **LE / 1 Mbps**

TX Measurement Modulation

Statistics	Current	Average	Max	Min
CTE Freq Offset [kHz]	−1.5	−1.4	−0.6	−2.5
CTE Freq drift [kHz]	−0.5	−0.3	2.2	−2.8
CTE Initial Freq Drift [kHz]	−0.6	−0.8	0.8	−2.3
CTE Max Drift Rate [kHz]	−0.4	0.0	1.5	−1.6

Fig. 4-19: Example Test Results of Testcase Carrier frequency offset and drift with CTE

4.2.2 Receiver Measurements

General

The goal of the AoA receiver test is to verify if the DUT does the sampling and the switching correctly.

CMW RF tester transmits a special Supplemental using a single antenna port and applies 2µs switching and sampling slot.

DUT receives the Supplemental using multiple antennas and sends captured IQ Samples via HCI DTM interface back to the CMW.

Antenna array configuration and switching pattern are known to the CMW.

CMW checks if switching and sampling have been done by DUT correctly.

Setup

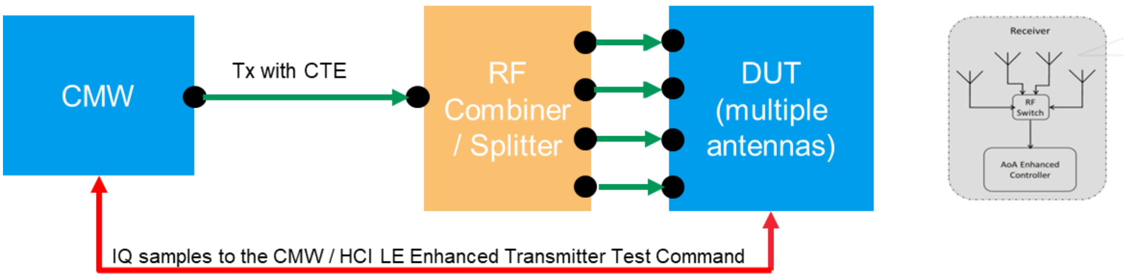


Fig. 4-20: Test Setup for AoA Receiver Test (IQ Sample Coherency and IQ Samples Dynamic Range)

4.2.2.1 IQ Samples Coherency (Test Spec Chapter 4.5.38.1, RF-PHY/RCV/IQC/BV-05-C) (Test Spec Chapter 4.5.38.2, RF-PHY/RCV/IQC/BV-06-C)

Test Purpose

Verifies that the measured relative phase values derived from the I and Q samples on the DUT AoA receiver from a CTE are within limits

CMW Settings

Conf. Field	Setting*
PHY	1 Mbps (for TC05) | 2 Mbps (for TC06)
Channel	0 (lowest) | 19 (middle) | 39 (highest)
Tx Level (CMW)	-67 dBm
Payload Length	0
CTE Type	AoA
CTE Unit	20
Slot Duration (EUT)	2 µs

* Refer to Table 4-3 for the rest of the CMW settings

Execute Test

- Switch on **Bluetooth Signaling**
- Goto **Bluetooth RX Measurement**
- Click on **IQ Coherency** page
- Switch on **IQ Coherency Measurement**
- Click on **Display** Button, Toggel between **RP[m]** and **RPD** view to see the result of non-reference antenna and reference antenna, respectively

Remark

The CMW (lower tester) will send BLE test packets until:

- the maximum defined number of packets is reached, see [1], or
- The RP(m) or RPD measurement sets each contain at least 10,000 values

Pass Criteria

- DUT reports 10,000 valid measurements per non-reference antenna and reference antenna
- At least 95% of the Mean Relative Phase (RP(m) values per non-reference antenna shall be within ±0.52 radians or ±0.166 rad/PI*
- The Mean Reference Phase Deviation RPD value shall be within ±1.125 radians = ±0.358 rad/PI*

* Note: the unit rad/PI normalizes X-axis to be in the range of -1 and +1 in the result diagram on CMW

The CMW (upper tester) will calculate the phase of each IQ pair $Phase = \arctan(\frac{Q}{I})$ for all valid measurements

Both Fig. 4-21 and Fig. 4-22 shows the example measurement results which are PASS

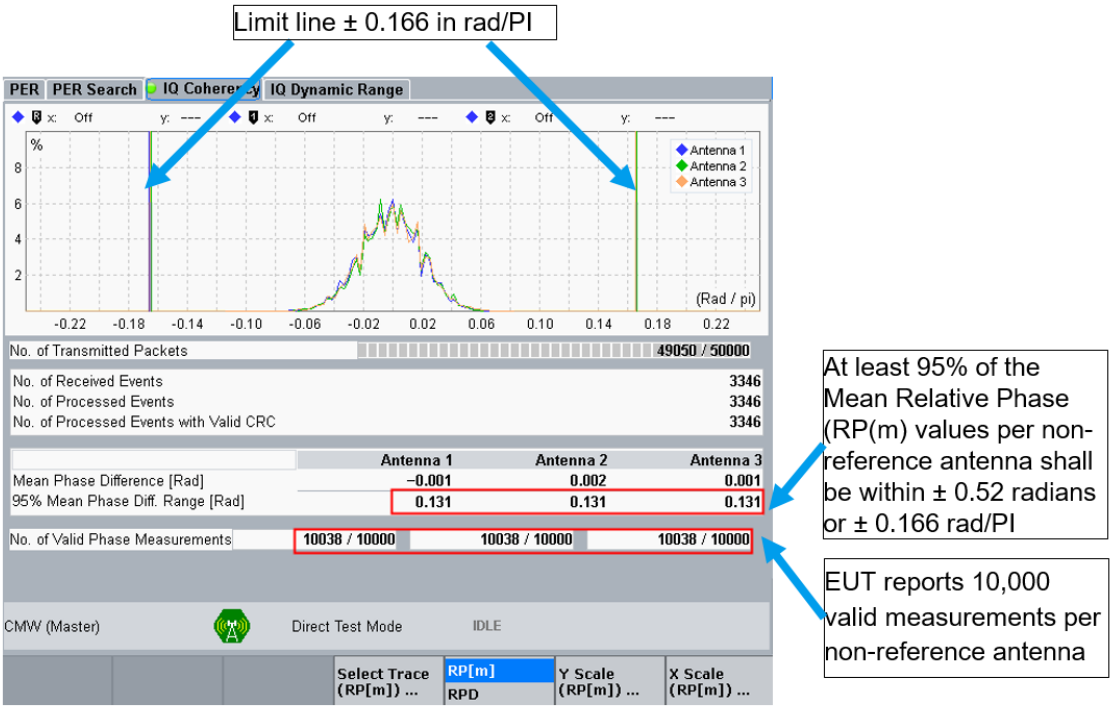


Fig. 4-21: Mean Relative Phase measurements (RPm) on non-reference antenna (Antenna 1, 2 and 3). All antennas have the measurement value 0.131 Radians which are within the limit ± 0.52 radians, therefore, the testcase is PASS.

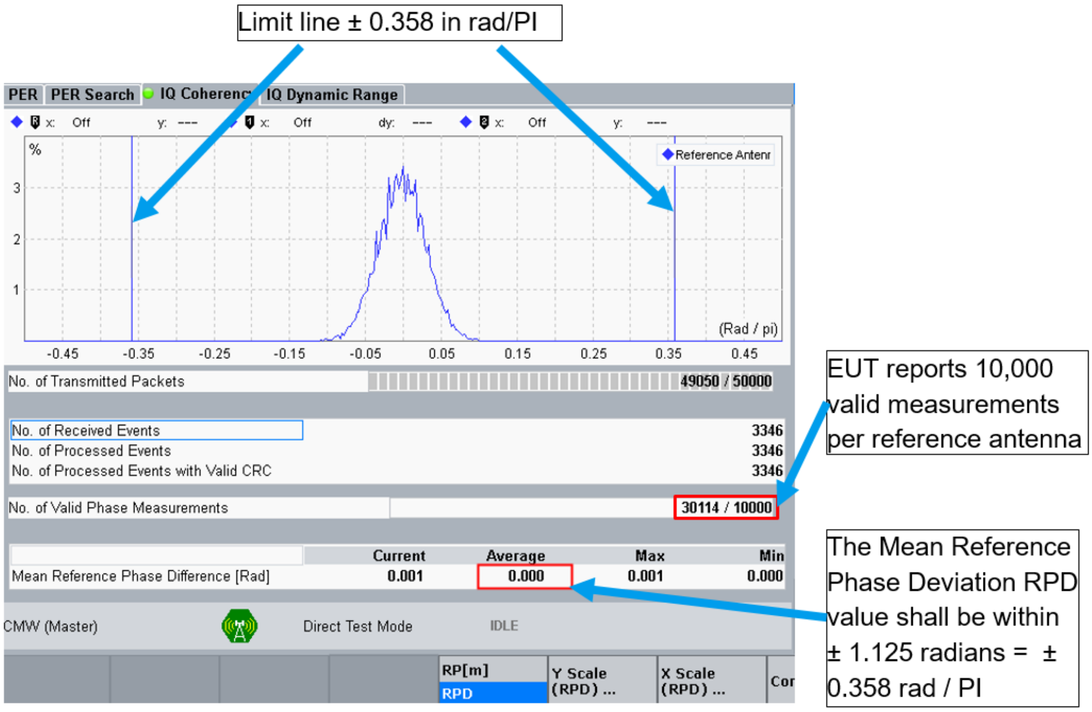


Fig. 4-22: Mean Reference Phase Deviation (RPD) on reference antenna. The reference antenna has the Mean Phase Difference value measured at -0.000 Rad which is in the limit of ± 1.125 Rad, therefore, the test is PASS.

Test Repetition

The testcase needs to be repeated in different channels, i.e. Channel 0 (lowest), 19 (middle) and 39 (highest)

4.2.2.2 IQ Samples Dynamic Range (Test Spec Chapter 4.5.40.1, RF-PHY/RCV/IQDR/BV-11-C) (Test Spec Chapter 4.5.40.2, RF-PHY/RCV/IQDR/BV-12-C)

Test Purpose

Verifies that the I and Q values have specified values varying the dynamic range of the CTE

CMW Settings

Conf. Field	Setting*
PHY	1 Mbps (for TC11) | 2 Mbps (for TC12)
Channel	0 (lowest) | 19 (middle) | 39 (highest)
Tx Level (CMW)	-52 dBm
Payload Length	0
CTE Type	AoA
CTE Unit	20
Slot Duration (EUT)	2 µs

* Refer to Table 4-3 for the rest of the CMW settings

In accordance with the test requirement, CMW controls a variable attenuator that applies an additional attenuation (offset) on the line while sending the CTE on a per slot basis, such that the input power to the DUT receiver is set to the value described in Table 4-4, for each antenna index. Four antennas, including reference antenna is assumed. The input power at the DUT receiver side in the ascend order is: Ant 3 < Ant 2 < Ant 0 < Ant 1.

Antenna Index	Input Power [dBm]	Offset to Ref. Ant [dB]
0 (Reference Antenna)	-52	0
1	-49	3
2	-57	-5
3	-62	-10

Table 4-4: Input power at each DUT receiver antenna element

To enter the power level offset of the non-reference antenna in relation to the reference antenna on CMW, go through the following steps:

- Switch on **Bluetooth Signaling**
- Goto **Bluetooth RX Measurement**
- Click on **IQ Dynamic Range page**
- Click on **Signal Characterist.**
- Click on **Antenna Config.** In the opened configuration window, enter the offset values given in Table 4-4. The configuration GUI is shown in Fig. 4-23

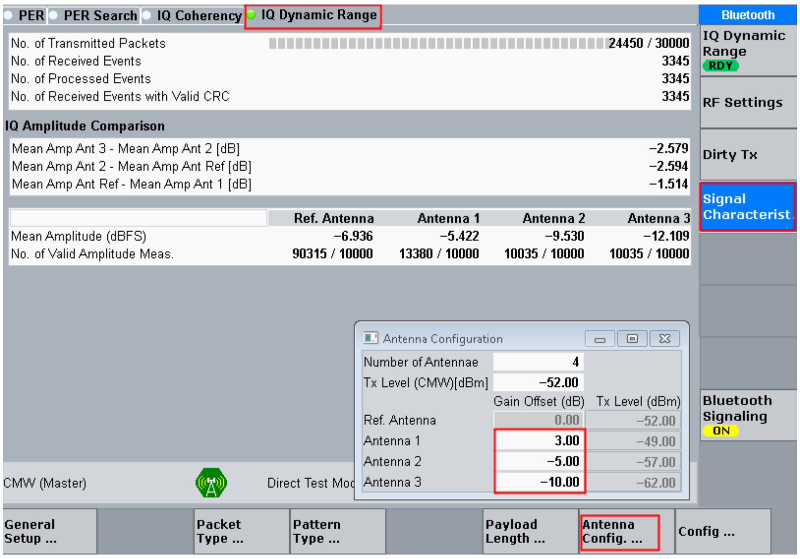


Fig. 4-23: Antenna Configuration on CMW

Execute Test

- Switch on **IQ Dynamic Range Measurement**

Remark

The CMW (lower tester) will send BLE test packets until

- the max defined number of packets is reached, see [1] or,
- The RP(m) or RPD sets each contain at least 10,000 sample pairs

The CMW (upper tester) will calculate the I/Q magnitude $A = \sqrt{I^2 + Q^2}$ for all valid measurements

Pass Criteria

- DUT reports 10,000 valid measurements per antenna
- Mean ANT3 < Mean ANT2 < Mean ANT0 < Mean ANT1
- If no valid samples are available on ANT1 due to saturation then Mean ANT3 < Mean ANT2 < Mean ANT0

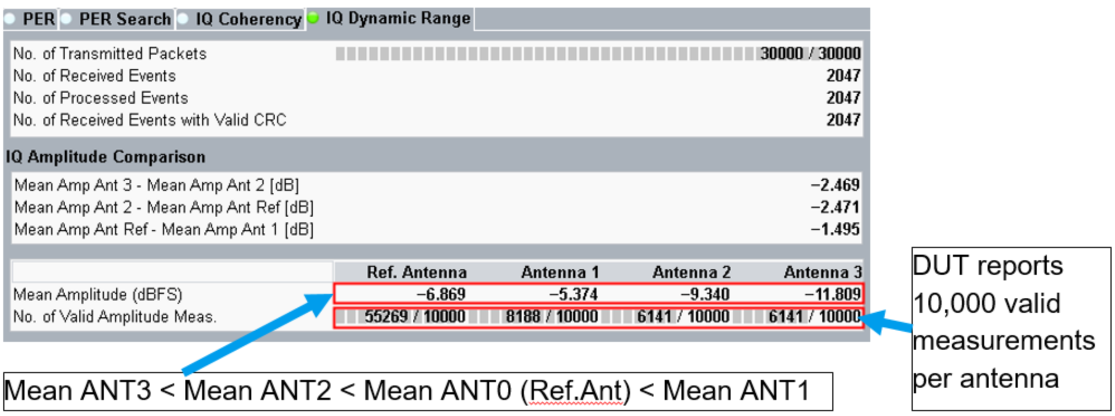


Fig. 4-24 shows the passed example measurement results

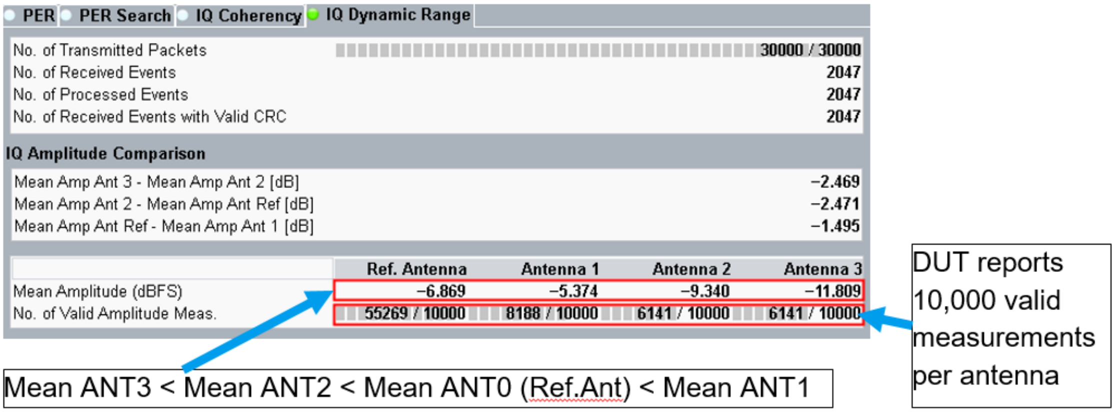


Fig. 4-24: AoA Receiver: Mean Amplitude measured has the ascend order ANT3 < ANT2 < ANT0 (Ref.Ant) < ANT1. Therefore, the test is PASS

Test Repetition

The testcase needs to be repeated in different channels, i.e. Channel 0 (lowest), 19 (middle) and 39 (highest)

4.3 AoD Measurements

4.3.1 Transmitter Measurements

General

The goal of AoD transmitter tests is to check whether DUT does the antenna switching correctly while transmitting the supplemental using multiple antennas.

Antenna array configuration and switching pattern are known to CMW via HCI and CMW checks if switching is done correctly. The DUT should follow the antenna switching pattern described in Chapter 2.2.7.

The AoD transmitter tests consists of:

- Tx Power Stability
- Antenna switching integrity

An external RF Combiner/Splitter is required. Therefore, there is no need for multiple receiver ports in the CMW.

Whereas for Antenna switching integrity test, RF switching unit OSP is recommended for an automation process. Details of the setup can be referred in the section 3.1.

4.3.1.1 Tx Power Stability (Test Spec Chapter 4.4.15.1, RF-PHY/TRM/PS/BV-01-C) (Test Spec Chapter 4.4.15.2, RF-PHY/TRM/PS/BV-02-C) (Test Spec Chapter 4.4.15.3, RF-PHY/TRM/PS/BV-03-C) (Test Spec Chapter 4.4.15.4, RF-PHY/TRM/PS/BV-04-C)

Test Purpose

The testcase verifies

- AoD TX signal has settled at the beginning of the reference period and the transmit slots
- AoD TX signal remains stable during reference period and the transmit slots

Setup

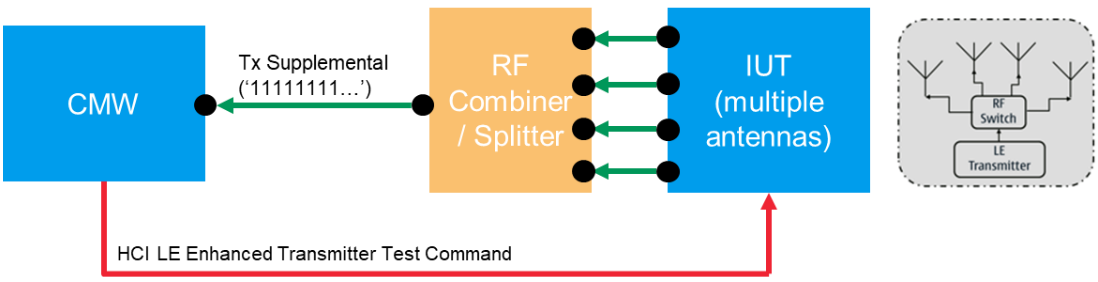


Fig. 4-25: Test Setup for AoD Transmission Test Tx Power Stability

CMW Settings

Conf. Field	Setting*
PHY	1 Mbps (for TC01/02) | 2 Mbps (for TC03/04)
Channel	0 (lowest) | 19 (middle) | 39 (highest)
CTE Type	AoD 1µs
Slot Duration (CMW)	1µs (for TC02/04) | 2µs (for TC01/03)
Slot Duration (EUT)	1µs (for TC02/04) | 2µs (for TC01/03)

* Refer to Table 4-3 for the rest of the CMW settings

Execute Test

- Switch on **Bluetooth Signaling**
- Goto **Bluetooth Multi Evaluation**
- Switch on **Multi Evaluation**
- Select **Power vs. Slot** view, this opens the Diagram View
- If needed, click on Table View

Pass Criteria

- P_{DEV} / P_{AVE} < 0.25 (±6.02 dB)

Where

P_{AVE} is the average power measured in CTE

- on slot 0 (reference period), and
- on transmit slot n (n=1, 2,3,…,k, where k is the number of the transmit slots)

P_{DEV} is the maximum absolute power deviation to the average power on the associated slot, i.e. reference and transmit slot.

Fig. 4-26 shows the test results in bar chart representation on CMW.

In X-axis, the slot 0 denotes the reference period followed by the n transmit slots. The upper part of the measurements deliver the average power measurements P_{AVE} over slots and lower part of the measurements are P_{DEV} / P_{AVE} over slots. If the measured values are within the ±6.02 dB corridor known as limit line, then the test is passed.

Fig. 4-27 is a tabulated view of the same test results on CMW which gives more details on the measured P_{AVE} and P_{DEV} values over each slot.

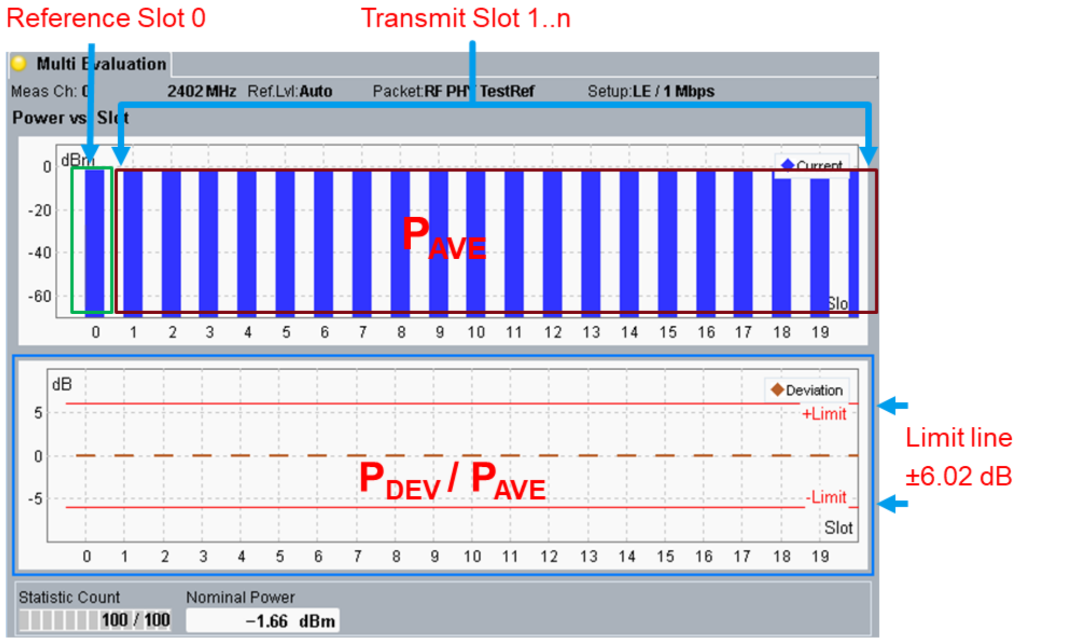


Fig. 4-26: Example test result from CMW in bar chart view, the lower part of the results are within the limit of ±6.02 dB, therefore the test is PASSED

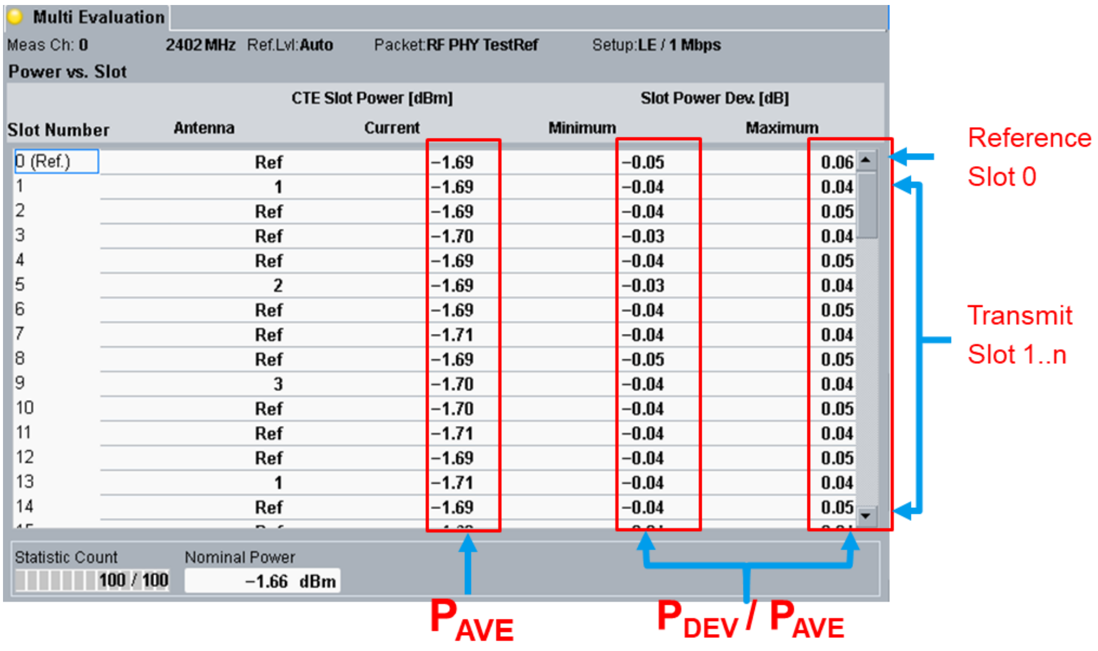


Fig. 4-27: Example test result from CMW in tabulated view, all slot power deviations are within the limit of ±6.02 dB, therefore the test is PASSED

Test Repetition

The testcase needs to be repeated in different channels, i.e. Channel 0 (lowest), 19 (middle) and 39 (highest)

4.3.1.2 Antenna Switching Integrity (Test Spec Chapter 4.4.16.1, RF-PHY/TRM/ASI/BV-05-C) (Test Spec Chapter 4.4.16.2, RF-PHY/TRM/ASI/BV-06-C) (Test Spec Chapter 4.4.16.3, RF-PHY/TRM/ASI/BV-07-C) (Test Spec Chapter 4.4.16.4, RF-PHY/TRM/ASI/BV-08-C)

Test Purpose

This test verifies that the antenna switching occurs during the switching slots of the CTE for an AoD transmit signal

Setup

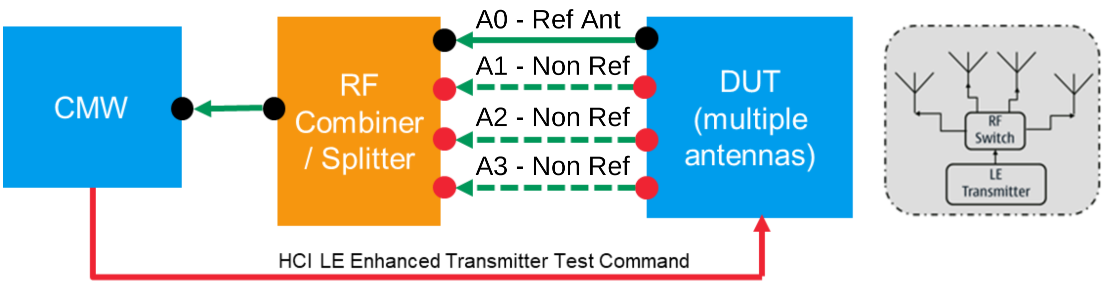


Fig. 4-28: Test Setup for AoD Transmission Test Antenna Switching Integrity (Manual Operation)

CMW Settings

Conf. Field	Setting*
PHY	1 Mbps (for TC05/06) | 2 Mbps (for TC07/08)
Channel	0 (lowest) | 19 (middle) | 39 (highest)
CTE Type	AoD
Slot Duration (CMW)	1µs (for TC06/08) | 2µs (for TC05/07)
Slot Duration (EUT)	1µs (for TC06/08) | 2µs (for TC05/07)

* Refer to Table 4-3 for the rest of the CMW settings

Execute Test

This test case requires multiple steps that are summarized in Table 4-5.

Step	Conn. Ant.	Relevant Power Measurement
1	A0	$P_{n,AVE,OFF}$ n= Transmit slot of non-reference antenna A1, A2, A3 acc. to antenna switching pattern*
2	A0+A1	$P_{n,1,AVE,ON}$ n= Transmit slot of non-reference antenna A1 acc. to antenna switching pattern
3	A0+A2	$P_{n,2,AVE,ON}$ n= Transmit slot of non-reference antenna A2 acc. to antenna switching pattern
4	A0+A3	$P_{n,3,AVE,ON}$ n= Transmit slot of non-reference antenna A3 acc. to antenna switching pattern

Table 4-5: Four Antennas for ASI Test and Relevant Power Measurements

* Antenna switching pattern, refer to Table 2-3

Example ASI measurements based on 4 antennas (A0=reference antenna, A1...A3=non reference antenna), 2µs slot duration and 20 units CTE length is illustrated in Fig. 4-29.

As mentioned in Chapter 2.2.7, the number of the antennas influences the antenna switching pattern according to Table 2-3. The CTE type (1 µs slots or 2 µs slots) and CTE Time determine the total number of the switching and transmit slots in the CTE portion of the BLE DF packet.

Therefore, in the example given in Fig. 4-29, the antenna switching pattern in one CTE packet containing 37 transmit slots should looks like A0 A1 A0 A0 A0 A2 A0 A0 A0 A3 A0 A0 A0 … that means the A1, A2 and A3 transmits 4, 3 and 3 times at the marked transmit slots, respectively.

		Ref																		
	Pattern ->	A0	A1	A0	A0	A0	A2	A0	A0	A0	A3	A0	A0	A0	A1	A0	A0	A0	A2	A0
Step	Antennae	0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
#1	A0	-	OFF	-	-	-	OFF	-	-	-	OFF	-	-	-	OFF	-	-	-	OFF	-
#2	A0 + A1	-	ON	-	-	-	OFF	-	-	-	OFF	-	-	-	ON	-	-	-	OFF	-
#3	A0 + A2	-	OFF	-	-	-	ON	-	-	-	OFF	-	-	-	OFF	-	-	-	ON	-
#4	A0 + A3	-	OFF	-	-	-	OFF	-	-	-	ON	-	-	-	OFF	-	-	-	OFF	-

	Pattern	A0	A0	A3	A0	A0	A0	A1	A0	A0	A0	A2	A0	A0	A0	A3	A0	A0	A0	A1
Step	Antennae	19	20	21	22	23	24	25	26	27	28	29	30	31	32	33	34	35	36	37
#1	A0	-	-	OFF	-	-	-	OFF	-	-	-	OFF	-	-	-	OFF	-	-	-	OFF
#2	A0 + A1	-	-	OFF	-	-	-	ON	-	-	-	OFF	-	-	-	OFF	-	-	-	ON
#3	A0 + A2	-	-	OFF	-	-	-	OFF	-	-	-	ON	-	-	-	OFF	-	-	-	OFF
#4	A0 + A3	-	-	ON	-	-	-	OFF	-	-	-	OFF	-	-	-	ON	-	-	-	OFF

Antennae	No. of Meas. Per Packet
A0	-
A1	4
A2	3
A3	3

Fig. 4-29: Example ASI measurements based on 2µs switching slot duration and 20 units CTE length (37 transmit slots in total) and number of the measurements per packet of each non-reference antenna

The whole test procedure is as follows:

1. Initially, only reference antenna A0 is connected and the average transmit power $P_{n,AVE,OFF}$ in each TX slot is measured. However, only n TX slots where non-reference antennas transmit according to the antenna switching pattern are of relevance here for the test purpose. The example given in Fig. 4-29 shows that TX slot 1, 5, 9, 13, 17, 21, 25, 29, 33 and 37 needs to be considered for the pass verdict calculation.
2. Non-reference antenna A1 is connected in addition to reference antenna A0 and average transmit power $P_{n,1,AVE,ON}$ in each TX slots is measured. In the example scenario given in Fig. 4-29, measurements of TX slot 1, 13, 25 and 37 (4 measurements per packet) according to the antenna switch pattern are of relevance.
3. Non-reference antenna A2 is connected in addition to reference antenna A0 and average transmit power $P_{n,2,AVE,ON}$ in each TX slots is measured. In the example

scenario given in Fig. 4-29, measurements of TX slot 5, 17, 29 (3 measurements per packet) according to the antenna switch pattern are of relevance.

4. Non-reference antenna A3 is connected in addition to reference antenna A0 and average transmit power $P_{n,3,AVE,ON}$ in each TX slots is measured. In the example scenario given in Fig. 4-29, measurements of TX slot 9, 21, 33 (3 measurements per packet) according to the antenna switch pattern are of relevance.

The execution of the power measurements on CMW is the same as mentioned in Chapter 4.3.1.1.

Be noted that maximum four antennas are tested in the above described procedure, one reference and with three other non-reference antennas. In case there are more than four antennas under test, the whole test needs to be split into several iterations. For example, if seven antennas are in use, then the reference antenna plus three non-reference antennas are selected for the first iteration. In the second iteration, the reference antenna plus the rest three non-reference antennas are then tested.

This test case requires the manual intervention (un-cabling) on the test setup and post processing of the power measurements to determine the PASS/FAIL verdict. Therefore, automation solution explained in Chapter 3.1 is highly recommended

Pass Criteria

- $P_{n,X,AVE,ON} - P_{n,AVE,OFF} \geq 10$ dB

$P_{n,AVE,OFF}$ is the measured average signal power of each transmit slot in CTE. Only the reference antenna is connected, the other non-reference antennas are all terminated.

$P_{n,X,AVE,ON}$ is the measured average signal power of each transmit slot associated to the selected Xth non-reference antenna in CTE , where n is the transmit slot of the Xth non-reference antenna according to the antenna switching pattern. The other non-reference antennas are all terminated.

Test Repetition

The testcase needs to be repeated in different channels, i.e. Channel 0 (lowest), 19 (middle) and 39 (highest)

4.3.2 Receiver Measurements

General

The goal of the AoD receiver test is to verify if the DUT does the sampling correctly

CMW RF tester transmits a special Supplemental (in transmit slot) using a single antenna depending on the switch/transmit slot duration as follows:

- 1µs slot duration: 01010101…
- 2µs slot duration: 00110011…

DUT receives the Supplemental using a single antenna and sends captured I&Q Samples via HCI DTM interface back to the CMW

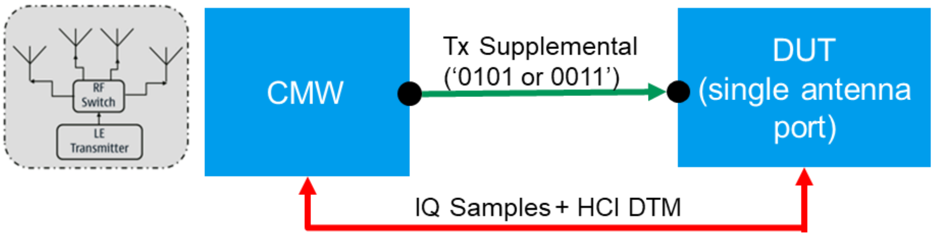


Fig. 4-30: Test Setup for AoD Receiver Test (IQ Sample Coherency and IQ Samples Dynamic Range)

4.3.2.1 IQ Samples Coherency (Test Spec Chapter 4.5.37.1, RF-PHY/RCV/IQC/BV-01-C) (Test Spec Chapter 4.5.37.2, RF-PHY/RCV/IQC/BV-02-C) (Test Spec Chapter 4.5.37.3, RF-PHY/RCV/IQC/BV-03-C) (Test Spec Chapter 4.5.37.4, RF-PHY/RCV/IQC/BV-04-C)

Test Purpose

Verifies that the measured relative phase values derived from the I/Q samples on the AoD receiver of the DUT from a CTE are within limits

CMW Settings

Conf. Field	Setting*
PHY	1 Mbps (for TC01/02) | 2 Mbps (for TC03/04)
Channel	0 (lowest) | 19 (middle) | 39 (highest)
Tx Level (CMW)	-67 dBm
Payload Length	0
CTE Type	AoD
CTE Units	20
Slot Duration (CMW)	1µs (for TC02/04) | 2µs (for TC01/03)

* Refer to Table 4-3 for the rest of the CMW settings

Execute Test

- Same as AoA Receiver Tests. Refer to 4.2.2.1

Pass Criteria

- Same as AoA Receiver Tests. Refer to 4.2.2.1
- Test Repetition
- Same as AoA Receiver Tests. Refer to 4.2.2.1

4.3.2.2 IQ Samples Dynamic Range (Test Spec Chapter 4.5.39.1, RF-PHY/RCV/IQDR/BV-07-C) (Test Spec Chapter 4.5.39.2, RF-PHY/RCV/IQDR/BV-08-C) (Test Spec Chapter 4.5.39.3, RF-PHY/RCV/IQDR/BV-09-C) (Test Spec Chapter 4.5.39.4, RF-PHY/RCV/IQDR/BV-10-C)

Test Purpose

Verifies that the I/Q samples on the AoD CTE have specified values when varying the dynamic range of the CTE.

CMW Settings

Conf. Field	Setting*
PHY	1 Mbps (for TC07/08) | 2 Mbps (for TC09/10)
Channel	0 (lowest) | 19 (middle) | 39 (highest)
Tx Level (CMW)	-52 dBm
Payload Length	0
CTE Type	AoD
CTE Unit	20
Slot Duration (CMW)	1µs (for TC08/10) | 2µs (for TC07/09)

* Refer to Table 4-3 for the rest of the CMW settings

RF power level offsets given in Table 4-4**Fehler! Verweisquelle konnte nicht gefunden werden.** between the reference antenna and non-reference antenna needs to be configured on CMW. Details refer to the description in 4.2.2.2

Execute Test

- Same as AoA Receiver Tests. Refer to 4.2.2.2

Pass Criteria

- Same as AoA Receiver Tests. Refer to 4.2.2.2

Test Repetition

- Same as AoA Receiver Tests. Refer to 4.2.2.2

4.4 Test Automation

Test automation can be achieved by utilizing R&S® CMWrun and optionally R&S® OSP in addition to improve the test efficiency. The automation test setups are described in Chapter 3.1.

CMWrun is a software tool offered by R&S to enable the test automation, generate the test plan, collect and create the test results with final pass/fail verdict. In CMWrun, an off-the-shelf BLE 5.1 DF test plan 'BLE_RF_PHY_TS_5_1_1_DF' is provided. The test plan is implemented closely align with the Bluetooth SIG RF PHY Test Suite Revision RF-PHY.TS.5.1.1 [1]

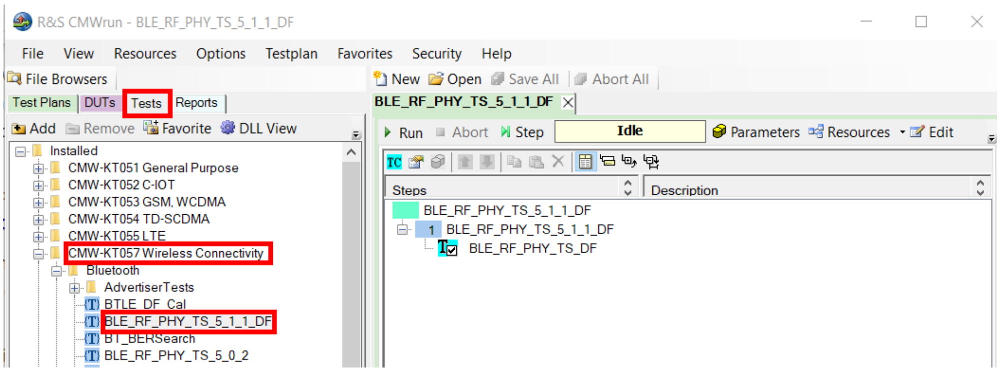


Fig. 4-31: BLE 5.1 DF Test Module in CMWrun

The BLE5.1 DF test module is selectable in CMWrun when CMW-KT057 Wireless Connectivity option is installed and licensed as shown in Fig. 4-31.

Starting from CMWrun V1.9.9, in addition to test setup 2, the setup 3 mentioned in Table 3-1 of Chapter 3.1 is supported. Therefore, with this feature extension, the AoD TX Antenna Switching Integrity RF-PHY/TRM/ASI/BV-05, (06, 07, 08)-C can be performed in full automatic way. The complete 23 BLE DF test cases shown in Fig. 4-32 are fully supported in CMWrun.

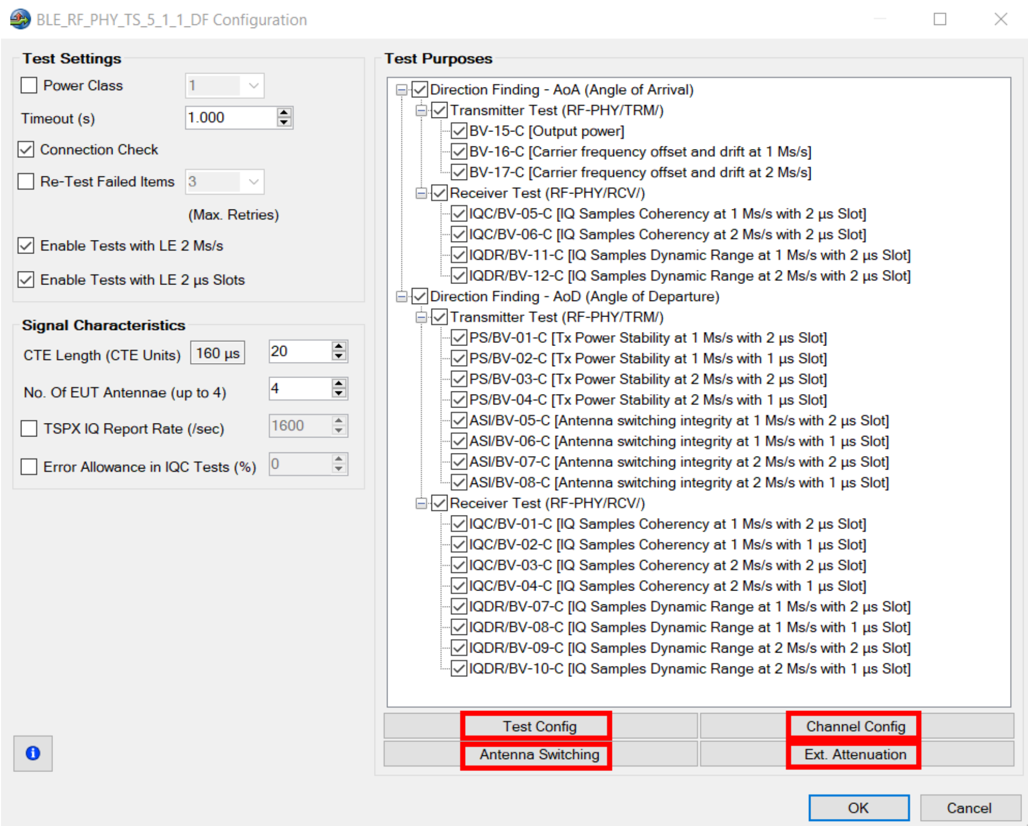


Fig. 4-32: 'BLE_RF_PHY_TS_5_1_1_DF' Test Module

Table 4-6 outlines the distribution of the transmitter and receiver test case numbers with respect to AoA and AoD.

	AoA	AoD
Transmitter (TRM)	3	8
Receiver (RCV)	4	8

Table 4-6: Number of BLE DF Test cases supported starting from CMWrun V1.9.9

"**Test Config**" button in Fig. 4-32 allows the configuration of the following parameters:

AoA Tx Tests (see Fig. 4-33)

- Statistic Count ; Range 1 - 1000
- Payload Length ; Range 0 - 255 bytes

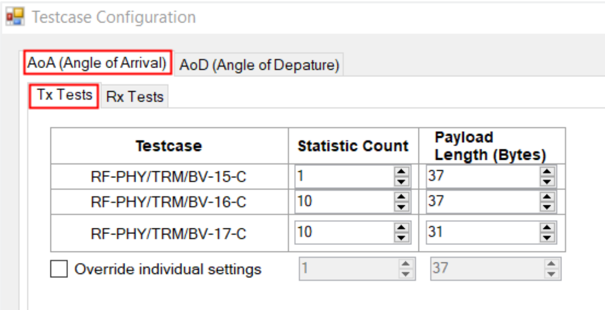


Fig. 4-33: Testcase Configuration | AoA Tx Tests

AoA Rx (see Fig. 4-34)

- TX Level at DUT input (default -67dBm for IQ Coherency; -52dBm Ant#0; -49dBm Ant#1; -57dBm Ant#2; -62dBm Ant#3 of IQ Dynamic Range)
- IQ sample pairs per Antenna ; 0 - 30,000 (default 10,000)
- Custom Payload Length ; 0 - 255 bytes (default 0 bytes)

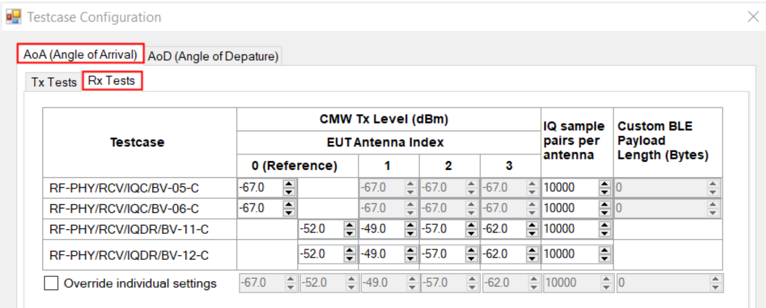


Fig. 4-34: Testcase Configuration | AoA Rx Tests

AoD Tx Tests (see Fig. 4-35)

- Statistic Count ; Range 1 - 1000 (default 1)
- Pattern Type ; All 0; All 1; P11; P44; PRBS9 (default pattern) where All 0 = 00000000 (Payload Type ..), All 1 = 11111111 (Payload Type ..), P11= 10101010 (Payload Type 0010), P44= 11110000 (Payload Type 0001) as defined in section 2.2
- Payload Length ; Range 0 - 255 bytes (default 0 bytes)

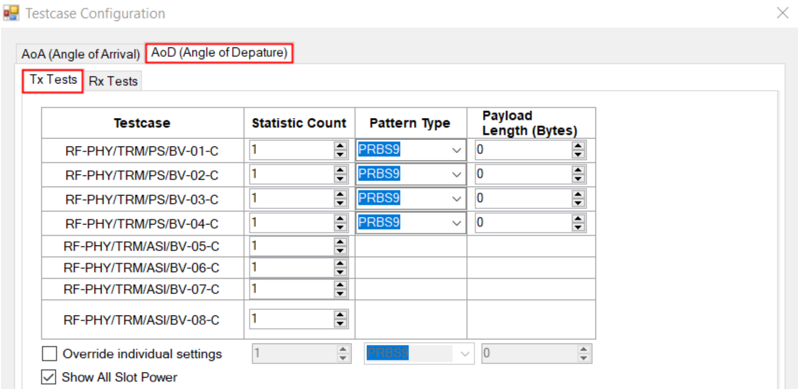


Fig. 4-35: Testcase Configuration | AoD Tx Tests

AoD Rx Tests (see Fig. 4-36)

- TX Level at DUT input (default -67dBm for IQ Coherency; -52dBm Ant#0; -49dBm Ant#1; -57dBm Ant#2; -62dBm Ant#3 of IQ Dynamic Range)
- IQ sample pairs per Antenna ; 0 - 30,000 (default 10,000)
- Custom Payload Length ; 0 - 255 bytes (default 0 bytes)

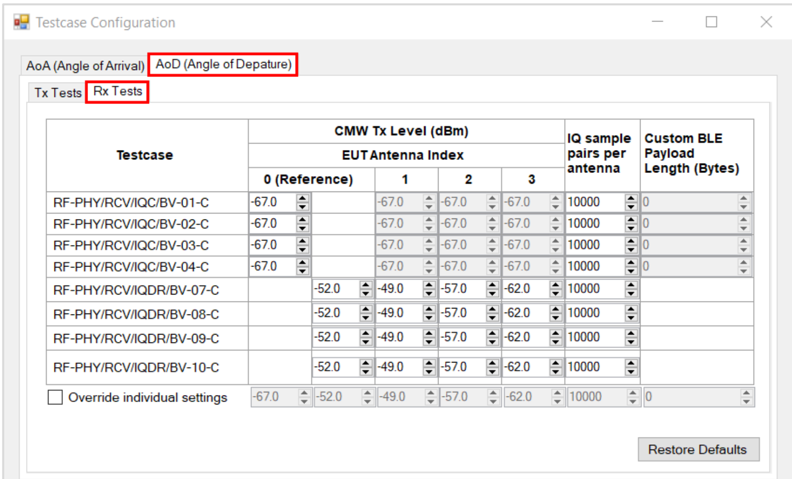


Fig. 4-36: Testcase Configuration | AoD Rx Tests

" **Ext. Attenuation**" button in Fig. 4-32 opens the configuration window Fig. 4-37 where the attenuation offset values between reference antenna and non-reference antenna can be entered. To obtain the offset values, follow the steps described in Chapter 4.1.1.

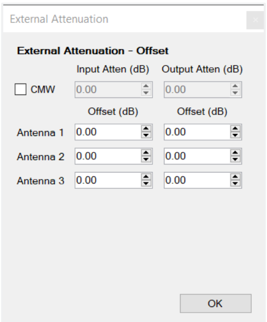


Fig. 4-37: Setting of External Attenuation Offset

" **Channel Config**" button in Fig. 4-32 opens the configuration window Fig. 4-38 where test mode can be chosen between single test and loop test. As long as the single test is selected, the Tx Channel for testing can be entered. Default one is Channel Low = 0, Channel Mid = 19, Channel High = 39.

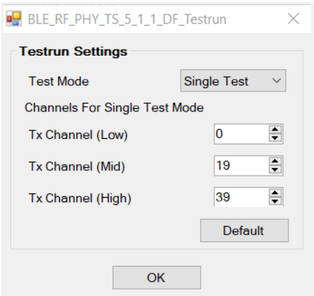


Fig. 4-38: Settings of Channel Config

" **Antenna Switching**" button in Fig. 4-32 opens the configuration window Fig. 4-39 where either the manual or automatic switching using OSP can be chosen.

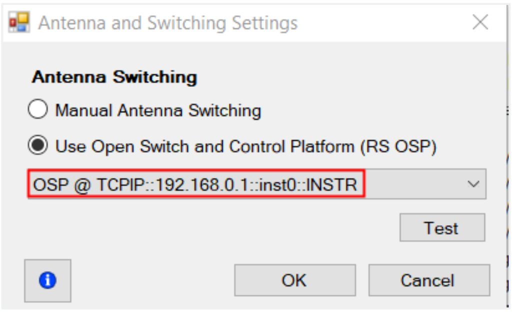


Fig. 4-39: Antenna and Switching Settings

In case the automatic switching is chosen, select the OSP in the drop down menu. For doing that, the SCPI connection from CMWrun to OSP has to be defined beforehand. For doing that, goto Recources > SCPI Connections… from CMWrun main GUI. In window shown in Fig. 4-40, select OSP and configure this connection, e.g. by giving the IP address of the OSP.

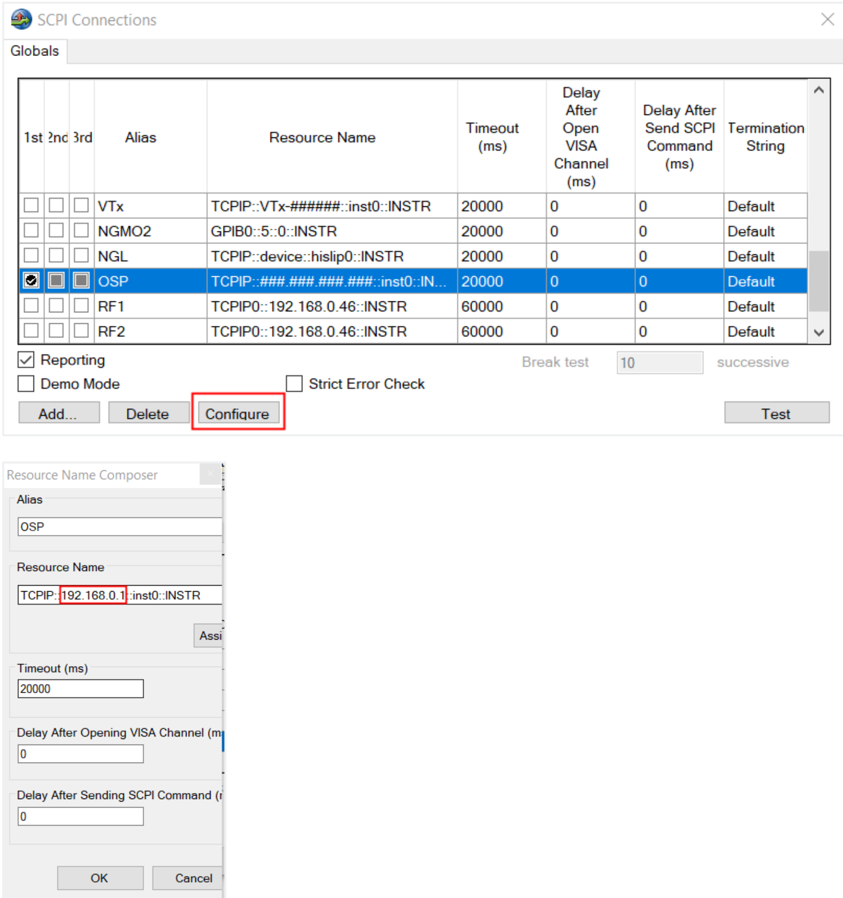


Fig. 4-40: Resource Configuration

5 Revision History

Revision	Date	Comment
0e	2019/10/30	Initial version based on BLE5.1 RF specification RF-PHY.TS.5.1.0
1e	2020/05	Update according to BLE5.1 RF specification revision RF-PHY.TS.p15 OSP support in CMWrun v.1.9.9 CMW Bluetooth Signaling Firmware GUI update according v.3.7.90

6 Literature

[1] Bluetooth 5.1 Radio Frequency Physical Layer (RF PHY) Revision: RF-PHY.TS.p15, Revision Date: 2020-01-07

[2] Bluetooth 5.1 Core specification

[3] R&S White Paper, 1MA108 Bluetooth White Paper

[4] R&S Application Note, 1MA282 Bluetooth Low Energy (V5.0) RF-Test for Internet of Things Applications

[5] R&S Application Note, 1C105 Configuration of the R&S CMW for Bluetooth Low Energy Direct Test Mode

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Regional contact

Europe, Africa, Middle East
+49 89 4129 12345
customersupport@rohde-schwarz.com

North America
1 888 TEST RSA (1 888 837 87 72)
customer.support@rsa.rohde-schwarz.com

Latin America
+1 410 910 79 88
customersupport.la@rohde-schwarz.com

Asia Pacific
+65 65 13 04 88
customersupport.asia@rohde-schwarz.com

China
+86 800 810 82 28 |+86 400 650 58 96
customersupport.china@rohde-schwarz.com

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Rohde & Schwarz GmbH & Co. KG
Mühldorfstraße 15 | 81671 Munich, Germany
Phone + 49 89 4129 - 0 | Fax + 49 89 4129 – 13777

www.rohde-schwarz.com