Application Note

HRP UWB TESTING WITH CMP200 RADIO COMMUNICATION TESTER

Products:

► R&S®CMP200

The UWB (Ultra-Wide Band) technology is a low power wide-band technology specified for device to device communication. It is an optimal RF positioning technology that enables accurate and secure peer-to-peer distance measurement between mobile devices with robust resistance to interference while consuming very low energy and coexisting well with other radio communication systems.

This application note describes how to use the UWB measurement functionality provided by R&S®CMP200 radio communication tester to perform HRP UWB PHY measurements for R&D and production purposes.

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Contents

1 Introduction

Core UWB services as define by the FiRa™ Consortium are hands-free access control, location-based services and device-to-device services. Key element of the UWB (Ultra-Wide Band) technology is the measurement of the distance between devices and their relative positions with a high level of accuracy and security. In addition, the wide bandwidth of the UWB signal secures robust resistance to interference in multi-path fading environments both indoor and outdoor while consuming very low energy. There are already multiple technologies to determine the positions of mobile devices including GPS, cellular, Bluetooth, and Lidar, but the fact that UWB uses direct peer-to-peer radio communication with accuracy to within only a few centimeters and its ultra-wide bandwidth nature makes it a very popular positioning technology especially in obstacle-prone indoor environments. In addition, UWB's very-low emitted power level ensures its comfortable coexistence with other existing radio communication systems.

This application note starts with a brief overview of the UWB technology and then provides a step-by-step guide on how to perform UWB measurements on RF transmitter characteristics and receiver characteristics using CMP200 according to the IEEE 802.15.4-2020 [1] specification Chapter 15.4 "RF Requirements" plus how to perform ToF (Time of Flight) measurements with CMP200.

2 Overview of UWB Technology

2.1 IEEE 802.15.4 HRP UWB PHY

IEEE 802.15 specifies PHY details including the frequency ranges, data rates and modulation schemes. Two UWB physical layers are defined in IEEE 802.15.4-2020: HRP (high rate pulse) UWB and LRP (low rate pulse) UWB. The R&S®CMP200 supports the HRP UWB PHY.

According to IEEE 802.15.4z-2020 [3], an HRP enhanced ranging device (HRP-ERDEV) should support operation in the base pulse repetition frequency (BPRF) mode at the nominal 64 MHz PRF (Pulse Repetition Frequency) and the operation in a higher pulse repetition frequency (HPRF) mode, which has a data modulations with mean PRFs of 124.8 MHz or 249.6 MHz.

2.2 Operating Frequency Bands

Table 2-1 shows the carrier center frequencies for UWB signals defined in IEEE 802.15.4-2020 Chapter 15.4.1 "Operating frequency bands". The CMP200 supports band group 2 (high-band) channels above 6 GHz with a bandwidth of 499.2 MHz.

Table 2-1: UWB operating frequency bands

Band group	Channel	Frequency (MHz)	Bandwidth (MHz)	Mandatory/optional	CMP200 support
0	0	499.2	499.2	Sub-gigahertz	
1	1	3494.4	499.2	Low band	
	2	3993.6	499.2	Low band	
	3	4492.8	499.2	Low band mandatory	
	4	3993.6	1331.2	Low band	
2	5	6489.6	499.2	High band	Yes
	6	6988.8	499.2	High band	Yes
	7	6489.6	1081.6	High band	
	8	7488	499.2	High band	Yes
	9	7987.2	499.2	High band mandatory	Yes
	10	8486.4	499.2	High band	Yes
	11	7987.2	1331.2	High band	
	12	8985.6	499.2	High band	Yes
	13	9484.8	499.2	High band	Yes
	14	9984	499.2	High band	Yes
	15	9484.8	1354.97	High band	

2.3 UWB PHY Signal Properties

The HRP UWB PHY waveform is based on an impulse radio signaling scheme using band-limited data pulses. The duration of the impulse radio (IR) pulses for the UWB communications system is in the order of a two nanoseconds (2 ns) for the 500 MHz bandwidth signals. A combination of several IR pulses with variations in their positions and polarities represents one information symbol.

2.3.1 Baseband Impulse Response (UWB Waveform)

The reference UWB pulse r(t) is a root raised cosine pulse with a roll-off factor of $\beta = 0.5$. Mathematically this is defined as follows:

$$r(t) = \frac{4\beta}{\pi\sqrt{T_p}} \frac{\cos\left[(1+\beta)\,\pi t/T_p\right] + \dfrac{\sin\left[(1-\beta)\,\pi t/T_p\right]}{4\beta t/T_p}}{1-\left(4\beta t/T_p\right)^2}$$

where T_p is the inverse of the chip frequency. For better interoperability in ranging applications it is recommended to support a mode, which transmits pulses with minimum precursor energy.

Figure 2-1 is a compliant reference pulse example.

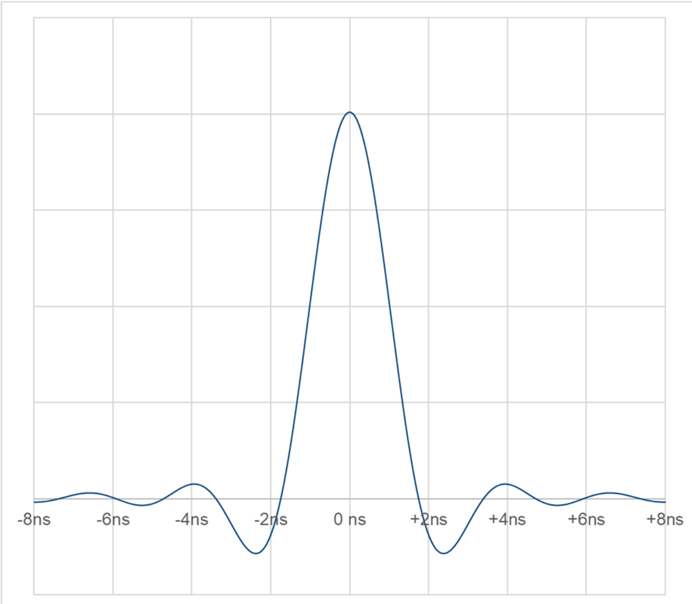


Figure 2-1: Compliant UWB reference pulse example

2.3.2 UWB PHY modulation

Figure 2-2 shows the structure and timing of an HRP UWB PHY symbol according to IEEE 802.15.4-2020. One burst (T_{burst}) of IR pulses is transmitted during the symbol duration (T_{dsym}), and the burst can occur in the first half of either of the two halves (T_{BPM}) of T_{dsym}, representing the first bit output from the convolution coder. Within T_{burst}, the polarity of the IR pulses represents the second bit output of the coder. A time-varying spreader sequence is used to generate the pulse sequence of the burst and to calculate the burst hopping position.

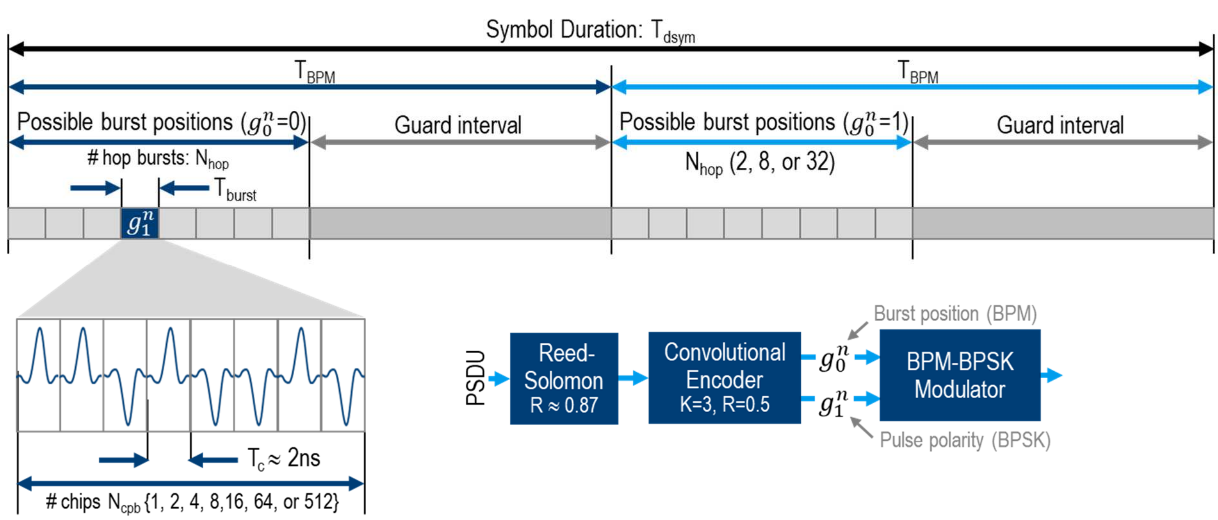


Figure 2-2: HRP UWB PHY symbol structure

2.3.3 UWB PHY packet (frame) structure

UWB devices communicate using the packet format illustrated in Figure 2-3. An HRP UWB PHY frame (PPDU) consists of a preamble part that contains the synchronization header (SHR) and a data part that contains a PHY header (PHR) and a PHY payload (PSDU). The SHR is comprised of the synchronization (SYNC) field constructed by preamble symbols and a start-of-frame delimiter (SFD) field which signals the end of the preamble. As a result, SFD is used to establish frame timing which is important for accurate ranging counting.

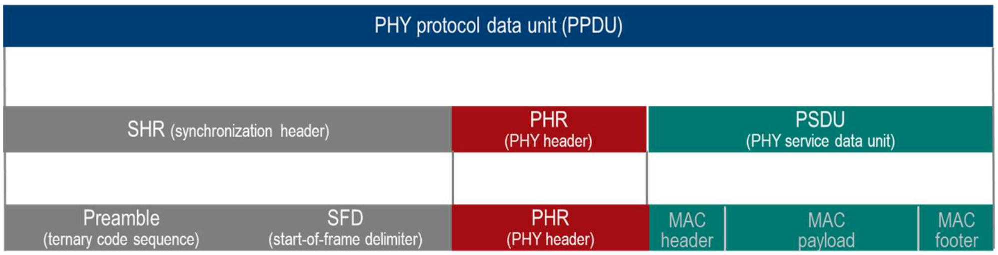


Figure 2-3: PHY packet structure

The preamble in the synchronization header (SHR) is a known sequence of pulses which is used for signal detection, synchronization, and the estimation of the channel impulse response (CIR). The PHR contains information required to decode the packet including the payload data rate and payload length.

The IEEE 802.15.4z-2020 amendment includes means to enhance the ranging device (RDEV) by defining additional modes associated with the HRP enhanced ranging device (HRP-ERDEV). The main PHY enhancements are the inclusion of the Scrambled Timestamp Sequence (STS) field in the basic HRP PPDU format, and increased pulse repetition frequency (PRF) during preamble and data field to improve timestamp robustness and security and to increase the accuracy of ranging measurements.

A device incorporating these modes is referred to as a higher rate pulse repetition frequency UWB PHY based enhanced ranging capable device (HRP-ERDEV) and defined in IEEE 802.15.4z-2020 Chapter 15.1 "General." Operation at the nominal 64 MHz pulse repetition frequency (PRF) is referred to as the base pulse repetition frequency (BPRF) mode. Operation at a higher PRF than the BPRF mode is referred to as the higher pulse repetition frequency (HPRF) mode.

The frame structure of HRP-ERDEV is shown in Figure 2-4 with the STS in different positions. STS packet configuration 0 specifies no STS field in the PPDU, which is the same as in IEEE 802.15.4a. In configuration 1, the STS field is placed immediately after the SFD field and before the PHR field, and in configuration 2, the STS field is placed after the PHY Payload field. In configuration 3, the STS field takes the place of PHR and PHY payload, and there are no PHR and data fields. The support for configurations 0, 1 and 3 are mandatory and configuration 2 is optional. The upward arrow shows the RMARKER (ranging marker) reference position for each configuration, which is the peak pulse location associated with the first chip following SFD.

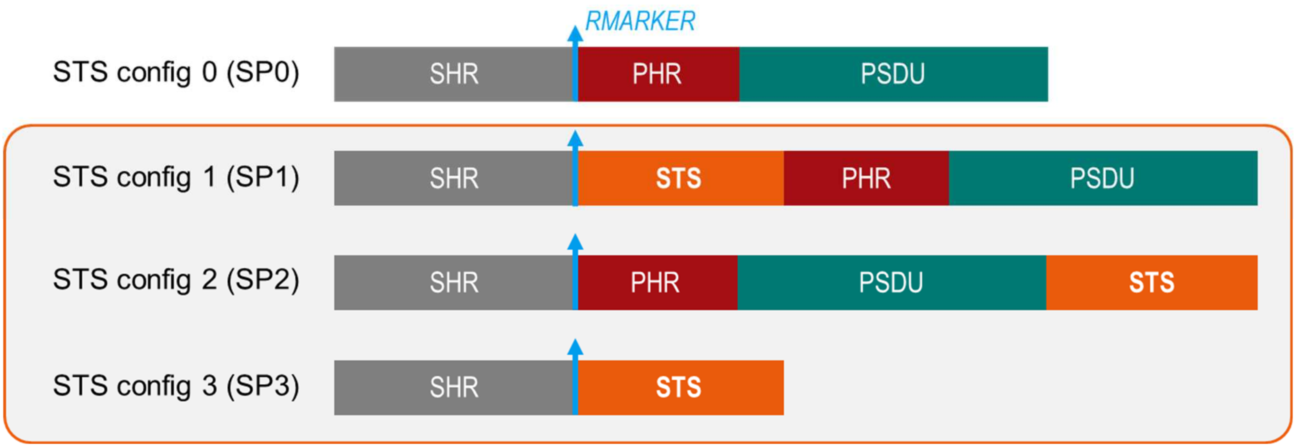


Figure 2-4: HRP-ERDEV UWB PPDU format

2.3.3.1 SYNC

Each preamble code is a sequence of pulses representing -1, 0, and +1. The preamble code is spread to construct a preamble symbol, and this preamble symbol is then repeated to constitute the SYNC field portion of the SHR as shown in the example in Figure 2-5. The SYNC field contains simple repetitions of the preamble symbol and the number of preamble symbol repetitions are 16, 64, 1024 and 4096 as defined in IEEE 802.15.4-2020. In HPRF mode (PRF > 64 MHz), the HRP-ERDEV shall support 32 and 64 preamble symbol repetitions with optional values being 16, 24, 48, 96, 128 and 256 as defined in IEEE 802.15.4z-2020 chapter 15.2.6.

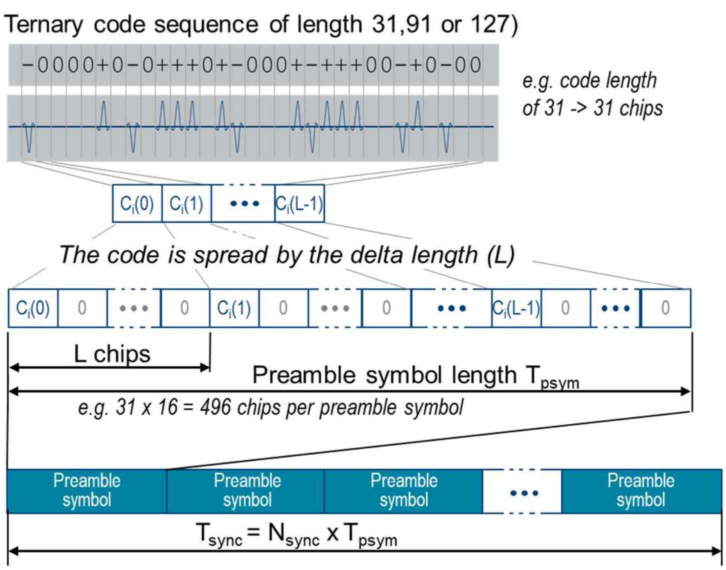


Figure 2-5: Preamble code & preamble symbol example

The HRP UWB PHY supports two lengths of preamble code in IEEE 802.15.4-2020 which are a length 31 code and an optional length 127 code, and IEEE 802.15.4z-2020 added a length 91 code. For example, the length 31 code sequences are shown in Table 2-2 where the + and - signs denote the phase of the pulse, and 0 means no pulse. Different code sequences which are indexed by code index can be assigned depending on the channel number.

Table 2-2: Length 31 ternary codes

Code index	Code sequence	Channel number
1	-0000+0-0+++0+-000+-+++00-+0-00	0, 1, 8, 12
2	0+0+-0+0+000-++0-+---00+00++000	0, 1, 8, 12
3	-+0++000-+-++00++0+00-0000-0+0-	2, 5, 9, 13
4	0000+-00-00-++++0+-+000+0-0++0-	2, 5, 9, 13
5	-0+-00+++-+000-+0+++0-0+0000-00	3, 6, 10, 14
6	++00+00---+-0++-000+0+0-+0+0000	3, 6, 10, 14
7	+0000+-0+0+00+000+0++---0-+00-+	4, 7, 11, 15
8	0+00-0-0++0000--+00-+0++-++0+00	4, 7, 11, 15

2.3.3.2 SFD (Start of Frame Delimiter)

SFD marks the end of the preamble and the start of PHR by breaking the preamble symbol pattern. The SFD signal is created by multiplying an SFD code with the preamble symbol, which is also used in the SYNC field. Table 2-3 shows the supported SFD sequences corresponding to the BPRF and HPRF modes a as defined in IEEE 802.15.4z-2020.

Table 2-3: SFD Codes for BPRF and HPRF

SFD#	SFD length	SFD Code	BPRF	HPRF
0	8	0 +1 0 -1+1 0 0 -1	Mandatory	n.a.
1	4	-1 -1 +1 -1	n.a	Mandatory
2	8	-1 -1 -1 +1 -1 -1 +1 -1	Mandatory	Mandatory
3	16	-1 -1 -1 -1 -1 +1 +1 -1 -1 +1 -1 +1 -1 -1 +1 -1	n.a	Mandatory
4	32	-1 -1 -1 -1 -1 -1 -1 +1 -1 -1 +1 -1 -1 +1 -1 +1 -1 -1 -1 +1 +1 -1 -1 -1 +1 -1 +1 +1 -1 -1	n.a	Optional

2.3.3.3 Data

The PHR and PSDU symbols are modulated using a combination of burst position modulation (BPM) and binary phase-shift keying (BPSK). Each symbol is composed of an active burst of UWB pulses and can carry two bits from the convolutional encoder.

In the BPRF mode, the systematic bit output is used to determine the position of a burst of pulses (whether in the 1st or 2nd half of the symbol), while the parity bit is used for the polarity of the burst. Various data rates are supported by using variable-length bursts.

In HPRF mode, modulation at 249.6 MHz PRF and at 124.8 MHz PRF are supported. The systematic bit output of the encoder together with the parity bit output bit determine the parity of the pulse sequences at the first and second burst position (4 pulses over 4 chips or 8 pulses spread over 16 chips) . The mapping of symbols from the outputs of the convolutional encoder to burst polarities for the HPRF mode are specified in Tables 15-10c, 15-10d, 15-10e and 15-10f of IEEE 802.15.4z-2020 [3].

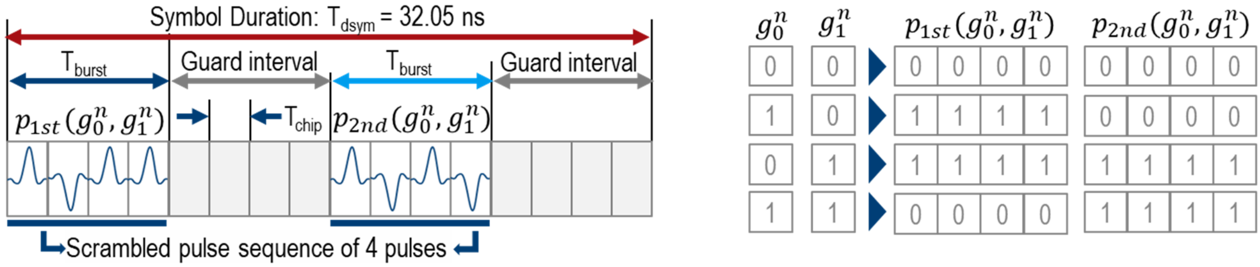


Figure 2-6: HPRF PSDU modulation @ Mean PRF of 249.6 MHz

2.3.3.4 PHR (PHY field)

The PHR field conveys the information necessary to decode the packet to the receiver including the following:

- Data rate used to transmit the PHY payload (BPRF)
- Length of PHY payload field (BPRF/HPRF)
- Ranging indicator (BPRF/HPRF)
- Preamble duration (BPRF)
- STS gap configuration (HPRF)

For the BPRF mode, the PHR is modulated using BPM-BPSK at 850 kb/s (or optionally at 6.8 Mb/s). For HPRF mode the PHR is modulated with the same data rates that apply for the PSDU.

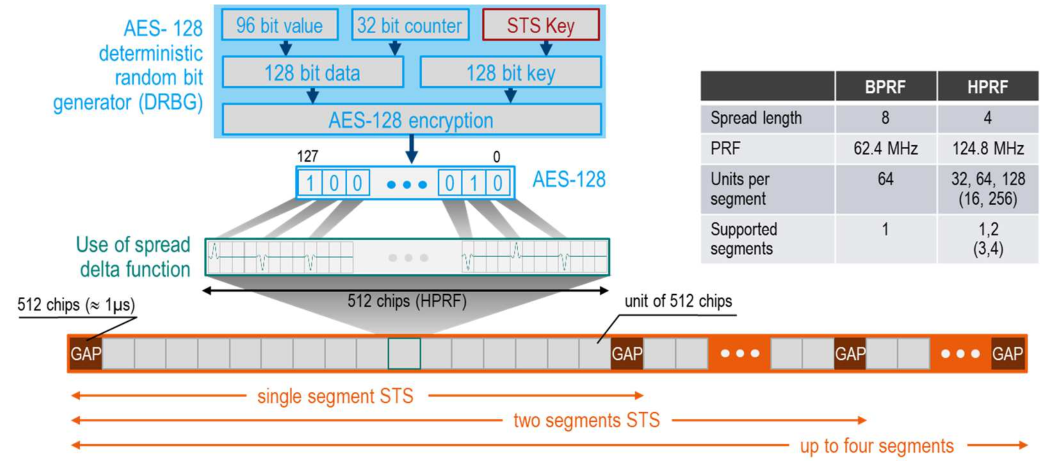
2.3.3.5 PSDU PHY Payload

The PHY payload field is sent at the data rate indicated in the PHR. Due to the variable code sequence lengths and the different corresponding pulse repetition frequencies (PRFs) in the preamble, there are several admissible data rates the UWB PHY can support. The supported data rates are defined in IEEE 802.15.4z-2020 Chapter 15.2.7 PHR field.

The MAC frames are passed to the PHY as the PSDU, which becomes the PHY payload as shown in Figure 2-3.

2.3.3.6 STS (Scrambled Timestamp Sequence)

IEEE 802.15.4z-2020 introduced a sequence of pseudo-randomly generated pulses called Scrambled Timestamp Sequence (STS) for enhanced ranging in HRP mode. This is generated using an AES128 based deterministic random bit generator (DRBG). Only valid transmitters and receivers know the key used to generate and correctly receive the sequence.



	BPRF	HPRF
Spread length	8	4
PRF	62.4 MHz	124.8 MHz
Units per segment	64	32, 64, 128 (16, 256)
Supported segments	1	1,2 (3,4)

Figure 2-7: Generation of STS segments

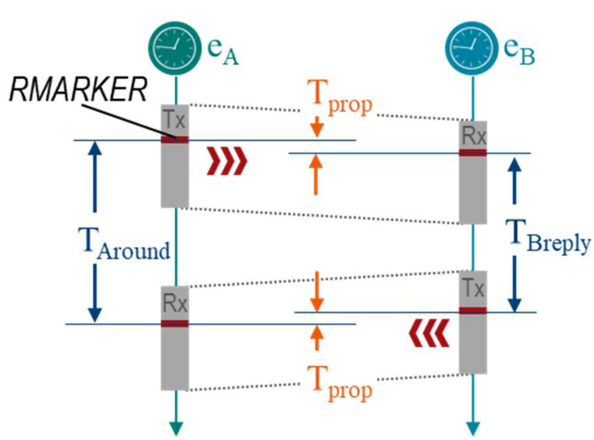
2.4 Ranging (Time of Flight)

To measure the distance between two devices, or Time of Flight (ToF), two-way ranging methods are used for UWB where the distance is obtained by multiplying the ToF with the speed of light. The benefit of the two-way-ranging method is that it can measure the wave propagation time, and thus can calculate the distance while not requiring accurate time alignment between the two devices. The IEEE 802.15.4z-2020 supports single-sided two-way ranging (SS-TWR) and double-sided two-way ranging (DS-TWR) which do not require time synchronization between devices.

2.4.1 Single-Sided Time of Flight measurement

SS-TWR involves a measurement of the round-trip delay of a single message from one device to another and a response sent back to the original device. The operation of SS-TWR is as shown in Figure 2-8, where device A initiates the exchange and device B responds to complete the exchange and T_{prop} is the propagation time of the RMARKER between the devices.

The times T_{Around} and T_{Breply} are measured independently by device A and B using their local clocks. This means that as long as each device's clocking cycle is precise (i.e., as long as each device can measure the time delta accurately) the distance can be calculated accurately because you are not measuring the absolute time, but comparing only the time lapses between the departure and arrival of the signal on each device.



$$T_{prop} = \frac{(1+e_A) \times T_{Around} - (1+e_B) \times T_{Breply}}{2}$$

$$\text{error} = 0.5\,(e_B \times T_{Breply} - e_A \times T_{Around})$$

$e_B;\ e_A$ – clock offset error

$$Distance = c_{AIR} \times T_{prop}$$

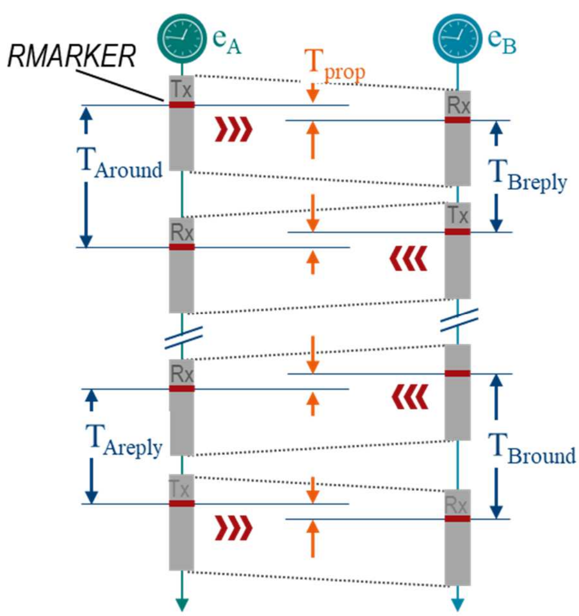
$$c_{AIR} = 29.97\ cm / ns$$

Figure 2-8: Single-Sided Time of Flight measurement

In case both devices have some clock frequency offset error e_A and e_B, respectively, from their nominal frequency, the resulting ToF estimate would have a considerable error that increases as the reply times get larger. However, if e_A and e_B can be obtained, this may be used to adjust the T_{prop} to improve the accuracy of SS-TWR as shown in Figure 2-8.

2.4.2 Double-Sided Time of Flight measurement

DS-TWR is an extension of the SS-TWR in which two round-trip time measurements are used and combined to give the ToF result with a reduced error in the presence of uncorrected clock frequency offset even for quite long response delays. This means it doesn't even require that the DUTs' clock frequencies should be precise as in SS-TWR. The operation of DS-TWR is shown in Figure 2-9, where device A initiates the first round-trip time measurement to which device B responds, after which device B initiates the second round-trip time measurement to which device A responds completing the full DS-TWR exchange. T_{prop} is the propagation time of the RMARKER between the devices.



$$\hat{T}_{prop} = \frac{T_{Around} \times T_{Bround} - T_{Areply} \times T_{Breply}}{T_{Around} + T_{Bround} + T_{Areply} + T_{Breply}}$$

$$Distance = c_{AIR} \times T_{prop}$$

$$c_{AIR} = 29.97\ cm / ns$$

Figure 2-9: Double-Sided Time of Flight measurement

3 UWB Measurement with CMP200

3.1 IEEE 802.15.4-2020 RF Test Items

UWB RF test items are explained in IEEE 802.15.4-2020 Chapter 15.4 RF requirements.

3.1.1 Measurement Configuration

3.1.1.1 Physical Setup

Figure 3-1 shows a basic physical setup for UWB measurements. The RF In/Out ports are connected to the TX/RX ports of the DUT. Since CMP200 is a non-signaling mode tester, DUT needs to be controlled through the DUT control driver interfacing the control PC. The specific DUT that was used in this example is Qorvo's DW3000. The graphical user interface embedded in CMP200 can be accessed through the DHCP IP address of the CMP200 on any Web browser of the control PC.

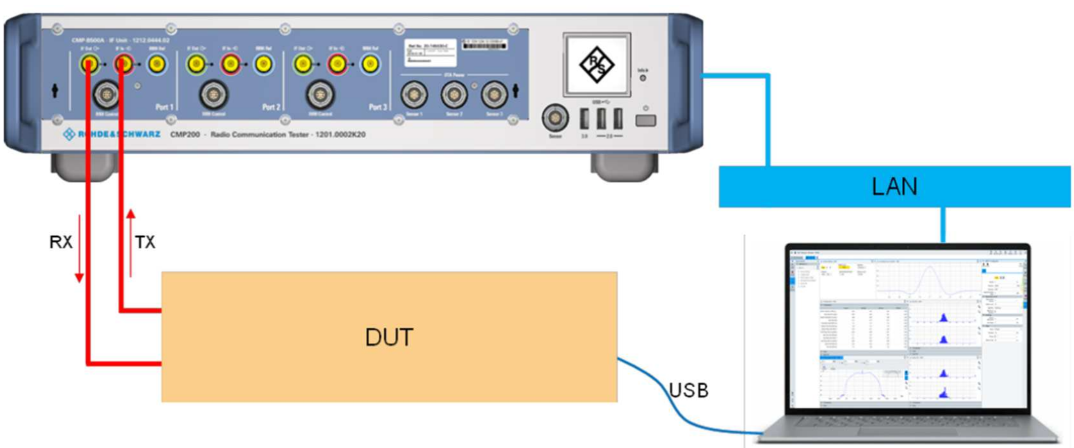


Figure 3-1: UWB measurement setup

3.1.1.2 DUT Configuration: TX Measurement

As Figure 3-2 shows, open the DW3000 control GUI (Decaranging_C0_3P10.exe) and put it into the TX mode by selecting Role = Tag. On configuration interface, parameters such as channel, preamble code, preamble length, SFD type, STS configuration, PHR mode, Pulse Repetition Frequency, Data Rate and PAC size need to be configured.

In this example,

Channel Selection = 5

Preamble Length = 128

SFD Type = 8 STD

STS configuration = OFF

PHR mode = standard (850 kbps)

Preamble code = 9

Pulse Repetition Frequency = 64 MHz

Data Rate = 6.81 Mbps

PAC size = 8

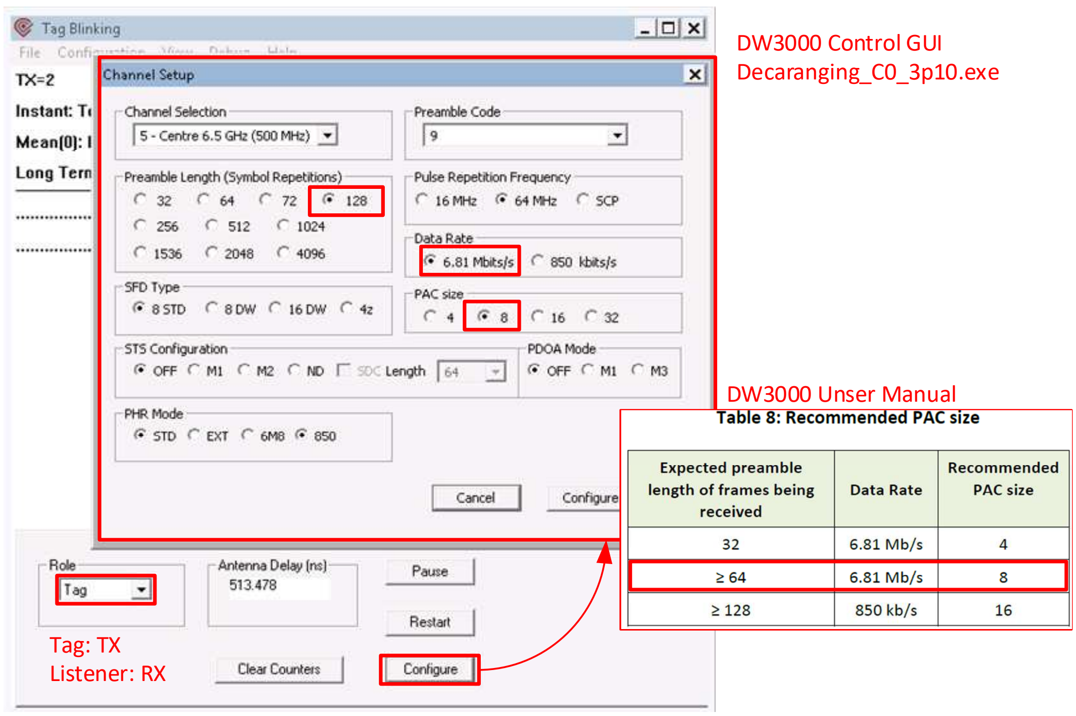


Figure 3-2: DUT configuration (DW3000)

The following are the meanings of the channel setup parameters. More details about the parameters are found in the DW3000 user manual and PC user guide [4].

SFD (Start of Frame Delimiter): Marks the end of the preamble and the precise start of the switch into the BPM/BPSK modulation of the PHR.

STS (Scrambled Timestamp Sequence): In addition to the problem of preamble search in HRP, the new IEEE 802.15.4z-2020 has also introduced a sequence of randomly generated pulses referred to as Scrambled Timestamp Sequence (STS) for enhanced ranging in HRP mode.

SDC (Super Deterministic Code): The Super Deterministic Code (SDC) can be used with STS, this means that the two units do not need to have the STS KEY/IV pairs synchronized. The STS code is a pre-programmed code inside the DW3000. The STS KEY and IV are ignored in this case.

PAC (Preamble Acquisition Chunk): The preamble sequence is detected by cross-correlating in preamble acquisition chunks (PACs) which are a number of preamble symbols long. Preamble acquisition chunk size, this should be set to 8 or 4 when preamble length is <=128, to 16 for preamble length of 256 and 32 for greater preamble lengths.

PHR (PHY header): A 19-bit section of the IEEE 802.15.4 frame that comes directly after the SFD and before the message payload and defines various characteristics of that payload required by the receiver for successful reception.

PDOA (Phase Difference of Arrival): If the packet contains an STS, depending on the configured mode, the device can compute the PDoA from either the preamble, STS or both.

3.1.1.3 CMP200 Configuration

Figure 3-3 is a snapshot of the CMSquares, CMP200's user GUI, with the UWB TX measurement items enabled.

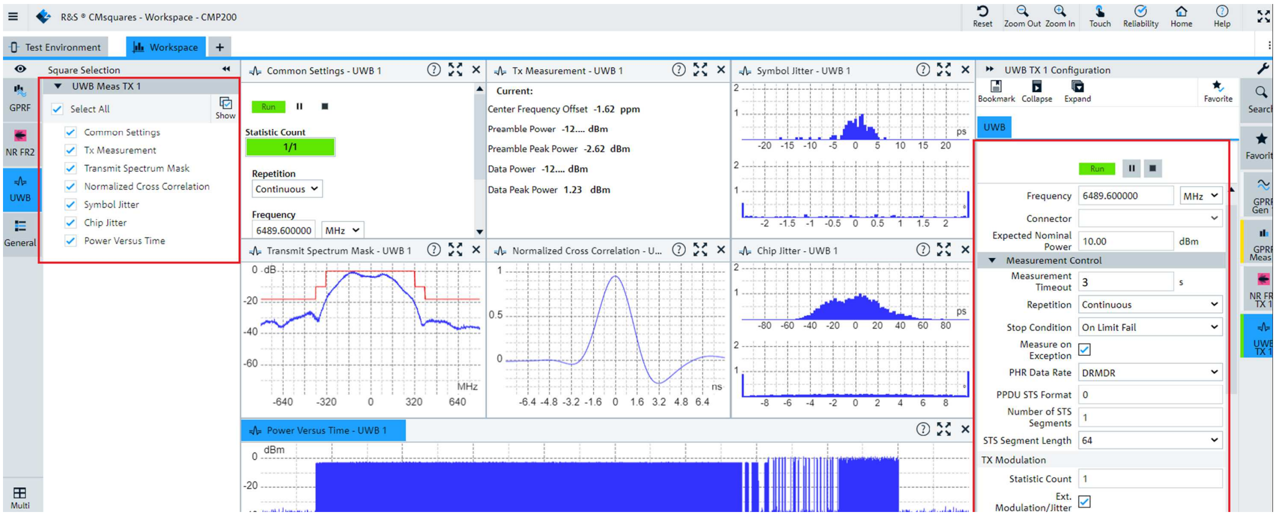


Figure 3-3: CMSquares: CMP200 User GUI

As in Figure 3-4, enable CMSquares via "Workspace" > "Square Selection" > "UWB" button > "UWB Meas TX n" section.

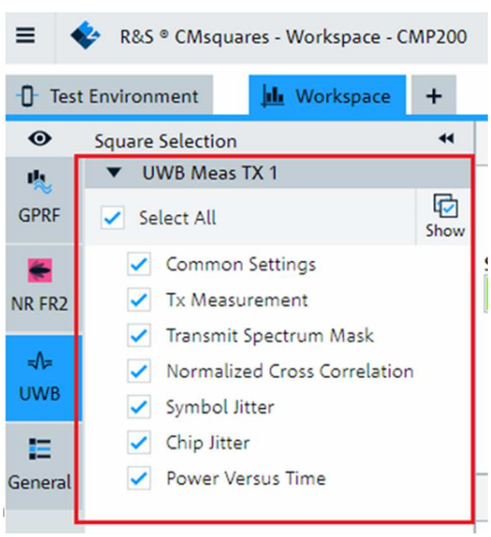


Figure 3-4: Enable UWB Meas TX

Configure the UWB TX measurement configuration section found on the right-most side of CMSquares as shown in Figure 3-5. The configuration must correspond to the settings on DUT in 3.1.1.2 DUT Configuration.

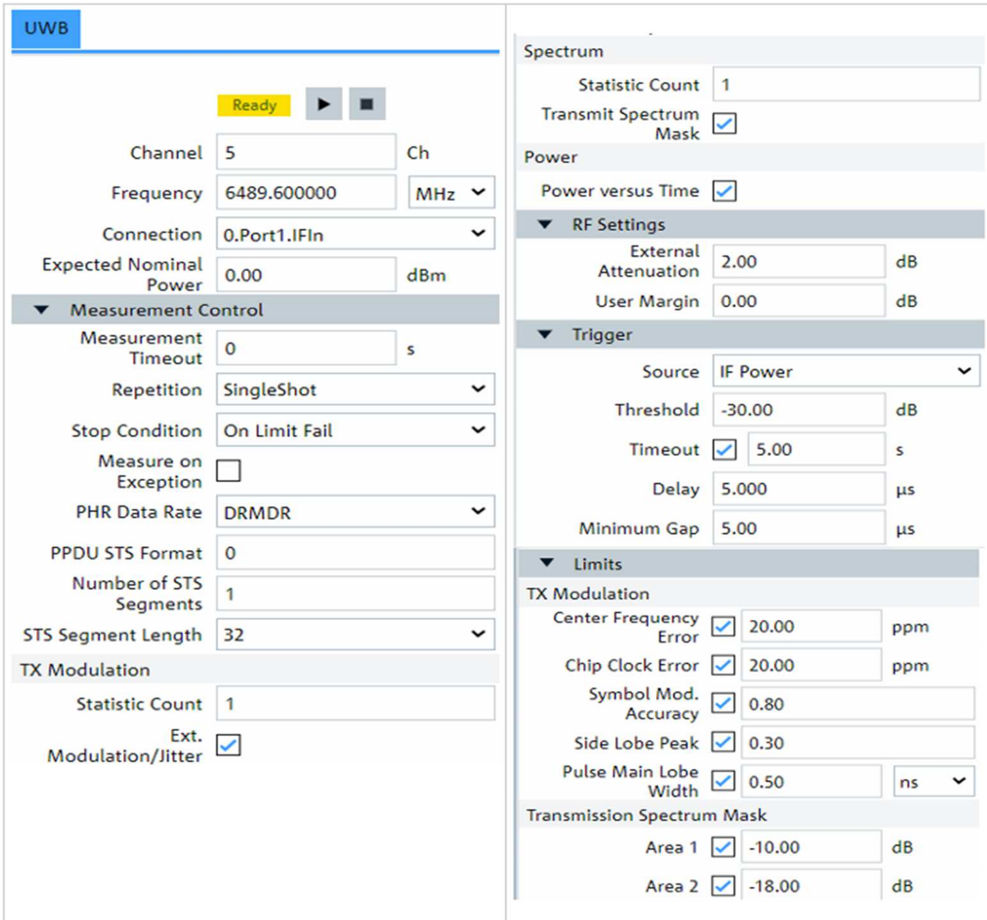


Figure 3-5: UWB TX Measurement Configuration

3.1.1.4 CMP200 Configuration: packet configuration parameters

Among the UWB configurations, the four parameters shown in Figure 3-6 need to be correctly configured to enable proper header decoding.

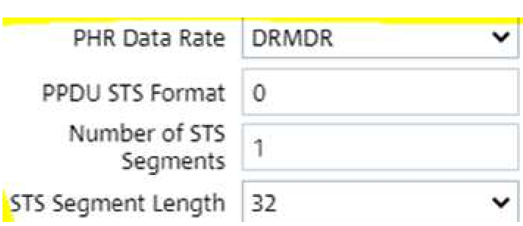


Figure 3-6: Packet Configuration

3.1.1.4.1 PHR & Data Rate

DRMDR (as per legacy IEEE 802.15.4-2020):

► Case 1: PHR bit rate of 110 kb/s and payload (data rate) of 110 kb/s.

► Case 2: PHR bit rate of 850 kb/s and payload (data rate) of >= 850 kb/s

The two parameters below are for BPRF (Base Pulse Repetition Frequency operating at nominal 64 MHz PRF (pulses/sec)).

DRBM_LP: PHR bit rate of 850 kb/s and payload (data rate) bit rate of 6.8 Mb/s

DRMDR_HP: PHR bit rate of 6.8 Mb/s and payload (data rate) bit rate of 6.8 Mb/s

For the DUT channel configuration in this example, DMRDR or DMBM_LP can be set for PHR Data Rate since PHR bit rate = 850 kb/s, Data rate = 850 kb/s and Pulse Repetition Frequency = 64 MHz.

3.1.1.4.2 PPDU STS Format

STS Format 3: In case there's no header or payload (if there's no need to decode header)

If you set STS format to 3 (no PHR), since the header is not decoded (thus no payload data decoding is performed), the analysis is done only on the preamble, and the data power appears as NCAP in the power measurement.

▼ Power

	Current	Average	Min	Max	Std Dev
Preamble Power [dBm]	-28.51	-28.48	-28.54	-28.43	0.04
Preamble Peak Power [...	-20.39	-20.37	-20.49	-20.26	0.05
Data Power [dBm]	NCAP	NCAP	NCAP	NCAP	NCAP
Data Peak Power [dBm]	NCAP	NCAP	NCAP	NCAP	NCAP
Max. Spectral Power [d...	-54.16	-54.11	-54.16	-54.03	0.03

▼ Signal Information

Data Rate	PHR Checksum	Sync Symbols	Code Sequence L...	PSDU Length	Delta Length	Code Index
NCAP	NCAP	64 Sym	91	NCAP	4	25

If STS is set to non-3 value (0, 1, 2), the header (PHR) decoding is performed and the data power is measured.

▼ Power

	Current	Average	Min	Max	Std Dev
Preamble Power [dBm]	-28.52	-28.49	-28.54	-28.45	0.04
Preamble Peak Power [...	-20.36	-20.34	-20.49	-20.21	0.09
Data Power [dBm]	-30.93	-30.95	-30.97	-30.93	0.01
Data Peak Power [dBm]	-18.58	-18.70	-18.86	-18.58	0.09
Max. Spectral Power [d...	-54.06	-54.04	-54.07	-53.99	0.03

▼ Signal Information

Data Rate	PHR Checksum	Sync Symbols	Code Sequence L...	PSDU Length	Delta Length	Code Index
6.81 Mbit/s	Pass	64 Sym	91	5 Byte	4	25

Note: The spectrum measurement and power tracing are done over the whole packet (Preamble + Header + STS + Payload). The measured power is the average power over the whole packet period which includes both pulses and empty space.

3.1.1.4.3 Number of STS Segments

The number of STS segments is configured as per the value of number of segments specifier according to Table 15-9f of IEEE 802.15.4z-2020 (Table 3-1).

Table 3-1: STS number of segments configuration

Value of number of segments specifier	Selected number of STS segments in transmitted or expected in the receiver
0	1
1	2
2	3
3	4

3.1.1.4.4 STS Segment length

The STS segment length is configured as per the value of segment length specifier according to Table 15-9e of IEEE 802.15.4z-2020 (Table 3-2).

Table 3-2: STS segment length configuration

Value of segment length specifier	Selected length of active STS segment in units of 512 chips (~1µs)
0	16
1	32
2	64
3	128
4	256

3.1.2 Baseband impulse response (Normalized Cross Correlation)

3.1.2.1 Test specification

The transmitted pulse shape p(t) shall be constrained by the shape of its cross-correlation function with a standard reference pulse, r(t). The normalized cross-correlation between two waveforms is defined as follows:

$$\phi(\tau) = \frac{1}{\sqrt{E_r E_p}} Re \int_{-\infty}^{\infty} r(t) p^* (t + \tau) dt$$

where E_r and E_p are the energies of r(t) and p(t), respectively. The reference r(t) pulse used in the calculation of $|\phi(\tau)|$ is a root raised cosine pulse with a roll-off factor of β = 0.5.

Figure 3-7 shows the shapes of the UWB pulse, UWB reference pulse and their correlation. The integrity of the UWB pulse can be evaluated by measuring the shape of the correlation of the UWB pulse and the UWB reference pulse.

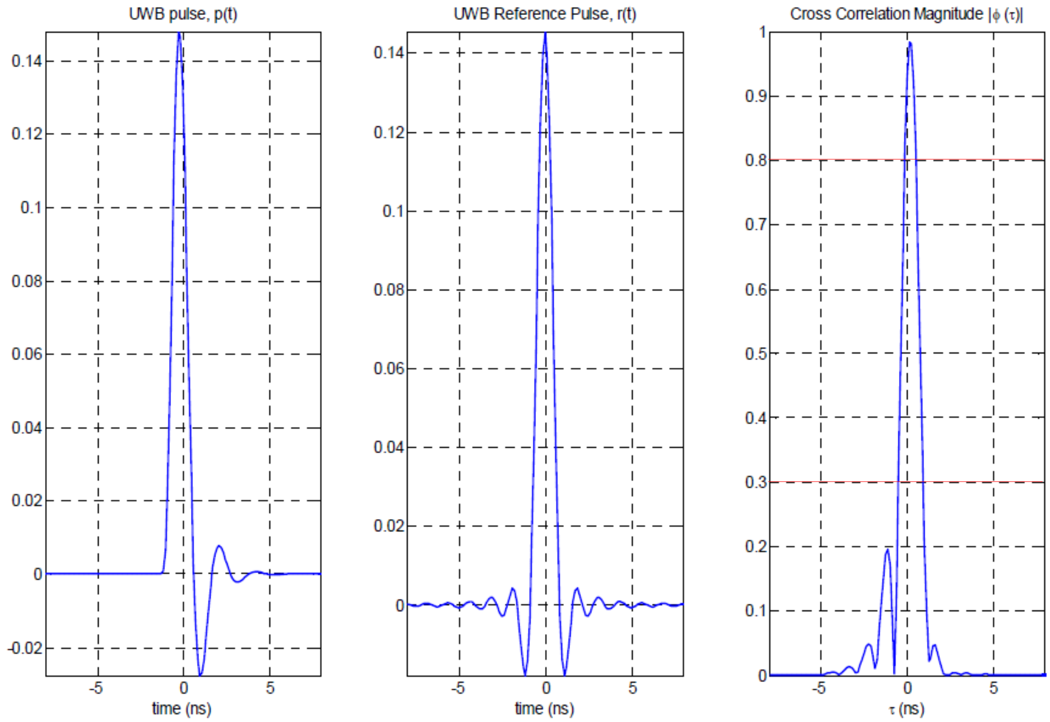


Figure 3-7: Compliant pulse example (based on 802.15.4)

According to IEEE 802.15.4-2020, in order for an HRP UWB PHY transmitter to be compliant with this standard, the transmitted pulse shall have a magnitude of the cross-correlation function whose main lobe is greater than or equal to 0.8 for a duration of at least T_w, as defined in Table 3-3, and any sidelobe shall be no greater than 0.3.

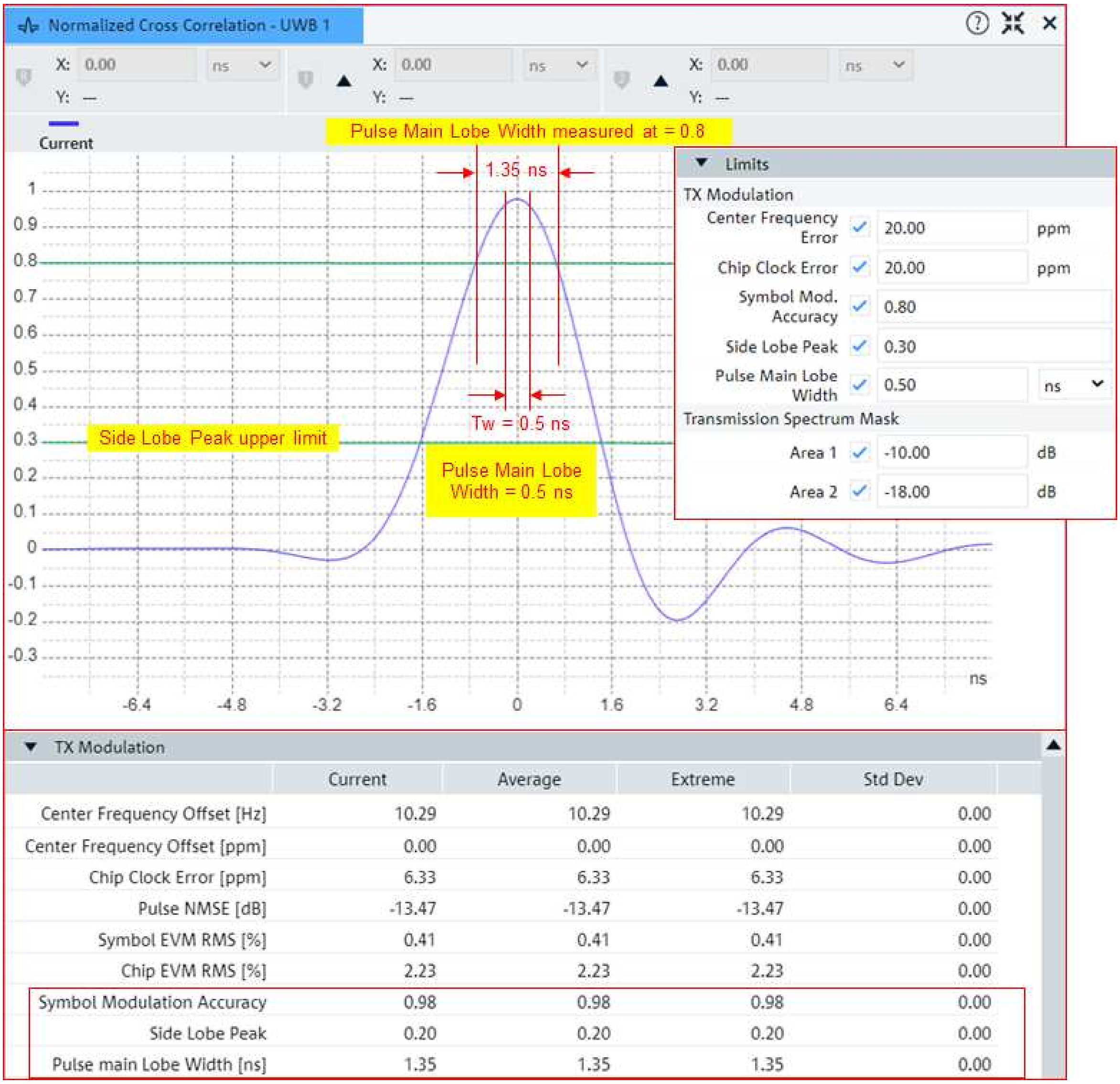
Table 3-3: Required reference pulse durations in each channel

Channel number	Pules duration T_p	Main lobe with, T_w
{0:3, 5:6, 8:10, 12:14)	2.00 ns	0.5 ns
7	0.92 ns	0.2 ns
{4, 11}	0.75 ns	0.2 ns
15	0.74 ns	0.2 ns

3.1.2.2 Test with CMP200

Configure the measurement according to 3.1.1 Measurement Configuration, and start the measurement by starting the measurement on CMSquares and starting the UWB signal transmission from the DUT.

Examine the measurement results in the "Normalized Cross Correlation" section of CMSquares. As seen in Figure 3-8, the UWB pulse of the DUT is displayed. The textual measurement results for this test item are expressed as Pulse Main Lobe Width [ns] and Side Lobe Peak. In the example of Figure 3-8, Pulse Main Lobe Width was measured as 1.35 ns for the duration above the cross-correlation of 0.8 against the lower limit of 0.5 ns and the Side Lobe Peak was measured as the cross-correlation of 0.20 against the upper limit of 0.3. Also available as an indicator of the signal integrity is Symbol Modulation Accuracy which is the magnitude of the cross correlation, $|\phi(\tau)|$, between the measured pulse and the reference pulse. In this example, Symbol Modulation Accuracy was measured as 0.98 against the lower limit of 0.8.



	Current	Average	Extreme	Std Dev
Center Frequency Offset [Hz]	10.29	10.29	10.29	0.00
Center Frequency Offset [ppm]	0.00	0.00	0.00	0.00
Chip Clock Error [ppm]	6.33	6.33	6.33	0.00
Pulse NMSE [dB]	-13.47	-13.47	-13.47	0.00
Symbol EVM RMS [%]	0.41	0.41	0.41	0.00
Chip EVM RMS [%]	2.23	2.23	2.23	0.00
Symbol Modulation Accuracy	0.98	0.98	0.98	0.00
Side Lobe Peak	0.20	0.20	0.20	0.00
Pulse main Lobe Width [ns]	1.35	1.35	1.35	0.00

Figure 3-8: Measurement of Normalized Cross Correlation on CMP200

3.1.3 Transmit Power Spectral Density (PSD) mask

3.1.3.1 Test specification

According to Chapter 15.4.5 Transmit PSD mask of IEEE 802.15.4-2020, the transmitted spectrum shall be less than –10 dB relative to the maximum spectral density of the signal for $0.65/T_p < |f - fc| < 0.8/T_p$ and –18 dB for $|f - f_c| > 0.8/T_p$. For example, the transmit spectrum mask for channel 9 is shown in Figure 3-9. The measurements shall be made using a 1 MHz resolution bandwidth and a 1 kHz video bandwidth.

Likewise, in the case of channel 5 as shown in Figure 3-10 with the PSD mask measurement by CMP200, the transmitted spectrum shall be less than -10 dBr between ±400 MHz (±0.8/T_p) and ±325 (±0.65/T_p) MHz from the center frequency, and less than -18 dBr in the regions farther than ±400 MHz from the center frequency.

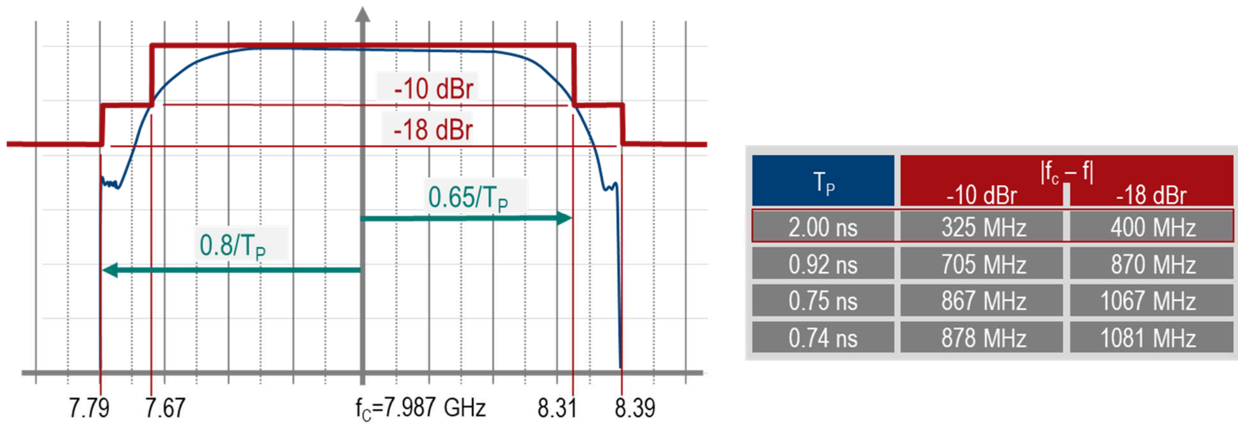


Figure 3-9: Transmit spectrum mask for channel 9 (499 MHz bandwidth)

3.1.3.2 Test with CMP200

Configure the measurement according to 3.1.1 Measurement Configuration, and start the measurement by starting the measurement on CMSquares and starting the UWB signal transmission from the DUT.

Examine the measurement results in the "Transmit Spectrum Mask" section of CMSquares. As seen in Figure 3-10, the UWB spectrum of the DUT is displayed. The graphical measurement results show the spectrum and the mask as set in the "Transmission Spectrum Mask" section of the Limits configuration. In this example, the spectrum is within the mask.

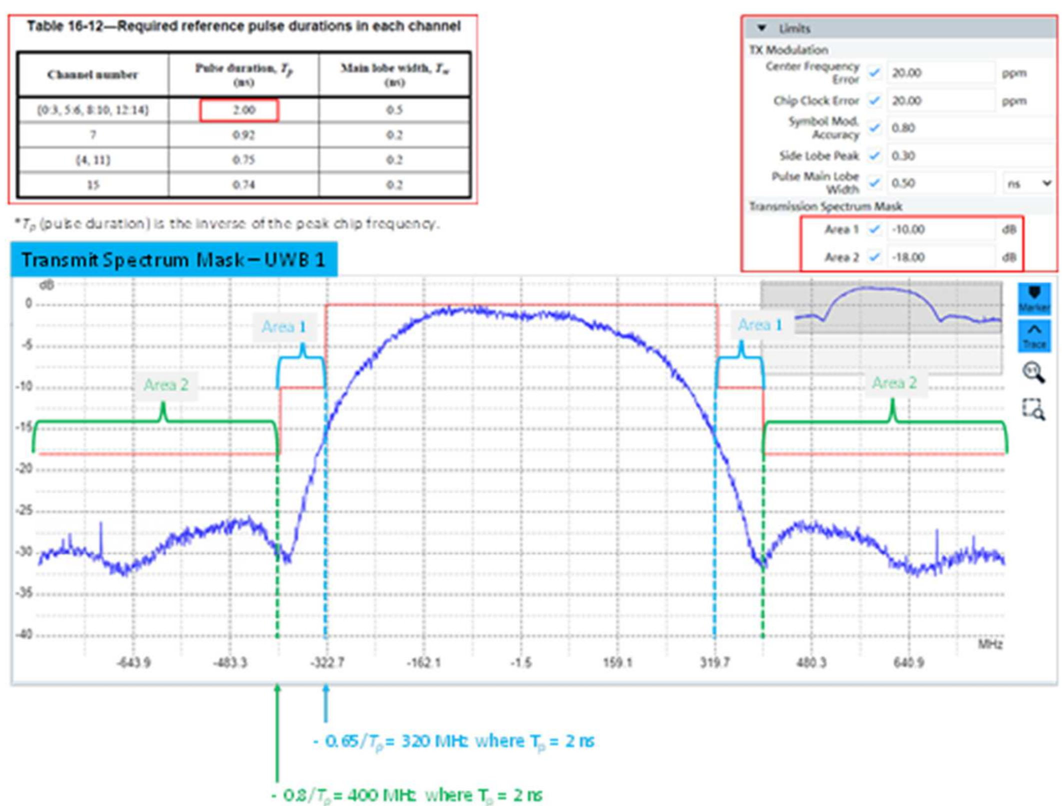


Figure 3-10: Transmit spectrum mask for band 5 (500 MHz bandwidth)

3.1.4 Chip Rate Clock and Chip Rate Carrier Alignment

3.1.4.1 Test specification

According to Chapter 15.4.6 Chip rate clock and chip carrier alignment of IEEE 802.15.4-2020, an HRP UWB transmitter shall be capable of chipping at the peak PRF of 499.2 MHz with an accuracy of ±20 $\times$ 10^{-6}. In addition, for each HRP UWB PHY channel, the center of transmitted energy shall be within the center frequency values listed in Table 2-1 also with an accuracy of ±20 $\times$ 10^{-6}. The measurements shall be made using a 1 MHz resolution bandwidth and a 1 kHz video bandwidth.

3.1.4.2 Test with CMP200

Configure the measurement according to 3.1.1 Measurement Configuration, and start the measurement by starting the measurement on CMSquares and starting the UWB signal transmission from the DUT.

Examine the measurement results in the textual data section under "Transmit Spectrum Mask" of CMSquares. Figure 3-11 shows the measured chip clock error is within the configured limit of 20 ppm.

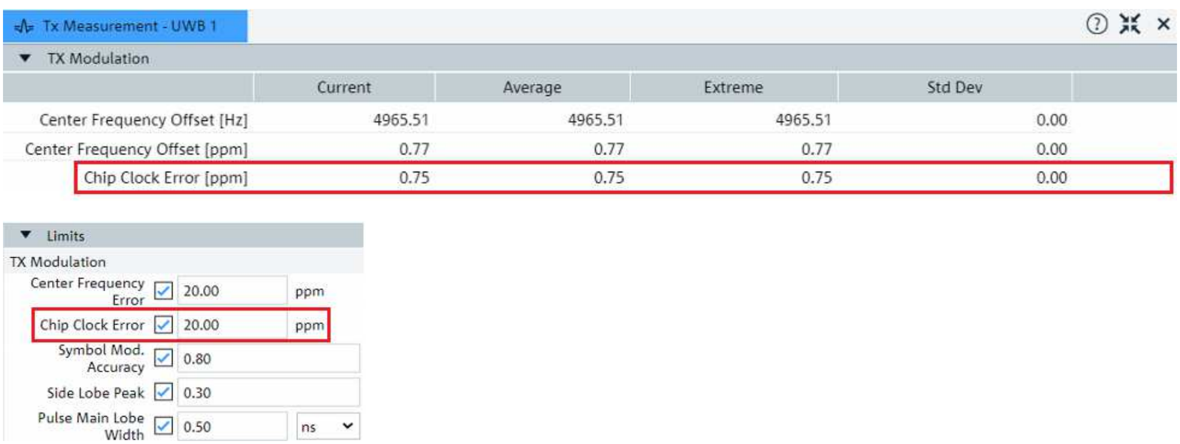


Figure 3-11: Chip clock error measurements

The chip clock error represents the measured signal's offset to the ideal peak PRF (499.2 MHz).

3.1.5 Transmit Center Frequency Tolerance

3.1.5.1 Test specification

Chapter 15.4.9 Transmit center frequency tolerance of IEEE 802.15.4-2020 specifies that the HRP UWB PHY transmit center frequency tolerance shall be ±20 $\times$ 10^{-6}, but it states that the tolerance on the chipping clock given in Chapter 15.4.6 takes precedence over this requirement.

3.1.5.2 Test with CMP200

Examine the measurement results in the textual data section under "Transmit Spectrum Mask" of CMSquares. Figure 3-12 shows the measured center frequency offset is within the configured limit of 20 ppm.

The center frequency offset represents the measured signal's frequency offset to the expected center frequency of the channel.

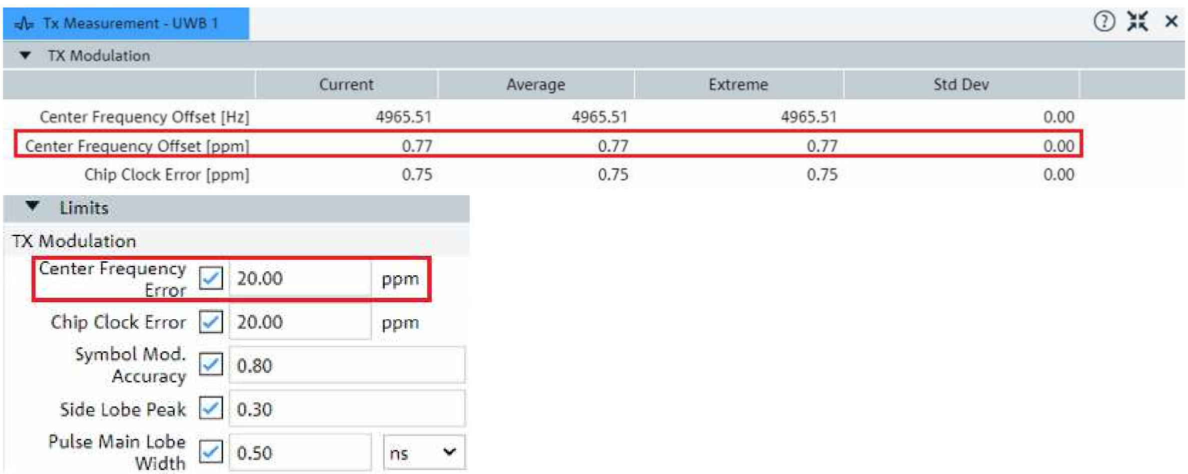


Figure 3-12: Center frequency offset measurements

3.2 Time of Flight Measurement with CMP200

ToF measurement with CMP200 means two things. The first is what is called "antenna delay calibration" or "analog frontend delay calibration," which is finding the roundtrip traveling time between the DUT’s antenna to the transceiver TX/RX block. The second is to validate the accuracy of the ToF measurement itself after the calibration.

T_{loop} is obtained by the CMP200 analyzer capturing the PPDU packets originating from the CMP200 and the DUT, and measuring the time distance between the RMARKERS of those packets. Since this is a non-signaling mode testing, the T_{reply} information is obtained through the DUT’s driver interface. Additionally, T_{reply} is corrected by compensating for the error in T_{reply} based on the frequency error in the DUT response signal. So from the RF signals, only the PPDU packets plus the DUT frequency error are detected, and no real-time packet decoding is used.

3.2.1 CMP200 TOF Measurement Concept

First, Figure 3-13 illustrates the concept of the single-sided two-way ranging (SS-TWR) performed with CMP200 and a DUT where CMP200 plays the role of another device.

Here, the coupler works as the timing reference, which means only the ToF of the right-hand side of the coupler, green T_f has to be known, and the right-hand side of the coupler can be either cable or over the air (OTA).

The benefit of this setup is that whatever time delay between the CMP200 including the internal paths to the coupler is automatically eliminated during the ToF calculation.

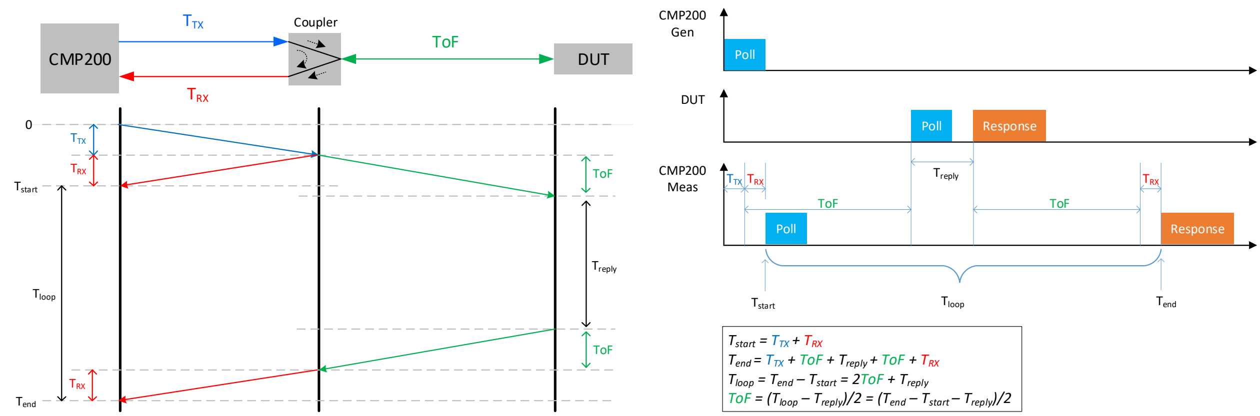


Figure 3-13: CMP200 TOF Measurement Concept

The measurement procedure is as follows:

1. CMP200 Analyzer is put into continuous-capturing mode.
2. CMP200 Generator transmits a poll packet.
3. CMP200 Analyzer begins to receive the poll packet routed back from the coupler at T_{start}.
4. The DUT receives the poll packet, too.
5. The DUT sends a response packet, and measures T_{reply}.
6. CMP200 Analyzer begins to receive the response packet from the DUT at T_{end}.
7. CMP200 Analyzer has received the packets from both CMP200 Generator and DUT.
8. T_{loop} is the interval between the RMARKES of the poll packet and the response packet at CMP200 Analyzer.
9. T_{reply} is the interval between the arrival of the poll packet and the departure of the response packet at DUT.
10. Calculate ToF from T_{loop} and T_{reply}.

The expected ToF can be calculated by using a known length of RF cable with a known velocity factor. Since a coupler (combiner) is used and both T_{start} and T_{end} include T_{TX} and T_{RX}, the time delay between CMP200 and the combiner ($T_{TX} + T_{RX}$) can be eliminated as shown in the equation to obtain ToF which, then, can be compared to the expected ToF for antenna delay calibration and verification.

$$
\begin{aligned}
&T_{start} = T_{TX} + T_{RX} \\
&T_{end} = T_{TX} + ToF + T_{reply} + ToF + T_{RX} \\
&T_{loop} = T_{end} - T_{start} = 2ToF + T_{reply} \\
&ToF = (T_{loop} - T_{reply})/2 = (T_{end} - T_{start} - T_{reply})/2
\end{aligned}
$$

The CMP200 poll packet is a special signal generated by the ARB Generator for both the DUT and for CMP200 Analyzer.

The group delays caused by the combiner module are also compensated for in the ToF calculation for further accuracy.

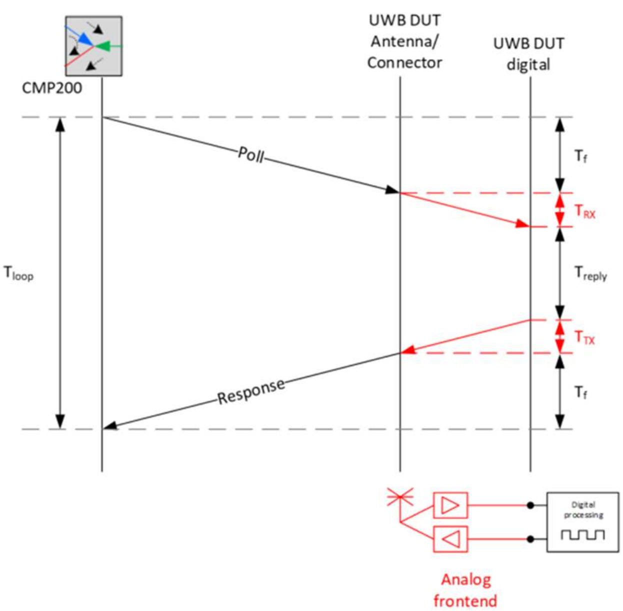
3.2.2 Antenna Delay Calibration through TOF measurement

3.2.2.1 Antenna delay calibration: implementation

The goal of antenna delay calibration is obtaining the aggregate antenna delay or analog frontend delay of the DUT ($T_{RX} + T_{TX}$) which is a DUT internal delay between the antenna and the transceiver.

In the ToF measurement concept in Chapter 3.2.1, the assumption was that the T_{reply} is the time delta between the arrival and departure of the signal at the DUT's antenna, but in reality, there is some time delay between the DUT's antenna and the digital block of the transceiver where the timestamps are generated to be used in measuring T_{reply}.

As seen in the diagram of Figure 3-14, this aggregate front-end time delay, $T_{RX} + T_{TX}$, can be calculated once we know the expected ToF which is obtained from the known length of cable and velocity factor.



Set DUT into anchor mode in order to respond on poll.

CMP200 sends poll packet.

DUT responds.

CMP200 measures T_{loop}.

Clock Error / Frequency Error is measured as well so that T_{Reply} can be corrected accordingly.

The analog frontend delay ($T_{RX} + T_{TX}$) can be calculated.

$$ToF_{expected} = (T_{loop} - T_{reply} - T_{RX} - T_{TX})/2$$

$$T_{RX} + T_{TX} = T_{loop} - T_{reply} - 2ToF_{expected}$$

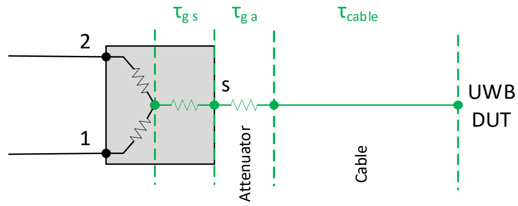
*$ToF_{expected}$ is obtained from the known cable length and velocity factor.

Figure 3-14: CMP-initiated antenna delay calibration

In addition to the traveling time along the cable, there is a group delay on the paths through the coupler and attenuator as shown in Figure 3-15. The group delay can be obtained by measuring the S-parameter group delay. The total delay due to this group delay and the cable between the coupler and the device represents the known ToF that is used in the ToF calculation.

Therefore, the only information we need for the setup is the group delay of the coupler-attenuator, $T_{gs} + T_{ga}$, and the length and velocity factor of the RF cable between the coupler and the DUT.

As a standard ToF measurement kit for R&S®CMP200, R&S®CM-Z300A provides the cables, splitter attenuator and their delay values which allows the ToF calibration. Hence, when CM-Z300A is used in the TOF measurement (Figure 3-15), a total delay of 1 ns has to be taken into account as the expected ToF. In case an additional cable or over-the-air path is added between CM-Z300A and the DUT, the expected ToF will be 1 ns plus the time delay of the additional path.



Component	Delay
2 x 2 m cable	Don't care
Power Splitter	T_{gs} = 120 ps
Attenuator	T_{ga} = 100 ps
Cable	T_{cable} = 780 ps
Overall chain	$T_{gs} + T_{ga} + T_{cable}$ = 1000 ps = 1 ns

Figure 3-15: CM-Z300A TOF measurement kit for CMP200

As illustrated in Figure 3-16, when the DUT antenna fronted delay, T_{RX} +T_{TX}, is calculated, the error in T_{reply} is also corrected by measuring the clock error of the DUT packet. Here, t(1) represents the time from the moment the PPDU packet is sent from the CMP200 generator (t = 0) to the moment it arrives at the CMP200 analyzer (t1), and t(2) represents the time lapse from t=0 to the moment the response packet from the DUT arrives at the CMP200 analyzer (t2).

The CMP200 gen packet at t(1) and DUT response packet at t(2) are captured in the PvT screen of CMP200 (Figure 3-19) and the intervals between them are measured in the form of the distance between the RMARKERS of the two packets.

Packet #	Packet belongs to	Chip Clock Error [ppm]	Center Freq Offset [ppm] (optional)	Packet Time [s]
1	CMP200	SFO(1)	CFO(1)	t(1)
2	DUT	SFO(2)	CFO(2)	t(2)

$$T_{loop} = t(2) - t(1) = T_f + T_{RX} + T_{reply} + T_{TX} + T_f$$

$$T_{RX} + T_{TX} = t(2) - t(1) - 2 \cdot T_f - T_{reply}$$

Corrected by the clock error of the DUT:

$$T_{RX} + T_{TX} = t(2) - t(1) - 2 \cdot T_f - \frac{T_{reply}}{1 + SFO_{DUT}}$$

$t(2) - t(1)$: Measurement result

$2 \cdot T_f$: known setup (ideally very small, see chapter 3.2)

SFO_{DUT} : Measurement result

T_{reply} : Number reported by DUT

$T_{RX} + T_{TX}$: result of the calibration. RX and TX can't be separated.

Figure 3-16: Calculation for CMP200-initiated measurement

3.2.2.2 Antenna delay calibration: real example

Figure 3-17 illustrates an example of antenna delay calibration with CMP200 and a real DUT.

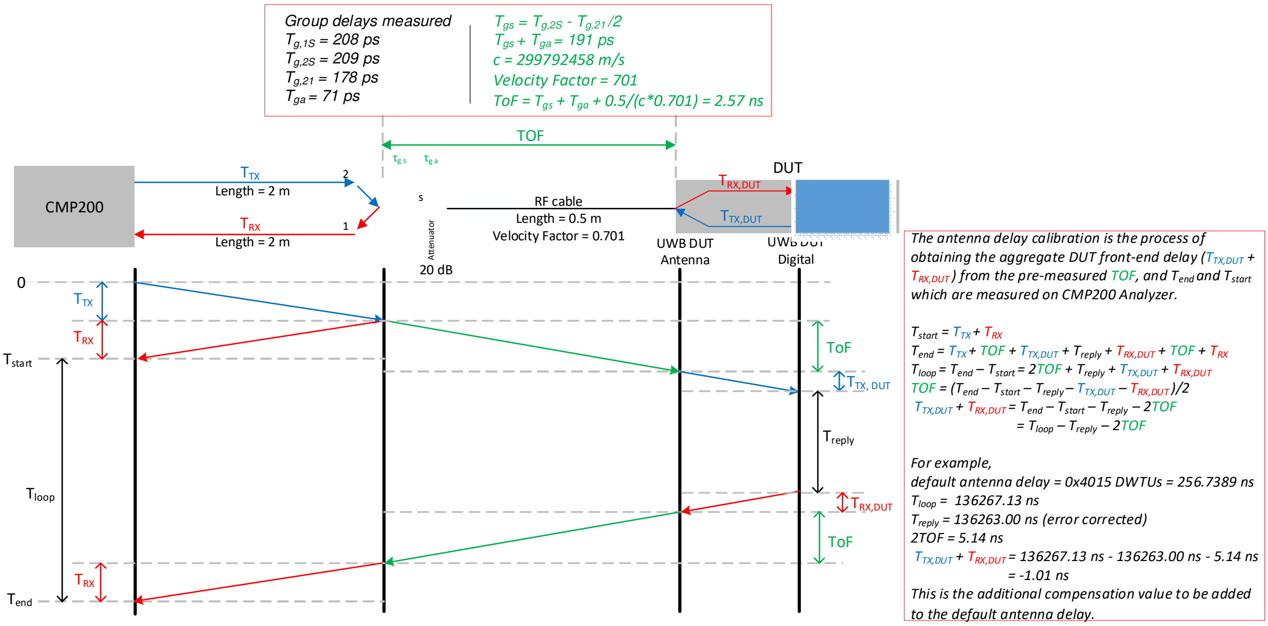


Figure 3-17: Example of Antenna Delay Calibration

To ensure stable TOF measurement, Figure 3-18 shows target RMS power levels recommended at the input/output of CMP200 and the DUT. The peak power levels of the PPDU packets from CMP200 Generator and DUT need to be between Expected Nominal Power (ENP) and Trigger Threshold with the delta less than 10 dB. The RX level of the DUT also needs to be strong enough. The criteria to ensure accurate capturing of the PPDU times is Symbol Time Jitter RMS < 25 ps. In the measurement example shown in Figure 3-20, the symbol time jitters are 2.22 ps for Generator and 1.73 ps for DUT.

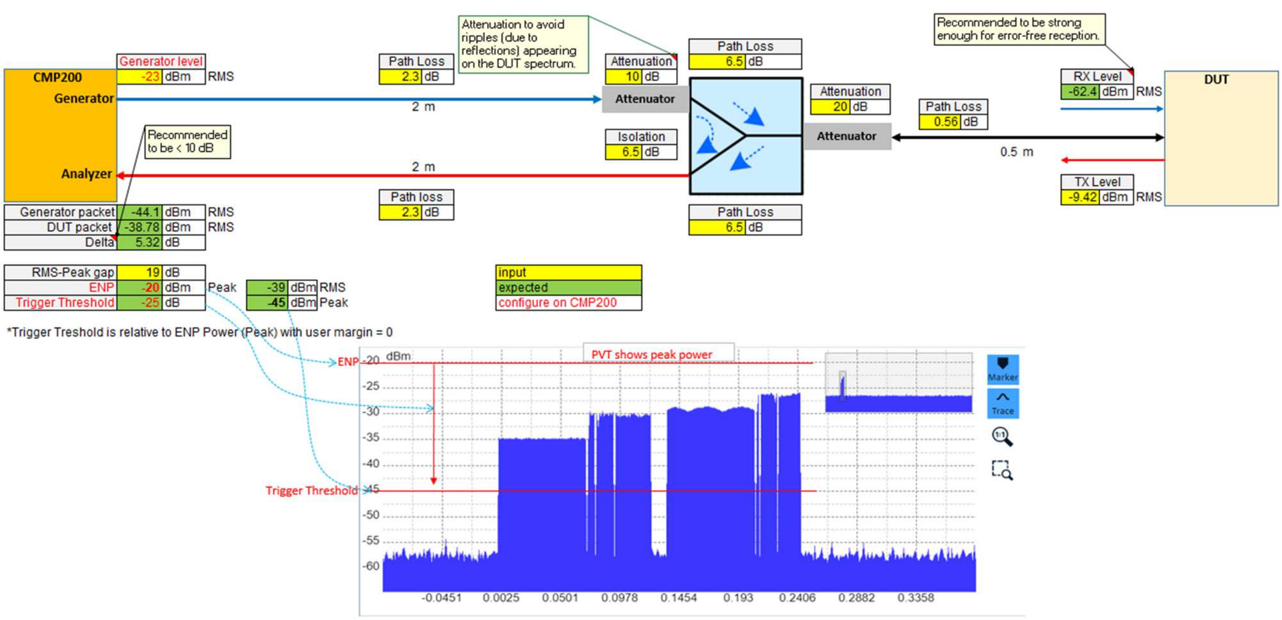


Figure 3-18: Level plan for TOF setup

Figure 3-19 and Figure 3-20 show the two PPDU packets, PPDU1 and PPDU2, captured in CMP200's PVT measurement screen in Multi-PPDU mode after a single TOF measurement. PPDU1 is the packet that originated from CMP200's generator and PPDU2 is a response packet sent by the DUT. The RMARKER of each PPDU serves as the point for PPDU time measurement.

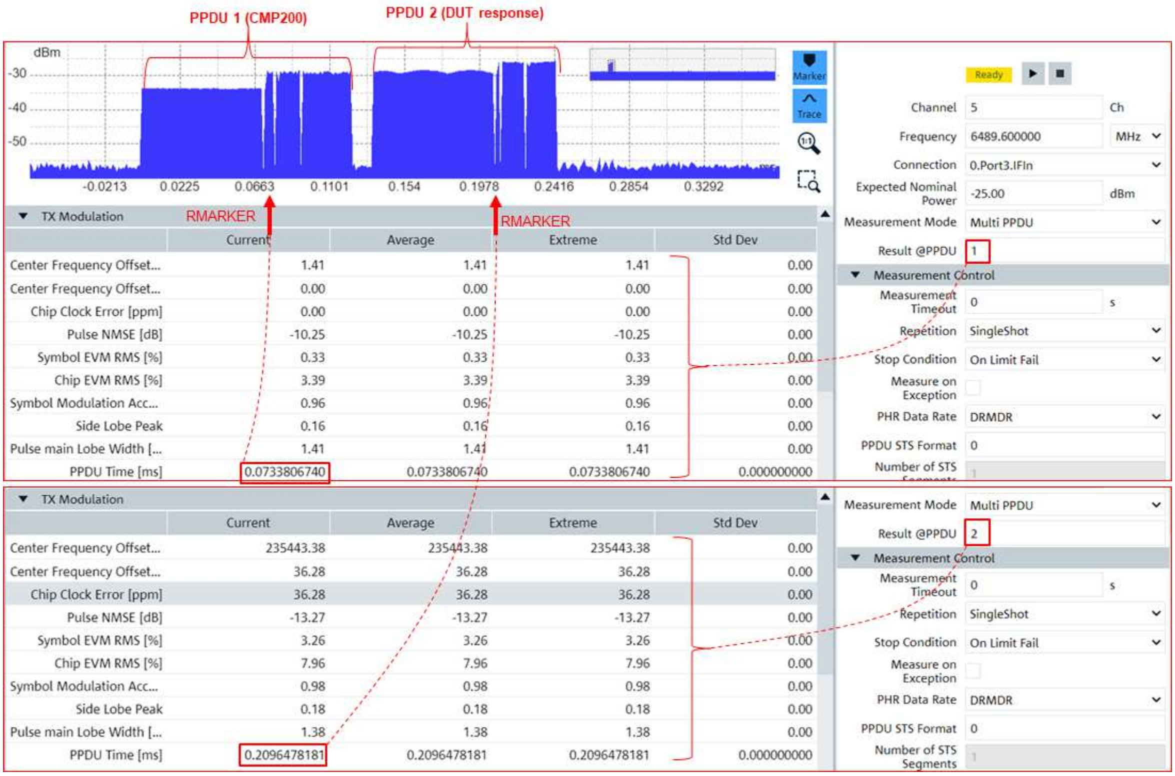


Figure 3-19: PPDU Packets captured on CMP200: Power versus time

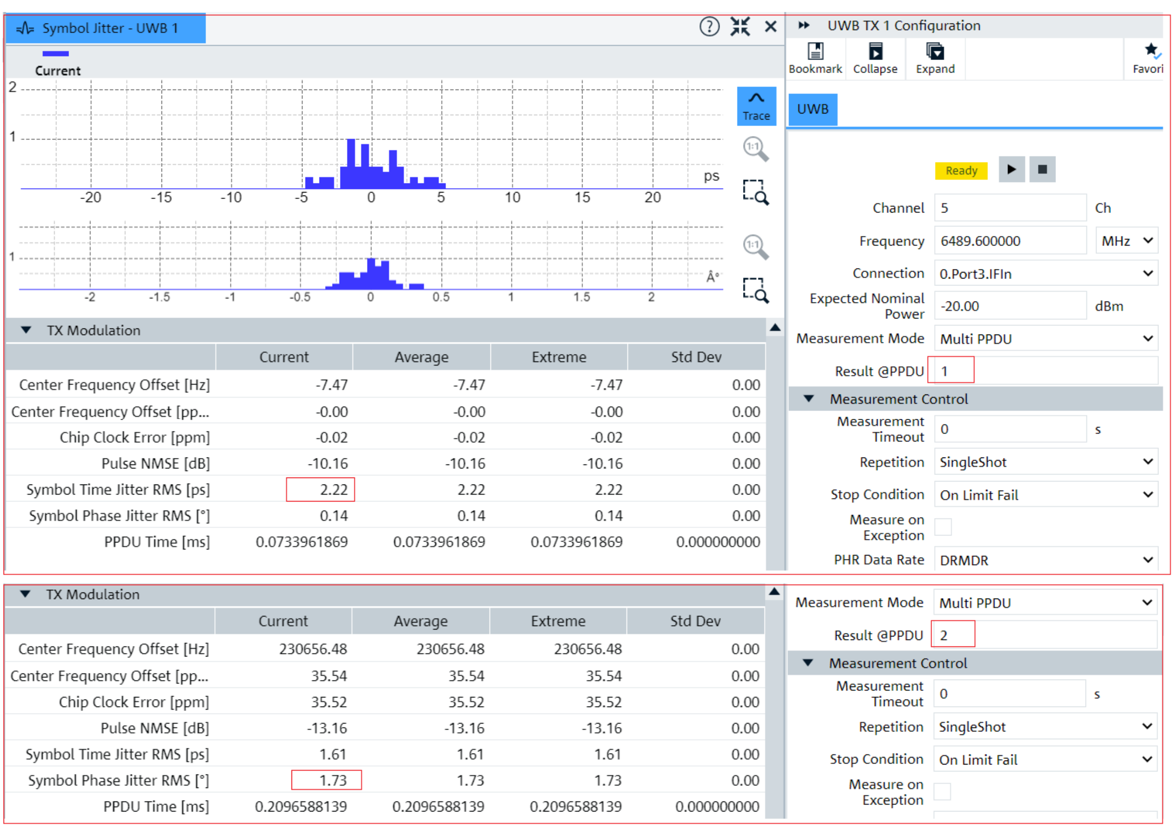


Figure 3-20: PPDU Packets captured on CMP200: Symbol Jitter

Figure 3-21 shows the 200-loop measurements of the $T_{TX} + T_{RX}$ before and after the calibration where the antenna delay is centered near 0 when the calibrated value is applied.

In this example,

- CMP200 was put into Multi-PPDU mode as shown in Figure 3-19.
- DUT was set with an initial antenna delay (ANT_DLY) value.
- CMP200's GPRF Gen1>ARB Sequencer played a waveform file: customerConfig_1Frames_64PL_11PC_5258SRC_4341DST_inv_part2.wv.
- PPDU_Time1, PPDU_Time2 and Frequency Error were fetched from CMP200.
- TX_Time_Stamp and RX_Time_Stamp were retrieved from the DUT registers.

As a result, the aggregate antenna delay, $T_{TX} + T_{RX}$, was obtained as 2T_TRX(µs) = -0.0010160350 µs which corresponds to the length of 2L_Trx(m) = -0.3045996312 m, assuming velocity factor = 1 (free space). One half of this aggregate antenna delay, $(T_{TX} + T_{RX})/2$, represents the correction value to be added to the default one-way antenna delay (ANT_DLY). So the new antenna delay, ANT_DLY_new (s) = ANT_DLY(s) + (2T_TRX(s)/2).

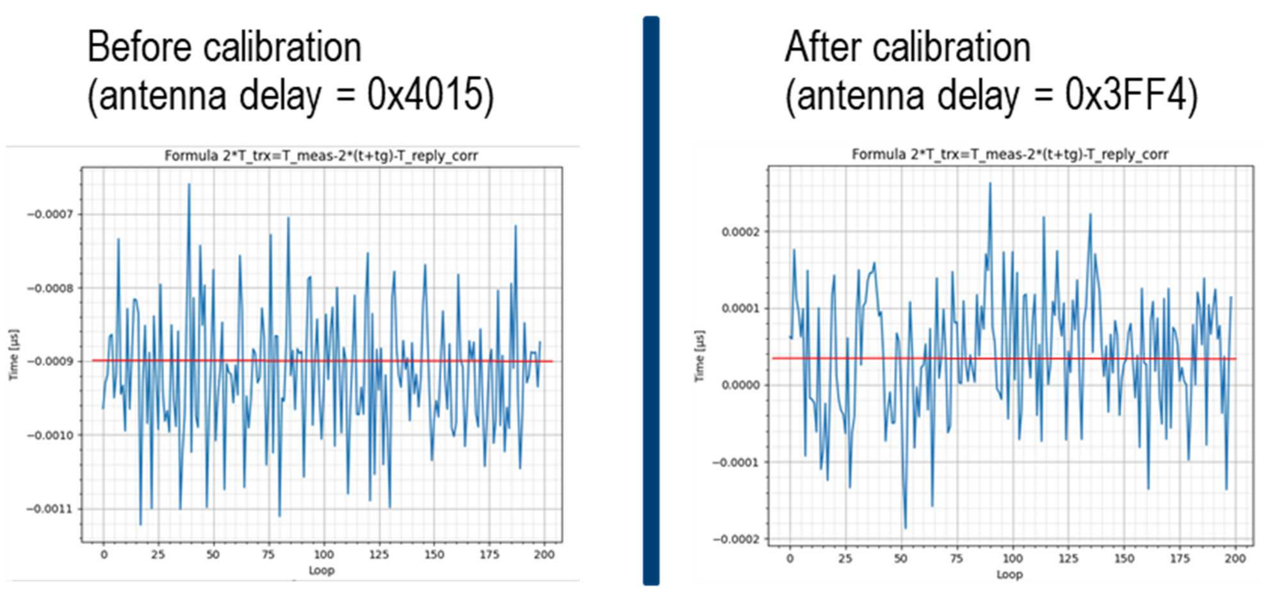


Figure 3-21: TTX + TRX before and after calibration

4 References

[1] IEEE 802.15.4-2020; IEEE Standard for Low-Rate; Revision of IEEE Std 802.15.4-2015, May 2020.

[2] Qorvo, DecaRanging_PC_User_Guide_DW3000_1p3.pdf.

[3] IEEE 802.15.4z-2020; Amendment: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques, June 2020.

[4] Decawave, DecaRanging_PC_User_Guide_DW3000_1p3.pdf, 2019.

5 Ordering Information

Designation	Type	Order No.
Radio Communication Tester CMP200	R&S®CMP200	1201.0002K20
CMP200 Basic Assembly	R&S®CMP_PB20A	1212.0209.02
IF Unit	R&S®CMP-B500A	1212.0444.02
UWB Measurements (SL)	R&S®CMP-KM300	1212.1886.02
UWB WinIQSIM2 waveforms for ARB generator (SL)	R&S®CMP-KW300	1212.1892.02
Accessory kit for UWB time of flight (ToF) measurement	R&S®CM-Z300A	1212.2724.02

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