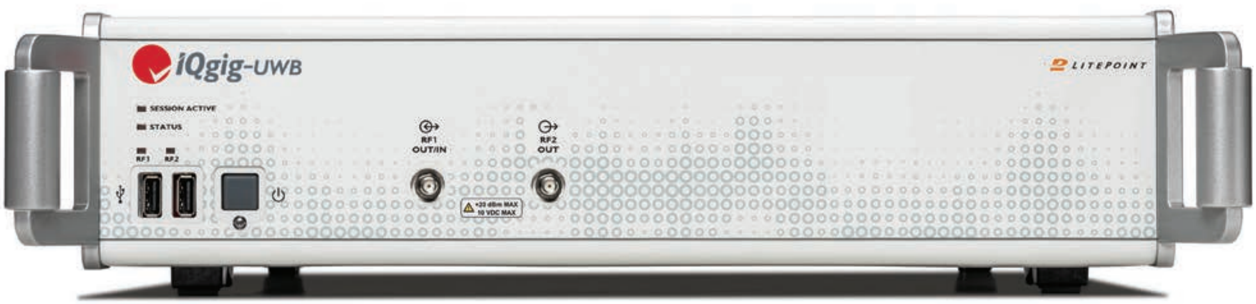
WHITEPAPER

Ultra Wideband Testing

Practical Introduction to UWB Measurements

LITEPOINT

Contents



1 Preface

This whitepaper provides an overview of the Ultra Wideband (UWB) technology based on the IEEE 802.15.4z amendment to the IEEE 802.15.4 standard. An introduction to the technology is included that covers frame formats, modulation techniques used in UWB communication, and how distance measurements are made.

A key aspect of the ranging features of UWB is measuring distance. Time of Flight (ToF) is detailed in this paper and the three different ranging methods defined in IEEE 802.15.4z are outlined.

The remaining part of the paper will focus on an overview of testing UWB devices:

- TX Testing focuses on the transmitter performance measurements.
- RX Testing describes the receiver tests that verify the reception and sensitivity performance of a Device Under Test (DUT).
- ToF Testing outlines how to perform calibration of delays in a DUT's frontend, and explain why this is important.

The paper closes with an introduction to the IQgig-UWB, LitePoint's fully-integrated test systems that enables both characterization and verification of the performance of an UWB DUT.

2 Introduction to HRP UWB Communication

Ultra-Wideband communication is a wireless communication technology that adds a missing dimension to products by enabling localization. Knowing the location of an object or a person of interest opens possibilities for a wide variety of new applications. The location of an object or person can be found using trilateration. Trilateration is the use of distances and fixed positions to calculate the position of an object or person. Since radio waves travel with known speed, transmission, and reception times, it is possible to calculate distance.

This opens a new wide variety of applications, such as asset tracking, indoor navigation systems, secure access/payment, patient tracking, accurate autonomous robot control, and many others.

The technology is based on IEEE 802.15.4z, an amendment to the IEEE802.15.4-2015 standard. The 4z standard specifies enhancements to the High Rate Pulse (HRP)- & Low Rate Pulse (LRP)-UWB PHY standards.

2.1 UWB Frequencies and Modulation types

UWB uses frequencies in 3 different bands, Band 0 at 500MHz, Band 1 at 3.5GHz to 4.5GHz, and Band 2 at 6.5GHz to 10GHz. All of these channels using a variety of Bandwidth (BW) ranging from 500MHz to 1.35GHz:

Band Group (decimal)	Channel Number (decimal)	Center Frequency (MHz)	Band Width (MHz)	Mandatory/Optional
0	0	499.2	499.2	Mandatory below 1 GHz
1	1	3494.4	499.2	Optional
	2	3993.6	499.2	Optional
	3	4492.8	499.2	Mandatory in low band
	4	3993.6	1311.2	Optional
2	5	6489.6	499.2	Optional
	6	6988.8	499.2	Optional
	7	6489.6	1081.6	Optional
	8	7488.0	499.2	Optional
	9	7987.2	499.2	Mandatory in high band
	10	8486.4	499.2	Optional
	11	7987.2	1331.2	Optional
	12	8985.6	499.2	Optional
	13	9484.8	499.2	Optional
	14	9984.0	499.2	Optional
	15	9484.8	1354.97	Optional

UWB communication is achieved by sending ultra-short, time-domain pulses in predefined bursts and sequences to achieve different functionalities. A single pulse can be less than 1ns long, which results in a very large bandwidth in the frequency domain.

The Pulse Repetition frequency (PRF) is a measure of how often a pulse is sent with the peak PRF rate being 499.2MHz.

In the original IEEE 802.15.4 standard, a legacy Base Pulse Repetition Frequency (BPRF) is defined at a mean pulse rate of 64MHz and below. In the amendment IEEE 802.15.4z, a newer mode of operation is defined: High Pulse Repetition Frequency (HPRF). The HPRF is chipping at a mean rate of 128MHz and higher. The Low Pulse Rate Repetition Frequency (LRPF), also defined in the 802.15.4z amendment, uses mean chipping rates of only 1-2MHz, and is not covered in detail in this paper.

The modulation of the data in the frames are shown in table below:

Mode	Modulation Technique	Maximum Data-rate
LRP	Pulse Position Modulation (PPM) or On/Off Keying (OOK)	1 Mb/s
HRP - BPRF	Burst Position Modulation - Binary Phase Shift Keying (BPM-BPSK)	27.24 Mb/s
HRP - HPRF	Binary Phase Shift Keying (BPSK)	31.2 Mb/s

The BPRF and HPRF maximum data-rates are nearly identical, however the HPRF operation mode results in a reduced on-air time, thereby resulting in reduced power consumption. The HPRF mode also includes a cipher mode, enabled using a Scrambled Timestamp Sequence (STS) thereby adding an additional level of security.

The security of UWB technology is based on two things; first being encryption (ciphering), and second being distance measurements/proximity.

2.2 Packet format

A set of different frame formats are defined for UWB packet configurations. Below is an overview of the four different configurations:

Configuration 0: A format without the STS, used for legacy BPRF devices. Can also use HPRF mode without additional security

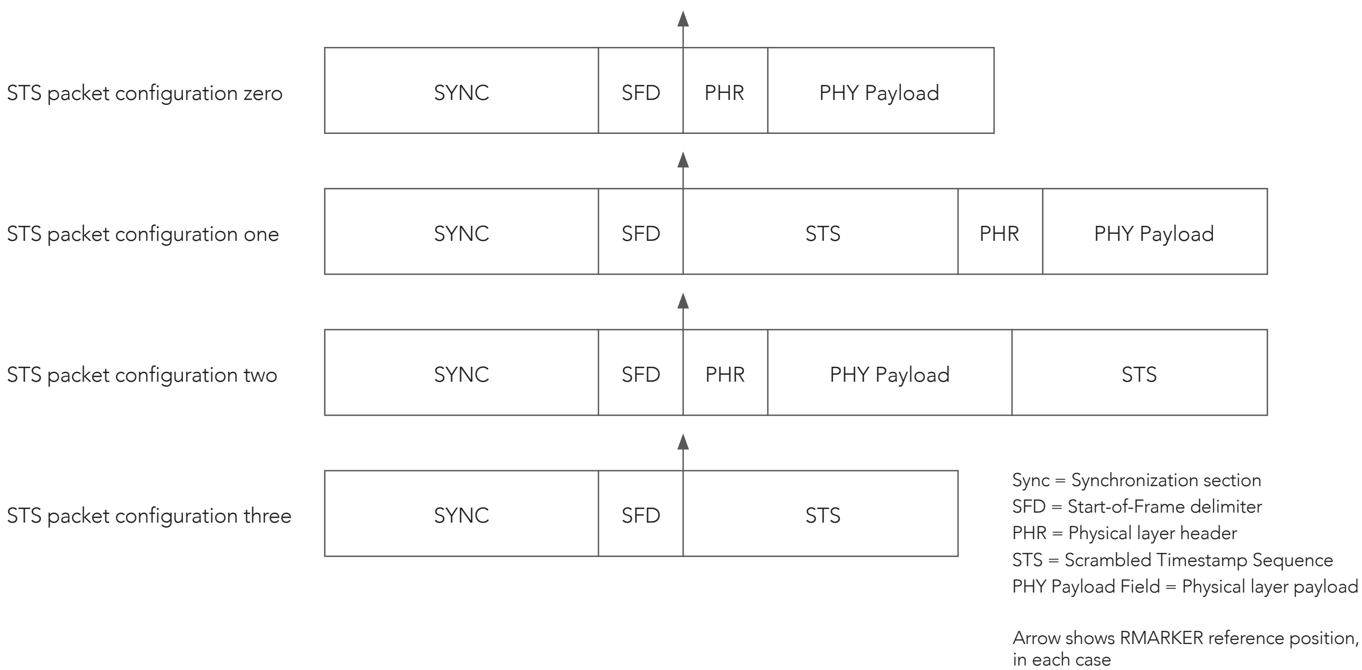
Configuration 1 and 2: Simply changing the STS location within the frame

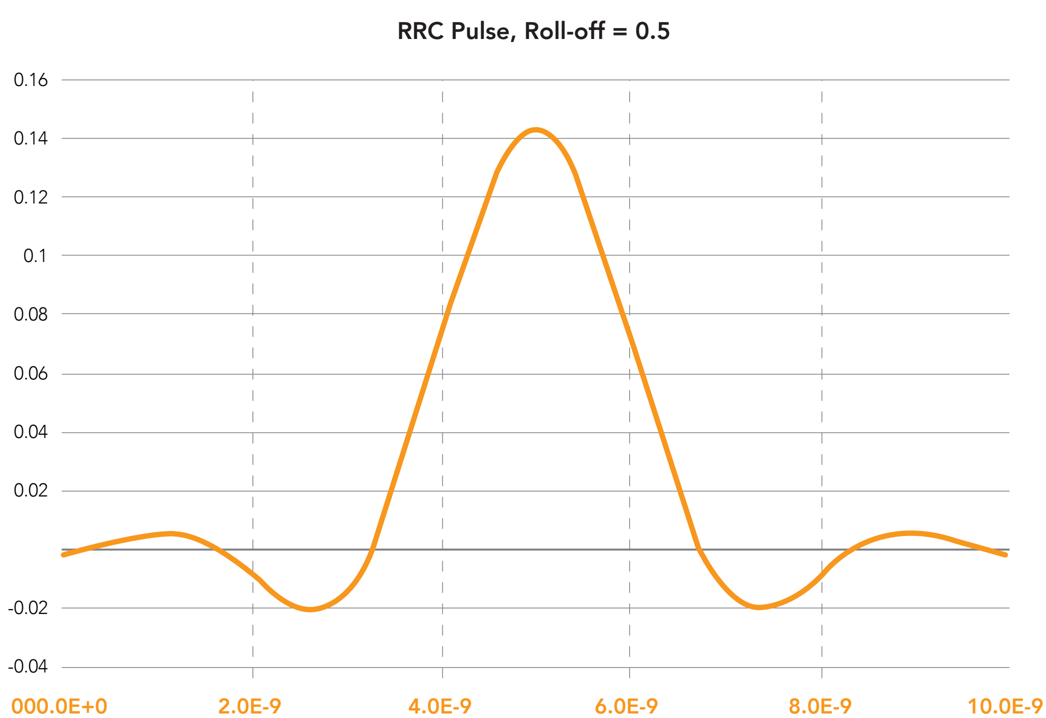
Configuration 3: Carries no data

2.3 SYNC field

For optimal synchronization, a SYNC field is transmitted as first part of a frame. It consists of a predetermined sequence of pulses which is repeated a number of times. A brief description is provided, but more information can be found in the IEEE 802.15.4z specification.

The pulses used can be any which comply with the requirements given in the IEEE 802.15.4z specification. The IEEE reference pulse suggest a Root-Raised Cosine (RRC) with roll-off factor of 0.5.



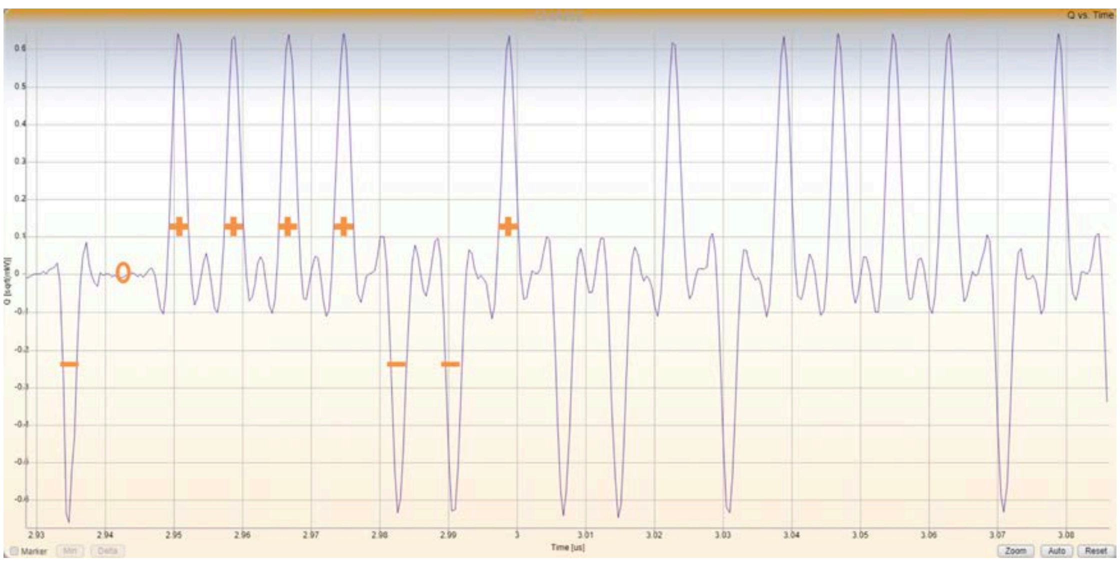


The reference pulse is then used to create a sequence of pulses called the code sequence. A sequence consists of either 31, 91 or 127 possible pulse positions, depending on BPRF and HPRF mode. A code sequence is indicated by the Code Index and in the 4z standard is a total of 32 different codes. The different code indexes apply in different operation modes.

An example of a code sequence could be, e.g. Code Index 25. A “minus” represents a negative pulse, a “plus” represents a positive pulse, and a “zero” is no pulse:

```
-0++++--+--+-++++-+---++--++++++-++-+00+--+0--+0+++++--+++--0--0+-+----0-+-+-+0+--++-+-+++0
```

Using the Litepoint IQgig-UWB tester for capturing a sequence with Code Index 25, the first few pulses of the sequence can be found below:



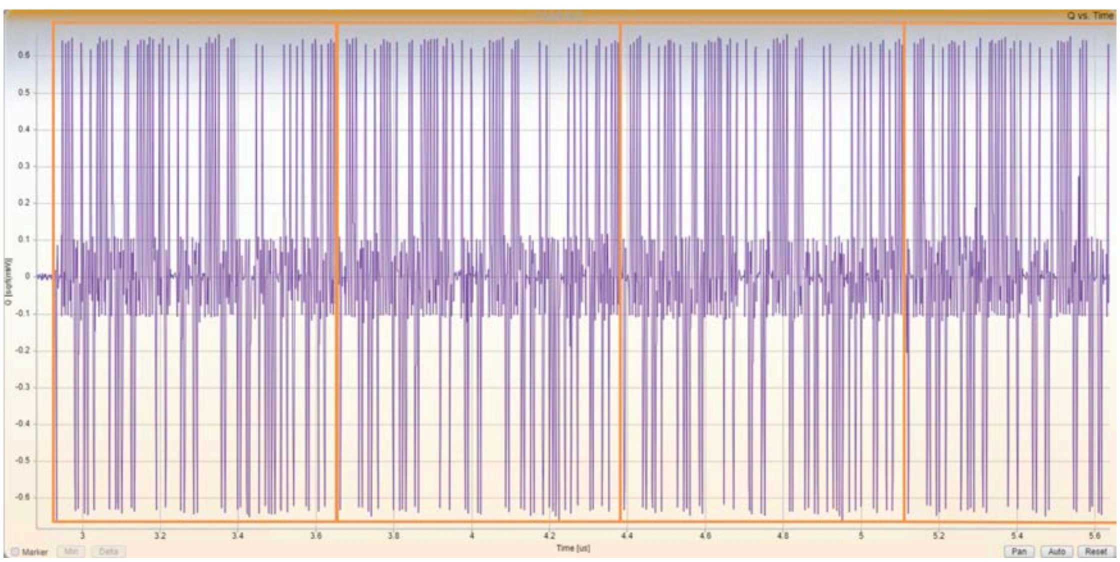
The number of sequences is repeated a number of times defined by the Preamble Symbol repetitions (PSR), which can vary from 16 to 4096 repetitions.

As an example, a sequence of 91 pulses with 16 repetitions would result in a total of 1456 (91 x 16) pulses in the SYNC field.

The possible PSR and Code Index for the different modes can be found below:

	PSR	Code Index
BPRF	16 (short) 64 (default) 1024 (Medium) 4096 (Long)	1-8 (mandatory) 9-24 (optional)
HPRF	16 (optional) 24 (optional) 32 (mandatory) 48 (optional) 64 (mandatory) 96 (optional) 128 (optional) 256 (optional)	25-32

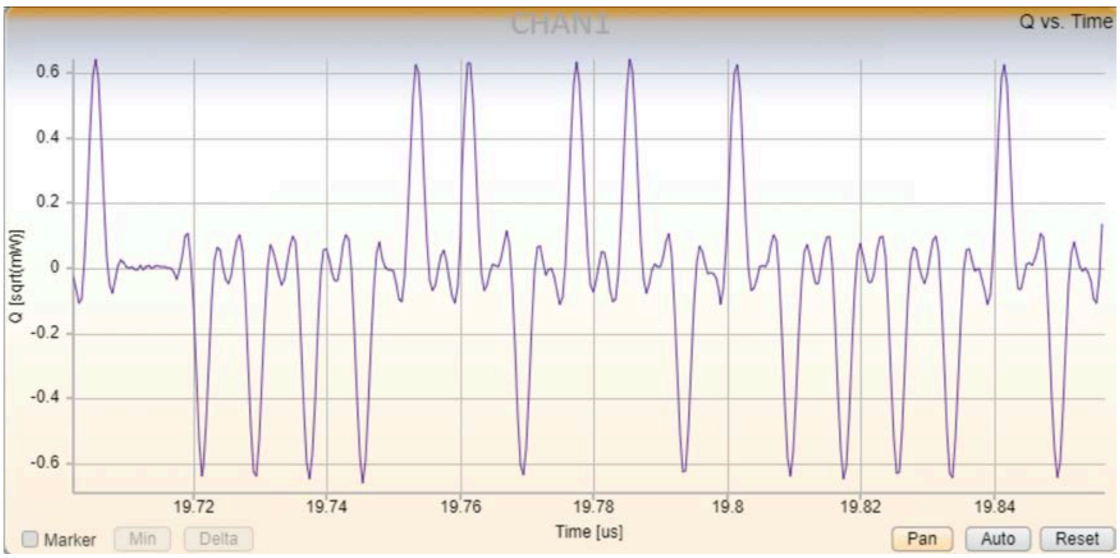
Looking closely at a capture of the first few microseconds of a frame also shows the repetition of a sequence. Looking closely, a pattern can be seen which indicates that the capture contains more than three sequences.



2.4 SFD Field

Following the SYNC field is a Start-of-Frame Delimiter (SFD) used to indicate the end of the Preamble, and the start of the physical layer header (PHR). The SFD is the last chance for receiver preparation and synchronization.

Compared with the SYNC Field, which consists of all PSRs having the same phase, the SFD indicates the end of the Preamble by spreading the code sequence by the SFD sequence. This means that the sequence given by the Code Index might be reversed, thereby resulting in a negative correlation. An example of a SFD sequence, using Code Index 25 and a phase shifted pulse is shown below, compared with previous picture of a positive sequence:



The preamble sequence is also defined for both the BPRF and HPRF modes. A device operating in the BPRF mode shall support the SFD with "SFD-Selector"values 0 and 2. In the HPRF mode the device shall support "SFD-selector"values 1, 2, 3, and optional 4.

SFD-Selector	SFD Length	SFD Spreading Sequence	Support-mode
0	8	[0 +1 0 –1 +1 0 0 –1]	BPRF
1	4	[-1 -1 +1 -1]	HPRF
2	8	[-1 -1 -1 +1 -1 -1 +1 -1]	BPRF & HPRF
3	16	[-1 -1 -1 -1 -1 +1 +1 -1 -1 +1 -1 +1 -1 -1 +1 -1]	HPRF
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 -1 -1]	HPRF (Optional)

2.5 PHR field

After the SYNC and SFD parts of the frame, the actual data held in the package will start. First is the PHR, which for the BPRF and HPRF modes contain different configurations. For both modes the PHRs have a length of 19 bytes.

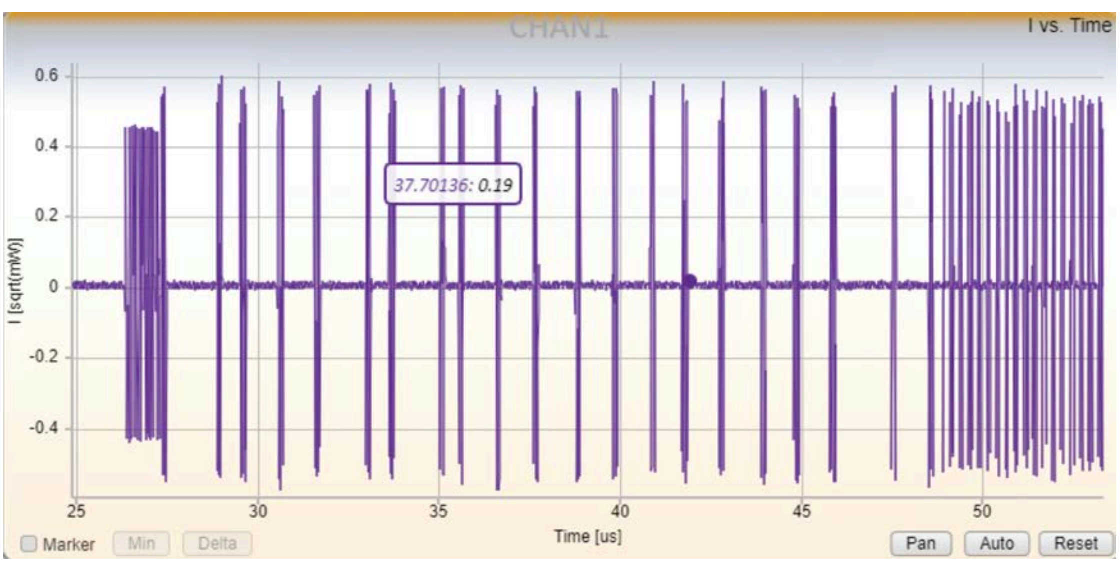
Devices operating in the **BPRF** mode shall transmit its PHR using the following configuration:

Bit(s):	0-1	2-8	9	10	11-12	13-18
Info	Data-rate	Frame Length	Ranging	Reserved	Preamble Duration	SECDED

- The Data-rate indicates the rate of the incoming PHY Payload field.
- The Frame Length is 7 bits indicating the number of octets in the Payload, thereby limiting the length to 127 octets.
- The ranging bit is used to indicate whether this frame is used in a ranging sequence.
- Bit 10 is reserved.
- The Preamble Bits 11-12 are used to indicate the PSR as described in the IEEE 802.15.4z specification
- The SECDED bits are used in the PHR for Single Error Correction Double Error detection.

The BPRF PHR is transmitted using Burst position modulation – Binary phase shift keying (BPM-BPSK). More information can be found in the IEEE802.15.4z specification.

In the following plot, variations in the pulse positions can be seen, and there are also phase shifts included in the bursts:



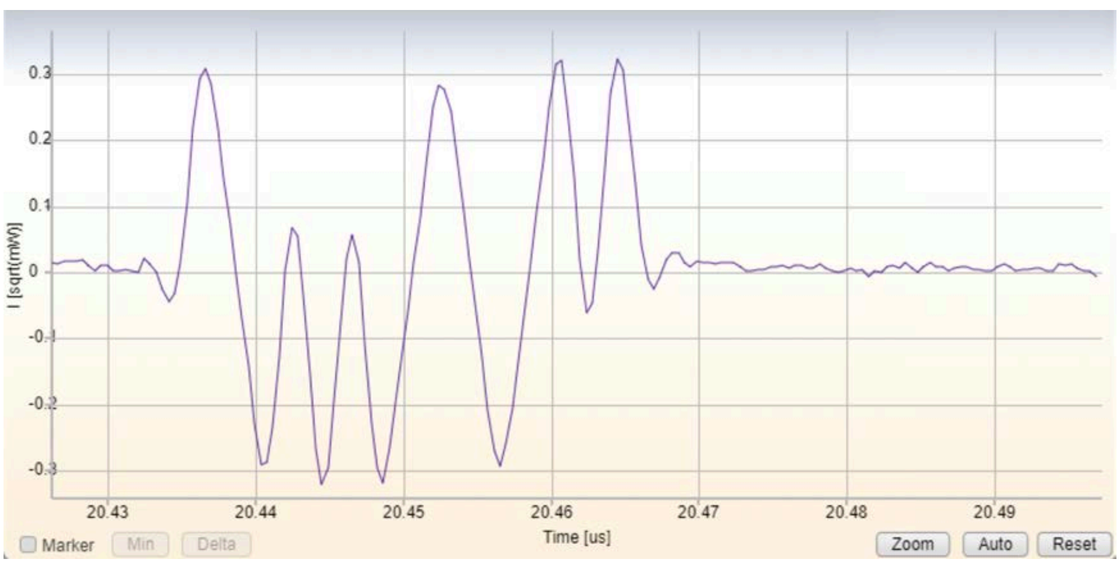
Devices operating in the **HPRF** mode shall transmit its PHR using the following configuration:

Bit(s):	0-1	2-11	12	13-18
Info	Additional Functionality	Frame Length	Ranging	SECDED

- The Additional Functionality bits can be used for different purposes, such as extra STS Gab indication or longer Frame length.
- The standard frame length can be a maximum of 1023 octets, and using the additional functionality bits can be a maximum of 2047 or 4095 octets.
- The ranging bit is used to indicate whether this frame is used in a ranging sequence.
- The SECDED bits are used in the PHR for Single Error Correction Double Error detection.

The HPRF PHR is transmitted using a convolution encoder and a spreading sequence. First, the data-bit is input to a convolution encoder, resulting in 2 output bits. Using a symbol mapping, the two output bits are converted into a set of pulses. The pulses are then spread by a sequence depending on the Code Index. The calculations of the spreading sequence can be found in the IEEE 802.15.4z specification.

In the plot below, the first symbol of the HPRF PHR using Preamble Index 25 is shown. After the spreading of Code Index 25, the first 8 pulses in the burst is: [1 0 0 0 1 0 1 1 ……..]



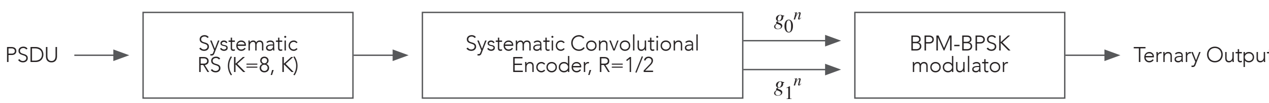
More information on modulation, symbol mapping, and spreading can be found in the IEEE 802.15.4z specification.

2.6 PHY Payload Field

The Payload carries the actual application data within a packet. This could be information about transmission or reception timestamps, or data for an application.

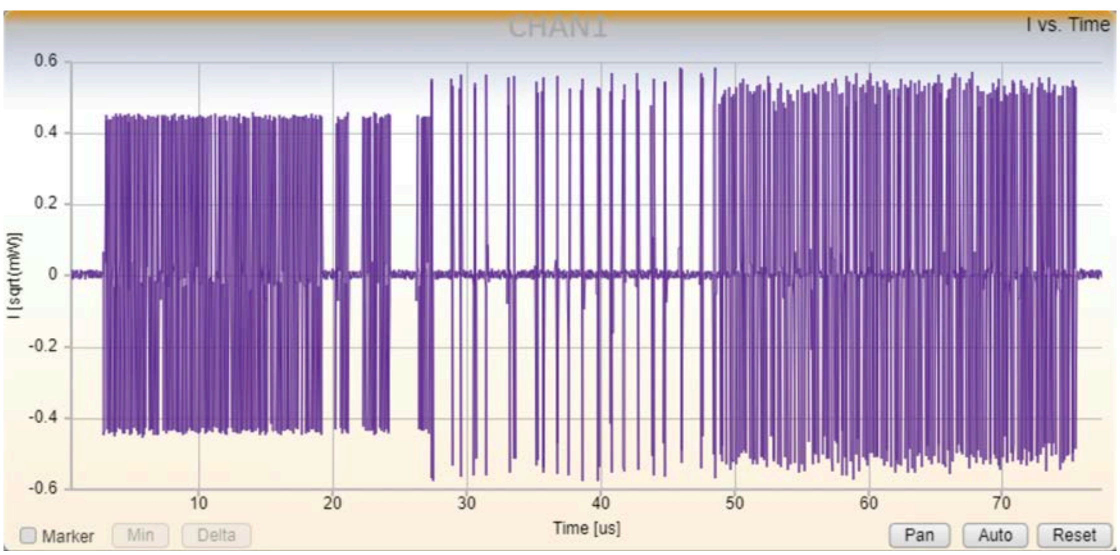
The data is, as with the PHR, modulated using different methods in BPRF and HPRF modes.

Data in the **BPRF** mode is transmitted using BPM-BPSK modulation, where the PSDU is first sent through a Reed-Solomon encoder and convolved using rate ½:



The actual data-rate depends on a set of parameters, such as the numbers of chips used in the bursts, the amount of burst positions available, the reed Solomon coding, the mean PRF, and more.

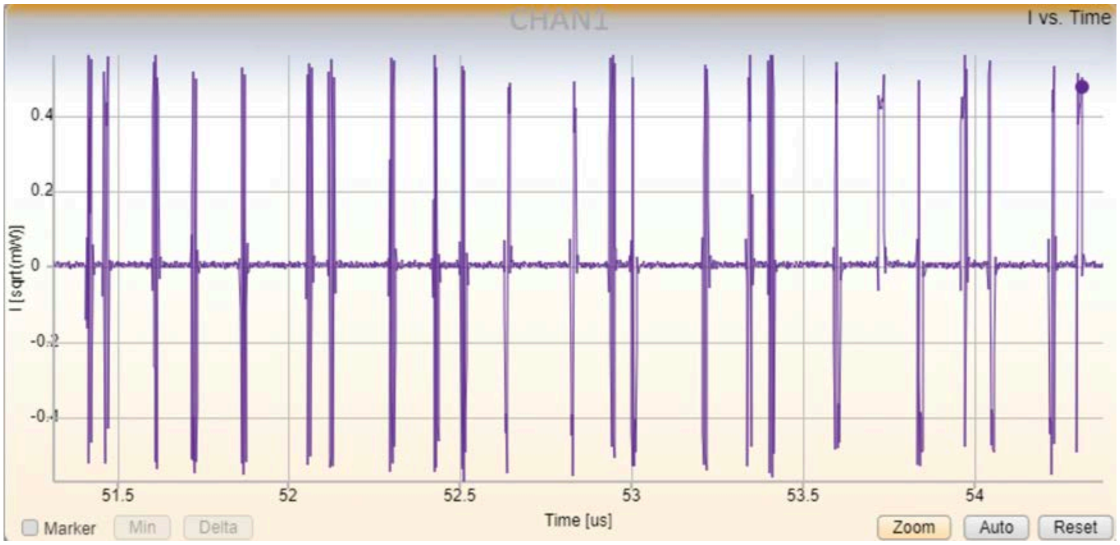
A capture of a full BPRF Frame is found below:



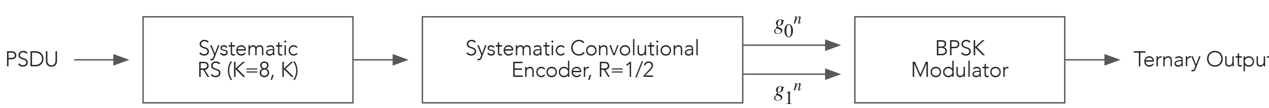
The capture contains the following configuration:

Frame-field	Start-Stop-timestamps [us]	Notes
SYNC	3 to 19	Preamble Index 10, PSR 16
SFD	19 to 27	SFD selector 0
PHR	27 to 48	Rate = 0.85Mb/s
PHY Payload	48 to 75	Rate = 6.8Mb/s, Length = 20 Bytes

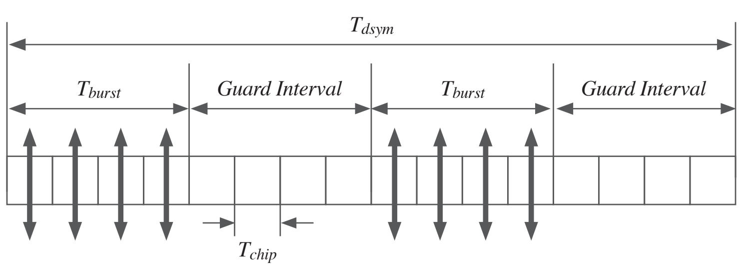
A closer look at the Payload also shows pulses changed in time for position modulation:



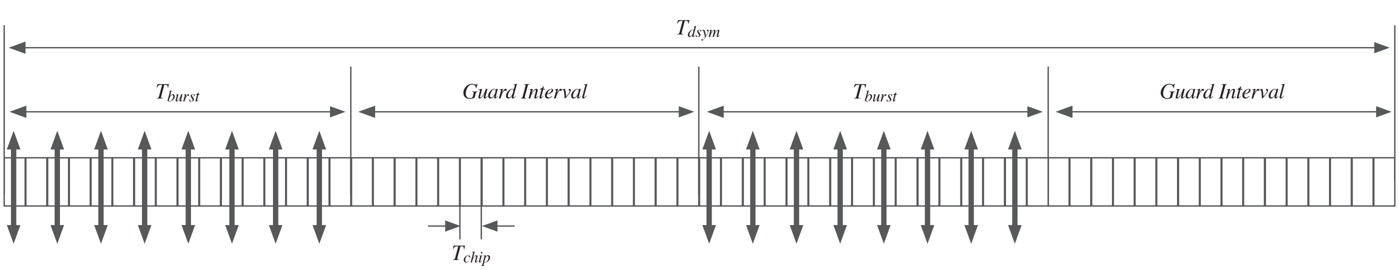
Data in the **HPRF** mode is transmitted using only BPSK modulation, a convolution encoder, Reed-Solomon encoding, and the applied spreading to create bursts of pulses. No position modulation is applied in this case.



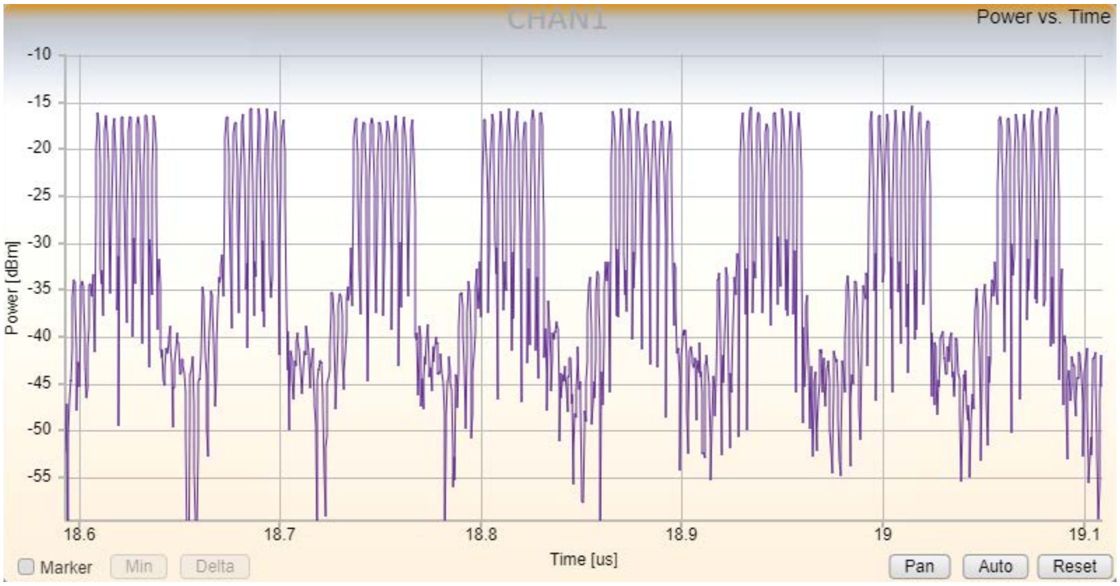
The burst pulses are transmitted at different PRF rates and a different number of pulses. For a mean PRF 256 MHz the modulation is shown below, where arrows indicate pulse positions:



For the more common mean PRF of 128 MHz, the modulation looks the same, however the number of pulses per burst is different. Additionally, a chip-period in between the pulses is introduced:

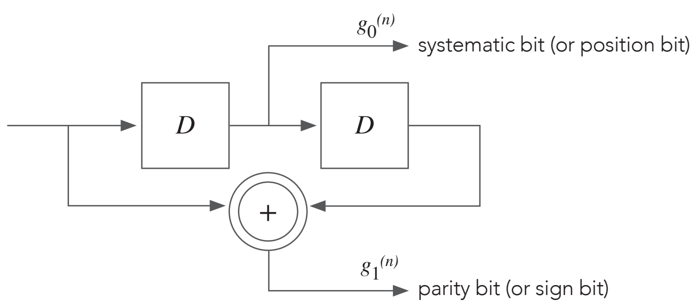


Compared with the BPRF mode, where the positions of the burst are changing, in the HPRF mode bursts are static in time. This can easily be seen from a Power vs. Time plot of the Payload portion of a frame:

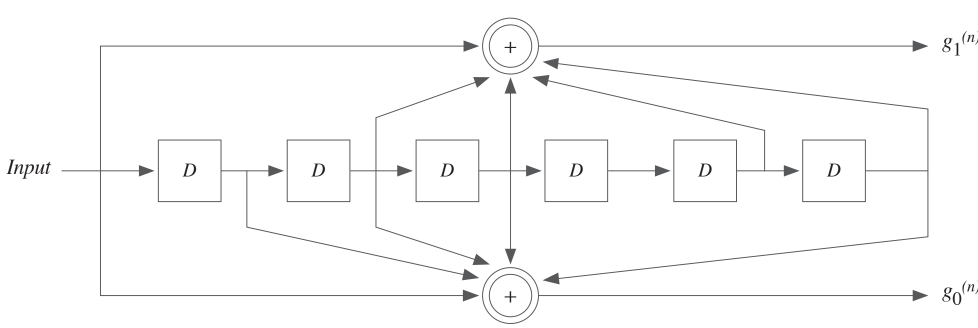


2.7 Convolution Encoding

The two transmitted bits, g_0 and g_1 are outputs from a convolutional encoder. The encoder, referred to as K3, uses generator polynomials g_0=[010]^2 and g_1 = [101]^2. This is the common encoder used both in BPRF and HPRF mode:



The HPRF mode also employs a K7 encoder, which is optional. When this encoder is used, the Reed-Solomon encoding is not applied to the PSDU:



The output of K3 or K7 in HPRF mode is used to choose the pulse sequence used before spreading and transmission. The effective set of positive and negative pulses is chosen from IEEE 802.15.4z specification shown below:

Symbol Mapping at 124.8 MHz PRF

$g_0^{(n)}$	$g_1^{(n)}$	First Burst	Second Burst	(PHR only) Third Burst	(PHR only) Fourth Burst
0	0	00000000	00000000	00000000	00000000
1	0	11111111	00000000	11111111	00000000
0	1	11111111	11111111	11111111	11111111
1	1	00000000	11111111	00000000	11111111

Symbol Mapping at 124.8 MHz PRF for the optional convolutional encoder

$g_0^{(n)}$	$g_1^{(n)}$	First Burst	Second Burst
0	0	00000000	00000000
1	0	11111111	00000000
0	1	11111111	11111111
1	1	00000000	11111111

2.8 STS Field

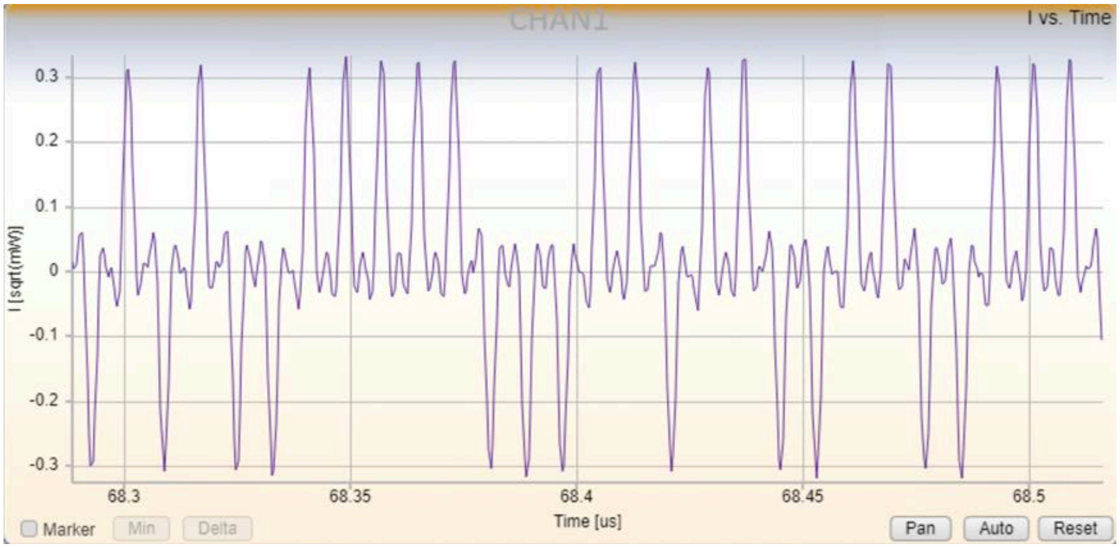
Above, Packet format was described as an additional field, which is not necessarily used. It is the Scrambled Timestamp Sequence (STS), used to add additional integrity and accuracy for the ranging measurements. A device incorporating the STS and the HPRF is called a higher rate pulse repetition frequency ultra-wide band PHY based enhanced ranging capable device (HRP-ERDEV).

The sequence is a set of pseudo random pulses, generated by a Deterministic Random Bit Generator (DRBG) used for AES-128 encryption. The bits generated by the DRBG are transmitted as '1' being a positive pulse and a '0' being a negative pulse.

In the BPRF mode, the STS is transmitted at a 64 MHz PRF. In the HPRF the pulses are repeated at 128MHz.

STS requires additional synchronization between AES-128 keys and Counter values. For more information, see the IEEE 802.15.4z specification for DRBG generation and a potential Synchronization scheme.

Part of an STS for HRPF 128 MHz is shown below:



The STS can be sent in multiple repetitions with gaps, and be located before or after the PSDU. Also, the length of the STS can vary as well. A description of possible configurations is below:

HRP-ERDEV mode	Delta length ὸL	Pulse spacing (chips)	PRF (MHz)	Length of active segment in units of 512 chips (~1 µs)	Number of segments supported
BPRF mode	8	8	62.4	64 mandatory	1 mandatory
HPRF mode	4	4	124.8	32, 64, 128 mandatory 256 optional	1, 2 mandatory 3, 4 optional

3 Distance measurements – Time of Flight

One of the features in UWB technology is the ability to measure a distance between two UWB devices with accuracies of <10 cm. This is due to the very large bandwidth and the correlation receiver techniques utilized when receiving the SYNC field in a frame. The technique is called Time of Flight (ToF). This is a measure of the time between the transmission and reception of a radio wave, which travels at the speed of light.

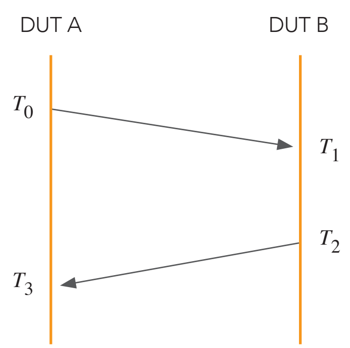
In technologies like Bluetooth, it is possible to intercept and relay the data transmitted between two devices. Bluetooth is one of the communication technologies used between a car and a key when used for wireless access when approaching a car. If someone can sniff and replay the data going back and forth between key and car, it is possible to unlock and steal it. The enabling of access is based on measuring the signal strength of a Bluetooth packet. When capturing and replaying such packets, it is easy to change the power level to indicate that a key is very close to a car. This signal interception and replay is referred to as a “relay attack.”

The usage of AES-128 encryption and distance measurements between two UWB devices, prevents the use of relay attacks. Distance measurements are used in the case where someone approaches a device (a payment terminal, a car, or door access). The distance between the two devices can then be measured with centimeter level accuracy, and this information can be used to unlock a car or grant access when you are in close proximity.

ToF measurements can be made in a variety of different ways, however the 802.15.4z standard suggest three main approaches for a Device Under Test (DUT):

- Single-sided Two-way Ranging (SS-TWR)
- Double-sided Two-way Ranging (DS-TWR)
- Double-sided Two-way Ranging (DS-TWR) with three messages

SS-TWR Is a measurement of the Round Trip Time (RTT) from transmission at DUT A to DUT B and back from DUT B to DUT A. Illustration found below:



$$T_2 - T_1 = Reply$$

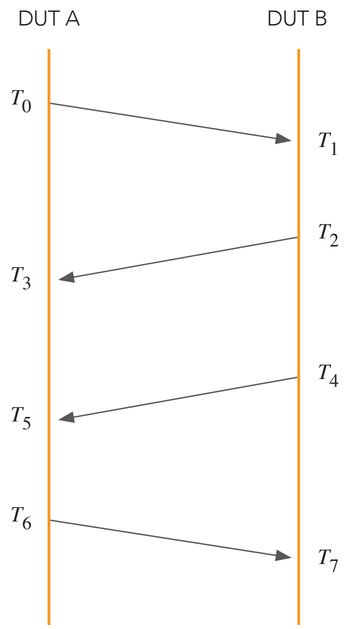
$$T_3 - T_0 = RTT$$

$$ToF = \frac{RTT - Reply}{2}$$

$$Distance = ToF * speed\ of\ light$$

The measurements rely on the DUTs to accurately measure their reception and transmission times. For DUT A to know the distance, it needs to know the timestamps of DUT B. These are embedded into the message going back to DUT A. When DUT A knows all 4 timestamps it is possible to accurately calculate the distance between the two DUTs. This is called the “Ping-Pong” approach, referring to a ping as an initial message, and a pong referring to a responding message. This approach relies on both DUTs to have their clock calibrated and synchronized. Any offset in clocks will result in errors in timestamps, thereby resulting in distance measurement errors.

DS-TWR is used when a reduced error is wanted and the clock frequencies of DUT A and DUT B are uncorrected. Double sided scheme is more robust for clock errors. A scheme for using it is found below:



$$T_2 - T_1 = Reply_1$$

$$T_3 - T_0 = RTT_1$$

$$T_6 - T_6 = Reply_2$$

$$T_7 - T_4 = RTT_2$$

$$ToF = \frac{RTT_1 \, x \, RTT_2 - Reply_1 \, x \, Reply_2}{RTT_1 + RTT_2 + Reply_1 + Reply_2}$$

$$Distance = ToF * speed\ of\ light$$

The above approach is called the “Ping-Pong-Ping-Pong”-approach.

The last option is to use **DS-TWR with three messages** which is simply that the above transmission scheme, can be reduces to three messages. It can be seen that the transmission T2->T3 and T4->T5 is same direction message, following each other. These can be reduced to a single message thereby resulting in a “Ping-Pong-Ping” approach. The RTT and reply times depend on different time-stamps, but overall the same measurements are needed, and can be used to calculate the distance that the signal has travelled.

The timing of UWB is critical for optimal performance. As the travel-time for a radio wave is what is measured for distance estimation, even the slightest offset in timing can result in huge variations in distance. Radio waves travel at the speed of light which is approximately 300.000 km/s. A ToF measurement of 10ns would be a distance of 3m.

4 What to test?

The upcoming sections describe in more depth what to test in terms of both the transmitter and receiver of a UWB DUT. This is written with a focus on production tests for compliance and consistency. Compliance due to the regional regulations set, such as those created by the FCC and ETSI for power transmission, and Consistency used for minimizing the device-to-device variations to ensure same performance of DUTs.

Overall the tests that should be implemented in Production are:

Transmit measurements

- Power spectral density
- Power spectral density Mask
- Carrier frequency offset

Pulse related measurements

- Symbol Modulation Accuracy
- Main Lobe width
- Side Lobe Power
- Chip Clock Error
- Chip Frequency Error
- Time domain mask
- Jitter

Receiver measurement

- Sensitivity - PER

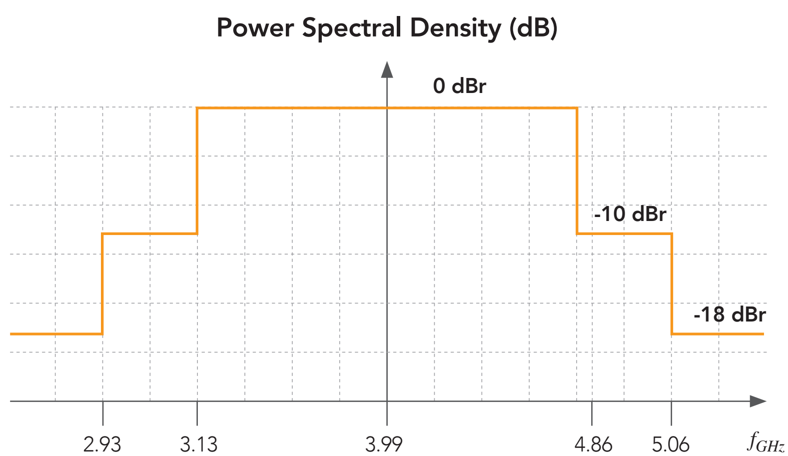
ToF calibration and/or verification

4.1 Transmit measurements (TX)

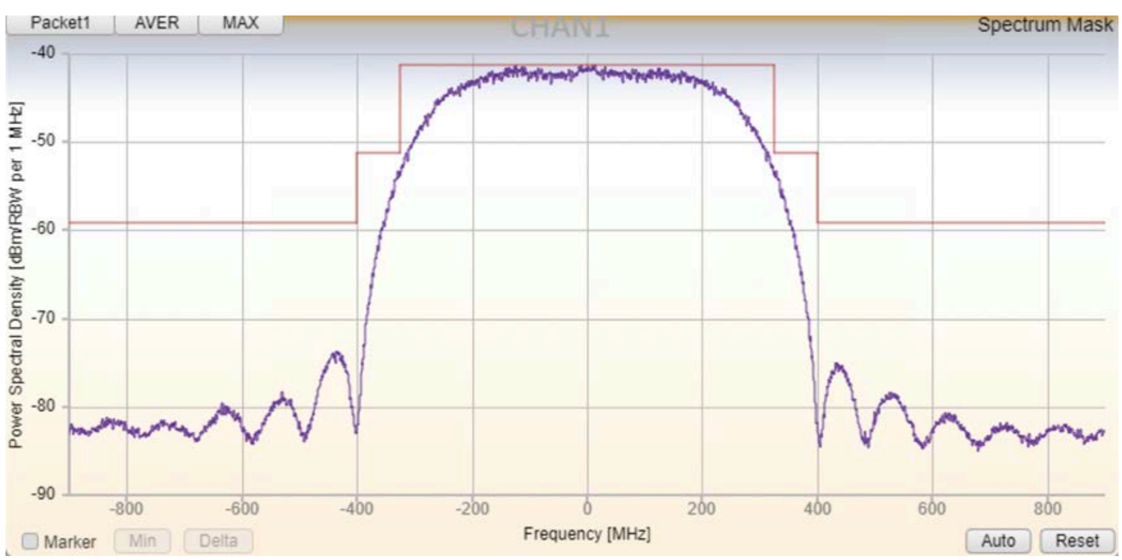
The TX measurements are based on a UWB DUT transmitting a signal or Frame to a signal analyzer. The reason for testing is to identify any issues with chips, components, soldering errors, or simply limit issues due to tolerances.

Power Spectral Density is a regulatory limit, which limits a UWB Frame transmission to not exceed a maximum transmission power of -41.3 dBm/MHz. These limits are given for different countries by their national regulatory authorities and assures coexistence of different devices. The spectral density is a regulatory limit, and therefore for any channel that an UWB device will be using, the limit should be checked.

Power Spectral Density Mask is measured on the spectrum and defines limits at offsets from the Carrier frequency at which a relative limit can't be exceeded. This allows for coexistence and interference limitations at same or neighboring bands. The limits in the IEEE802.15.4z specification are shown in the following graphic, where dBr refers to the relative spectral limit compared to the peak transmission power:



An example of a captured UWB frame with -41.3dBm/MHz regulatory limit compliance and IEEE mask compliance is found below:



The measurement is conducted using a 1 MHz Resolution Bandwidth and a 1kHz Video Bandwidth.

Carrier Frequency Offset (CFO) as with other wireless communication systems is the measure of the carrier frequency deviation with respect to the channel frequencies specified in the given standards. The carrier frequencies are listed in section 2.1 "UWB Frequencies and Modulation types." An 802.15.4z compliant device shall transmit at the channel frequencies with tolerances of ±20ppm, or potentially to a tighter specification for an industry certification consortium.

4.2 Pulse related measurements

For ensuring interoperability and performance, the pulse shape and different pulse parameters are an important metric to ensure that other DUTs can communicate. Pulse measurements are time domain based analysis.

Symbol Modulation Accuracy describes the comparison of an ideal pulse shape with the pulse shape measured with a signal analyzer. The Symbol Modulation accuracy is a percentage-number where 100% is a perfect correlation. The Symbol modulation accuracy, would correspond with the EVM measurement in WIFI, which is also a measure of a signal compared with the ideal sample.

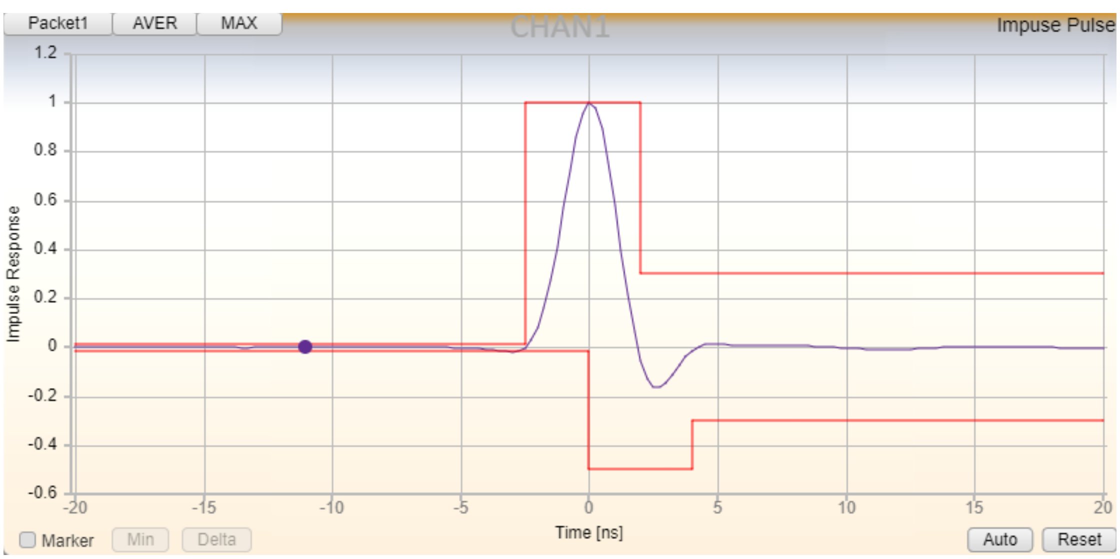
Main Lobe Width indicates the duration of which the pulse main lobe of the amplitude of cross correlation output is >0.8 and where the side lobe cross correlation amplitude never exceeds 0.3. More information on this can be found in the IEEE 802.15.4z specification.

Side Lobe Power is a measure of how much of total power from a given pulse shape is located in the side lobes.

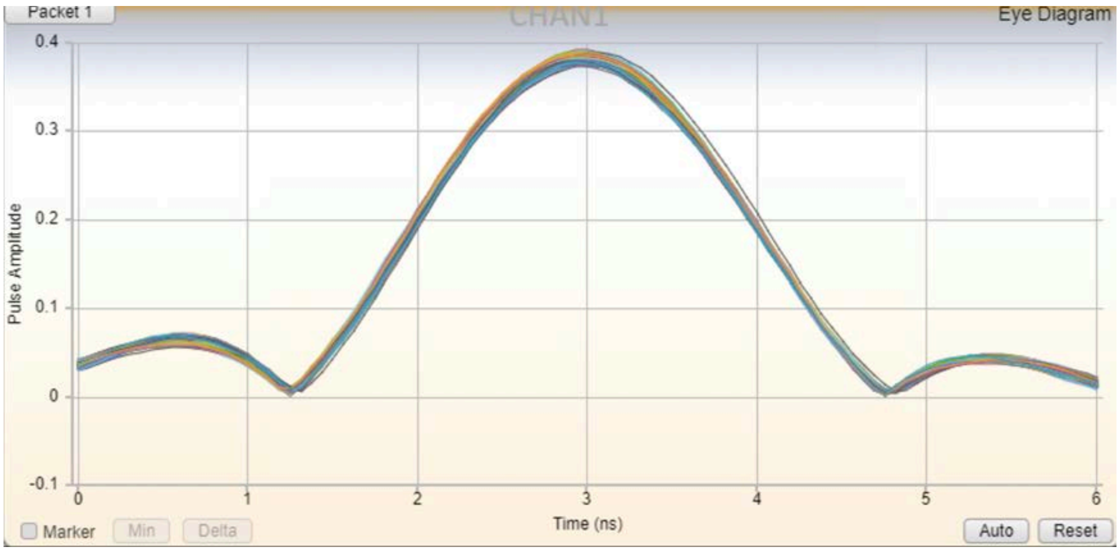
Chip clock error is an 802.15.4z measurement related to the chipping rate of a device. A device should be able to chip at the peak PRF (499.2 MHz) with an accuracy of ±20ppm, or potentially to a tighter specification for an industry compliance consortium.

Chip Frequency Error is a measure of the chip carrier alignment, and is measured on a chip or pulse basis. Pulses are measured and the center frequency of the transmitted energy is calculated. The measured frequency error must be within ±20ppm. This measurement is performed with a 1 MHz Resolution BW and a 1 kHz Video BW.

Time Domain Mask is an additional measurement based on masking the Time Domain Pulse to further ensure interoperability between devices to enforce the usage of a similar-looking time domain pulse. An example time domain mask is shown below:



Jitter measures the difference of a time-domain signal: edges, peaks or other. The jitter for UWB is measured by applying correction CFO and Chip clock error, then aligning the pulses and measuring the time differences of the peaks.



4.3 Receiver measurements

For the receiver performance in production no specifications are given in the 802.15.4z standard as to what tests or limits should be tested. However, a recommended list of tests can be determined based on defects that are intended to be detected:

Packet Error Rate (PER) testing is performed to ensure that a minimum sensitivity level is met for the different data-rates. Typically, limits are set in such a way to guarantee that the DUT will achieve less than 1% PER at a specific received input signal.

While it is important to test a variety of different combinations of the receiver settings, it is recommended to choose Code Indexes and PSR combinations that are relevant to the end-application. Testing the different combinations is needed not only for testing synchronization capabilities, but also to ensure correct marker setting (Time-stamping) of the reception of a packet. This is used in ToF Testing as issues with Time-stamping will result in errors of distance measurements.

4.4 ToF Testing

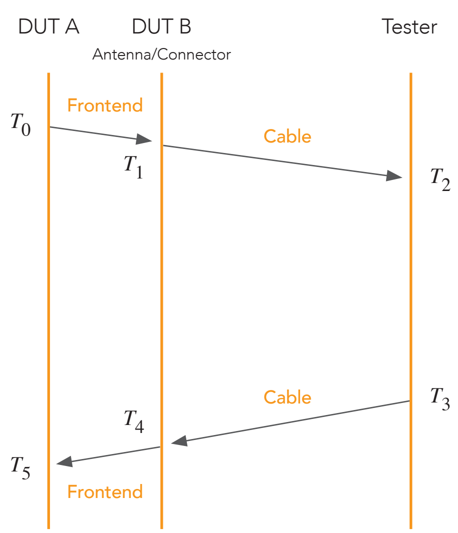
As some of the additional security in UWB is based on distance measurement for a proximity test, it is of important that error in these measurements are within certain limits. However, other UWB applications require even more precise measurements, such as Augmented Reality, Automatic Carriage, Asset tracking, Autonomous driving/parking, Drone control and others. The limits depend on the end-application for the device, and the manufacturing performance of a chip/module.

Before performing a ToF test, a CFO adjustment is needed since any offset in the clock will impact the timestamps due to drifting. This error is more critical than the delay-calibration, but also depends on the specifications of the clock reference used to run the DUT.

ToF testing is a two step process in production. First is the calibration of a DUT, and the second is the verification. The two are similar in the method for testing, however writing calibration values to a DUT might add extra test time. Therefore, a pre-calibrated module might only need verification.

The simplest and fastest way of testing ToF is using a SS-TWR approach. A DUT will send out a ping-packet, and the test system responds with a pong-packet. The tester should have excellent timing performance to make sure that any error introduced in the measurement is a minimal contribution from the test equipment.

To run DUT calibration, the distance between DUT and tester has to be known. Thereby the SS-TWR measurement scheme can be expanded into smaller parts as shown below:



$$T_3 - T_2 = \textit{Tester Delay}$$

$$T_4 - T_1 = (2 \textit{ x Cable}) + \textit{Tester Delay}$$

$$T_5 = \textit{DUT Reception Time}$$

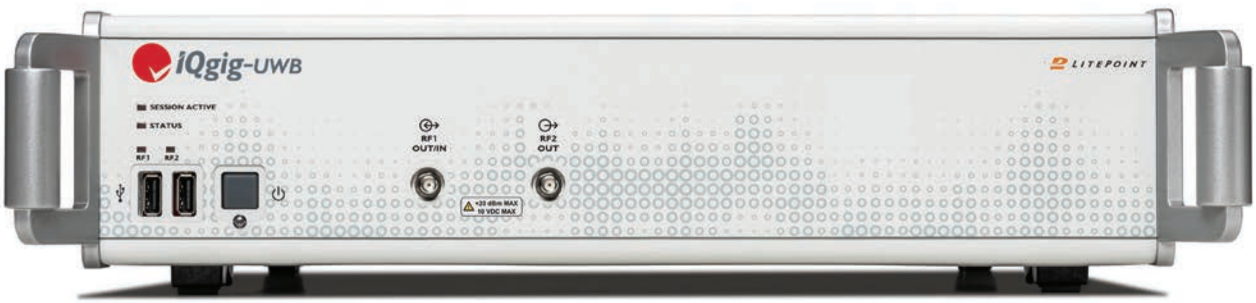
$$T_0 = \textit{DUT Transmission Time}$$

$$\textit{Frontend} = \frac{(T_5 - T_0) - (T_4 - T_1)}{2}$$

Where the Tester delay is a known parameter set or configured in a tester. The cable(s) used in the setup also has to be of known length (known delay). T0 is the time of “Ping” transmission and T3 Is the time of “Pong” transmission. The resulting error measurements will only be that which is introduced either by chip-variation or front-end and antenna variations.

5 Litepoint IQgig-UWB tester

For testing UWB devices, Litepoint offers a fully-integrated, all-in-one-box solution: IQgig-UWB. The tester includes both a Vector Signal Analyzer (VSA) and a Vector Signal Generator (VSG). It is an essential instrument both in R&D as well as production.



The tester supports a frequency range of 5 GHz to 19 GHz, covering the essential UWB channels in the 6.0-10.5GHz frequencies (IEEE Band 2), with an instantaneous bandwidth of 1.7 GHz. The latest IEEE 802.15.4z measurements are fully-integrated in the analyzer and generator, thereby making compatibility testing an easy task. Any configuration of UWB frames is possible to enter into the system, making anything from pulse related measurements and TX quality, to PER and ToF testing a very simple task.

The IQgig-UWB is controlled through a TCP/IP connection where SCPI commands are used to setup, control the instrument, and fetch measurement results. A small example of SCPI commands for capturing and analyzing is found below:

```
ROUT1;PORT:RES RF1A,VSA1
VSA1;FREQ:CENT 6489.6e6
VSA1;RLEV -10.30
VSA1;CAPT:TIME 0.26ms
VSA1;INIT;
UWBP;CALC:POWER 0,1
UWBP;CALC:TXQ 0,1
```

For manual measurements, the IQgig-UWB has a built-in Graphical User Interface (GUI) which allows users to access a control panel from any web browser, simply by entering the test system Serial Number or IP address:

With an optional external expansion module, the IQ5631 expands the number of ports to four bidirectional ports. This increases the number of DUTs that can be connected to an IQgig-UWB in production, or it can enable testing of multi-antenna UWB devices. Additionally, the IQ5631 enables PER testing at lower power levels than possible with the tester directly. With the IQ5631's internal attenuators, PER testing can be performed down to -110 dBm. Lastly the IQ5631 can be used for Angle of Arrival (AoA) testing, as the 4-ports on the IQ5631 have integrated, configurable delay lines.

6 Testing References & SCPI control

This section provides an overview of each test which should be conducted in an UWB evaluation with reference to respective specifications. Example SCPI commands for fetching measurement results is provided. This section also includes example code to demonstrate how some of these tests can be implemented using the IQgig-UWB test system.

6.1 Reference overview

Test	IEEE 802.15.4z	Additional reference	SCPI-function
Maximum Output Power		ETSI EN 302 065 FCC	FETC:POW:PEAK? FETC:POW:PEAK:AVER?
Maximum Power Density	16.4.6	ETSI EN 302 065 FCC	FETC:SPEC? FETC:SPEC:CHEC?
Carrier Frequency Offset	16.4.10		FETC:TXQ? FETC:TXQ:AVER?
Chip Clock Error	16.4.7		FETC:TXQ? FETC:TXQ:AVER?
Chip Frequency Offset	16.4.7		FETC:TXQ? FETC:TXQ:AVER?
Pulse Main Lobe Width	16.4.5		FETC:TXQ? FETC:TXQ:AVER?
Pulse Side Lobe Power	16.4.5		FETC:TXQ:PULS:LLOB? FETC:TXQ:PULS:RLOB?
Jitter		Litepoint Proprietary Measurement	FETC:TXQ:PULS:JITT?
Symbol Modulation Accuracy		Litepoint "EVM"-like Measurement	FETC:TXQ? FETC:TXQ:AVER?
Time Domain Mask			FETC:PRE:IRES?
Sensitivity – PER			DUT-reported

6.2 Example code

The following section provides a set of example code for performing different measurements using SCPI commands. These can be mixed and matched to achieve different functionalities, and optimize test-times on a DUT. Simple snippets for performing different functionalities are provided.

Configure ports for VSA or VSG setup:

```
PORT:RES RF1,VSA1             #Route port RF1 to the VSA
PORT:RES RF2,VSG1             #Route port RF2 to the VSG
FESW1;PORT:RES RF1A, RF1      #Route the IQ5631 RF1A port to RF1
FESW1;PORT:RES RF2A, RF2      #Route the IQ5631 RF2A port to RF2
FESW1;GAIN RF2A, -20          #Set the gain on RF2A path to be -20dB
```

Setup the VSA, perform a capture, and analyze:

```
#Setup VSA
VSA1;FREQ:CENT 6489.6e6       #Set the center frequency of the VSA
VSA1;RLEV -10.30              #Set the expected peak power level on the VSA port
VSA1;CAPT:TIME 0.260ms        #Configure the capture time

#Execute, capture, & Analyze
VSA1;INIT;                    #Initialize the capture

#Calculate TX quality on the capture, skipping 0 packets and analyzing 1 packet
UWBP;CALC:TXQ 0,1

#Calculate power on the capture, skipping 0 packets and analyzing 1 packet
UWBP;CALC:POWER 0,1
```

Analyzer configuration & data fetching:

```
#Set the analyzer configuration to use for analysis:
CONF:PRE:IND 25               #Preamble index 25
CONF:HPRF:SFD:DUR HPRF8       #SFD with HPRF setting 8 bit sequence
CONF:MPRF 62P40               #PRF setting using 62.40 MHz
CONF:TXQ:PST ON               #Calculation of Packet start time ON
CONF:DRAT 6P81                #using 6.81 Mpbs Data rate
CONF:SYNC:DUR DUR_64          #64 repetitions of preamble symbol

#Analyze the capture
UWBP;CALC:TXQ 0,1             #Calculate TX Quality
UWBP;CALC:POWER 0,1           #Calculate Power

#Fetch results from the analysis:
FETCH:TXQ?                    #TX Quality results
FETC:TXQ:INFO:DRAT?           #detected data rate
FETC:TXQ:POW:PEAK:DATA?       #peak power calculated on data
FETC:TXQ:POW:DATA?            #average power on data
FETC:TXQ:POW:PREamble?        #peak power on preamble
FETC:TXQ:POW:PEAK:PRE?        #Average power on preamble
FETC:SEGM1:PHR:CRC?           #Pass/fail status on CRC check on PHR
FETC:SEGM1:PSDU:CRC?          #Pass/fail status on CRC check on PSDU
```

Generate a Frame:

```
#Configure VSG Waveform Settings
CONF:WAVE:MPRF 62P40          #Set generated waveform to use 62.40MHz PRF
CONF:WAVE:PSDU:CRC CRC16      #Set the PSDU to include 16bit CRC check
CONF:WAVE:PSDU:NBYT 10        #Set the number of bytes to be 10
CONF:WAVE:DRAT 6P81           #Set the data rate of wave to use 6.81 Mbps
CONF:WAVE:SYNC:DUR DUR_64     #Set the symbol repetition to be 64 times
CONF:WAVE:PRE:IND 9           #set the preamble index to be 9
CONF:WAVE:GAP(10e-6,10e-6)    #set the time gap before/after frame to be 10us.

#Generate the waveform and output to the “user” folder
WAVE:GEN:MMEM ‘/user/uwb.iqvsg’, ‘Used for RX testing’;*WAI
```

Frame transmission:

```
#Load a waveform to the VSG
VSG1;WAVE:LOAD ‘/user/uwb.iqvsg’;*wai

VSG1;FREQ:CENT 6489.6e6       #Set the VSG center frequency
VSG1;POW:LEV -10              #Set the VSG output power at tester-port
VSG1;WAVE:EXEC ON             #Play the VSG waveform with continuous transmission
```

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