HIGH RATE PULSE ULTRAWIDEBAND PHYSICAL LAYER TESTING AND CERTIFICATION

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PRODUCTS FROM ROHDE & SCHWARZ

- R&S®CMP200 radio communication tester
- R&S®FSW signal and spectrum analyzer
- R&S®RTP high-performance oscilloscope
- R&S®SMBV100B vector signal generator
- R&S®SMM100A vector signal generator
- R&S®SMW200A vector signal generator
- R&S®VSE vector signal explorer software
- R&S®WinIQSIM2™ simulation software

1 INTRODUCTION

Ultrawideband (UWB) is a radio technology operating in the unlicensed spectrum for near-field communications with low power consumption and low complexity at low cost.

UWB has existed for quite a long time and was mainly used for traditional radar imaging without a ratified communications standard for worldwide deployment until it was authorized for the first time in 2002 by the American Federal Communications Commission (FCC). In addition to the FCC, the Institute of Electrical and Electronics Engineers (IEEE) also later elaborated UWB standardization. Since then, UWB technology has grown in commercial importance for short-range data communications as well as high-accuracy ranging applications.

During recent years, UWB technology has shown a steady growth in market size. Based on the market forecast of the UWB Alliance [Ref. 1], it is expected that well over 1 billion UWB-capable devices will be produced by 2025. UWB is used in various market segments such as telecommunications, the automotive industry, banking and financial services, healthcare and the public sector. It is estimated that 80 % of smartphones and related accessories and 11 % of car access devices will be equipped with UWB technology by 2025.

This white paper is an introduction to UWB physical layer fundamentals, the associated test requirements and appropriate test solutions. The paper is organized as follows:

- Chapter 2 gives a brief introduction to the UWB standards and international UWB consortia.
- Chapter 3 provides technical fundamentals of UWB technology.
- Chapter 4 outlines the high rate pulse (HRP) UWB physical (PHY) layer based on the IEEE 802.15.4 standard.
- Chapter 5 presents the IEEE 802.15.4z standard that serves as an amendment to chapter 4.
- Chapter 6 and chapter 7 explain the UWB ranging technique and location method.
- Chapter 8 presents the testing aspects of UWB devices with respect to the physical layer and ranging function.
- Last but not least, a summary of Rohde & Schwarz test solutions for UWB PHY verification is given in chapter 9.

2 STANDARDS AND CONSORTIA

2.1 Evolution of IEEE 802.15.4 series

IEEE 802.15.4 is a task working group within the IEEE 802.15 family. First released in 2003, the standard defines low-rate wireless personal area networks (WPAN) and focuses on long battery life and low complexity devices. Basically, it specifies the physical (PHY) and media access control (MAC) layer. Upper-level extensions have resulted in the development of different WPAN standards such as ZigBee.

In 2007, IEEE 802.15.4a was first introduced in the specification to include UWB as an addition to the existing IEEE 802.15.4 WPAN standard. The main goal of this amendment was to boost power efficiency and to achieve a high data rate and precise ranging by means of specified high rate pulse (HRP) repetition UWB PHY. HRP-RDEV was named as a ranging-capable device. The introduction of this very first UWB standard laid the foundation for worldwide deployment.

Another milestone of the IEEE 802.15.4 standard was the release of the IEEE 802.15.4 2015 edition. A major amendment to the existing standard was to incorporate low rate pulse (LRP) repetition UWB PHY which was initially specified in the IEEE 802.15.4f-2012 amendment.

The latest revision, IEEE 802.15.4z, was published in 2020 and is an amendment to the IEEE 802.15.4 2015 edition that enhances HRP and LRP UWB PHY in terms of power consumption and security. It also improves the MAC to support control of time-of-flight (ToF) ranging procedures and exchange ranging-related information between the participating ranging devices. In this revision, enhanced ranging device (ERDEV) operating in either base pulse repetition frequency (BPRF) mode or high rate pulse repetition frequency (HPRF) mode was introduced. More details can be found in chapter 5.

Table 2-1 gives an overview of UWB PHYs with respect to their applied standards.

In this white paper, only HRP UWB PHY will be addressed. For simplicity, throughout the remainder of the paper, the legacy HRP-RDEV in compliance with IEEE 802.15.4a is referred to as RDEV, and the new HRP-ERDEV with HRP UWB PHY enhancement conformant to IEEE 802.15.4z is referred to as ERDEV.

Table 2-1: Overview of UWB PHY

HRP UWB PHY High rate pulse repetition frequency			LRP UWB PHY Low rate pulse repetition frequency					
RDEV	ERDEV		RDEV			ERDEV		
Base	BPRF	HPRF	Base	Extended	Long-range	DF	Enhanced DF	DF with EPC
Modulation: BPM-BPSK **Pulse rate:** 3.9 Hz 15.6 Hz 62.4 MHz	**Modulation:** BPM-BPSK **Pulse rate:** 62.4 MHz	**Modulation:** BPSK **Pulse rate:** 124.8 Hz 249.6 Hz	**Modulation:** OOK **Pulse rate:** 1 MHz	**Modulation:** OOK **Pulse rate:** 1 MHz	**Modulation:** OOK **Pulse rate:** 2 MHz	**Modulation:** PBFSK **Pulse rate:** 1 MHz 2 MHz 4 MHz	**Modulation:** PBFSK **Pulse rate:** 1 MHz 2 MHz 4 MHz	**Modulation:** PBFSK-PPM **Pulse rate:** 1 MHz 2 MHz
IEEE 802.15.4a/ IEEE 802.15.4z	IEEE 802.15.4z		IEEE 802.15.4f/ IEEE 802.15.4z			IEEE 802.15.4z		

RDEV: ranging device
ERDEV: enhanced ranging device
BPM: burst position modulation
BPRF: base pulse repetition frequency
HPRF: high pulse repetition frequency
PBFSK: pulsed binary frequency shift keying

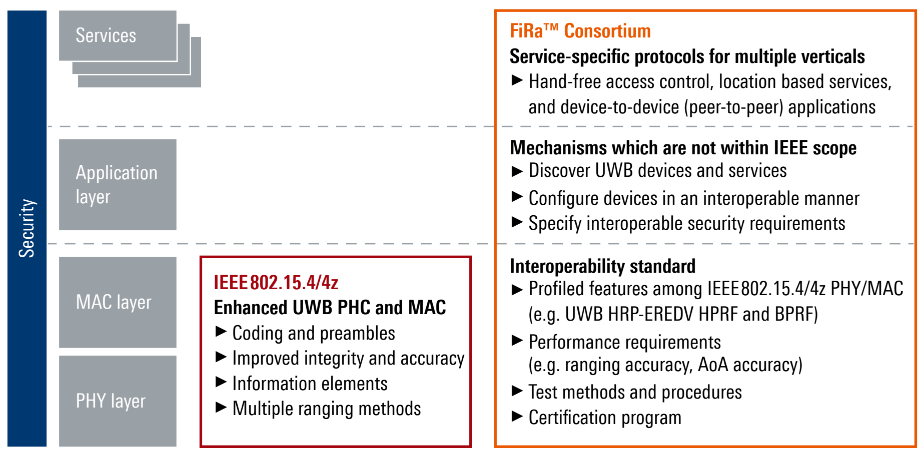
2.2 UWB Alliance

Founded in 2018, the UWB Alliance is an international non-profit organization headquartered in Washington D.C. dedicated to the promotion and growth of the UWB ecosystem. The UWB Alliance promotes large-scale UWB deployments by fostering the advancement of regulatory UWB environments. It provides a center of excellence for UWB education and coexistence, while endorsing cooperation with interoperable specifications and standards. For more information on the UWB Alliance, visit www.uwballiance.org.

2.3 FiRa™ Consortium

The FiRa™ Consortium is an organization founded in 2019 dedicated to expanding the UWB ecosystem by ensuring interoperability between multiple devices through compliance and certification programs. The FiRa™ Consortium focuses on three core UWB services: hands-free access control, location based services and device-to-device services that rely on the latest UWB based secure ranging technology specified by the IEEE 802.15.4z. Figure 2-1 shows the overall framework of the FiRa™ organization.

Figure 2-1: FiRa™ Consortium drives interoperability at all levels



As a T&M solution provider, Rohde & Schwarz is an associate member in the FiRa™ Consortium and collaborates actively in defining test methodologies, procedures and certification processes in the FiRa™ compliance and certification working group.

Visit www.firaconsortium.org to learn more about the FiRa™ Consortium.

2.4 Omlox

Around 60 partners support the Omlox standard, an industrial open standard that harmonizes all existing positioning technologies such as UWB, Bluetooth® Low Energy (BLE), RFID, 5G and GPS with a standardized interface. This approach simplifies interoperability of diverse positioning technologies and improves efficiency, particularly in the logistics and smart factory segments.

Visit www.omlox.com to learn more about Omlox standard.

2.5 Car Connectivity Consortium (CCC)

CCC is a global automotive industry consortium. The primary goal of the CCC is to specify a standardized interface between vehicles and smartphones for ensuring consistent user experience and increasing interoperability. Digital key release (DKR) 3.0 is an enhancement of DKR 2.0 and uses UWB technology to allow the smartphone to access the vehicle in a secure and privacy-preserving way.

Visit www.carconnectivity.org to learn more about CCC.

3 UWB FUNDAMENTALS

3.1 UWB – introduction

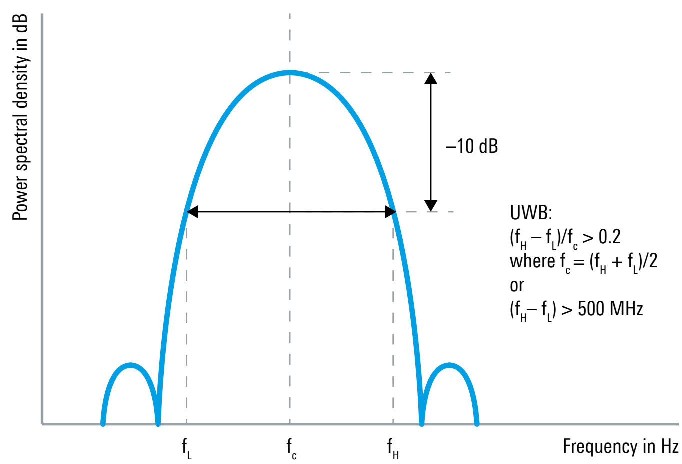
UWB is a radio technology that distributes the signal power over a wide bandwidth of more than 500 MHz by employing very short pulses with a duration of max. 2 ns. The transmitted power spectral density is strictly limited in order not to interfere with other radio technologies operating in the same frequency band.

As shown in Figure 3-1, the FCC specifies the UWB pulse signal to be transmitted at any point in time in line with the following criteria:

- Fractional bandwidth $(f_H – f_L)/f_C$ is greater than 0.2, or
- Absolute bandwidth $f_H – f_L$ is greater than 500 MHz, regardless of the fractional bandwidth.

Where $f_H – f_L$ is the UWB frequency bandwidth which is the frequency band bounded by the points that are 10 dB below the highest radiated emission, i.e. 10 dB bandwidth. f_H and f_L denote the higher and lower boundaries, respectively. f_C is the center frequency, equal to $(f_H + f_L)/2$.

Figure 3-1: Definition of UWB



UWB technology operates in the unlicensed spectrum in the defined frequency range (for details about UWB channels, see chapter 3.2) with a very strict transmission power density limit of –41.3 dBm/MHz. Due to its low-power and wideband characteristics, UWB can be deployed as an overlay transmission technology parallel to the Wi-Fi, Bluetooth® and cellular mobile communications systems.

UWB provides robust performance in multipath environments thanks to its extremely short pulse width that allows very fine timing resolution at the receiver side. Several multipath reflections of the signal can be easily distinguished. This enables accurate ranging even in places with a large number of signal reflections such as in indoor environments.

UWB technology makes it possible to achieve a data throughput of up to 31 Mbit/s and centimeter-accuracy ranging. The latter is achieved based on time-of-flight (ToF) and angle-of-arrival (AoA) measurements, which differs from the conventional positioning method based on the measurement of signal strength. Details are given in chapter 6 and chapter 7. In addition, a high level of security to prevent eavesdropping and attacks on signals is possible for ERDEV UWB implementations.

Smart car access, asset tracking, secure wireless payment, medical radars, indoor positioning etc., are the most promising UWB applications for wireless near-field communications.

In contrast to other narrowband wireless technologies, UWB has outstanding immunity to multipath fading, superior time-domain resolution for accurate ranging, and noise-like signal properties that limit cross-technology interference.

3.2 UWB channels

The UWB channel allocation based on IEEE 802.15.4 [Ref. 2] is summarized in Table 3-1.

HRP UWB PHY operates 16 channels in three band groups, i.e. subgigahertz (subGHz), low band and high band, denoted as band group 0, 1 and 2, respectively.

Table 3-1: HRP UWB PHY channel allocation

Band group	Frequency range	Channel number	Center frequency (in MHz)	Bandwidth (in MHz)	Mandatory (M)/ optional (O)
0 (subGHz)	249.6 MHz to 749.6 MHz	0	499.2	499.2	M
1 (low band)	3.1 GHz to 4.8 GHz	1	3494.4	499.2	O
		2	3993.6	499.2	O
		3	4492.8	499.2	M
		4	3993.6	1331.2	O
2 (high band)	6.0 GHz to 10.6 GHz	5	6489.6	499.2	O
		6	6988.8	499.2	O
		7	6489.6	1081.6	O
		8	7488	499.2	O
		9	7987.2	499.2	M
		10	8486.4	499.2	O
		11	7987.2	1331.2	O
		12	8985.6	499.2	O
		13	9484.8	499.2	O
		14	9984	499.2	O
		15	9484.8	1354.97	O

The majority of the defined channels span a bandwidth of 500 MHz. There are, however, a few exceptions:

- Channel 4 in low band has 1.3312 GHz bandwidth
- Channel 7 in high band has 1.0816 GHz bandwidth
- Channel 11 in high band has 1.3312 GHz bandwidth
- Channel 15 in high band has 1.35497 GHz bandwidth

The high bandwidth channels overlap the lower bandwidth ones. UWB devices operating with a high bandwidth are allowed to transmit higher power (under the constraint of a –41.3 dBm/MHz fixed power spectral density) and achieve longer communications distances. Larger bandwidth pulses are more multipath-resistant and have higher ranging accuracy [Ref. 3]. Support of channel 0, 3 and 9 is mandatory for UWB implementations in the related bands.

Most UWB products currently available on the market focus on the high band group, particularly on channel 5 and channel 9 with 500 MHz bandwidth.

3.3 UWB pulse

As specified in [Ref. 2], a mandatory root raised cosine (RRC) pulse shape with roll-off factor β = 0.5 has to be applied as a reference pulse (see Figure 3-2). Its impulse response r(t) is as follows:

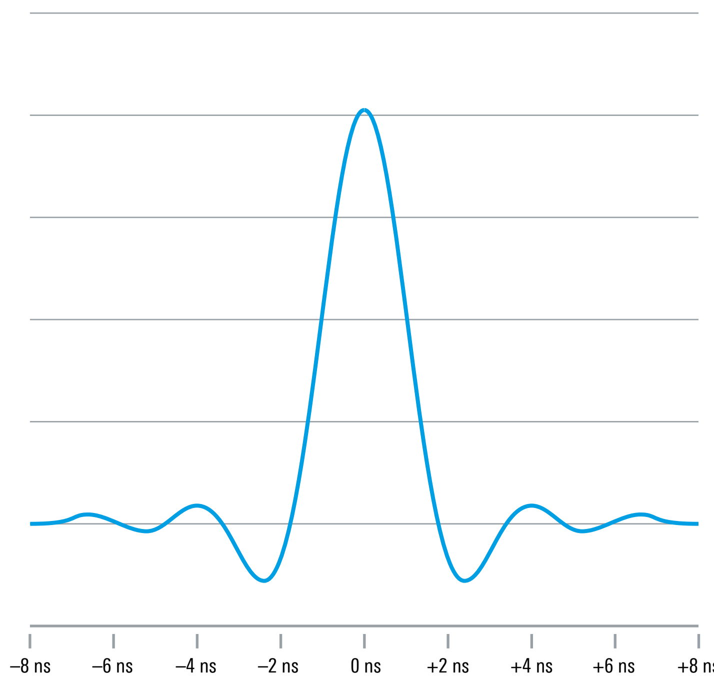
Equation 1: UWB impulse response

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

where T_p is the pulse duration, measured in nanoseconds.

Depending on the different channel bandwidths given in Table 3-1, four pulse durations T_p are possible for UWB, i.e. 2 ns, 0.92 ns, 0.75 ns and 0.74 ns (see also Table 8-2).

Figure 3-2: Ideal RRC pulse shape (roll-off factor ß = 0.5, T_P = 2 ns)



Besides the mandatory pulse given in Equation 1, other optional pulse shapes defined by the standard [Ref. 2] can also be adopted, e.g. CoU pulse, continuous spectrum (CS) pulse and linear combination of pulses (LCP).

To characterize the UWB system, pulse repetition frequency (PRF) is often used to denote the frequency of the pulse being emitted, particularly the mean PRF, which is actually the effective PRF of the pulse transmission rate.

In Table 3-2, the predefined mean PRFs for the RDEV and ERDEV with respect to each field in the PHY protocol data unit (PPDU) are summarized. Chapters 4.1 and 5.1 provide details about the PPDU of the RDEV and ERDEV.

Table 3-2: Mean pulse repetition frequency (PRF) of HRP UWB PHY

Field in PPDU	HRP RDEV (in MHz)	HRP ERDEV, BPRF mode (in MHz)	HRP ERDEV, HPRF mode (in MHz)
Preamble	4.03/16.1/62.89 (optional)	62.89 (optional)/111.09	62.89 (optional)/111.09
Data	3.90/15.6/62.4 (optional)	62.4	124.8/249.6
STS	n.a.	62.4	124.8

Different PRFs are used mainly because devices need to operate in various environments with wide variations in delay spread. Devices that support multiple PRFs can adapt the PRF based on the channel conditions.

PRF of the ERDEV is higher than the RDEV, especially in HPRF mode where mean PRFs of 124.8 MHz and 249.6 MHz are supported. A report in [Ref. 4] indicates that the receiver dynamic range can be improved by increasing the PRF.

4 HRP UWB RDEV (IEEE 802.15.4)

HRP ranging-capable devices (RDEV) facilitate the ranging function based on physical layer implementations in line with IEEE 802.15.4 [Ref. 2].

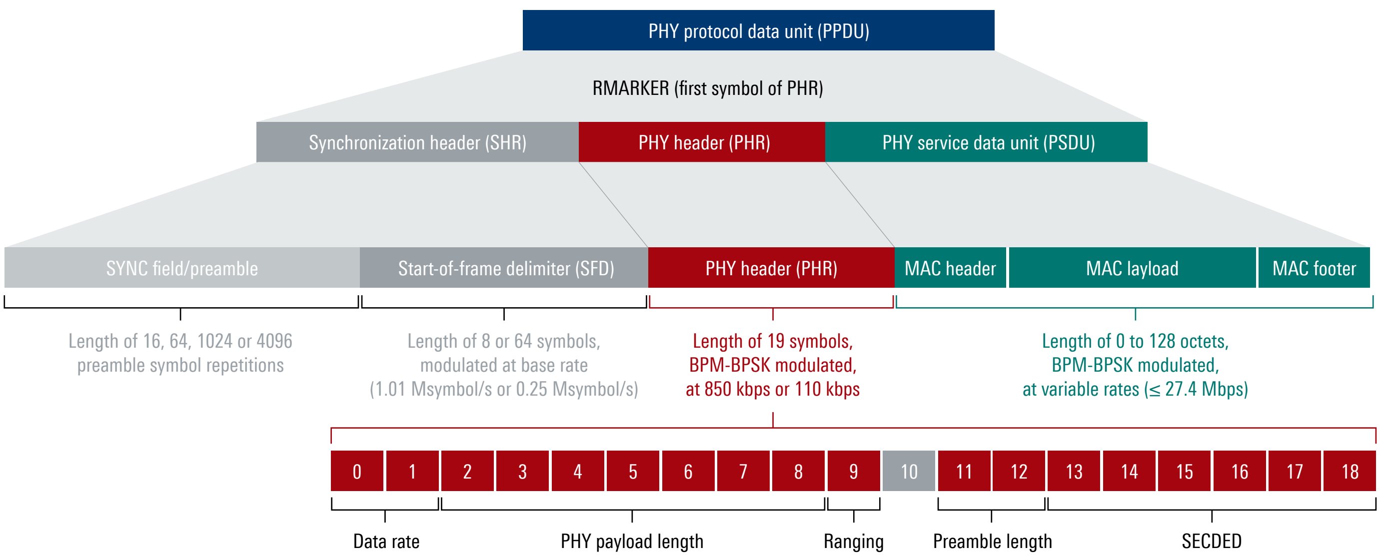
4.1 PPDU frame configurations

The PHY protocol data unit (PPDU) frame configuration of an RDEV is composed of the synchronization header (SHR), physical layer header (PHR) and physical layer service data unit (PSDU) as shown in Figure 4-1.

RMARKER stands for ranging marker. It is the first symbol of the PHR and serves as a reference for frame timestamping.

Each PPDU field is described in detail in the following chapters.

Figure 4-1: PPDU of HRP UWB RDEV (IEEE 802.15.4 [Ref. 3])



4.1.1 Synchronization header (SHR)

The SHR contains two subsections: SYNC field and start of frame delimiter (SFD).

4.1.1.1 SYNC field/preamble

The SYNC field, also known as preamble, is used for timing synchronization, packet detection, and carrier frequency offset recovery.

Each preamble symbol consists of a predefined preamble code sequence drawn from a ternary alphabet {–1,0,1}. IEEE 802.15.4 [Ref. 2] specifies length-31 and length-127 preamble code sequences. In Table 4-1, the length-31 preamble code sequences are listed with an individual index (1 to 8). The use of length-127 ternary preamble code sequences is optional; further information can be found in [Ref. 2]. In total, 16 length-127 ternary sequences indexed from 9 to 24 are defined.

RDEVs need to support two unique length-31 preamble code sequences for the implemented channels. The code sequence may only be used for the associated channel as given in Table 4-1.

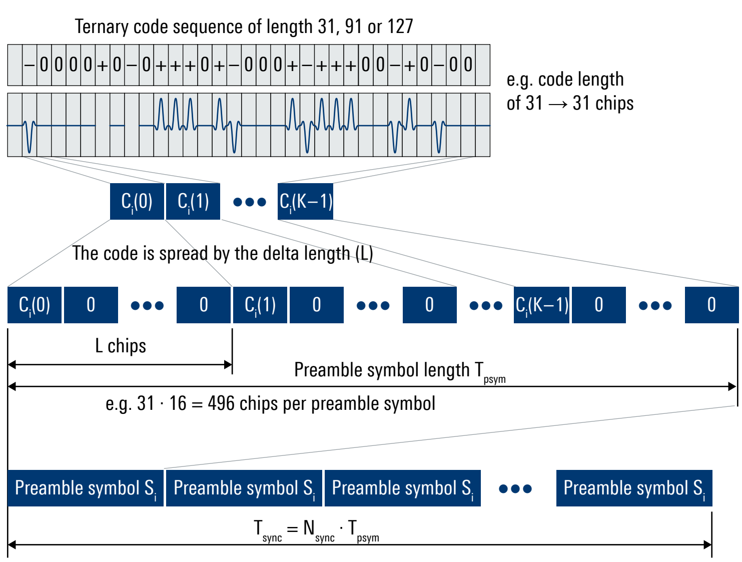
Table 4-1: Length-31 ternary preamble code sequence [Ref. 3]

Index	Code sequence C_i	Channel number [1)]
1	– 0 0 0 0 + 0 – 0 + + + 0 + – 0 0 0 + – + + + 0 0 – + 0 – 0 0	0, 1, 8, 12
2	0 + 0 + – 0 + 0 + 0 0 0 – + + 0 – + – – – 0 0 + 0 0 + + 0 0 0	0, 1, 8, 12
3	– + 0 + + 0 0 0 – + – + + 0 0 + + 0 + 0 0 – 0 0 0 0 – 0 + 0 –	2, 5, 9, 13
4	0 0 0 0 + – 0 0 – 0 0 – + + + + 0 + – + 0 0 0 + 0 – 0 + + 0 –	2, 5, 9, 13
5	– 0 + – 0 0 + + + – + 0 0 0 – + 0 + + + 0 – 0 + 0 0 0 0 – 0 0	3, 6, 10, 14
6	+ + 0 0 + 0 0 – – – + – 0 + + – 0 0 0 + 0 + 0 – + 0 + 0 0 0 0	3, 6, 10, 14
7	+ 0 0 0 0 + – 0 + 0 + 0 0 + 0 0 0 + 0 + + – – – 0 – + 0 0 – +	4, 7, 11, 15
8	0 + 0 0 – 0 – 0 + + 0 0 0 0 – – + 0 0 – + 0 + + – + + 0 + 0 0	4, 7, 11, 15

Each length-31 code sequence contains 15 zeros and 16 non-zero codes (denoted as "+" and "–" signs). 0 means no pulse, the "+" and "–" sign denote the pulse phase. Preamble code sequences have a perfect periodic auto correlation function observed by coherent and non-coherent receivers, meaning the sidelobes of the auto correlation function are zero and in between the peaks is the channel power delay profile (PDP). The code sequences minimize channel cross-correlation to reduce multi-user interference.

To meet each target (mean) PRF requirement, the preamble symbol S_i is constructed from a preamble code sequence C_i listed in Table 4-1. This is achieved by inserting L–1 zeros between each ternary element, where L is the length of the delta function δ_L. The possible value of L is chosen between 4, 16 and 64. Figure 4-2 illustrates the insertion procedure.

Figure 4-2: Construction of a preamble symbol S_i by spreading [Ref. 3]



$C_i()$	Preamble code sequence with code index i
K	Preamble code sequence length: 31, 127 or 91 (only for HRP ERDEV)
L	Spreading factor (length of delta function δ_L)
S_i	Preamble symbol after spreading containing K · L chips

[1)] Code index 1 to 6 may also be used for HRP UWB channel 4, 7, 11, 15 (channel bandwidth > 500 MHz) if inter-channel communication is desired.

For example, a length-31 preamble code sequence with delta length corresponding to 16 forms one preamble symbol which consists of 31 · 16 = 496 chips that corresponds to 993.59 ns. (1 chip duration ≈ 2.003 ns for a PRF of 499.2 MHz)

Table 4-2 lists possible configurations of SYNC parameters where the mandatory mean PRFs based on the length-31 preamble code sequence are 16.1 MHz and 4.03 MHz, which result in a base rate of 1.01 Msymbol/s and 0.25 Msymbol/s accordingly. Optionally, the length-127 preamble code sequence can be adopted which is emitted at 62.89 MHz mean PRF, and a base rate of 0.98 Msymbol/s can therefore be reached.

Table 4-2: Preamble timing parameters with length-31 and length-127 code sequences [Ref. 3]

Channel number	C_i code length	Peak PRF (in MHz)	Mean PRF (in MHz)	Delta length L	Number of chips per symbol [2)]	Symbol duration T_{psym} (in ns)	Base rate (in Msymbol/s)	Support
{0:15}	31	31.20	16.10	16	496	993.59	1.01	M
{0:15} except 4, 7, 11, 15	31	7.80	4.03	64	1984	3974.36	0.25	M
{0:15}	127	124.80	62.89	4	508	1017.63	0.98	O

To increase the receiver synchronization performance, the transmitted preamble symbol in the SYNC field needs to be redundant. The standard [Ref. 2] specifies 16, 64, 1024, or 4096 time repetitions of a preamble symbol S_i to construct the entire SYNC field. Higher 1024 and 4096 repetitions are preferred for non-coherent receivers, e.g. energy detection, to help them improve the signal-to-noise ratio (SNR) by means of processing gain [Ref. 3].

4.1.1.2 Start of frame delimiter (SFD)

The SFD signals the end of the preamble and start of the PHY header (PHR), which means that the receiver has to switch to BPM-BPSK modulation in order to receive the data. Furthermore, the SFD is also used to establish the frame timing, which is important for ranging accuracy.

As defined in [Ref. 2], the SFD supports 8 symbols (short) and optional 64 symbols (long) as shown in Table 4-3, depending on the subsequent transmitted data rate.

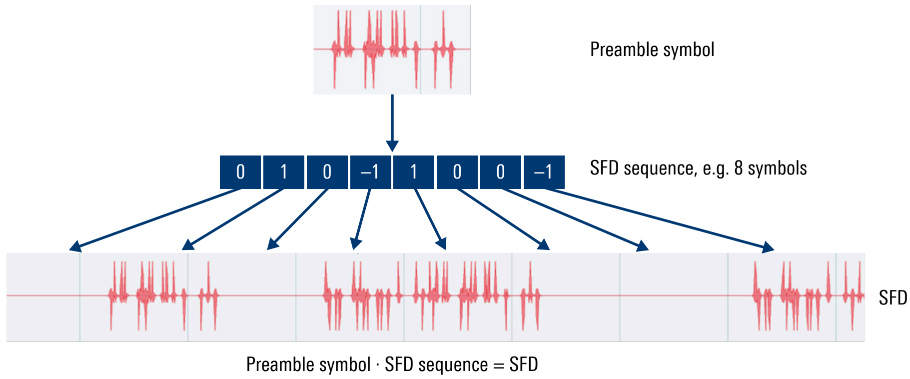
Table 4-3: SFD sequence of HRP-RDEV

Type	Code sequence	Applicability
64 symbols (long)	0 + 0 – + 0 0 – 0 + 0 – + 0 0 – – 0 0 + 0 – 0 + 0 + 0 0 0 – 0 – 0 – 0 0 + 0 – – 0 – + 0 0 0 0 + + 0 0 – – – + – + + 0 0 0 0 + +	for low data rate (110 kbit/s)
8 symbols (short)	0 + 0 – + 0 0 –	for other data rates

2) Chip duration is 2 ns.

Figure 4-3 explains SFD generation, where the SFD is constructed by spreading the SFD sequence with preamble symbol S_i. It has the same base rate as the SYNC field.

Figure 4-3: SED generation



4.1.2 PHY header (PHR)

The PHR consists of 19 bits. It conveys the necessary information for successful decoding to the receiver. Table 4-4 gives the PHR field format.

Table 4-4: PHR field format

Bit	Designation	Comment
0 to 1	data rate	indicates the data rate of the received PHY payload field (0.11 Mbit/s, 0.85 Mbit/s, 1.70 Mbit/s, 6.81 Mbit/s or 27.24 Mbit/s)
2 to 8	frame length	indicates the number of octets in the PSDU field (1 to 128 octets)
9	ranging	set to one if the current frame is an RFRAME for ranging or set to zero otherwise
10	reserved	
11 to 12	preamble duration	gives the length (in preamble symbols) of the SYNC field in the SHR (16, 64, 1024 or 4096)
13 to 18	SECDED[3]	Hamming block code that enables the correction of a single error and the detection of two errors at the receiver

The PHR is transmitted at 850 kbit/s for all PHY payload data rates greater than or equal to 850 kbit/s, and at 110 kbit/s when the PHY payload data is transmitted at 110 kbit/s.

Information bits are modulated by combined BPM-BPSK modulation, where BPM stands for burst position modulation (for details, see chapter 4.2).

4.1.3 PHY service data unit (PSDU)

The PSDU is known as the PHY payload whose data is passed from MAC frames to the PHY via the PHY service access point (SAP). For HRP UWB PHY devices, only the admissible transmission data rates are allowed (see Appendix B.1 or [Ref. 2]).

The mean PRF plays a central role in the payload data rate. It is defined as the total number of pulses emitted during a symbol period divided by the length of the symbol period. There are three possible mean PRFs, i.e. 15.6 MHz, 3.90 MHz and 62.4 MHz in line with the standard [Ref. 2]. Depending on the preamble code length, the compliant device shall support a mean PRF of 15.6 MHz and 3.90 MHz when a length-31 preamble code is applied. Optionally, a length-127 preamble code can be adopted which yields a mean PRF of 62.4 MHz.

[3] SECDED: single error correct, double error detect; it is calculated from b0 to b12 of the PHR [Ref. 2].

With each target mean PRF, the RDEV bit rate can be scaled by configuring a different number of chips per burst. This approach enables RDEV bit rates of 0.11 Mbit/s, 0.85 Mbit/s, 6.81 Mbit/s and 27.24 Mbit/s. RDEV devices must support at least 0.85 Mbit/s.

Table 4-5 summarizes the bit rate correlation and associated parameters. All PSDU timing parameters can be found in [Ref. 2] or Appendix B.1 of this paper.

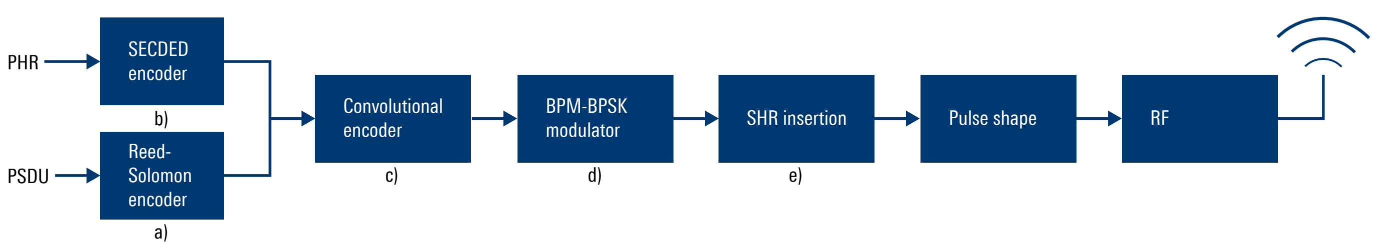
Table 4-5: PSDU data bit rate versus mean PRF

Mean PRF (in MHz)	Preamble code length	Number of burst positions per symbol [4]	Number of chips per burst	Admissible bit rate (Mbit/s)	Support
15.60	31	32	{128, 16, 2, 1}	{0.11, 0.85, 6.81, 15.60}	M
3.90 [5]	31	128	{32, 4, 2, 1}	{0.11, 0.85, 1.70, 6.81}	M
62.40	127	8	{512, 64, 8, 2}	{0.11, 0.85, 6.81, 27.24}	O

4.2 RDEV FEC coding and modulation

The entire PPDU of the RDEV, including the PHR and PSDU, is encoded and processed following the steps shown in Figure 4-4 [Ref. 2].

Figure 4-4: HRP UWB PHY signal flow [Ref. 2]



a) Apply Reed-Solomon encoding to the PHY payload (PSDU) part; for details, see chapter 15.3.3.2 of [Ref. 2].

b) Generate the PHR as described in chapter 15.2.7 of [Ref. 2], include the single error correct, double error detect (SECDED) field and prepend it to the PSDU.

c) Perform further convolutional coding as described in chapter 15.3.3.3 of [Ref. 2]. Note that in some instances at the 27 Mbit/s data rate, the convolutional encoding of the PHY payload field is effectively bypassed and two data bits are encoded per BPM-BPSK symbol.

d) Modulate and spread the PSDU according to the method described in chapter 15.3.1 and chapter 15.3.2 of [Ref. 2]. The PHR is modulated using BPM-BPSK at either 850 kbit/s or 110 kbit/s and the PHY payload field is modulated at the rate specified in the PHR.

e) Generate the SHR field from the SYNC field and SFD, as described in chapter 4.1.1.

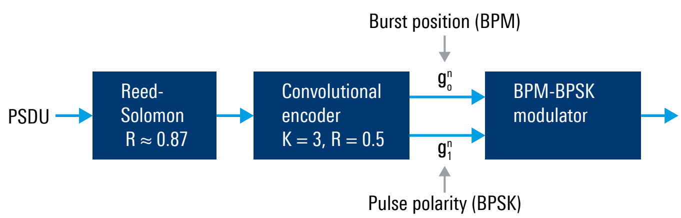
[4] Mean PRF= 1/(number of burst position per symbol · T_C), where pulse duration T_C is approximately 2 ns.
[5] Channel 4, 7, 11 and 15 do not support 3.90 MHz mean PRF.

4.2.1 Forward error correction coding

Figure 4-4 shows that the processing procedures for the PHR and PSDU are slightly different. The PHR incorporates the extended Hamming code known as SECDED to detect and correct the transmission error. As shown in Figure 4-5, the PSDU uses forward error correction (FEC) by concatenating an outer Reed-Solomon (RS) block code with a code rate of roughly 0.87 and an inner half-rate convolutional encoder (Viterbi rate R = 0.5). With a half-rate convolutional encoder, the overall FEC code rate reaches approximately 0.44. The convolutional encoder may be bypassed in some cases to achieve higher transmission data rates (Viterbi rate R = 1).

The PHR with SECDED followed by the bit streams from the PSDU after RS coding are sequentially fed into the convolutional encoder. Further details about convolutional coding can be found in [Ref. 2].

Figure 4-5: PSDU encoding process



4.2.2 Modulation

Only the PHR and PSDU of the PPDU can use combined BPM-BPSK modulation. The information is encoded in the burst position (burst position modulation or BPM) and in the burst phase (binary phase shift keying or BPSK).

In the BPM-BPSK modulation scheme as shown in Figure 4-6, each symbol carries two information bits from the convolutional encoder: one bit g_0^n (systematic bit) is used to determine the pulse burst position, and the other bit g_1^n (parity bit) is used to determine the polarity of the same burst. This modulation method enables both coherent and noncoherent receivers to be supported by the standard. Non-coherent receivers such as the energy detector and auto correlation receiver multiply the received signal with itself followed by an integration and thus can only obtain the signal envelope. This causes loss of phase information and only the information encoded in the burst position is usable. Rake receivers are able to exploit the phase information of the received signal. As a result, also the information encoded in the burst phase can be used to provide higher coding gain and improve robustness [Ref. 5].

Figure 4-6: BPM-BPSK modulation scheme

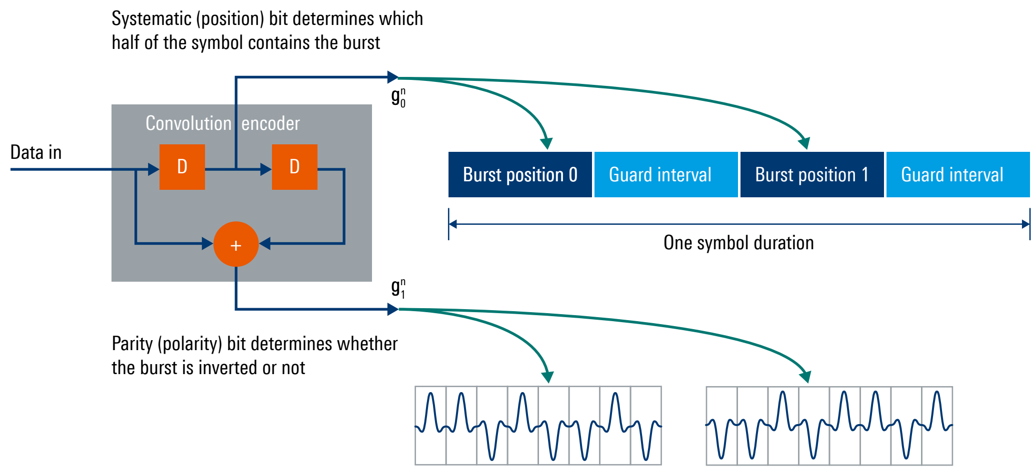
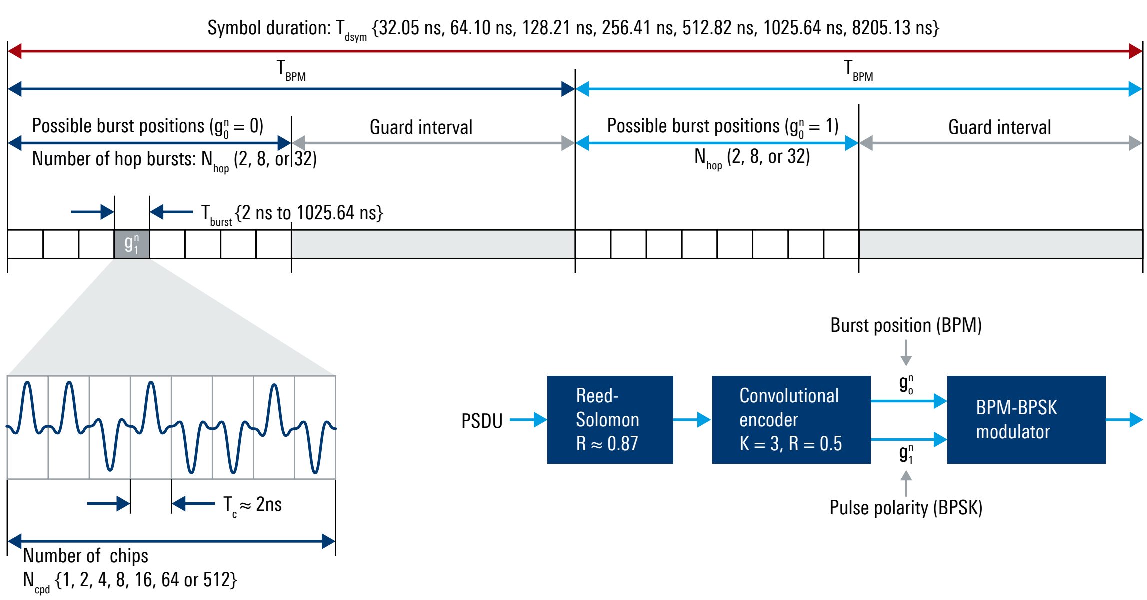


Figure 4-7 shows the BPM-BPSK modulation structure and possible symbol timing parameters.

Figure 4-7: HRP UWB PHY BPM-BPSK modulation structure and timing



4.2.2.1 Burst position modulation (BPM)

BPM is a time based modulation scheme. A UWB symbol is transmitted within the symbol duration T_{dsym}. The symbol duration is subdivided into two BPM intervals each with duration $T_{BPM} = T_{dsym}/2$. Every BPM interval is further divided into two halves. UWB bursts are only allowed to be transmitted in the first half of the BPM interval. The second half of each BPM interval serves only as guard interval to mitigate the amount of inter symbol interference (ISI) caused by multipath. The systematic bit g_0^n from the convolution encoder determines which burst position is to be in the first or second BPM interval ($g_0^n = 0$: first BPM interval; $g_0^n = 1$: second BPM interval).

The T_{BPM} duration is further segmented into multiple possible burst positions N_{hop}. For example, eight possible hop burst positions can be configured, as shown in Figure 4-7. In each symbol, the UWB burst is transmitted in only one of the possible burst positions N_{hop}, which can vary on a symbol-to-symbol basis following a time hopping (TH) code. The use of a TH code provides resistance to multi-user interference in cases where all users have their own TH code. Such a TH code is generated by a scrambler defined in [Ref. 2].

4.2.2.2 BPSK modulation

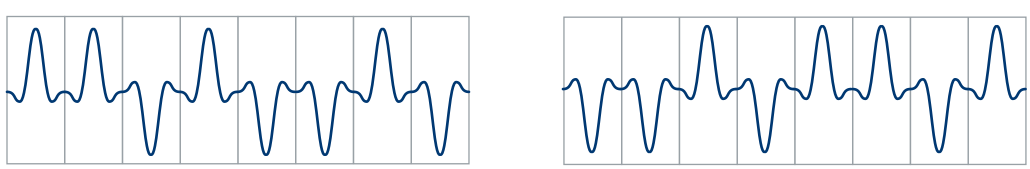
Each transmitted burst is scrambled by N_{cpb} chips which have a positive or negative polarity as determined by the time-varying spreader sequence generated by a PRBS scrambler (see chapter 15.3.2 in [Ref. 2]). The polarity of each chip is chosen in such a way that the spectrum of the transmitted waveform is smoothened [Ref. 6]. The chip scrambling operation also provides some extra interference suppression among coherent receivers [Ref. 2].

Note that the polarity of the burst as a whole is determined by the polarity bit g_1^n.

Each chip duration T_C is 2 ns, which corresponds to a peak PRF of 499.2 MHz.

Figure 4-8 shows an example of BPSK modulation where eight chips N_{cpb} are contained in one burst (the polarity of each chip is determined by the scrambler). The overall polarity of the burst is determined by g_1^n.

Figure 4-8: BPSK modulation ($N_{cpb} = 8$)



Positive burst polarity ($g_1^n = 0$) Negative burst polarity ($g_1^n = 1$)

5 HRP UWB ERDEV (IEEE 802.15.4z)

As a supplement to the IEEE 802.15.4 [Ref. 2] standard, IEEE 802.15.4z [Ref. 7] meets the ever increasing demands of highly secure, high-precision ranging. The key enhancements in [Ref. 7] are:

- Inclusion of the scrambled timestamp sequence (STS) field in the HRP PPDU format
- PRF increment applied for preamble and data field

Devices supporting these enhancements are called HRP enhanced ranging devices (ERDEV). The two following mandatory functions must be supported:

- Operation in base pulse repetition frequency (BPRF) mode at a nominal PRF of 64 MHz
- Operation in higher pulse repetition frequency (HPRF) mode at a higher PRF of 124.8 MHz or 249.6 MHz

The HPRF mode allows the device to reduce the total on-air transmission using its higher data rate capability. This has an impact on the following system performance [Ref. 8]:

- Increased radio channel capacity
- Increased battery life
- Less interference among UWB devices
- Increased security – smaller time window for malicious attacks

In this chapter, ERDEV-related enhancements are highlighted.

5.1 PPDU frame configurations

5.1.1 SHR (preamble and SFD)

ERDEVs must support additional length-91 preamble code sequences. The 8 codes which are indexed from 25 to 32 correspond to length-91 preamble codes (see [Ref. 7] Table 42).

Each length-91 preamble code is spread to generate preamble symbols by means of delta function δ_L whose length L is fixed to 4. Therefore, each preamble symbol S_i always consists of 364 chips, which translates to 729 ns.

The final SYNC field is scaled by the number of preamble symbol repetitions, selected from the mandatory values 32 and 64, and the optional values 16, 24, 48, 96, 128 and 256.

The preamble timing parameters of ERDEV devices are shown in Table 5-1. As we can see, the base rate is now extended to 1.37 Msymbol/s in comparison to RDEVs (1.01 Msymbol/s and 0.25 Msymbol/s with length-31 preamble).

Table 5-1: Preamble timing parameters with length-91 preamble code sequence [Ref. 7]

C_i code length	Peak PRF	Mean PRF	Delta length L	Number of chips per symbol	Symbol duration T_{psym}	Base rate
91	124.8 MHz	111.09 MHz	4	364	729.17 ns	1.37 Msymbol/s

In the SFD portion of the SHR, [Ref. 7] introduces the five SFD numbers from 0 to 4. Table 5-2 gives an overview of the ERDEV SFDs and their applicability with respect to ERDEV mode.

Table 5-2: SFD sequence of HRP-ERDEV

SFD number	SFD length	SFD sequence	HRP-ERDEV mode
0	8	8 symbol short SFD of HRP-RDEV[6]	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)

The spreading procedure is the same as that defined for the legacy RDEV (see chapter 4.1.1.2); the SFD sequence of the ERDEV is spread by the preamble symbol S_i.

Devices operating in ERDEV BPRF mode with the SFD number 0 and STS packet configuration 0 (without STS, see STS in chapter 5.1.3) are downwardly compatible with RDEVs.

5.1.2 PHR and PSDU

5.1.2.1 BPRF mode

In BPRF mode, the PHR frame format is the same as the legacy RDEV, but differs with respect to the modulation rate. The PHR is now modulated using BPM-BPSK at 850 kbit/s or optionally 6.8 Mbit/s. The PSDU modulation rate is again specified in the PHR as it is in the case of the RDEV.

The supported PHR bit rate in BPRF mode is listed in Table 5-3 (details on the timing parameters can be found in Appendix C.1).

Table 5-3: PHR and PSDU data rate in HRP-ERDEV BPRF mode

PHR data rate mode	PHR bit rate	PSDU bit rate
DRBM_LP	975 kbit/s (850 kbit/s nominal)	6.8 Mbit/s
DRBM_HP	7.8 Mbit/s (6.8 Mbit/s nominal)	6.8 Mbit/s

5.1.2.2 HPRF mode

HPRF mode features a new PHR frame format (see Table 5-4).

Table 5-4: PHR format in HPRF mode

Bit	Designation	Comment
0	A1	functionality bit
1	A0	functionality bit
2 to 11	PHY payload length	indicates the number of octets in the PSDU field (0 to 1023 octets)
12	ranging	set to one if the current frame is an RFRAME or set to zero otherwise
13 to 18	SECDED[7]	a simple Hamming block code that enables the correction of a single error and the detection of two errors at the receiver

[6] See Table 4-3.

[7] SECDED: single error correct, double error detect; it is calculated from b0 to b12 of the PHR [Ref. 2].

The A0 and A1 functionality bits may be optionally used to signal an additional gap between the payload and the scrambled timestamp sequence (STS), when STS packet configuration 2 is adopted (for STS, see chapter 5.1.3). Alternatively, the A0 and A1 bit can be used to extend the PHY payload length field to max. 12 bits, which corresponds to the maximum PHY payload size of 4096 octets.

Table 5-5 lists the possible PHR and PSDU data rates in HPRF mode. Two data rate modes (DRHM_LR and DRHM_HR) are defined. Each can choose the Viterbi constraint length (CL) of the convolution encoder between 3 and 7. Among these predefined configurations, the maximum achievable data rate can reach about 31 Mbit/s. See Appendix C.2 for details on the HPRF mode timing parameters.

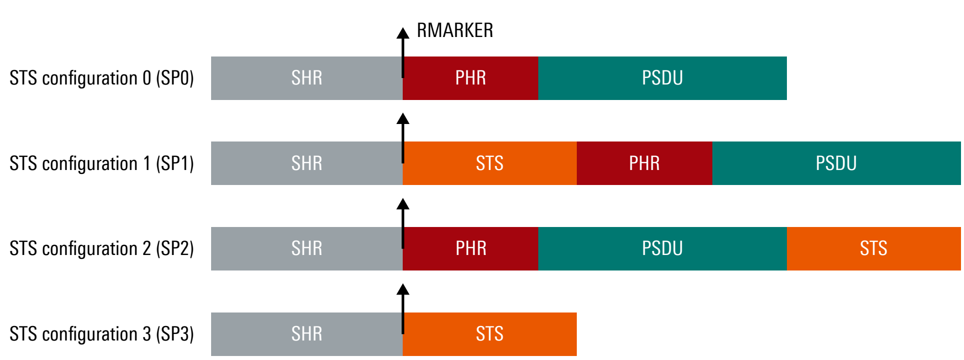
Table 5-5: PHR and PSDU data rate in HRP-ERDEV HPRF mode

PHR data rate mode	Viterbi constraint length	PHR bit rate	PSDU bit rate	Mean PRF
DRHM_LR	CL3	3.9 Mbit/s	6.8 Mbit/s	124.8 MHz
DRHM_LR	CL7	7.8 Mbit/s	7.8 Mbit/s	124.8 MHz
DRHM_HR	CL3	15.6 Mbit/s	27.2 Mbit/s	249.6 MHz
DRHM_HR	CL7	31.2 Mbit/s	31.2 Mbit/s	249.6 MHz

5.1.3 Scrambled timestamp sequence (STS)

IEEE 802.15.4z introduced a new frame structure by incorporating a scrambled timestamp sequence (STS), which is basically a pulse sequence generated using the AES-128 algorithm and then added to the HRP UWB PHY frame structure. Only the receiver that knows the correct seed will generate its own sequence, and the cross-correlation with the untampered received sequence will exceed a certain match level threshold. This enables estimation of the channel impulse response (CIR) used to detect malicious attacks and increase the integrity and accuracy of ranging measurements performed by the ERDEV.

Figure 5-1: Scrambled timestamp sequence (STS) packet configurations



Introduction of the STS extends the frame structure inherited from the RDEV to four frame configurations, as shown in Figure 5-1.

Configuration 0 has no STS and is used for BPRF mode (backwardly compatible to the legacy RDEV) or HPRF mode without security. Configurations 1 and 2 differ with respect to STS positions. Configuration 1 places the STS portion ahead of the PSDU and PHR to avoid STS timing dependency on PSDU length. Configuration 2 is intended to provide backward compatibility in the case of a mean PRF of 62.4 MHz and a legacy PHR data rate. Configuration 3 is the PPDU without the PHY header and PHY payload transmitted. It is intended for use cases where secure ranging exchange participants are known to each other such that information about source and/or destination is implicit in the knowledge of which STS is used for transmission and reception between the connected devices [Ref. 9]. Support of all configurations is mandatory, with exception of configuration 2.

In each STS packet configuration, the RMARKER plays the same role as it does for the legacy RDEV, i.e. it serves as a reference point for frame timestamping.

Figure 5-2 illustrates the concept of how the STS sequence is generated and formed. A sequence of pseudo randomized pulses is generated using a deterministic random bit generator (DRBG) based on the AES-128 algorithm. Each bit of value zero from the DRBG produces a positive polarity pulse and each bit of value one produces a negative polarity pulse. The 128-bit pulse sequence is spread by the spread length L, e.g. 4 in HPRF mode, to avoid interpulse interference. As a result, the pulse sequence being spread is assembled in the numeral units in a segment (512 chips in each unit) and a series of active segments encapsulated between silent intervals known as "gaps" (approx. 1 µs duration) can be formed. In HPRF, up to 4 active segments can be supported. The STS parameters for BPRF and HPRF mode are listed in Table 5-6.

Figure 5-2: STS generation (with spread length 4, HPRF)

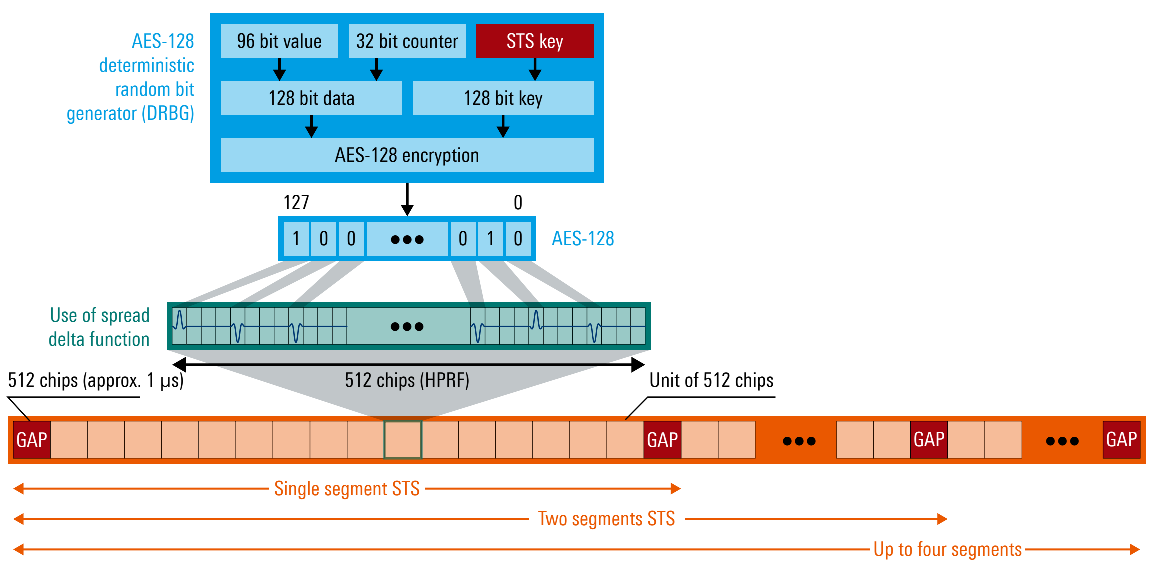


Table 5-6: STS parameters

HRP-ERDEV mode	Spread length L	Pulse spacing	Mean PRF	Unit per segment	Number of supported segment
BPRF	8	8 chips	62.4 MHz	64	1
HPRF	4	4 chips	124.8 MHz	32, 64, 128, optional: 16, 2569	1, 2, 39, optional: 3, 49

The transmitter and the target receiver should have the same 128-bit initial value and 128-bit STS key, which are managed and synchronized by the higher layer. This mechanism provides better security against malicious attacks or accidental interference.

The mean PRF for the STS field can be increased to 124.8 MHz in HPRF mode. This provides a larger entropy/time ratio and increases the achievable dynamic range in channel estimation [Ref. 10].

5.2 ERDEV FEC encoding and modulation

5.2.1 Convolutional encoding

The FEC procedure of ERDEVs in BPRF mode remains the same as for legacy RDEVs.

For HPRF mode, the standard [Ref. 7] additionally defines an optional constraint length (CL) 7 convolutional encoder. In this case, the PSDU part bypasses Reed-Solomon encoding. The final bit rate of the PHR and PSDU remains the same when the CL7 convolutional encoder is adopted (see Table 5-5 and Appendix C.2 details)

A summary of the FEC encoding combination is given in Table 5-7. Note that the PHR and PSDU use the same convolution encoder, either both with CL3 or CL7.

Table 5-7: Combination of PHR/PSDU encoding in HPR-ERDEV in HPRF mode

Field	Reed-Solomon encoding	Constraint length of convolutional encoder
PHR	no	CL3/CL7
PSDU	yes	CL3
PSDU	no	CL7

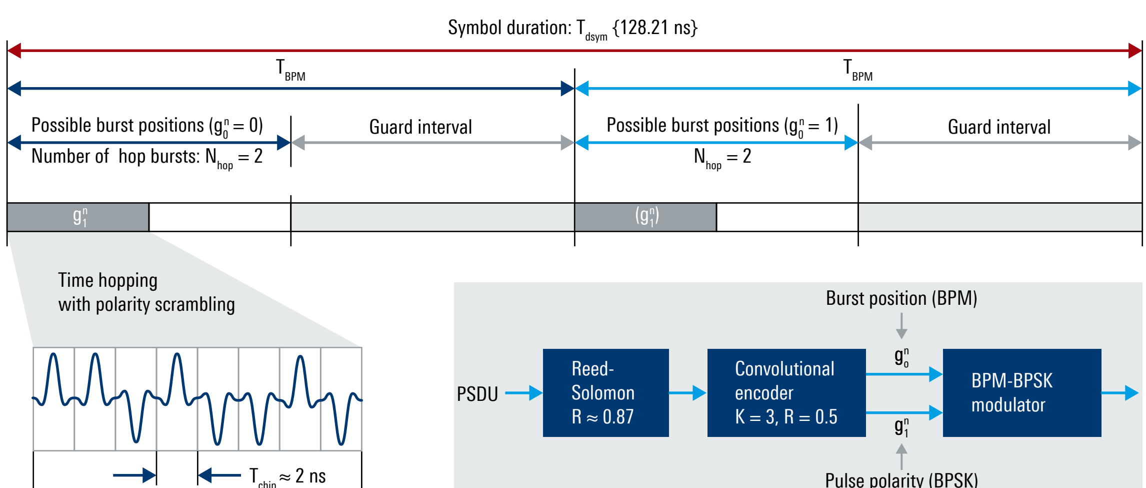
5.2.2 Modulation

5.2.2.1 BPRF mode

The same combined BPM-BPSK modulation scheme as described in chapter 4.2.2 is utilized by the ERDEV in BPRF mode to modulate the PHR and PSDU.

Figure 5-3 shows the BPM-BPSK modulation and the timing parameters for the PSDU. BPRF mode is equivalent to the legacy RDEV operating at a mean PRF of 62.4 MHz with 8 chips per burst. All of the timing parameters are listed in Appendix C.1.

Figure 5-3: Modulation of HRP-ERDEV BPRF mode



Peak PRF	Chips per symbol	Pulses per burst	FEC	Bit rate	Mean PRF
499.2 MHz	64	8	0.435	6.8 Mbps	62.4 MHz

5.2.2.2 HPRF mode

HPRF mode facilitates two data rate modes, DRHM_LR mode (mean PRF 124.8 MHz) and DRHM_HR mode (mean PRF 249.6 MHz). The resulting modulation parameters are listed in Table 5-8.

Table 5-8: Modulation parameters for PSDU in HRP-ERDEV HPRF mode [Ref. 2]

Data rate mode	Peak PRF	Mean PRF	Number of pulses per data symbol	Number of chips per data symbol	Data symbol duration	Data symbol rate	Bit rate, Reed-Solomon used, CL3	Bit rate, Reed-Solomon not used, CL7
DRHM_HR	499.2 MHz	249.6 MHz	8	16	32.05 ns	31.2 MHz	27.24 Mbit/s	31.2 Mbit/s
DRHM_LR	249.6 MHz	124.8 MHz	16	64	128.21 ns	7.8 MHz	6.81 Mbit/s	7.8 Mbit/s

Since the HPRF receiver employs the coherent receiver architecture [Ref. 10], only BPSK modulation is adopted.

The timing and structure of a symbol is similar to BPM-BPSK, which means that each symbol is divided into two intervals. In each of the intervals, the symbol is further segmented into two subintervals where the burst is only transmitted in the first half of the interval. The second half serves as a guard interval to mitigate interpulse interference. Figure 5-6 and Figure 5-7 show the timing arrangement.

As shown in Figure 5-4, two convolutional encoder output bits g_0^n and g_1^n determine the bit pattern of the 1st and 2nd burst. The mapping between them depends on the selected data rate mode and applied convolutional encoder constraint length (CL3 or CL7). The corresponding mapping tables are defined in chapter 15.3.4.2 and chapter 15.3.4.3 of [Ref. 7]. The burst bit pattern is then scrambled by the time-varying spreading sequence as shown in Figure 5-5. The "0" in the burst bit pattern stands for the positive polarity of the pulse, whereas "1" stands for the negative polarity.

Figure 5-4: FEC of HRP-ERDEV HPRF mode

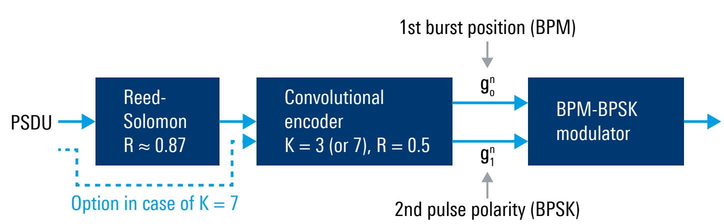


Figure 5-5: Scrambled pulse sequence

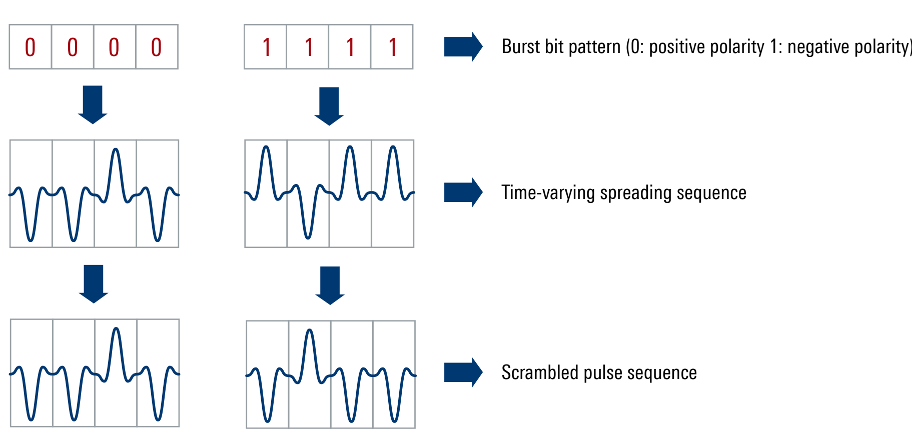


Figure 5-6 and Figure 5-7 show PSDU modulation in data rate mode DRHM_HR (mean PRF 249.6 MHz) and DRHM_LR (mean PRF 124.8 MHz), respectively. As we can see, modulation in both data rate modes has commonality. Independent of the selected data rate mode, two bursts are used for transmitting the pulse. The difference lies in the fact that, on one hand, the number of pulses per data symbol in DRHM_LR mode doubles compared to DRHM_HR but, on the other hand, the chipping rate of DRHM_LR is half that in DRHM_HR mode. This results in a data symbol duration in DRHM_LR mode that is four times longer than in DRHM_HR mode (see Table 5-8 for data symbol duration).

Figure 5-6: PSDU modulation of HRP-ERDEV HPRF mode at mean PRF 249.6 MHz (in DRHM_HR mode)

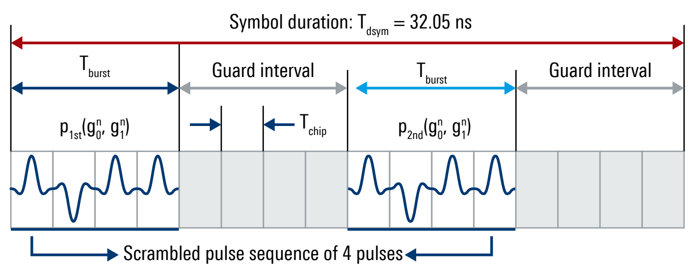
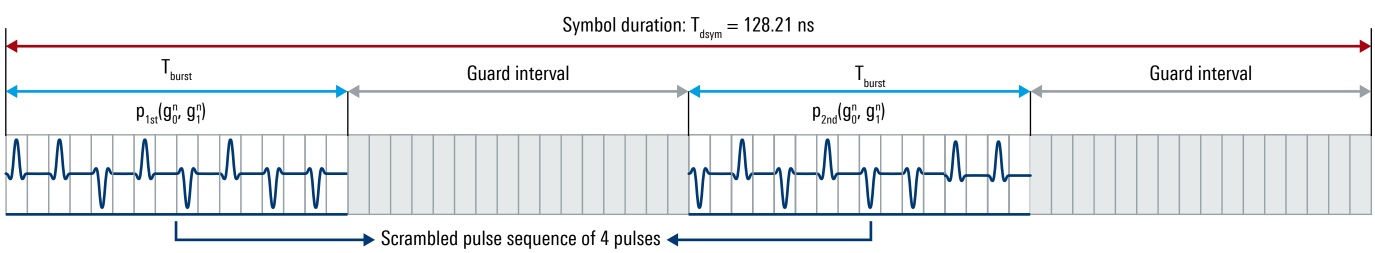


Figure 5-7: PSDU modulation of HRP-ERDEV HPRF mode at mean PRF 124.8 MHz (in DRHM_LR mode)



For PHR modulation with applied CL3 convolutional encoder, each set of convolutional encoder output bits g_0^n and g_1^n is mapped to two consecutive data symbols (the second data symbol replicates the first one). This results in a symbol duration twice that of the PSDU. Therefore, the data symbol rate is half that of the PSDU. The final achievable PHR bit rate is shown in Table 5-5.

If the optional CL7 is applied, Reed-Solomon encoding for the PSDU is bypassed, and modulation of the PHR has to follow the same scheme as given in Figure 5-6 or Figure 5-7. Therefore, the final PHR and PSDU bit rate is the same in this case (see Table 5-5).

Based on the applied data rate mode together with the adopted CL of the convolutional encoder, four different bit rates of the PHR/PSDU in HPRF mode are realized (see Table 5-5 and Table 5-8).

The overall timing parameters for both the PHR and PSDU in HPRF mode can be found in Appendix C.2.

6 TIME-OF-FLIGHT (ToF) ESTIMATION

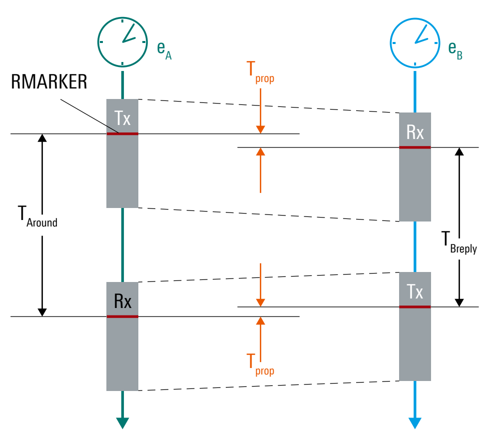
UWB technology adopts time-of-flight (ToF) methods for distance ranging. ToF is basically the time the signal needs to travel between the initiator and receiver in free space. It is based on the reliable and robust ranging timestamp.

Two-way ranging (TWR) is a common method to measure the distance between two UWB devices, particularly when clock synchronization between them is absent. In other words, each device uses its own clock reference to perform the measurements independently. If the ToF between the two devices is known, the distance can be easily calculated as the ToF multiplied by the speed of light.

There are two different TWR flavors described in the following sections: single-sided two-way ranging (SS-TWR) and double-sided two-way ranging (DS-TWR). With the amendment in [Ref. 7], the ranging capability is further enhanced to support secure ranging by including STS to prevent distance fraud attacks in which an attacker influences the distance estimation process.

6.1 Single-sided two-way ranging (SS-TWR)

Figure 6-1: Single-sided two-way ranging



$$T_{prop} = \frac{T_{Around} - T_{Breply}}{2}$$

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

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

As shown in Figure 6-1, device A (tag) wants to determine the distance to device B (anchor) by estimating the ToF. It sends a poll message in a ranging frame (the RFRAME flag is set in the PHR) to device B and receives the response message returned by device B. RMARKER is defined to be the time at which the beginning of the first symbol of the RFRAME set in the PHR is at the local antenna. It functions like a stopwatch to measure the round trip time of a message.

Several time differences are measured or calculated. T_{prop} is the over-the-air propagation time. T_{Around} and T_{Breply} are processing times measured independently by device A and B using their own local clock. The measured T_{Breply} is piggy-backed in the response message from device B to A. If T_{Around} and T_{Breply} are known, device A can calculate its ToF using the formula

$$T_{prop} = \frac{T_{Around} - T_{Breply}}{2}$$

The distance corresponds to $c_{AIR} \cdot T_{prop}$, where c_{AIR} is the speed of light, i.e. 29.97 cm/ns.

SS-TWR does not require a synchronized clock on both the transmitter side and receiver side. In reality, however, the ToF estimation error calculated in Equation 2 is caused due to the clock jitter or clock offset error generated on both sides by clock oscillator imperfection. The reply time T_{Breply} is the dominant factor of the distance estimation error. T_{Breply} is determined by the packet length as well as the processing speed of the responder. It can be in the order of milliseconds, causing estimation errors of several meters [Ref. 5].

Equation 2: Distance estimation error due to clock offset error

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

$$Error = 0.5 \cdot \left(e_B \cdot T_{Breply} - e_A \cdot T_{Around}\right)$$

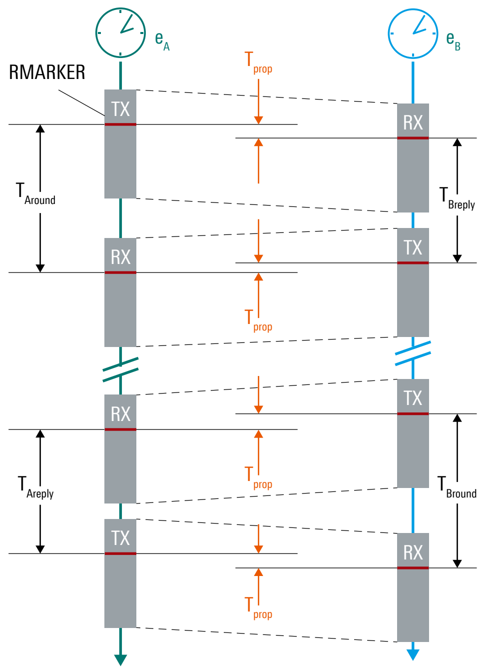
where e_A and e_B are clock offset errors.

A key advantage of SS-TWR lies in the fact that it requires two message exchanges instead of three or four messages, which is the case with DS-TWR, and the overall on-air time is reduced. This helps prolong the battery life of the UWB device and, of course, also increases the channel capacity.

6.2 Double-sided two-way ranging (DS-TWR)

Like SS-TWR, DS-TWR is an asymmetrical ranging method, which means that the response times do not need to be the same on both devices. It is a combination of two SS-TWR procedures which differs with respect to the direction of initiation.

Figure 6-2: Double-sided two-way ranging



$$T_{prop} = \frac{T_{Around} \cdot T_{Bround} - T_{Areply} \cdot T_{Breply}}{T_{Around} + T_{Bround} + T_{Areply} + T_{Breply}}$$

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

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

Figure 6-2 shows the DS-TWR principle. The whole procedure is initiated by device A (tag) towards device B (anchor). Device B sends a response to device A and, in the same way, device B initiates a second round SS-TWR towards device A. The whole procedure is completed after device B receives the response from device A. Usually, the poll message and response message from device B towards device A can be combined into one message. Therefore, DS-TWR involves practically three messages in total.

The resultant ToF estimation is

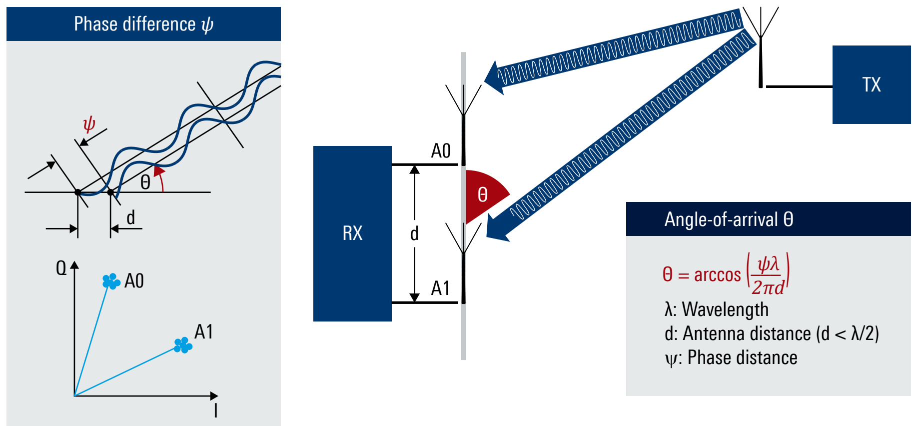
$$T_{prop} = \frac{T_{Around} \cdot T_{Bround} - T_{Areply} \cdot T_{Breply}}{T_{Around} + T_{Bround} + T_{Areply} + T_{Breply}}$$

If the ToF estimation T_{prop} is known, the distance can be calculated based on the same principle as with SS-TWR, i.e. the estimated ToF is multiplied by the speed of light to determine the distance. Compared to SS-TWR, the impact of clock offset on the ToF estimation is significantly reduced. The estimation error in DS-TWR solely depends on the ToF, but not on T_{Breply} as is the case with SS-TWR [Ref. 5].

However, the obvious drawback of DS-TWR is that it requires higher power consumption than the SS-TWR procedure due to increased computational effort.

7 ANGLE-OF-ARRIVAL (AoA) ESTIMATION

Figure 7-1: Concept of angle-of-arrival (AoA)



The angle-of-arrival (AoA) estimation based on the phase array technique is an object location method. Like with other radio technologies (e.g. Bluetooth®, Wi-Fi), AoA functionality is a key feature of the UWB based real-time locating system (RTLS). It provides additional information to enable positioning. In theory, a device can be located by combining ToF and AoA. Typical AoA applications include asset tracking, healthcare monitoring and campus security.

The basic principle of AoA is explained in Figure 7-1. The AoA transmitter (tag) emits a UWB pulse signal using a single antenna. The AoA receiver (anchor) employs multiple antennas in an antenna array, typically a uniform linear array (ULA) with a minimum of two antenna elements. In our example, two antenna elements A0 and A1 are deployed at a distance d apart. Due to the difference in propagation length between the transmitter (tag) and each antenna element on the receiver side, a phase difference ψ arises which can be analyzed within the receiver. The difference in propagation length between the consecutive antenna elements can therefore be denoted as $\psi\lambda/2\pi$, where λ is the wavelength of the operating frequency of the UWB signal, e.g. 3.75 cm for channel 9. Finally, the AoA θ is determined by calculating $\theta = arccos\,(\psi\lambda/2\pi d)$. AoA can be extended to allow 3D positioning, which includes the azimuth and elevation angles. There are few drawbacks of AoA positioning: it is quite sensitive to non-line-of-sight (NLOS) conditions and multipath signal propagation, and the distance between the AoA tag and anchor is limited to just a few meters in order to maintain reasonable accuracy.

8 TEST ASPECTS FOR HRP UWB PHY

8.1 Regulatory requirements

Like other radio technologies, crucial RF characteristics of the HRP UWB PHY have to comply with the norms mandated by the regulatory authorities to ensure that the device under test (DUT) does not emit excessive power that could cause interference in other devices operating in the same frequency band.

Some of the regulatory norms are listed in Table 8-1.

Table 8-1: Regulatory norms for UWB PSD testing

Regulatory norm	Designation
ETSI EN 303883	short range devices (SRD) and ultrawideband (UWB)
ETSI EN 302065	electromagnetic compatibility and radio spectrum matters (ERM); short range devices (SRD) using ultrawideband (UWB) technology
FCC CFR 47, part 15.250	operation of wideband systems in the 5925 MHz to 7250 MHz band
FCC CFR 47, part 15.5xx	UWB technical requirements and measurement techniques

The maximum allowable output power spectral density (PSD) of UWB devices must be in line with the standards of the relevant regulatory bodies. For example, ETSI EN 302065 requires that the maximum allowable output power spectral density of a UWB device should not exceed –41.3 dBm/MHz.

8.2 Conformance requirements

The standard [Ref. 7] and [Ref. 2] specifies transmitter and receiver conformance test cases to ensure minimum quality requirements of UWB products and interoperability between UWB devices. Furthermore, the ranging feature of UWB devices needs to be verified, in particular DUT ToF measurement accuracy.

Some fundamental conformance requirements are explained below.

8.2.1 Normalized cross-correlation

The transmitted pulse shape p(t) shall be constrained by the shape of its cross-correlation function with a standard reference pulse, r(t), which is a root raised cosine pulse with a roll-off factor of $\beta = 0.5$ (see also chapter 3.3).

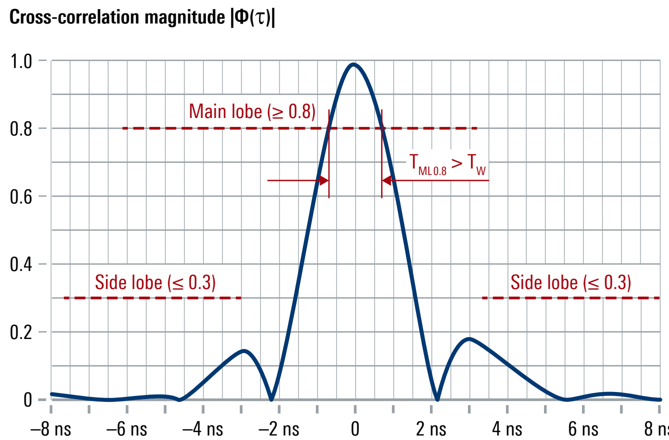
The normalized cross-correlation function $\Phi(\tau)$ between the actual transmitted pulse p(t) and the ideal pulse shape r(t) can be used to verify the conformance of a pulse emitted by a UWB device.

The magnitude of the normalized cross-correlation function $|\Phi(\tau)|$ has a mainlobe which is greater than or equal to 0.8 for a mainlobe width duration of at least T_w, as defined in Table 8-2, and any sidelobe magnitude shall be no greater than 0.3. This compliance requirement is graphically represented in Figure 8-1.

Table 8-2: Requirement of UWB pulse duration and mainlobe width in each channel

Channel number	Pulse duration, T_p	Mainlobe width, T_w
All (except 4, 7, 11 and 15)	2 ns	0.5 ns
7	0.92 ns	0.2 ns
4 and 11	0.75 ns	0.2 ns
15	0.74 ns	0.2 ns

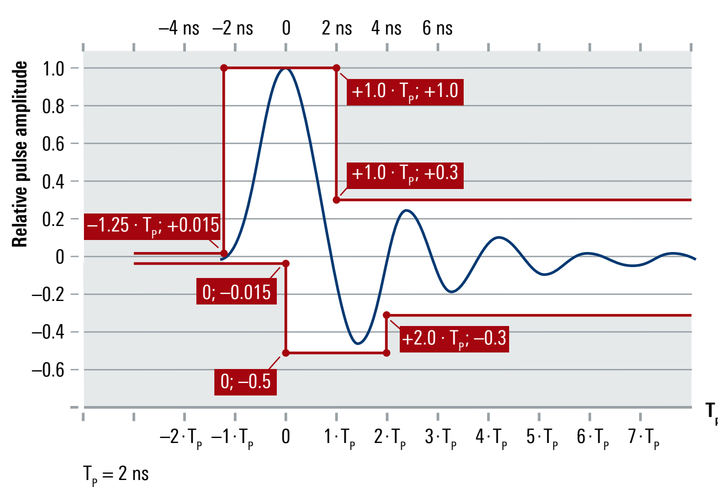
Figure 8-1: Compliance of a HRP UWB PHY pulse



8.2.2 Pulse amplitude mask

If the transmitted pulse follows the minimum precursor pulse recommendation [Ref. 7], the pulse shape should be constrained by the time domain mask (see Figure 8-2), where the peak magnitude of the pulse is normalized to a value of one, and the time unit is pulse duration T_P (see Table 8-2).

Figure 8-2: Time domain mask of a HRP UWB PHY pulse



8.2.3 Transmit power spectral density mask

The transmitted spectrum shall be less than –10 dB relative to the maximum spectral density of the signal for $0.65/T_p < |f - f_C| < 0.8/T_p$ and –18 dB for $|f - f_C| > 0.8/T_p$.

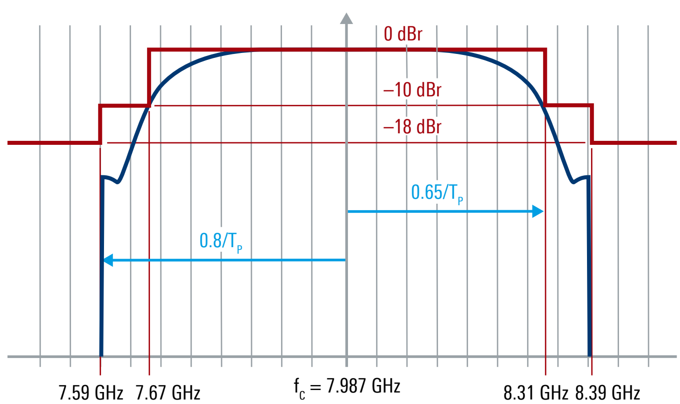
f_C is the center frequency of the channel, e.g. f_C for channel 9 is 7.987 GHz, and T_p is the pulse duration of the associated channel (see Table 8-2), 2 ns for channel 9. Table 8-3 shows the limit line of the transmit PSD mask.

Table 8-3: Limit lines of the transmit power spectrum density mask

T_P	$\|f_C - f\|$ –10 dBr	$\|f_C - f\|$ –18 dBr
2.00 ns	325 MHz	400 MHz
0.92 ns	705 MHz	870 MHz
0.75 ns	867 MHz	1067 MHz
0.74 ns	878 MHz	1081 MHz

The example in Figure 8-3 shows the transmit power spectral density mask for UWB channel 9.

Figure 8-3: Transmit power spectrum density (PSD) mask for channel 9



8.2.4 Other conformance aspects

Other HRP UWB PHY conformance requirements include:

- ▶ Chip rate clock and chip carrier alignment accuracy must be $\pm 20 \cdot 10^{-6}$
- ▶ Transmit center frequency tolerance must be $\pm 20 \cdot 10^{-6}$
- ▶ (TX to RX) and (RX to TX) turnaround time
- ▶ Receiver maximum input level greater than or equal to –45 dBm/MHz for which the PER < 1 %

8.3 FiRa™ PHY certification testing

The FiRa™ certification program aims at ensuring interoperable secure and accurate ranging between UWB devices in the entire ecosystem and improving the user experience. The program includes PHY layer certification, MAC layer certification and a universal control interface specification to control the devices under test. The FiRa™ UWB physical layer test specification defines a set of transmitter and receiver tests based on the related IEEE 802.15.4 specification, such as

- ▶ Packet format
- ▶ Power spectral density mask
- ▶ Carrier frequency tolerance and pulse timing
- ▶ Baseband impulse response
- ▶ TX signal quality
- ▶ RX sensitivity
- ▶ Dirty packet test

FiRa-certified UWB devices must fulfill the requirements in [Ref. 2], [Ref. 7]. In addition, they must be in line with the technical specifications elaborated by the FiRa™ Technical Working Group (TWG) that profiles the device features from [Ref. 2] and [Ref. 7], defines performance requirements such as ranging and AoA accuracy, and standardizes the PHY test mode.

UWB ranging devices passing through the FiRa™ certification process will be eligible to display a compliance certification logo. This means that the mechanisms for discovering UWB devices and services, device configurations as well as the security requirements are all verified. Interoperability is sustained.

8.4 Miscellaneous measurements

Users benefit from additional UWB device measurements for debugging, optimizing and benchmarking purposes. These include the following:

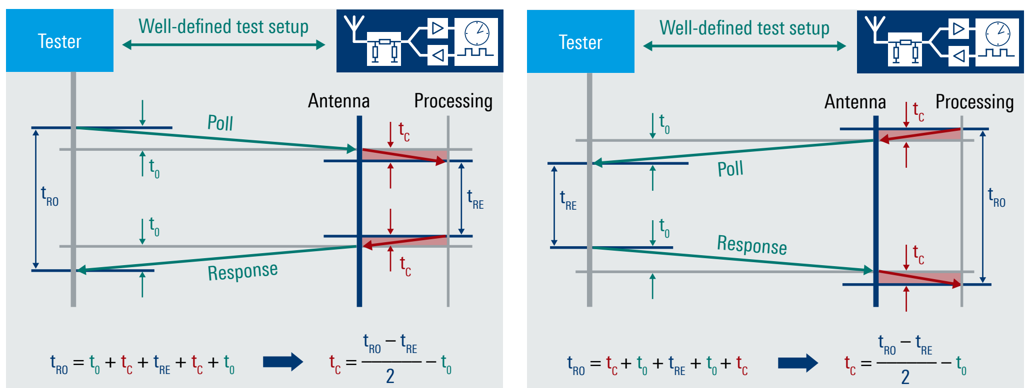
- ▶ Chip/symbol clock jitter analysis
- ▶ Chip/symbol phase jitter analysis
- ▶ Mainlobe width and peak measurement
- ▶ Sidelobe width and peak measurement
- ▶ Transmit signal quality evaluation using a normalized root mean square error (NRMSE) metric
- ▶ Chip/symbol EVM measurement
- ▶ PPDU (incl. preamble and data portion) power measurement
- ▶ Power versus time measurement
- ▶ Receiver sensitivity (lowest receive power for which PER < 1 %)

8.5 ToF and AoA measurement

UWB ranging accuracy is expected to be in the centimeter range. The DUT internal time delay caused between the TX/RX antenna connector (analog frontend) and the digital signal processing block should therefore never be neglected. 1 ns deviation in time can cause a 30 cm ToF estimation error. Calibration needs to be conducted in order to mitigate such delays.

As shown in Figure 8-4, the additional delay $t_C = ((t_{RO} - t_{RE})/2) - t_0$ between the on-board antenna and digital signal processing unit of the DUT has to be determined in both directions (ranging initiated by the tester or DUT) under well-defined test setup conditions (i.e. t_0 is given), by ensuring that the cables used to connect the tester and DUT TX/RX antenna have identical characteristics, e.g. equal length. The antenna delay t_C will then be configured in the UWB device or chipset as the outcome of the calibration and considered in the subsequent ToF calculation. Precise ToF calculation is only possible after the calibration (see details in [Ref. 11]).

Figure 8-4: Compensation of antenna delay on a UWB device



Tester initiated ranging

DUT initiated ranging

9 TEST SOLUTIONS

The UWB technology characteristics and deployment pose a challenge for testing. Measuring equipment should therefore fulfill the following requirements to be able to perform all T&M tasks.

- Analysis bandwidth according to the ultrawideband channel (500 MHz to 1400 MHz)
- Very low signal power of maximum –41.3 dBm/MHz (challenge of high dynamic range)
- Receiver sensitivity in the range of –90 dBm to 110 dBm
- Transmit power and antenna delay are critical parameters that need to be calibrated
- Accurate ToF measurements

The following sections give an overview of the UWB test solutions from Rohde & Schwarz that meet various testing requirements.

9.1 One-box solution

The R&S®CMP200 radio communication tester is a one-box UWB test solution with integrated signal generator and signal analyzer. Together with R&S®CMsquares and a shielded chamber (selection shown in Figure 9-1), the R&S®CMP200 offers a complete solution in conducted and radiated test mode for R&D and production purposes.

R&S®CMP200 features:

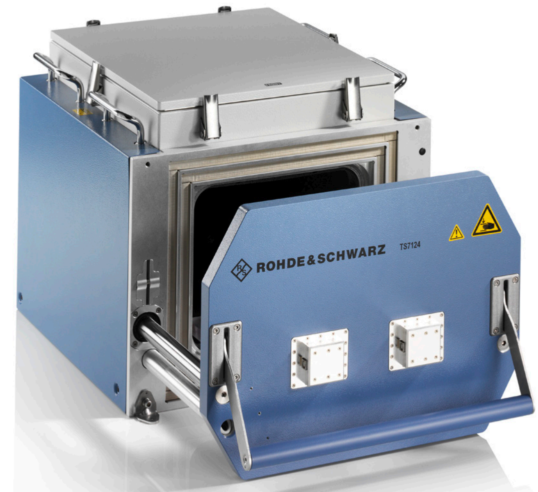
- One general purpose analyzer (frequency range: 4 GHz to 20 GHz)
- One ARB generator (frequency range: 6 GHz to 20 GHz)
- Replay of predefined waveforms (–90 dBm)
- Three switchable ports with 1 GHz bandwidth

R&S®CMP200 UWB measurements:

- TX measurement
- Transmit spectrum mask
- Normalized cross-correlation
- Symbol jitter
- Chip jitter
- Power versus time
- ToF and AoA measurement
- Receive sensitivity/maximum input level

Figure 9-1: UWB test solution based on the R&S®CMP200 radio communication tester

R&S®CMP200 radio communication tester



R&S®TS7124 RF shielded box

Figure 9-2 shows a snapshot of the UWB transmitter measurements as well as the R&S®CMP200 UWB configuration.

Figure 9-2: UWB tests on the R&S®CMP200

The test solution based on R&S®CMP200 and R&S®CMsquares is described in detail in application note [Ref. 11].

Rohde & Schwarz WMT is a software service for automated chipset and module RF testing. The modular software framework is tailored for high volume production testing and non-signaling R&D applications. It allows flexible integration into an automated testing environment. An optional user-friendly and highly customizable GUI is available for sequencing and test plan creation. Rohde & Schwarz WMT is an ideal platform to support your UWB testing.

By the time this white paper is released, the R&S®CMP200 together with Rohde & Schwarz WMT will already support UWB chipsets from well-established vendors such as Decawave/Qorvo, NXP. The list of supported chipsets is growing steadily.

9.2 Signal generators and signal analyzer

Rohde & Schwarz offers a series of signal generators (see Figure 9-3) with different frequency coverage and modulation bandwidths to meet individual testing requirements, from the low-cost R&S®SMBV100B vector signal generator supporting the subgigahertz band to the high-end R&S®SMW200A vector signal generator supporting all UWB bands.

Baseband signal generation allows free parameterization of the HRP UWB PHY in full compliance with the IEEE 802.15.4 and IEEE 802.15.4z standard and supports artificial impairments, e.g. symbol timing error and frequency offset, to test DUT receiver robustness. Figure 9-4 shows UWB baseband configurations on a signal generator from Rohde & Schwarz.

Figure 9-3: Rohde & Schwarz signal generators and signal analyzer for UWB applications

Vector signal generators

R&S®SMW200A
(12.75 GHz; 2 GHz bandwidth)

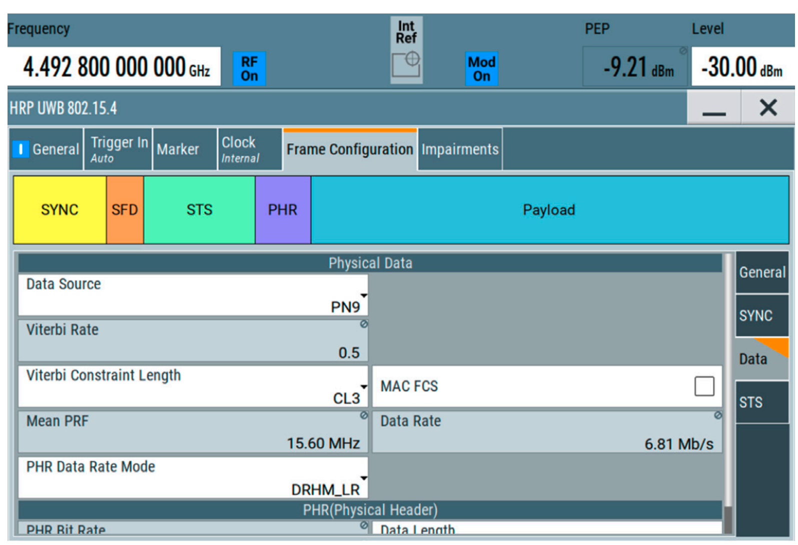
R&S®SMM100A
(12.75 GHz; 1 GHz bandwidth)

R&S®SMBV100B
(6 GHz; 500 MHz bandwidth)

Signal and spectrum analyzer

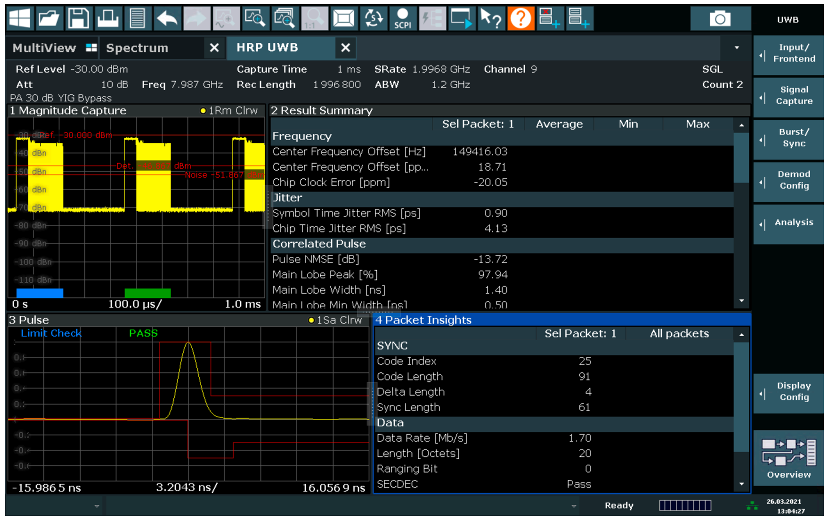
R&S®FSW26

Figure 9-4: UWB baseband configurations on a signal generator from Rohde & Schwarz



To complement the signal generator family, the R&S®FSW26 signal and spectrum analyzer (see Figure 9-3) enables comprehensive UWB signal analysis. It not only captures and analyzes signals, it can also perform analyses based on the playback of pre-recorded I/Q files. Figure 9-5 shows R&S®FSW26 signal analysis details.

Figure 9-5: UWB signal analysis on the R&S®FSW26 signal and spectrum analyzer



In addition to UWB signal analysis, the R&S®FSW26 offers noise figure, phase noise and amplifier measurements, which makes it ideal for the development and verification of chipsets, modulators and amplifiers supporting UWB.

The combination of signal generator and signal analyzer is the must-have test solution for UWB R&D.

R&S®FSW26 features:

- Support of all band groups from 0 (subGHz) to 2 (high band), (frequency range: 10 MHz to 26.5 GHz)
- Support of 499.2 MHz and 1355 MHz wide UWB channels (analysis bandwidth up to 2 GHz)
- Real-time spectrum analysis up to 800 MHz
- Excellent EVM and phase noise performance

R&S®FSW26 UWB measurements:

- TX measurements
- Transmit spectrum mask
- Normalized root mean square error (NRMSE) metric
- Normalized cross-correlation
- Pulse amplitude mask
- Measurement of chip/symbol EVM
- Symbol jitter
- Chip jitter
- PPDU (incl. preamble and data portion) power measurement
- Power versus time

9.3 Oscilloscope based R&D test solution

In addition to the R&D solution described in chapter 9.2, the R&S®RTP134/R&S®RTP164 high-performance oscilloscope together with R&S®VSE vector signal explorer software can be also deployed as an UWB testing solution (see Figure 9-6).

The R&S®RTP134/R&S®RTP164 serves as a wideband RF frontend and acquires the UWB RF signal directly without any need for downconversion. R&S®VSE analyzes the UWB signal with the corresponding measurement details as shown in Figure 9-7, which include the same features described in chapter 9.2.

Figure 9-6: UWB test solution with the R&S®RTP high-performance oscilloscope and R&S®VSE vector signal explorer software

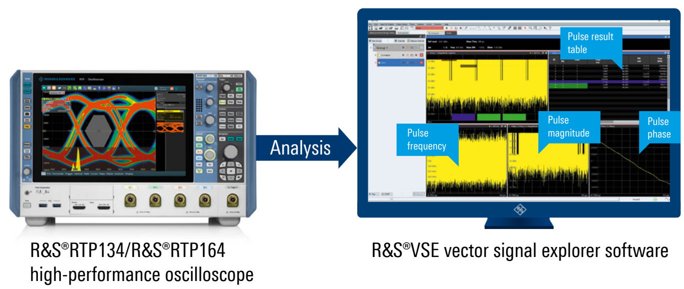
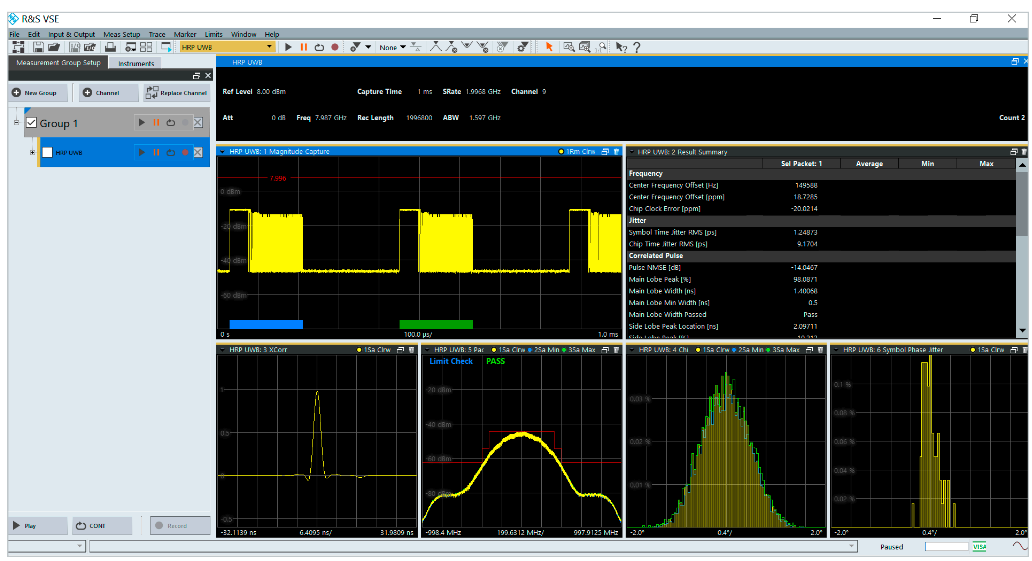


Figure 9-7: UWB signal analysis in the R&S®VSE vector signal explorer software



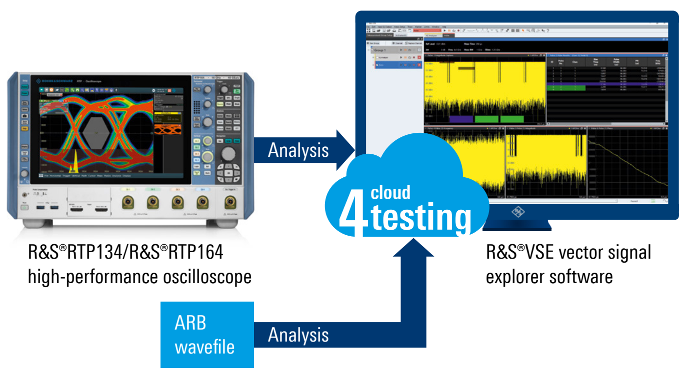
The solution takes advantage of the advanced oscilloscope trigger system which allows users to trigger precisely at the start of the UWB signal packet and use the available memory in a more efficient way.

9.4 R&S®Cloud4Testing

R&S®Cloud4Testing (R&S®C4T) is an on-demand cloud based test solution (see Figure 9-8) for RF testing and analysis. The advantages of the R&S®C4T solution are:

- Accessible anytime, anywhere
- Economic flexibility through annual or monthly subscriptions
- Access to renowned RF analysis software such as R&S®VSE and R&S®WinIQSIM2™ without the need for local administration
- Use R&S®C4T with your favorite internet browser – no additional software installation required
- Upload your recording as I/Q data capture files, or connect to third-party cloud storage solutions for convenient data exchange
- Attractive subscription packages for specific software solutions – including UWB
- Quick and easy start

Figure 9-8: R&S®Cloud4Testing solution for UWB signal analysis



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Note: All links have been checked and were functional when this document was created. However, we cannot rule out subsequent changes to the links in the reference list.

APPENDIX

A.1 Overview of HPR-RDEV and HPR-ERDEV

Parameter	Condition	HRP UWB RDEV	HRP UWB ERDEV	
			BPRF mode	HPRF mode
Standard		IEEE 802.15.4	IEEE 802.15.4z	IEEE 802.15.4z
Channel (carrier frequency)	mandatory		channel 0 (499.2 MHz), channel 3 (4492.8 MHz), channel 9 (7987.2 MHz)	
	optional		channel 1 (3494.4 MHz), channel 2 (3993.6 MHz), channel 4 (3993.6 MHz), channel 5 (6489.6 MHz), channel 6 (6988.8 MHz), channel 7 (6489.6 MHz), channel 8 (7488.0 MHz), channel 10 (8486.4 MHz), channel 11 (7987.2 MHz), channel 12 (8985.6 MHz), channel 13 (9484.8 MHz), channel 14 (9984.0 MHz), channel 15 (9484.8 MHz)	
Peak PRF (in MHz)		499.2		499.2 / 249.6
Mean PRF (in MHz)	SHR	4.03 / 16.1 / 62.89 (optional)	62.89 (optional) / 111.09	62.89 (optional) / 111.09
	PHR and PSDU	3.9 / 15.6 / 62.4 (optional)	62.4	124.8 (DRHM_LR) / 249.6 (DRHM_HR)
	STS	–	62.4	124.8
SYNC	preamble code sequence length	31 / 127 (optional)	91	91
	delta length L	4 / 16 / 64	4	4
	preamble symbol repetition	16 / 64 / 1024 / 4096	32 / 64, optional: 16 / 24 / 48 / 96 / 128 / 256	32 / 64, optional: 16 / 24 / 48 / 96 / 128 / 256
	length (in symbols)	8 / 64 (optional)	8 [8]	–
	number	–	0 [8] / 2	1 / 2 / 3, optional: 4
	STS packet configuration	–	0: no STS, 1: STS after SFD, 2: STS after PSDU, 3: STS after SFD, no PSDU	
	number of segments	–	1	1 / 2, optional: 3 / 4
	segment length (× 512 chips)	–	64	32 / 64 / 128, optional: 16 / 256
PHR	PHR bit length	19	19	19
	PSDU data length	1 to 127 octets	1 to 127 octets	1 to 4096 octets [9]
	number of hop bursts	2 [10] / 8 / 32	2	–
	number of chips per burst	4 / 16 / 32 / 64 [10] / 128 / 512 [10]	8 / 64	–
	number of chips per symbol	512 / 4096	64 / 512	16 (DRHM_HR+CL7), 32 (DRHM_HR+CL3), 64 (DRHM_LR+CL7), 128 (DRHM_LR+CL3)
	PHR bit rate (in Mbit/s)	0.11 or 0.85	0.975 (DRBM_LP), 7.8 (DRBM_HP)	3.9 (DRHM_LR+CL3), 7.8 (DRHM_LR+CL7), 15.6 (DRHM_HR+CL3), 31.2 (DRHM_HR+CL7)

[8] It uses 8 symbols (short) SFD of legacy RDEV if SFD number is 0.
[9] A0 and A1 functional bits in PHR are used to indicate the long frame length.
[10] It is optional, when mean PRF = 62.4 MHz.

Parameter	Condition	HRP UWB RDEV	HRP UWB ERDEV	
			BPRF mode	HPRF mode
PSDU	number of hop bursts	213 / 8 / 32	2	–
	number of chip per burst	1 / 2 [10] / 4 / 8 [10] / 16 / 32 / 64 [10] / 128 / 512 [10]	8	–
	number of chips per symbol	16 [10] / 32 / 64 / 128 / 256 / 512 / 4096	64	16 (DRHM_HR), 64 (DRHM_LR)
	Viterbi constraint length	CL3	CL3	CL3 / CL7
	PSDU bit rate (in Mbit/s)	0.11, 0.85, 6.81, 27.24 at mean PRF of 15.6 MHz or 62.4 MHz; 0.11, 0.85, 1.70, 6.81 at mean PRF of 3.90 MHz	6.8	6.8 (DRHM_LR+CL3), 7.8 (DRHM_LR+CL7), 27.2 (DRHM_HR+CL3), 31.2 (DRHM_HR+CL7)

B.1 Legacy HPR UWB PHY RDEV rate-dependent and timing parameters [11]

				Modulation and coding			Data symbol structure					Data			
Channel number	Peak PRF in MHz	Band-width in MHz	Preamble code length	Viterbi rate	Reed-Solomon rate	Overall FEC rate	Number of burst positions per symbol N_{burst}	Number of hop bursts N_{hop}	Number of chips per burst N_{cpb}	Number of chips per symbol	Burst duration T_{burst} in ns	Symbol duration T_{dsym} in ns	Symbol rate in MHz	Bit rate in Mbit/s	Mean PRF in MHz
{0:3, 5:6, 8:10, 12:14}	499.2	499.2	31	0.5	0.87	0.44	32	8	128	4096	256.41	8205.13	0.12	0.11	15.60
	499.2	499.2	31	0.5	0.87	0.44	32	8	16	512	32.05	1025.64	0.98	0.85	15.60
	499.2	499.2	31	0.5	0.87	0.44	32	8	2	64	4.01	128.21	7.80	6.81	15.60
	499.2	499.2	31	1	0.87	0.87	32	8	1	32	2.00	64.10	15.60	27.24	15.60
{0:3, 5:6, 8:10, 12:14}	499.2	499.2	31	0.5	0.87	0.44	128	32	32	4096	64.10	8205.13	0.12	0.11	3.90
	499.2	499.2	31	0.5	0.87	0.44	128	32	4	512	8.01	1025.64	0.98	0.85	3.90
	499.2	499.2	31	0.5	0.87	0.44	128	32	2	256	4.01	512.82	1.95	1.70	3.90
	499.2	499.2	31	1	0.87	0.87	128	32	1	128	2.00	256.41	3.90	6.81	3.90
{0:3, 5:6, 8:10, 12:14}	499.2	499.2	127	0.5	0.87	0.44	8	2	512	4096	1025.64	8205.13	0.12	0.11	62.40
	499.2	499.2	127	0.5	0.87	0.44	8	2	64	512	128.21	1025.64	0.98	0.85	62.40
	499.2	499.2	127	0.5	0.87	0.44	8	2	8	64	16.03	128.21	7.80	6.81	62.40
	499.2	499.2	127	0.5	0.87	0.44	8	2	2	16	4.01	32.05	31.20	27.24	62.40
{4, 11}	499.2	1331.2	31	0.5	0.87	0.44	32	8	128	4096	256.41	8205.13	0.12	0.11	15.60
	499.2	1331.2	31	0.5	0.87	0.44	32	8	16	512	32.05	1025.64	0.98	0.85	15.60
	499.2	1331.2	31	0.5	0.87	0.44	32	8	2	64	4.01	128.21	7.80	6.81	15.60
	499.2	1331.2	31	1	0.87	0.87	32	8	1	32	2.00	64.10	15.60	27.24	15.60
{4, 11}	499.2	1331.2	127	0.5	0.87	0.44	8	2	512	4096	1025.64	8205.13	0.12	0.11	62.40
	499.2	1331.2	127	0.5	0.87	0.44	8	2	64	512	128.21	1025.64	0.98	0.85	62.40
	499.2	1331.2	127	0.5	0.87	0.44	8	2	8	64	16.03	128.21	7.80	6.81	62.40
	499.2	1331.2	127	0.5	0.87	0.44	8	2	2	16	4.01	32.05	31.20	27.24	62.40
7	499.2	1081.6	31	0.5	0.87	0.44	32	8	128	4096	256.41	8205.13	0.12	0.11	15.60
	499.2	1081.6	31	0.5	0.87	0.44	32	8	16	512	32.05	1025.64	0.98	0.85	15.60
	499.2	1081.6	31	0.5	0.87	0.44	32	8	2	64	4.01	128.21	7.80	6.81	15.60
	499.2	1081.6	31	1	0.87	0.87	32	8	1	32	2.00	64.10	15.60	27.24	15.60
7	499.2	1081.6	127	0.5	0.87	0.44	8	2	512	4096	1025.64	8205.13	0.12	0.11	62.40
	499.2	1081.6	127	0.5	0.87	0.44	8	2	64	512	128.21	1025.64	0.98	0.85	62.40
	499.2	1081.6	127	0.5	0.87	0.44	8	2	8	64	16.03	128.21	7.80	6.81	62.40
	499.2	1081.6	127	0.5	0.87	0.44	8	2	2	16	4.01	32.05	31.20	27.24	62.40
15	499.2	1354.97	31	0.5	0.87	0.44	32	8	128	4096	256.41	8205.13	0.12	0.11	15.60
	499.2	1354.97	31	0.5	0.87	0.44	32	8	16	512	32.05	1025.64	0.98	0.85	15.60
	499.2	1354.97	31	0.5	0.87	0.44	32	8	2	64	4.01	128.21	7.80	6.81	15.60
	499.2	1354.97	31	1	0.87	0.87	32	8	1	32	2.00	64.10	15.60	27.24	15.60
15	499.2	1354.97	127	0.5	0.87	0.44	8	2	512	4096	1025.64	8205.13	0.12	0.11	62.40
	499.2	1354.97	127	0.5	0.87	0.44	8	2	64	512	128.21	1025.64	0.98	0.85	62.40
	499.2	1354.97	127	0.5	0.87	0.44	8	2	8	64	16.03	128.21	7.80	6.81	62.40
	499.2	1354.97	127	0.5	0.87	0.44	8	2	2	16	4.01	32.05	31.20	27.24	62.40

[11] This is a copy of Table 15-3 from [Ref. 2].

C.1 HPR UWB PHY ERDEV rate-dependent and timing parameters – BPRF mode

	Data rate mode	Peak PRF (in MHz)	Mean PRF (in MHz)	Viterbi rate	Reed-Solomon rate	FEC rate	Number of pulses per data symbol	Number of hops per symbol	Number of chips per burst	Number of chips per symbol	Burst duration (in ns)	Data symbol duration (in ns)	Bit rate (in Mbit/s)
PHR	DRBM_LP	499.2	62.4	0.5	1	0.5	8	2	64	512	128.2	1025.6	0.975
	DRBM_HP	499.2	62.4	0.5	1	0.5	8	2	8	64	16.0	128.2	7.8
PSDU		499.2	62.4	0.5	0.87	0.435	8	2	8	64	16.0	128.2	6.79

C.2 HPR UWB PHY ERDEV rate-dependent and timing parameters – HPRF mode

	Data rate mode	Peak PRF (in MHz)	Mean PRF (in MHz)	Viterbi rate	Reed-Solomon rate	FEC rate	Number of pulses per data symbol	Number of chips per symbol	Data symbol duration (in ns)	Bit rate (in Mbit/s)
PHR	DRHM_HR	499.2	249.6	0.5	1	0.5	8	16	32.1	31.2 [12]
		499.2	249.6	0.5	1	0.5	16	32	64.1	15.6
	DRHM_LR	249.6	124.8	0.5	1	0.5	16	64	128.2	7.8 [12]
		249.6	124.8	0.5	1	0.5	32	128	256.4	3.9
PSDU	DRHM_HR	499.2	249.6	0.5	1	0.5	8	16	32.1	31.2 [12]
		499.2	249.6	0.5	0.87	0.435	8	16	32.1	27.2
	DRHM_LR	249.6	124.8	0.5	1	0.5	16	64	128.2	7.8 [12]
		249.6	124.8	0.5	0.87	0.435	16	64	128.2	6.8

[12] Constraint length (CL) 7 convolution encoder is used.

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