Ultra-wideband (UWB) communication based on IEEE 802.15.4a/z/ab

Application Engineer
Chuck Lo

ROHDE&SCHWARZ

Make ideas real

Impulse radio ultra-wideband (IR-UWB) standardization by IEEE was/is driven by a strong ecosystem

2007
IEEE 802.15.4a
High Rate Pulse Repetition UWB

2020
IEEE 802.15.4z
HRP UWB enhanced ranging

2024
IEEE 802.15.4ab
Next generation UWB

2018
UWB ALLIANCE
uwballiance.org

2019
fira
firaconsortium.org

2020
omlox
omlox.com

2020
CCC
carconnectivity.org

UWB Alliance

Since 2019, UWB has been expanding into a mainstream consumer technology for smartphones, wearables, automotive and industry, forecasted to drive sales volumes in excess of one billion devices annually by 2025.
The mission of the UWB Alliance is to be the voice of the designers and manufacturers committed to establishing ultra wideband (UWB) technology as a significant open standards industry.

- Establish Ultra-Wideband (UWB) technology as a significant open standards industry
- Promote 802.15.4z and other standards based UWB technologies
- Define and propose interoperability profiles through multiple industry use cases
- Define testing methodology for interoperability
- Develop relationships to provide recommended test facilities

https://uwballiance.org/

Fine Ranging (FiRa): UWB accuracy and security in measuring distance to a target or determining position

Goal to develop compelling UWB use cases, ensure seamless UWB interoperability and promote UWB ranging

Service-specific protocols for multiple verticals

- Hands-free access control, location-based services, and device-to-device (peer-to-peer) applications;

Mechanisms which are not within IEEE scope

- Discover UWB devices and services
- Configure devices in an interoperable manner
- Specify interoperable security requirements

Interoperability Standard

- Profiled features among 802.15.4/4z PHY/MAC
- Performance requirements
- Test methods and procedures
- Certification program

Rohde & Schwarz ins member of FiRa, actively working in several the FiRa working groups

https://www.firaconsortium.org/

FiRa Consortium: the scope of use cases

Source: FiRa Consortium Webpage

FiRa™ Consortium drives interoperability at all levels

Rohde & Schwarz member of FiRa – The Power to Be Precise

Security

Services

Application Layer

MAC Layer

PHY Layer

FiRa CERTIFIED

IEEE 802.15.4/4z

Enhanced UWB PHY & MAC

- Coding and preambles
- Improved integrity & accuracy
- Information elements
- Multiple ranging methods

FiRa Consortium

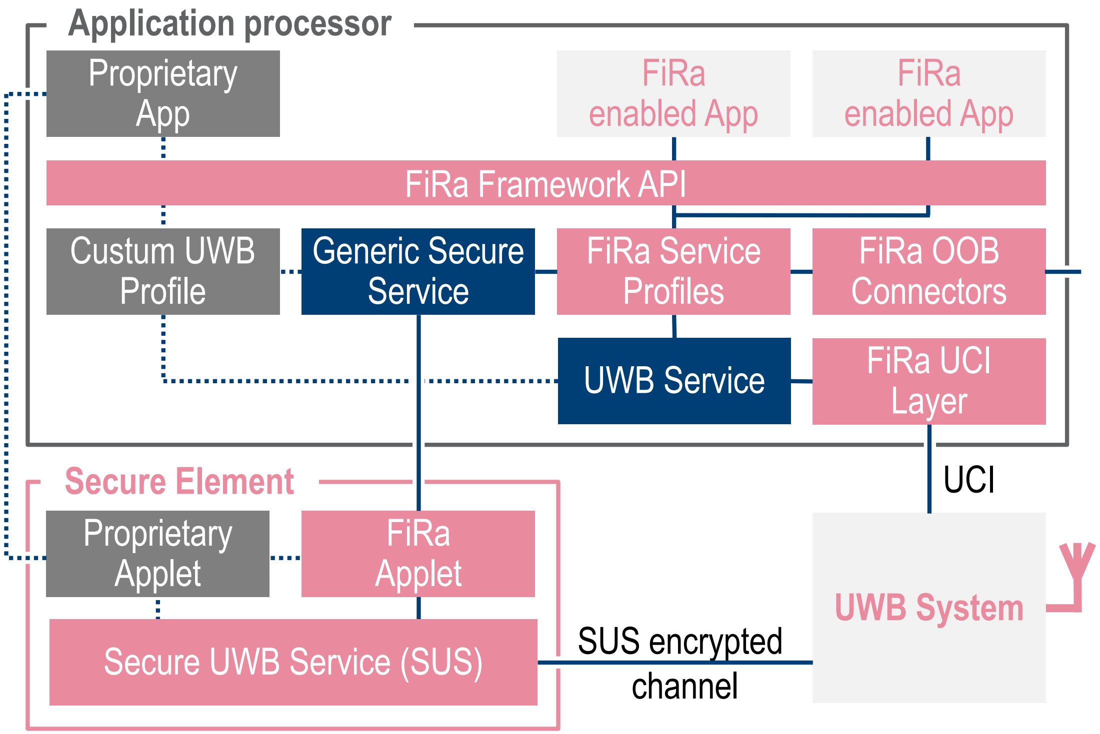
Service-specific protocols for multiple verticals

- Hands-free access control, location-based services, and device-to-device (peer-to-peer) applications

Interoperability Standard

- Profiled features among 802.15.4/4z PHY/MAC (e.g. UWB HRP-EREDV HPRF & BPRF)
- Performance requirements (e.g. ranging accuracy, AoA accuracy)
- Test methods and procedures
- Certification program

Transforming the way we interact with our environment by enabling precise location awareness for people and devices.



FiRa The Power to Be Precise

- Support the development of compelling use cases across broad business domains
- Define specifications and certify products to ensure interoperability
- Foster a robust UWB ecosystem to enable rapid technology deployment

www.firaconsortium.org

Cross-industry organizations for smartphone-to-car connectivity solutions

CARCONNECTIVITY consortium®

When it comes to cars and smartphones, the Car Connectivity Consortium (CCC) makes it possible to simply connect and ride.

- The CCC makes this possible via **MirrorLink™**, a standard for controlling handsets from the dashboard or steering wheel.
- **Digital Key** will enable consumers to conveniently lock/unlock their vehicle and start their engine using their smart devices. Advanced key provisioning and sharing will also be supported.
- And **Car Data** will connect consumers to service providers who will offer tailored vehicular services enhanced by vehicle data.

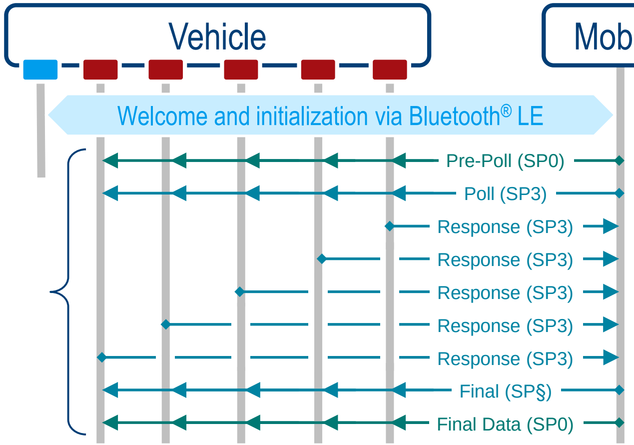
Digital Key 3.0 addresses security and usability by authenticating the Digital Key between a vehicle and the mobile device over Bluetooth Low Energy. UWB offers secure and accurate distance measurement allowing cars to locate authenticated mobile devices so that it not only prevents attacks but also adds a new level of convenience when entering, interacting and starting the car.

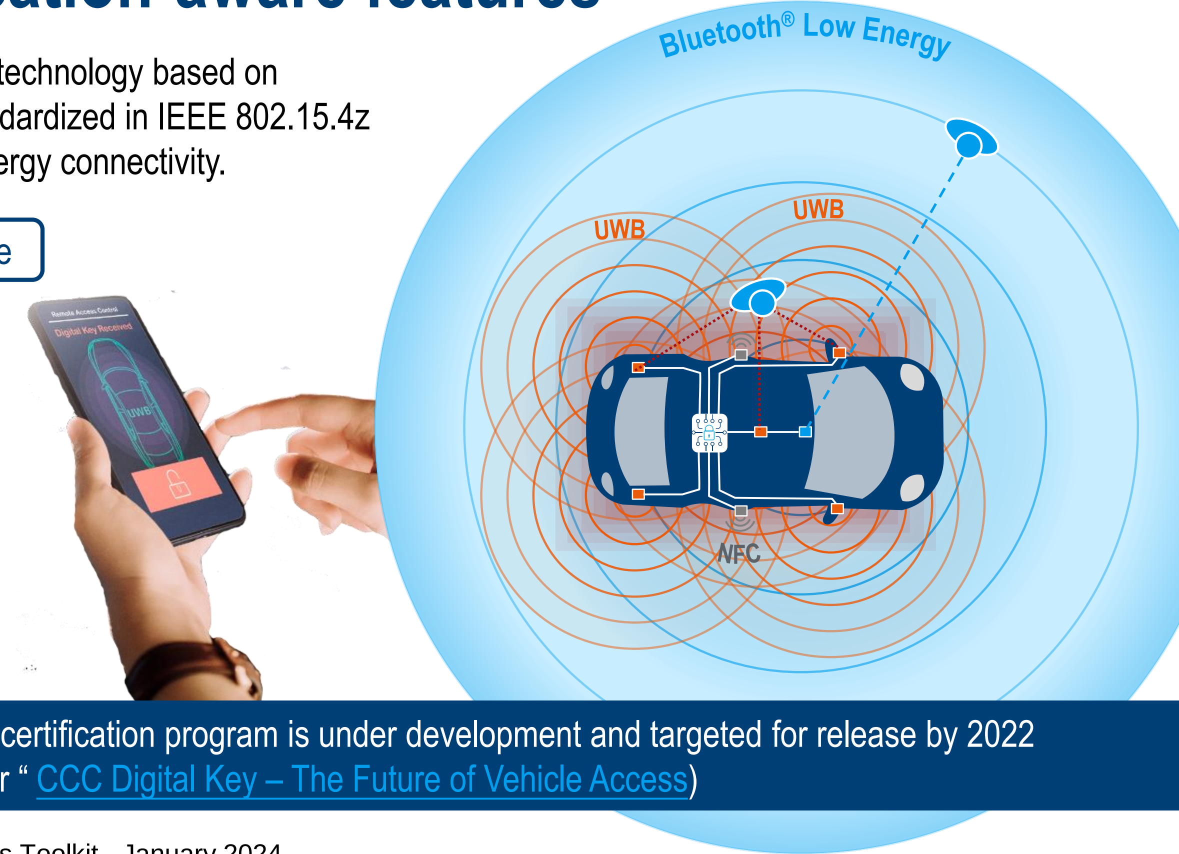
Through its well-developed certification programs, CCC rigorously evaluates and certifies devices, cars and apps for their compliance and interoperability.

https://carconnectivity.org/

CCC Digital Key Release 3.0 adds hands-free, location-aware keyless access and location-aware features

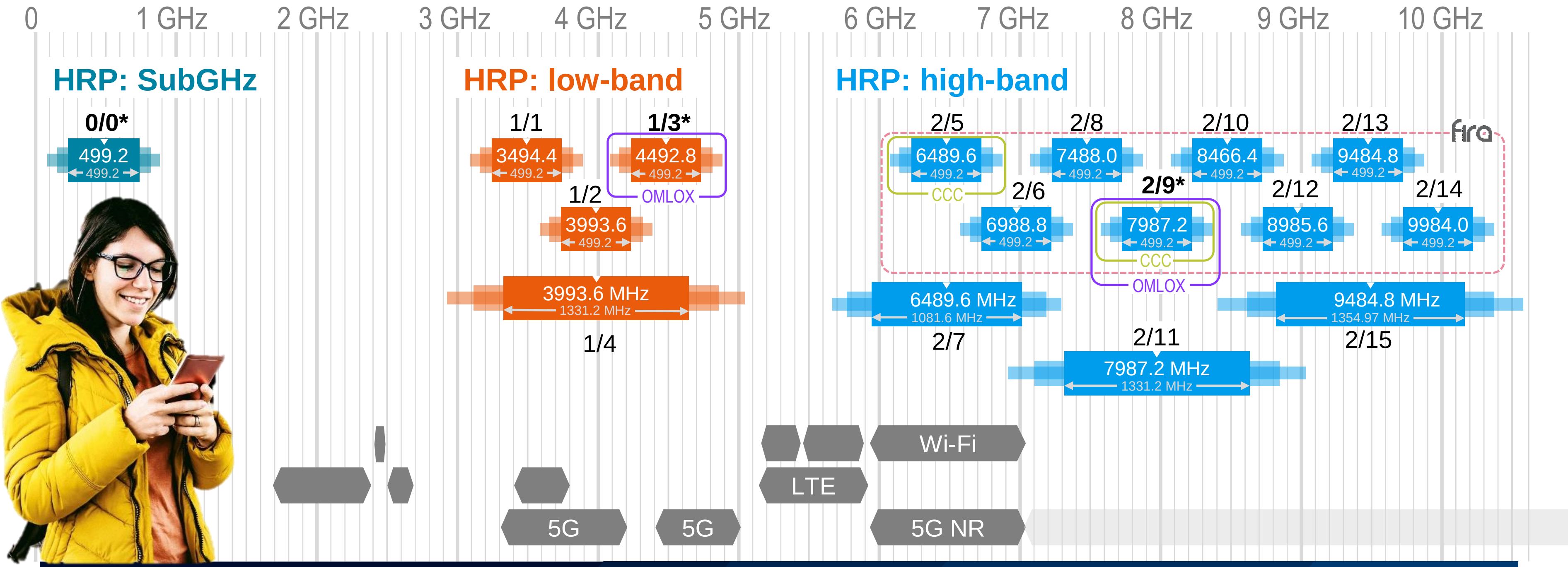
The CCC has adopted the UWB secure ranging technology based on High Rate Pulse repetition frequency (HRP) standardized in IEEE 802.15.4z in combination with standard Bluetooth® Low Energy connectivity.





Rohde & Schwarz member of CARCONNECTIVITY consortium®

The CCC Digital Key certification program is under development and targeted for release by 2022 (see CCC Whitepaper " CCC Digital Key – The Future of Vehicle Access)



UWB channel allocation based on IEEE 802.15.4z-2020

Ultra-wideband (UWB) standardization: IEEE 802.15.4

HRP UWB PHY (clause 15) High Rate Pulse repetition frequency			LRP UWB PHY (clause 18) Low Rate Pulse repetition frequency					
RDEV	ERDEV		RDEV			ERDEV		
base	BPRF	HPRF	base	extend	long-range	DF	enh. DF	DF w/ EPC
Modulation BPM-BPSK **Pulse Rate:** 3.9 MHz 15.6 MHz 62.4 MHz	**Modulation** BPM-BPSK **Pulse Rate:** 62.4 MHz	**Modulation** BPSK **Pulse Rate:** 124.8 MHz 249.6 MHz	**Modulation** OOK **Pulse Rate:** 1 MHz	**Modulation** OOK **Pulse Rate:** 1 MHz	**Modulation** PPM **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
802.15.4a/z	802.15.4z		802.15.4f/z			802.15.4z		

RDEV: Ranging device
ERDEV – Enhanced Ranging Device
BPM - burst position modulation

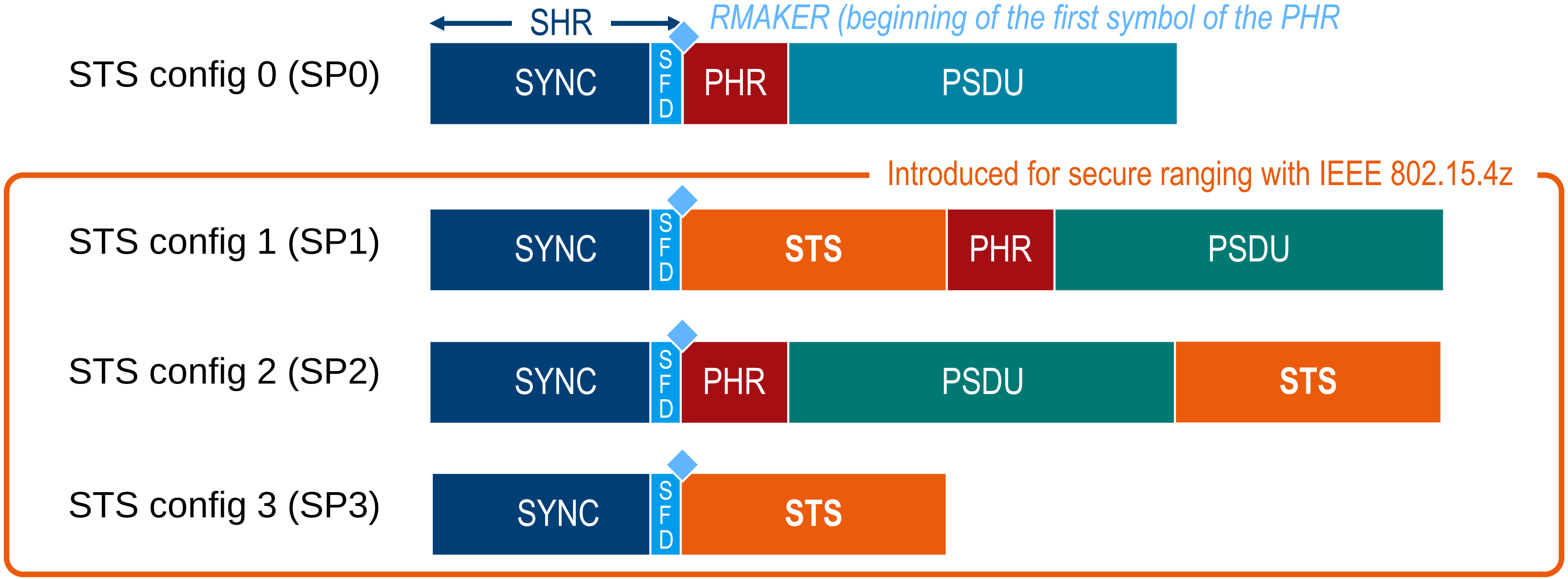
BPRF – Base pulse repetition frequency
HPRF – Higher pulse repetition frequency
PBFSK – Pulsed binary frequency shift keying

PPM – Pulse Positioning Modulation
EPC – Enhanced Payload capacity
BPSK - binary phase shift keying

DF – Dual frequency
OOK: On-Off Keying

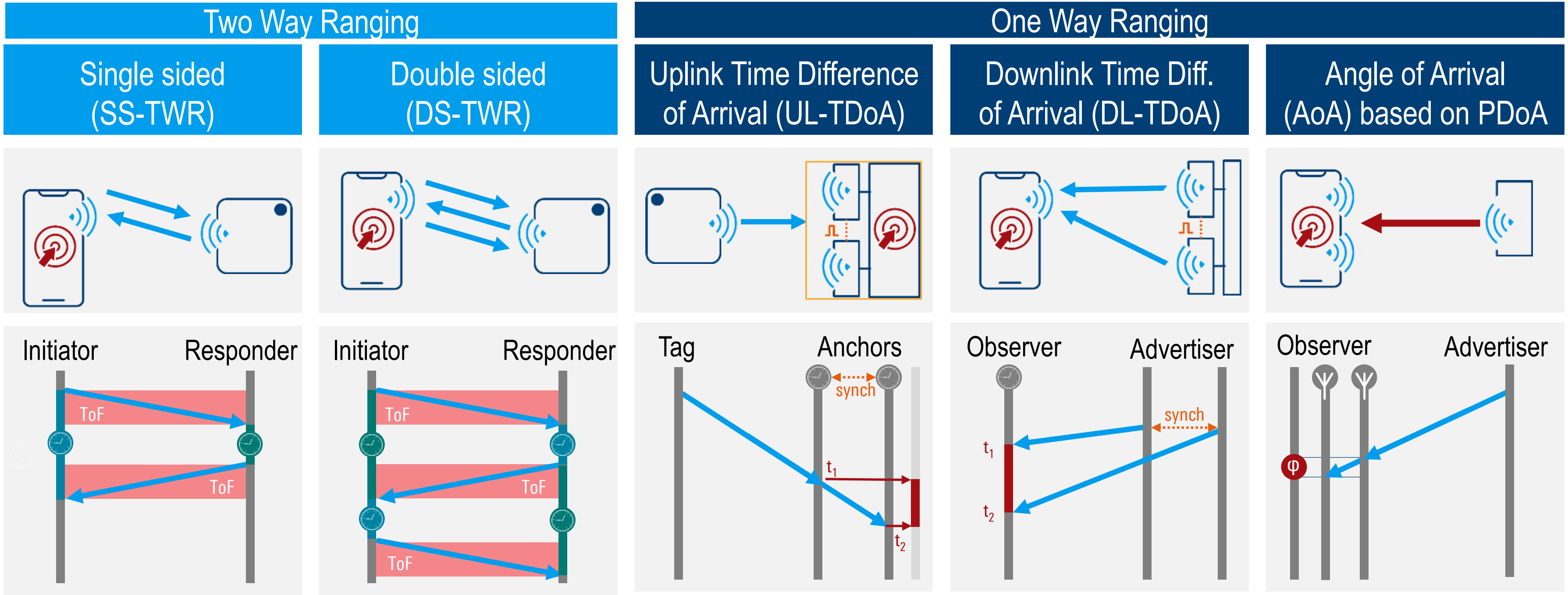
Sources: IEEE802.15.2-2020: IEEE Standard for Low -Rate Wireless Networks;
IEEE802.15.2-2020z: Amendment 1: Enhanced Ultra Wideband (UWB) Physical Layers (PHYs) and Associated Ranging Techniques

Secure ranging using a scrambled timestamp sequence (STS) generated by AES-128 based deterministic random bit generator



SFD: start-of-frame delimiter
SHR: synchronization header
RMARKER: ranging marker
PPDU: PHY protocol data unit
PSDU: PHY service data unit
PHR: PHY header
STS: scrambled timestamp sequence

UWB ranging and positioning is all about absolute/relative signal propagation time(s)



UWB physical layer test requirements

Standard conformance

- Operating frequency bands
- Channel assignments
- Baseband impulse response
- Transmit PSD mask
- Chip rate clock and chip carrier alignment

IEEE 802.15.4-2020
IEEE 802.15.4z-2020

Regulatory compliance

- Operating bandwidth
- Mean power spectral density
- Maximum value of peak power
- Other emissions
- Receiver spurious emissions
- Detect and avoid (DAA)
- Low duty cycle (LDC)

FCC part 15
§15.519, §15.517
ETSI EN 301 489-33 ,
EN 302 065, EN 303 883

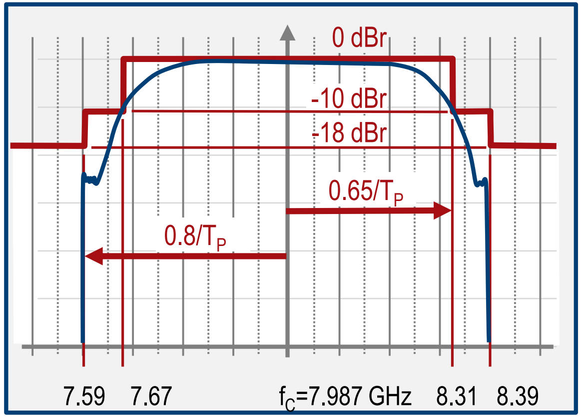
Interoperability certification

- Packet format
- Power spectral density mask
- Frequency tolerance, timing
- Baseband Impulse response
- NRMSE
- Packet reception sensitivity
- Dirty packet tests
- First path dynamic range

FiRa Consortium
UWB PHY Conformance
CCC Consortium
UWB PHY Test Suite

Specific UWB measurements (IEEE, FiRa)

Transmit Power Spectrum Density

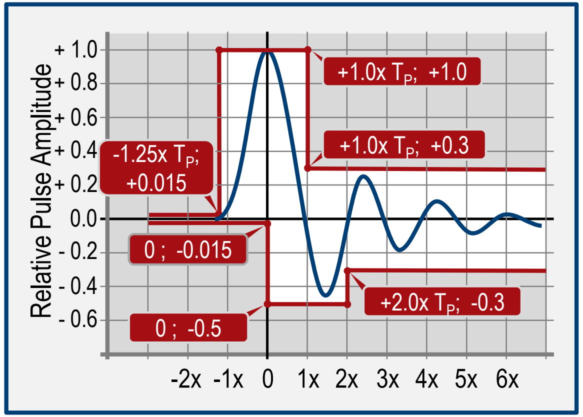


The transmitted spectrum shall be less than –10 dB relative to the maximum spectral density of the signal for

$0.65/T_P < |f - fc| < 0.8/T_P$

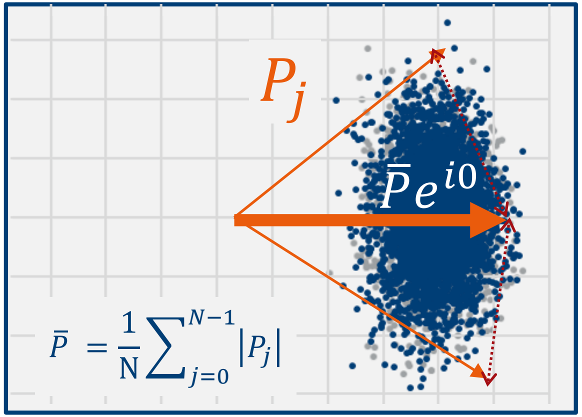
and –18 dB for $|f - fc| > 0.8/T_P$.

Impulse response



The pulse shape should be constrained by the time domain mask where the peak magnitude of the pulse is scaled to a value of one, and the time unit is pulse duration TP.

Transmitter quality (NRMSE)

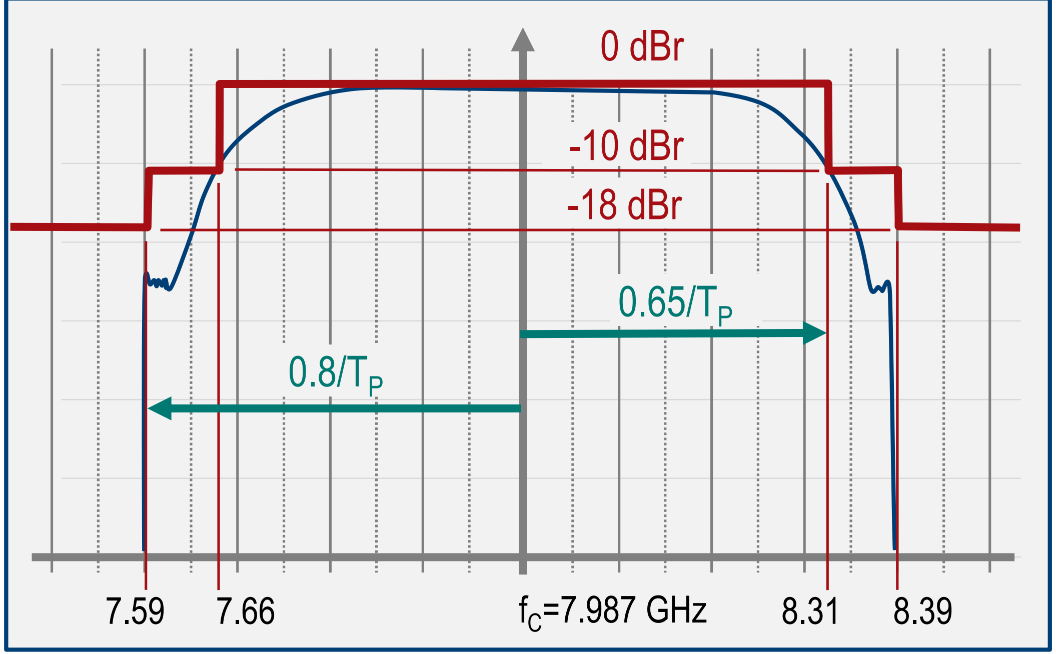


The transmit signal quality should be measured using a normalized root mean square error (NRMSE) metric with the mean pulse amplitude $\bar{P}$

$$NRMSE = \sqrt{\frac{1}{N}\sum_{j=0}^{N-1}\frac{\left|P_j - \bar{P}e^{i0}\right|^2}{\bar{P}^2}}$$

Transmit power spectrum density (PSD) in 802.15.4

Transmit Power Spectrum Density (PSD) mask

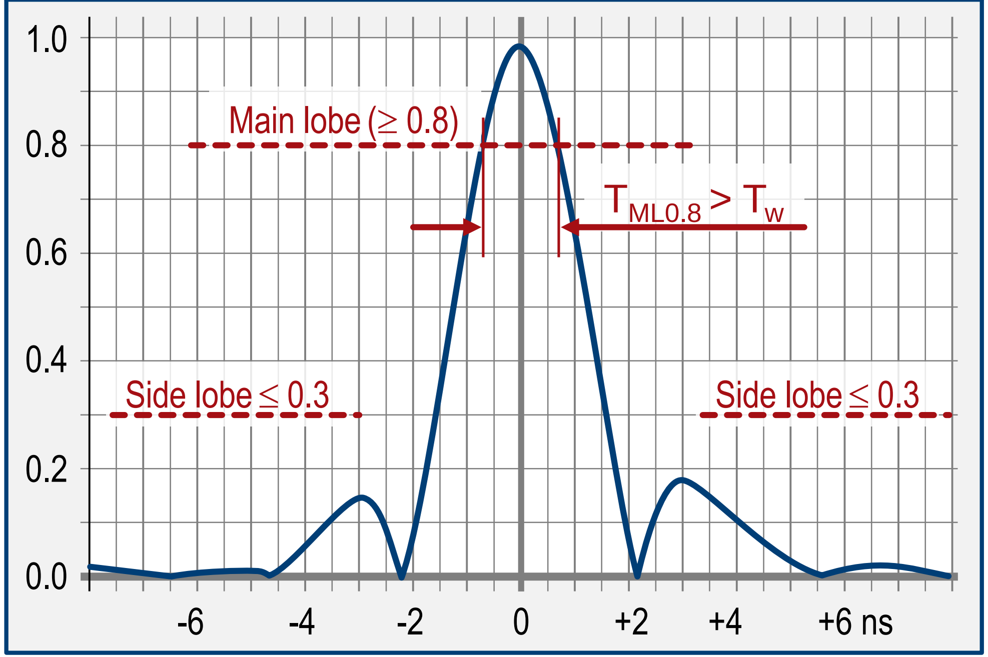


The transmitted spectrum shall be less than –10 dB relative to the maximum spectral density of the signal for $0.65/T_P < |f – fc| < 0.8/T_P$ and –18 dB for $|f – fc| > 0.8/Tp$.
The measurements shall be made using a 1 MHz resolution bandwidth and a 1 kHz video bandwidth.

T_P	$\lvert f_c – f \rvert$ -10 dBr	$\lvert f_c – f \rvert$ -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

Normalized RRC cross-correlation magnitude (802.15.4)

Cross-correlation magnitude $|\phi(\tau)|$



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 β = 0.5.

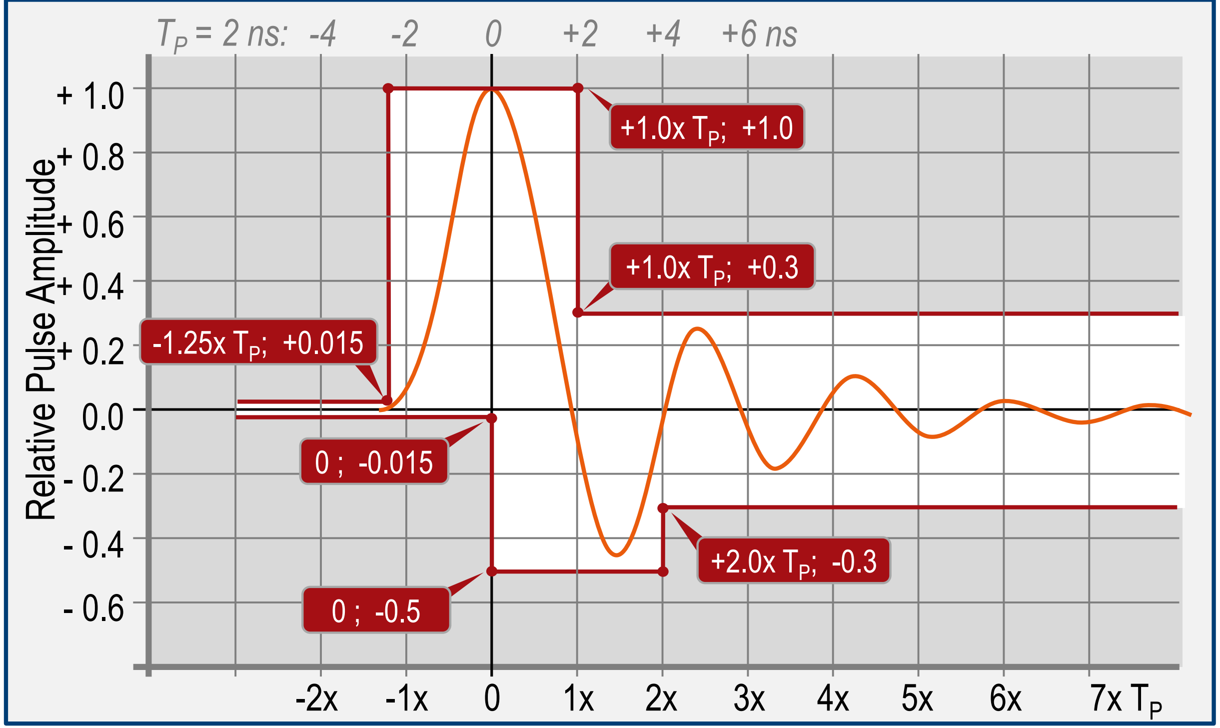
$$\phi(\tau) = \frac{1}{\sqrt{E_r E_p}} \int_{-\infty}^{\infty} r(t)\, p^*(t+\tau)\, dt$$

The main lobe should be $|\phi(\tau)| \geq 0.8$ for a duration of at least T_W. Any side lobe shall be no greater than 0.3.

Channel #	T_P	T_W
0:3. 5:6, 8:10; 12:14	2.00 ns	0.5 ns
7	0.92 ns	0.2 ns
4, 11	0.75 ns	0.2 ns
15	0.74 ns	0.2 ns

Recommended time domain mask for HRP-UWB (802.15.4)

Relative pulse amplitude – time domain mask



If the transmitted pulse follows the minimum precursor pulse recommendation, the pulse shape should be constrained by the time domain mask where the peak magnitude of the pulse is scaled to a value of one, and the time unit is pulse duration T_P.

Channel #	T_P
0:3. 5:6, 8:10; 12:14	2.00 ns
7	0.92 ns
4, 11	0.75 ns
15	0.74 ns

FiRa™ Certification test process and documents

Rohde & Schwarz member of FiRa The Power to Be Precise

UWB PHY Technical Requirements | UWB MAC Technical Requirements | Interoperability Requirements

PHY Compliance Test specification | MAC Compliance Test specification | Interoperability Test specification

UCI Test specification
Test mode and test Interface

Join FiRa

Prepare
(e.g. use validated test tools)

Certification testing
(by authorized test labs)

Apply

Promote

- FiRa validates **test tools to** ensure that they conform to the requirements defined in the FiRa test specifications
- FiRa authorizes **test labs** to ensure that they have the competence to conduct certification testing

FiRa physical layer conformance test cases (V1.3)

Transmitter Tests

PCT1.1.1: BPRF - Packet Format
PCT1.1.2: HPRF - Packet Format

PCT1.2.1: BPRF - Power Spectral Density Mask
PCT1.2.2: HPRF - Power Spectral Density Mask

PCT1.3.1: BPRF - Carrier Frequency Tolerance and Pulse Timing
PCT1.3.2: HPRF - Carrier Frequency Tolerance and Pulse Timing

PCT1.4.1: BPRF - Baseband Impulse Response
PCT1.4.2: HPRF - Baseband Impulse Response

PCT1.5.1: BPRF - Transmit Signal Quality (NRMSE)
PCT1.5.2: HPRF - Transmit Signal Quality (NRMSE)

Still in discussion in NRMSE Tiger team

Receiver Tests

PCT2.1.1: BPRF - SP0 & SP1 Packet Reception Sensitivity
PCT2.1.2: HPRF - SP0 & SP1 Packet Reception Sensitivity

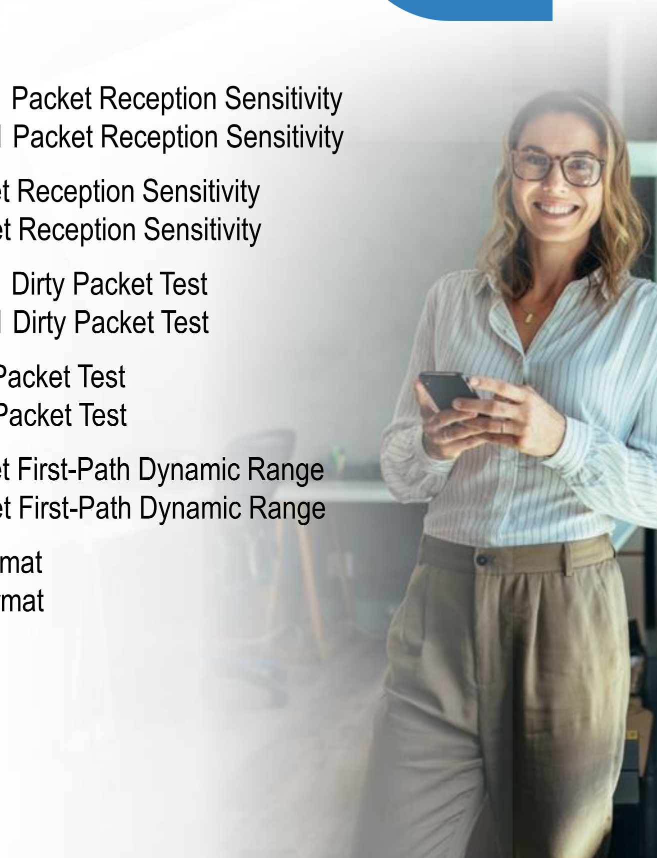
PCT2.2.1: BPRF - SP3 Packet Reception Sensitivity
PCT2.2.2: HPRF - SP3 Packet Reception Sensitivity

PCT2.3.1: BPRF - SP0 & SP1 Dirty Packet Test
PCT2.3.2: HPRF - SP0 & SP1 Dirty Packet Test

PCT2.4.1: BPRF - SP3 Dirty Packet Test
PCT2.4.2: HPRF - SP3 Dirty Packet Test

PCT2.5.1: BPRF - SP3 Packet First-Path Dynamic Range
PCT2.5.2: HPRF - SP3 Packet First-Path Dynamic Range

PCT2.6.1: BPRF - Packet Format
PCT2.6.2: HPRF - Packet Format



FiRa physical layer conformance test cases (V2.0) using the new UCI version 2.0

Rohde & Schwarz PCTT based on CMP200/UWB Test suite is fully validated for FiRa 2.0

Transmitter Tests

PCT_1_0_TX_BPRF_BV_01: Packet Format
PCT_1_0_TX_HPRF_BV_01: Packet Format

PCT_1_0_TX_BPRF_BV_02: Power Spectral Density Mask
PCT_1_0_TX_HPRF_BV_02: Power Spectral Density Mask

PCT_1_0_TX_BPRF_BV_03: CF Tolerance and Pulse Timing
PCT_1_0_TX_HPRF_BV_03: CF Tolerance and Pulse Timing

PCT_1_0_TX_BPRF_BV_04: Baseband Impulse Response
PCT_1_0_TX_HPRF_BV_04: Baseband Impulse Response

PCT_1_0_TX_BPRF_BV_05: Transmit Signal Quality (NRMSE)
PCT_1_0_TX_HPRF_BV_05: - Transmit Signal Quality (NRMSE)

New NRMSE test cases not yet defined/validated

Receiver Tests

PCT_1_0_RX_BPRF_BV_01: SP0 & SP1 Packet Reception Sensitivity
PCT_1_0_RX_HPRF_BV_01: SP0 & SP1 Packet Reception Sensitivity

PCT_1_0_RX_BPRF_BV_02: SP3 Packet Reception Sensitivity
PCT_1_0_RX_HPRF_BV_02: SP3 Packet Reception Sensitivity

PCT_1_0_RX_BPRF_BI_01: SP0 & SP1 Dirty Packet Test
PCT_1_0_RX_HPRF_BI_01: SP0 & SP1 Dirty Packet Test

PCT_1_0_RX_BPRF_BI_02: SP3 Dirty Packet Test
PCT_1_0_RX_HPRF_BI_02: SP3 Dirty Packet Test

PCT_1_0_RX_BPRF_BV_03: SP3 Packet First-Path Dynamic Range
PCT_1_0_RX_HPRF_BV_03: SP3 Packet First-Path Dynamic Range

PCT_1_0_RX_BPRF_BV_04: Packet Format
PCT_1_0_RX_HPRF_BV_04: Packet Format

New security test cases not part of 2.0 due to lack of devices supporting secure ranging

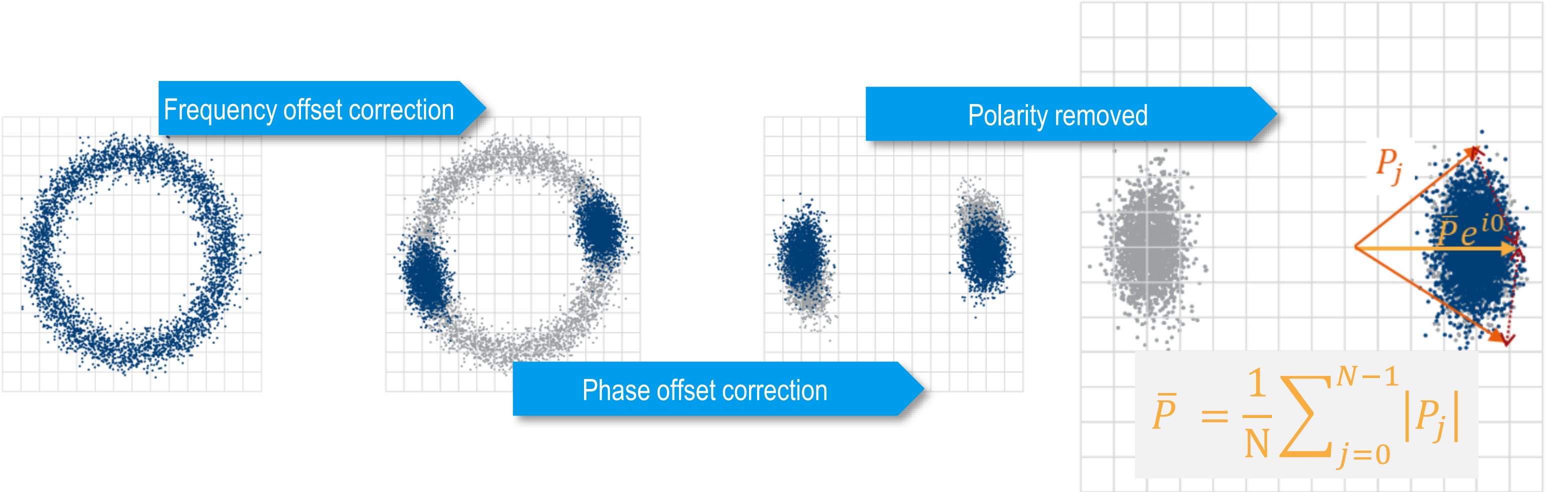
PCT_2_0_RX_BPRF_BI_01: Secure Ranging – Hamming Distance Test
PCT_2_0_RX_HPRF_BI_01: Secure Ranging – Hamming Distance Test

PCT_2_0_RX_BPRF_BV_01: Secure Ranging – First-Path Detection under Attack
PCT_2_0_RX_HPRF_BV_01: Secure Ranging – First-Path Detection under Attack

FiRa validated test tools: https://www.firaconsortium.org/certifications/fira-validated-test-tools

UWB transmitter quality: NRMSE based on FiRa Consortium

P_j is the complex pulse amplitude after frequency/phase offset and polarity are removed.



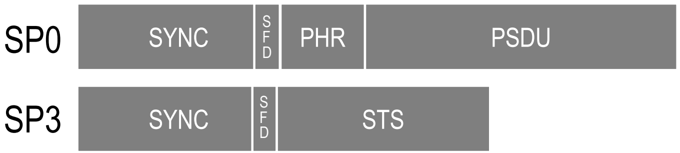
The transmit signal quality should be measured using a **normalized root mean square error** (NRMSE) metric with the mean pulse amplitude $\bar{P}$

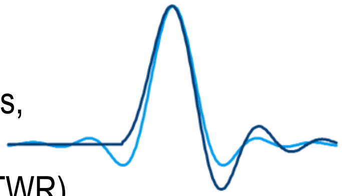
$$NRMSE = \sqrt{\frac{1}{N}\sum_{j=0}^{N-1}\frac{\left|P_j - \bar{P}e^{i0}\right|^2}{\overline{P^2}}}$$

CCC Digital Key Certification Program (UWB PHY/MAC)

The CCC Digital Key Certification program will ensure interoperability and security of the digital key solution, to deliver the best and most secure user experience between the mobile device and the vehicle.

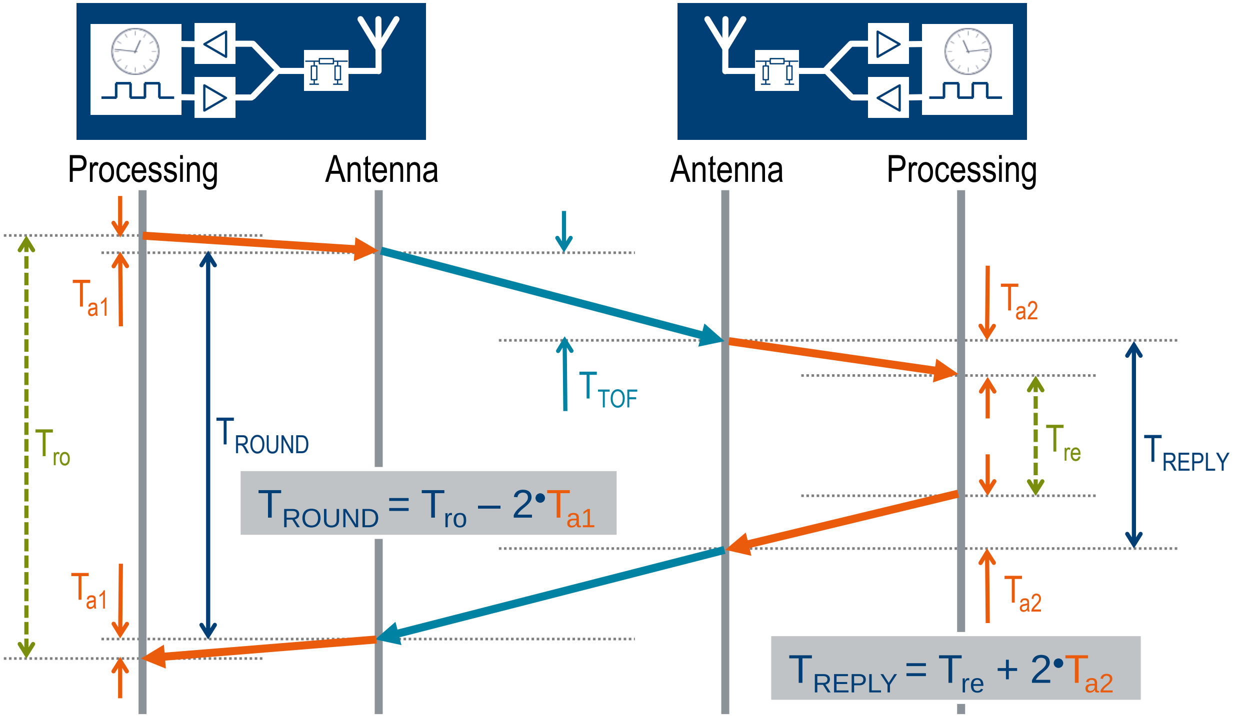
- CCC Digital Key certification testing covers several levels of interoperability including MAC/PHY-Layer certification
- Specification of PHY/MAC test cases as well as validation of test tools is still ongoing in close cooperation with FiRa consortium
- CCC is applying IEEE 802.15.4z HRP BPRF UWB SP0 and SP3 packets on channel 5 (6480 MHz) and 9 (7987 MHz) only





- Supporting different pulse shape combinations, symmetrical and precursor-free pulses
- Use only double sides two-way ranging (DS-TWR)

The on-board antenna delay determines the accuracy of the ToF and AoA measurements – need to calibrate and verify!

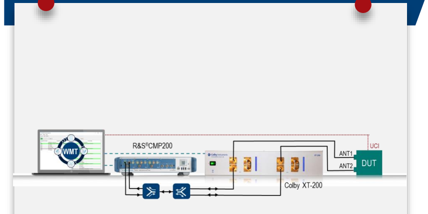


Dependent on the implementation the onboard antenna delay can easily vary by 1 ns which could result in a ranging error of more than 30 cm

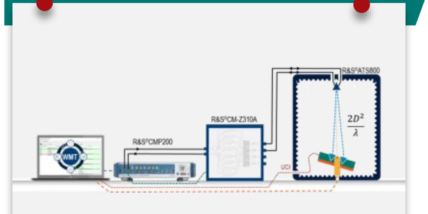
AoA verification and calibration in R&D and manufacturing

In practice specific UWB device designs (reference point), specific antenna radiation pattern, imperfect RF paths/switches as well as variations in manufacturing require for several stages of verification and calibration to ensure the AoA accuracy as required

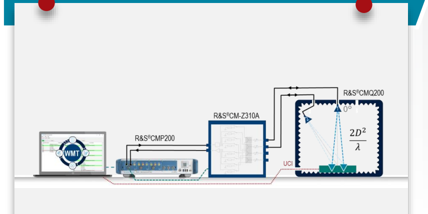
AoA/PDoA
Chipset Verification



AoA/PDoA
Device Reference Calibration



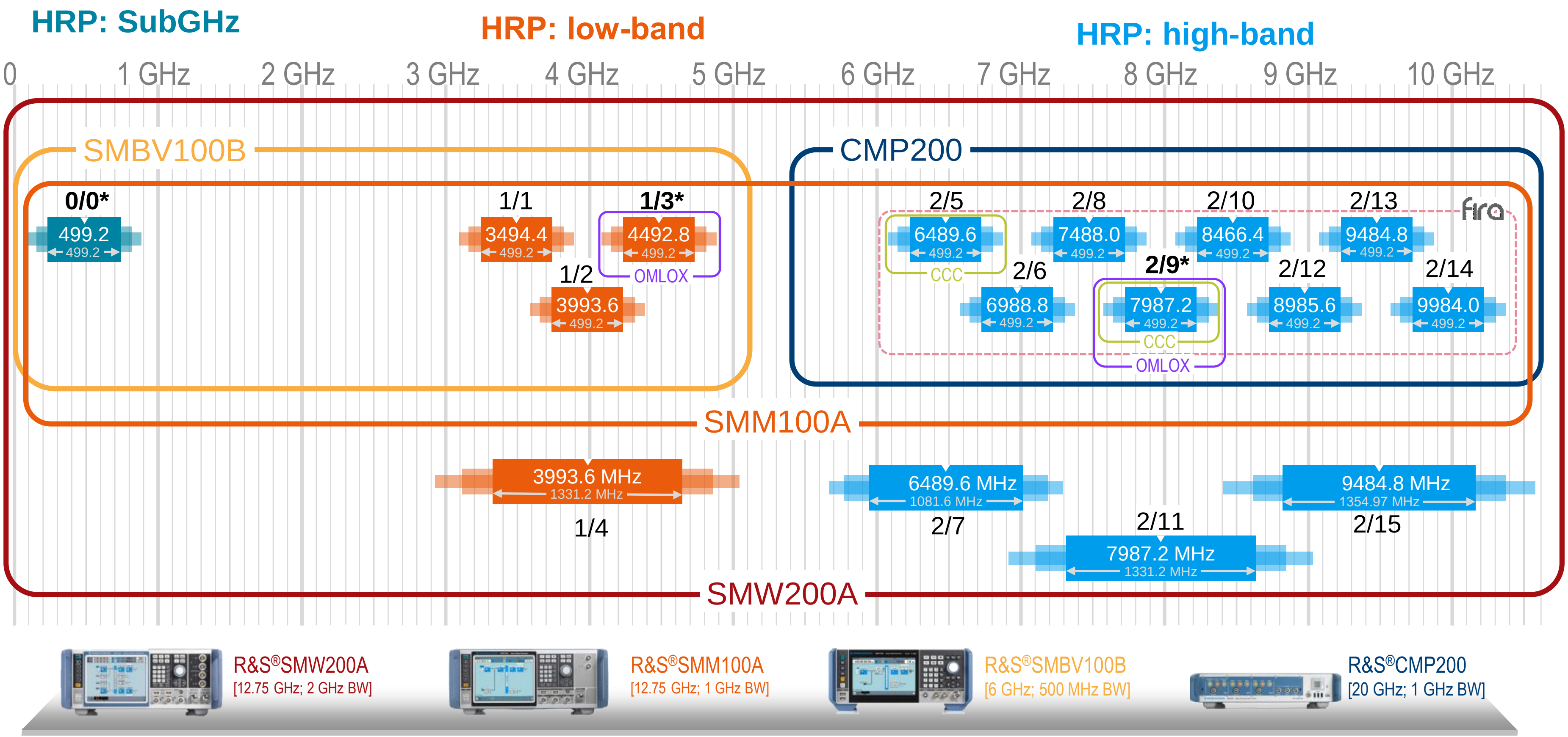
AoA/PDoA
Device Offset Calibration



UWB test and measurement solutions for all phases of the product lifecycle from the experts

R&S®ATS800R R&S®CMQ200 HS R&S®CMP200 UWB PHY Test Suite R&S®RTP+VSE R&S®SMM100 R&S®FSW26 R&S®TS7124

UWB HRP Signal generator options



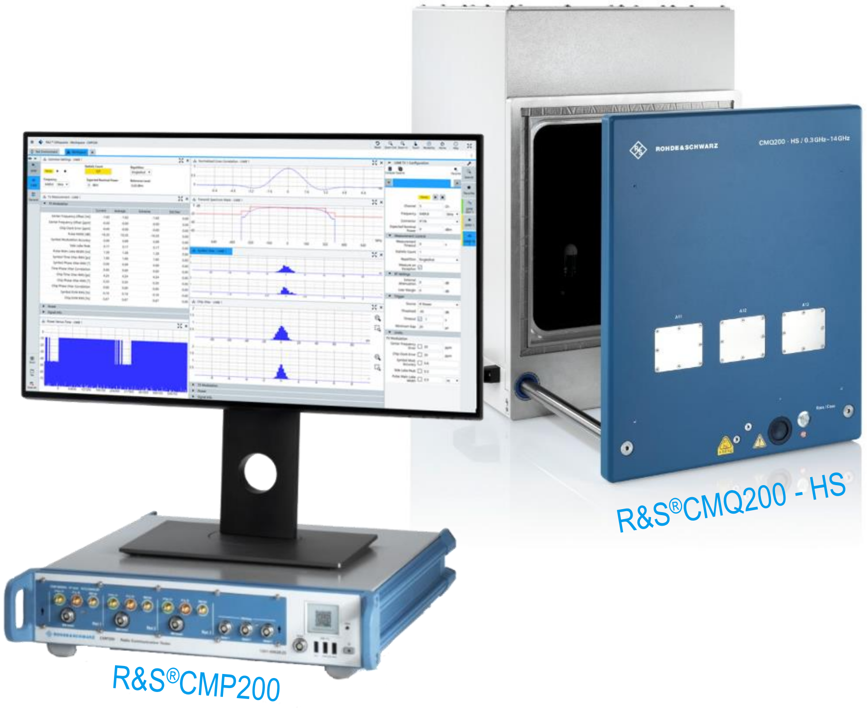
R&S®CMP200 – Wideband tester for UWB and more

CMP200 features

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

Compact UWB non-signaling tester for HRP in high band

- HRP UWB PHY TX measurements (802.15.4)
  Band group 2: 6.5 to 9.5 GHz
- HRP UWB RX measurements by use of customer waveforms or R&S®WinIQSIM2
- Time of flight and angle of arrival measurements
- New CMQ200-HS from 0.3 – 14 GHz @80dB shielding

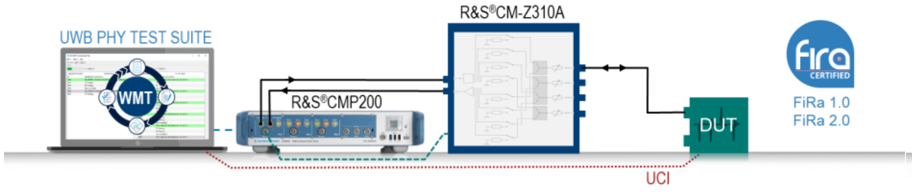


HRP UWB transmitter measurements with R&S®CMP200

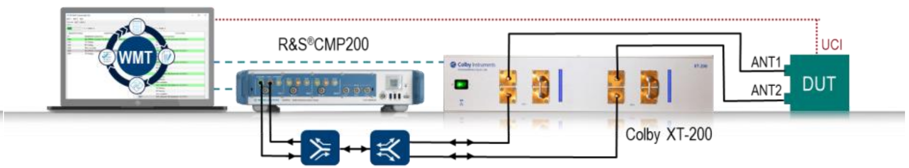
R&S®CMP200

UWB test solution for different use cases based on the CMP200

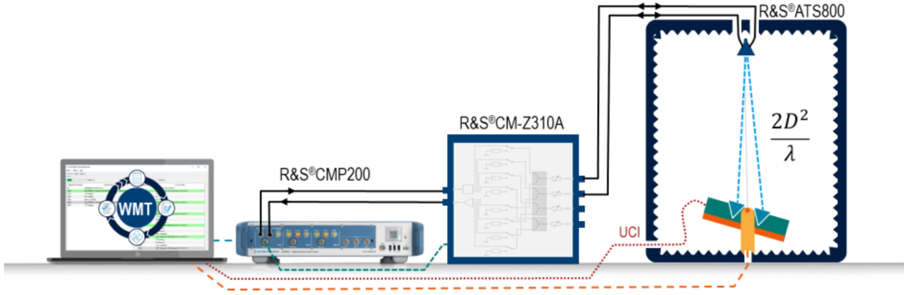
RF Performance and ToF incl FiRa



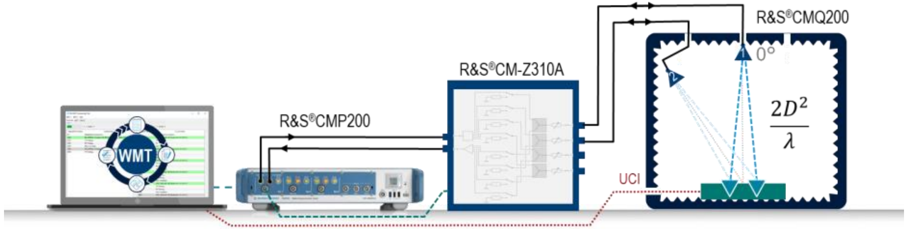
AoA verification and benchmarking



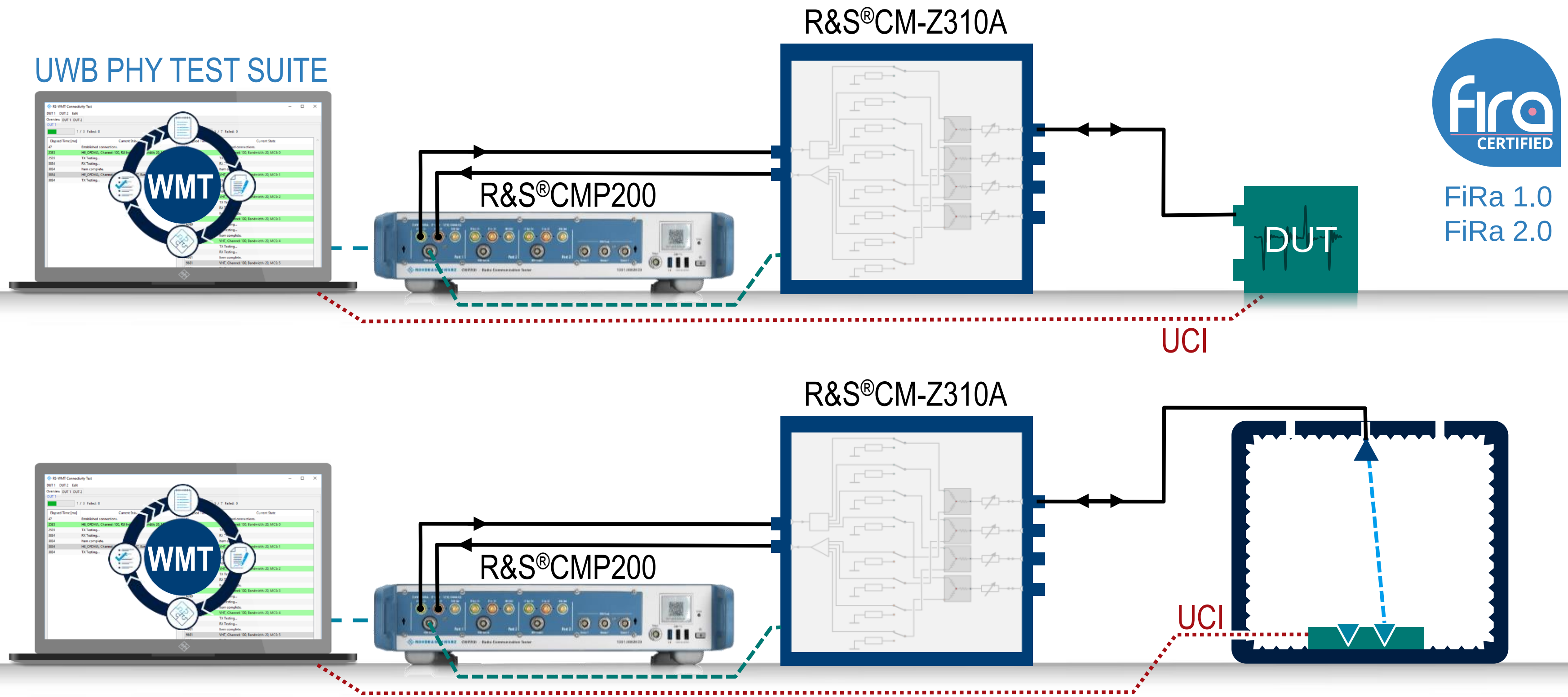
RF AoA verification and ref. calibration



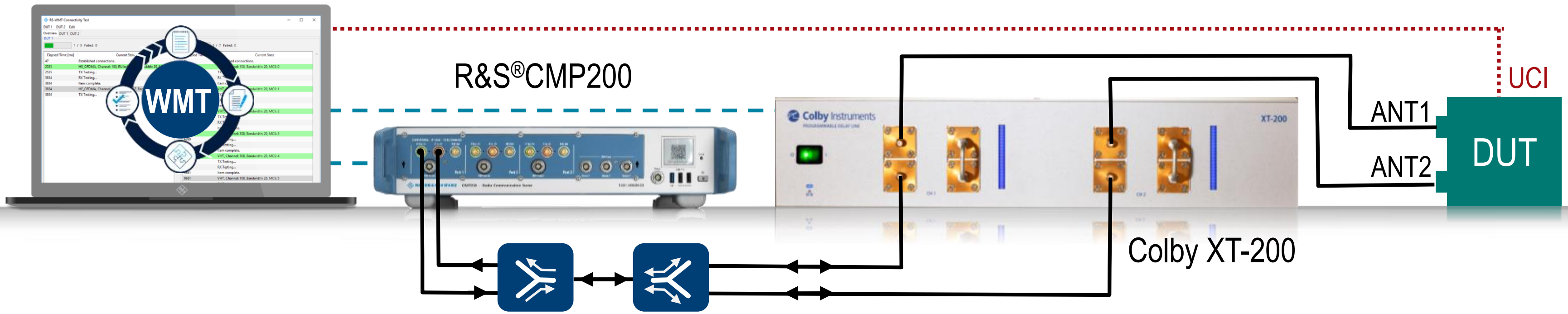
PHY Perf. Check, AoA/ToF calibration



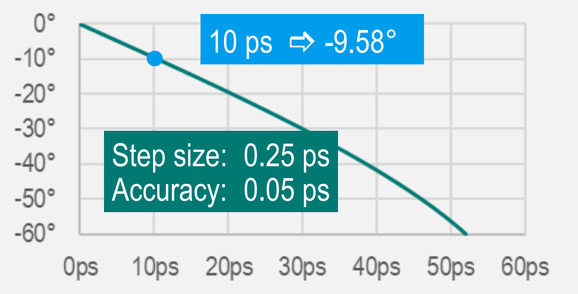
Time of flight measurements – conducted or over-the-air



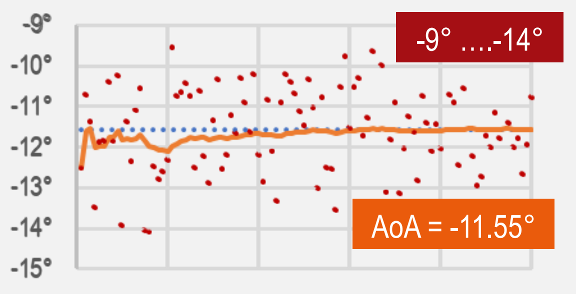
AoA verification in chipset R&D or benchmarking



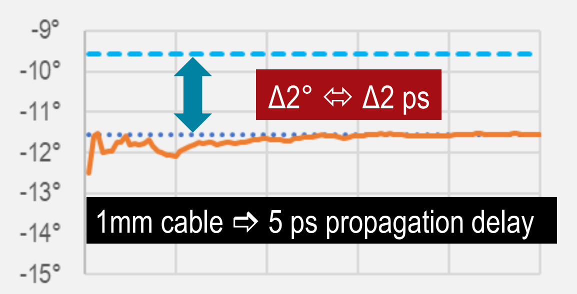
Delay line: delay (ps) vs AoA



Hundred PDoA/AoA measurements



A very sensitive test setup



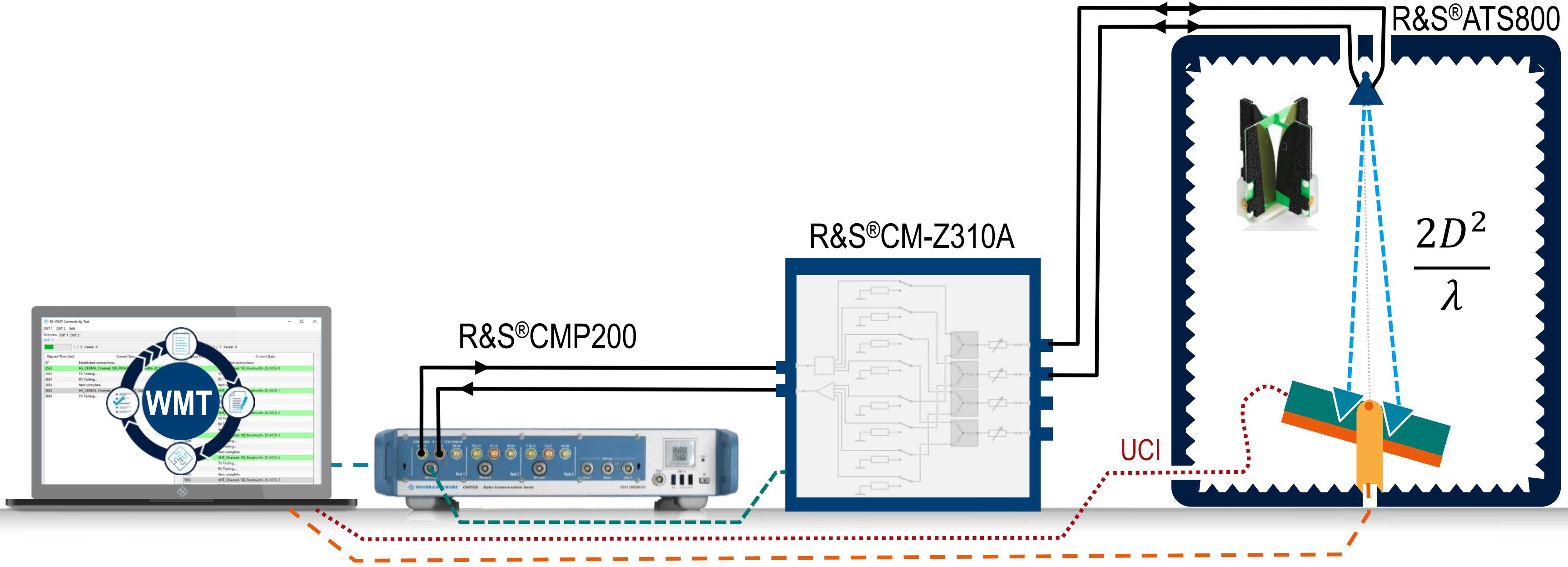
Recommended delay line from Colby Instruments

Programmable Delay Line Instrument XT-200
Phase shift RF/microwave signals with precise, repeatable, and accurate delay

- Signal input frequency range from DC to 18.0 GHz
- Precision resolution to 0.50 ps per step, 0.18° per 1.0 GHz
- Dual channels offer up to 625.0 ps delay in each channel
- Typical insertion loss for a single channel/trombone at 18.0 GHz:
  - -2.2 dBm (MIN delay)
  - -2.8 dBm (MAX delay)

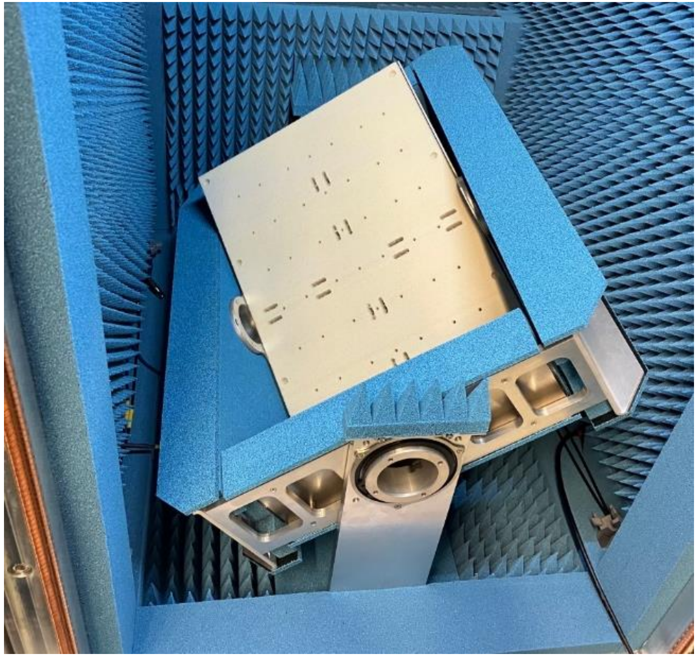
https://www.colbyinstruments.com/xt-200

AOA center position factory calibration:
PDoA - device reference calibration

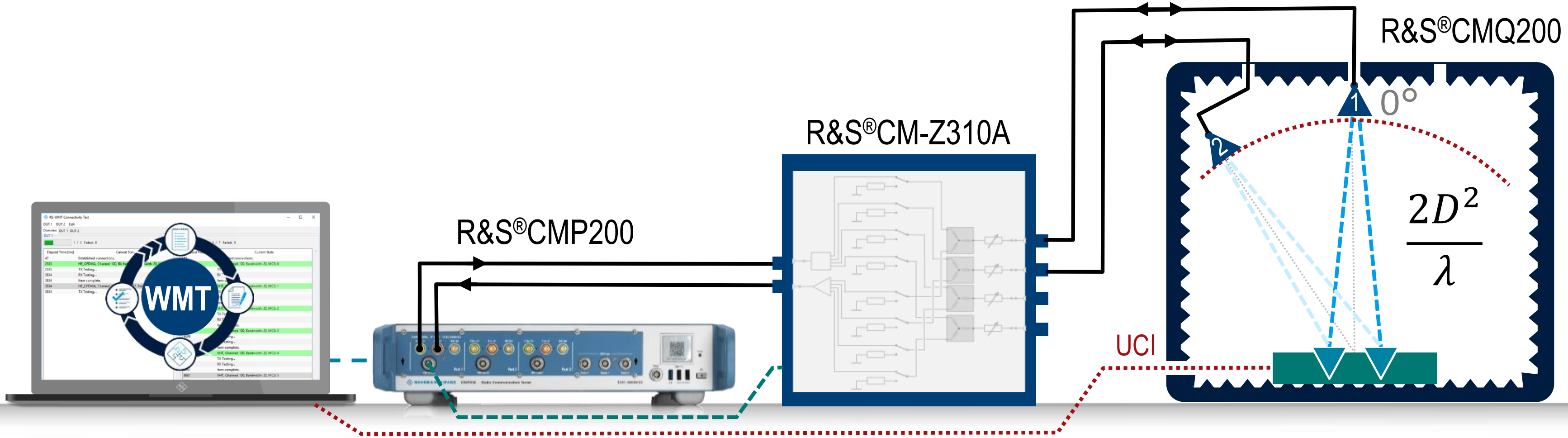


Tilt-tilt positioner for the ATS shielded chambers

Category	Value
Positioner Type	Tilt and pan
DUT Weight	< 2.5kg, centered
Resolution	0.01 degrees
Elevation accuracy	0.25 degrees @1kg 0.50 degrees @ 2.5kg
Tilt Range	+/- 90 degrees
Pan Range	+/- 90 degrees
Rotation speed	< 45 degree/sec



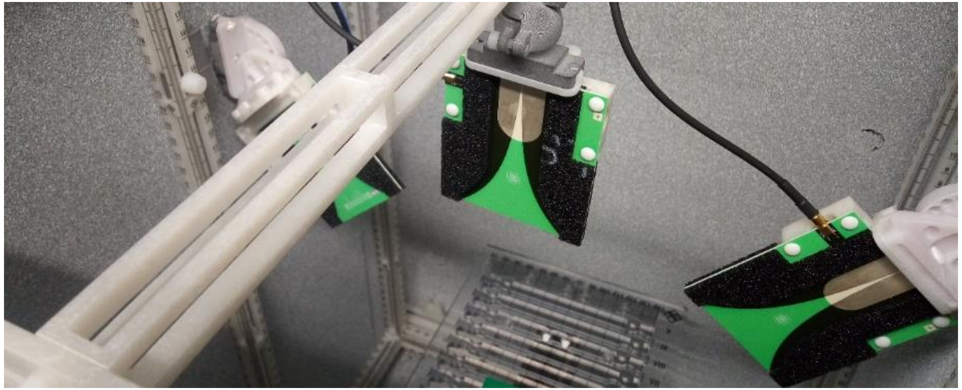
AOA center position factory calibration:
PDoA - device offset calibration



Correct antenna/DUT positioning and reasonable distance between antennas are essential for correct measurements

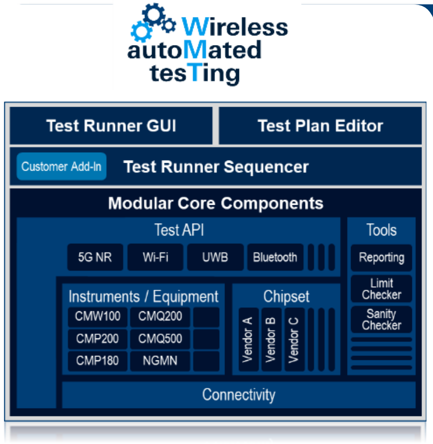
R&S®CMQ200-HS shielding cube designed for multi-antenna OTA testing for UWB in combination with the R&S®CMP200

- New member of the R&S® CMQ200/500 family for a frequency range of 0.3 to 14 GHz
- High shielding support of 80 dB
- Perfectly suited for multi-antenna setups required for UWB AoA measurements



Our offering to provide a customized automated test solution based on WMT

Wireless autoMated tesTing



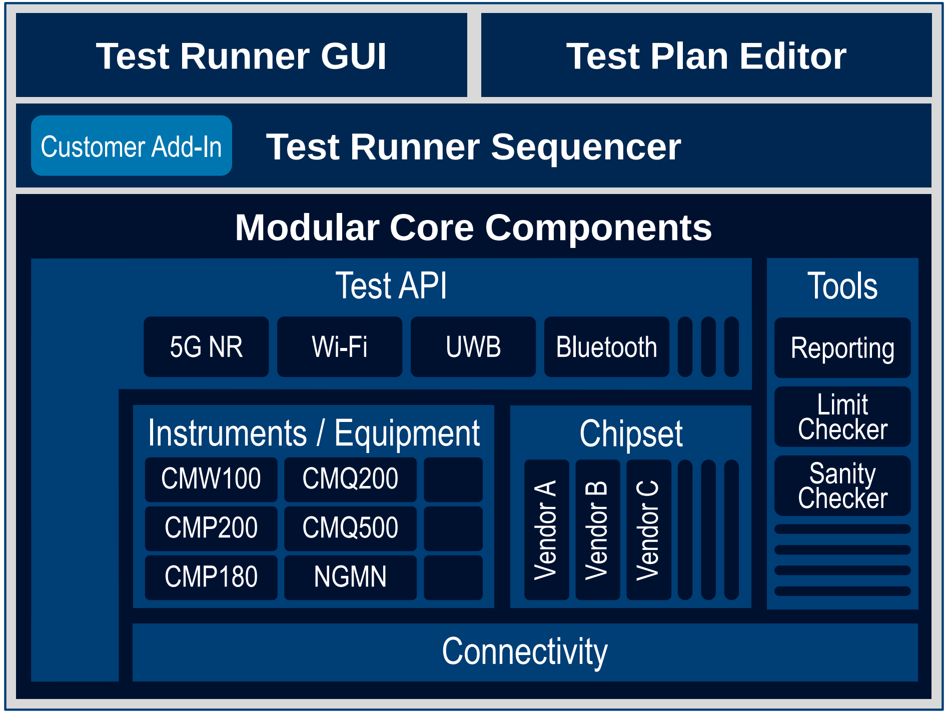
Phyton based Framework

Customization & Integration

Automated Test Solution

Ready to integrate wireless test automation framework which makes non-signaling testing fast, accurate & easy

Wireless autoMated tesTing



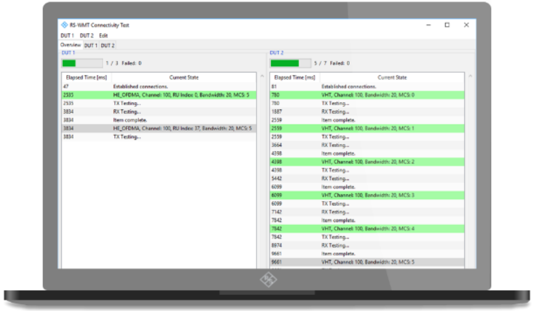
Tailored for production testing and non-signaling R&D applications

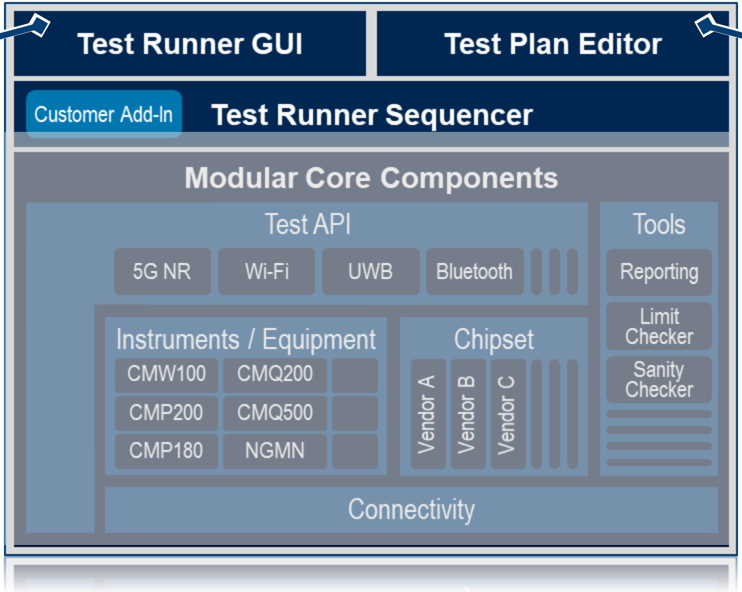
- Flexible integration into any automated testing environment
- Fully customizable from a basic test tool to a full-blown turnkey solution incl. Phyton based customer add-ins.
- Field-proven speed of test execution
- High efficiency by broadcasting and interleaving (smart channel)
- Insightful and easy customizable GUI for sequencing and test plan creation

R&S WMT Test Runner component functionalities

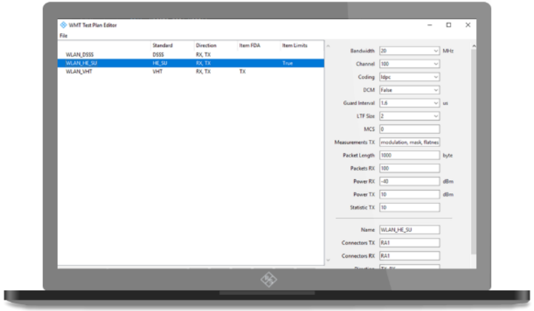
Wireless autoMated tesTing

Test Runner GUI
Lightweight graphical user interface (GUI) incl. support of optimized multi DUT testing





Test Plan Editor
Powerful creation ad modification of test plans incl. sanity checker and a build-in limit editor



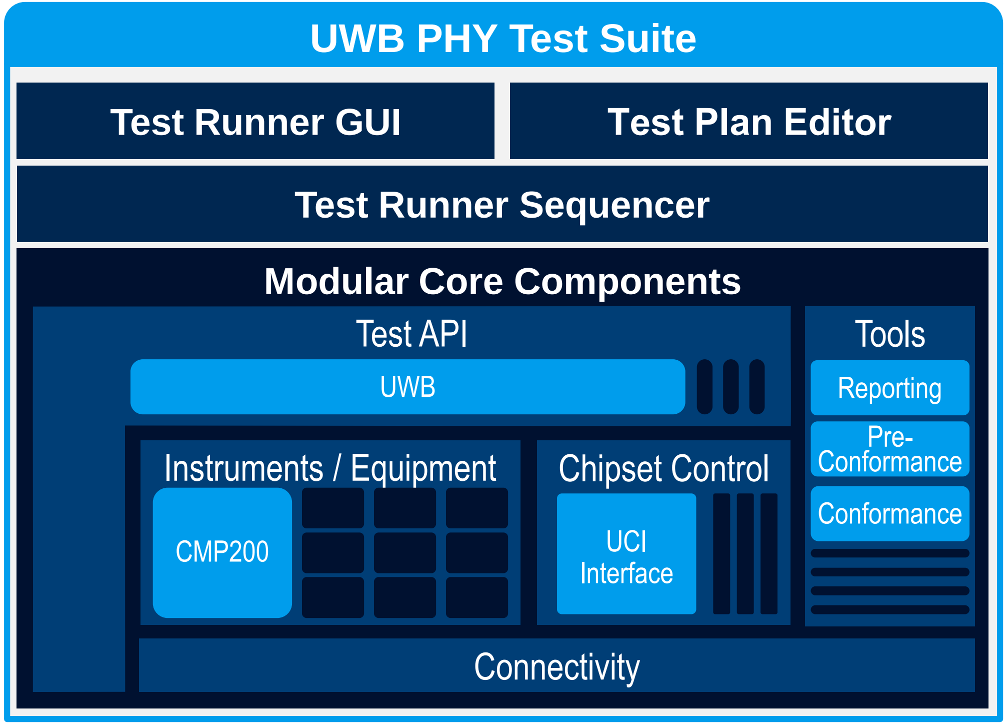
Test Runner Sequencer
Basic sequencer functionalities to schedule simple production and R&D test flows for verification tests, calibration tasks and also custom routines or scripts. It is a command line utility that used simple text based configuration files and JSON based test plans that also allows execution of customized scripts for extended usability.

fira | The Power to Be Precise

VALIDATED PHY LAYER CERTIFICATION TEST TOOL (PCTT) for FiRa 1.3 & 2.0

R&S UWB PHY Test Suite

Wireless autoMated tesTing



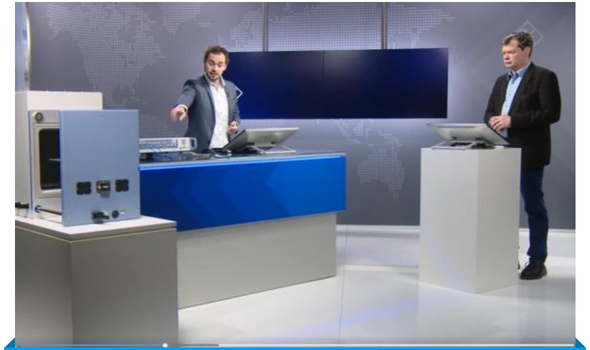
Tailored for UWB physical layer testing applications in R&D based on the R&S wireless non-signaling test solution framework (MWT) supporting

- Conformance and
- Pre-conformance

VALIDATED FiRa PHY LAYER CERTIFICATION TEST TOOL (PCTT)

Worthwhile to watch …

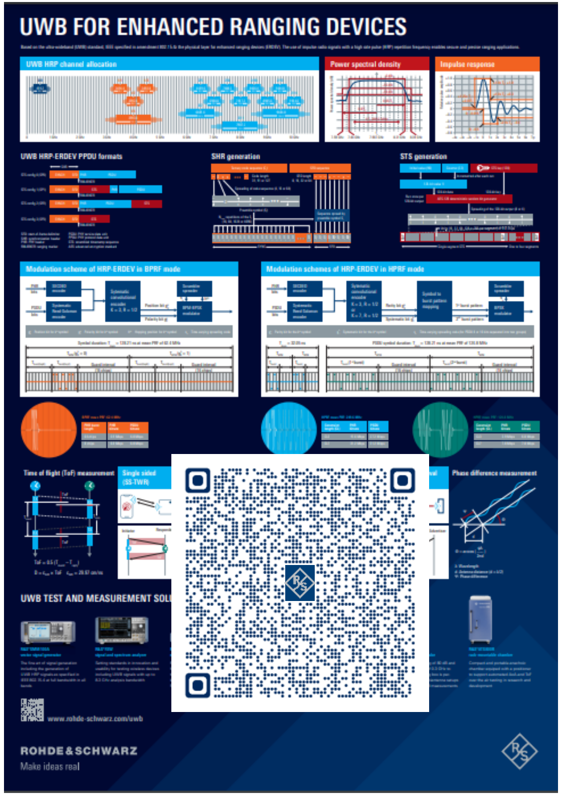
Testing ultra-wideband for automotive applications



Reinforce a seamless UWB experience

Realizing the full potential of UWB with smart testing

Worthwhile to read ….



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thank
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