Coexistence of UWB and Wi-Fi 6E

How does the latest IEEE 802.11ax standard challenge UWB-based radiofrequency communication in an automotive environment?

Presentation

Hendrik Krack

27. Juni 2022

TUHH Hamburg University of Technology

SECURE CONNECTIONS FOR A SMARTER WORLD

WHAT MAKES ELECTROMAGNETIC COMPATIBILITY SO IMPORTANT

Electromagnetic Interference

- EMI has been known to mankind ever since the early start of using any sort of electronic devices like radio transceivers

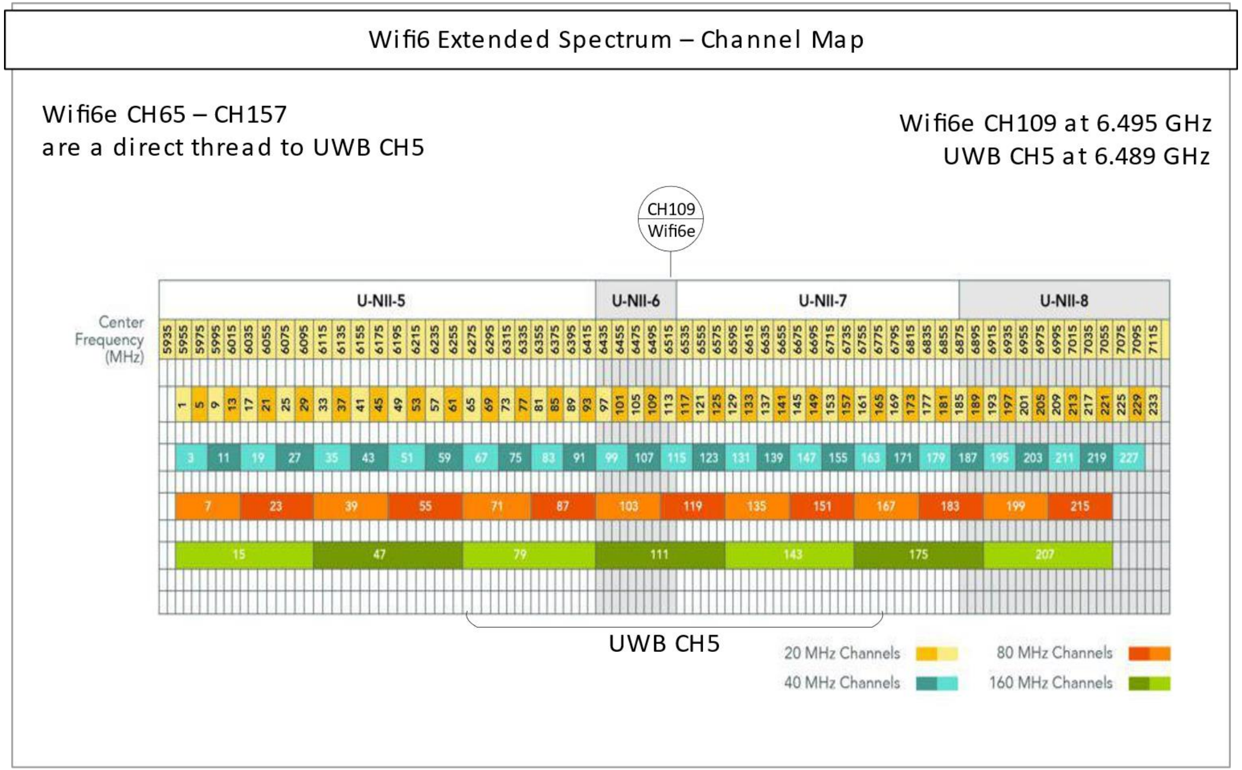
- With arising technological advancements the occurrence of EMI & especially radiofrequency interference increased

- Electromagnetic pollution is becoming a serious concern

Effects of EMI on radiofrequency communication systems

- EMI can have severe effects on any sort of electronic equipment
- 1967 – aircraft carrier U.S.S. Forrestal was severely damaged after the accidental release of ammunition by an incoming plane due to a voltage spike caused by RFI with the carrier-based radar

IEEE 802.11ax Channel Allocation



- Wi-Fi 6 extension to [5925 MHz, 7125 MHz] to tackle bandwidth problem (released 2021)
- Frequent use of 80 MHz & 160 MHz Wi-Fi Channels with 24 dBm & 27 dBm TX Power
- Threat to UWB in automotive industry

UWB IEEE 802.15.4 Channel 5

Center Frequency: 6489.6 MHz

Spanning [6240MHz, 6740MHz]

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Assignment

- Development of a test set-up + software to reproduce & understand the interference case of Wi-Fi 6E and UWB

Attempt to answer:

- **How does Wi-Fi 6E influence UWB ranging and communication performance?**
- **How can we mitigate the interference effects?**

Table of Content

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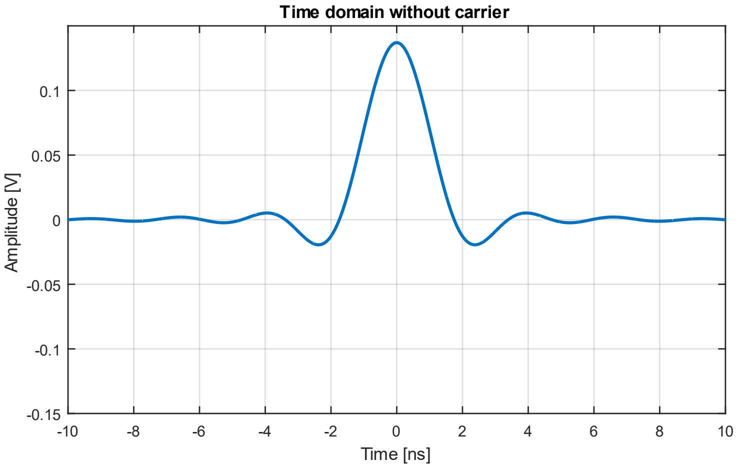
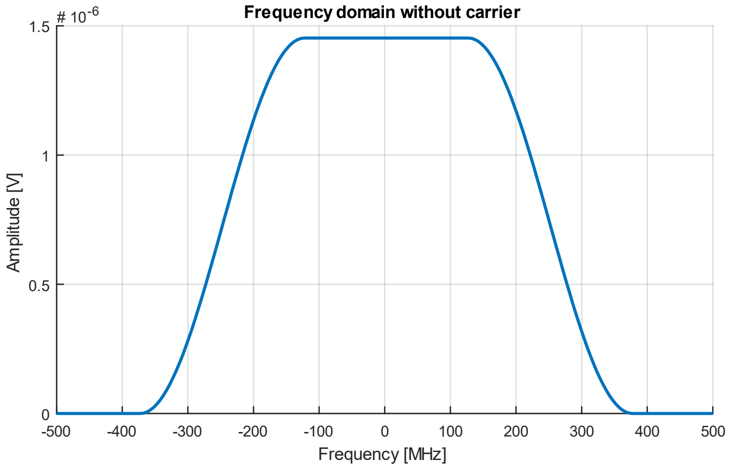
ULTRA-WIDEBAND RANGING

Ultra-Wideband Ranging

Pulse & Spectrum

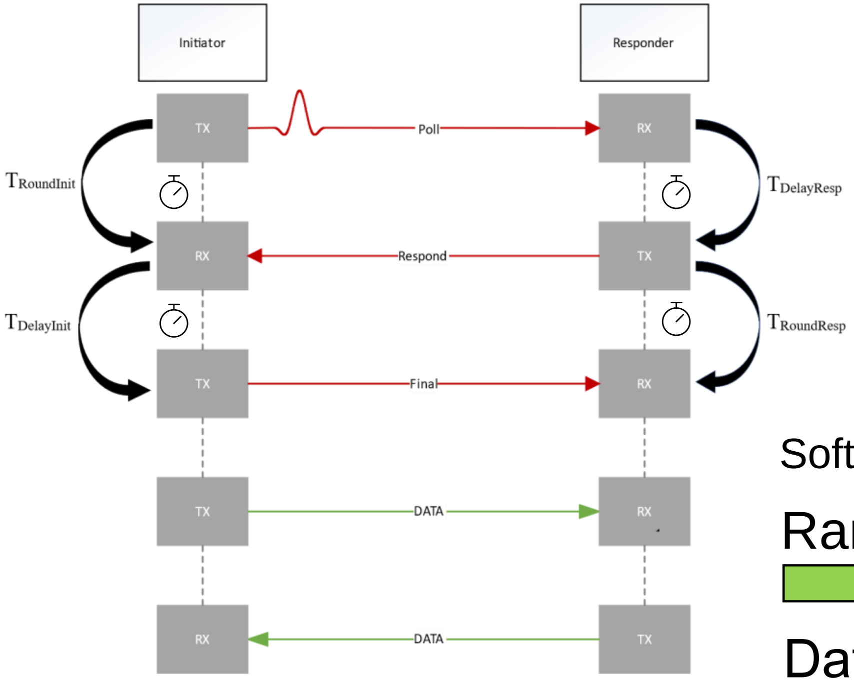
- Deployed IEEE UWB reference pulse with a width of $2\ \mathrm{ns}$
- UWB spectrum results in a width of $500\ \mathrm{MHz}$





Ultra-Wideband Ranging

Two-Way Ranging – Double Sided



- Stop-watches get timestamps on Initiator and Responder side by exchanging ranging frames
- Finally timestamps T_{Delay} & T_{Round} are exchanged in data frames

Software protocol differentiates two frame types:

Ranging Frame

SYNC	SFD	STS

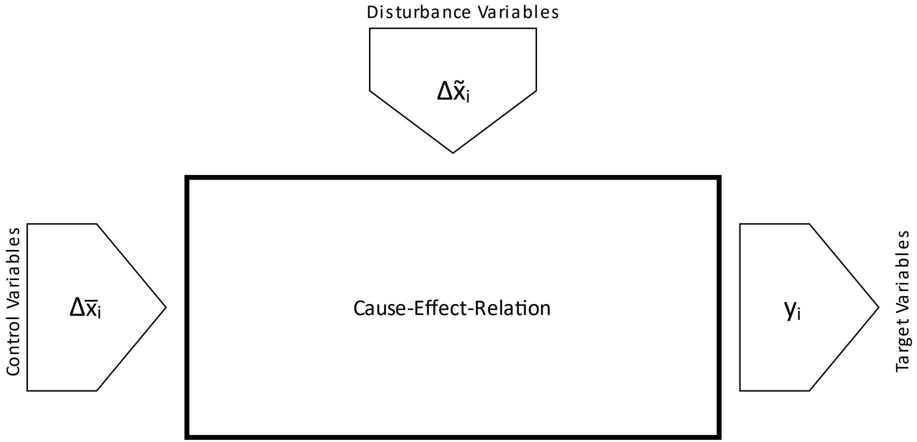
Data Frame

SYNC	SFD	PHR	PSDU

DESIGN OF EXPERIMENT

Design of Experiment

Influencing Variables & Cause/Effect - Relations



Influencing Variables:

$$X = \bar{X} \cup \tilde{X}$$

$\bar{X} = \{ d_{distance} , D_{stream} , f_{CenterWiFi} , B_{Channel} \}$

$\tilde{X} = \{ C_{Ethernet} , R_{Ferrit} , f_{Hopping} , \dots \}$

$Y_{PER} = \{ E_{PRMBL} , E_{STS} , E_{SFD} , E_{SECDEC} , D_{RS} , \dots \}$

- Systematic approach
- Understanding cause-effect relationships

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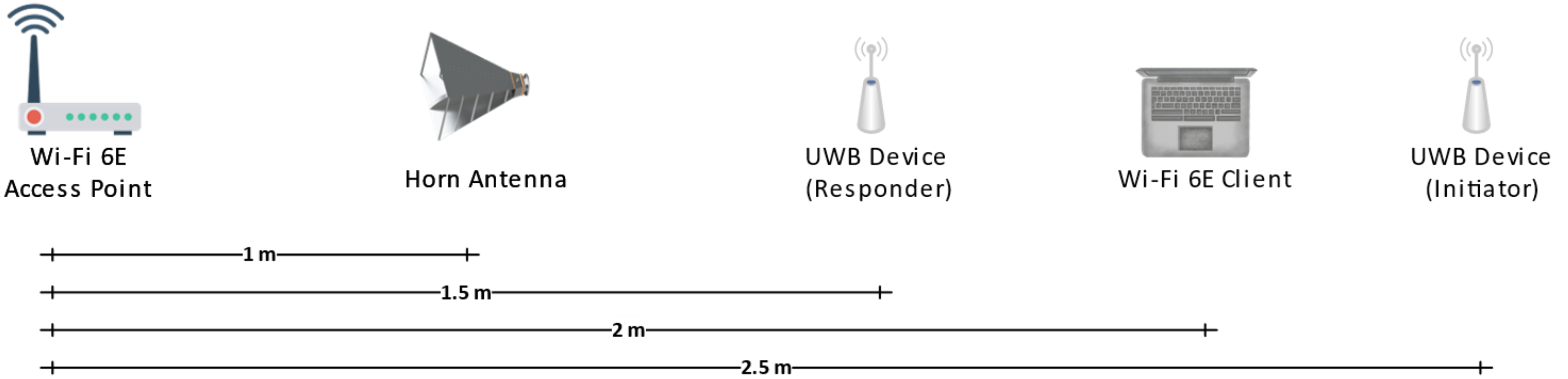
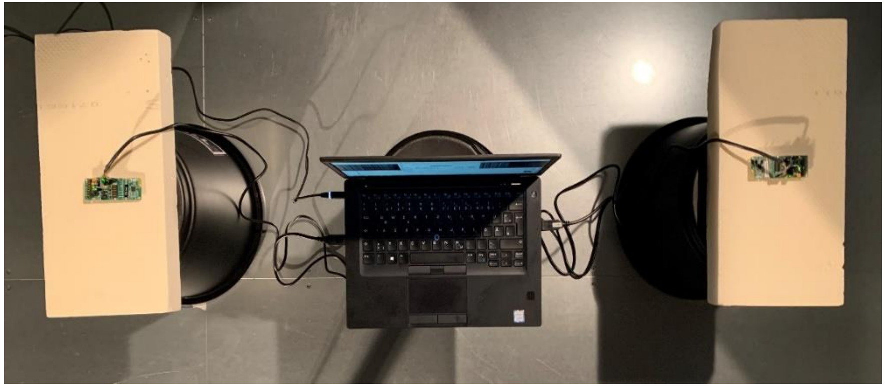
Design of Experiment

Schema of test set-up

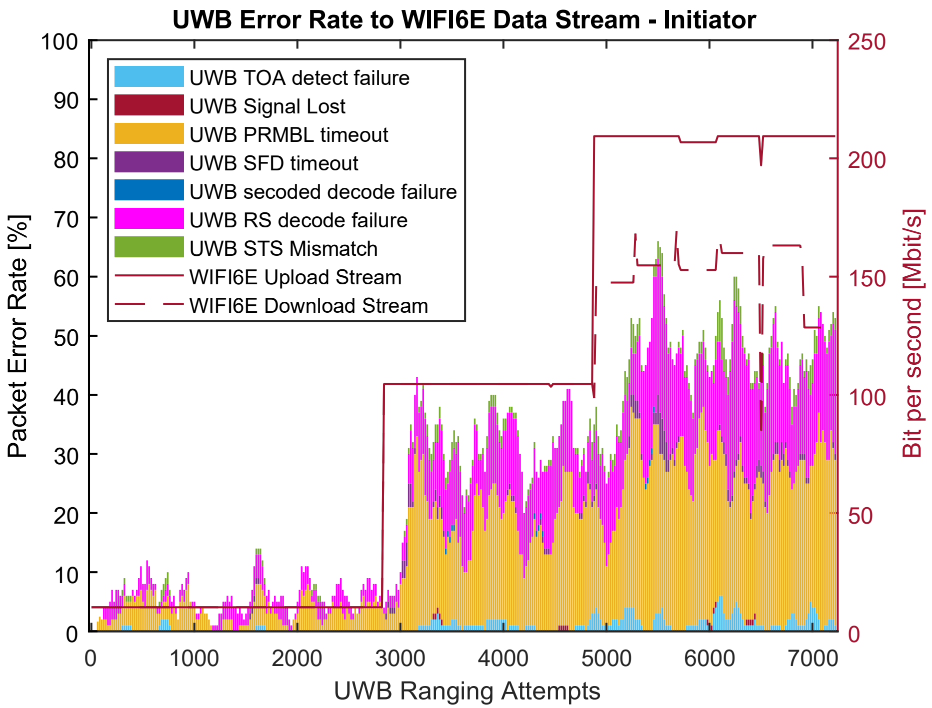




MEASUREMENTS

Measurements

Correlation of Wi-Fi 6E Data Stream and UWB Packet-Error Rate



Fundamental question: How does Wi-Fi 6E affect UWB ranging?

- Evidently a proportionality between the Wi-Fi data stream [Mbit/s] and the UWB PER exists

- An increase in Wi-Fi data stream causes an increase in PER

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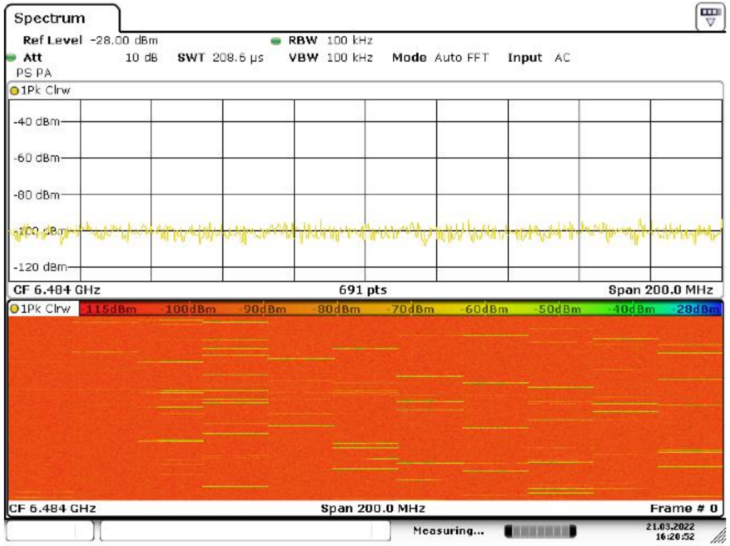
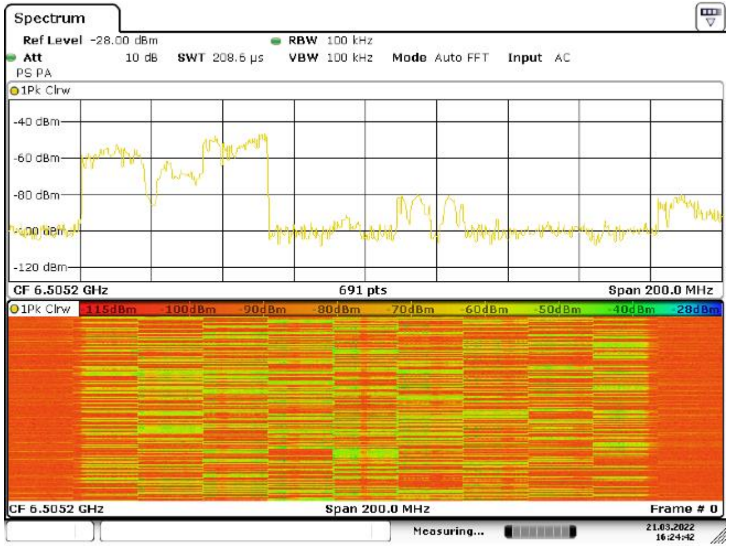
Measurements

Waterfall diagram of Wi-Fi 6E channel occupation



10 Mbit/s



300 Mbit/s

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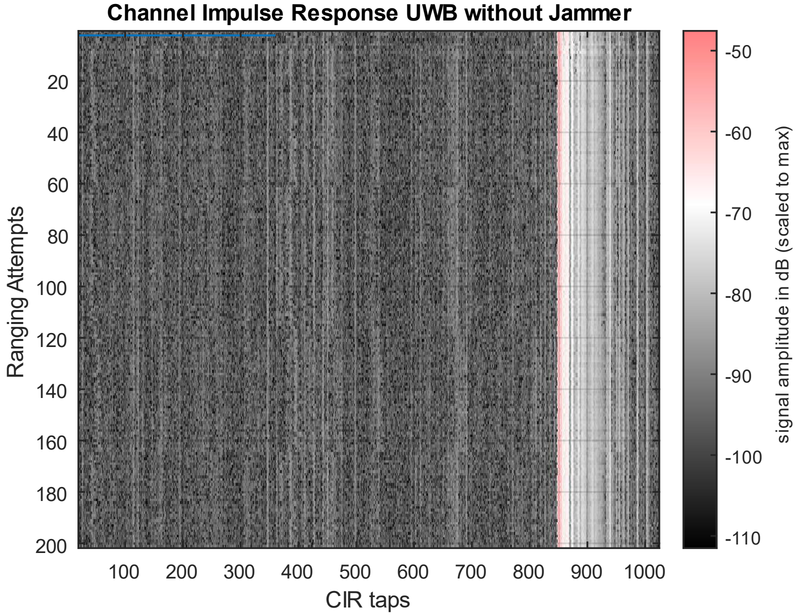
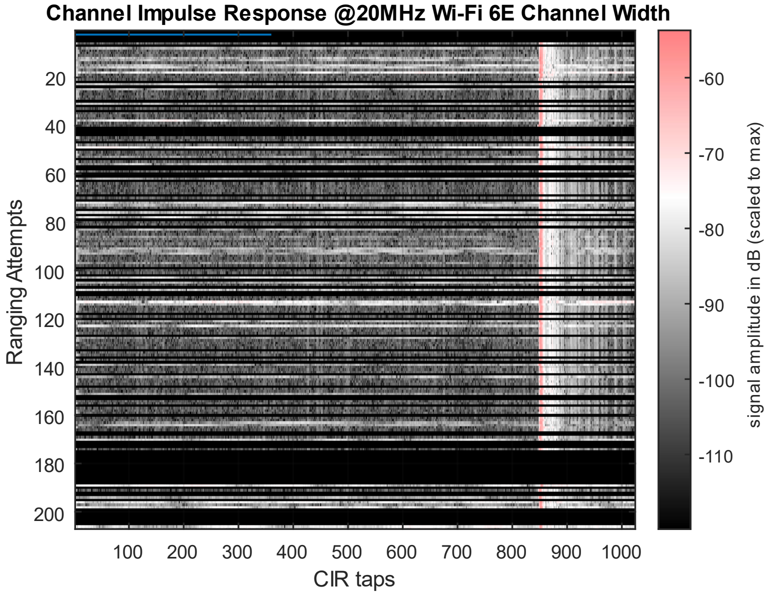
Measurements

Channel Impulse Response



UWB only



Wi-Fi 6E present

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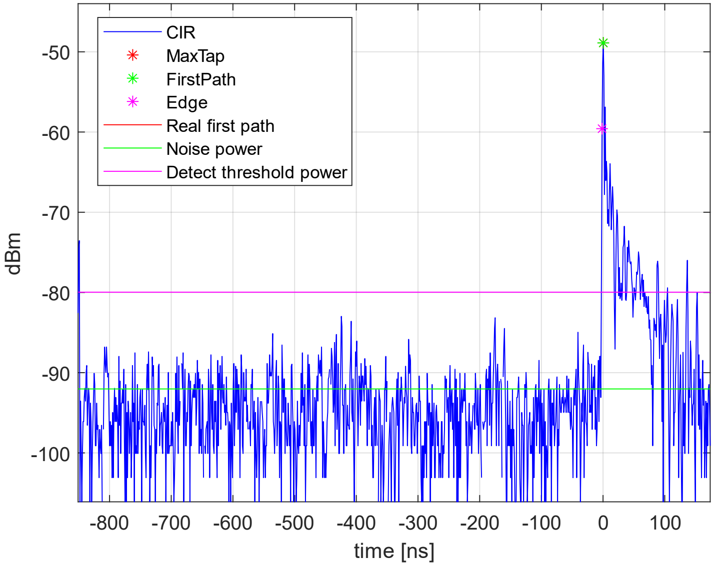
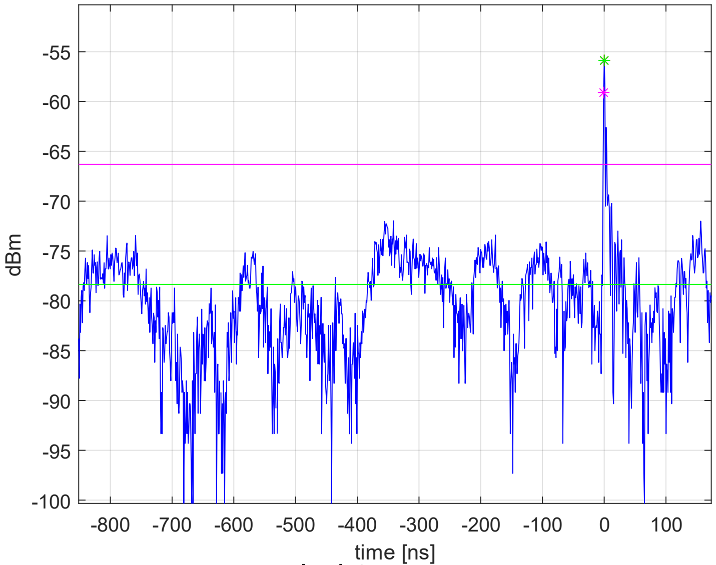
Measurements
Channel Impulse Response



UWB only



Wi-Fi 6E present

Δ14dB difference in measured noise power

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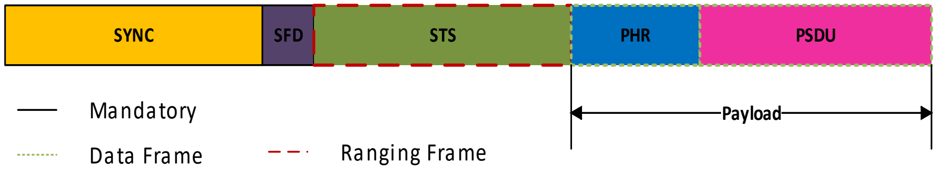
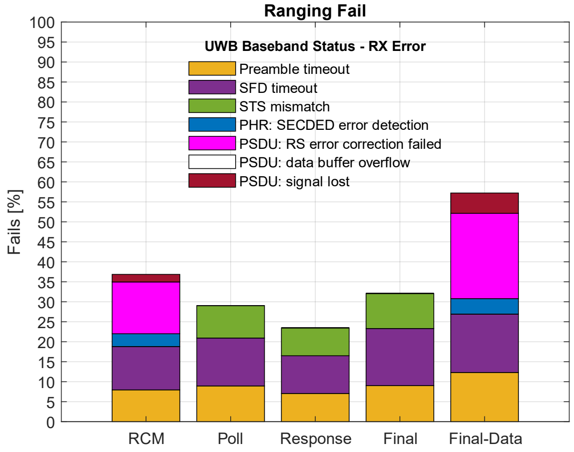
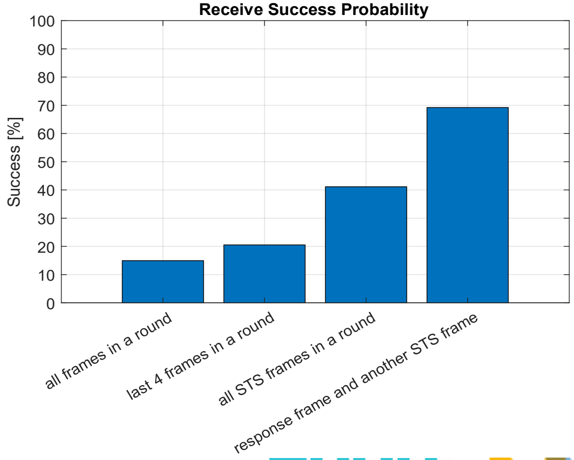
Measurements

Statistical Analysis

- Further measurements have shown that data frames seem to be more affected by Wi-Fi 6E interference than ranging frames
- Statisitcal analysis has shown that while TWR-DS only obtains a **15%** Success Rate, a choice of simpler protocols using less frames can succeed with up to **69%**

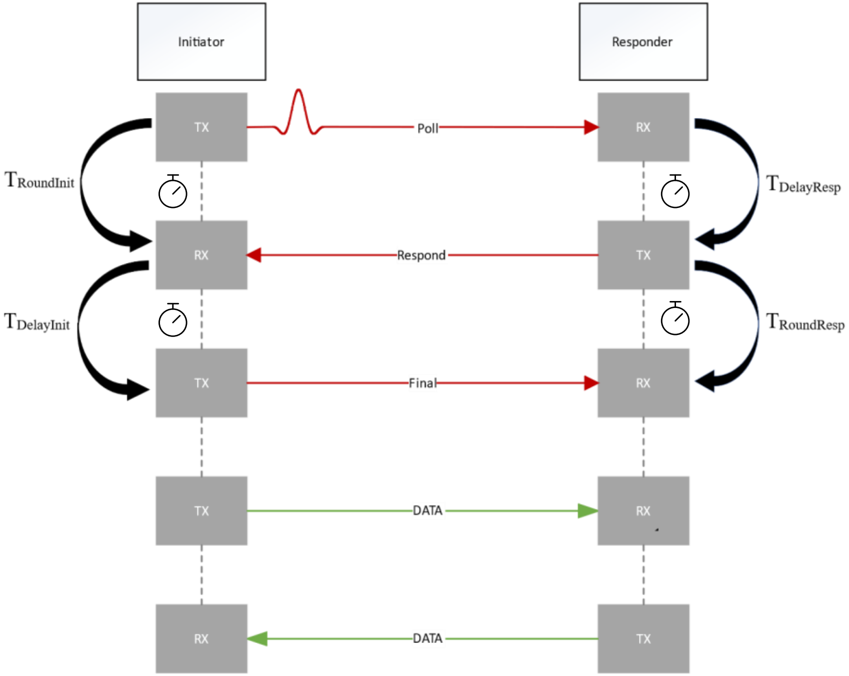


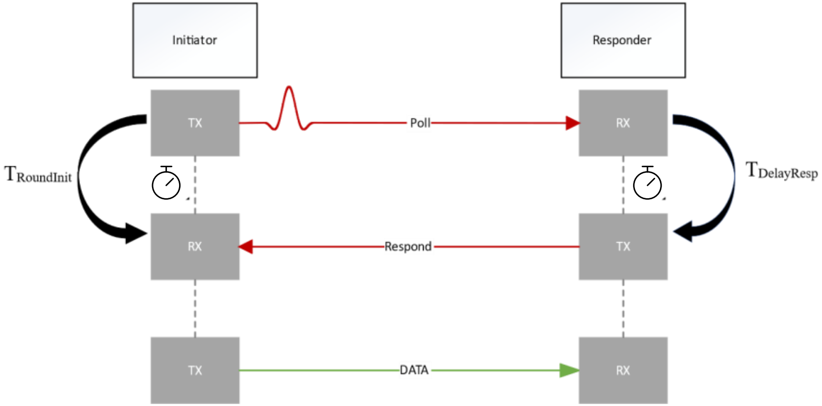




Ultra-Wideband Ranging

Two-Way Ranging – Double Sided / Single Sided





CONCLUSION

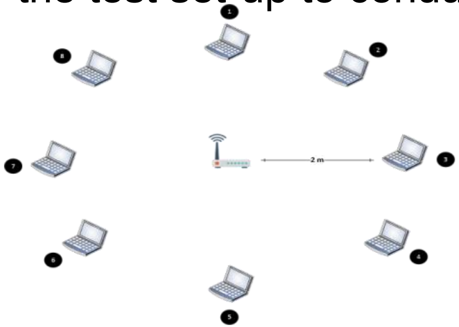
Conclusion

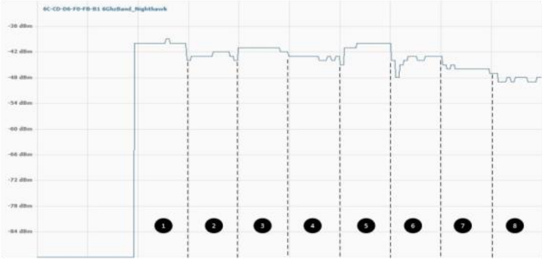
Summary

What has been done:

- Acquisition and configuration of hardware components

- Development of software and tools for the test set-up to conduct coexistence measurements





- Conductance and analysis of coexistence measurements using different software protocols, positioning, and arrangements of hardware components

Conclusions

Outlook

What has been achieved?

- Test set-up that can be used as a basis for future use
- Results that give inside on how Wi-Fi 6E work and which effects are visible
- First suggestions on mitigation strategies

What is next to come?

- Software protocol can be optimized to obtain a suitable coexistence solution for UWB
- Investigations into the coexistence should involve the influence of UWB on Wi-Fi 6E as well (TU Graz**)**

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Questions?

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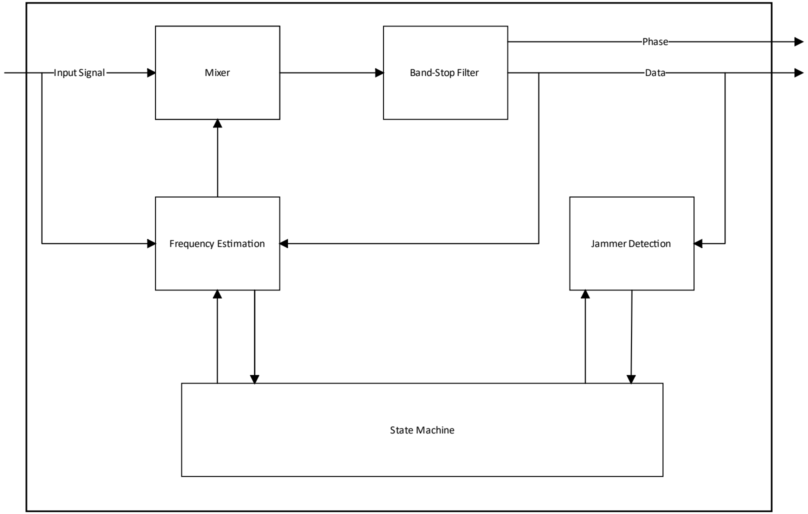
NARROWBAND INTERFERENCE CANCELATION BLOCK

Narrowband Interference Cancellation Block

Introduction & Fundamentals

- Already implemented on NCJ29D5 and initially intended for narrowband interferes
- Signal mixer, Band-Stop filter, Frequency Estimation & Jammer Detection Unit
- Means to lock onto a jammer and apply the band-stop filter to cancel out the unwanted interference of the UWB signal



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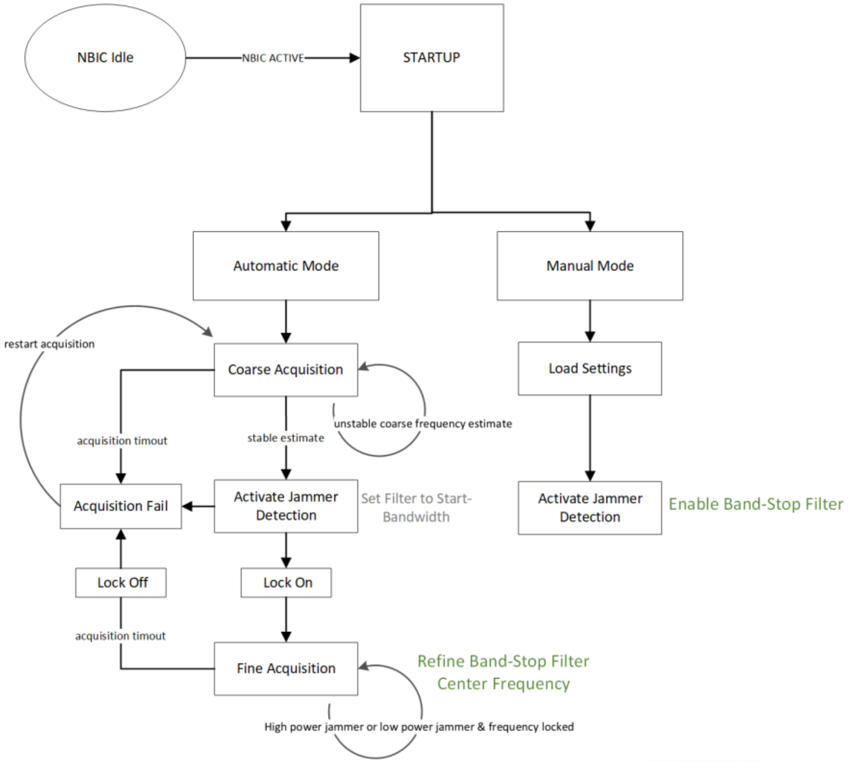
Narrowband Interference Cancellation Block

Introduction & Fundamentals

NBIC State Machine

Two modes:

- Automatic
- Manual



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Narrowband Interference Cancellation Block

Implementation

NBIC can be configured with a set of <u>Configuration Parameters:</u>

Filter Bandwith B_{Filter}

Initial Frequency Estimate f_{NBIC}

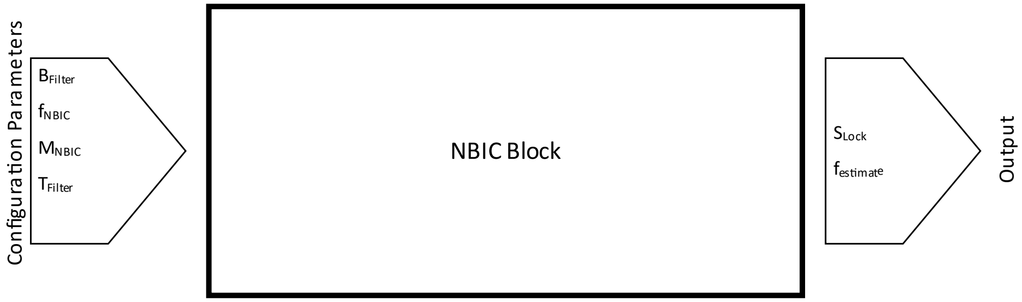
NBIC Operations Mode M_{NBIC}

Filter Type T_{filter}

<u>NBIC Output:</u>

Lock State S_{Lock}

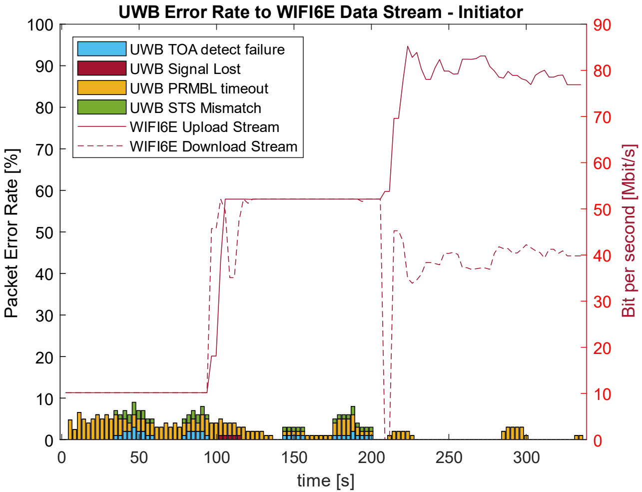
Frequency Estimate $f_{Estimate}$

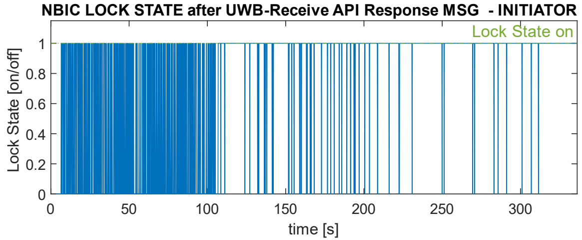


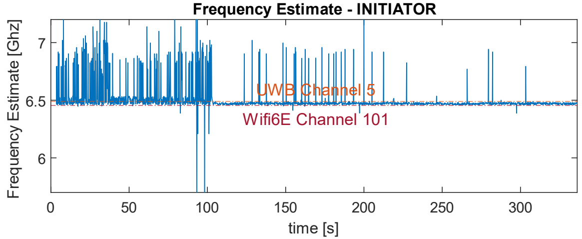
Narrowband Interference Cancellation Block

Measurements – 20 MHz Wi-Fi 6E Channel Bandwidth

- Massive improvement on the 20 MHz Wi-Fi jammer bandwidth
- Frequency estimate works more accurate at higher Wi-Fi data rates







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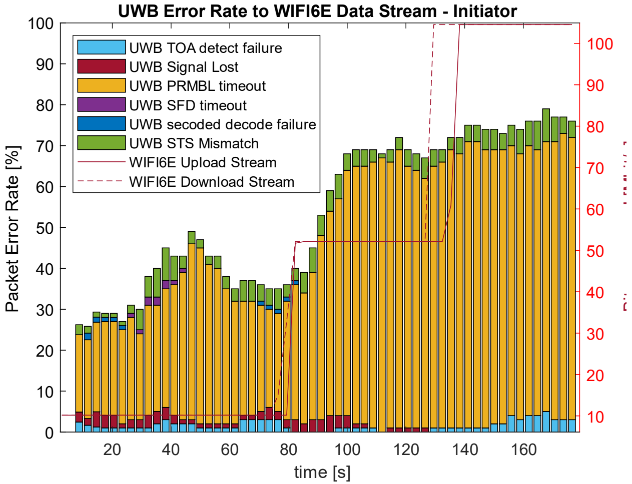
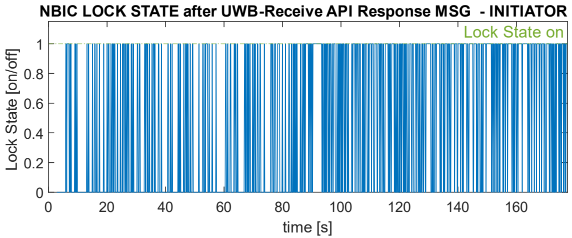
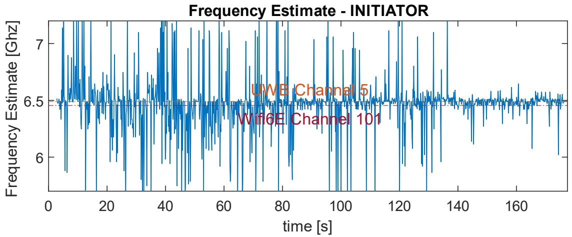
Narrowband Interference Cancellation Block

Measurements – 160 MHz Wi-Fi 6E Channel Bandwidth

- No real improvement on the 160 MHz Wi-Fi jammer bandwidth
- Semingly the lock-state cannot be locked on permanently







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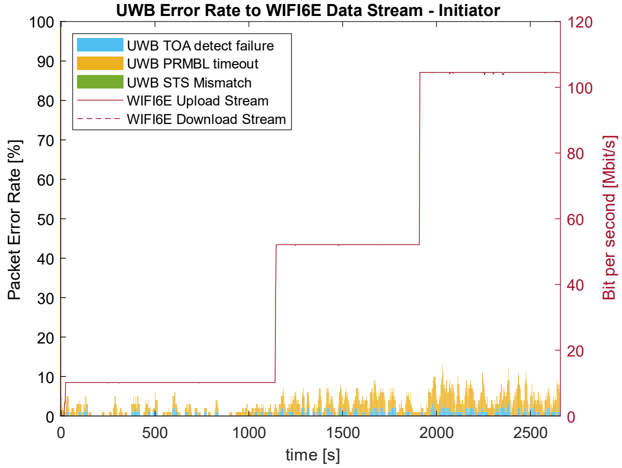
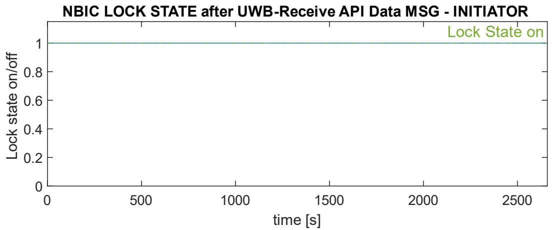
Narrowband Interference Cancellation Block

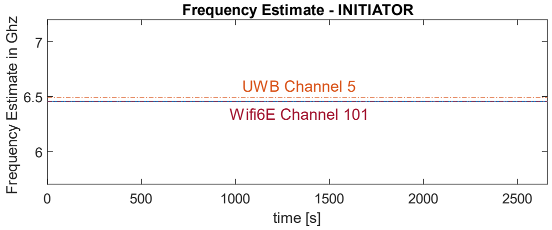
Measurements: 160 MHz Wi-Fi 6E Channel Bandwidth – Manual Mode

- Manual mode proves Band-Stop filter works effectively

- Data suggest a problem at the Jammer detection



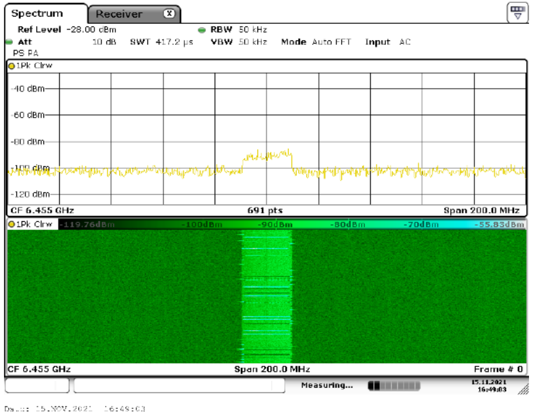


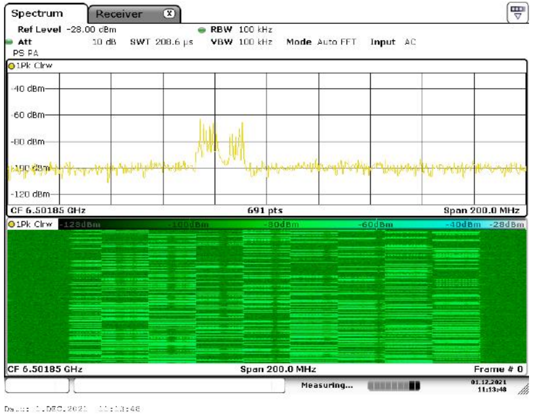


Narrowband Interference Cancellation Block

Discussion

- Closer look at the Wi-Fi packets in the frequency domain gives rise to a hypothesis
- Frequency hopping might confuse state-machine → Jammer detection unit cannot lock on and switched states in the state machine





Narrowband Interference Cancellation Block

Discussion - Conclusion

- NBIC does work very effectively against narrowband channels of 20 MHz & 40 MHz
- For larger bandwidths the NBIC automatic mode needs to be improved
- The NBIC Band-Stop filter can cancel the Wi-Fi160 MHz channel effectively
  → Suggests high potential of the NBIC as Wi-Fi 6E jammer mitigation strategy

Conclusions

Evaluation

- Overall, the investigations into the coexistence of Wi-Fi 6E and UWB can be summarized as a success
- Goal of developing a set-up capable of reproducing the interference case reliably has been achieved
- Set-up can be of help in the future for further investigation

Conclusions

Evaluation - Coexistence Measurements

- Does Wi-Fi 6E affect UWB communication performance? If so, how severe is the impact?

Evidently an impact of Wi-Fi 6E on UWB communication is measurable with an increase in PER = 90% and Per = 75 % for the 160 MHz bandwidth as an example

- How does the packet-error rate behave as a function of Wi-Fi data traffic and channel bandwidth?

As the measurements have shown a higher Wi-Fi data rate results in more airtime taken by Wi-Fi frames and thus more and likely severey UWB packet collistions. The Wi-Fi channel bandwidth has a strong portionlaty from 20 & 40 Mhz compared to 80 160 Mhz.

- Can we improve UWB ranging in Wi-Fi 6E presence by choosing a better protocol?

Data suggest a simpler protocol, like TWR-SS, using less frames can recover UWB ranging functionalty in the presence of Wi-Fi 6E

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Conclusions

Evaluation - Narrowband Interference Cancellation Block

- Can the NBIC block improve UWB performance as a permanent coexistence solution? If so, how good is the improvement?

NBIC does improve UWB ranging performance and can be used as it is for the 20 MHz & 40 MHz Wi-Fi channels. However, regarding the 80 MHz and 160 MHz channels improvement of the state machine is needed. The NBIC Band-Stop filter suggests promising results.

Conclusions

Outlook

Wi-Fi 6E will be an ongoing concern in the UWB automotive industry

Regarding future investigations:

- Correlation of the level of PER to a specific ranging protocol

- Optimizaztion of the accuracy of *Jammer Detection Unit* and *Frequency Estimation Unit*

  → Starting point: NBIC state machine

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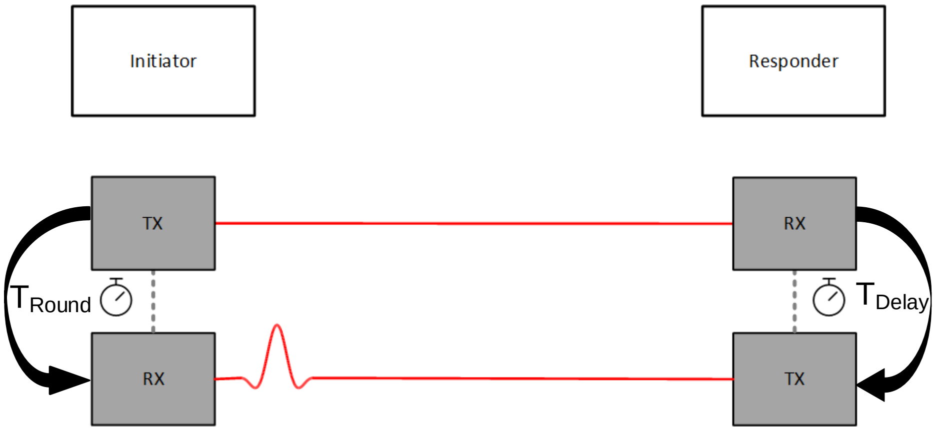
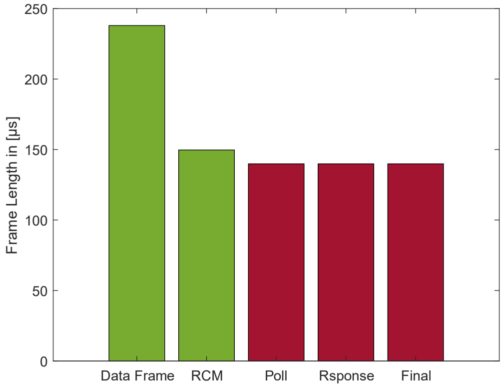
Redesign of Experiment
Discussion

- Data suggests that in case of Wi-Fi 6E jammer present a simpler protocol like TWR Single-Sided can be used for an improvement with 69 % success rate
- Frame length of the data frames correlates with the PER_{Data} =57 %
- PER_{RCM} = 39 % even though frame length is not particularly higher than ranging frames → Other influencing factors like data rate, Symbol-repetition rate, modulation technique?



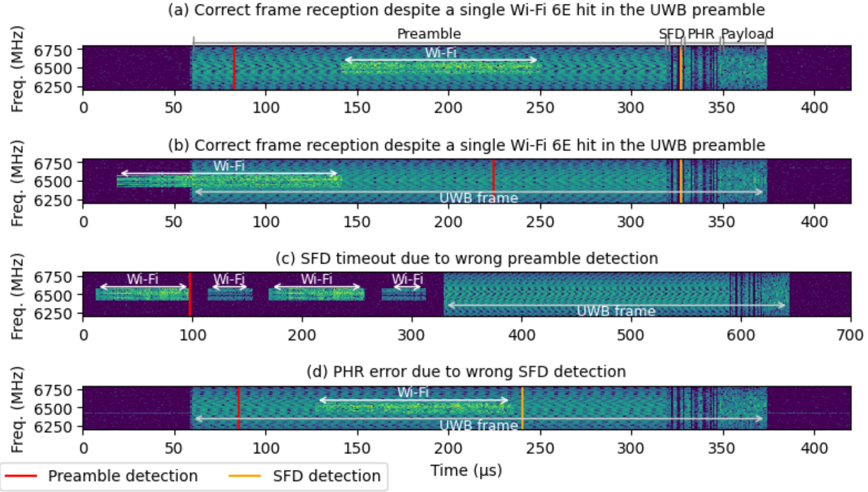


Comparing results to similar studies

Technical Institute of Informatics –TU Graz

TU Graz have built a very similar set-up:

- Investigations there have shown a correlation between the data rate proportional to the pulses transmitted per symbol (bit)
- Using a mixed-signal oscilloscope the TU Graz captured UWB – Wi-Fi 6E collisions → Verification of previous assumption regarding the SFD timeout



Redesign of Experiment

Discussion - Conclusions

- Data suggests at least a partial recovery of UWB ranging functionality with the use of an optimized protocol
- In accordance with the results from the TU Graz a tight synchronization pattern is of crucial importance to improve UWB ranging performance and avoid false detection
- Data frames are seemingly more vourlanvle to Wi-Fi 6E packet hits. This correlates to the length of the frame but may also have more reason in SRR & data rate → This needs to be further investigated

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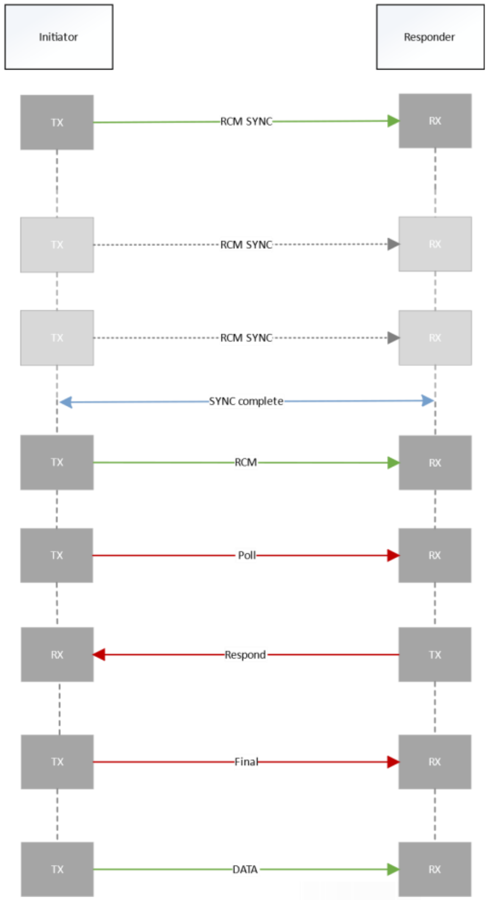
ULTRA WIDE BAND

Redesign of Experiment

Change of Protocol

- Introduction of SYNC-Phase
- After „SYNC complete“ ranging protocol commences
- Ranging in given roster – each frame has a given time-slot and ranging block
- Protocol is never aborded unless Initiator and Responder and are out-of-sync



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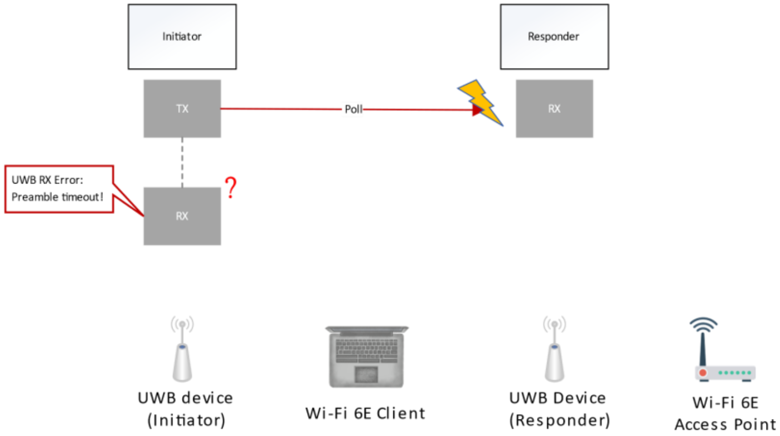
Measurements



Preamble Timeout Scenario E_{PRMBL} :

- Responder is in „listen-endlessly" mode before reception of the Poll-frame
- Responder is seemingly more affected by Wi-Fi traffic due to its spatial postion in the set-up
- Hypothisis: Preamble & SFD timeouts could resolve from the UWB receiver mistakingly synchronizing onto a Wi-Fi instead of a UWB packet

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Measurements

Discussion – Conclusion

Concluding from the first set of measurements first results can state:

- Correlation of PER to Wi-Fi data stream
- Increase of overall noise level due to Wi-Fi 6E

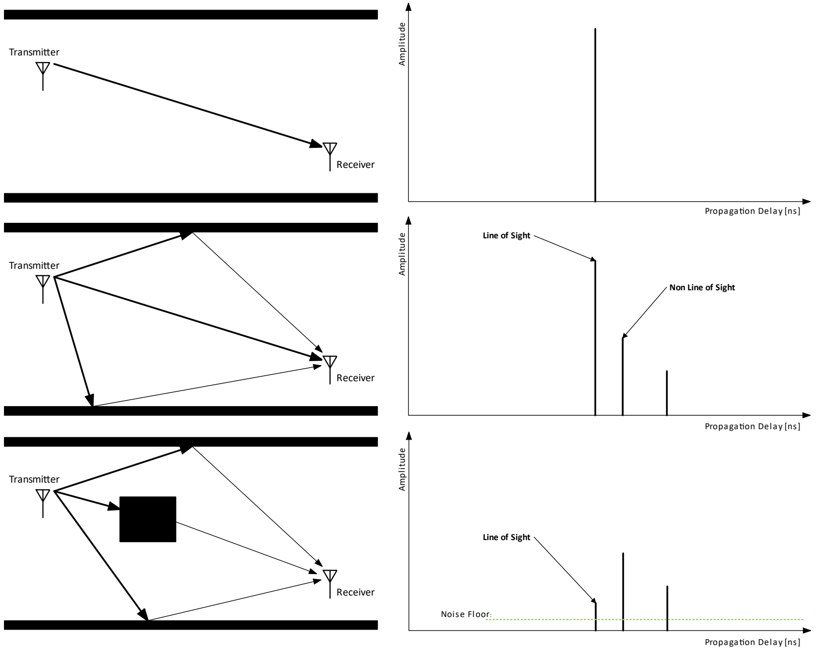
Measurements motivate a redesign of the protocol for the following reasons:

- Information which frame (Poll, Response Final $Data_{Init}$ or $Data_{Resp}$) has been erroneous
- Abortion of the protocol after a single error occurred

Ultra-Wideband Ranging

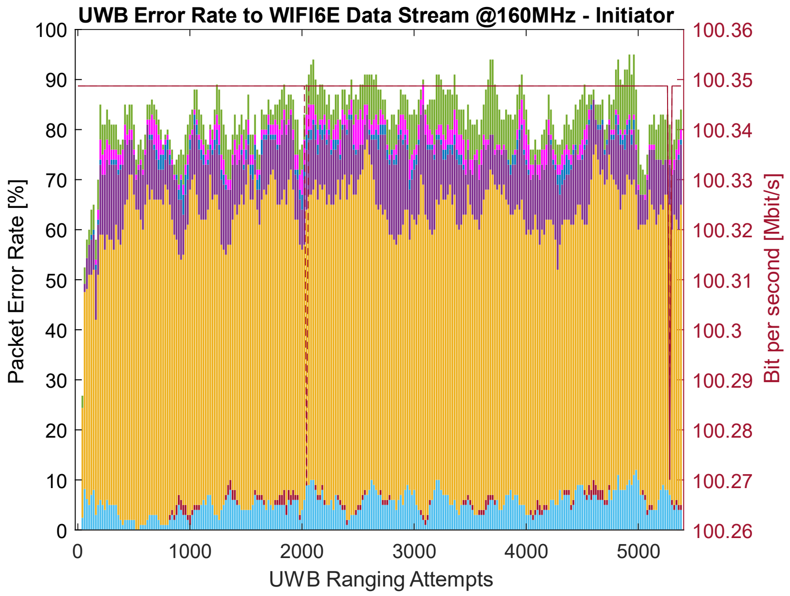
Channel Impulse Response

- The phenomenon of multipath propagation is visualized by means of the CIR
- Multiple reflections of the signal are captured and displayed according to their time of arrival and signal strength



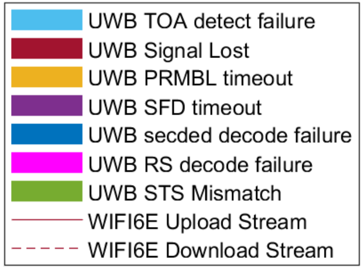
Measurements

Differentiating Failure Causes



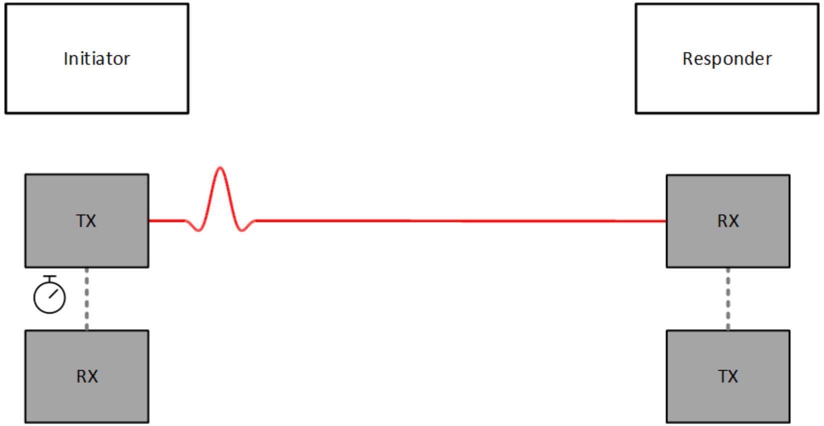
UWB Receiver predefined error codes:

- Time-of-Arrival detect Failure E_{TOA}
- Signal Lost E_{SL}
- Preamble Timeout E_{PRMBL}
- SFD timeout E_{STS}
- Secded decode failure E_{SECDED}
- Reed-Salomon decode failure E_{RS}
- STS mismatch E_{STS}



Ultra-Wideband Ranging
Two-Way Ranging

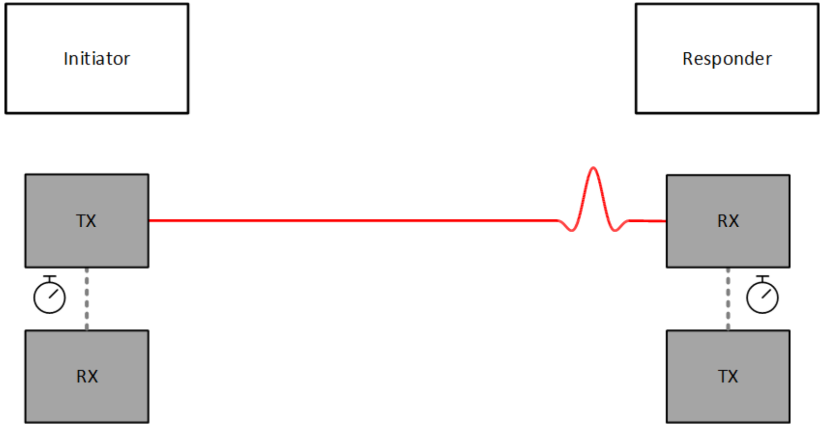
- Initiator sends UWB pulse to Responder
  - Timer is started



Ultra-Wideband Ranging

Two-Way Ranging

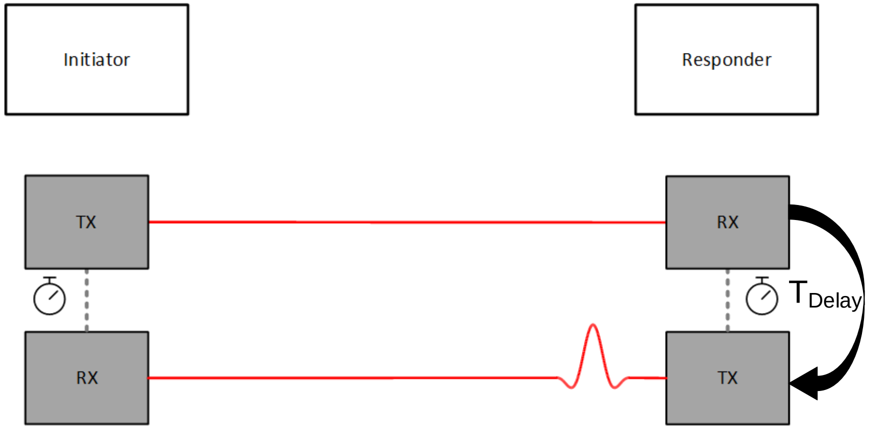
- Initiator sends UWB pulse to Responder
  - Timer is started
- Responder receives UWB pulse
  - Timer is started



Ultra-Wideband Ranging

Two-Way Ranging

- Initiator sends UWB pulse to Responder
  - Timer is started
- Responder receives UWB pulse
  - Timer is started
- Responder also sends a UWB pulse
  - Timer is stopped = T_{Delay}

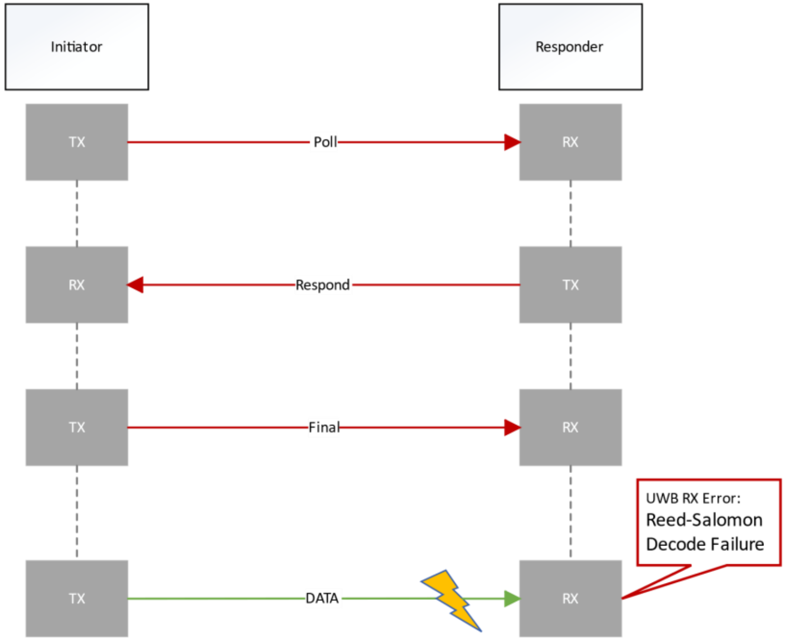


Ultra-Wideband Ranging
Two-Way Ranging

- Initiator sends UWB pulse to Responder
  - Timer is started
- Responder receives UWB pulse
  - Timer is started
- Responder also sends a UWB pulse
  - Timer is stopped = T_{Delay}
- Initiator receives UWB pulse
  - Timer is stopped = T_{Round}

Measurements

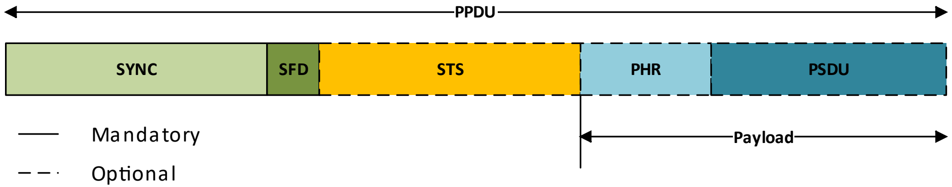
Discussion



Reed-Solomon decode failure E_{RS} :

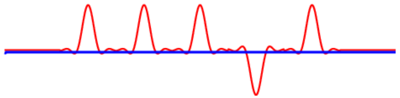
- Another great portion of UWB error codes resolve from the data frames
- All ranging frames succeed but only transmission of the timestamps fails
- Motivates investigation in influence of data length, data rate, and trace error to certain ranging attempts

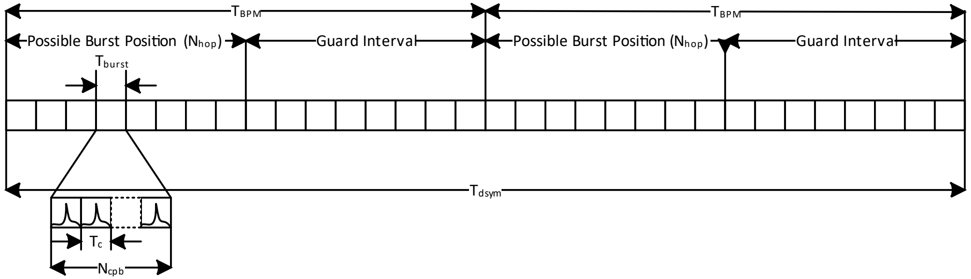
Ultra-Wideband Ranging
UWB Frame Structure



Depending on the frame type (Ranging/Data) a UWB frame consists of different fields:

- SYNC
- Start-of-Frame delimiter
- Secure-Time-Stamp
- Physical Layer Architecture Header (PHR)
- PHY Service Data Unit (PSDU)





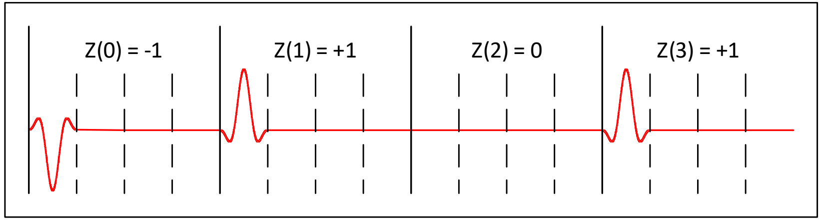
Ultra-Wideband Ranging

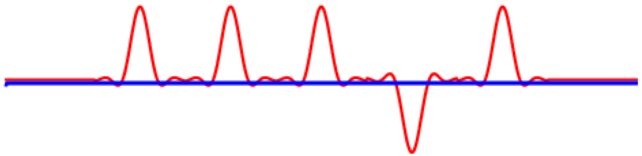
SYNC Field

- Serves to synchronize Initiator and Responder

- Holds the Preamble:
  A sequence of pulses from the ternary alphabet { 0 , -1 , 1 }

- Preamble correlator compares received signal with reference preamble

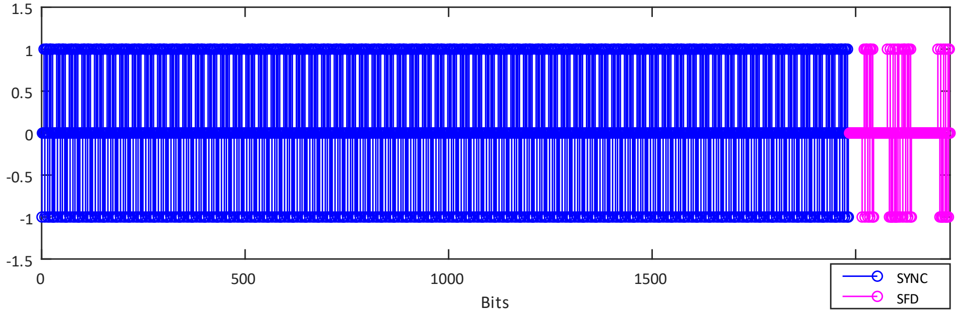




Ultra-Wideband Ranging

Start-of-Frame Delimiter

- While the preamble consists of a repetitive pattern – the SFD breaks this pattern and creates a starting point for decoding of the remaining frame after successful synchronisation



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Ultra-Wideband Ranging

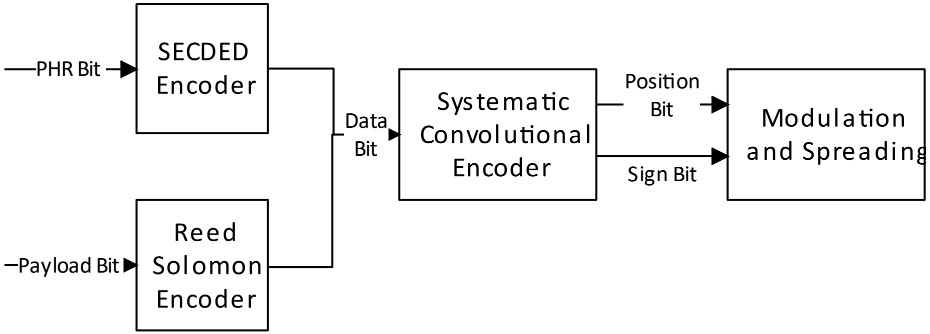
Secure-Time-Stamp

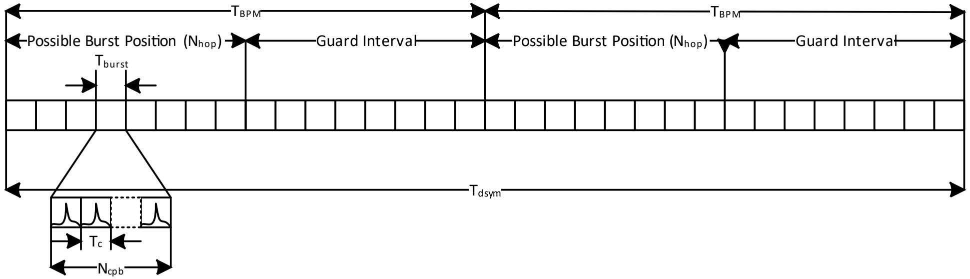
- While the preamble resambles from a set of predefined pulse sequences, the STS provides a safety measure in form of a AES128 encryption to protect from e.g. cicada attacks
- Initiator and Responder hold the respective key (salted hash) to decode the STS

Ultra-Wideband Ranging

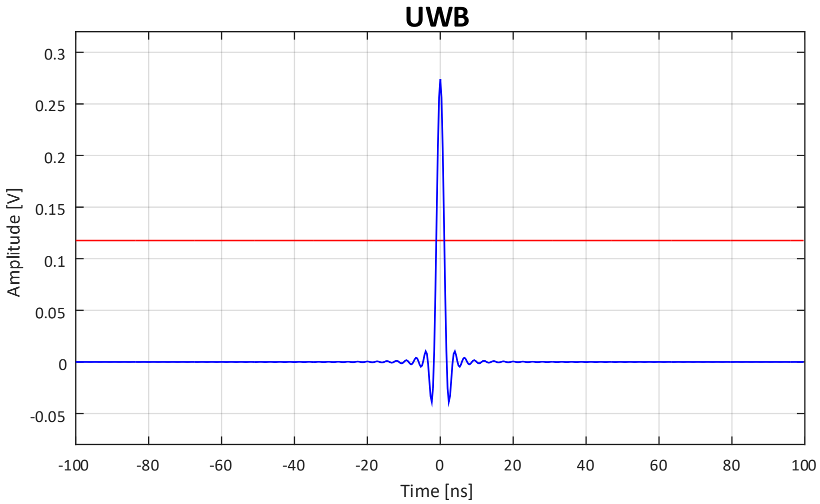
PHR & PSDU

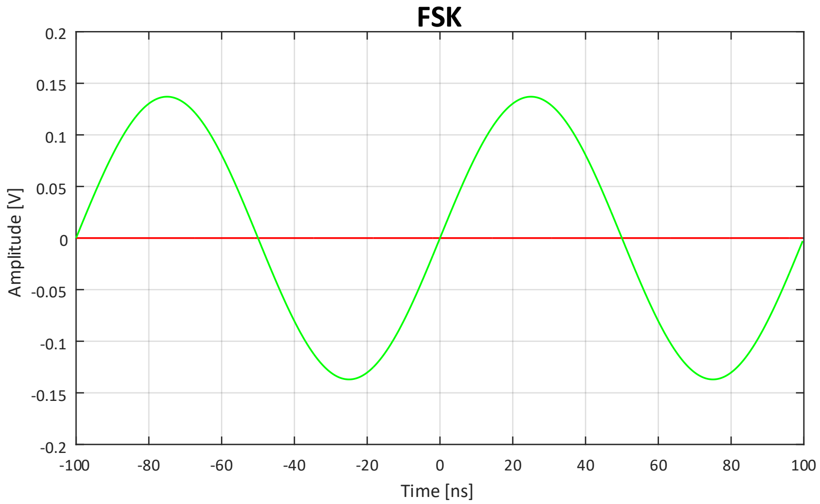
- PHR holding information about the data frame, such as its length, and is encoded using a Single Error Correct – Double Error Detect (SECDED) encoder
- PSDU holds the actual data and is encoded using the Reed-Solomon encoder
- PHR and PSDU, like the STS, are both encoded with a Burst-Position & Binary Phase-Shift Keying technique





UWB vs. Narrow Band





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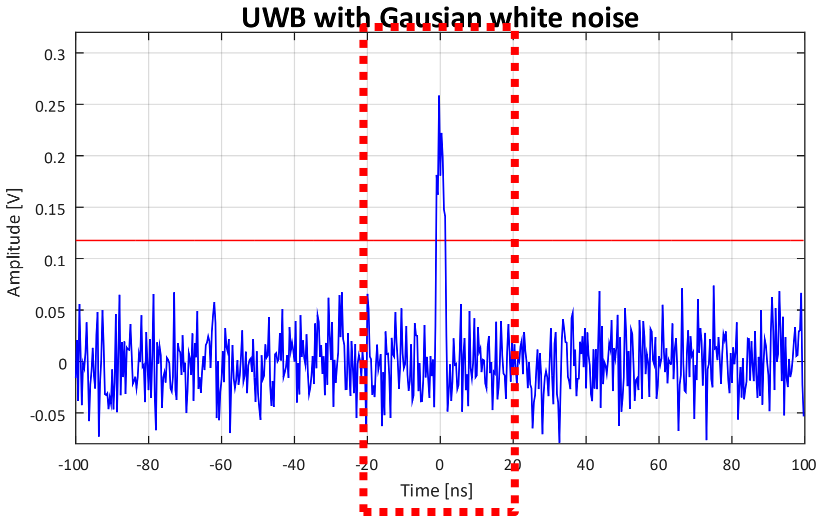
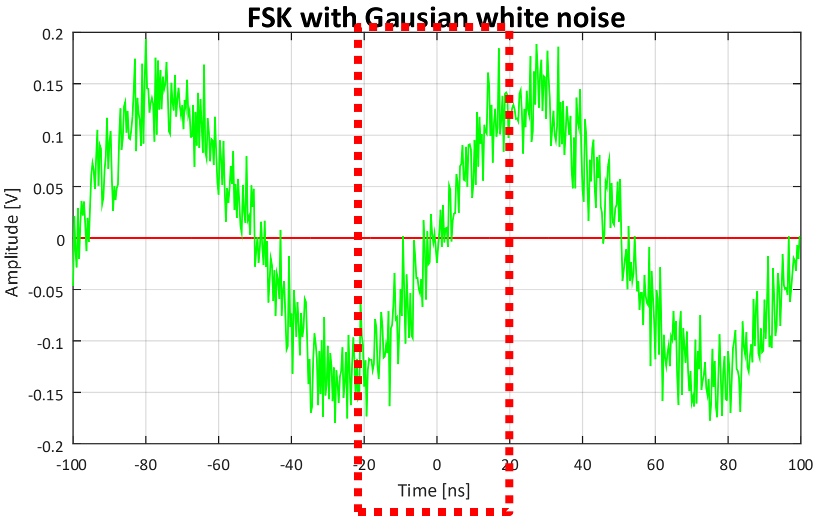
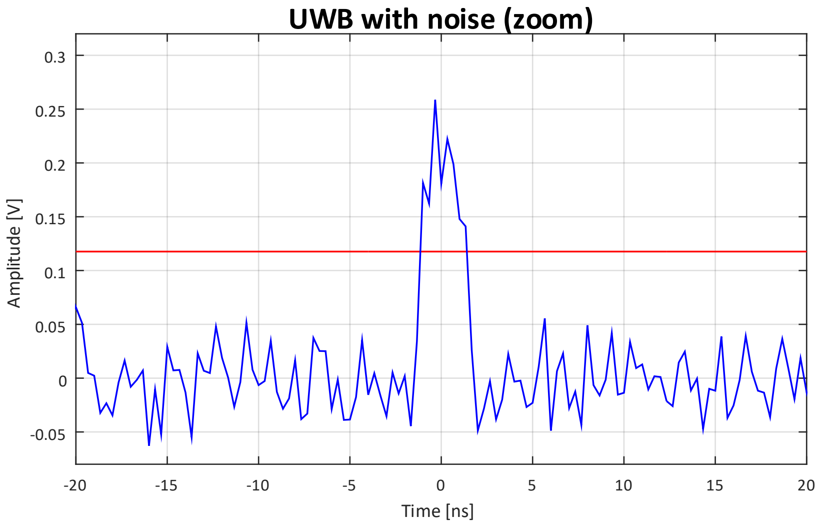
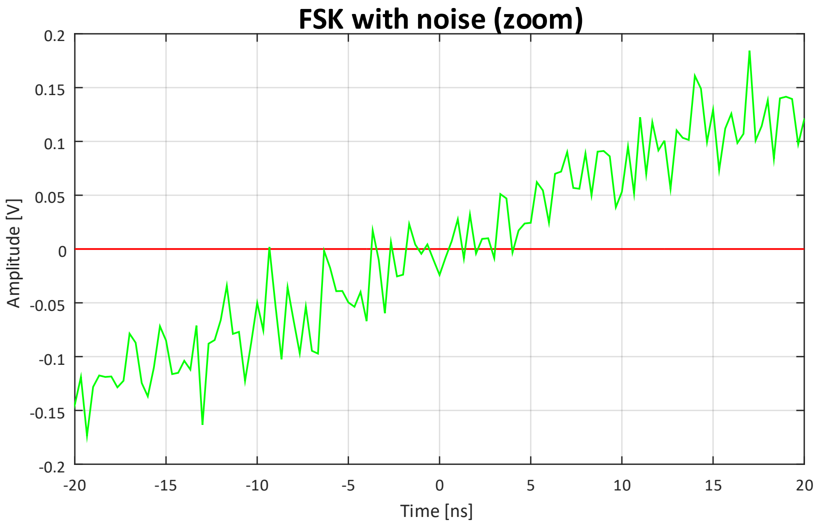
UWB vs. Narrow Band



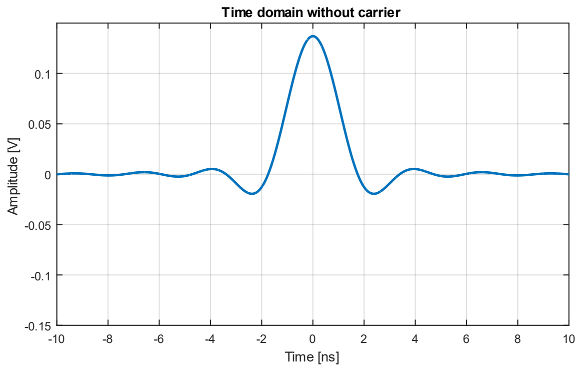


UWB vs. Narrow Band

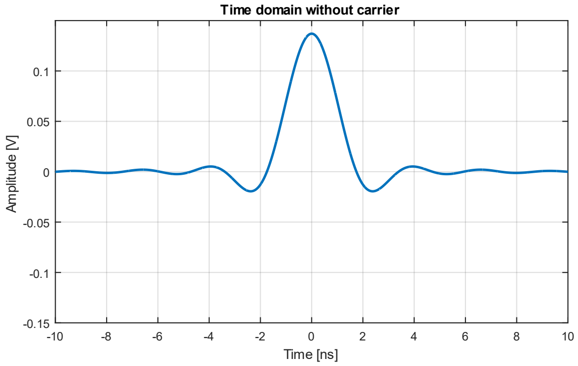


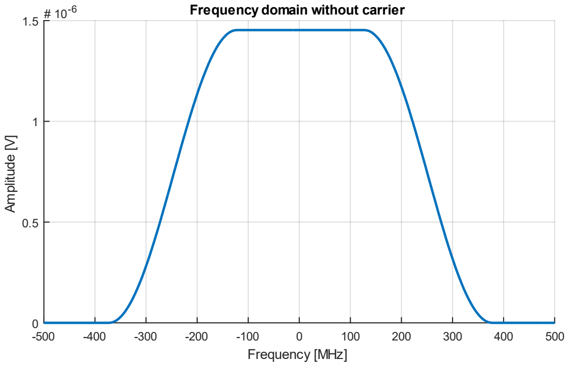


UWB-Pulse


Time domain without carrier
Amplitude [V]
0.1
0.05
0
-0.05
-0.1
-0.15
-10
-8
-6
-4
-2
0
2
4
6
8
10
Time [ns]

UWB-Pulse





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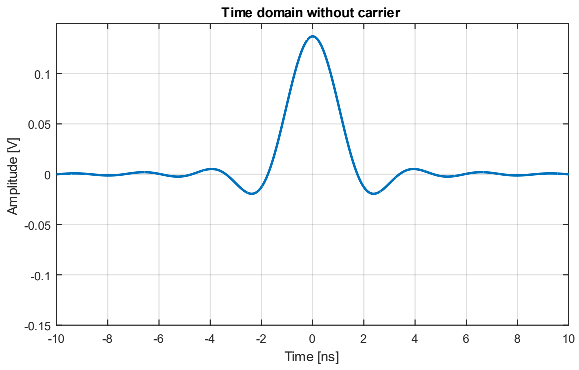
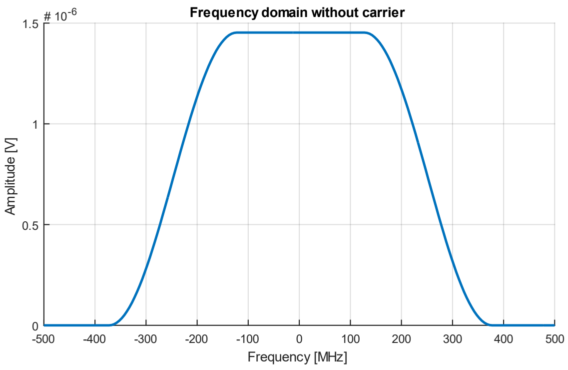
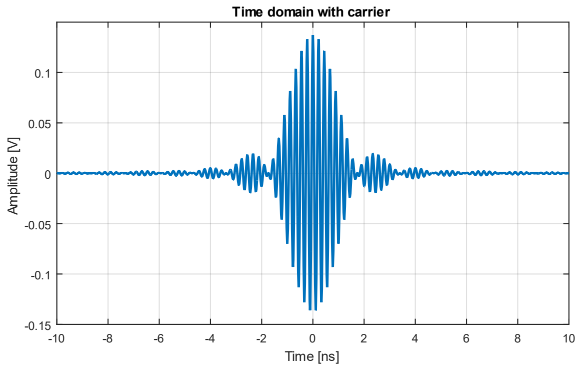
UWB-Pulse







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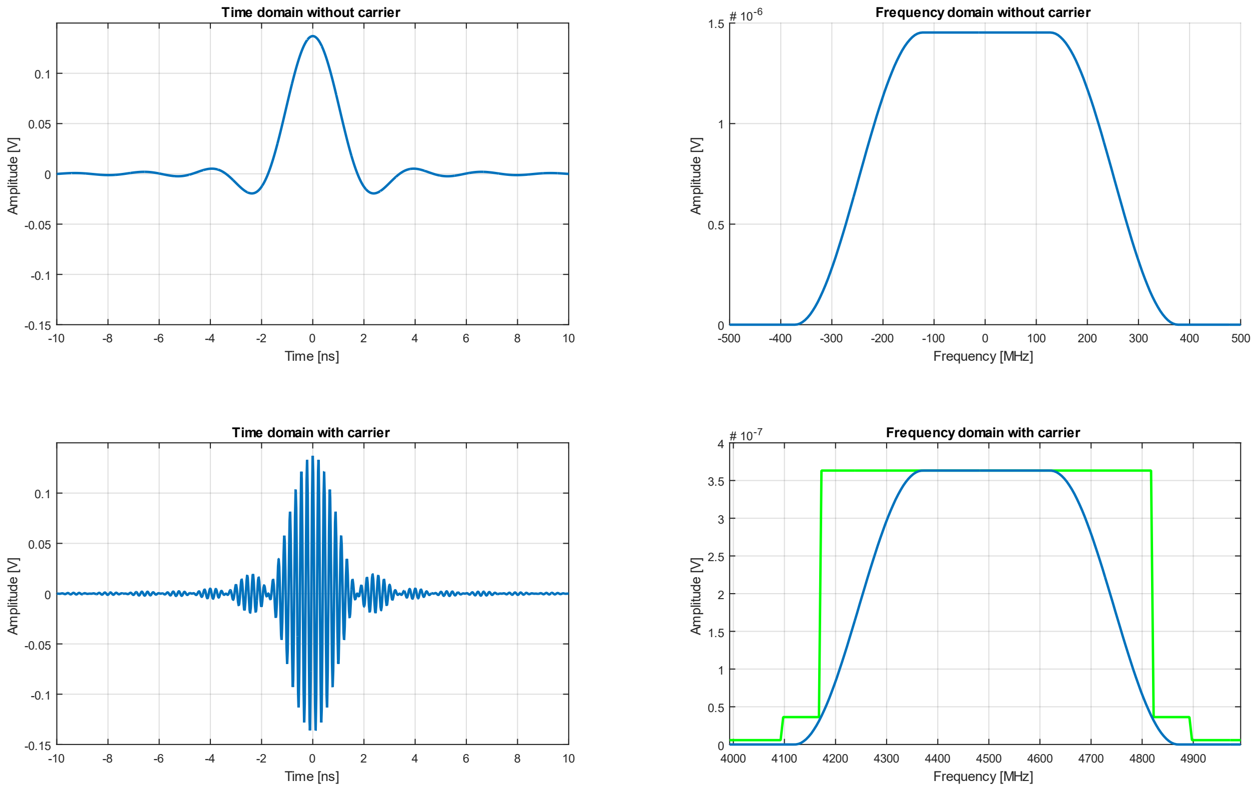
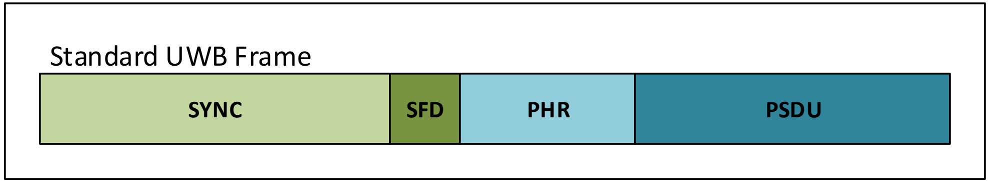
UWB-Pulse



Time domain without carrier
Amplitude [V]
Time [ns]
Frequency domain without carrier
10^-6
Amplitude [V]
Frequency [MHz]
Time domain with carrier
Amplitude [V]
Time [ns]
Frequency domain with carrier
10^-7
Amplitude [V]
Frequency [MHz]

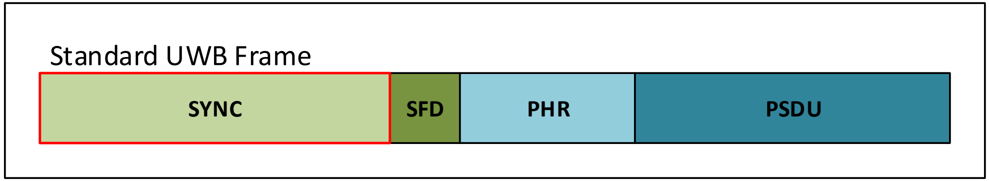
UWB-Frame

- SYNC (Preamble)
- SFD (Start Frame Delimiter)
- PHR (PHY Header)
- PSDU (PHY Service Data Unit)

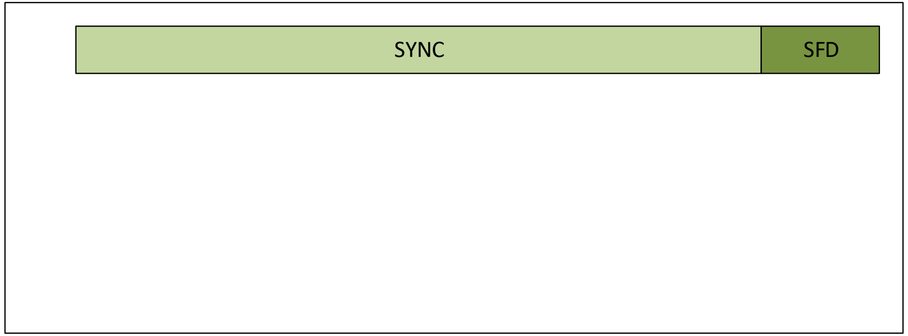


UWB-Frame

- SYNC (Preamble)
- SFD (Start Frame Delimiter)
- PHR (PHY Header)
- PSDU (PHY Service Data Unit)

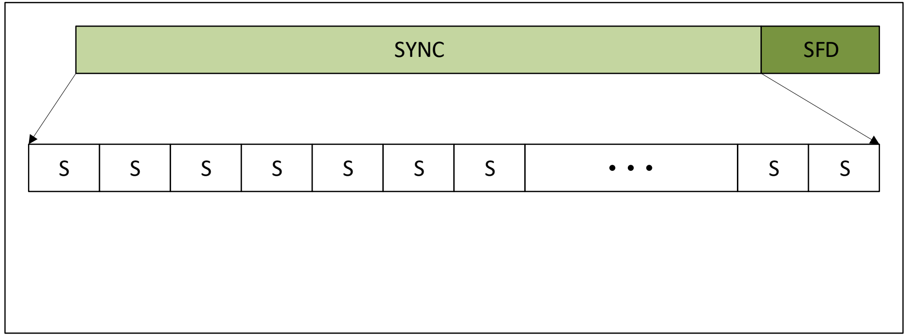


UWB-Frame – Preamble



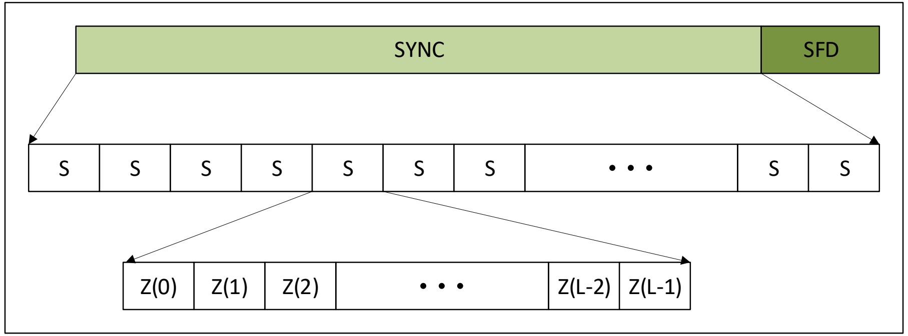
UWB-Frame – Preamble

- Preamble is repetition of same symbol



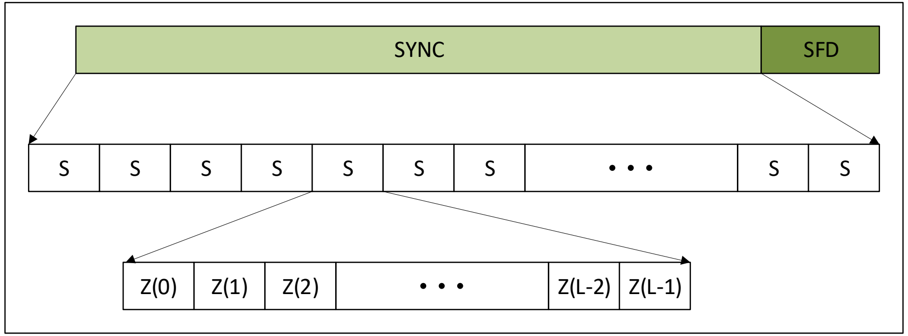
UWB-Frame – Preamble

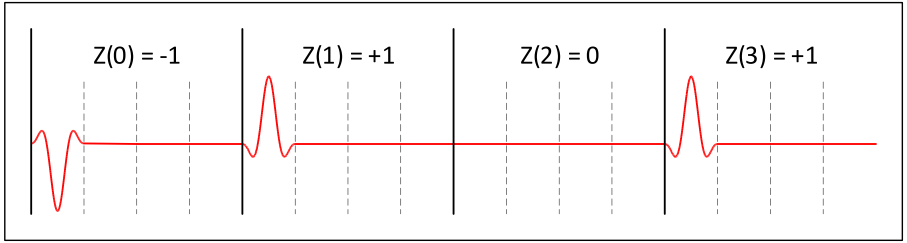
- Preamble is repetition of same symbol
- Each symbol holds 31 or 127 chips



UWB-Frame – Preamble

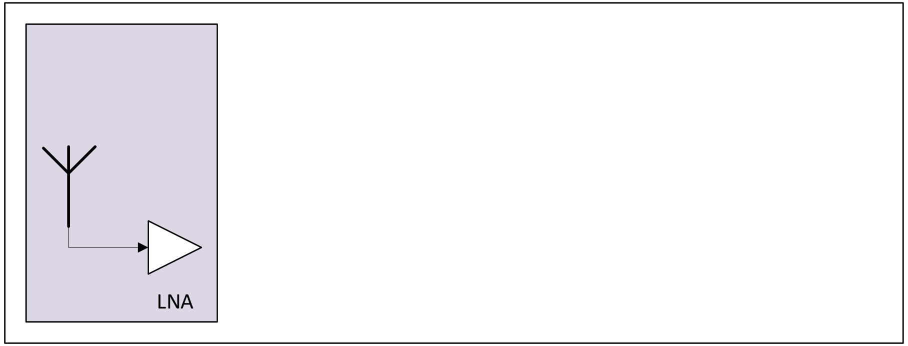
- Preamble is repetition of same symbol
- Each symbol holds 31 or 127 chips
- Each chip holds one ternary UWB Pulse





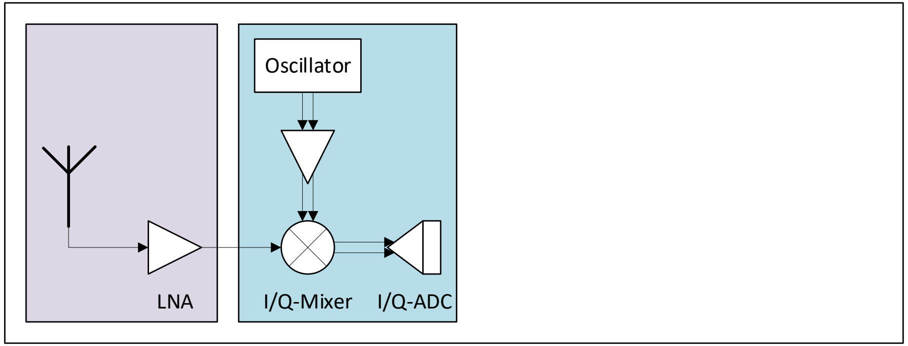
UWB-Receiver

- Low Noise Amplifier
  - Amplifies the signal from the antenna



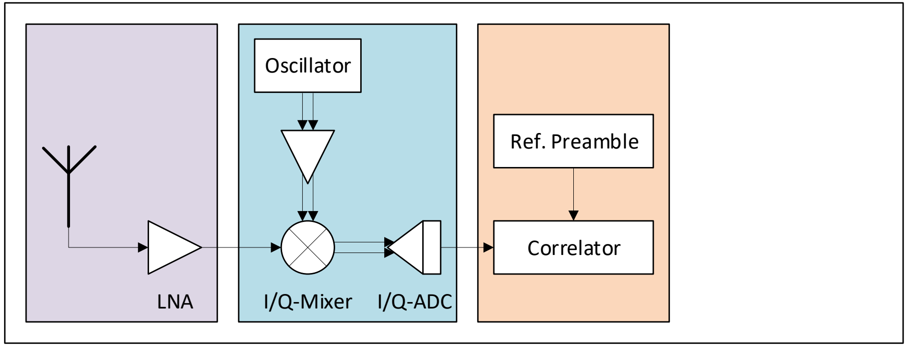
UWB-Receiver

- Low Noise Amplifier
- I/Q ADC
  - Converts the amplitude and phase of the signal into digital values.



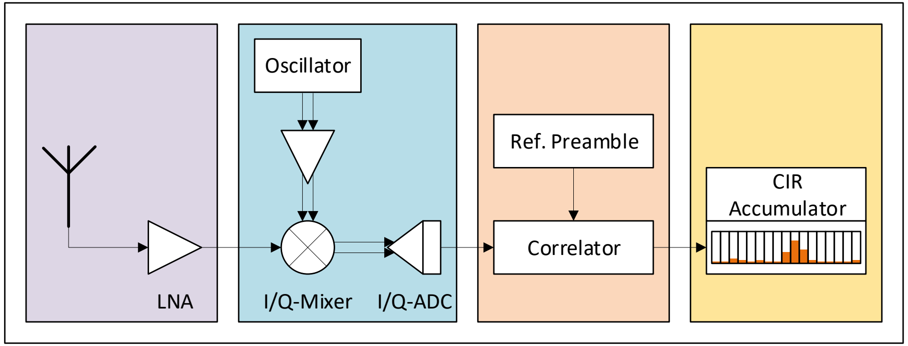
UWB-Receiver

- Low Noise Amplifier
- I/Q ADC
- Correlator
  - Correlates the incoming preamble with the defined preamble



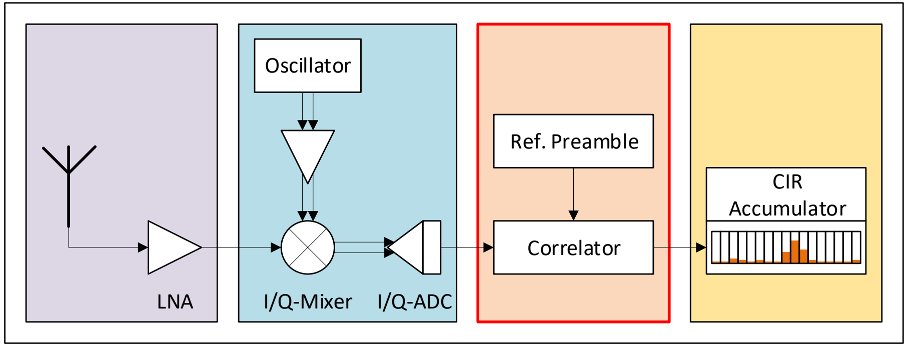
UWB-Receiver

- Low Noise Amplifier
- I/Q ADC
- Correlator
- Accumulator
  - Accumulates the results from the correlator over a symbol length



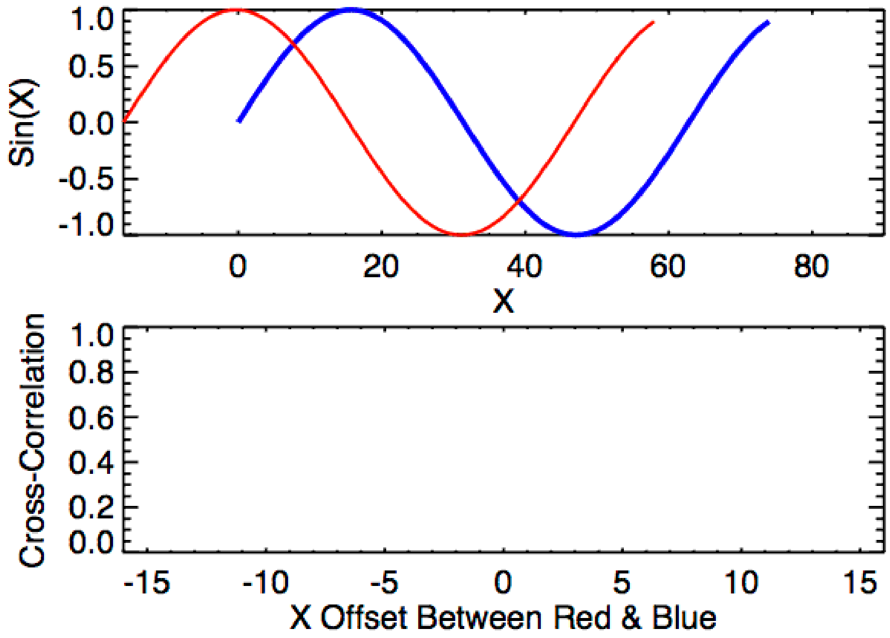
UWB-Receiver

- Low Noise Amplifier
- I/Q ADC
- Correlator
- Accumulator



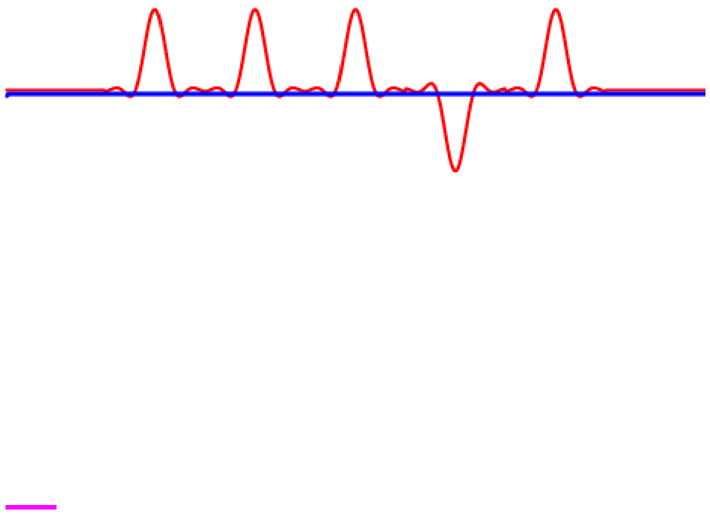
UWB: Auto Correlation

- Maxima as soon as both functions are aligned



UWB: Correlator

- Red: Compared signal
- Blue: Received signal
- Magenta: Correlated signal



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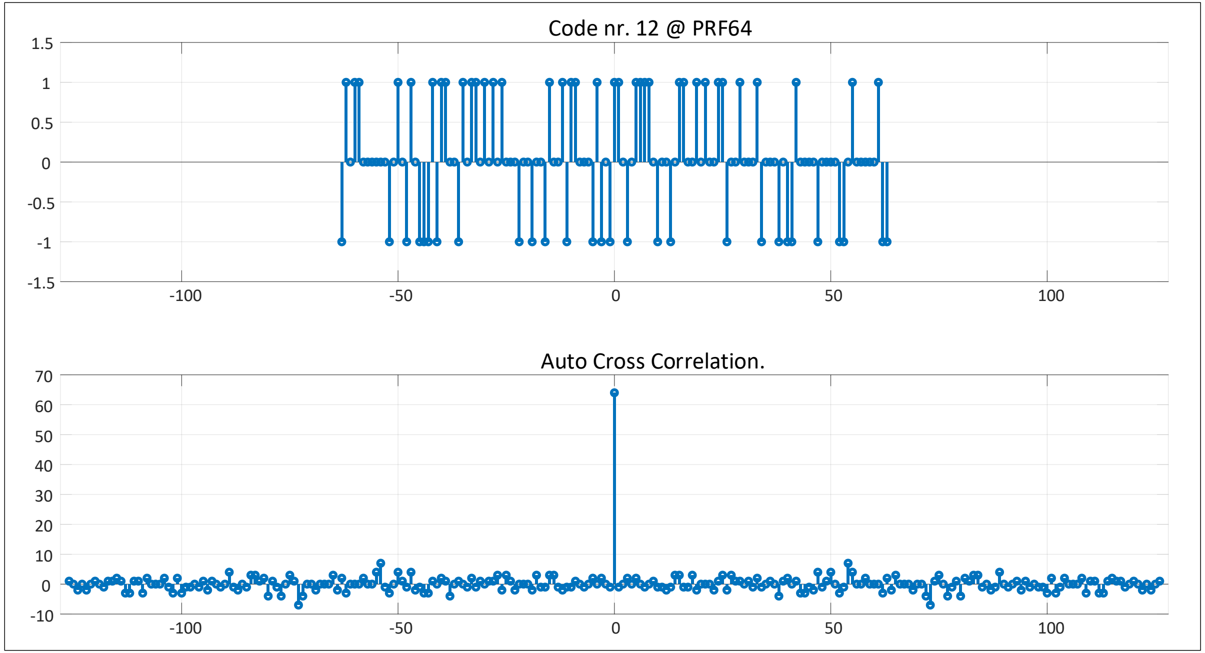
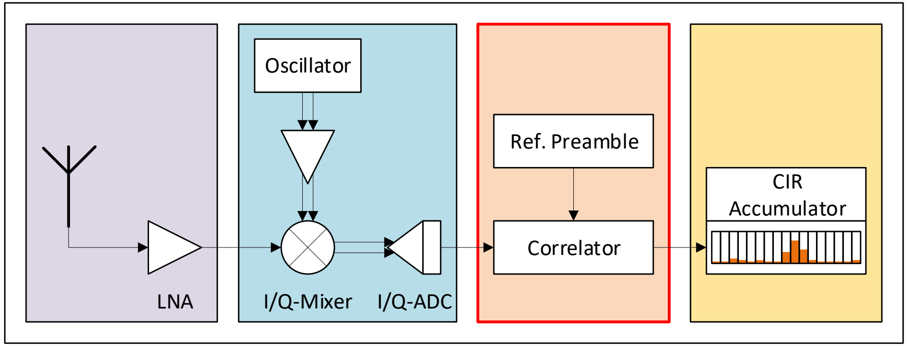
UWB: Correlator



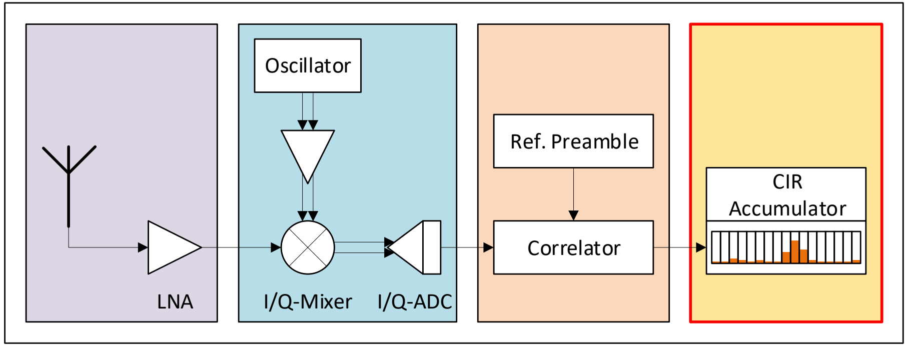
UWB-Receiver

- Low Noise Amplifier
- I/Q ADC
- Correlator
- Accumulator



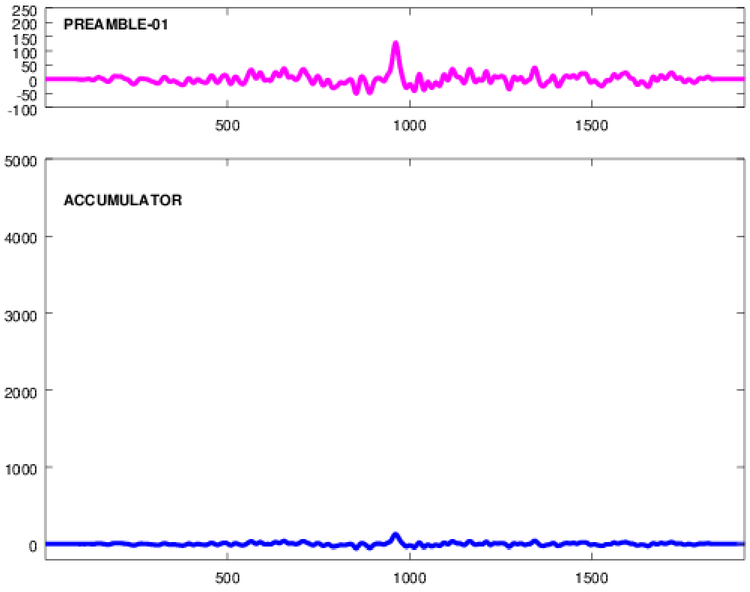
UWB-Receiver

- Low Noise Amplifier
- I/Q ADC
- Correlator
- Accumulator



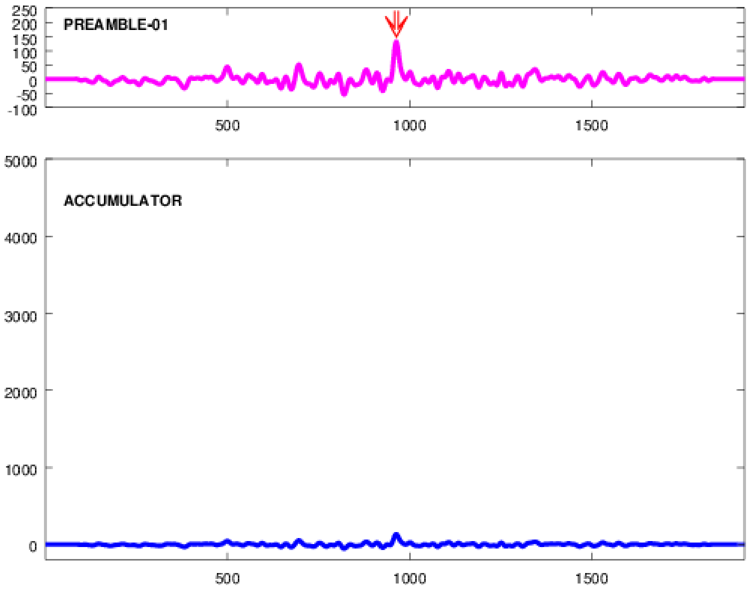
UWB: Accumulator

- Sums up the results from the correlator



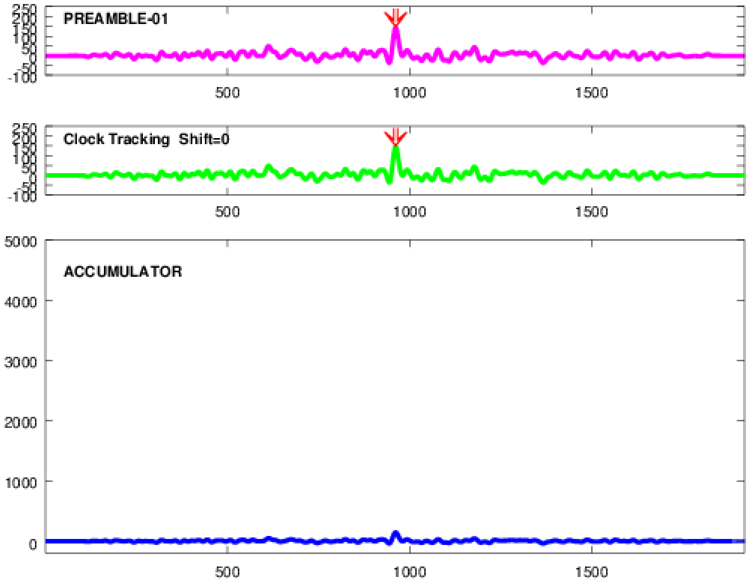
UWB: Accumulator

- Without Clock Tracking:
  - Incomming correlation drifts away



UWB: Accumulator

- With Clock Compensation:
  - Accumulator sees the drift and compensates the difference

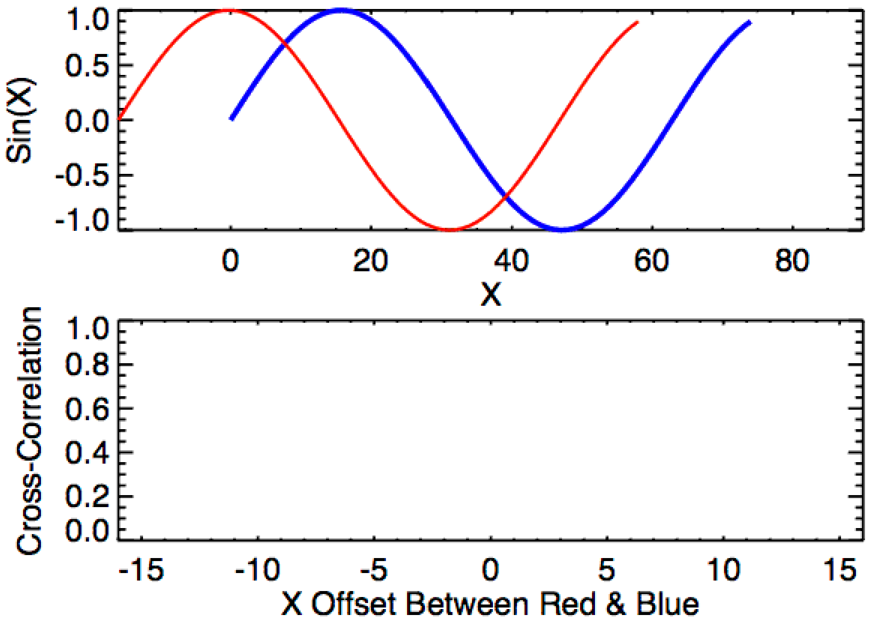


Correlation

Run this Page in
Slide Show !!

It demonstrates how the shift of two (sinus) signals create the correlation signal

The green signal is like our CIR:
1 = RED and BLUE are overlapping
0 = No correlation
-1 = (not shown)
but this means both signals are inverse



Correlation

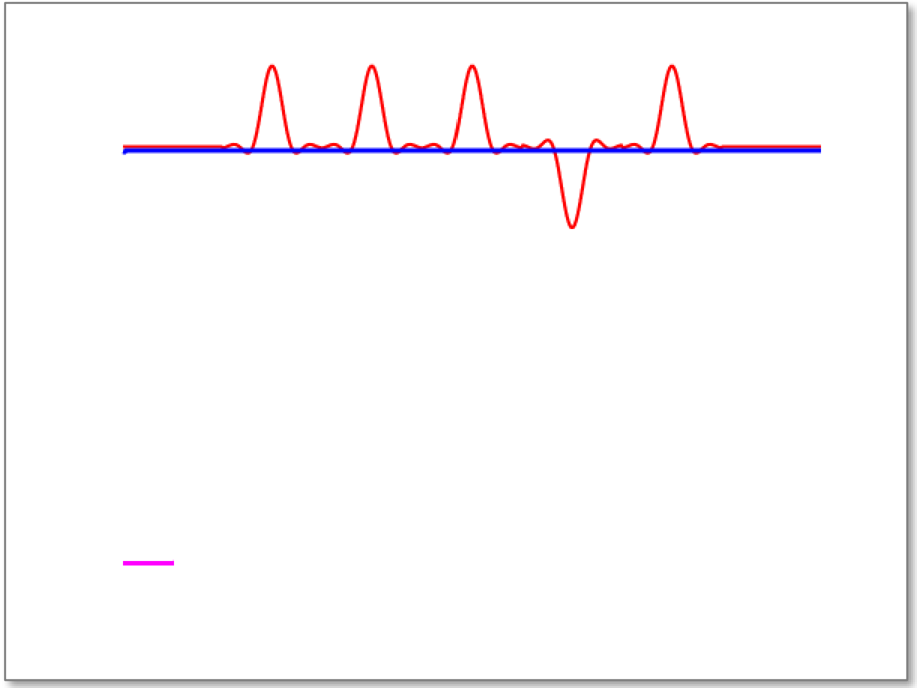
Run this Page in
Slide Show !!

It demonstrates how the UWB Correlator is working.

Red = Received Signal
Blue = Compared Signal
Magenta = Correlation

The maximum is given, if both curves are congruent.

The small peaks shows the side slopes. In this case with a code length of 5, the side slopes are 1/5



Correlation with Noise

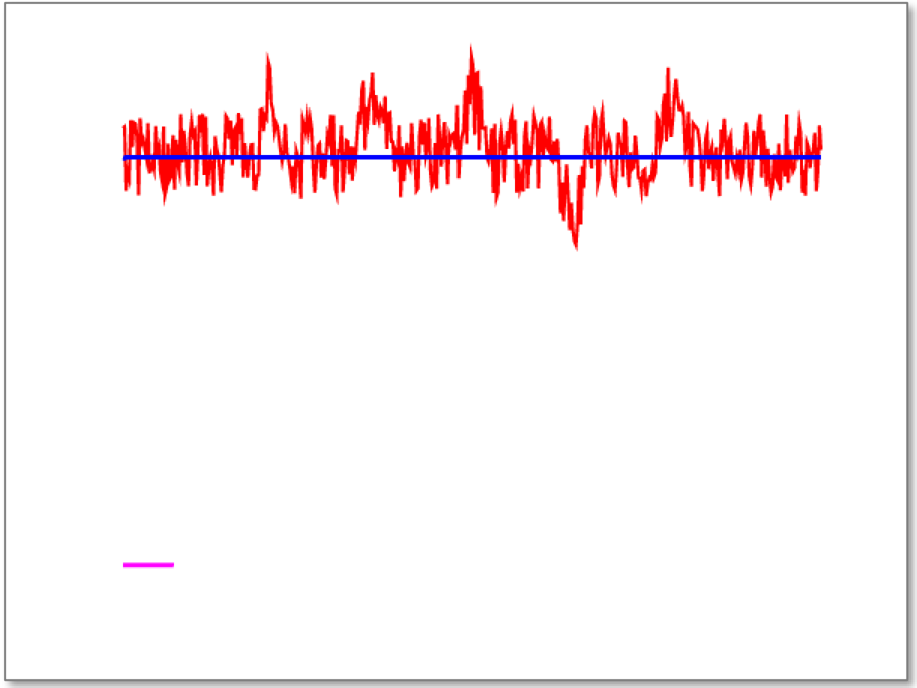
Run this Page in
Slide Show !!

It demonstrates how the UWB Correlator is working with noise.

Red	= Received Signal
Blue	= Compared Signal
Magenta	= Correlation

The maximum is given, if both curves are congruent.

The small peaks shows the side slopes. In this case with a code length of 5, the side slopes are 1/5



Accumulator

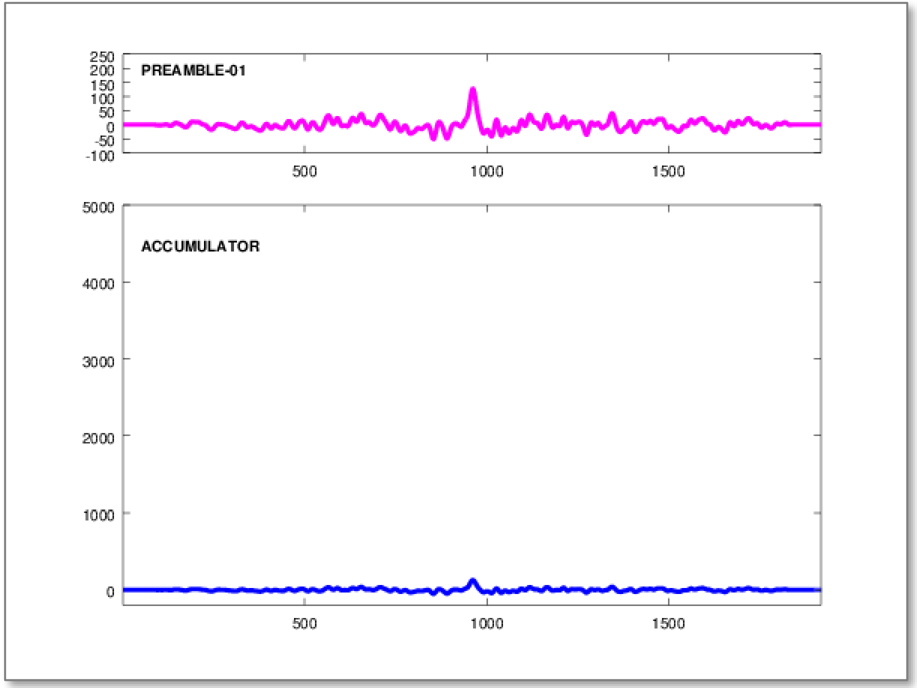
Run this Page in
Slide Show !!

It demonstrates how the UWB Accumulator is working.

Magenta = Correlation with Noise
Blue = Accumulator

It can be seen, the Accumulator will increase with every Preamble.

As more Preambles, as higher the Pulse.



Accumulator without Clock Tracking

Run this Page in
Slide Show !!

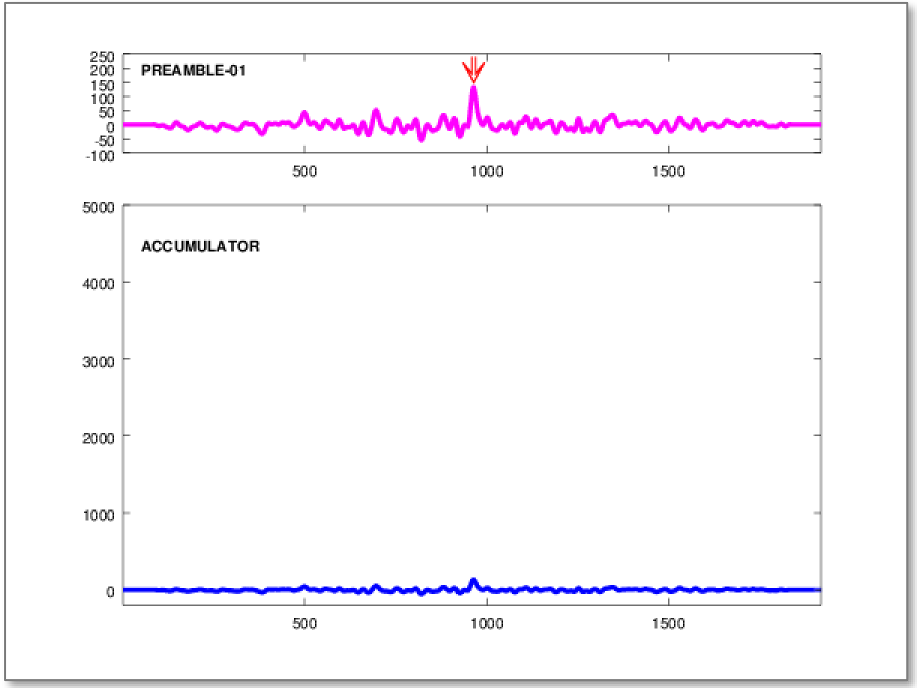
It demonstrates how the Accumulator would work without a clock adaption.

Magenta = Correlation with Noise
Blue = Accumulator

In the beginning, the Accumulator is increasing.

Due to Clock difference, after a time, the pulse will smear, and will not further increase

This will lead to sensitivity drop



Accumulator with Clock Tracking

Run this Page in
Slide Show !!

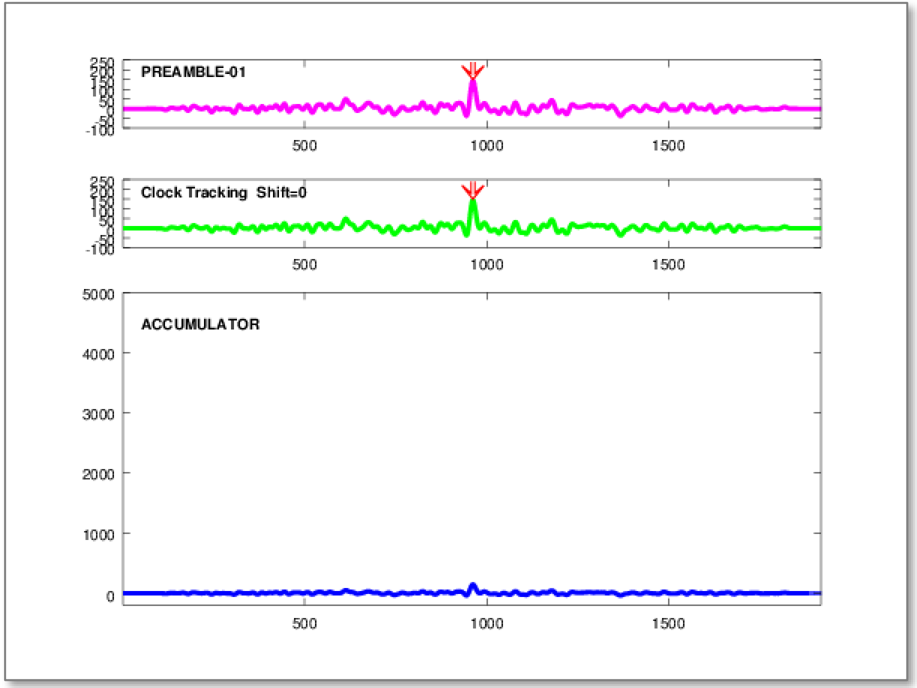
It demonstrates how the UWB Accumulator is working.

Magenta = Correlation with Noise
Blue = Accumulator

It can be seen, the Accumulator will increase with every Preamble.

As more Preambles, as higher the Pulse.

There is no problem with slightly different clock, as after each new preamble, the new Preamble will be adapted



The value of the adaption is stored in a register and can be used to increase distance calculation