Project: IEEE P802.15 Working Group for Wireless Personal Area Networks (WPANs)

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Abstract: UWB proposal for 802.15.4a alt-PHY

Purpose: Proposal based on UWB impulse radio for the IEEE 802.15.4a CFP

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Outline

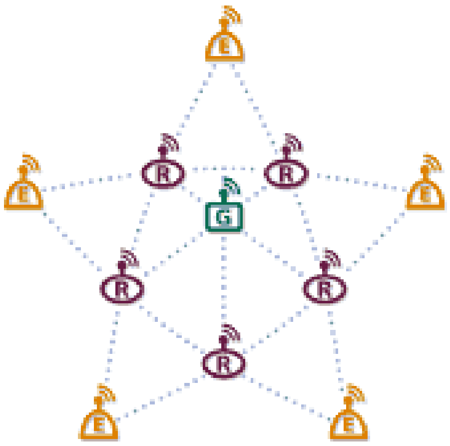
- Introduction
- Transmitter
- Receiver architectures
- System performances
- Link budget
- Framing, throughput
- Power Saving
- Ranging
- Proof of concept
- Conclusions

Introduction (1/2)

- Proposal main features:
  1. Impulse-radio based (pulse-shape independent)
  2. Pulse duration optimized to available spectrum
  3. Enables accurate ranging/positioning
  4. Robustness against SOP interference
  5. Robustness against other in-band interference
  6. Ad-hoc dynamic network organization
  7. Modulation format general enough to support different receiver architectures (coherent/non-coherent) → Trade-off complexity/performance

Introduction (2/2)

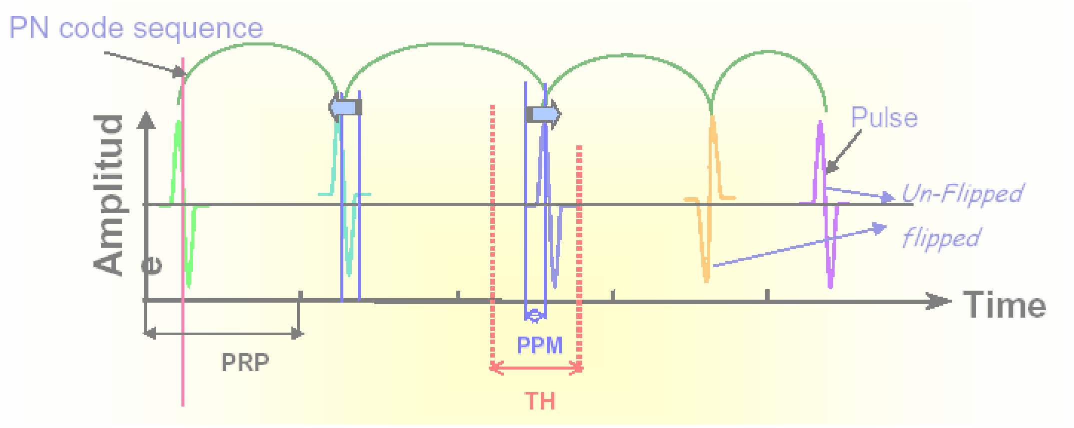
- Motivation for (**7**):



- Typical scenario: Self-organizing ad-hoc wireless network, where sensors send information towards a “concentrator” node (**G**)
- Different classes of nodes, with different reliability requirements (and $) must interwork, while sharing the same modulation format

Preliminaries (1/4)

- **Modulation**:



- TH code (PN sequence) and/or polarity flipping for channelization and spectral smoothing purposes
- Coherent integration (n pulses/symbol): Energy collection, proportional to TH code length, results in processing gain

Preliminaries (2/4)

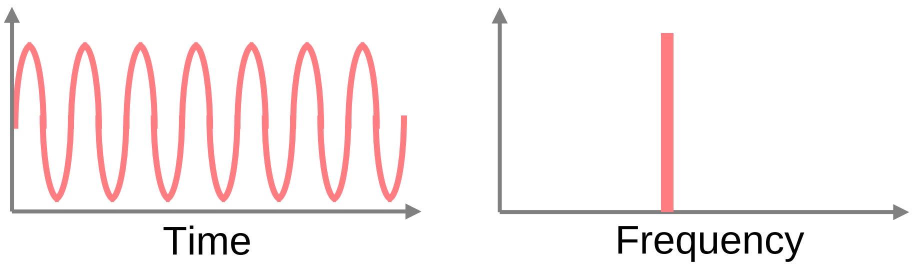
- **Definitions**:
  - Coherent RX: The phase of the received carrier waveform is known, and utilized for demodulation
  - Differentially-coherent RX: The carrier phase of the previous signaling interval is used as phase reference for demodulation
  - Non-coherent RX: The phase information (e.g. pulse polarity) is unknown at the receiver, that operates as an *energy collector*

Preliminaries (3/4)

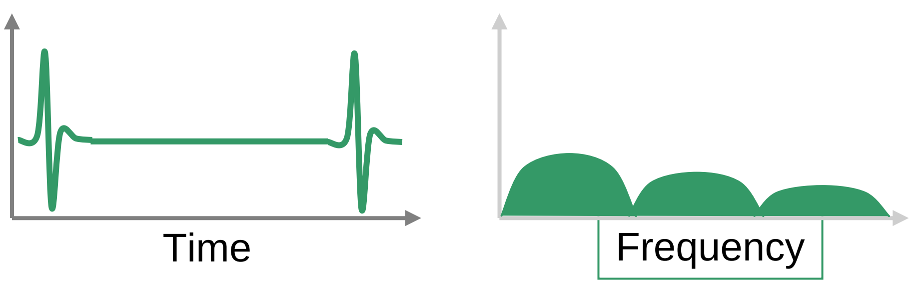
- Pros (+) and cons (-) of RX architectures:
  - Coherent
    - + : Sensitivity
    - + : Use of polarity to carry data or to perform multiple access
    - + : Optimal processing gain possible
    - - : Complexity of channel estimation and RAKE receiver
    - - : Longer acquisition time
  - Differential (or using Transmitted Reference)
    - +/- : Trade-off!
    - + : Gives a reference for faster channel estimation (coherent approach)
    - + : No channel estimation (non-coherent approach)
    - - : Asymptotic loss of 3dB for transmitted reference (not for DPSK)
  - Non-coherent
    - + : Low complexity
    - + : Acquisition speed
    - - : Sensitivity, robustness to SOP and interferers

Preliminaries (4/4)

Traditional Narrowband, Sinusoidal



UltraWideband, Pulse

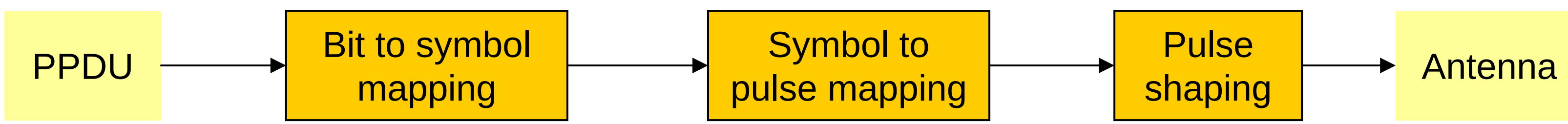


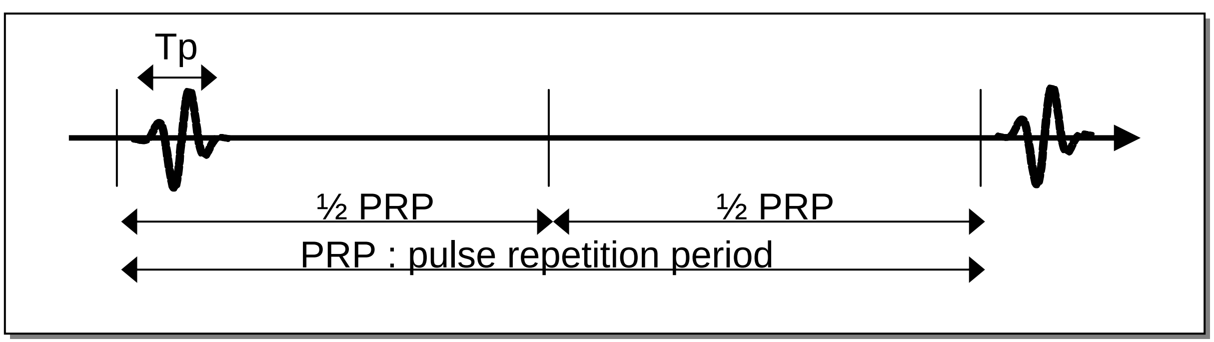
Spread Energy Over Existing Noise Floor

- UWB trades off bandwidth (> 1 GHz) for Radiated Power (< Part 15)
- UWB transmits pulses; there is no carrier frequency
- UWB requires high resolution in Time as opposed to high resolution in Frequency
- UWB design challenge is to provide accurate timing resolution without high-frequency clocks

Transmitter

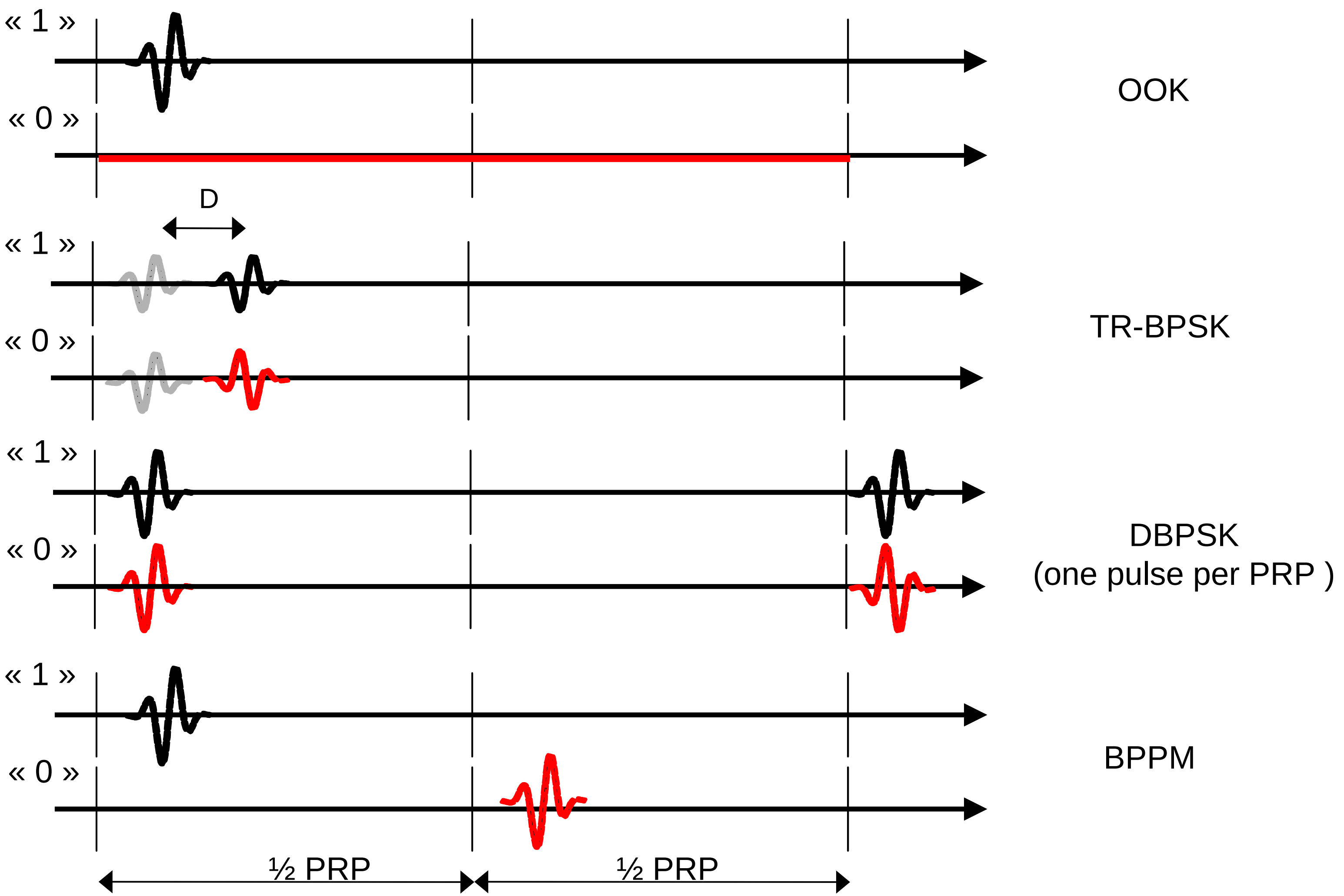
- Modulation, rate and spectrum
  - Modulation:
    - Symbol to pulse mapping: multiple schemes possible (TR, PPM, etc.)
  - Rate:
    - Bit to symbol mapping (modulation efficiency)
  - Spectrum:
    - Single pulse of duration Tp ~ 1/BW shape
    - Time hopping or polarity codes (smoothing)





Example

TX: Modulation Formats

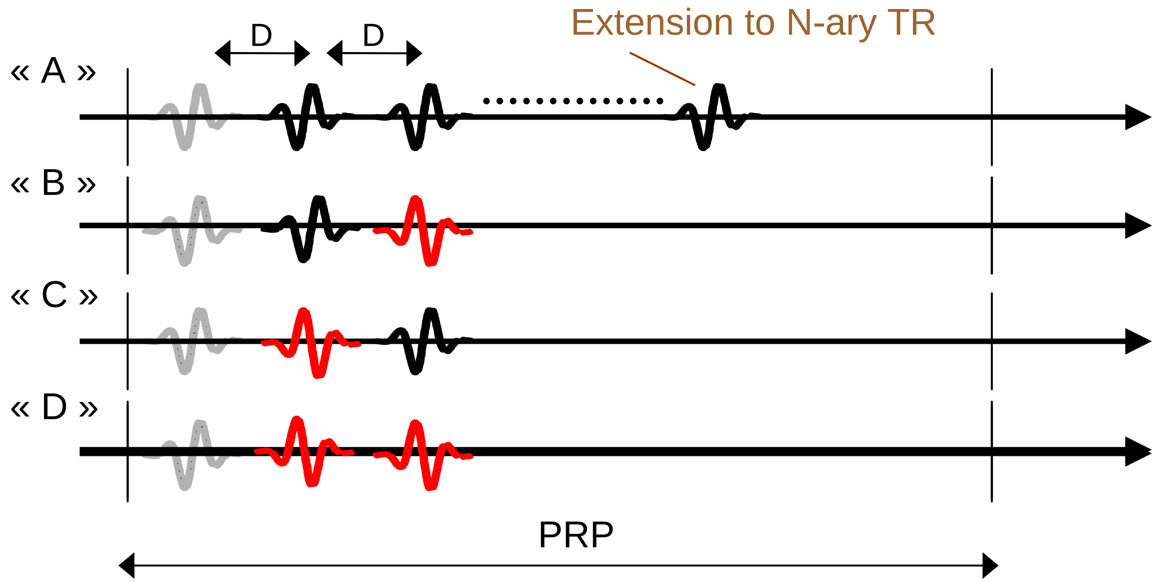


Transmitted Reference (TR)

- TR schemes simplify the channel estimation phase
- Reference waveform available for synch. purposes
- Potentially more robust (than non-coherent) under SOP operation
- Amenable of both coherent/non-coherent demodulation (see for instance TR-BPSK → OOK)
- For LDR systems, ISI can be avoided
- Energy efficiency can be improved (see next slides)
- Reference waveform averaging (non-coherent integration); see also GLRT [Franz, Mitra; Globecom'03, pp. 744-748, Dec 2003]
- Implementation challenges:
  - Analogue: Delay line (<10ns), delay mismatch, jitter
  - Digital: OK

TR Schemes (1/3)

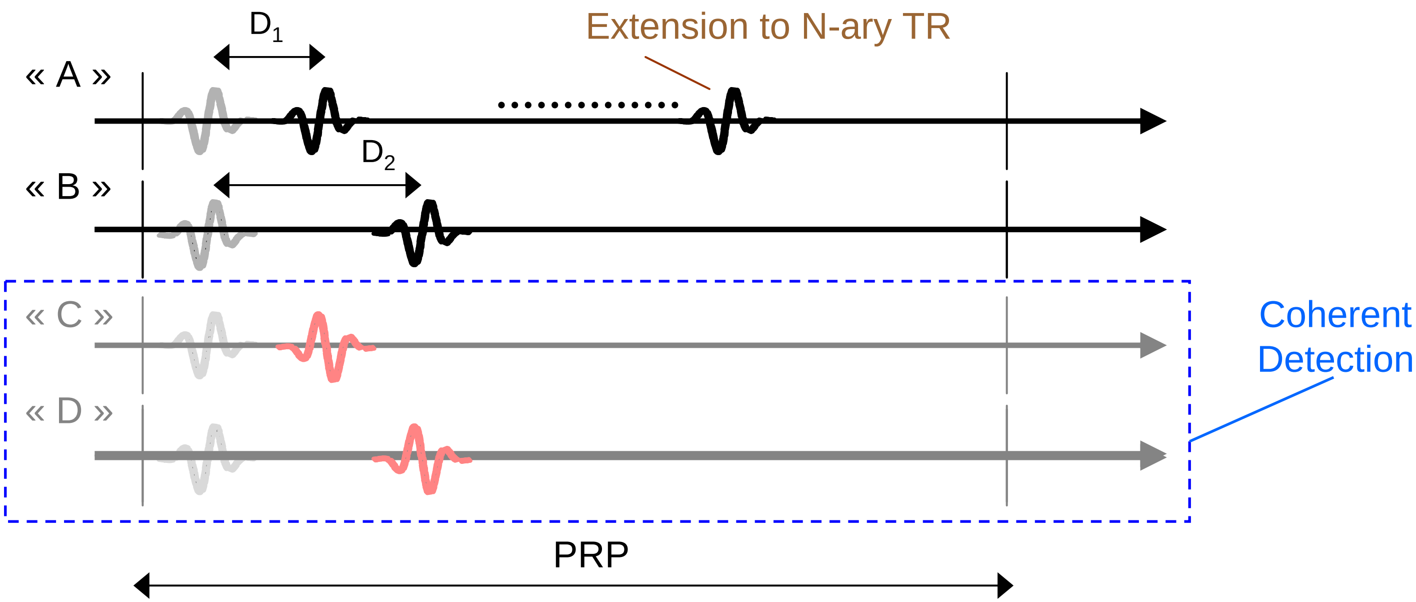
• GTR (Generalized Transmitted Reference) BPSK



• Concept: Multi-level version of the TR scheme, where the energy associated with the reference pulse is «shared» to improve efficiency

TR Schemes (2/3)

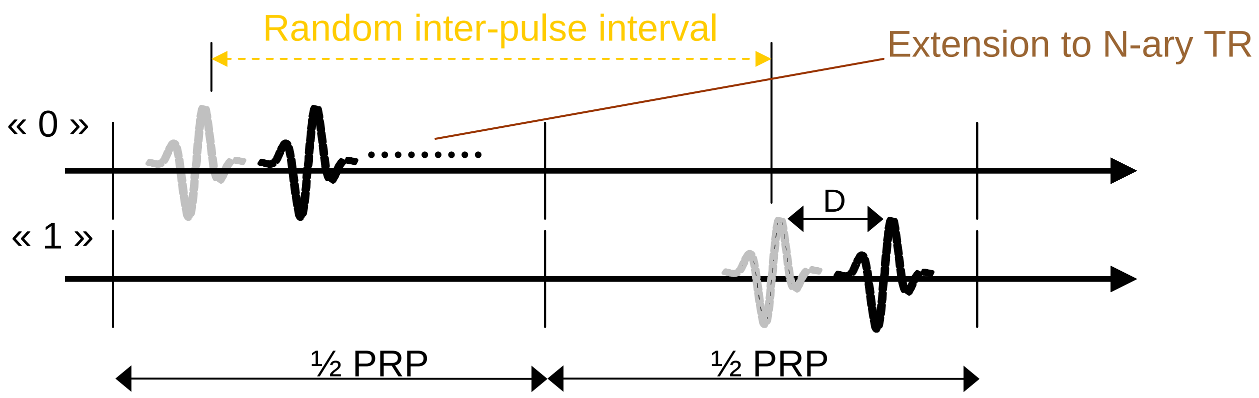
- TR-BPPM (with/without BPAM)



- Concept: Transmitted-reference version of BPPM, with BPAM [Zasowski, Althaus and Wittneben, Proc. IWUWBS/UWBST'04, Kyoto, Japan]
- TR-BPPM (non-coherent): Binary symbols restricted to "A" and "B"

TR Schemes (3/3)

- TR-PCTH (pseudo-chaotic time hopping)
  [Maggio, Reggiani, Rulkov; IEEE Trans. CAS-I, v. 48, no. 12, p. 1424, Dec 2001]



- **<u>Concept</u>: Random TH → Smoothes spectral lines in the PSD**
- **Modulation: Pulses in the first ½ PRP correspond to « 0 » and vice versa for « 1 »**
- **Demodulation: Similar to PPM, but more flexible (threshold or Viterbi detector)**

Transmission

- **Advantages of Episodic Transmission**
  - Very low power operation achievable with low duty-cycle
    - Typical 1% duty cycle with 1 ms cycle time
    - Network precise timing (~1ppb) allows extended sleep mode (~40s)
  - Back-and-forth Ranging exchange spans ≈20 μs
    - Better than 1 cm absolute accuracy with 2 ppm timebase

TX: Design Parameters (1/2)

- Motivation:
  - Flexible waveform
  - Still simple
  - **Compatible with multiple coherent/non-coherent receiver schemes**
- Preferred limitations (compliant with FCC)
  - ↗ Bandwidth for:
    - (+) High transmit power
    - (+) **High time resolution**
    - (-) Low power, low complexity
    - (-) Less stringent requirements on blockers filtering

    → **Signal BW of 1-2 GHz in 3-5 GHz band**
    Signal BW of 700 MHz in 0 to 960 MHz band (low band)
  - ↗ Pulse Repetition Period for:
    - (+) High « single pulse » detectability at the receiver
    - (+) **No inter-channel interference due to channel delay spread**
    - (-) Transmitter peak power compatible with technology
    - (-) Shorter acquisition time

    → **PRP Between 125ns and 2 μs**

TX: Design Parameters (2/2)

- Preferred limitations (cont')
  - Simple modulations:
    - Transmitted Reference

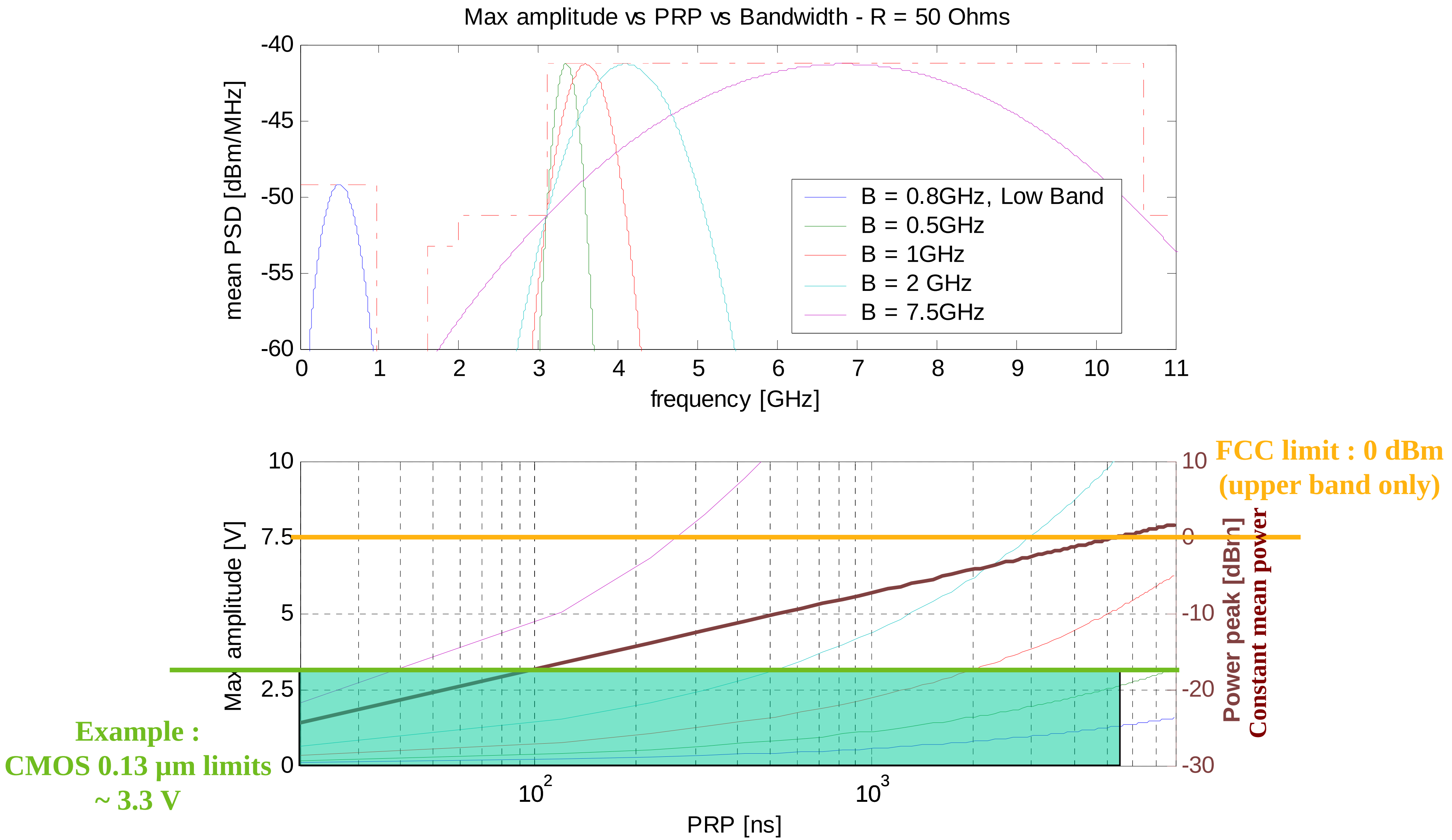
    ⇒ **At least 1-2 bits/symbol (more for GTR)**
  - Channelization (« nearly orthogonal » channels):
    - Coherent schemes: Use of TH codes and/or polarity codes
    - Non-coherent schemes: Use of TH codes (polarity codes for spectrum smoothing only)
  - TH code length:
    - (-) Faster acquisition, shorter frame size (synch. phase)
    - (+) Lower bit-rate, high processing gain

    ⇒ **TH code length from 1 to 16**
- Nominal scenario - high-band (X_0=250 Kbps):
  - **PRP = 500 ns, 2-level modulation, TH code of length 8: PHY-SAP payload bit rate (Xo) is 250 kbps**

•Nominal scenario - low-band (X0=250 Kbps):

- **PRP = 125 ns, 2-level modulation, code length of 31chips per bit:**
- **PHY-SAP payload bit rate (Xo) is 250 kbps**

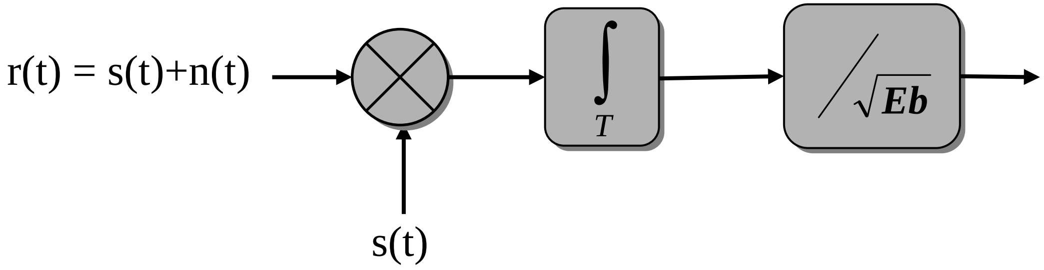
Pulse Amplitude and Peak Power vs. PRP



Receiver

- Optimal Receiver:

Filter matched to channel and pulse waveform for Maximum Ratio Combining (MRC)



$$\begin{cases} \textit{Signal} : Eb \\ \textit{Noise} : \sigma^2 = \dfrac{N_0}{2} \end{cases}$$

Example of 2-ary modulation (Symbol duration: T)

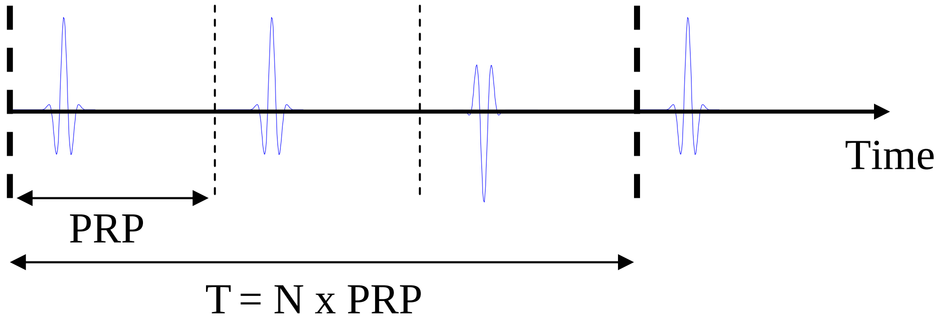
Matched filter input :

- Signal = r(t)
- Noise = n(t), Gaussian, PSD = N_0

Matched filter output :

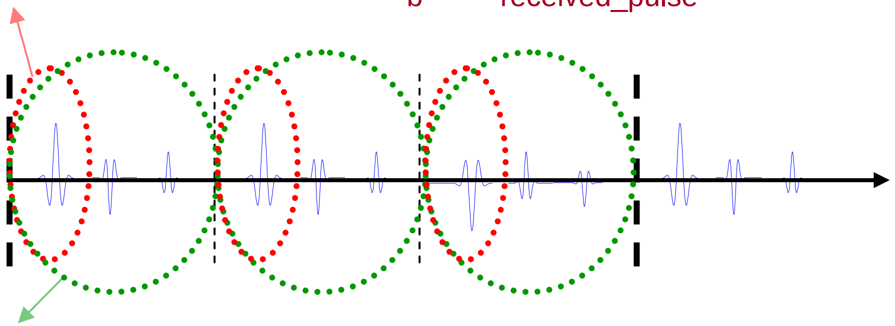
- Signal^2 = Eb
- Noise = Gaussian ($\mu = 0$, $\sigma^2 = N_0/2$)

«Bit Energy» Recovery



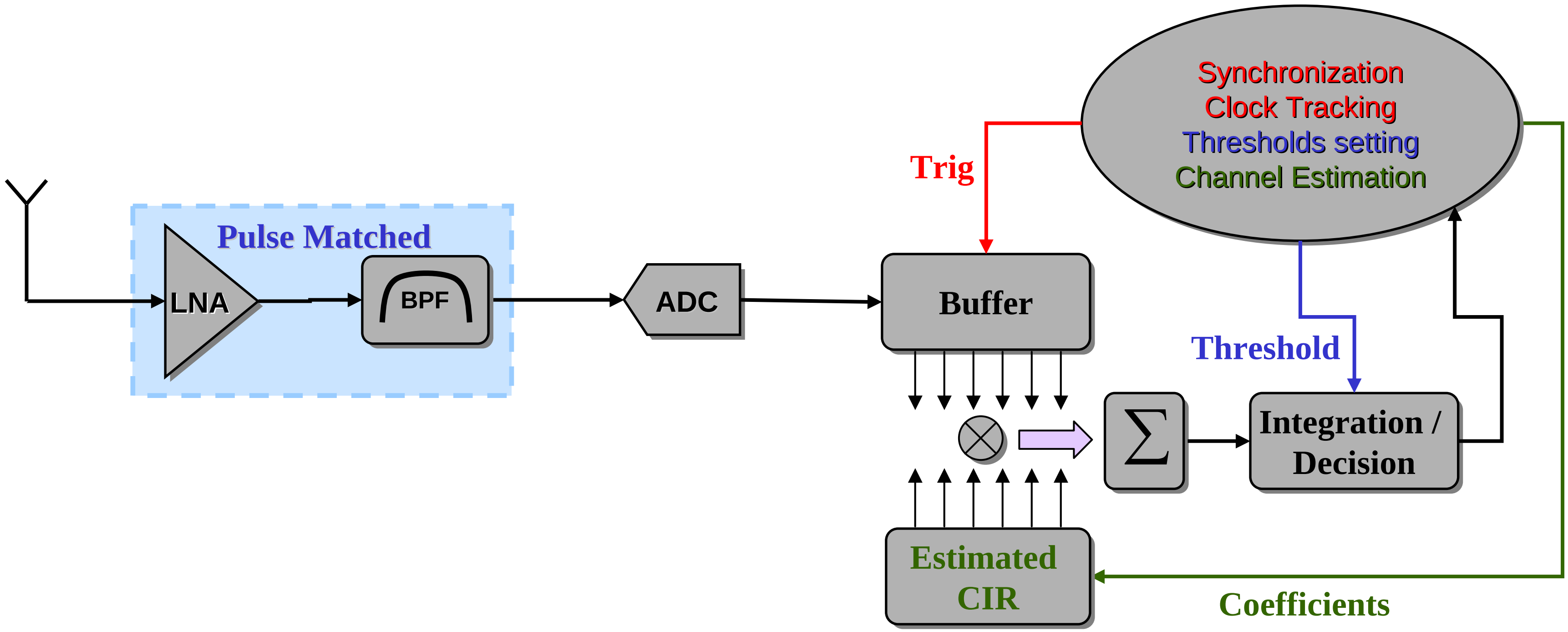
N = TH/polarity code length
Example with N = 3
Code is (1 1 -1)

Pulse matched filter : $E_b = E_{received\_pulse} \times N$: collects bit energy on a single path

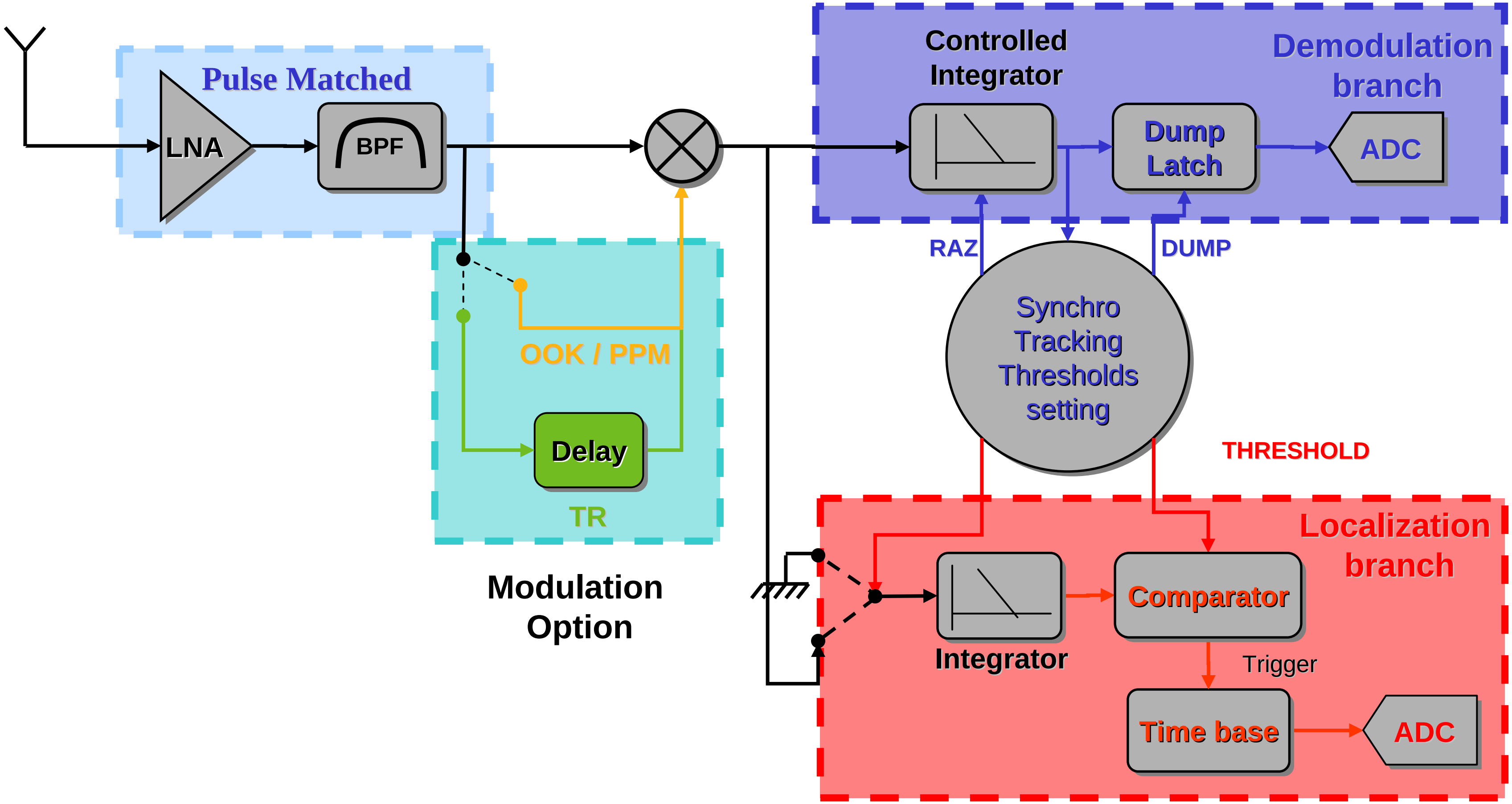


Compound Response matched filter : $E_b = E_{response} \times N$: collects all bit energy

Coherent Receiver Architecture

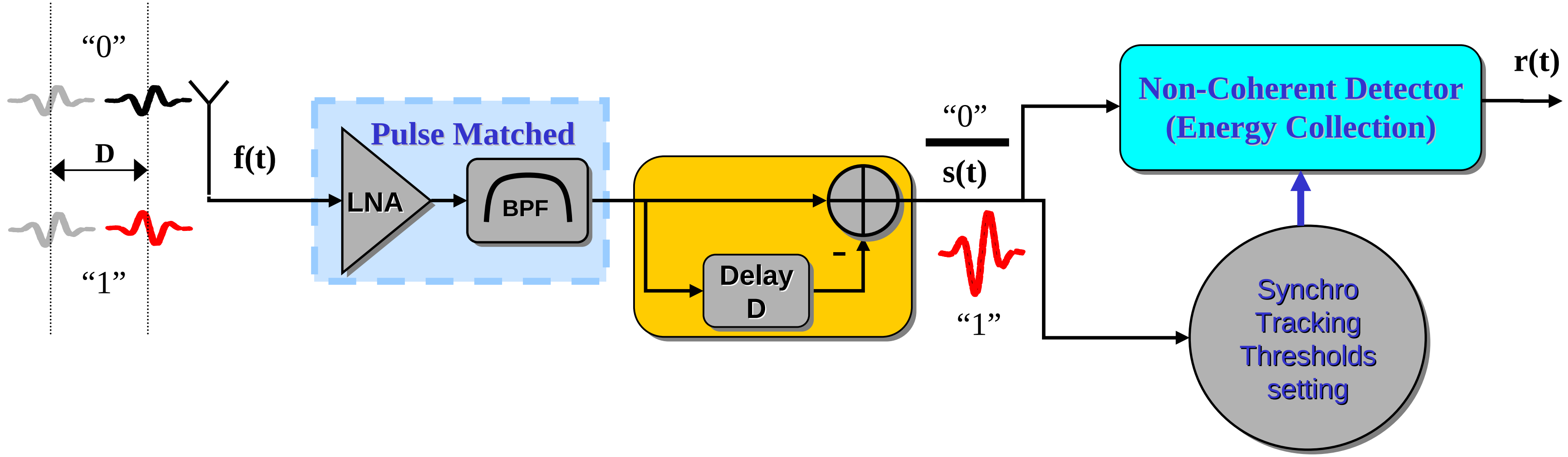


Differentially-Coherent/Non-Coherent Receiver Architecture



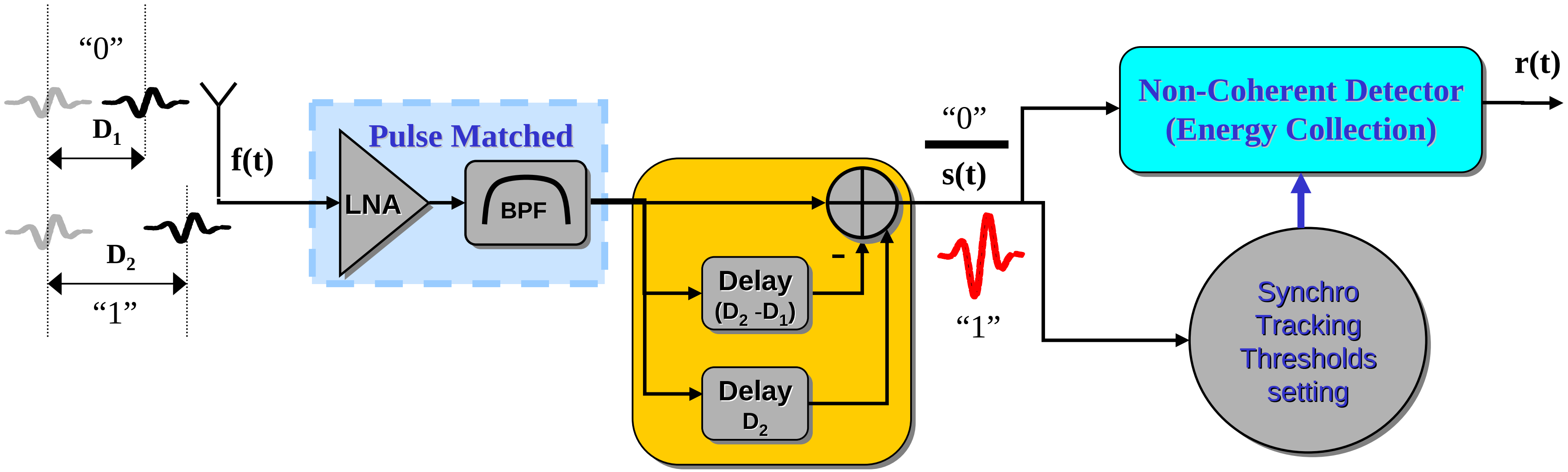
TR-BPSK → Non-Coherent Detection

- Concept: Transmitted-reference BPSK symbol can be decoded by a non-coherent detector (like OOK symbol)
- Advantages: Differential and non-coherent receiver may coexist; reference can be used for synch. and threshold estimation
- Concept can be generalized to N-ary TR-BPSK

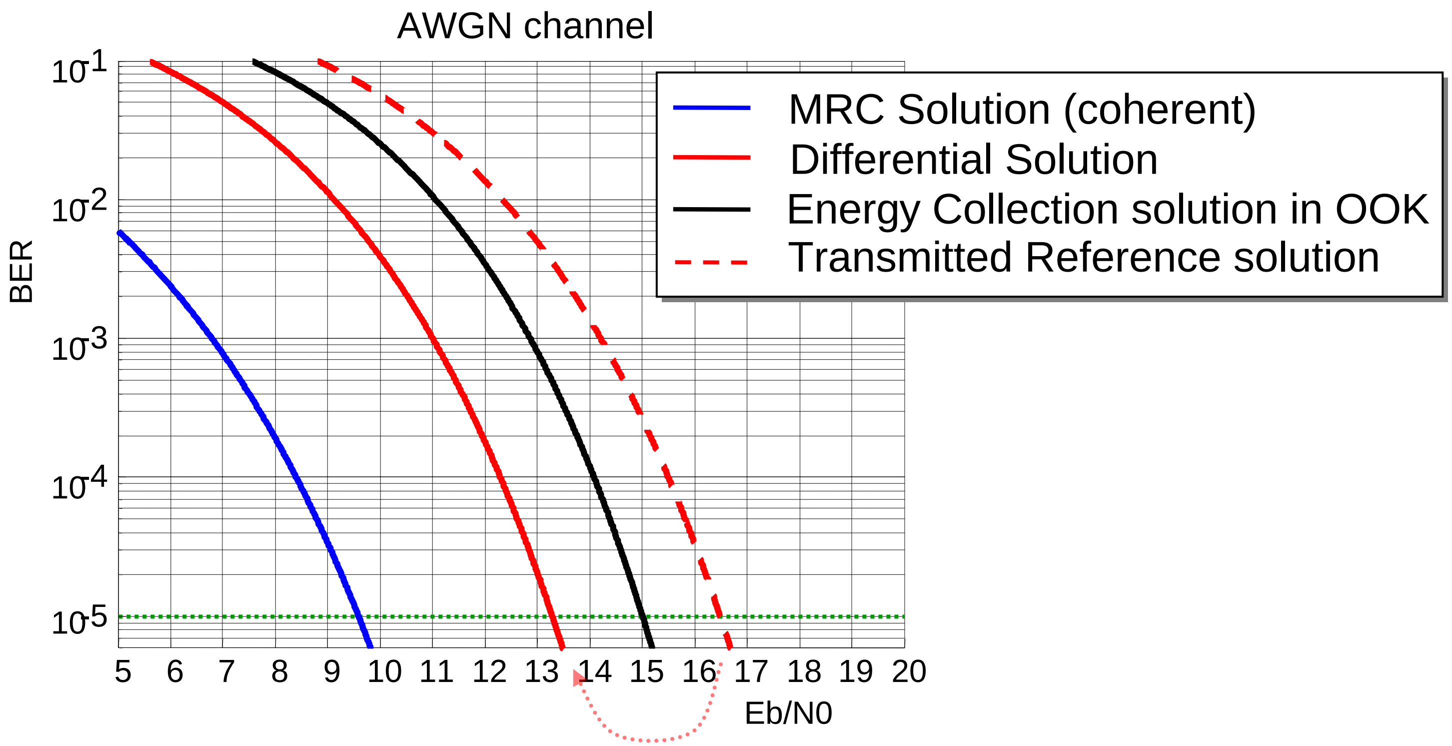


TR-BPPM → Non-Coherent Detection

- Concept: Transmitted-reference BPPM symbol can be decoded by a non-coherent receiver (like OOK symbol)
- Advantages: Different receiver schemes may coexist; Reference pulse can be used for synch. and threshold estimation
- Concept can be generalized to N-ary TR-BPPM



BER Performance (1/2)



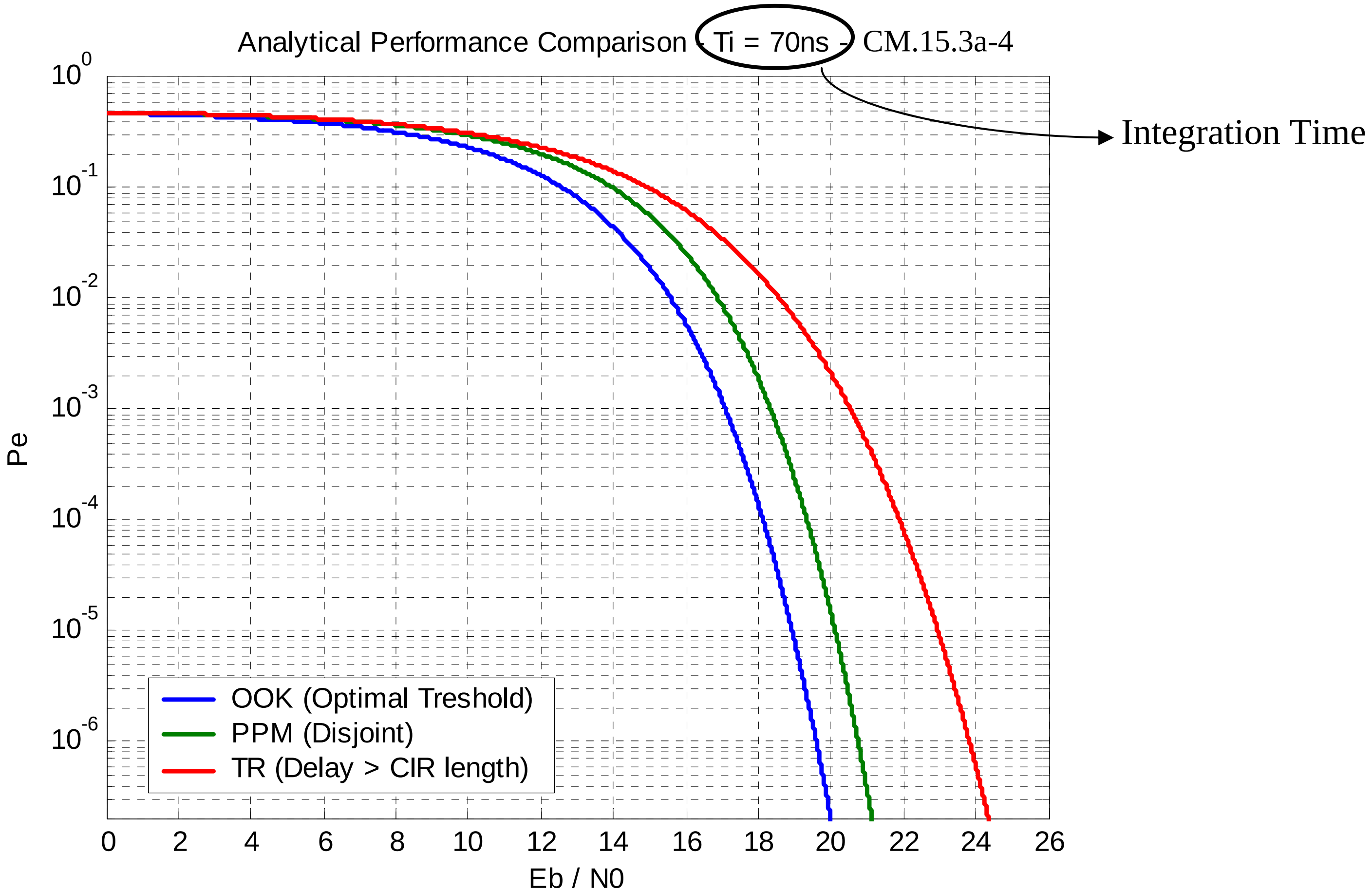
-3 dB : the « reference » is not in the same PRP !

$$p_{packet\ \ error} \geq 1-\left(1-_{bit\ error}\right)^{N}$$

PER = 1% with 32 bytes PSDU ➔ BER ~ 10^{-5} with no channel coding

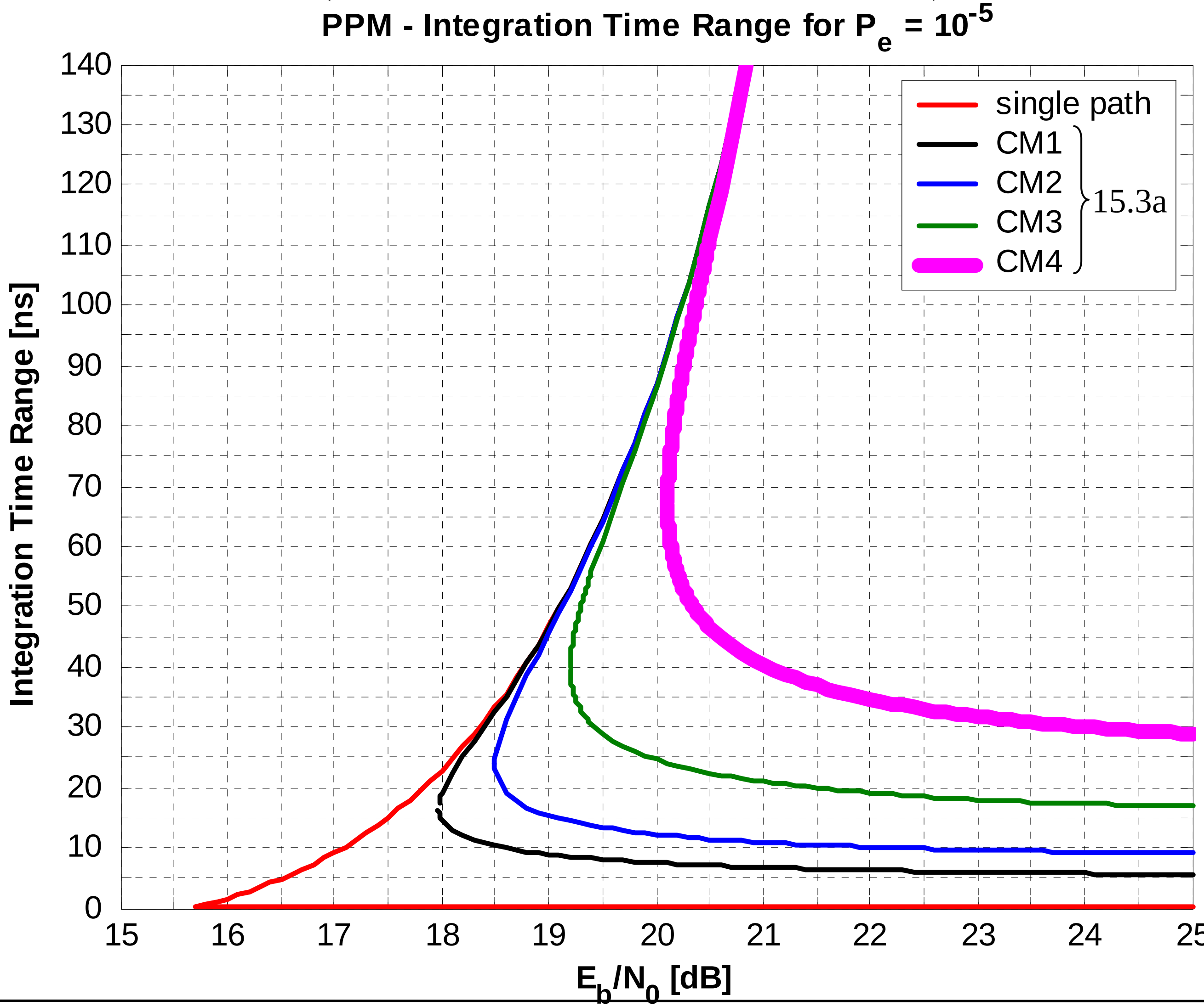
BER Performance (2/2)

- Comparison of receiver schemes : non coherent for 2PPM and OOK, differentially coherent for TR



Integration Time Range impact on BER

(for non coherent receiver on PPM)



Comparison Matrix for non coherent receivers

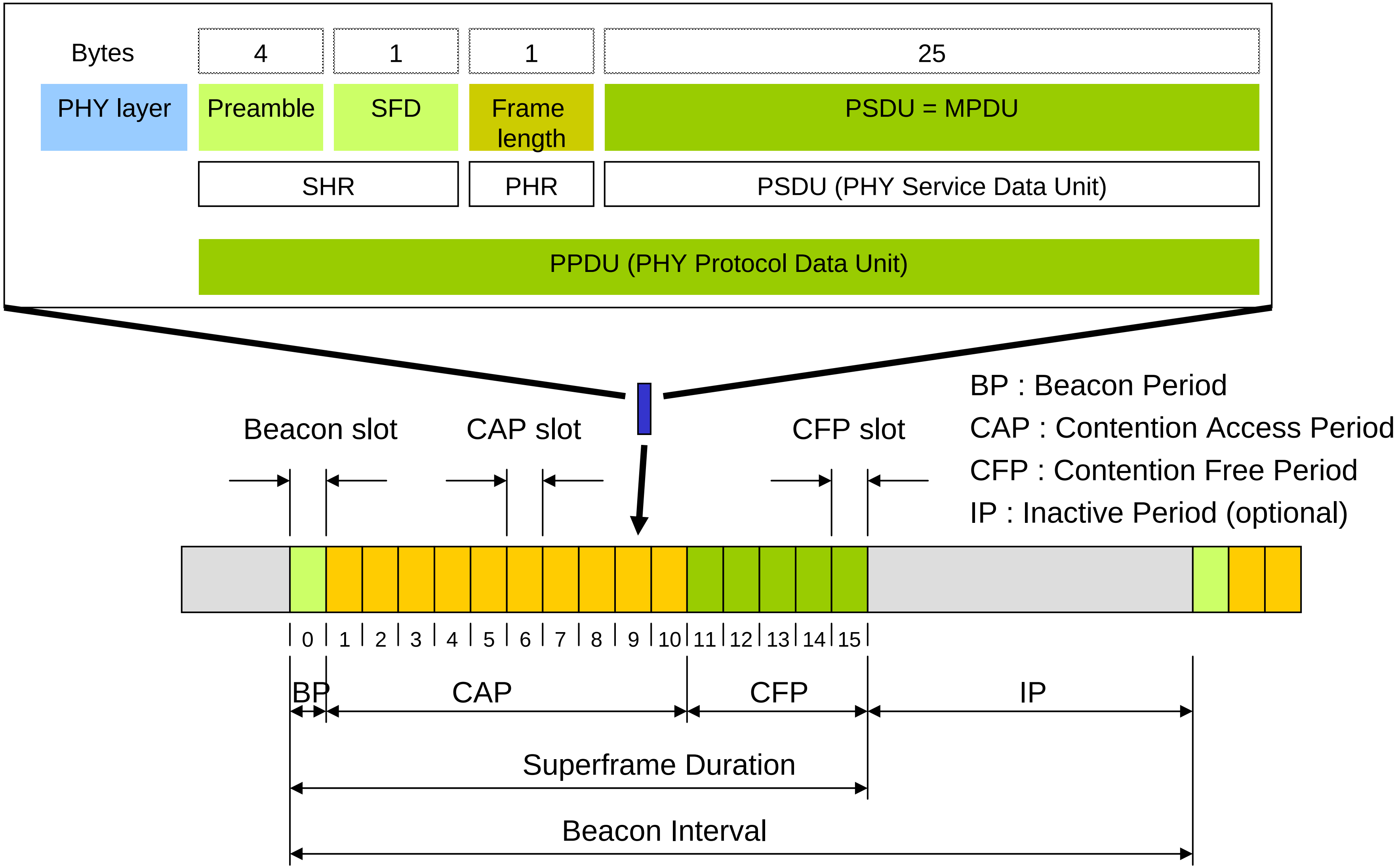
	OOK	PPM	TR (and variations)
Energy Efficiency	½ pulse per bit +	1 pulse per bit +/-	2 pulses per bit (or less) - (+/-)
Euclidean Distance	1 -	sqrt(2) +/-	2 +
Required E_b/N_0 [dB]	**18.9**	**20.1**	**22.9**
Max Range @ 10 kbps [m] – $\alpha = 3$	**30**	**31**	**29**
Threshold estimation	Yes -	No +	No (easy for TR→OOK) +
Synchronization & tracking	-	+/-	+
SOP robustness	-	-	+
Implementation challenges	« Multiplier / quadrator » +		Delay multiplier (or adder) +/-

Link Budget

Required Eb/N0 for diff-coherent receiver
on TR-BPSK using PRP = 4us, and no channel coding.
Remove X dB for coherent receiver, plus 3dB for DBPSK

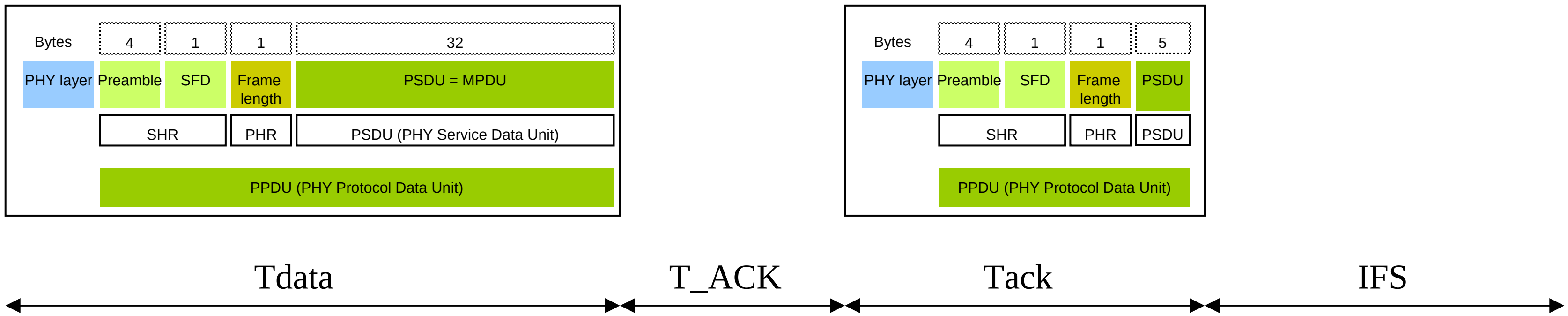
Parameter	Mandatory Value	Optional Value
Peak Payload bit rate (R_b)	250 kb/s	250 kb/s
Average Tx Power Gain (P_T)	-10.64 dBm	-10.64 dBm
Tx antenna gain (G_T)	0 dBi	0 dBi
f'c: (geometric frequency)	3.873 GHz	3.873 GHz
Path Loss @ 1m: $L_1 = 20\log10(4.\pi.f'_c / c)$	44.20 dB	44.20 dB
Path Loss @ d m: $L_2 = 20\log10(d)$	29.54 dB @ d = 30 m	12.04 dB @ d = 4 m
Rx Antenna Gain (G_R)	0 dBi	0 dBi
Rx Power ($P_R = P_T + G_T + G_R – L_1 – L_2$)	-84.38 dBm	-66.88 dBm
Average noise power per bit: $N = -174 + 10\log_{10}(Rb)$	-120.02 dBm	-123.02 dBm
Rx noise figure (N_F)	7 dB	7 dB
Average noise power per bit ($P_N = N + N_F$)	-113.02 dBm	-113.02 dBm
Minimum E_b/N_0 (S) in **15.3a CM4**	22.9 dB	22.9 dB
Implementation Loss (I)	5 dB	5 dB
Link Margin ($M = P_R - P_N – S – I$)	0.74 dB	18.24 dB
Proposed Min. Rx Sensitivity Level	-85.12 dBm	-85.12 dBm

Framing


Bytes
4
1
1
25
PHY layer
Preamble
SFD
Frame length
PSDU = MPDU
SHR
PHR
PSDU (PHY Service Data Unit)
PPDU (PHY Protocol Data Unit)
BP : Beacon Period
CAP : Contention Access Period
CFP : Contention Free Period
IP : Inactive Period (optional)
Beacon slot
CAP slot
CFP slot
0 1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
BP
CAP
CFP
IP
Superframe Duration
Beacon Interval

Throughput

Data Frame (32 bytes PSDU) **ACK Frame (5 bytes PSDU)**



- Numerical example (high-band)
  - Preamble + SFD + PHR = 6 bytes
  - Tdata = 1.216 ms
  - T_ACK = 50 μs (> turn around time requested by 15.4 is 192μs)
  - Tack = 0.352 ms
  - IFS = 100μs

  ⇒ Throughput = 32 bytes/1.718 ms = <u>149 kb/s</u>

  ⇒ Average data-rate at receiver PHY-SAP in excess of <u>250 kb/s</u>

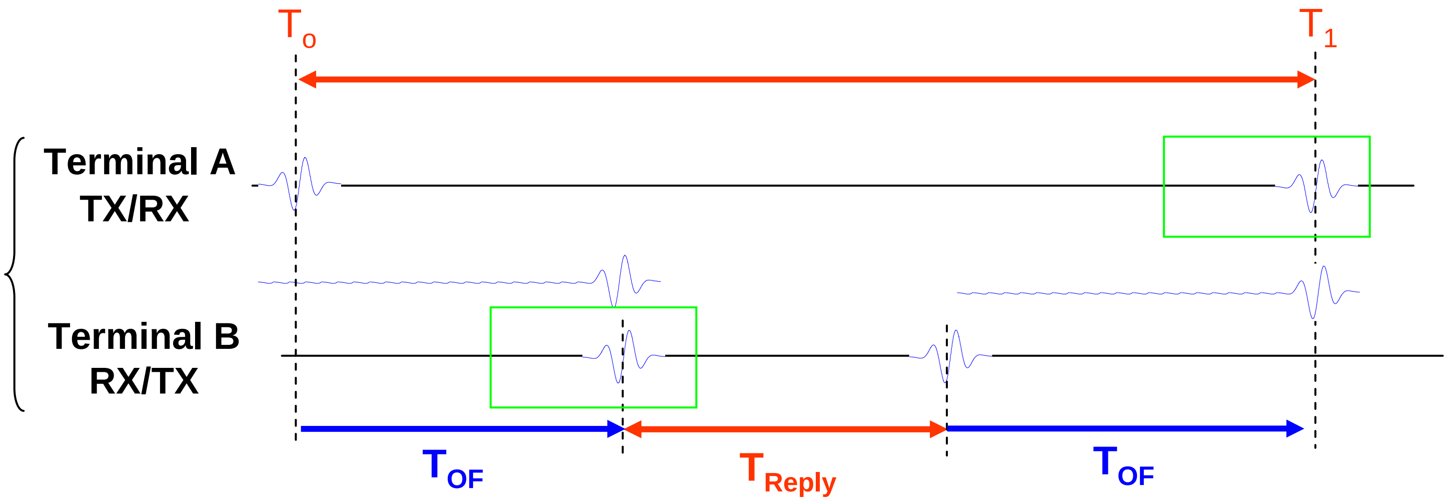
Saving Power

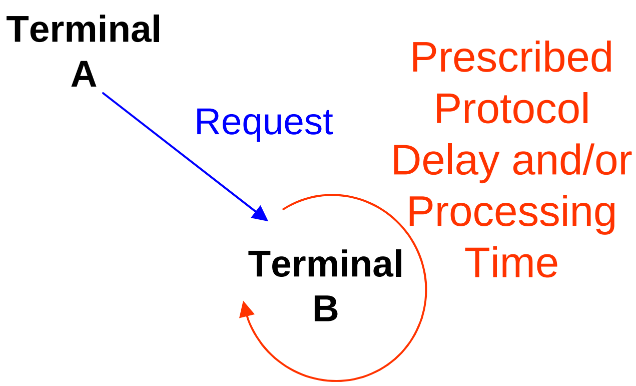
- Numerous Power Saving techniques can be achieved by combining advantages offered at 3 levels:
  - technology (best if CMOS)
  - Architecture (flexible schemes provided by the TH pulse modulation)
  - System level (framing, protocol usage)
- Here are selected techniques used in one of the current realizations (see proof of concept slides)
  - Low-duty cycle Episodic transmission/reception
    - Scheduled wake-up
    - 80μs RTOS tick
  - Ad-hoc networking using multi-hop
    - Special rapid acquisition codes / algorithm
    - Matchmaking further deduces acquisition time
  - Multi-stage time-of-day clock
    - Synchronous counter / current mode logic for highest speed stages
    - Ripple counter / static CMOS for lowest speed stages
  - Compute-intensive correlation done in hardware

Ranging

- Motivation :
  - Benefit from high time resolution (thanks to signal bandwidth):
    - Theoretically: 2GHz provides less than 20cm resolution
    - Practically: Impairments, low cost/complexity devices should lead to ~50cm accuracy with simple detection strategies (could be better with high resolution techniques)
- Approach :
  - Use Two Way Ranging between 2 devices with no network constraint (preferred); no need for time synchronization among nodes
  - Use One Way Ranging and TDOA under some network constraints (if supported)

Two Way Ranging (TWR)





T_{OF} Estimation

$$\tilde{T}_{OF\ A} = \frac{1}{2}\left[\left(T_1 - T_0\right) - T_{\mathrm{Reply}}\right]$$

$$\tilde{d}_{AB} = \tilde{T}_{OF\ A}.c$$

Two Way Ranging (TWR)

Main Limitations / Impact of Clock Drift on Perceived Time

$$\tilde{T}_{OF\,A} = T_{OF\,A}(1+\Delta_A) + \frac{T_{\text{Reply}}(\Delta_A - \Delta_B)}{2(1+\Delta_B)}$$

$\Delta . f_0$ Is the frequency offset relative to the nominal ideal frequency f_0

Range estimation is affected by :

- Relative clock drift between A and B
- Prescribed response delay
- Clock accuracy in A and B
- Channel response (weak direct path)

Δf/f \ Treply (max error)	192 µs	10 µs
4 ppm	0.23 m	0.01 m
40 ppm	2.30 m	0.12 m

Example using Imm-ACK SIFS of 15.4 and 15.3

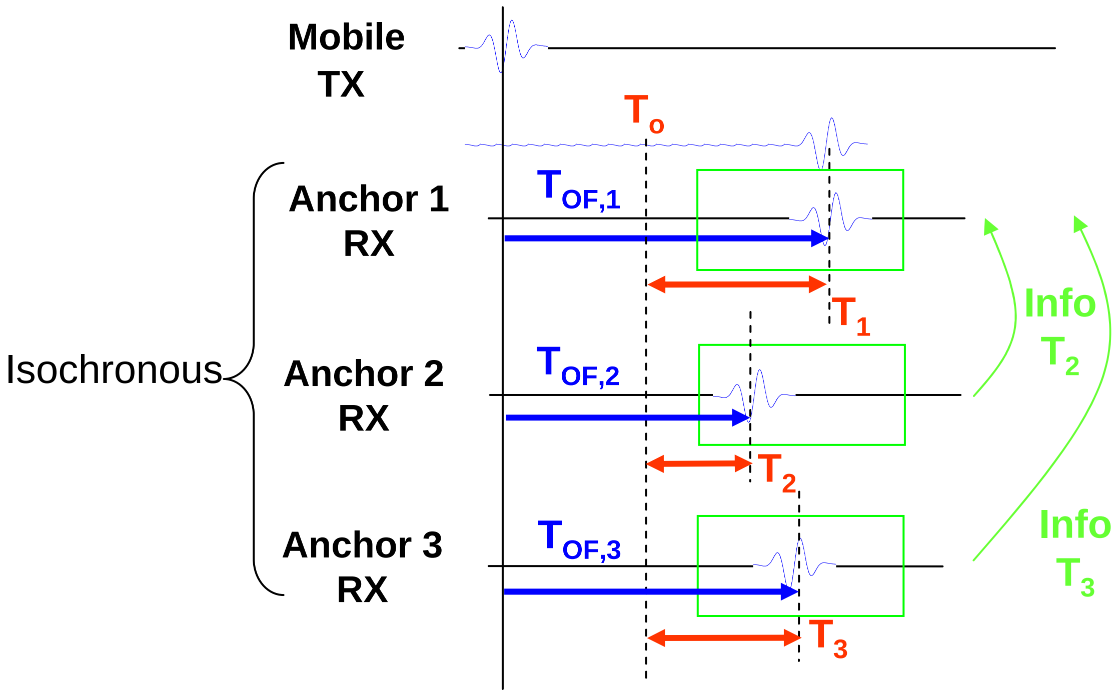
Relaxing constraints on clock accuracy is possible by

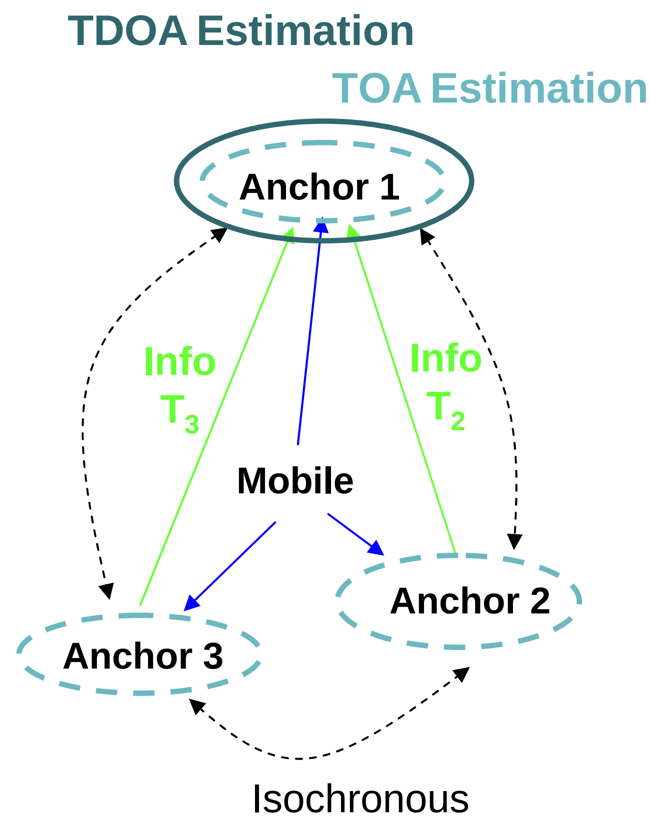
- Performing fine drift estimation/compensation
- **Benefiting from cooperative transactions (estimated clock ratios …)**
- Adjusting protocol durations (time stamp…)

Cooperative Networking

- **Position location using inexpensive timebases**
  - Quartz crystal or MEMS oscillator
    - 2 ppm (10^{-6}) with on-chip software-mediated temperature compensation
    - Nodes can track each other's clock frequencies for ppb (10^{-9}) matching
  - Absolute position accuracy of entire network is raised to the absolute accuracy of the best oscillator or known distance
  - Digital post-correction of actual versus expected arrival time
- **Potential for Code & Time Division** channelization **for a million Localizers per km^2**
- **Multi-hop communication**
  - Defeats $1/R^n$ received power reduction ($n \geq 3$)
  - Reduces probability of interference

Time Difference Of Arrival (TDOA) & One Way Ranging (OWR)





Passive Location

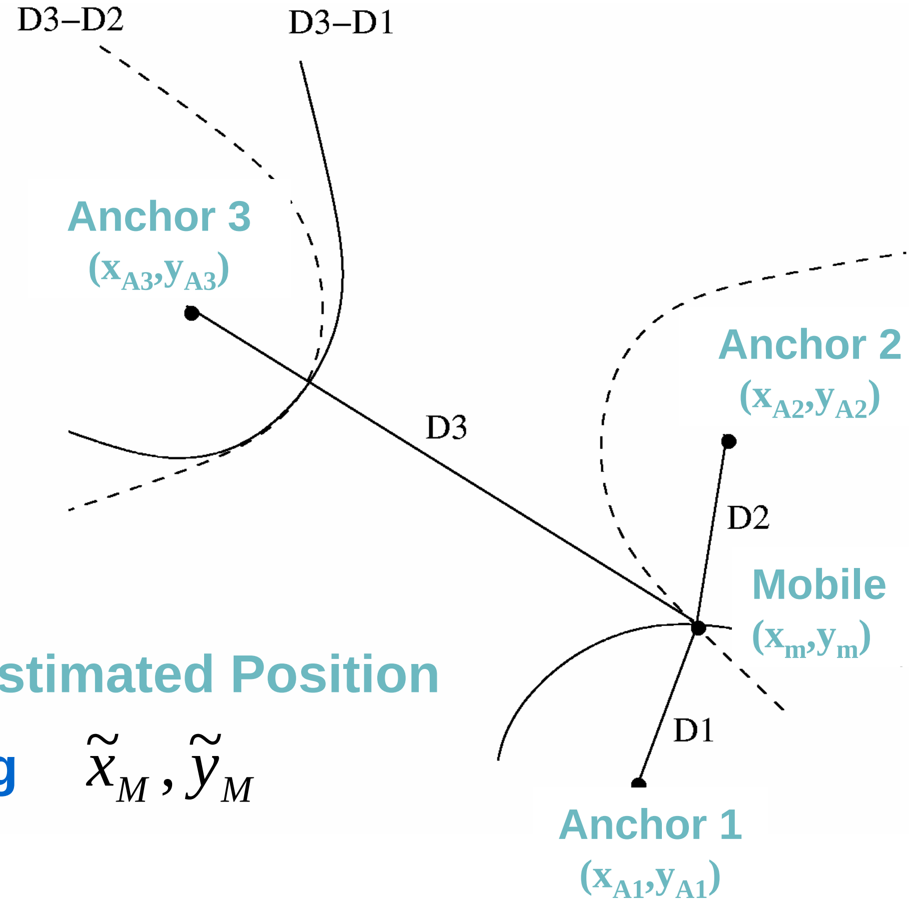
TOA Estimation → **TDOA Estimation**

$$T_1, T_2, T_3$$

$$\tilde{T}_{21} = T_1 - T_2 \Rightarrow \tilde{d}_{21} = \tilde{T}_{21}.c$$

$$\tilde{T}_{23} = T_3 - T_2 \Rightarrow \tilde{d}_{23} = \tilde{T}_{23}.c$$

Positioning from TDOA



3 anchors with known positions (at least) are required to find a 2D-position from a couple of TDOAs

Measurements → **Estimated Position**

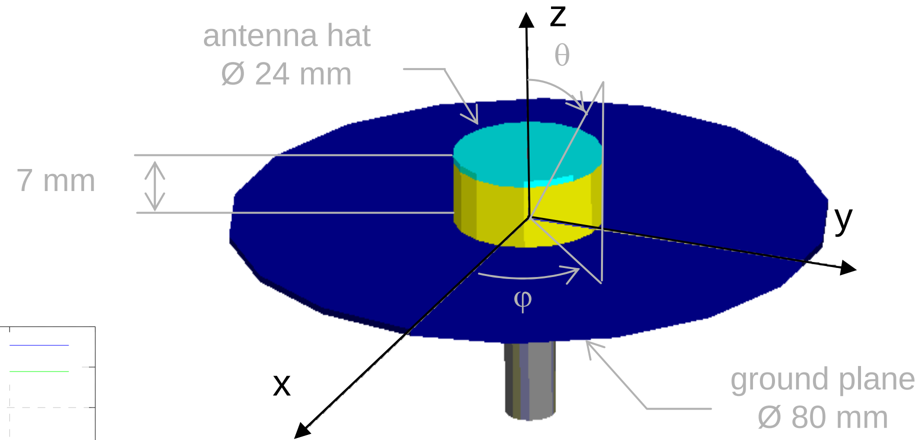
$\tilde{d}_{32}, \tilde{d}_{31}$ **Specific Positioning Algorithms** $\tilde{x}_M, \tilde{y}_M$

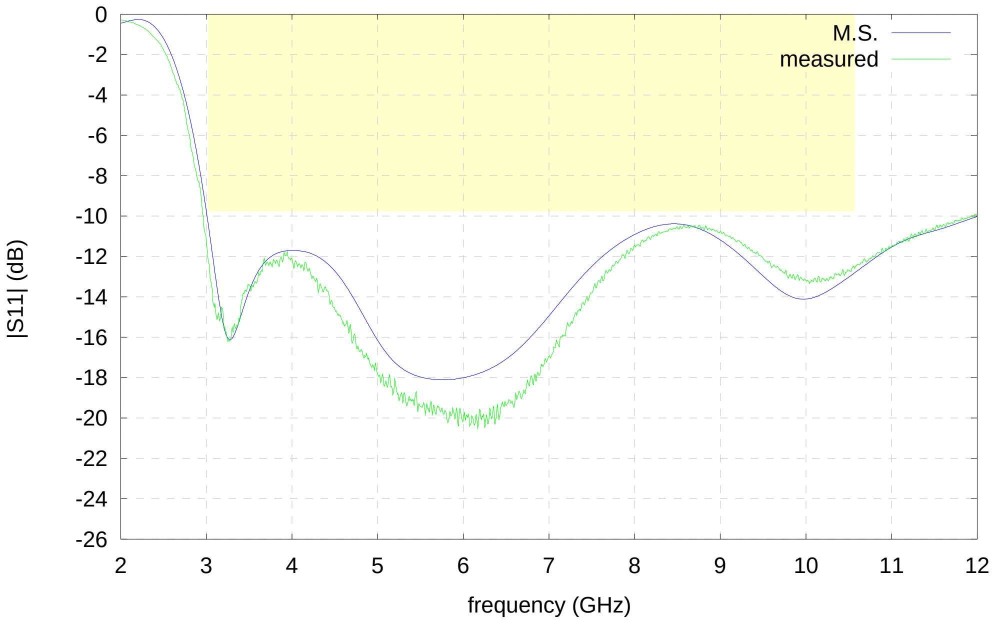
$$d_{32} = \sqrt{\left(x_{A_3} - x_M\right)^2 + \left(y_{A_3} - y_M\right)^2} - \sqrt{\left(x_{A_2} - x_M\right)^2 + \left(y_{A_2} - y_M\right)^2}$$

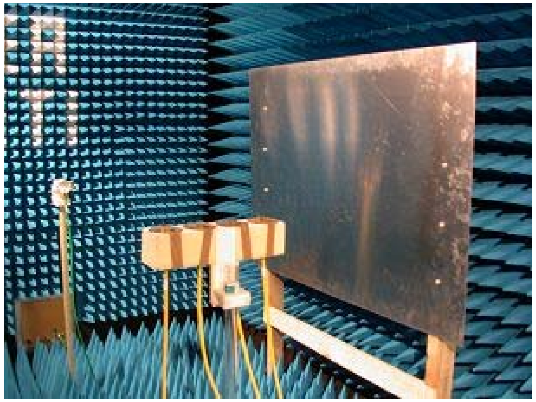
$$d_{31} = \sqrt{\left(x_{A_3} - x_M\right)^2 + \left(y_{A_3} - y_M\right)^2} - \sqrt{\left(x_{A_1} - x_M\right)^2 + \left(y_{A_1} - y_M\right)^2}$$

Antenna Practicality

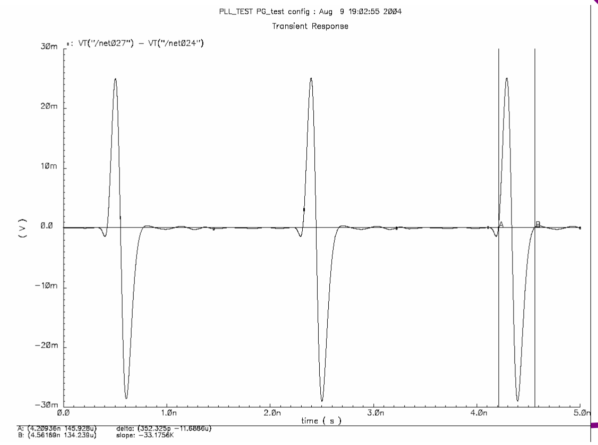
- Bandwidth: 3 GHz-10 GHz
- Form factor
- Omni-directional



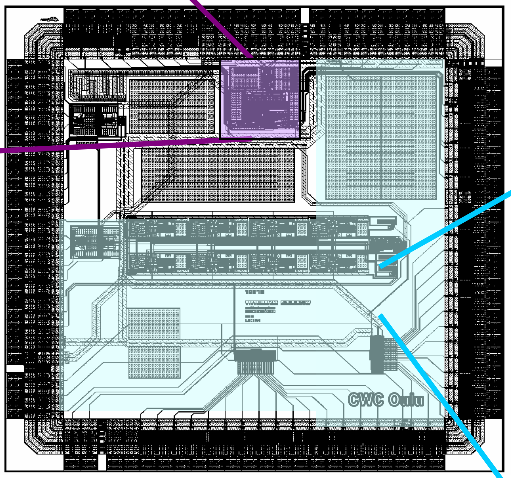




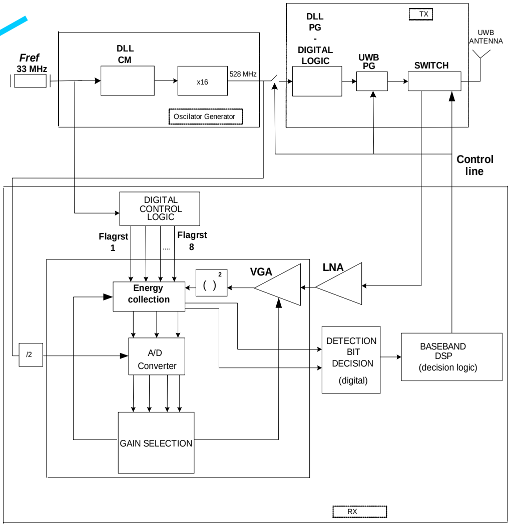
"Proof of concept" (1)



5 Mbps BPPM
350 ps pulse train
with long scrambling code

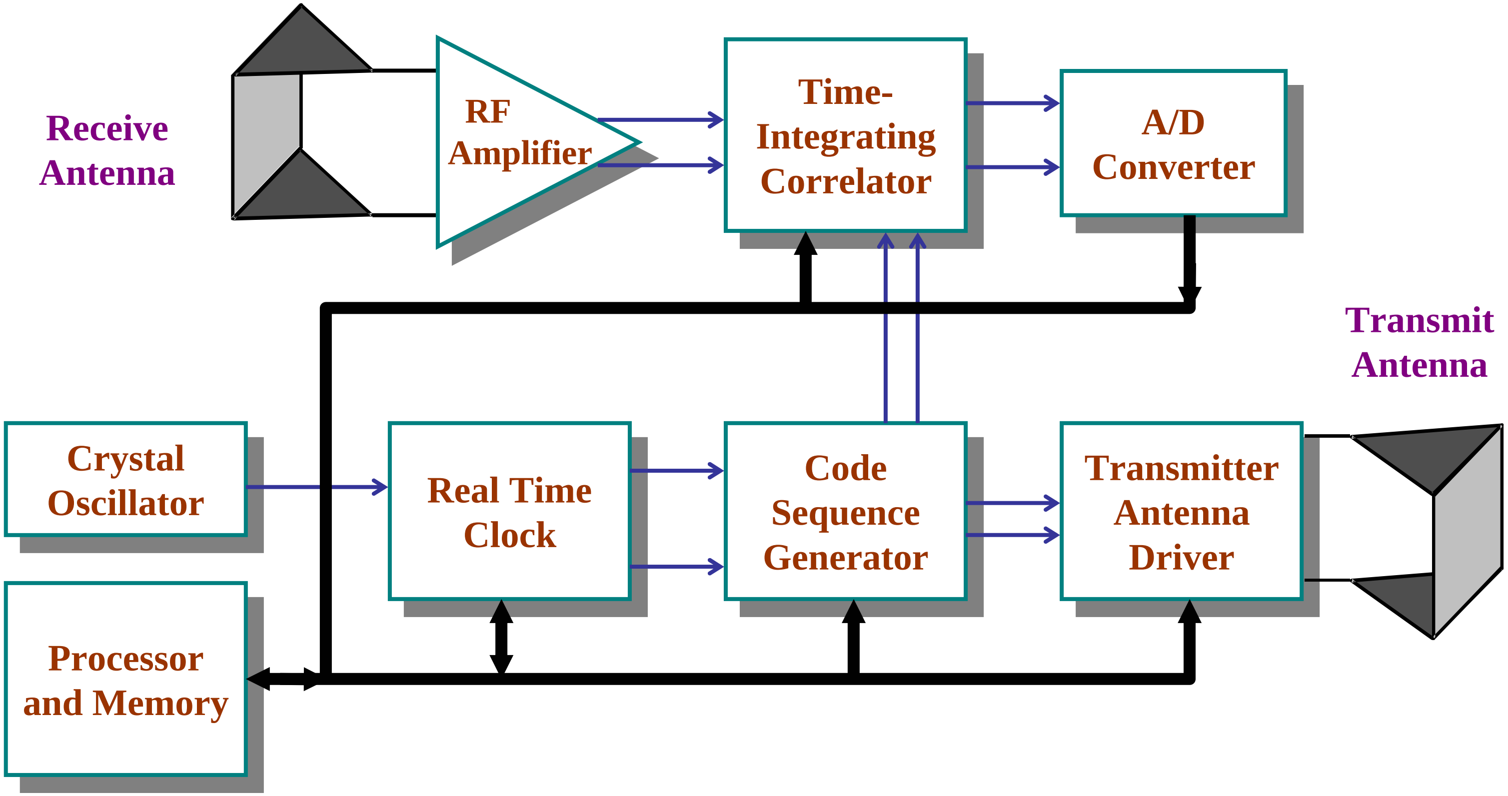


Non-coherent,
Energy Collection Receiver

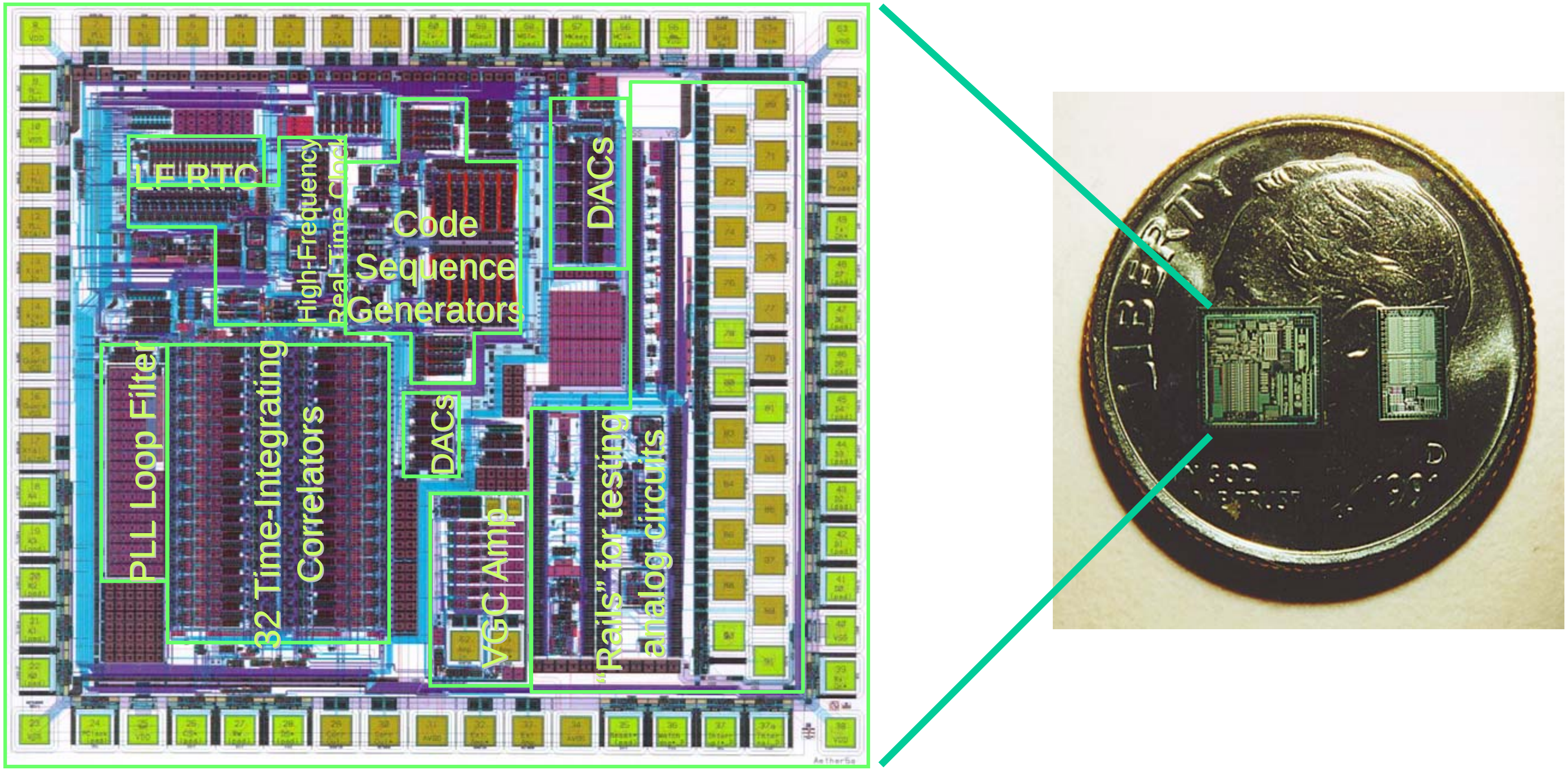


Proof of concept (2)

- Low-Band Coherent Transceiver Architecture

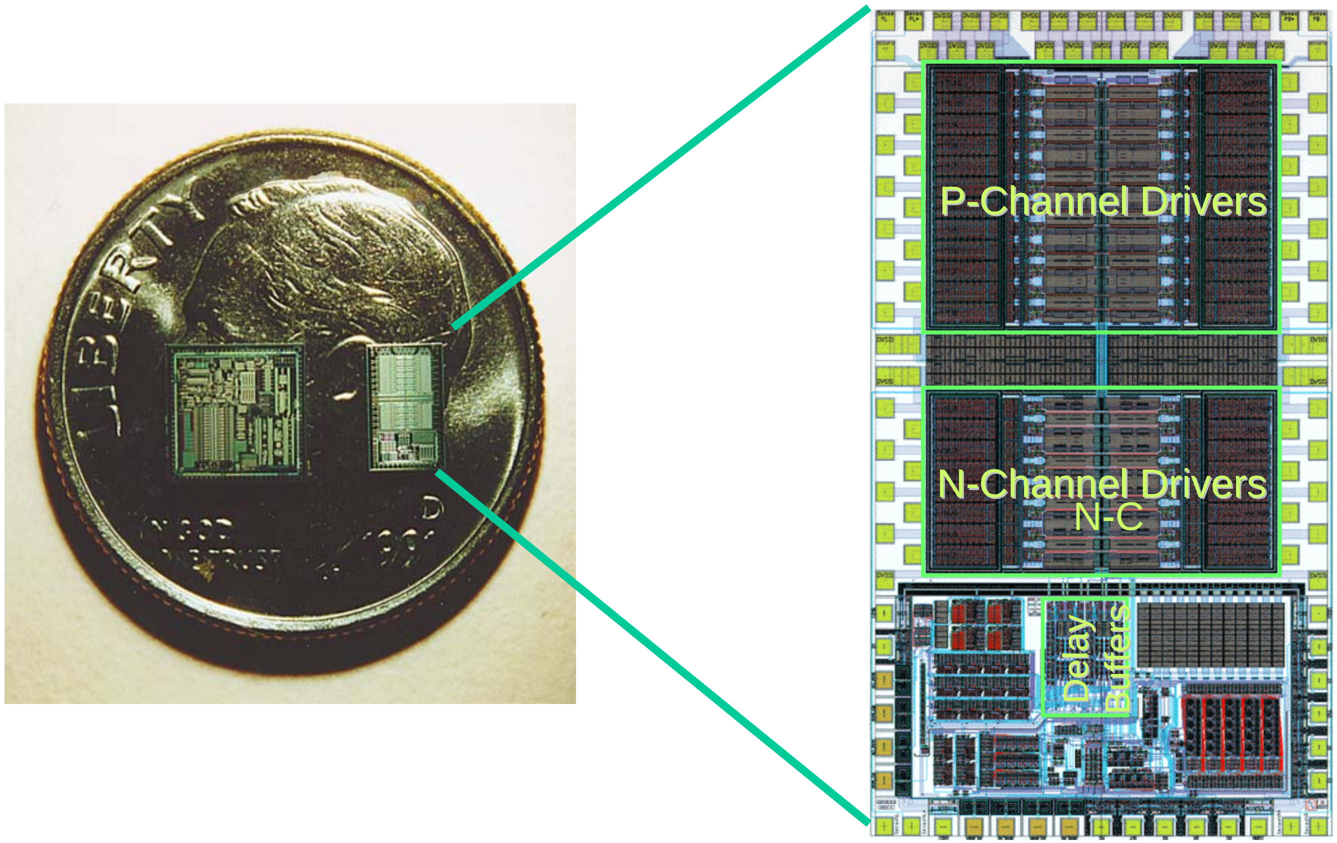


Proof of Concept (2):Receiver



Coherent UWB Receiver with
multiple time integrating correlators

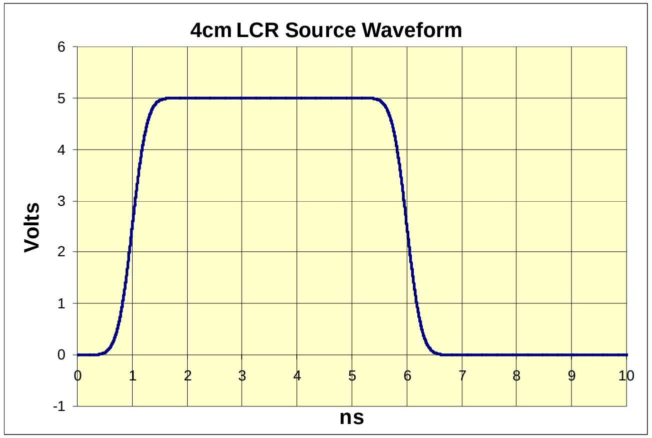
Proof of Concept (2): Transmitter

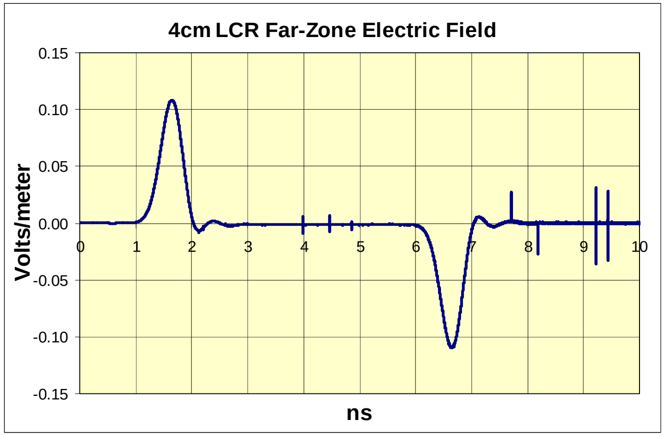


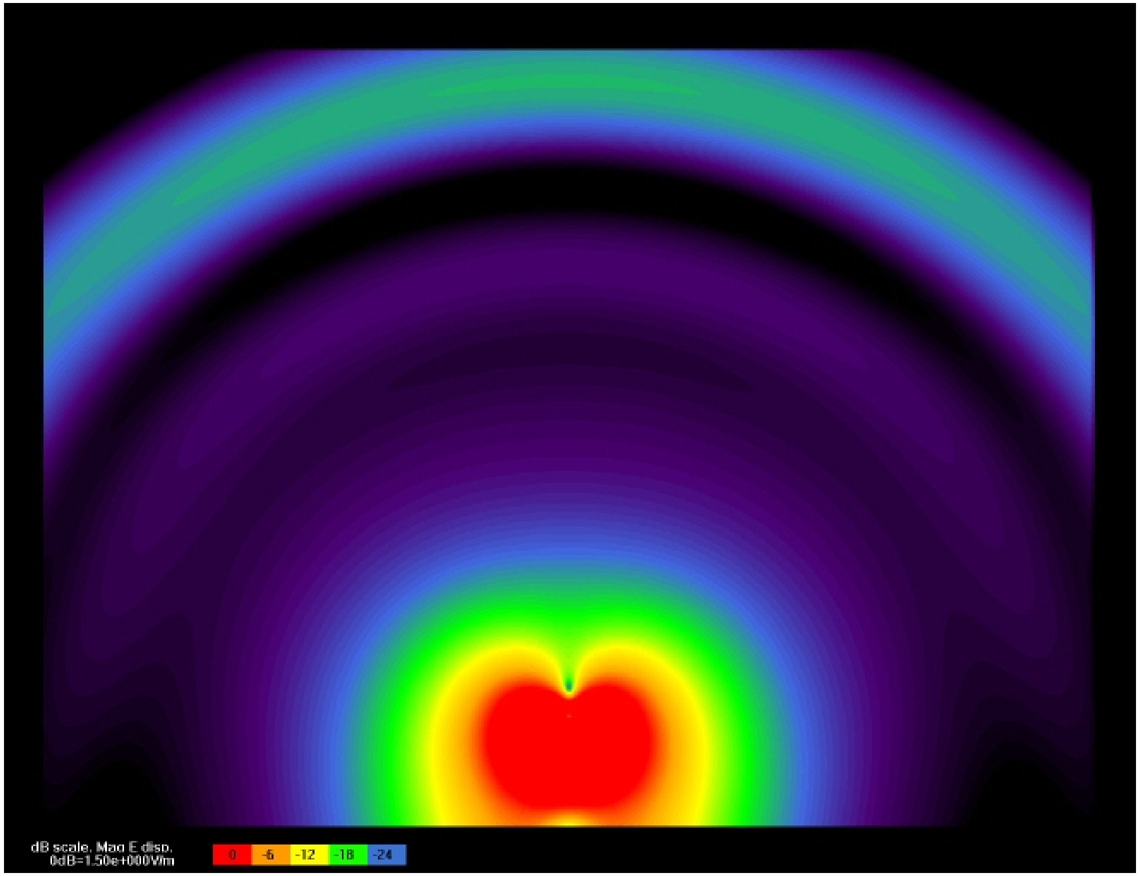
UWB Transmitter chip for generating impulse doublets

Proof of Concept(2) Antenna

Baseband impulses (<1GHz) can be effectively radiated from small (<4 cm) Large Current Radiator (LCR) antenna *(FDTD simulation)*

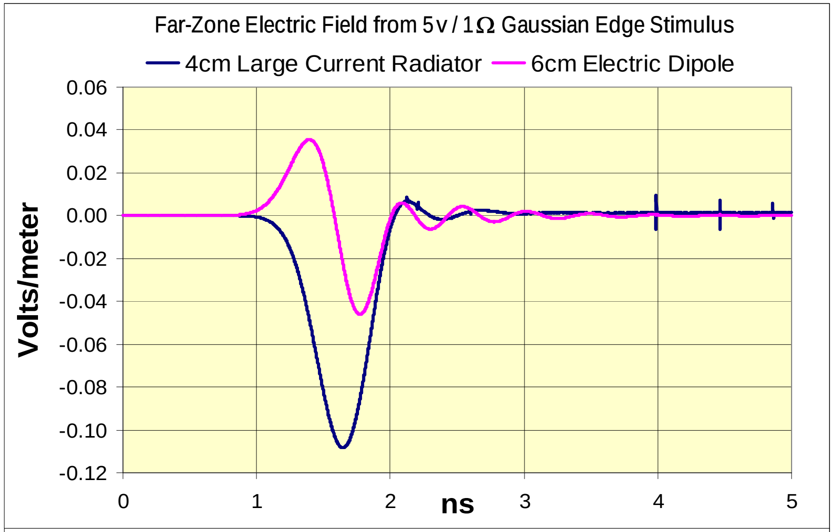


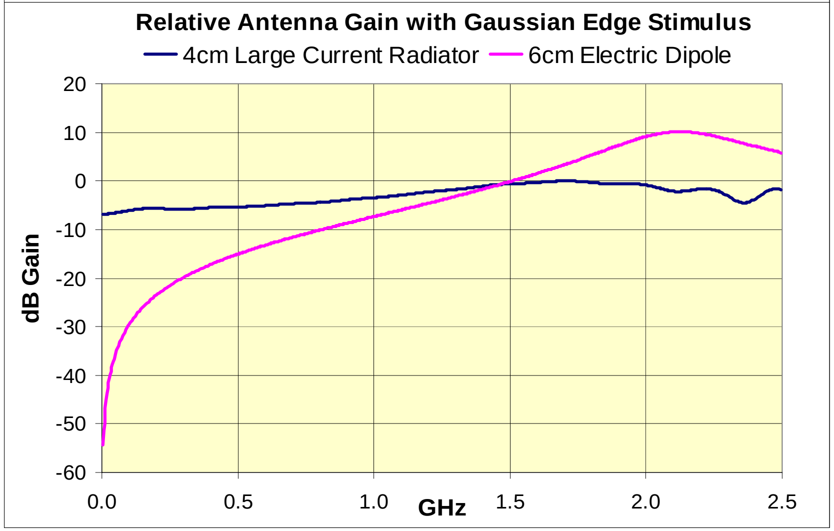




Proof of Concept (2): Antenna

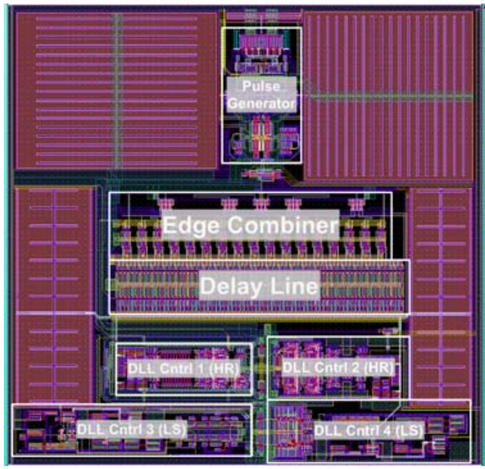
- Large Current Radiator
  - Preserves impulse shape
  - Frequency response varies <6 dB from <100 MHz to >2.5 GHz
  - Requires low (1Ω) source impedance
    - Direct drive from chip
    - No transmission line
- 6 cm Electric Dipole
  - Differentiates impulse shape
  - Gain varies 40 dB from 100 MHz to 2.2 GHz
- Other UWB antennas with comparable low-frequency response (*e.g.* TEM horn) are physically large (> 1 meter)



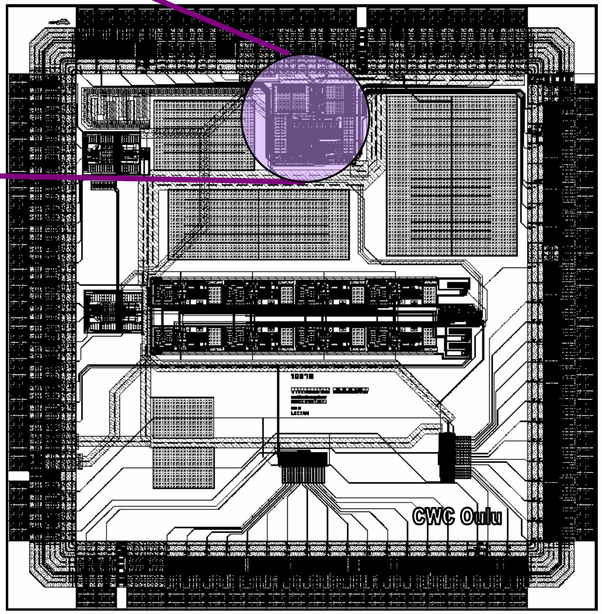


"Proof of concept" (3)

UWB-IR BPPM Non-Coherent Transceiver Implementation

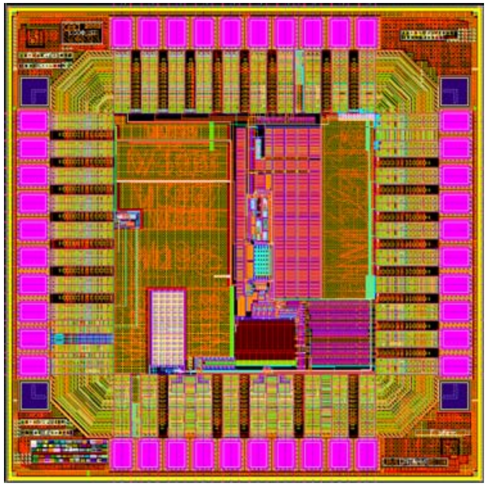


UWB Transmitter
400 µm x 400 µm
0.35 µm CMOS



UWB Transceiver
<10 mm²
0.35 µm SiGe Bi-CMOS

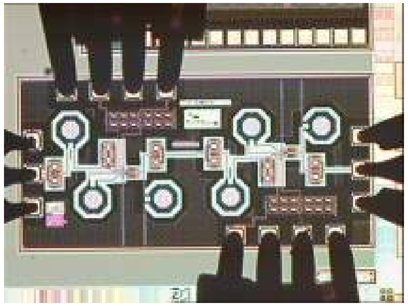
“Proof of concept” (4)



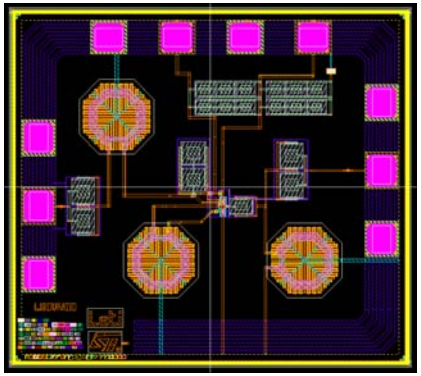
RF front end chipset in CMOS 0.13μm, 1.2V

20 GHz digitizer for UWB

20 GHz DLL for UWB



3-5 GHz LNA
Chip and layout

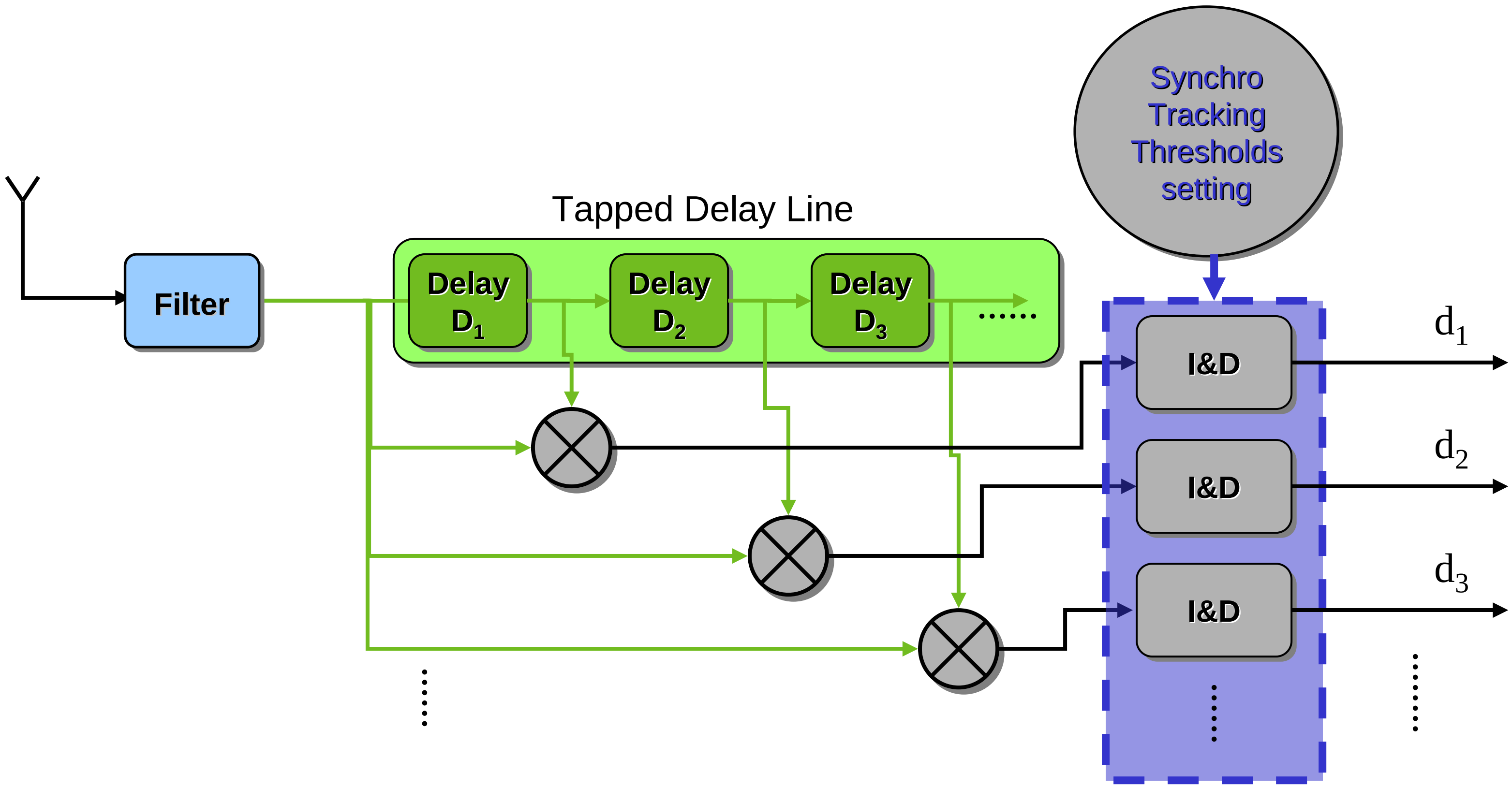


Conclusions

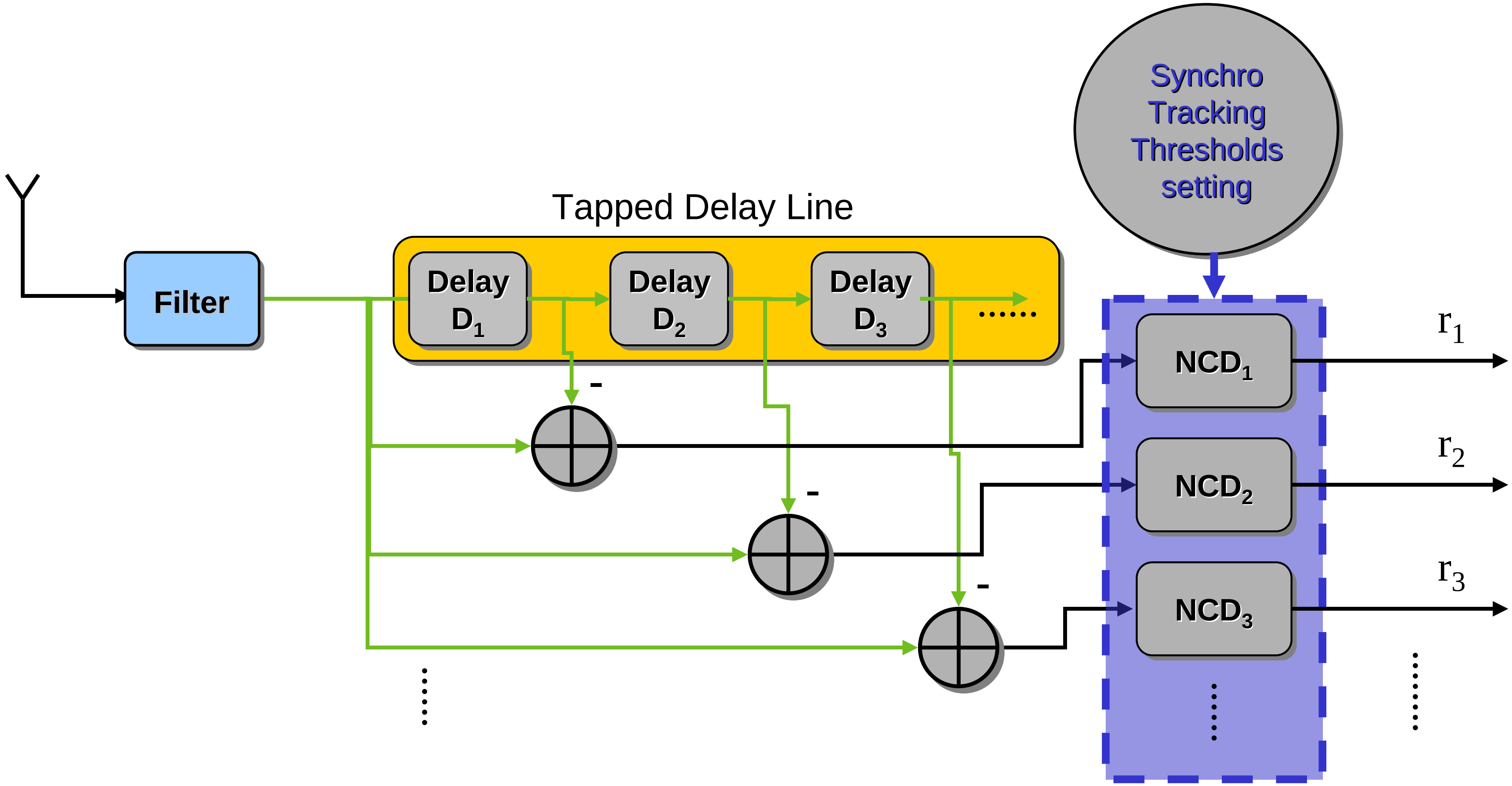
- Proposal based upon UWB impulse radio
  - High time resolution suitable for precise ranging using TOA
  - Modulation:
    - Pulse-shape independent
    - Robust under SOP operation
    - Facilitates synchronization/tracking
    - Supports multiple coherent/non-coherent RX architectures
- System tradeoffs
  - Modulation optimized for several aspects (requirements, performances, flexibility, technology)
  - Trade-off complexity/performance RX
- Flexible implementation of the receiver
  - Coherent, differential, non-coherent (energy collection)
  - Analogue, digital
- Fits with multiple technologies
  - Easy implementation in CMOS
  - Very low power solution (technology, architecture, system level)

Backup Slides

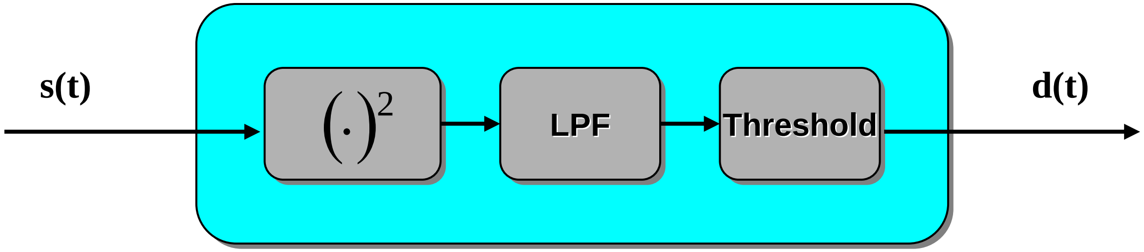
GTR-BPSK Differentially-Coherent Receiver



GTR-BPSK Non-Coherent Detection



Non-Coherent Detector (NCD)



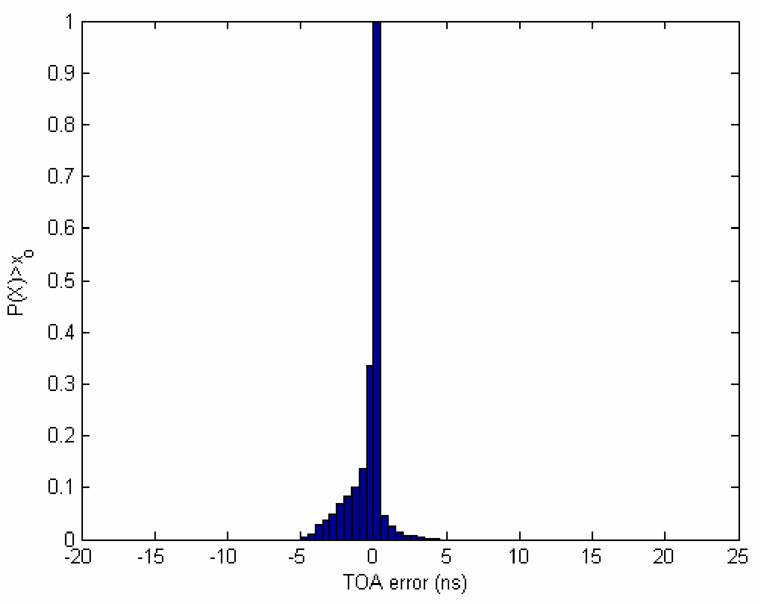
Delay Estimation With Energy Collection (1/2)

- Uses banks of integrators to locate symbol within confined window
- Integrators provide course synchronisation
- Two approaches have been considered to delay estimation:
  - **Approach #1 - <u>TOA estimation is based on threshold technique</u>.**
    - **First integrator output that crosses the threshold is used for TOA estimation.**
  - Approach #2 - the TOA is estimated by taking the peak value between the integrator outputs
    - Improvements on basic performance possible

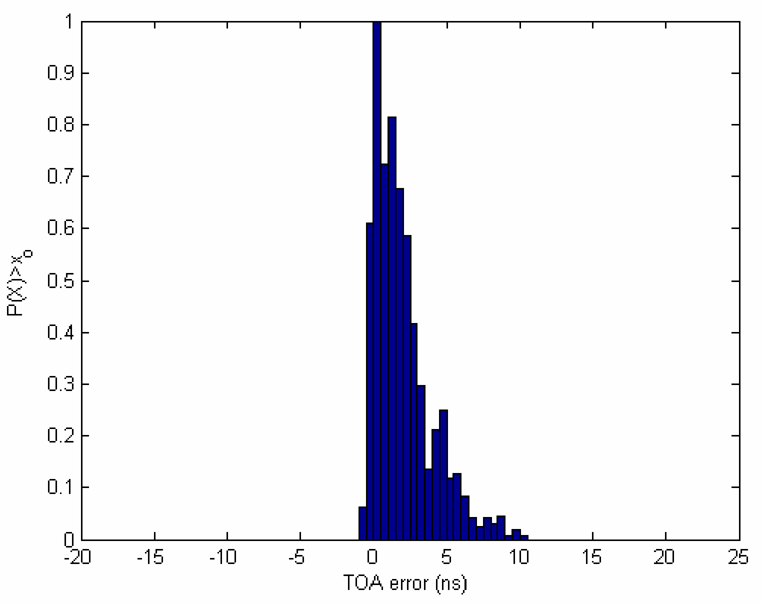
- Approach #1 trade-off is false alarm probability versus missed signal
- Approach #2 reduces the false alarm probability but increases the probability of a positive TOA error due to the channel characteristics

Delay Estimation With Energy Collection (2/2)

- TOA estimation error (normalised)



(1)



(2)

- Example: 20 integrators spanning 100 ns symbol period (T_{acc} 5 ns) in CM1 (1) without and (2) with peak method

Ranging Performance for Non-Coherent Receiver