Ultra Wide Band Communications

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Basics reminder

- *The radio spectrum is divided in dedicated bands where radio systems should operate (central frequency, BW).*
- *A radio wave is emitted on a carrier frequency, and modulated by an information signal*
  - *Amplitude, Phase, Frequency Modulation…*
- *The radio channel has a multiplicative effect on transmitted signal (additive in dB).*
  - *Pathloss, shadowing, fading (more the BW is, more multi-path are discernable).*
- *The signal BW is conditioned by time-domain shortness of BB signal.*

Note: a major part of this lecture is based on a document from B. Miscopein, Orange Labs

Outline

- *UWB, impulse radio*
  - *–Historical context and regulatory*
  - *–Pointed applications (high and low DR)*
  - *–Introduction to impulse radio*
  - *–UWB radio channel*
  - *–PHY layer (modulation, multiple access)*
  - *–Receiving system (coherent, non coherent)*
  - *–Distance Measurement in UWB (localization)*
- *UWB with MB-OFDM*

Introduction to UWB world

Historical Context - Radar

UWB impulse communications come from radar domain

- *Development during World War 2*
- *EM pulse emitted by a highly directive antenna, echo received after reflection on a target*
- *Time difference (T) between emitted and received signal is related to distance (R) between radar and target, as follows:*

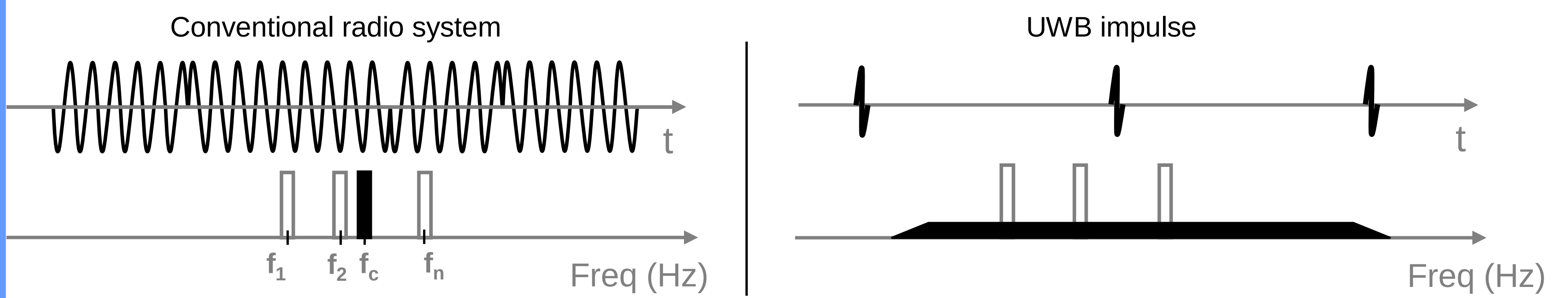
  $R = T.c/2$ *c : light speed*

- *The shorter the pulse is, the wider the frequency (B) band is, and the higher the radar resolution is ρ (ability to distinguish to close targets):*

  $\rho = c/2B$

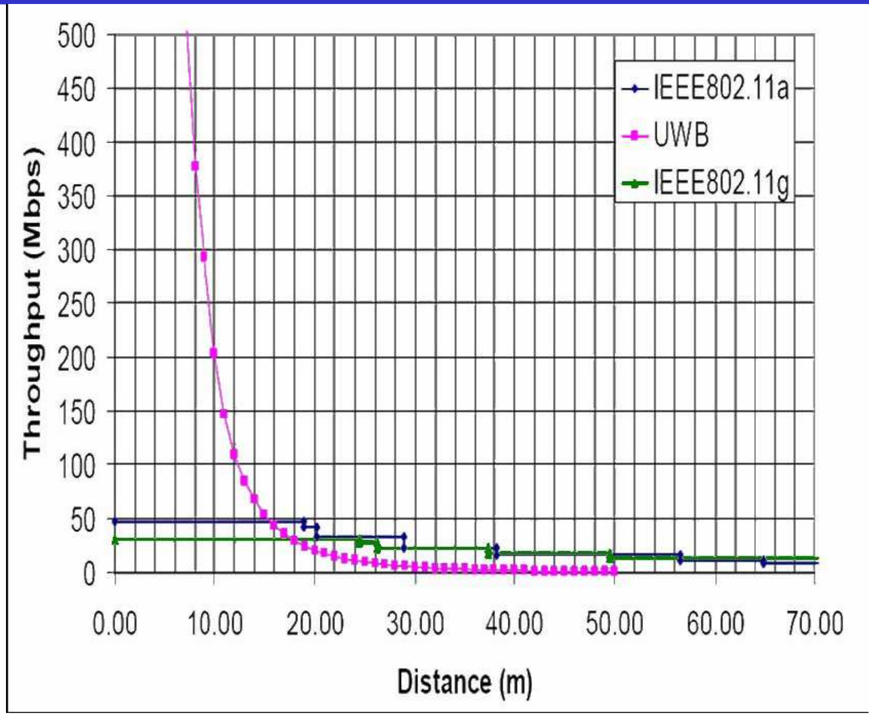
Impulse radio for communications

- *1993: Robert Scholtz wrote the foundation paper of impulse radio (University of Southern California)*
  - *"Multiple Access with Time-Hopping Impulse Radio", Proc. of the IEEE Milcom Conference, Boston, MA, USA, pp 447-450, Oct. 1993.*
- *The main idea is to transmit impulse signal with very low power density spreaded on several GHz and sharing the spectrum with other classical signal, eventually on licensed bands.*

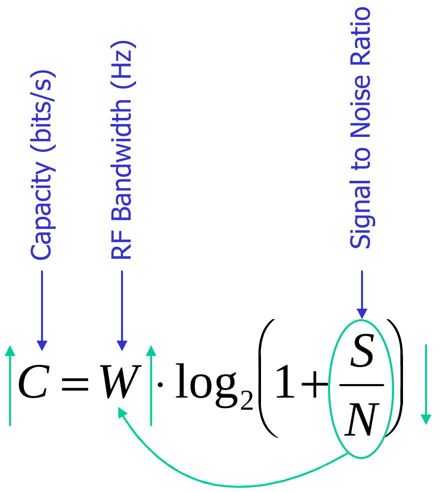


UWB Interest

- Capacity formula edicted by Shannon shows that it varies linearly with BW (log w.r.t. signal power)
- Very low power density enables spectrum reuse
- Capabilities of localization (near radar principle)

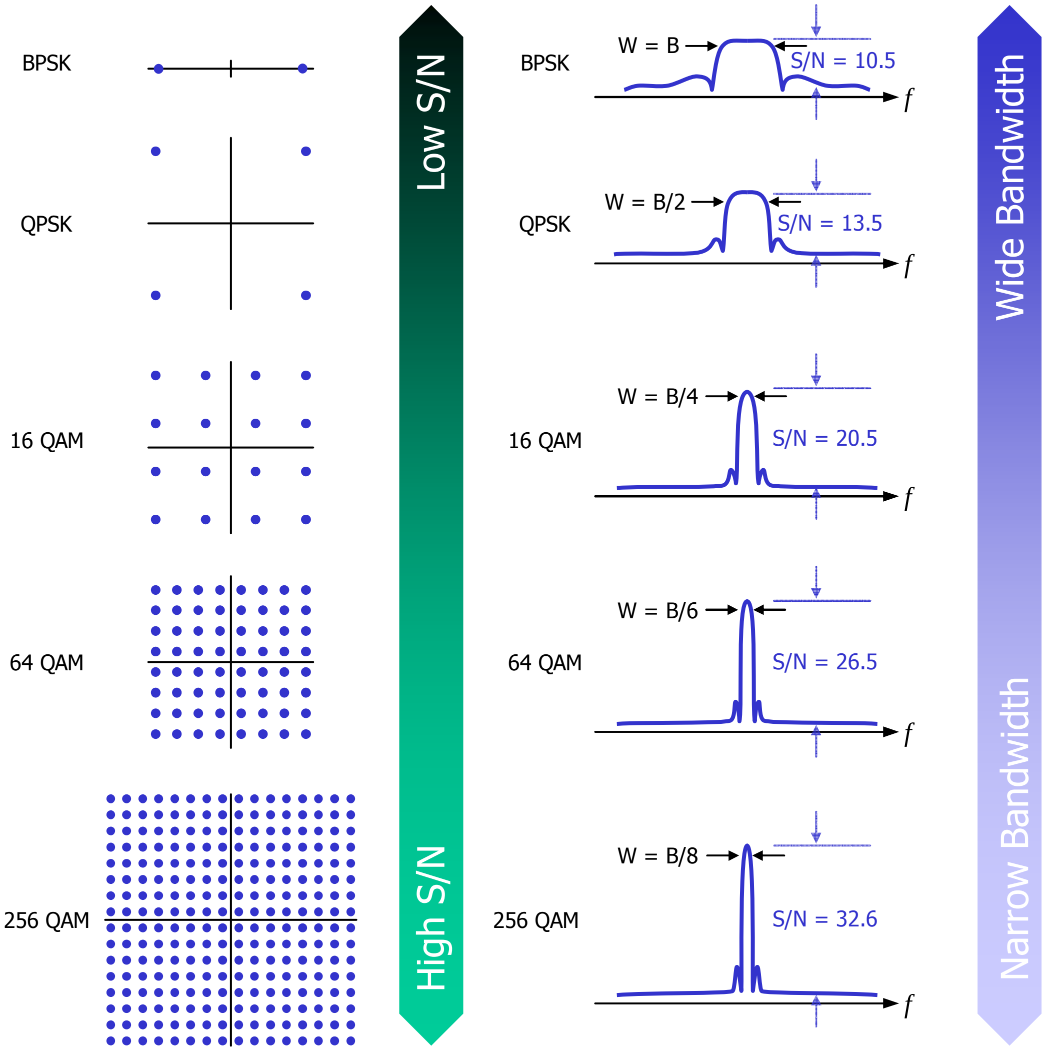


Capacity/ BW / SNR



$$C = W \cdot \log_2\left(1+\frac{S}{N}\right)$$

Low S/N Requires:
Ultra Wide Bandwidths
For High Capacity Data Links



UWB and regulatory

- USA were first at legalizing UWB usage
  - "First Report and Order" Feb 2002
  - UWB signal definition :
    - Instantaneous signal BW > 500 MHz
    - Or fractional BW Fc/B > 25 %
  - Pragmatic approach based on electrical equipment radiated fields
  - [3.1-10.6] GHz emitted band if
    - Mean PSD = -41.3 dBm/MHz
    - Peak PSD = 0 dBm/50 MHz
- Europe and Japan have chosen a more moderate approach, only taking official position at the end of 2006/begin of 2007

Power, PSD, what scale…

The PSD of an UWB signal is limited in mean and peak value:

- Mean PSD corresponds to a 10 dB BW, it varies in 10.log(W)
- Peak PSD corresponds to 3 dB BW, so it varies in 20.log(W)

What does Mean PSD= -41.3dBm / MHz means ?

0 dBm = 1 mW

-41.3 dBm = 7.41x10-5 mW

For a 1.5 GHz band (W = 1.5 GHz = 1500 MHz), an UWB signal must not be more than 0.11 mW mean power

Power, PSD, what scale…

If a pulse of 1 ns is transmitted every 100 ns, peak Power is 11 mW, so a peak Voltage over 50 ohms of:

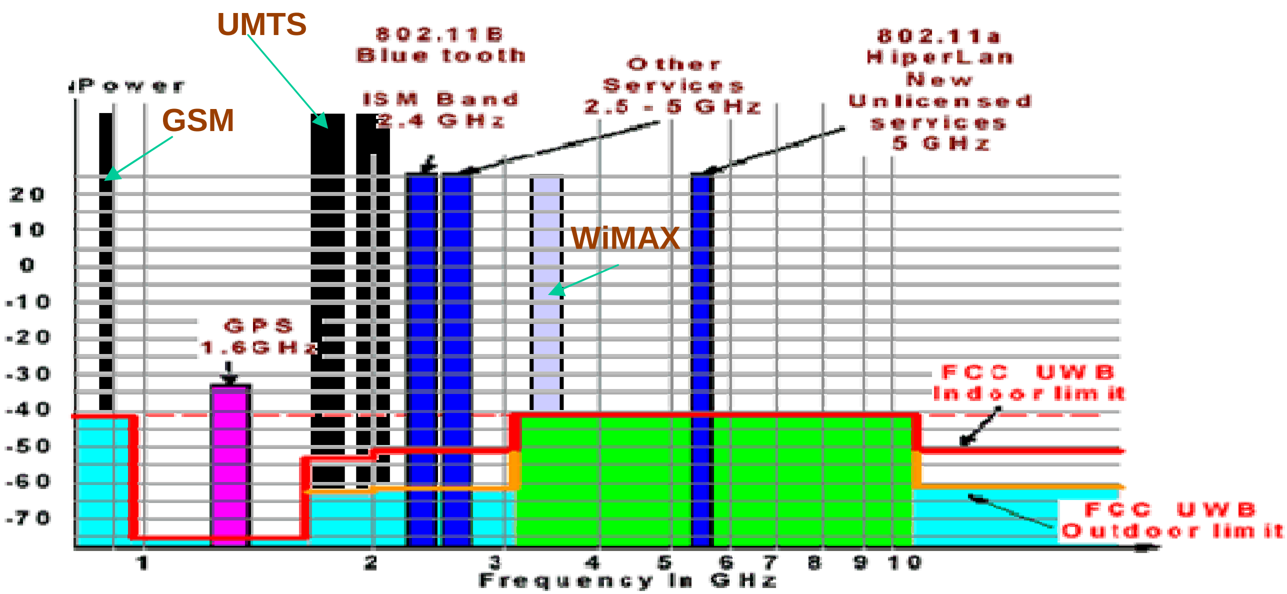
- Pout = 745 mV

Is 0.11 mW compatible with limt of peak power (0dBm/50 MHz) ?

0 dBm/ 50 MHz over 1.5 GHz equals to peak power of 0 dBm+20.log(1500/50) = 29.5 dBm (~1W), so it's OK !

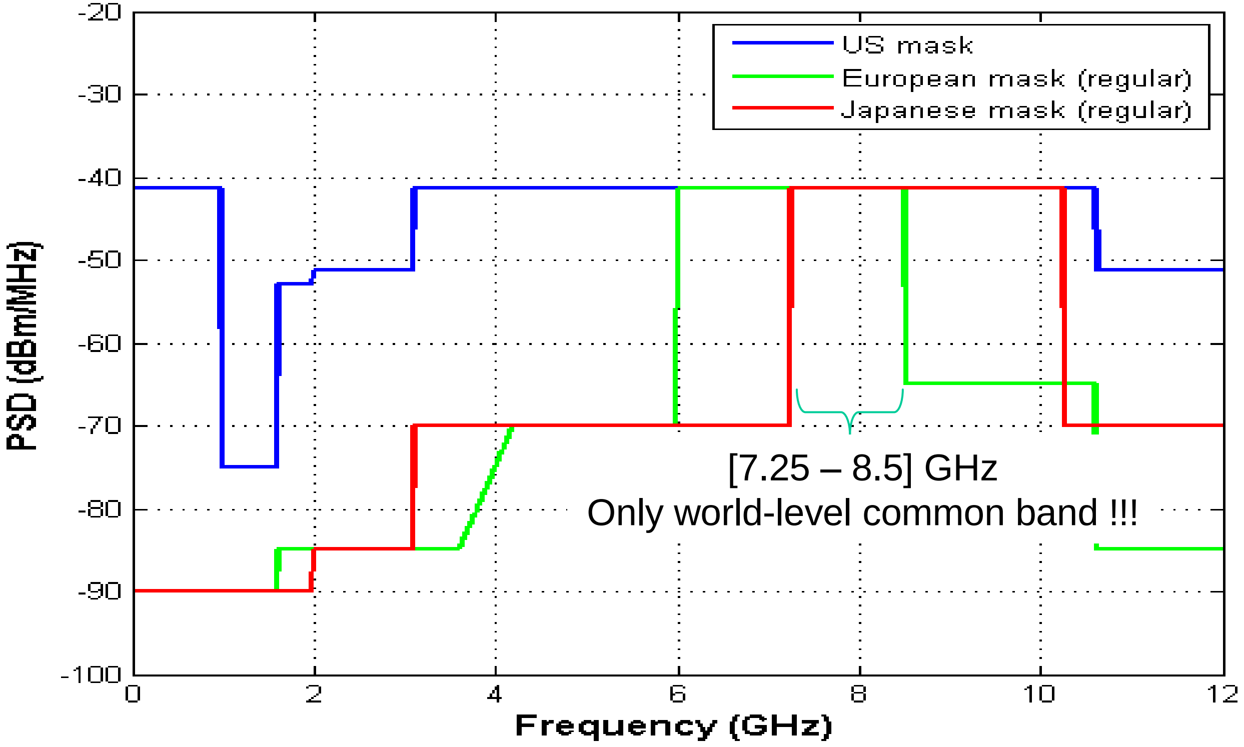
US Emitted Mask

Necessary cohabitation with several existing bands occupied by dedicated services and sometimes sensitive (GPS)



UWB in Europe and Japan

The US approach has been partially followed by other regions (Asia, Europe)

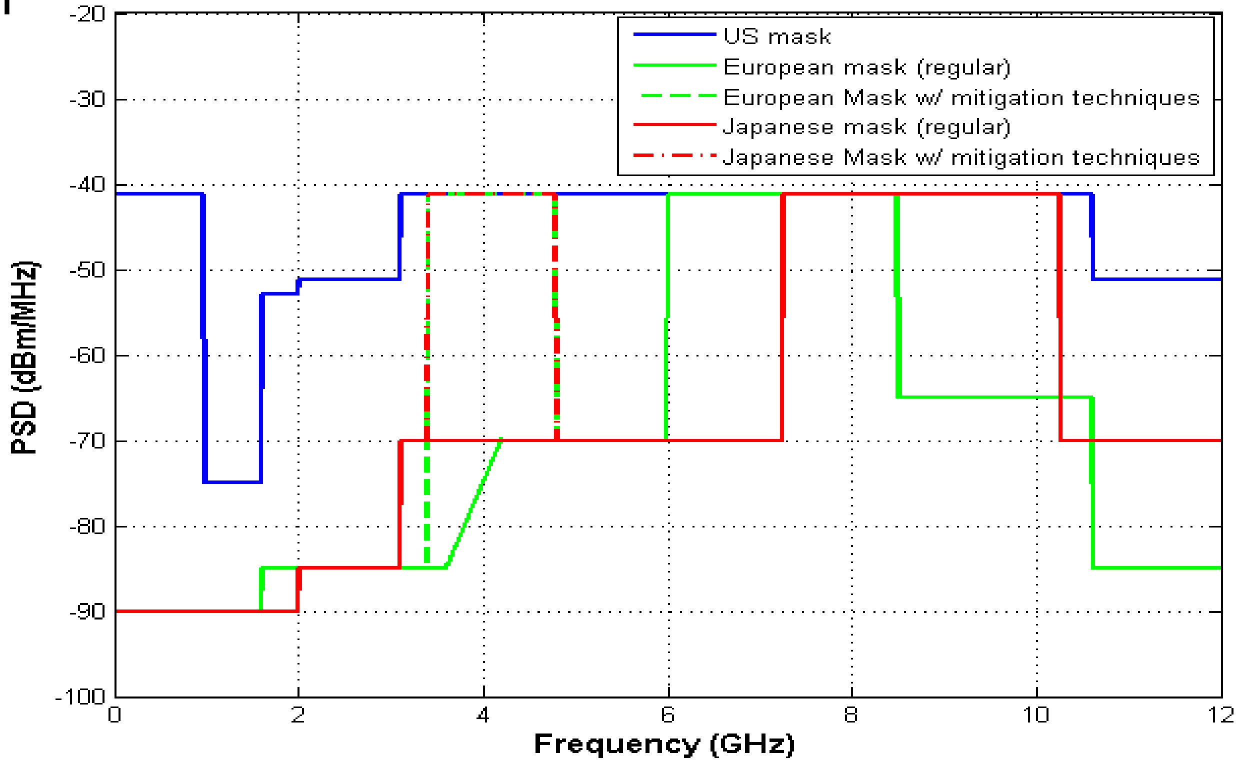


UWB in Europe and Japan

Europe and Japan add an <6 GHz harmonized with US with some restrictions to avoid interference

Constraints (choice)

- Activity Factor (5% over 1 s)
- Detect and Avoid

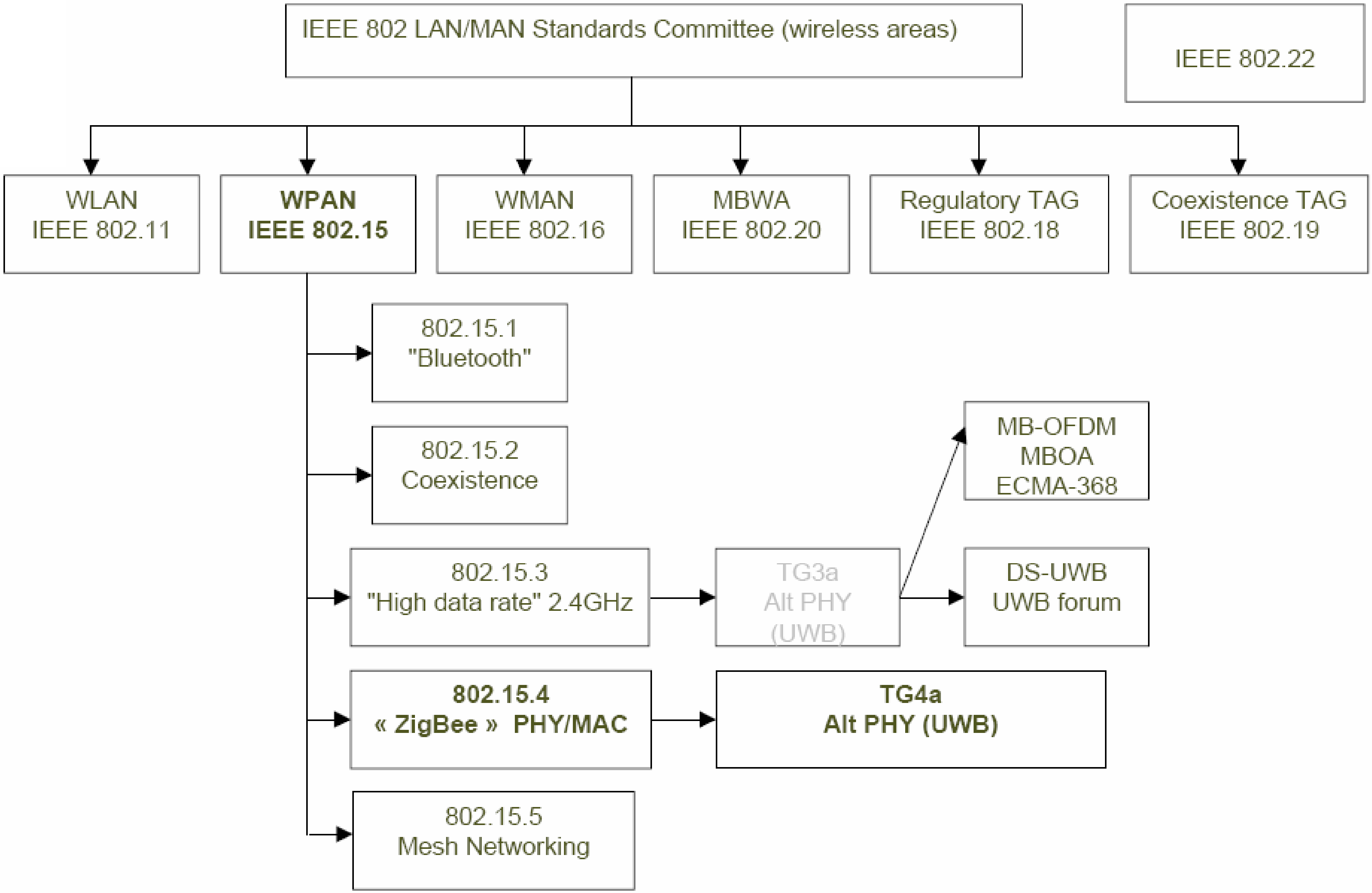


UWB and normalization

For UWB, IEEE has created two working groups:

- 802.15.3a for (very) high datares an (very) short range
  - 110 Mbps at 10 m up to 480 Mbps at 2m (wireless USB)
  - 2 concurrent proposal:
    - DS-UWB (supp. Freescale-Motorola)
    - MB-OFDM (Philips, TI, ST, Sony)
  - WG was suppressed because no consensus was found
  - OFDM work reuse by the WiMedia industrial alliance
  - DS-UWB was discarded
- 802.15.4a to publish a standard for low rate applications with very low energy (~Zigbee)
  - Several decades of kbps@30m and localization capabilities
  - UWB is one of possible PHYs

IEEE 802.15 Standards

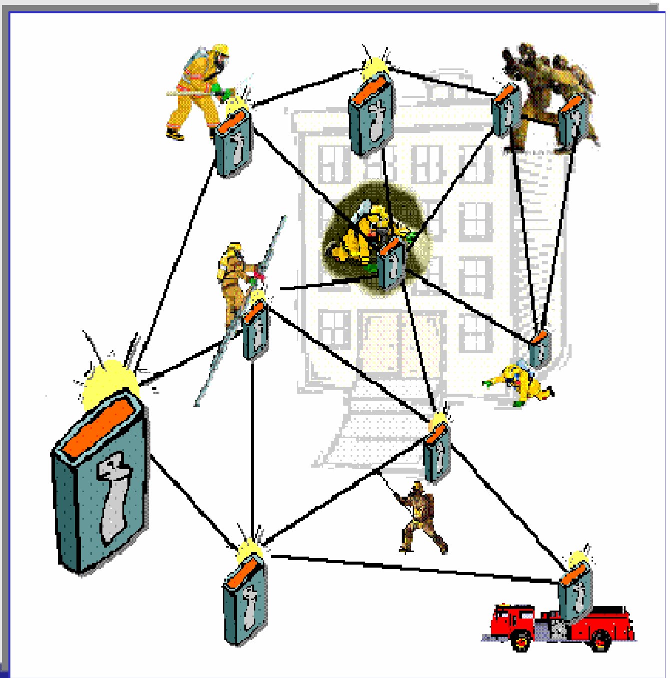


IEEE 802.15.4a

Standard in development: IEEE 802.15.4a

– *Applications : sensor networks*
  - *Safety / Health Monitoring*
  - *Personnel Security*
  - *Logistics*
  - *Industrial inventory control*
  - *Industrial Process Control and Maintenance*
  - *Home Sensing and Media Delivery*

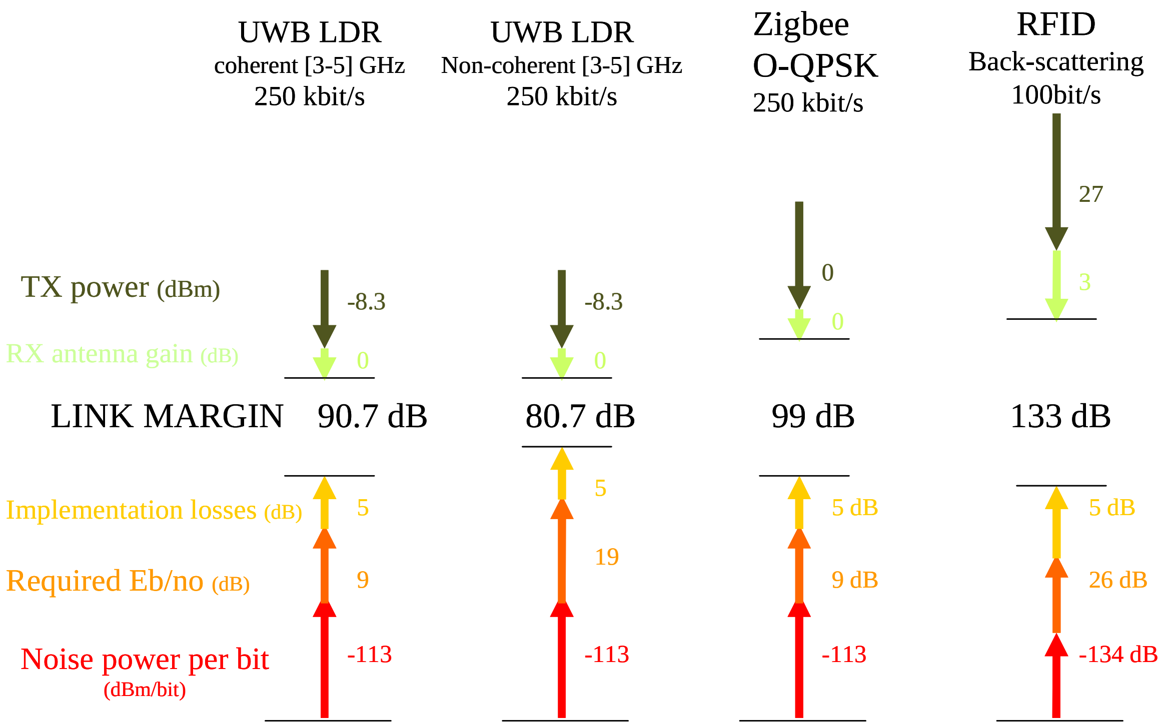
– *Principles Technical Requirements :*
  - *Bit Rate: few kbps up to 100kbps for node2node communications*
  - *Range: 0 – 30 m - Indoor/Outdoor and LOS/NLOS channels*
  - *Power Consumption: Battery life of months or years*
  - *Localization Awareness: from tens of cm to 1m precision*
  - *Mobility: industrial vehicle or higher speed*



Source: CEA-LETI

***Key words* : low power and localization capability**

Comparison UWB-Narrow band



UWB makes possible to take benefit from high temporal resolution :

=> low small scale fading margin(<2dB) in comparison with narrow band system (20 dB)

=> Facilitate TOA estimation for localization

Source: CEA-LETI

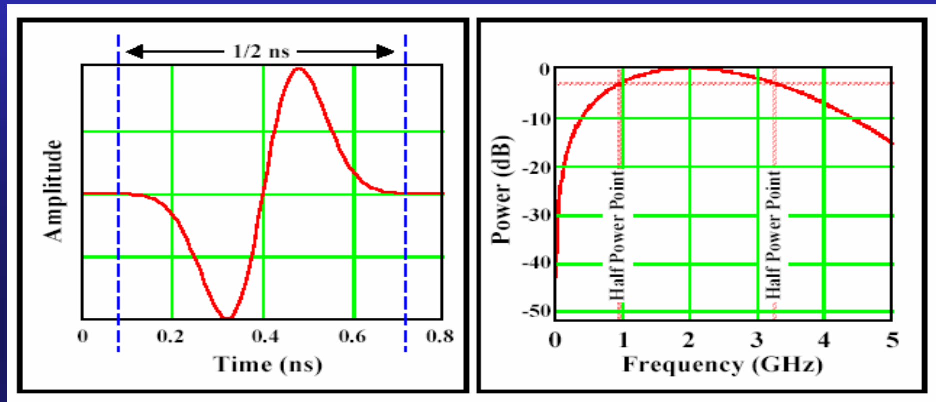
UWB Impulse radio

UWB Impulse Radio (IR)

- *Radiate very short pulses with a duty cycle very low (<1%) on a very wide BW*
- *Work with low power*
- *Ability of transmitting several pulses for a single symbol*
- *Mean PSD allowed is equal to that of jamming radiation of electrical equipments*
- *Radiated pulses could be directly in baseband ➡ no complex architecture integrating an oscillator and a mixer for frequency translation*

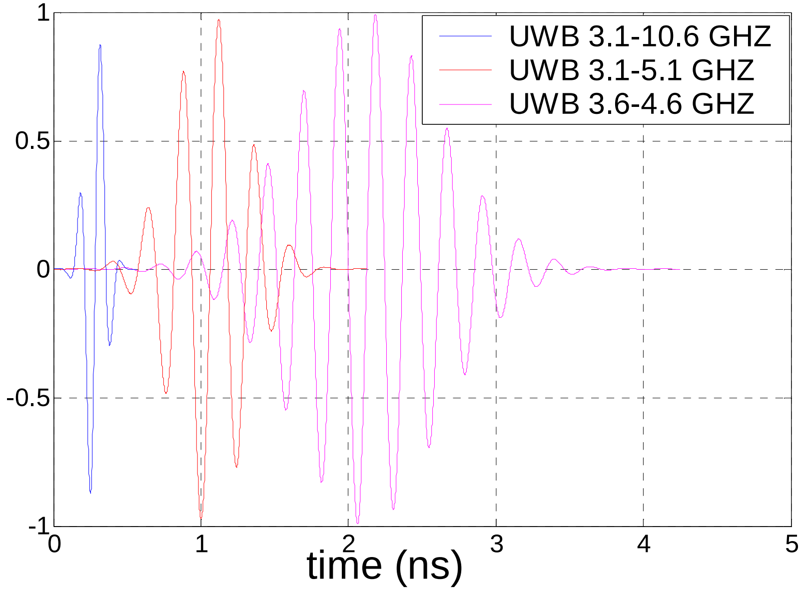
Fundamental Pulse

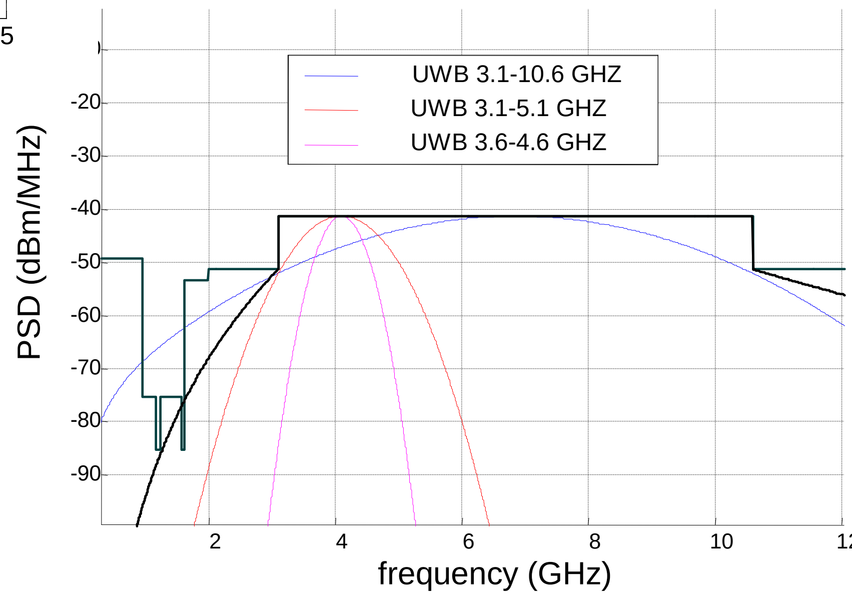
- *Starting point (Scholtz): derivation of a gaussian*
  - *10 dB BW= 116% of fc*
  - *Pb: does not fit FCC mask*



- *Other solutions:*
  - *Windowing of a sinusoid*
  - *Filtering of a pulse front by a filter corresponding to the FCC mask*
  - *500 MHz pulse (relaxed constraints) translated in frequency with oscillator and mixer: interesting for multi-band systems*

Examples depending on BW



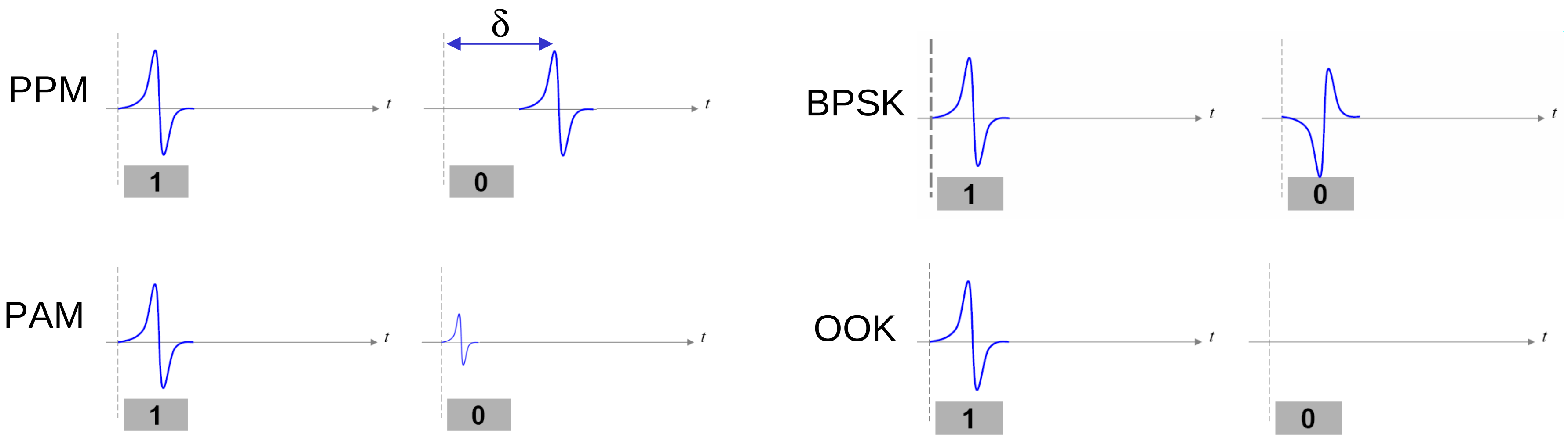


Source: CEA-LETI

Modulation

To modulate a symbol, once can modify:

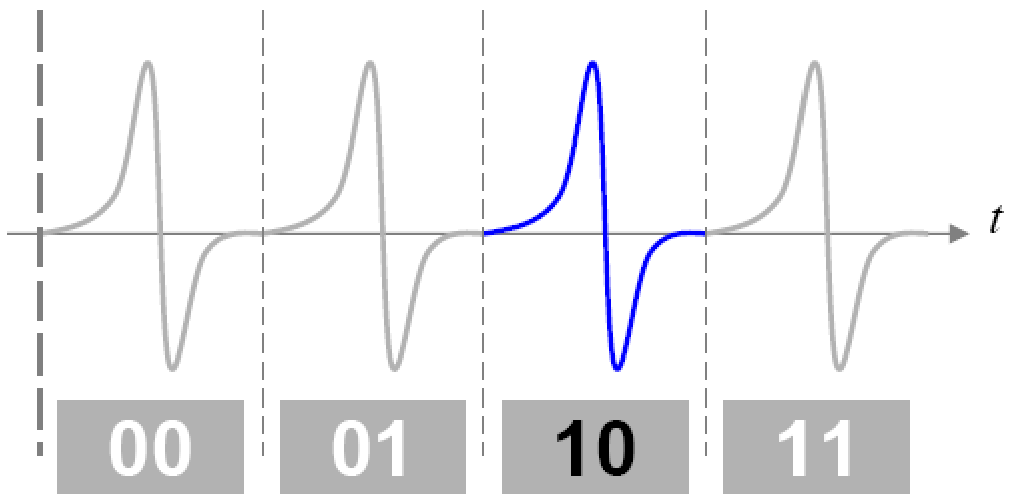
- *Its position in time (PPM, pulse position modulation)*
- *Its amplitude (PAM, pulse amplitide modulation)*
- *Its phase (BPSK, binary phase shift keying)*
- *Its presence or absence (OOK, on-off keying)*



Modulation

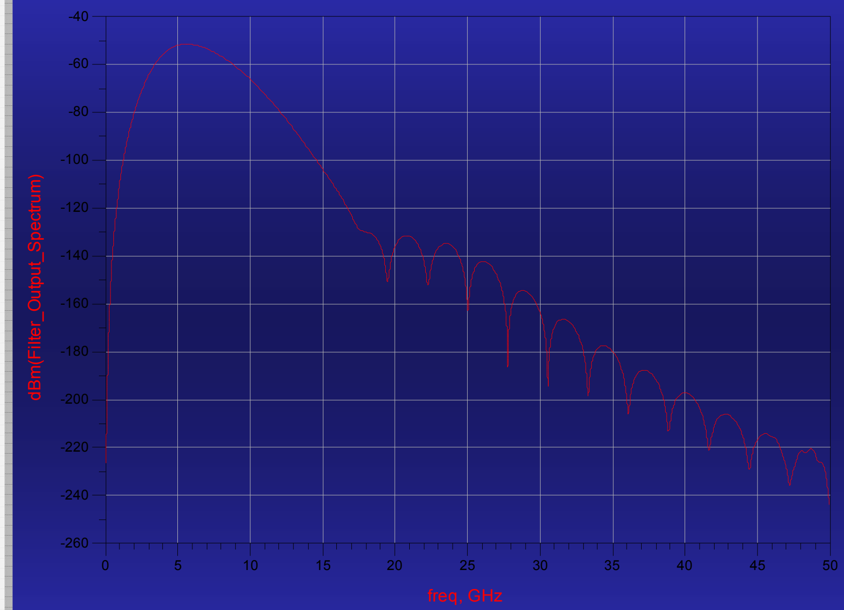
M-ary modulations are also possible, allowing higher datarates, decreasing robustness

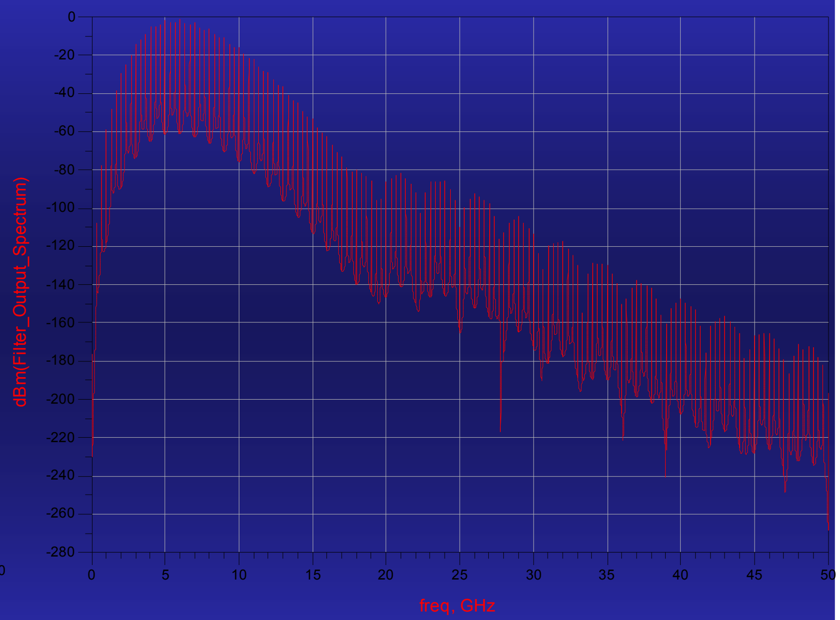
- *4PPM*
- *Combination of M-PPM and BPSK*



Pulse repetition

Pb: a pulse signal with PRP sec. delay, render diracs in spetrum spaced by 1/PRP Hz. These diracs could overcome PSD limit allowed.



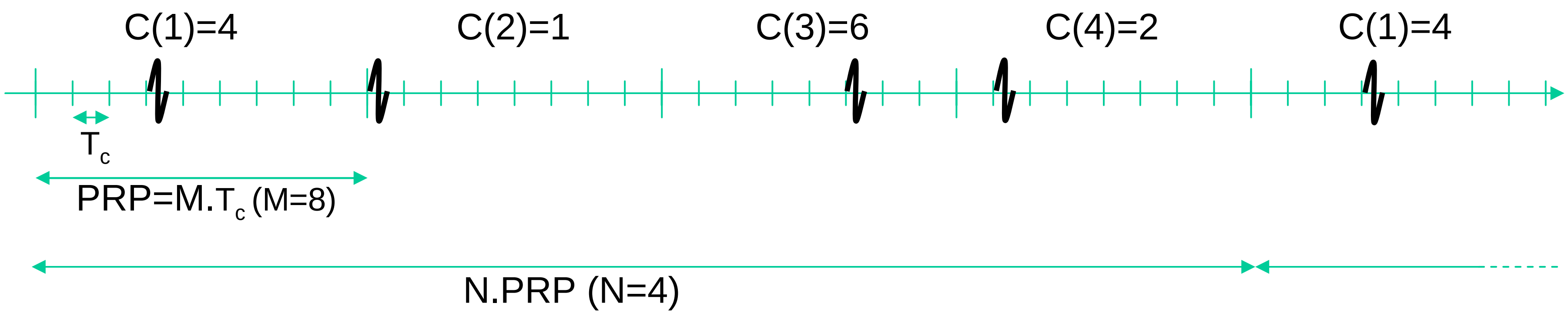


Solutions:

- *Use of BPSK to change pulse phases*
- *Find a way of breaking this repetition by a code of time hopping (TH)*

Time Hopping (TH) and UWB-IR

- *Like CDMA, a code is assigned to each communication*
- *This code is used to calculate time position of each pulse in PRP*
- *If $\{c(i)\}_{1<i<N}$ is TH code and $\forall i$, $c(i) \leq M$, the code is said M-ary of length N*
- *For $j \leq N$, position(j) = jxPRP + c(j)xTc with Tc is M^{th} of PRP*



TH advantages for UWB-IR

- *TH allows a smooth spectrum*
- *It also allows multiple access as CDMA*
  - *Users have different codes, known by the receiver, and collision probability of two pulses from two different users is very low*
  - *Probability of randomly choose 2 codes minimizing interference between 2 users rises to 1 when M is high*
- *Moreover it allows isolating independent networks using different codes*
  - *Inside a network, TDMA could be used*
  - *Constraint on generating several orthogonal codes is relaxed*

Possible implementation of TH

In practice, a symbol is coded by several tranmsitted pulses

- *If N pulses code a symbol, time = N. PRP*
- *Simpliest coding is repetition of symbol value*
  - *'1' -> '11111111' and '0' -> '00000000' for N=8*
  - *Words coding symbols are modulated in PPM, BPSK, OOK, etc.*
- *Possibility of using a real channel coding if N sufficiently high*

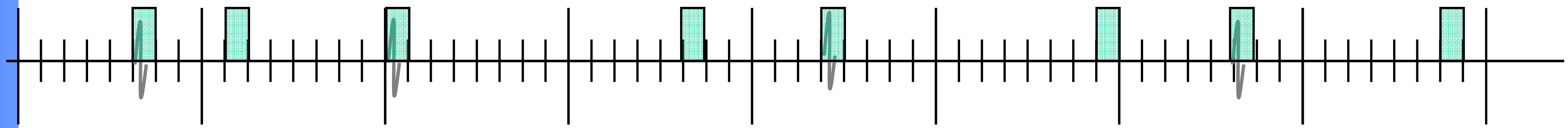
TH code is applied on symbol basis

- *Random generator resets each symbol time*

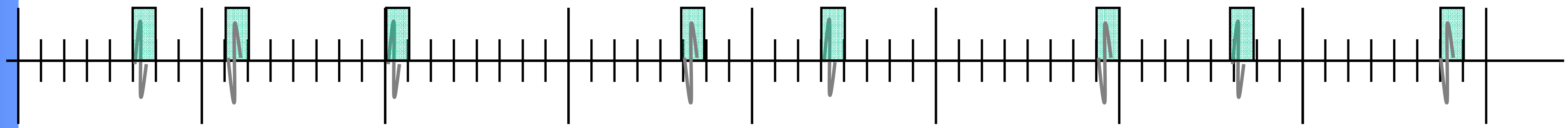
Examples

Transmission of symbol '1', coded by '10101010' with TH code {6,2,1,6,3,8,6,7}

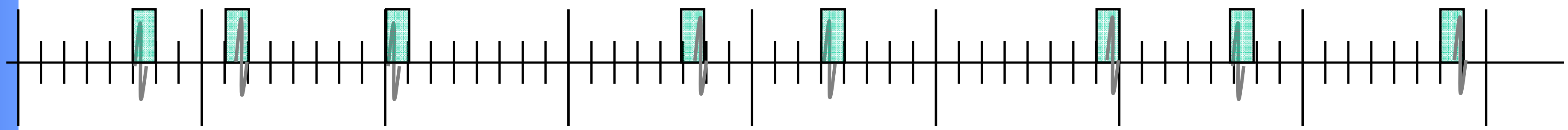
OOK



BPSK



2-PPM



UWB radio channel

UWB Channel Characteristics

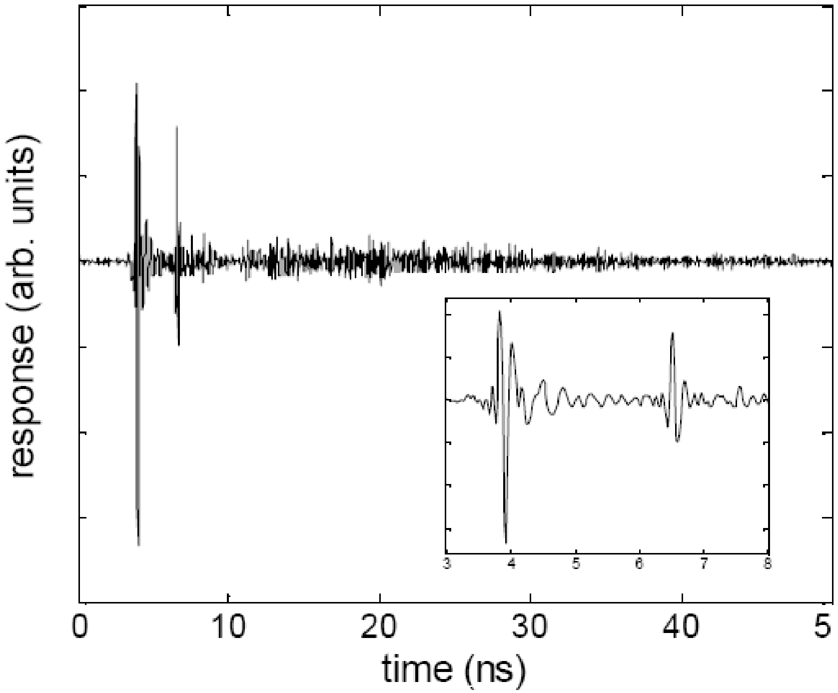
Rem: more signal BW is wide, more temporal resolution is high ➡ ability to separate close propagation paths

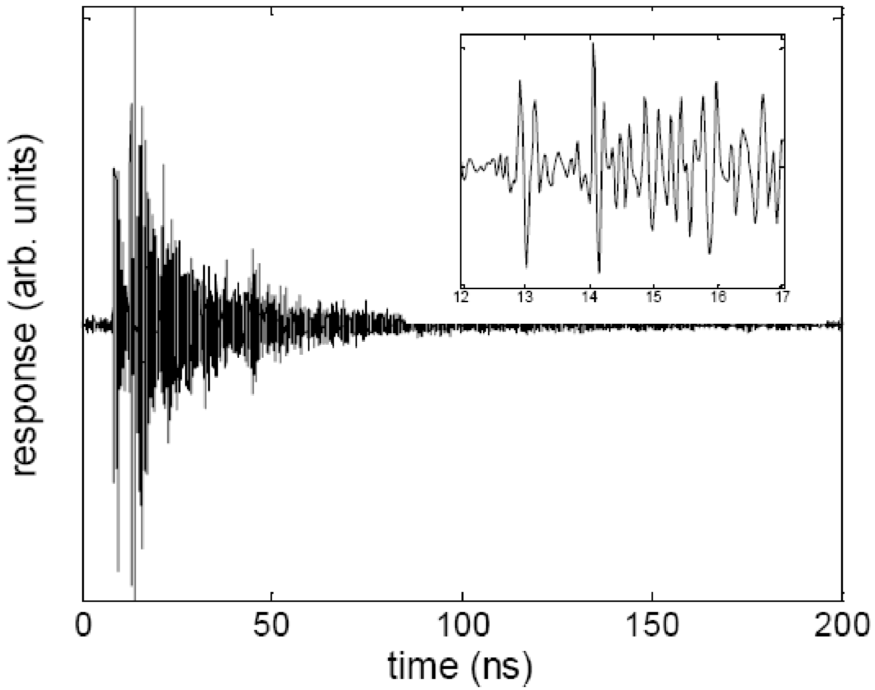
UWB channel models are characterized by a high number of separate propagation paths

- *Time spread of different paths is very long*
- *Energy is spreaded on every paths, each one being individually very low energy*
- *What strategy to recover a significant part of energy ?*

UWB Channel Characteristics

Channels with LOS and NLOS





Dimension order

By channel model (CM), related to environment type

- *Number of paths at 10 dB bellow highest (dominant path)*
- *Number of paths containing 85 % of total energy*
- *Mean delay spread*
- *Pathloss exponent*

Modèle de canal	Type de canal	$Npaths_{-10dB}$	$Npaths_{85\%}$	$\Gamma(ns)$	n
CM1	LOS résidentiel	17	55	16,4	1,79
CM2	NLOS résidentiel	37	115	18,5	4,58
CM3	LOS bureaux	22	45	11,5	1,63
CM4	NLOS bureaux	60	128	13,3	3,07
CM8	NLOS industriel	392	1134	88,8	2,15

Channel impact on transmission scheme

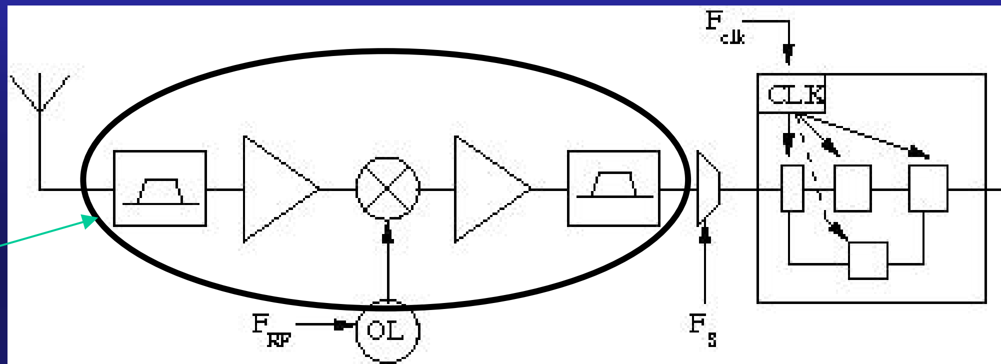
- *For interference limitation between pulses (pulse ovelap) and receiving operation simplification, PRP must be longer than channel spread*
- *Taking TH code into account must guarantee that the minimum gap between 2 pulses inside a symbol keeps bellow channel spread*
- *Impact on datarate:*
  - *Realistic channel spread = 80 ns*
  - *PRP real = 160 ns*
  - *Pulse rate = 6.25x106 pulse/s*
  - *For 8 pulses per bit = 780 kbits/s*
  - *Respecting european regulation for [3.4-4.8] GHz band which imposes a duty cycle of 0.5% on an hour => 4 kbits/s*

UWB receiving architecture

Basic concept

A traditional narrow band system with carrier (GSM, WiFi, UMTS, etc..) realizes a very fine frequency filtering over the channel to demodulate

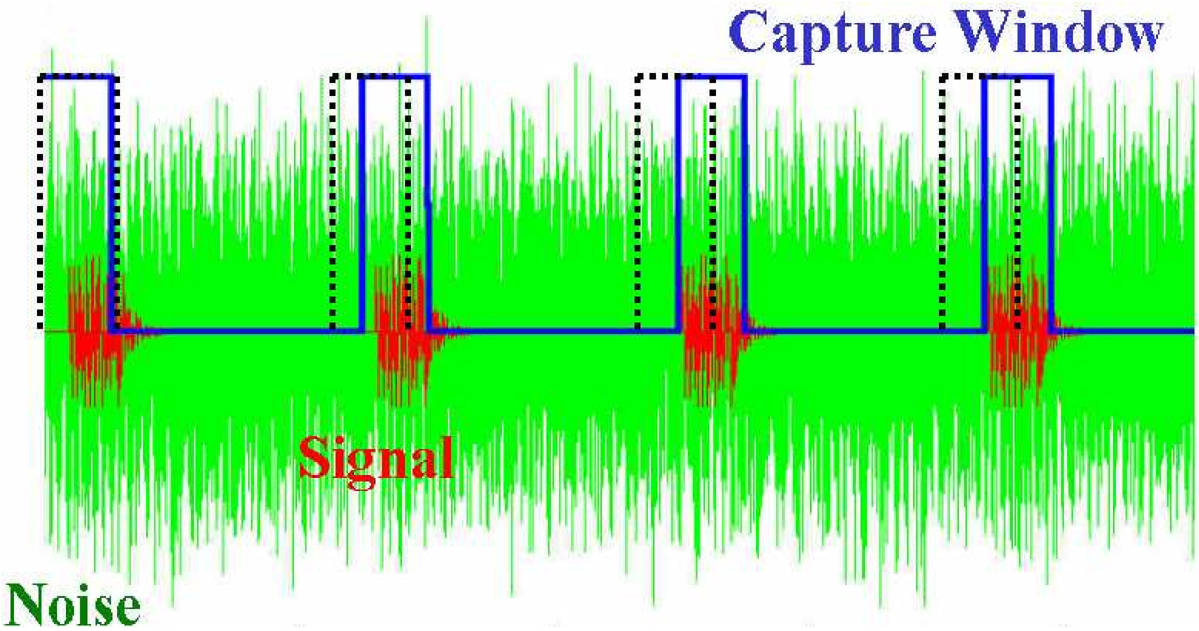
Frequency isolation of used signal



An UWB-IR system performs a very fine temporal filter over pulses to receive

- *Knowing TH code allows, when synchronization is done, to open the receiver to detect each pulse*

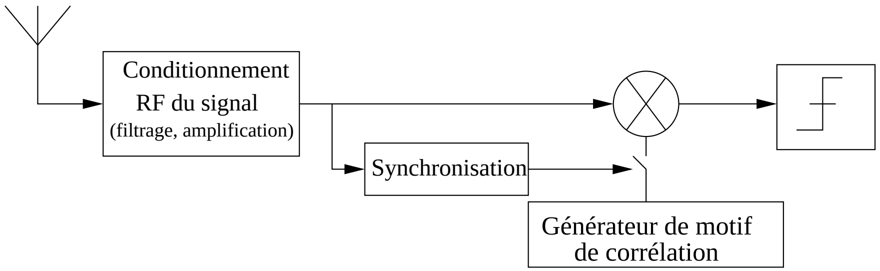
Basic concept

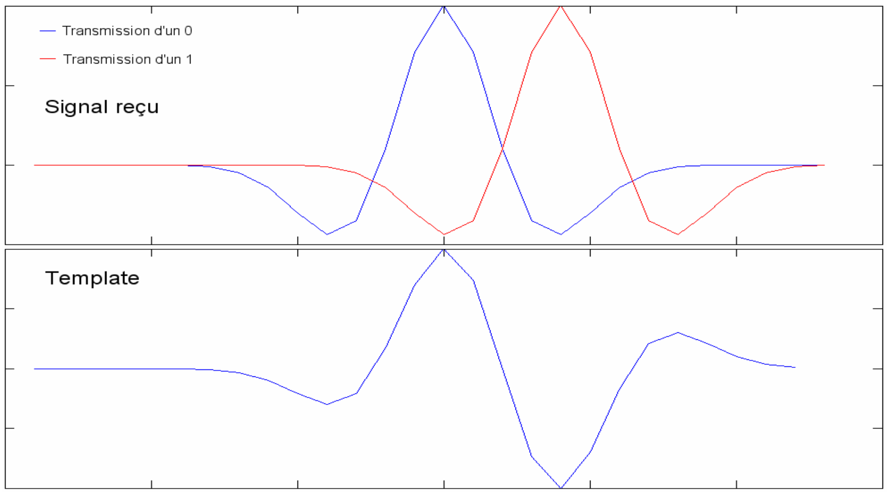


2 kinds of receivers

Coherent receiver

- *Receiver signal multiplied by a refrence signal allowing demodulation*
- *Performance highly dependent on the exact time of multiplication*





Pattern for 2PPM

Coherent receiving- constraints

Pulse shape (1.5 GHz baseband in [3.1–4.6] GHz)

"half-period" of pulse ~100 picosecondes

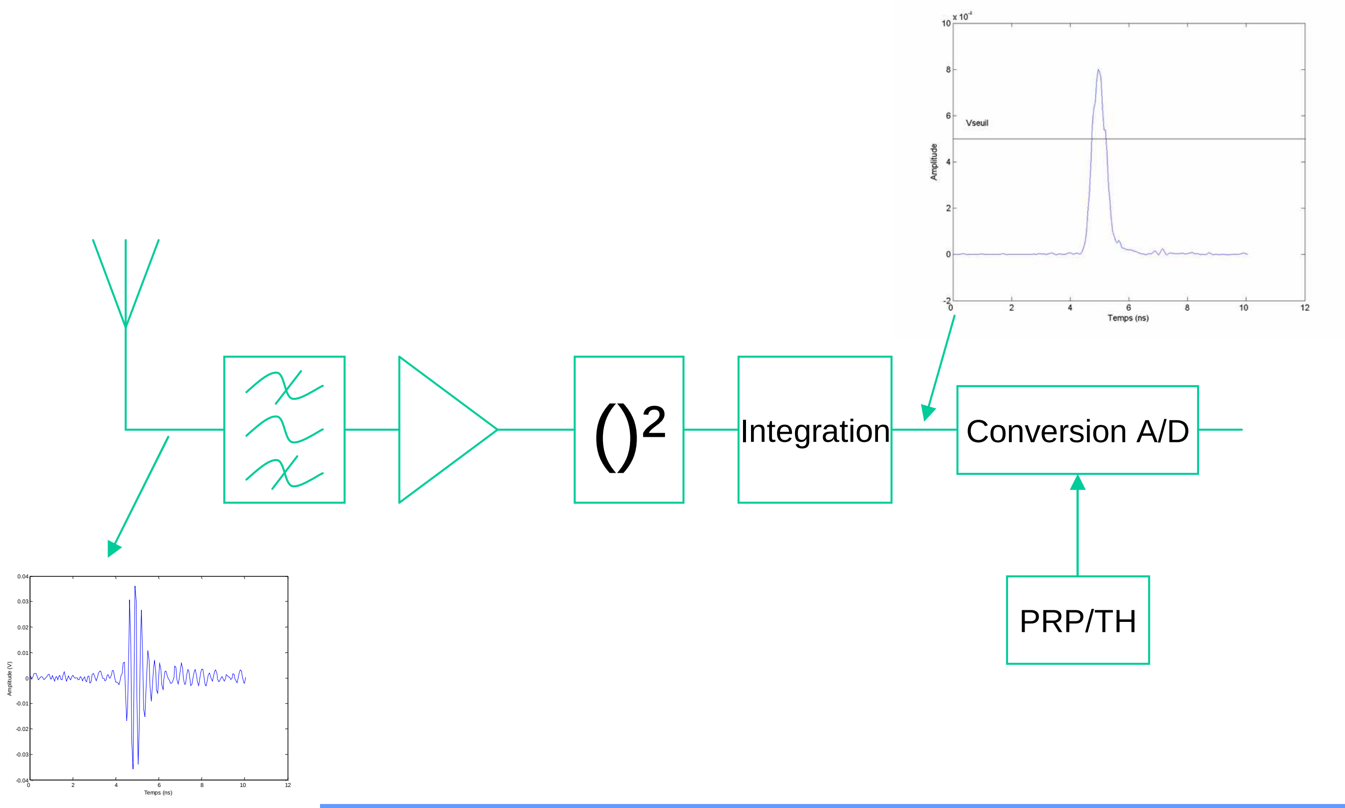
An error of 100 picoseconde equals to multiply 2 signals in quadrature -> results near to zero

Very high constraints on synchronization

Moreover, needs of multi-path processing to recover enough energy

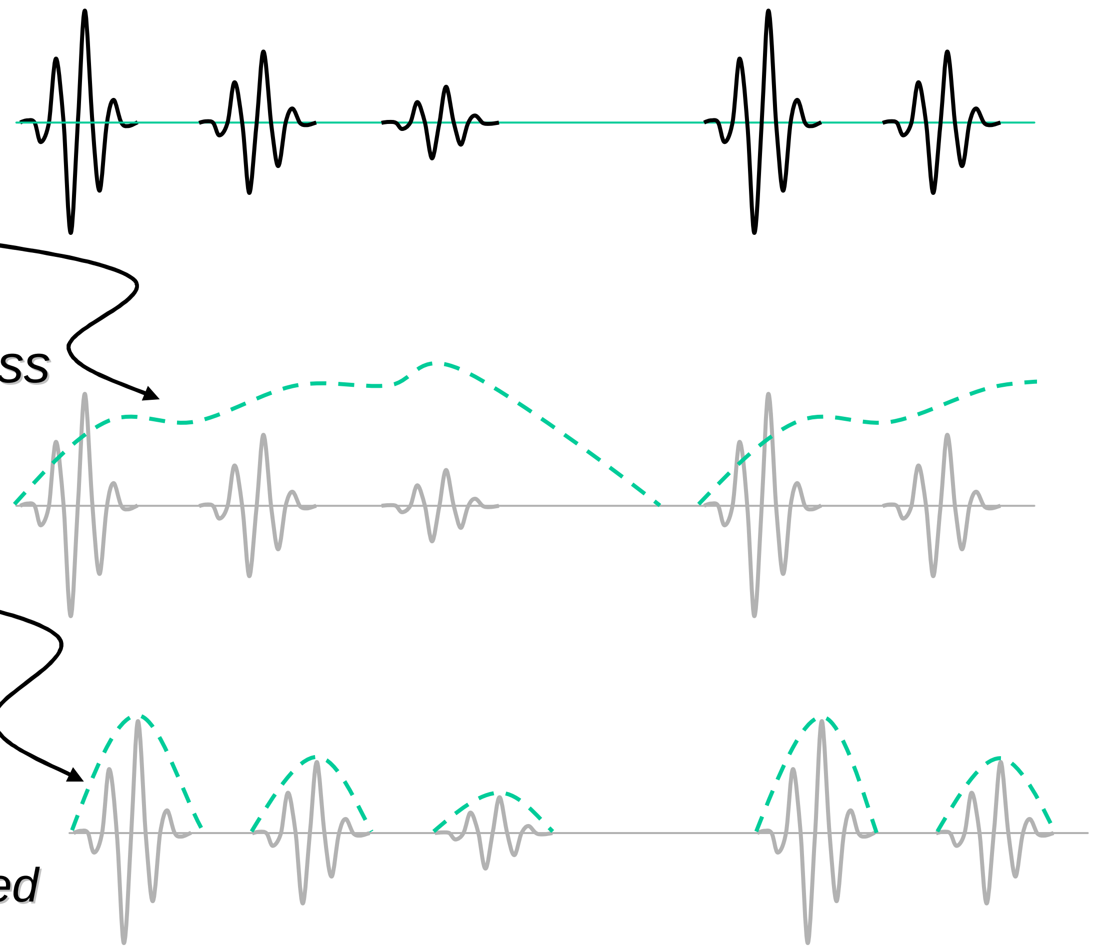
Non-coherent architecture

- *Based on energy detection (incompatible with BPSK)*
- *Big advantage: relaxes cosntraints on synchronization*



Non-coherent architecture

Time constant of filter τ could be chosen like this:



Received signal

Energy accumulation

- *$\tau \approx$ channel depth*
- *Temporal resolution loss*
- *More noise sensitive*

Energy detection

- *$\tau \approx$ pulse width*
- *Multi-path processing*
  - *Localization*
  - *Rake receiver required*
  - *Difficulty: lot of paths*

Non-coherent architecture

- *Integration in detector output could be done based on time spread of channel to aggregate energy*
- *A/D based on PRP and TH code allows to measure energy at the expected time and demodulate*
- *A simple comparator is sufficient*
- *Main drawback: lower performances than coherent one*

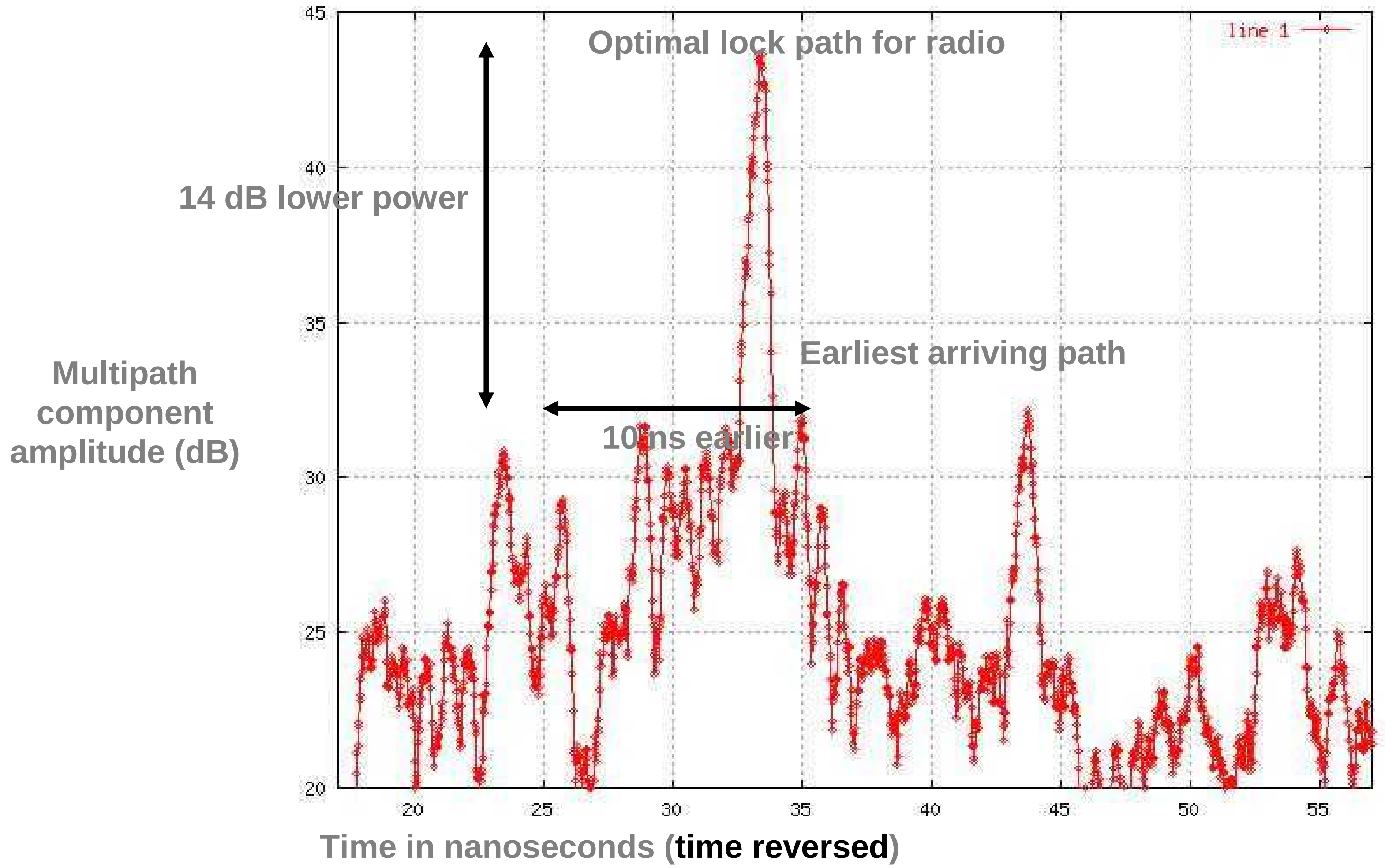
UWB localization

- *More than localization, it corresponds to distance measurement between two nodes to allow localization by an apllication*
- *Distance measurement is relative to the flying time of the wave (direct path)*
- *More BW is wide, more precise the measure will be :*
  - *Bw = 1 GHz -> t = 1 ns -> d = 30 cm*
- *UWB theoretically allows precise localization in buildings*

Distance evaluation technics

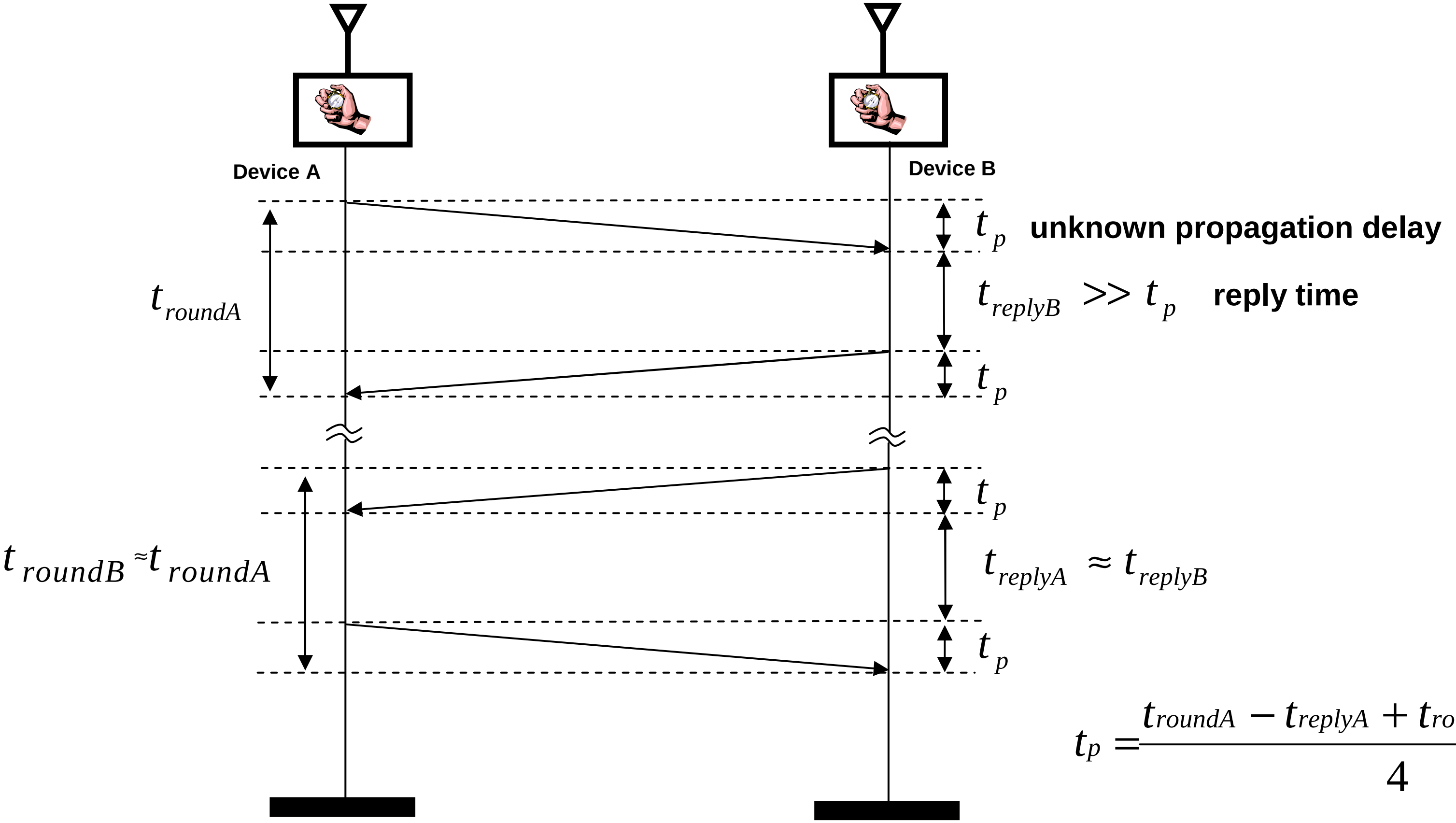
- *Lots of techniques, we detail two:*
  - *Two-Way Ranging : packets exchange between two nodes to estime flying time*
  - *Differential Time of Arrival : several synchronized nodes cooperate to compare time of arrival*
- *Whatever the technique, it supposes to transmite enough energy to compensate loss between firts path and dominant path (transmission of a long packet)*

Distance evaluation technics



Two way ranging

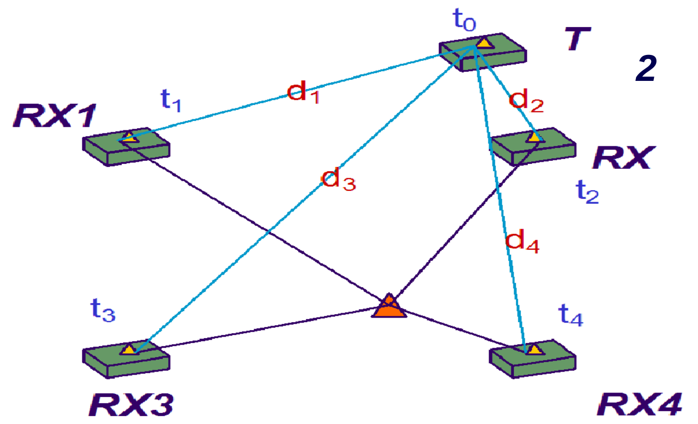
- Specification of a commutation time to wait between packets reception and response (t_{reply})



$$t_p = \frac{t_{roundA} - t_{replyA} + t_{roundB} - t_{replyB}}{4}$$

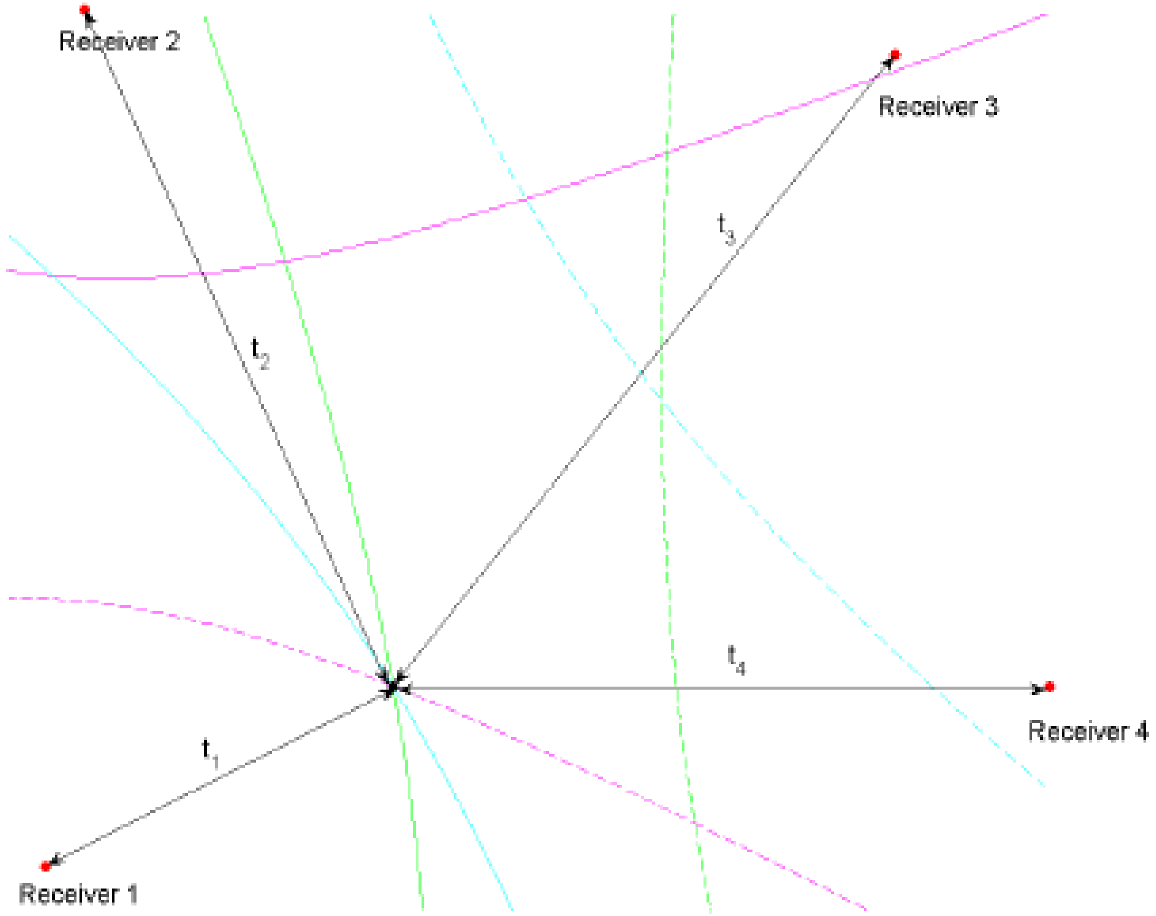
TDOA

- *T send a pulse at t_0, detected at t_i at receiver RXi.*
- *While receivers are synchronized, we take an RX as refrence (here RX1) and then*
  $c.t_{1j} = d_1 - d_j = [(t_1 - t_0) - (t_j - t_0)].c$
- *With 3 calculated distance, we could trace 3 hyperboles (with RXi focal points), with intersection at T position*



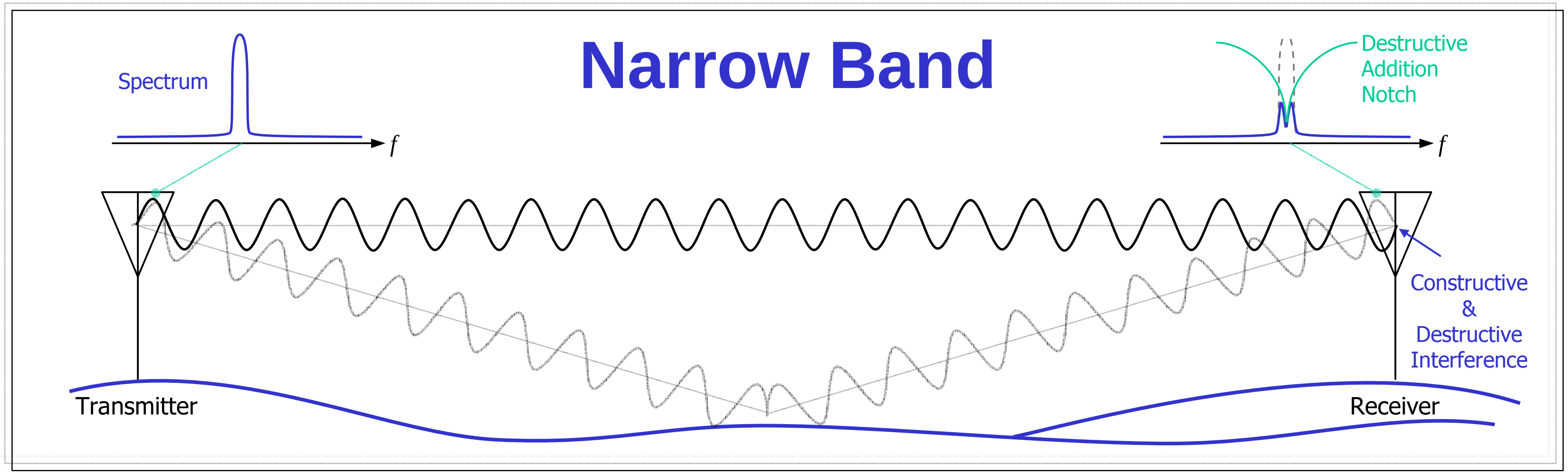
$$c \cdot t_{ij} = \sqrt{(X_i - X_M)^2 + (Y_i - Y_M)^2} - \sqrt{(X_j - X_M)^2 + (Y_j - Y_M)^2}$$

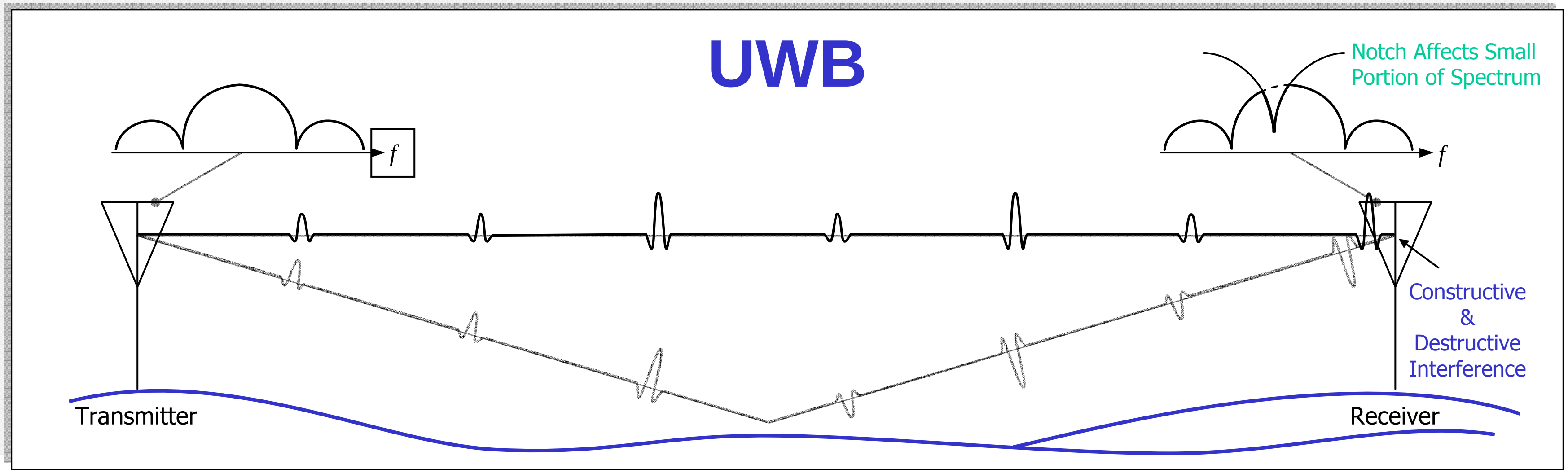
TDOA



UWB MB-OFDM

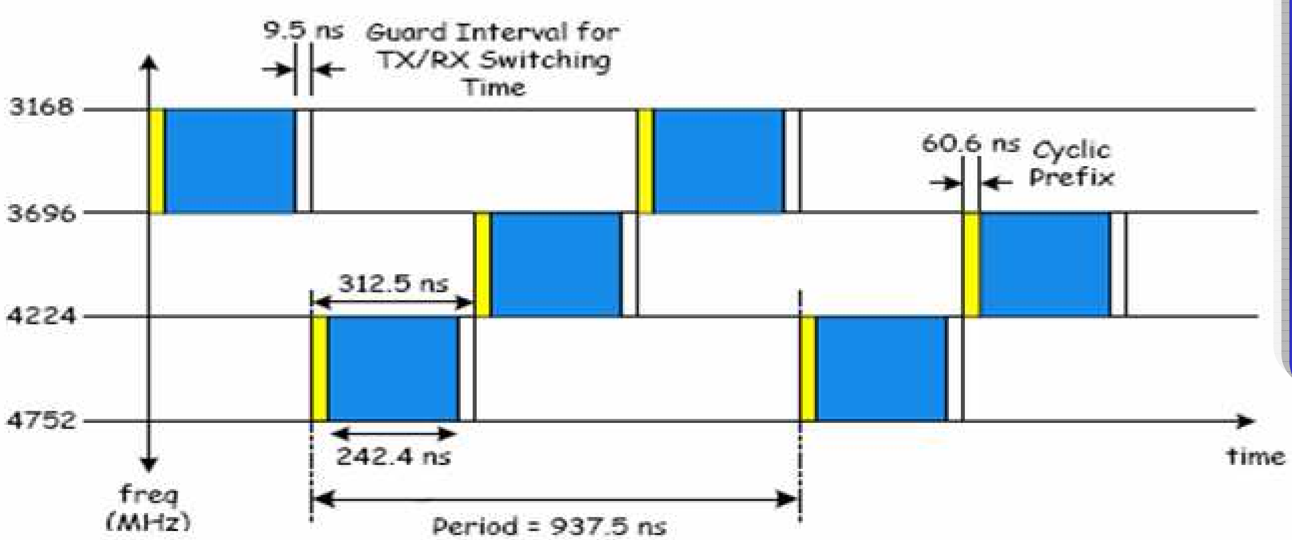
Multi-Path & Interference Immunity





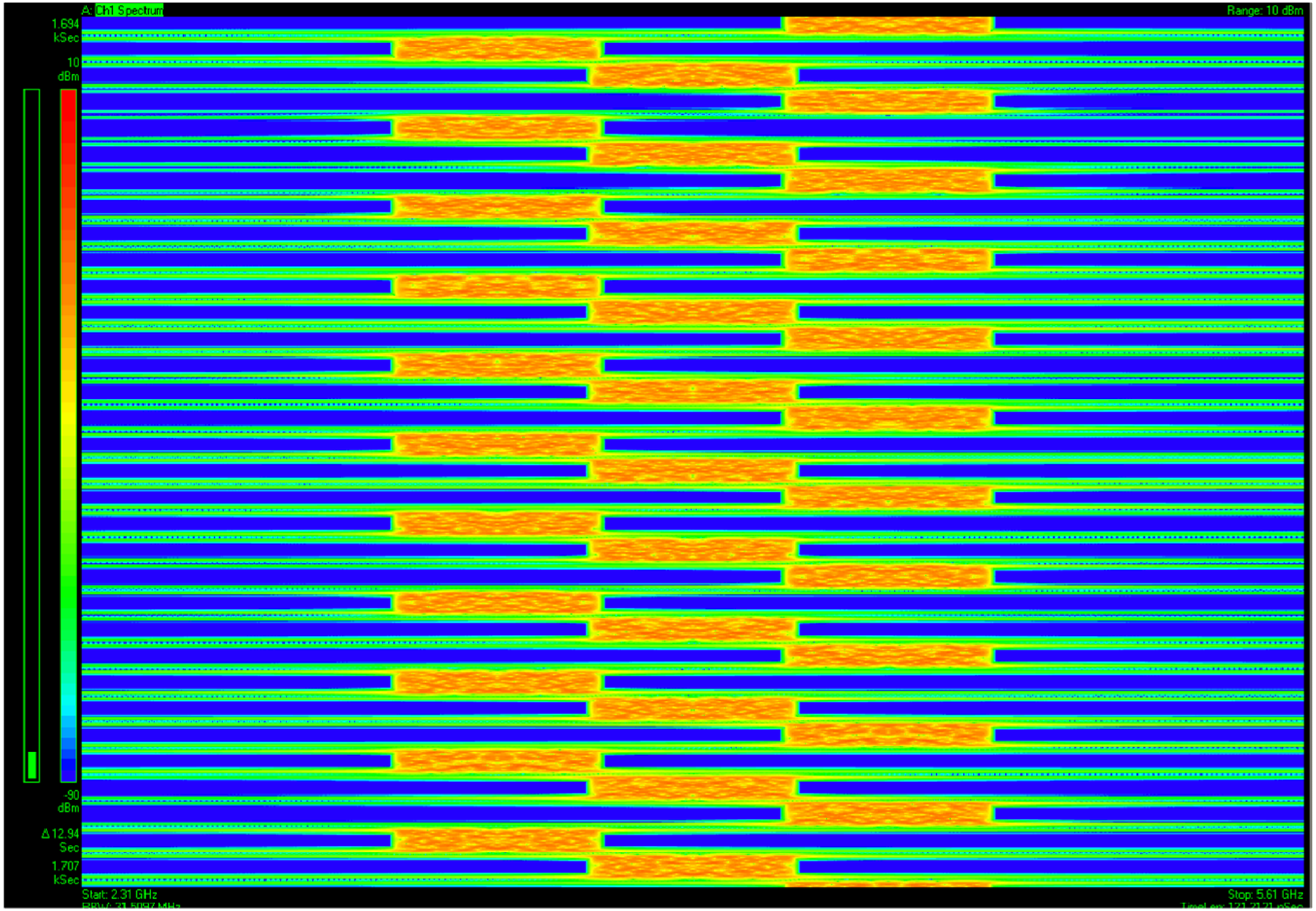
MB-OFDM principle

- *Spectrum divided in 528 MHz bands (difficult to modulate 1.6 GHz)*
- *OFDM modulation of information in each band*
  - *FFT 128*
  - *QPSK modulation on subcarriers*
- *Information is coded on each bands to exploit frequency diversity and combat multi-path*



CP of 60.6 ns

9.5 ns GI for inter-band commutation


A: Ch1 Spectrum
Range: 10 dBm
1.694 kSec
10 dBm
-90 dBm
Δ 12.94 Sec
1.707 kSec
Start: 2.31 GHz
Stop: 5.61 GHz

MB-OFDM tradeoff

OFDM technique: good performances in multi-path conditions

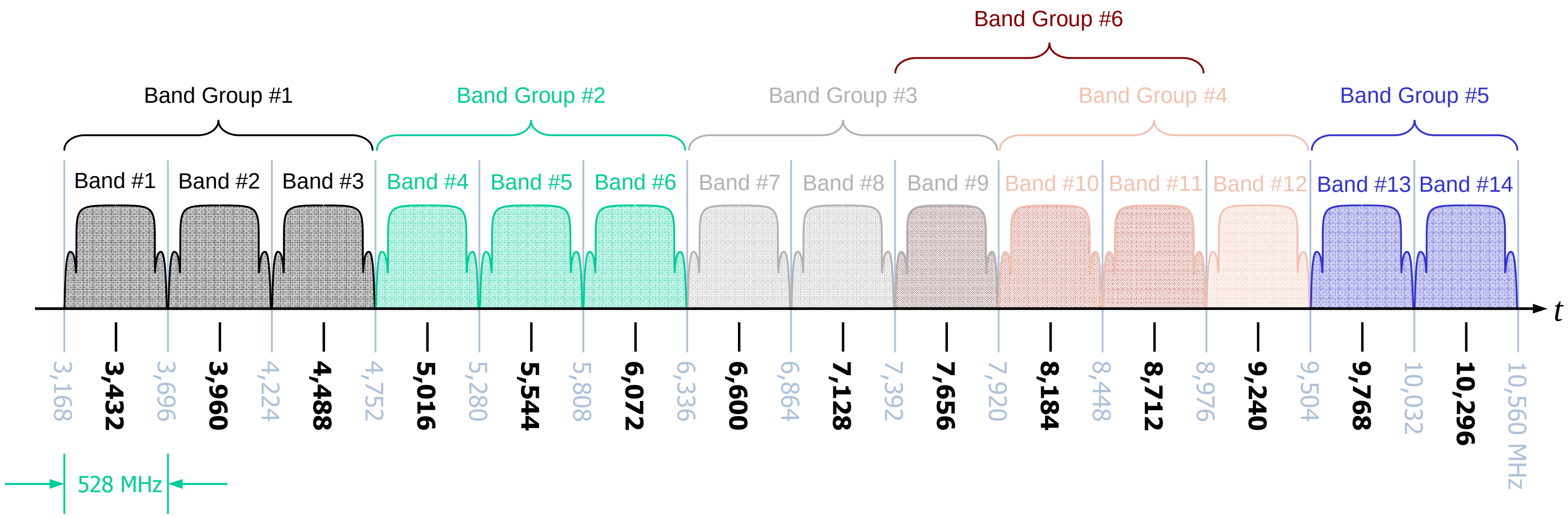
Technique really adapted to high rates in indoor environments

Spectrum shape flexibility

Complexity of realization: needs circuits to realize real-time FFT ➡ Digital part very complex

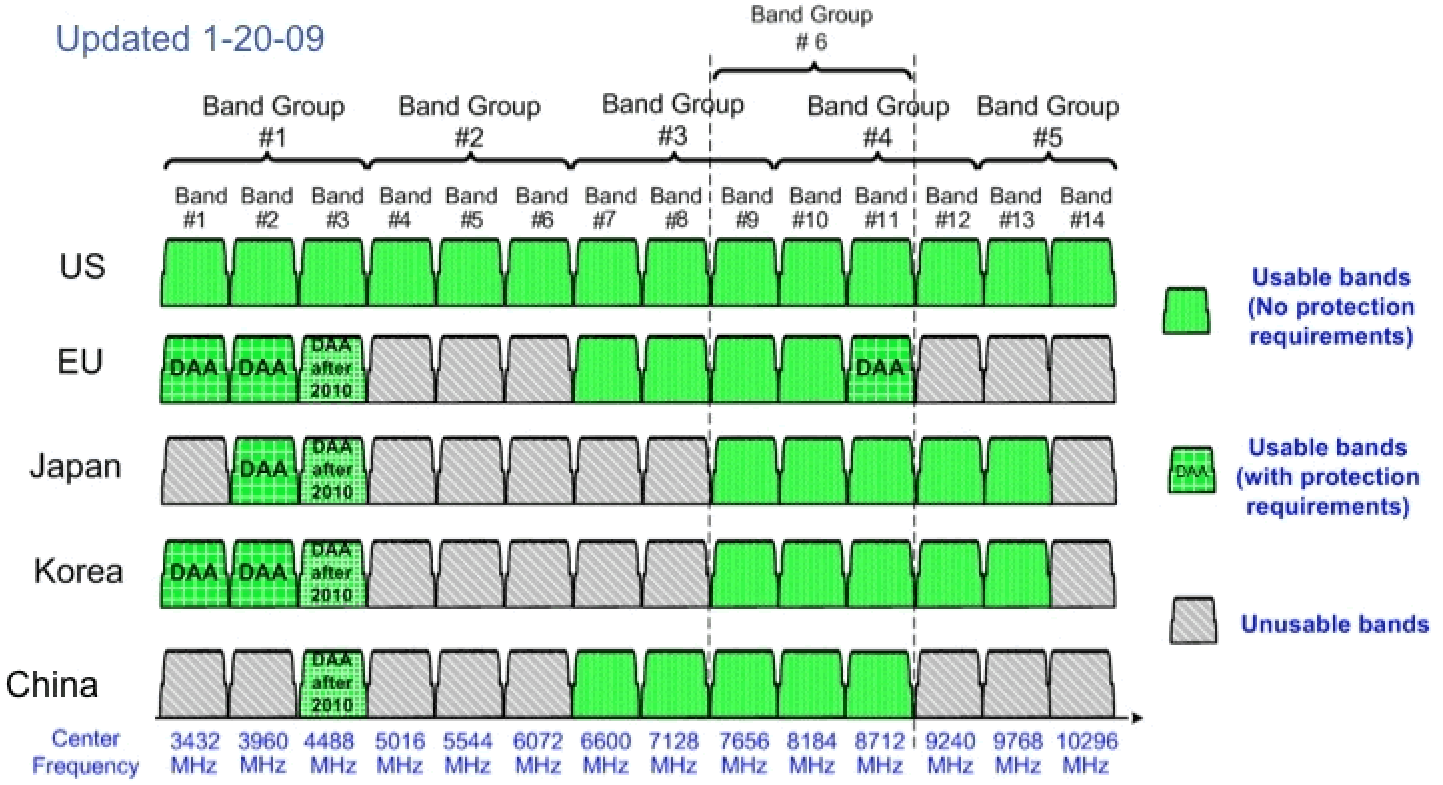
Needs highly linear front-ends, with low noise ➡ high consumption of analog part

MB-OFDM Spectrum Bands



MB-OFDM Spectrum Availability

WiMedia usable bands

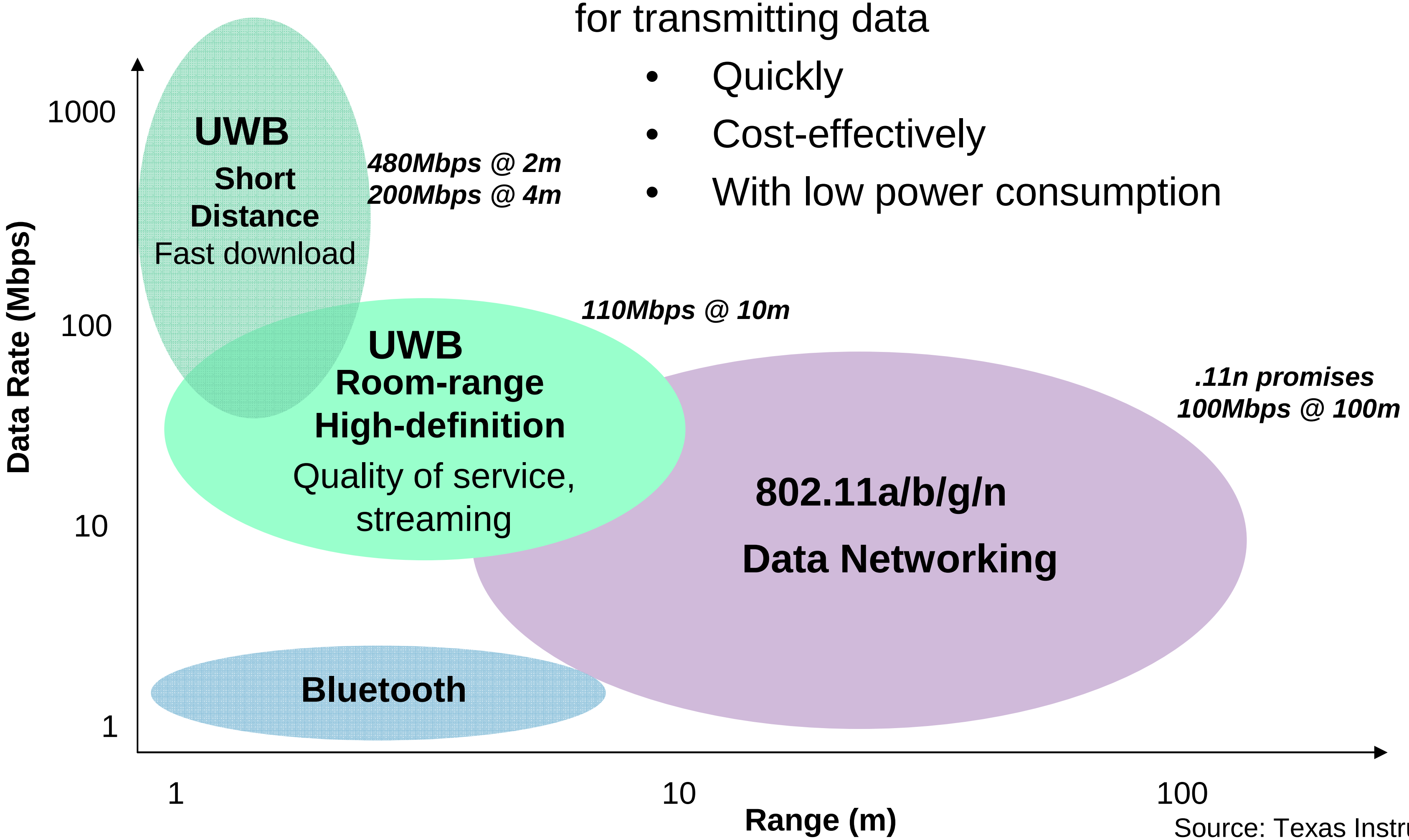


MB-OFDM Spectrum Availability

UWB is wireless personal area networking (WPAN) technology

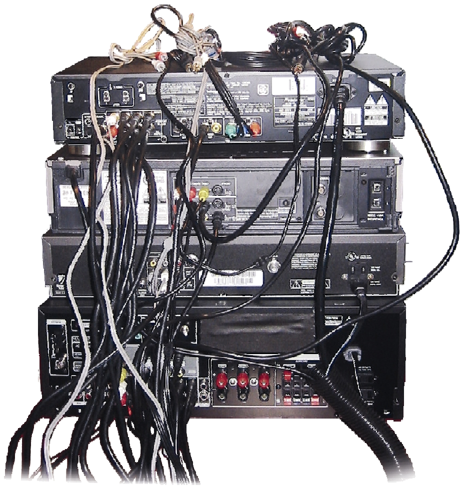
for transmitting data

- Quickly
- Cost-effectively
- With low power consumption



Source: Texas Instruments

MB-OFDM Spectrum Availability



The Customer's Frustration with Cables:

- Tangle of cables in our Homes and Offices
- Ever increasing file sizes of content to be downloaded and enjoyed by Consumers
- Consumers don't want to wait long for a file to transfer
- User Models limited by the use of Cables
- Customers to-day prefer Wireless

UWB is more than a Cable replacement technology

Create new User Models and product opportunities not possible today with cables

BUT.....MUST Match the Security of cables

MUST be easy to use

Source: WiMedia

WiMedia Alliance Roadmap

Today:
- High performance
  - 480Mb/s
- Lowest Power
  - Mb/unit energy
  - Or whatever
  - (need to qualify)
- Regulatory compliance
  - Major markets

By 2010:

Higher Throughput
For Video Applications
& Synch & Go Applications

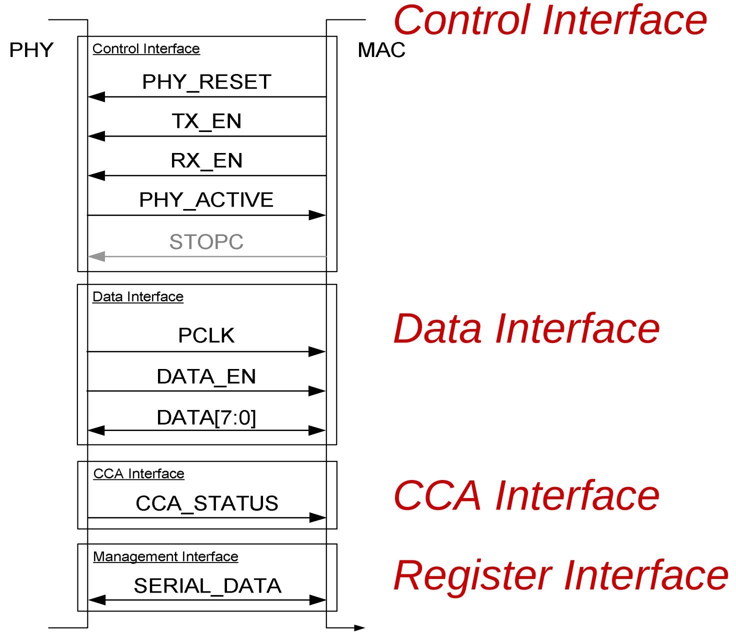
Spectrum Enhancements
For Worldwide
Regulatory Compliance

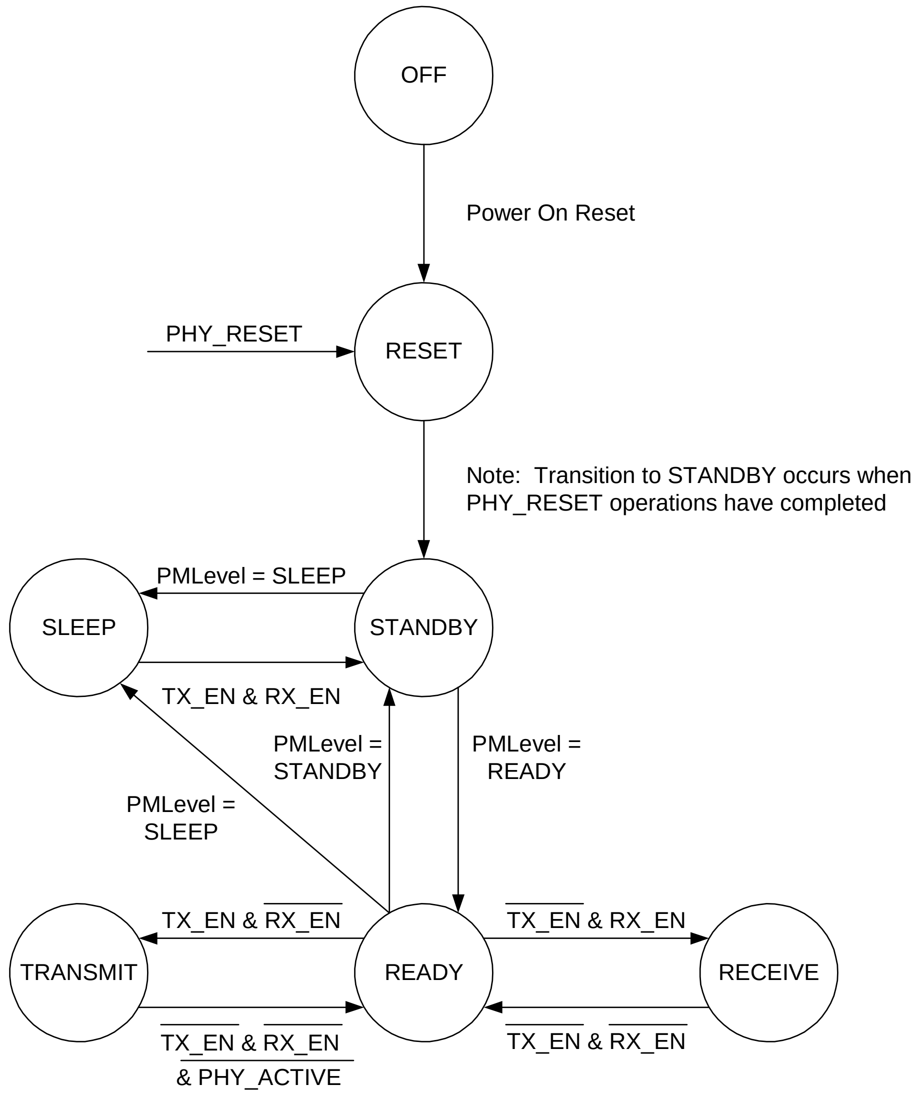
Ultra Low Power
Consumption for additional
Mobile Applications

PHY-MAC Interface Specification

Highlights:

- Simple State Machine Model





- Synchronous I/F
- Minimum # signal lines
- Sleep & Active States
- Flexible expression of frame exchange and IFS control

PHY and MAC Specification

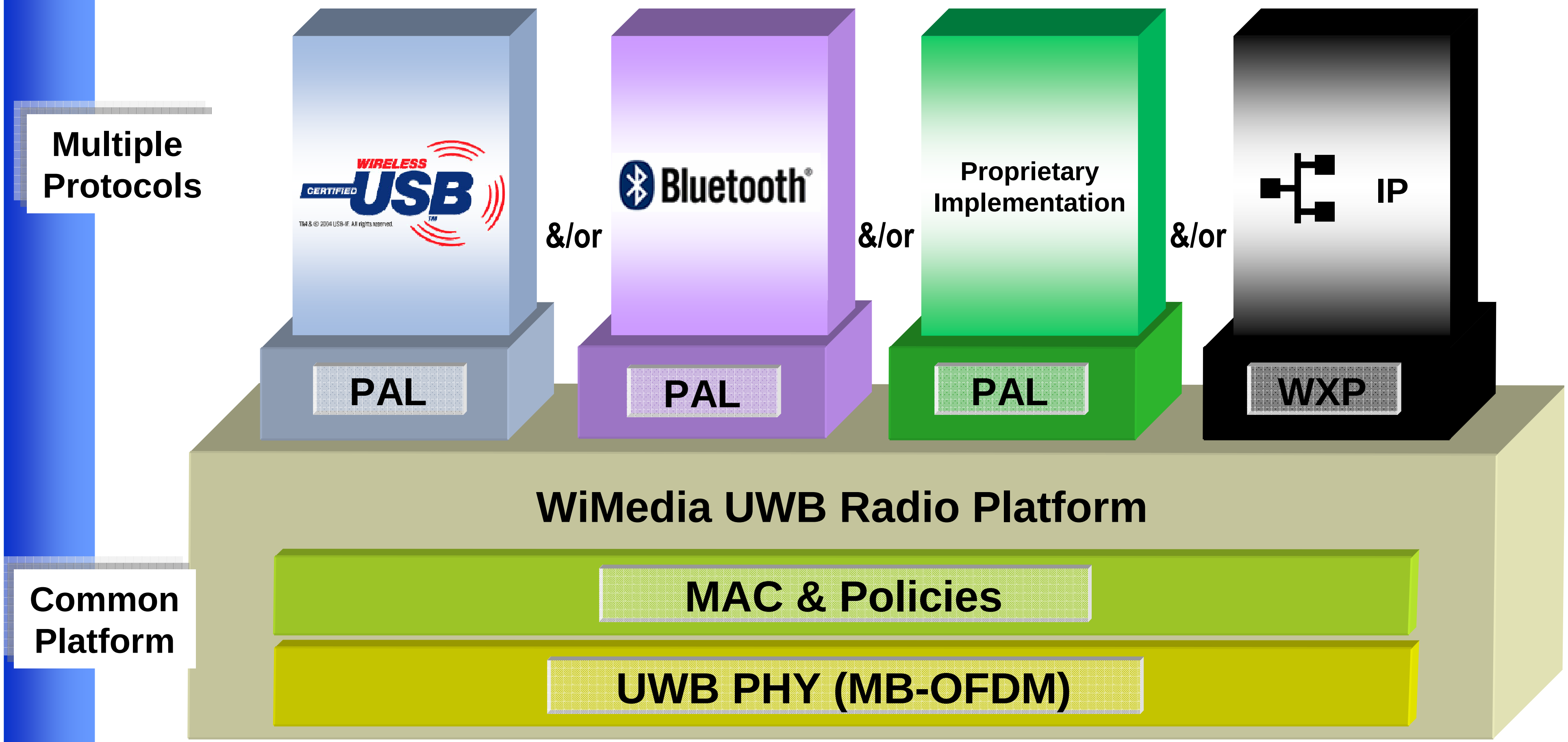
PHY

- *Data Rates – Selective and Scalable*
- *Power Consumption – Long Battery Life*
- *Cost*
- *Range*
- *Global Solution*
- *Scalability*
- *Modulation*

MAC

- *Distributed channel access and distributed management of network resources*
- *QoS support for Isochronous and Asynchronous traffic*
- *Enabling mobility within the mesh without interruption of QoS transmissions*
- *Supports simultaneous operating piconets (SoP)*
- *Four levels of power saving for optimized system power consumption*
- *Straight-forward design supports low-cost device implementations*

WiMedia Common Radio Platform



PAL: Protocol Adaptation Layer