Ultrawide-Band Systems for WSNs: Fundamentals

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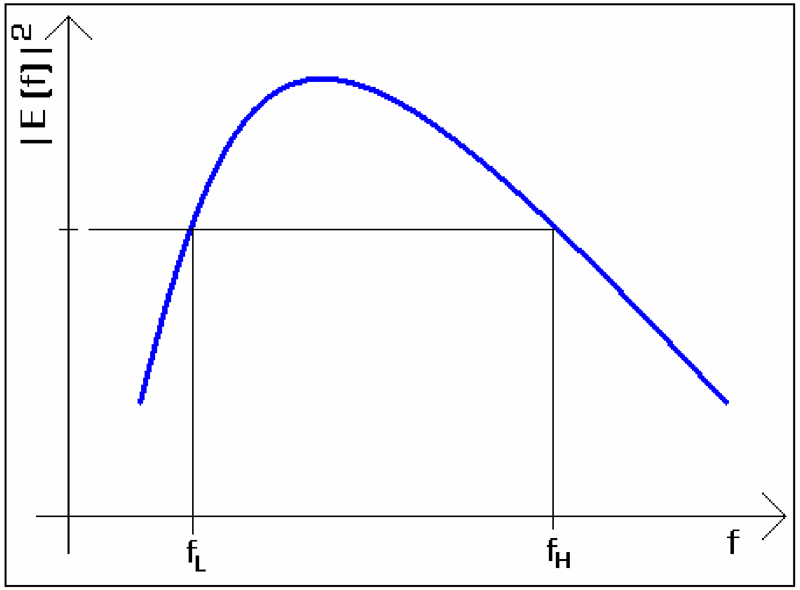
Summary

- What is a UWB signal?
- Motivations
- How to generate it
- UWB propagation and channel models
- The optimal UWB receiver
- Low-complexity UWB schemes
- The IEEE802.15.4a standard for low data rate networks (WSNs)
- Multiband OFDM
- WiMedia & ECMA-368 standard for high data rate WPANs
- Coexistence between UWB and NB systems
- Cognitive radio (fundamentals, UWB as an underlying technique, ...)
- Applications

Definition of a UWB signal

UWB signal is formally defined as any signal that (FCC):

- occupies more than *500 MHz* of spectrum or
- has a fractional bandwidth in excess of *20%*

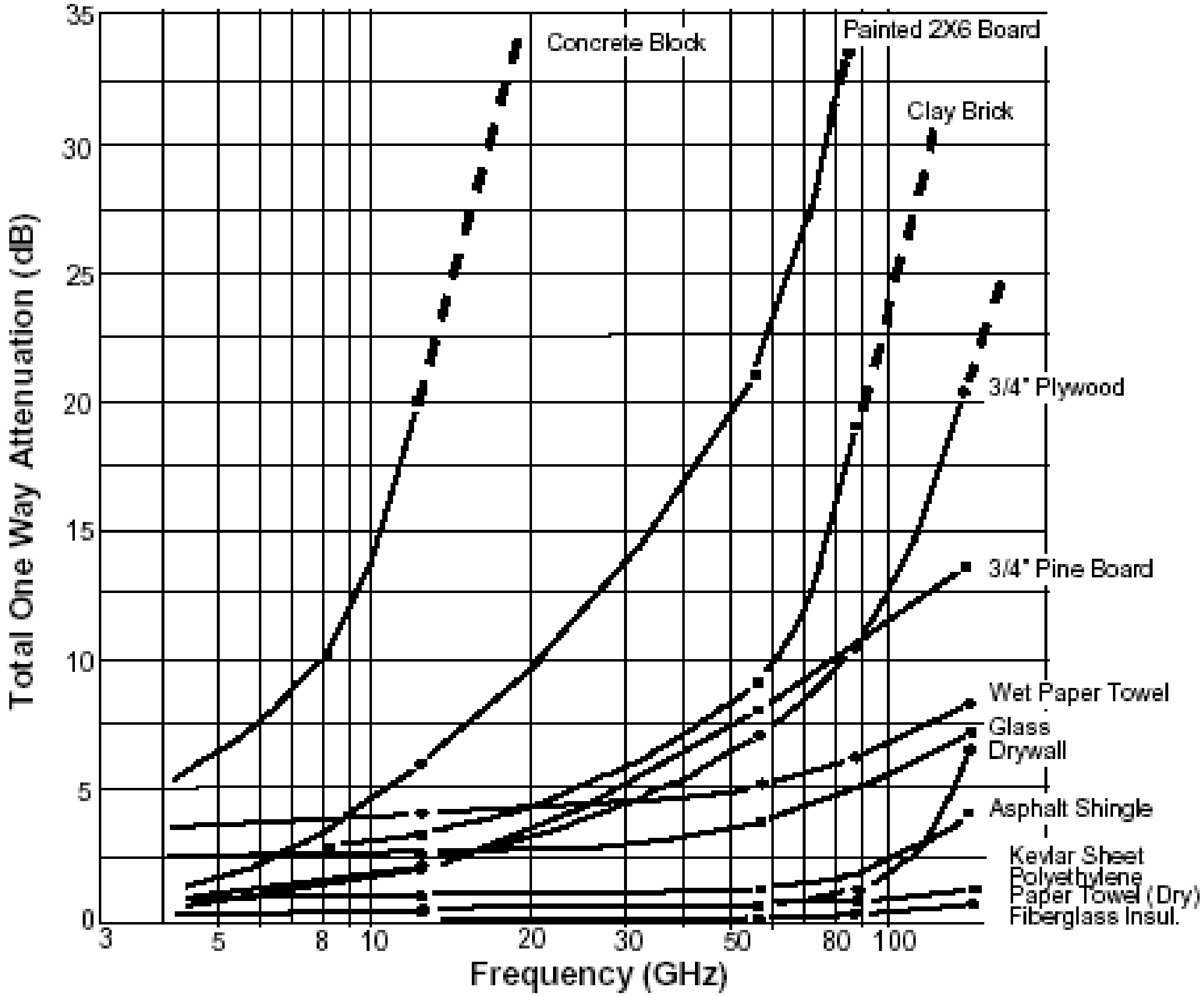


$$BF = \frac{f_H - f_L}{(f_H + f_L)/2} \geq 0.2$$

Brief history of UWB

- The Radio was born an UWB:
  spark gap transmission designs of Marconi in the late 1890s
- After the Marconi's “4 seven” patent (1900) the radio became “tuned”
- Time-domain electromagnetics theory in early 1960s
- Short-pulse generators using tunnel diodes in early 1970s
- Applications to radar in 1970-80s
- The term “UWB” originated with the Defense Advanced Research Projects (DARPA) in a radar study undertaken in 1990
- First studies of possible application of UWB to communication systems during 1990s (Win-Scholtz)
- 2/2002 - FCC adopted the First Report and Order (RO) that permits the marketing and operation of certain types of UWB products
- 2/2007 – Implementation of an UWB radio regulatory framework for the EU

Where do we find such a huge available bandwidth?



[16] L. M. Frazier, "Radar surveillance through solid materials," in *Command, Control, Communications, and Intelligence Systems for Law Enforcement*, vol. 2938, pp. 139–146, Boston, Mass, USA, November 1996.

Better to utilize already allocated bands using extremely low power spectral densities (PSD)

⇩

FCC limits ensure that UWB emission levels are exceedingly small

- at or below spurious emission limits for all radios
- at or below unintentional emitter limits
- lowest limits ever applied by FCC to any system

Part 15 limits equate to –41.25 dBm/MHz

For comparison, PSD limits for 2.4 GHz ISM and 5 GHz U-NII bands are +40 dB higher per MHz

Total emissions over several gigahertz of bandwidth are a small fraction of a milliwatt

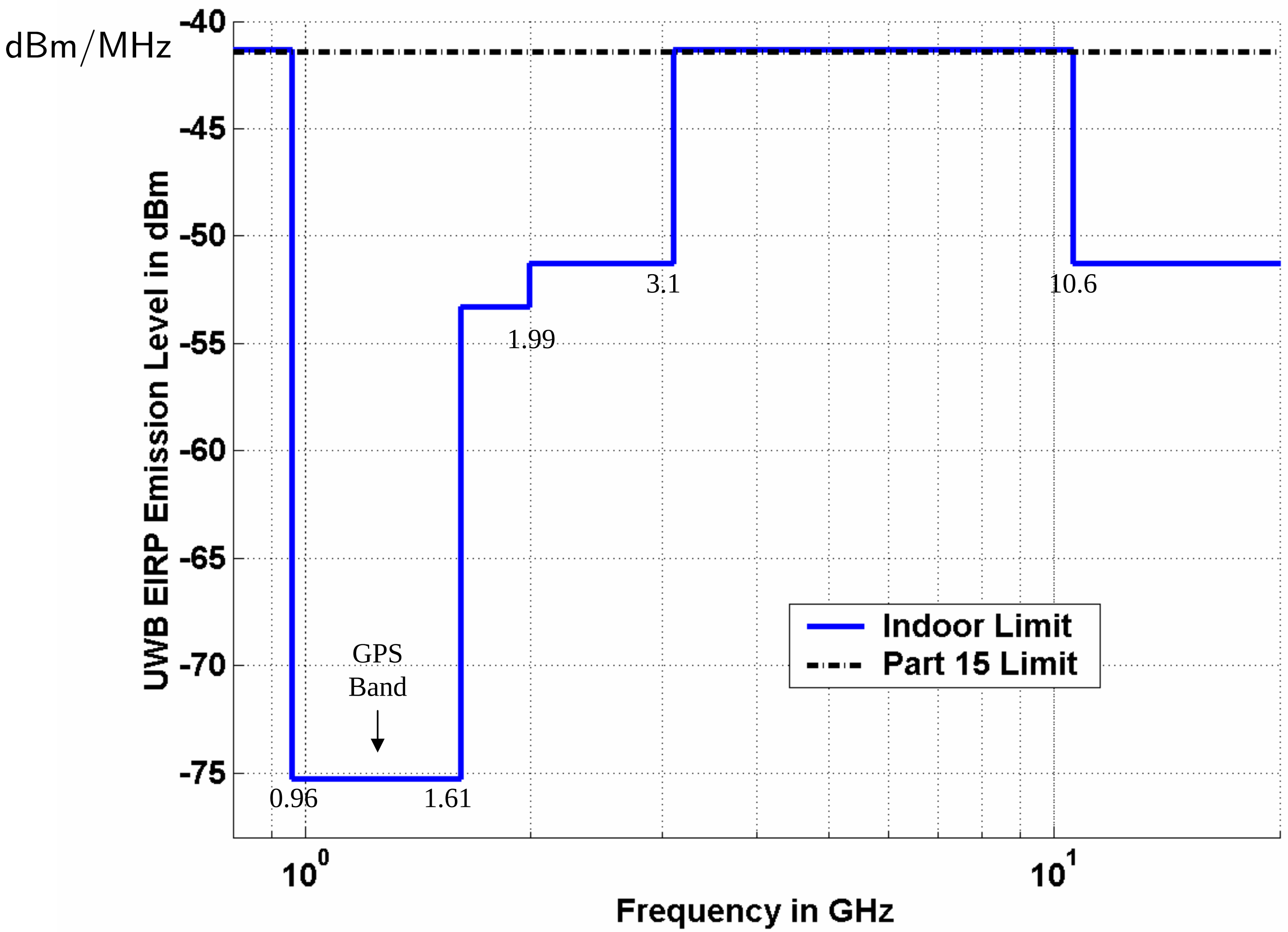
FCC masks

Different radiation masks were given for several UWB applications

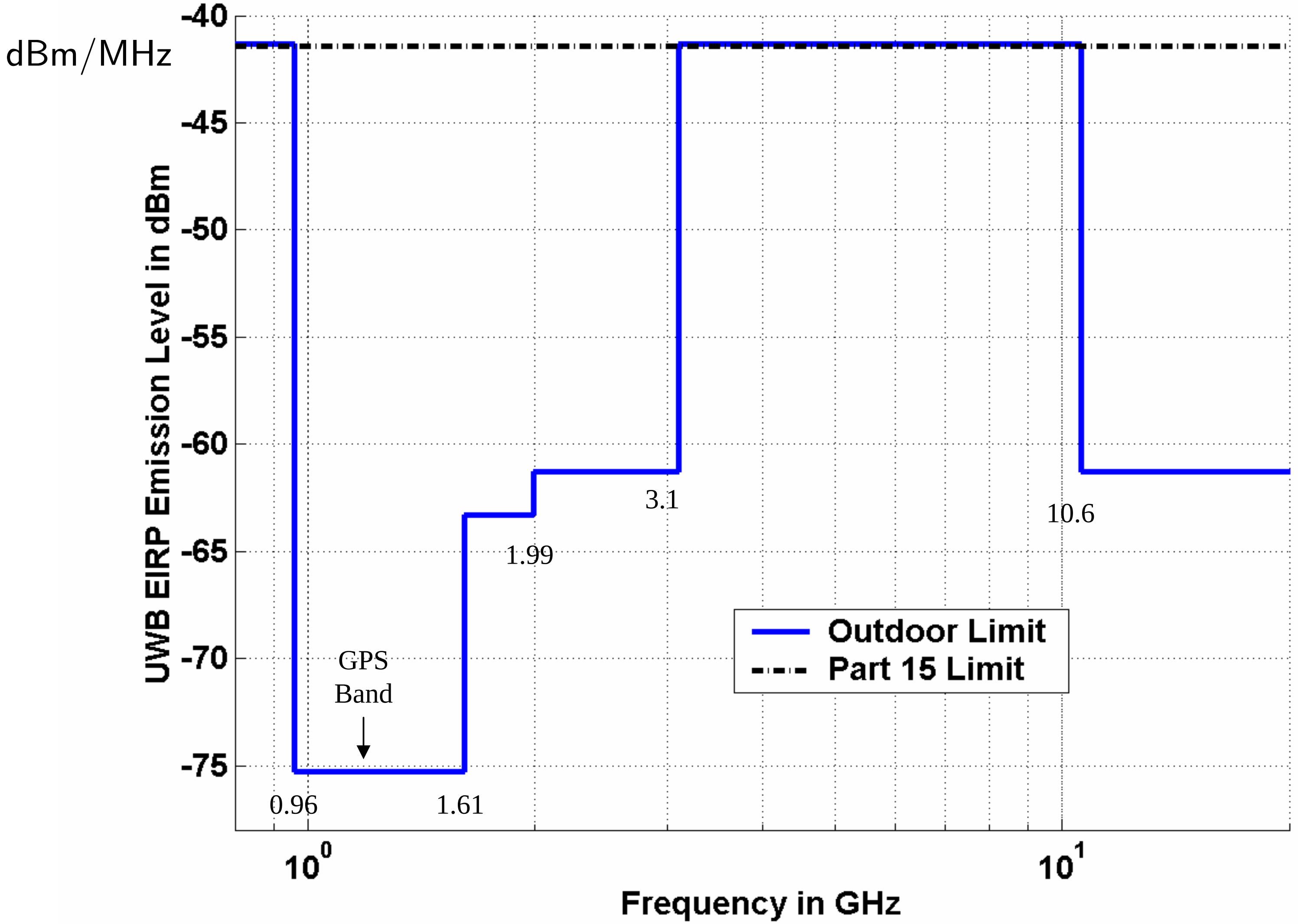
Application	*Frequency Band for Operation at Part 15 Limits*	*User Restrictions*
Ground penetrating radars, wall imaging systems	3.1 to 10.6 GHz	Yes
Through-wall imaging and surveillance systems	1.99 to 10.6 GHz	Yes
Communications (indoor & outdoor) and medical systems*	3.1 to 10.6 GHz	No
Vehicular radar systems	24 to 29 GHz	No

*Indoor and outdoor communications devices have different out-of-band emission limits

Example of indoor UWB mask



Example of outdoor UWB mask (hand-held)



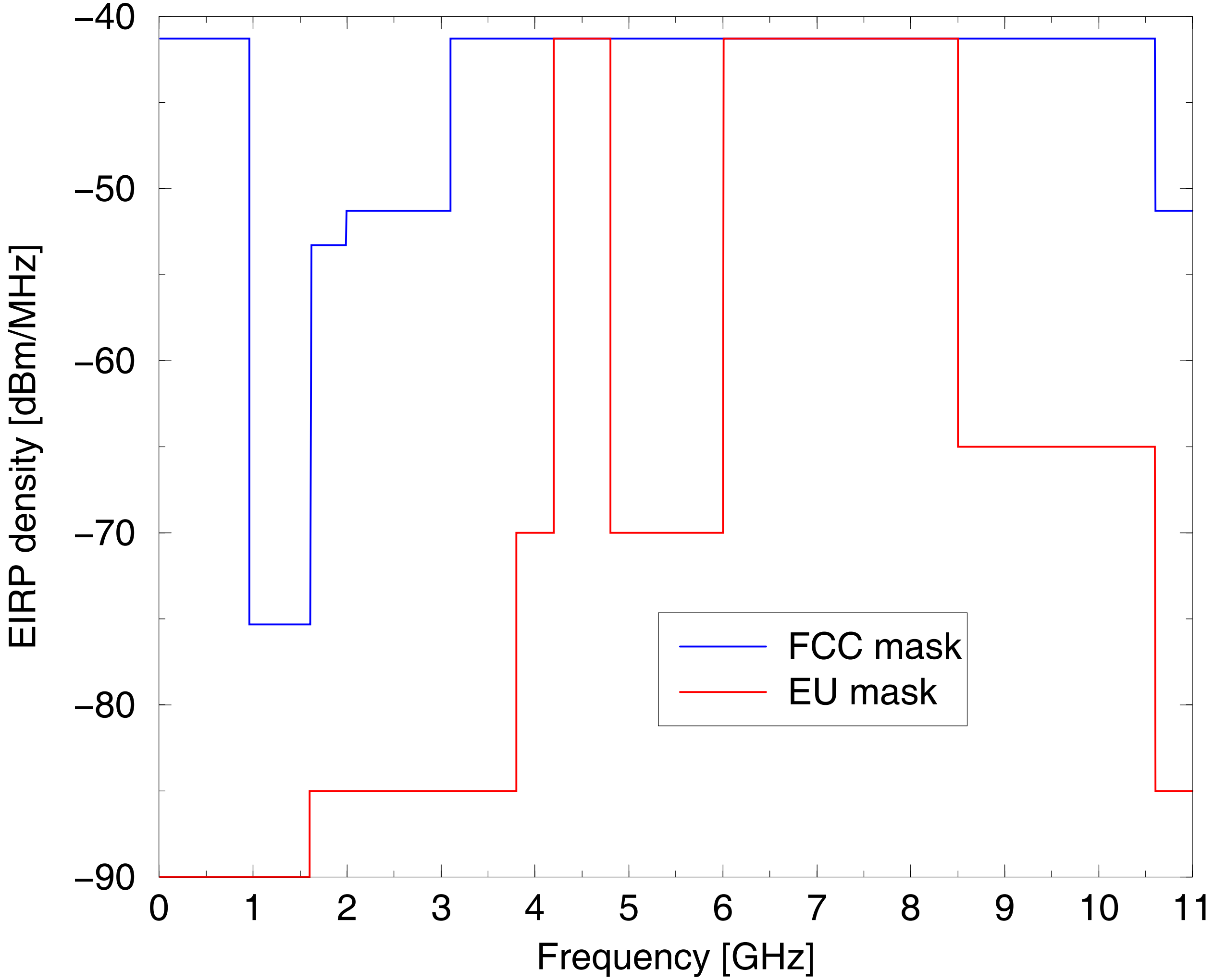
EU mask

Frequency Range [GHz]	Maximum Mean EIRP Density [dBm/MHz]	Maximum Peak EIRP Density [dBm/50 MHz]
Below 1.6	–90.0	–50
1.6 – 3.4	–85.0	–45
3.4 – 3.8	–85.0	–45
3.8 – 4.2	–70.0	–30
4.2 – 4.8	–41.3* * until 31/12/2010 –70.0** ** after 31/12/2010	–0.0* * until 31/12/2010 –30.0** ** after 31/12/2010
4.8 – 6.0	–70.0	–30.0
6.0 – 8.5	–41.3	0.0
8.5 – 10.6	–65.0	–25.0
Above 10.6	–85.0	–45.0

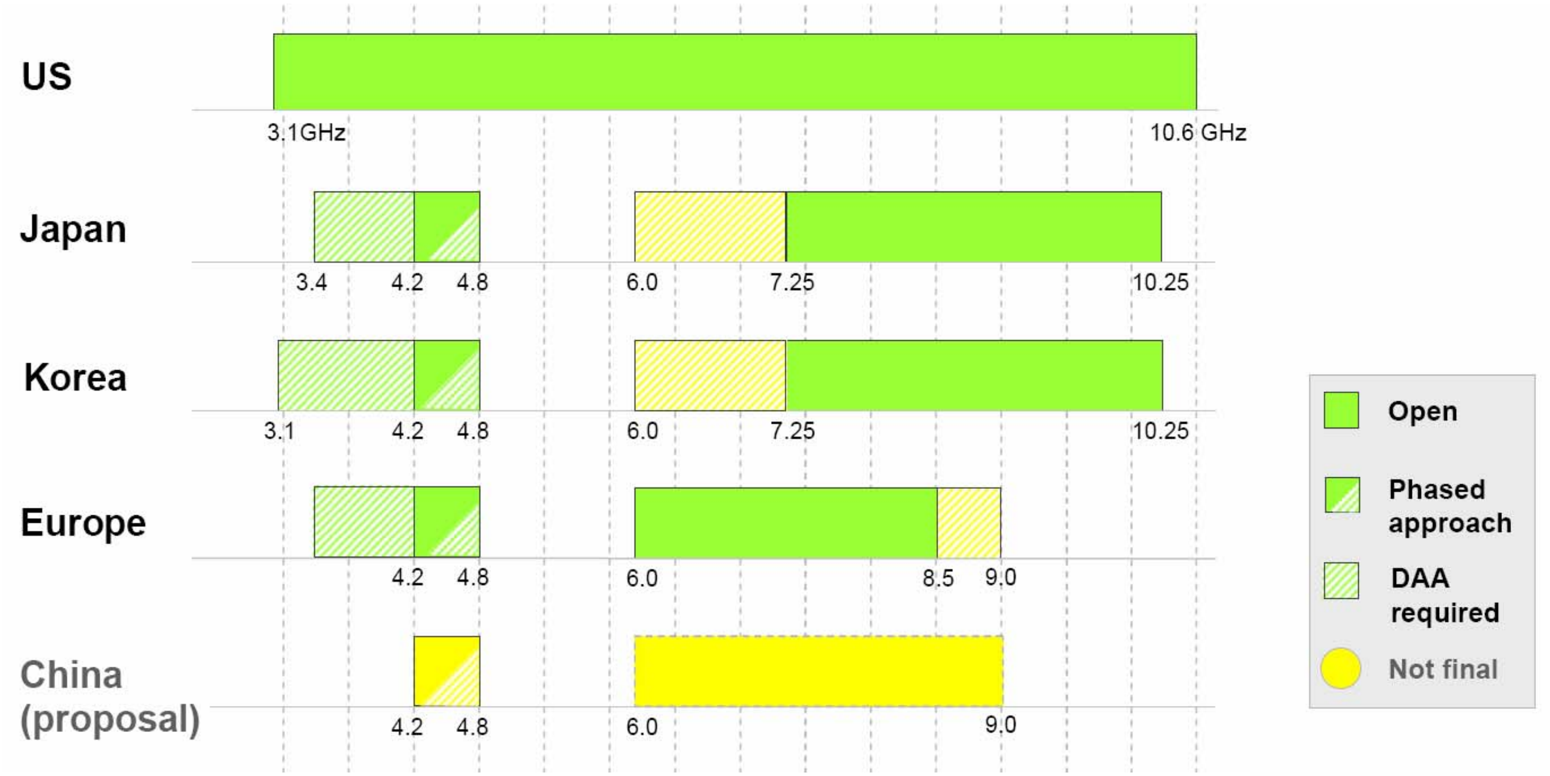
A maximum mean EIRP density of -41.3 dBm/MHz is allowed in the 3.4 - 4.8 GHz bands provided that a low duty cycle restriction is applied in which the sum of all transmitted signals is less than 5% of the time each second and less than 0.5% of the time each hour, and provided that each transmitted signal does not exceed 5 milliseconds. Limits can be overcome using appropriate mitigation techniques. “10 second” rule introduced.

W. Hirt “The European UWB Radio Regulatory and Standards Framework: Overview and Implications”, ICUWB 2007. IEEE International Conference on Ultra-Wideband, 2007. Sept. 2007, Singapore.

Comparison between FCC and EU masks



Worldwide regulations



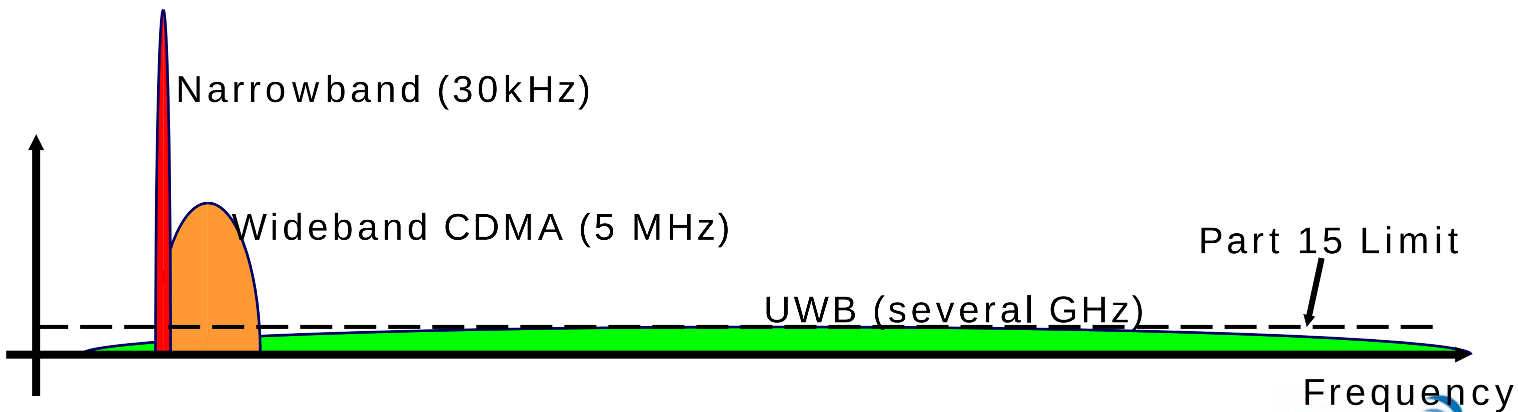
Why do we need UWB systems?

Motivations

- High temporal resolution (localization, multipath)
- High material penetration (according to the band used)
- Underlay technology (efficient spectrum usage)
- Multiple access
- Low probability of detection (LPD)

Main issues

- Keep complexity low
- Large bandwidth antennas
- Interference management (coexistence)



How to generate a UWB modulated signal

Conventional techniques over sinusoidal carrier

such as OFDM, DS-CDMA, FH-CDMA

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Higher complexity

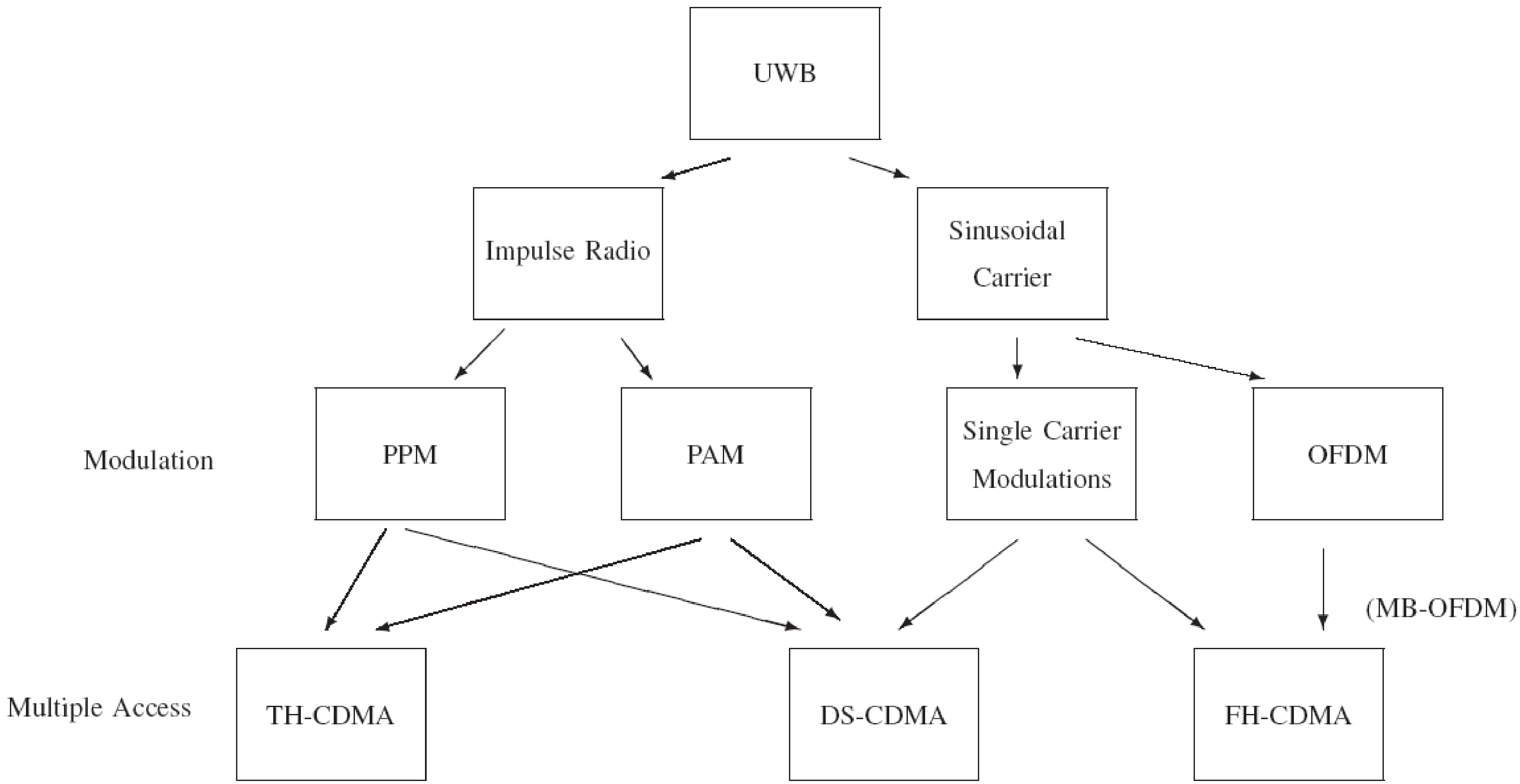
Impulse radio

Base-band transmission of short pulses (monocycles)

⇓

Lower complexity

UWB Taxonomy



Impulse Radio - UWB

Impulse Radio UWB (IR-UWB)

Base-band generation of the signal using short duration pulses

- Low complexity (no RF and IF stages)
- Low consumption
- New antenna design criteria

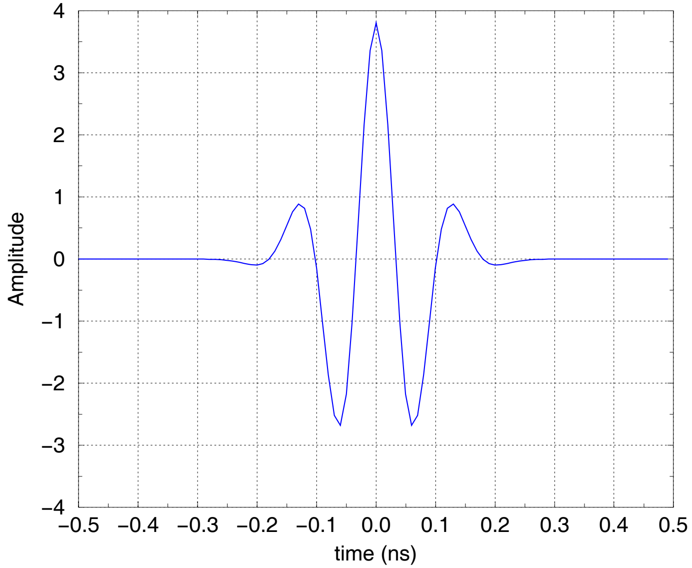
The Gaussian monocycle

- Gaussian *n*th derivative monocycle

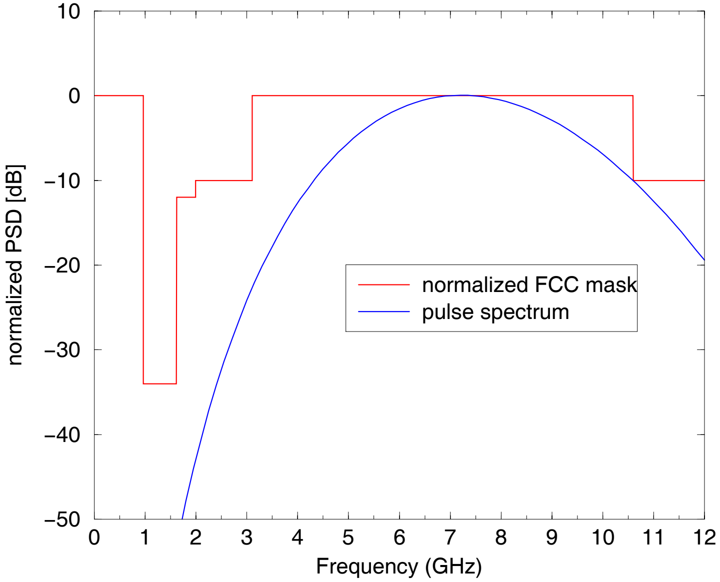
$$p_0(t) = \exp\left(-2\pi(t^2/\tau_p^2)\right) \qquad p(t) = p_0^{(n)}(t)\sqrt{\frac{(n-1)!}{(2n-1)!\pi^n \tau_p^{(1-2n)}}}$$

Example of Gaussian

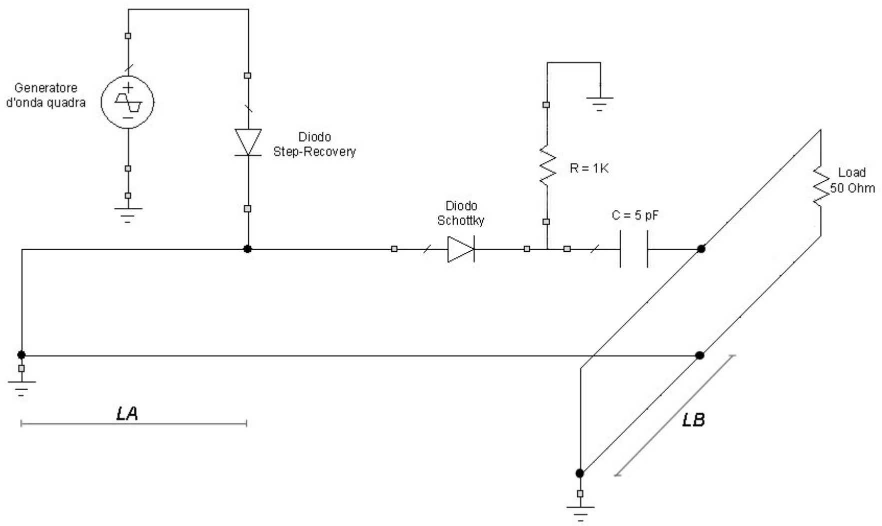
6th derivative monocycle

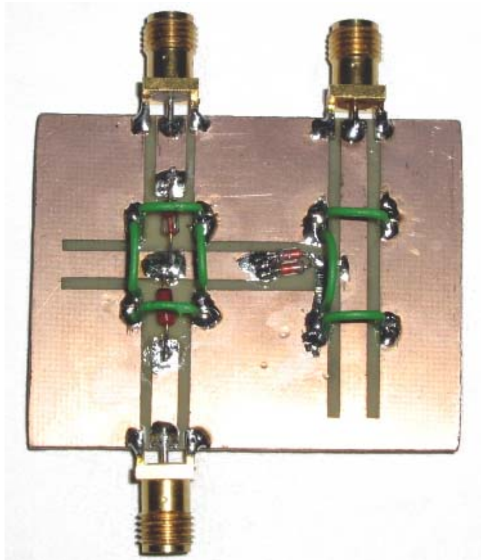


Spectrum



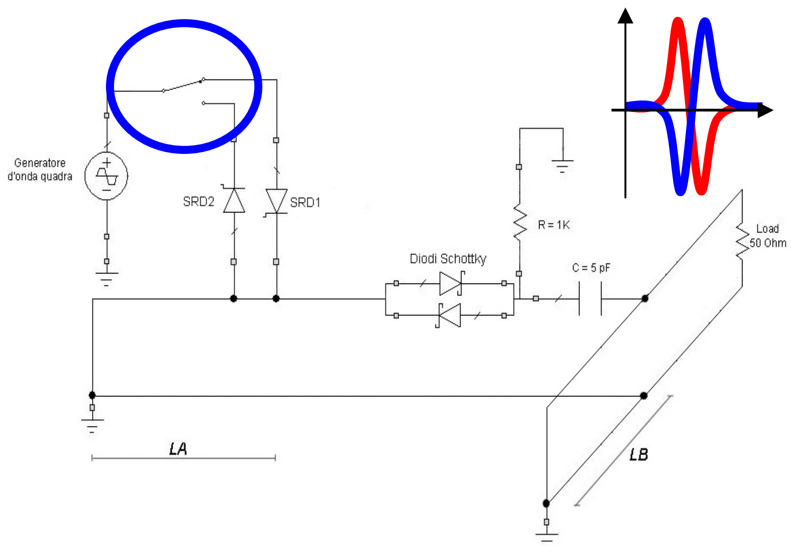
Example of simple impulse generator

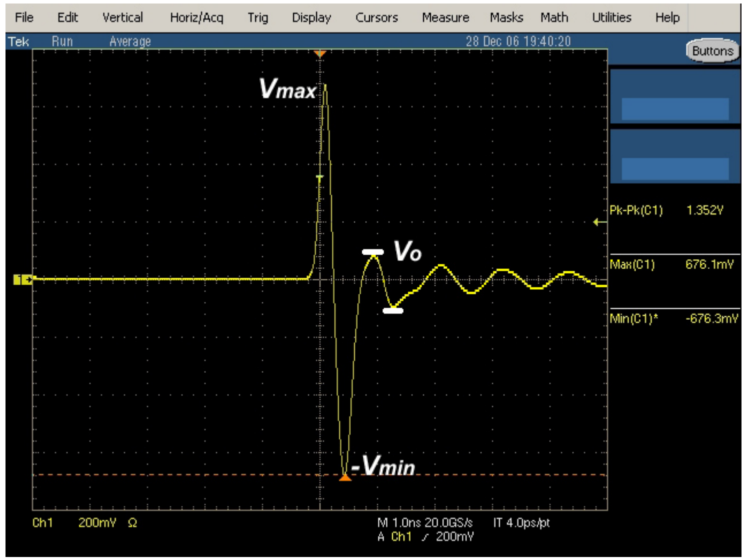




From J.S. Lee, C. Nguyen e T. Scullion, IEEE Microwave Theory and Tech. 2001

Bipolar version realized at WiLAB – University of Bologna





IR-UWB: signaling

36 IEEE COMMUNICATIONS LETTERS, VOL. 2, NO. 2, FEBRUARY 1998

Impulse Radio: How It Works

Moe Z. Win, *Member, IEEE*, and Robert A. Scholtz, *Fellow, IEEE*

***Abstract*— Impulse radio, a form of ultra-wide bandwidth (UWB) spread-spectrum signaling, has properties that make it a viable candidate for short-range communications in dense multipath environments. This letter describes the characteristics of impulse radio using a modulation format that can be supported by currently available impulse signal technology and gives analytical estimates of its multiple-access capability under ideal multiple-access channel conditions.**

***Index Terms*—Impulse radio, spread-spectrum multiple access, time hopping, ultra-wideband radio.**

I. A Rationale for Impulse Radio

IMPULSE RADIO communicates with baseband pulses of very short duration, typically on the order of a nanosecond, transmission suggests that an impulse radio may be manufactured inexpensively.

The same qualities that make this radio attractive also provide the design challenges. Regulatory considerations over such a wide bandwidth will limit the radiated power, ultra-fine time resolution will increase sync acquisition times and may require additional correlators to capture adequate signal energy, full mobility will exacerbate power control needs in multiple-access networks, etc.

II. Multiple-Access Techniques

A. Time-Hopping Format Using Impulses

VII. A Closing Comment

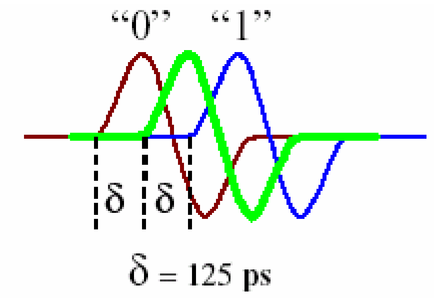
The potential of impulse radio to solve difficult indoor mobile communication problems is apparent because of its fine multipath resolution capability. As with most systems that push the capabilities of current technology, we believe that impulse radio eventually will become a practical solution to these problems.

IR-UWB: signaling

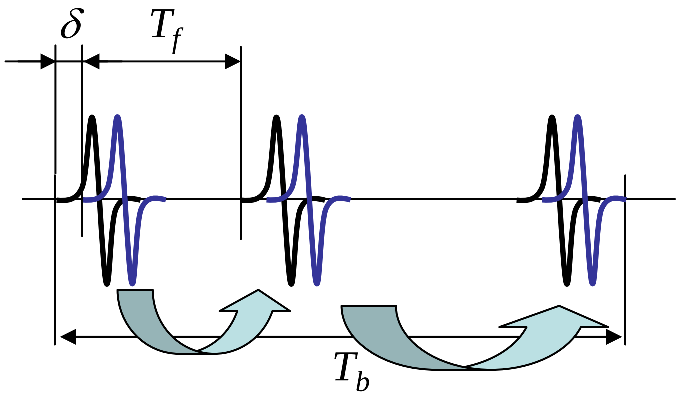
UWB signals are typically modulated pulse trains (low duty cycle)

At each bit several pulses (100-1000) are transmitted according to a certain "randomization" technique such as Time-hopping (TH) or Direct Sequence (DS) to allow multiple access (*each user adopts a different "code")*

Modulation techniques include pulse-position modulation (PPM), pulse amplitude modulation (PAM) and others



PPM signaling



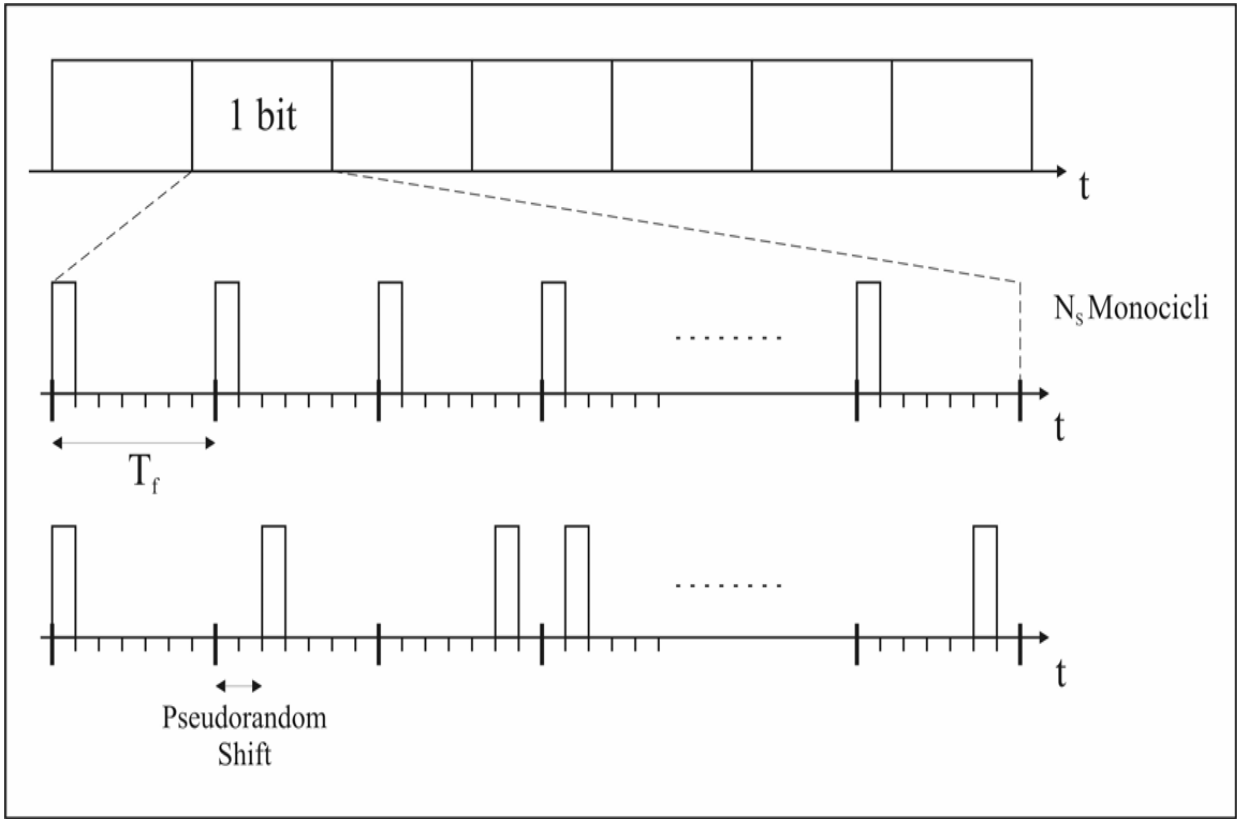
Randomized time hopping

Example: TH-PPM Impulse Radio

$$s^{(k)}(t) = \sum_{j=-\infty}^{\infty} p\left(t - jT_f - c_j^{(k)}T_c - \delta\, d_{\lfloor j/N_s \rfloor}^{(k)}\right)$$

Transmitted signal
K-th user

- Pseudorandom Time Hopping coding (TH)



- **T_f :** frame time
- **δ :** modulation index
- **N_s:** # pulses/symbol
- **$C_j^{(k)}$:** pseudo-random (PR) sequence (ex:1,3,6,2,…,6)
- **d:** data bits
- **Tc:** chip time

TH-PPM: optimum receiver in AWGN

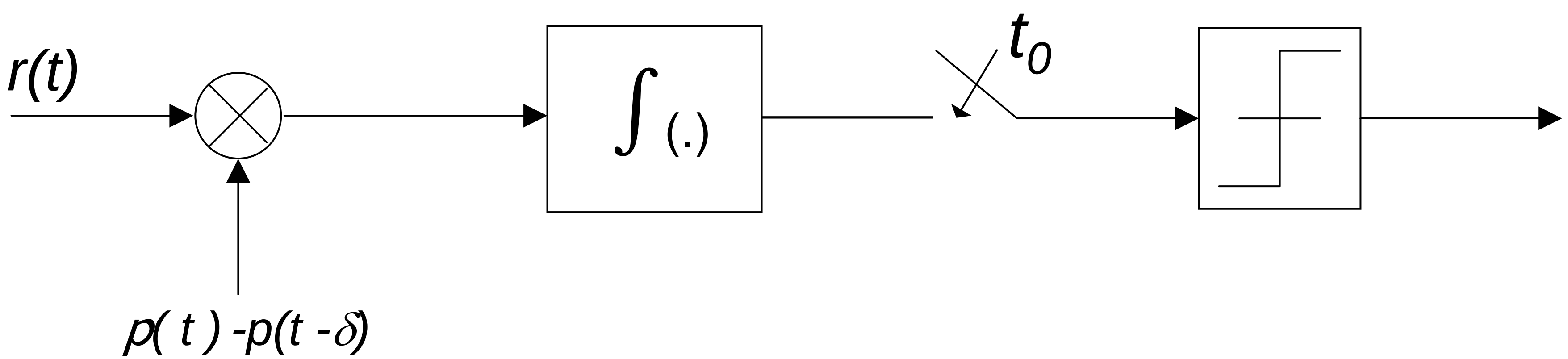
- Hp: one active user

received signal $$r(t) = \sqrt{E_p}\, s_r^{(1)}(t - \tau_1) + n(t)$$

n(t): thermal noise (one-sided spectral density No)

E_p: received energy per pulse

- optimum receiver ⇨ correlator (or matched filter)



TH-PPM: optimum receiver in AWGN

Bit error probability:

$$P_e = \frac{1}{2}\mathrm{erfc}\sqrt{\frac{E_d}{4N_0}} = \frac{1}{2}\mathrm{erfc}\sqrt{\frac{E_b(1-\rho)}{2N_0}}$$

where:

ρ: correlation coefficient

E_b: received energy per bit

$$\rho = \frac{1}{E_p}\int_{-\infty}^{\infty} p(t)\cdot\left[p(t) - p(t-\delta)\right]\cdot dt$$

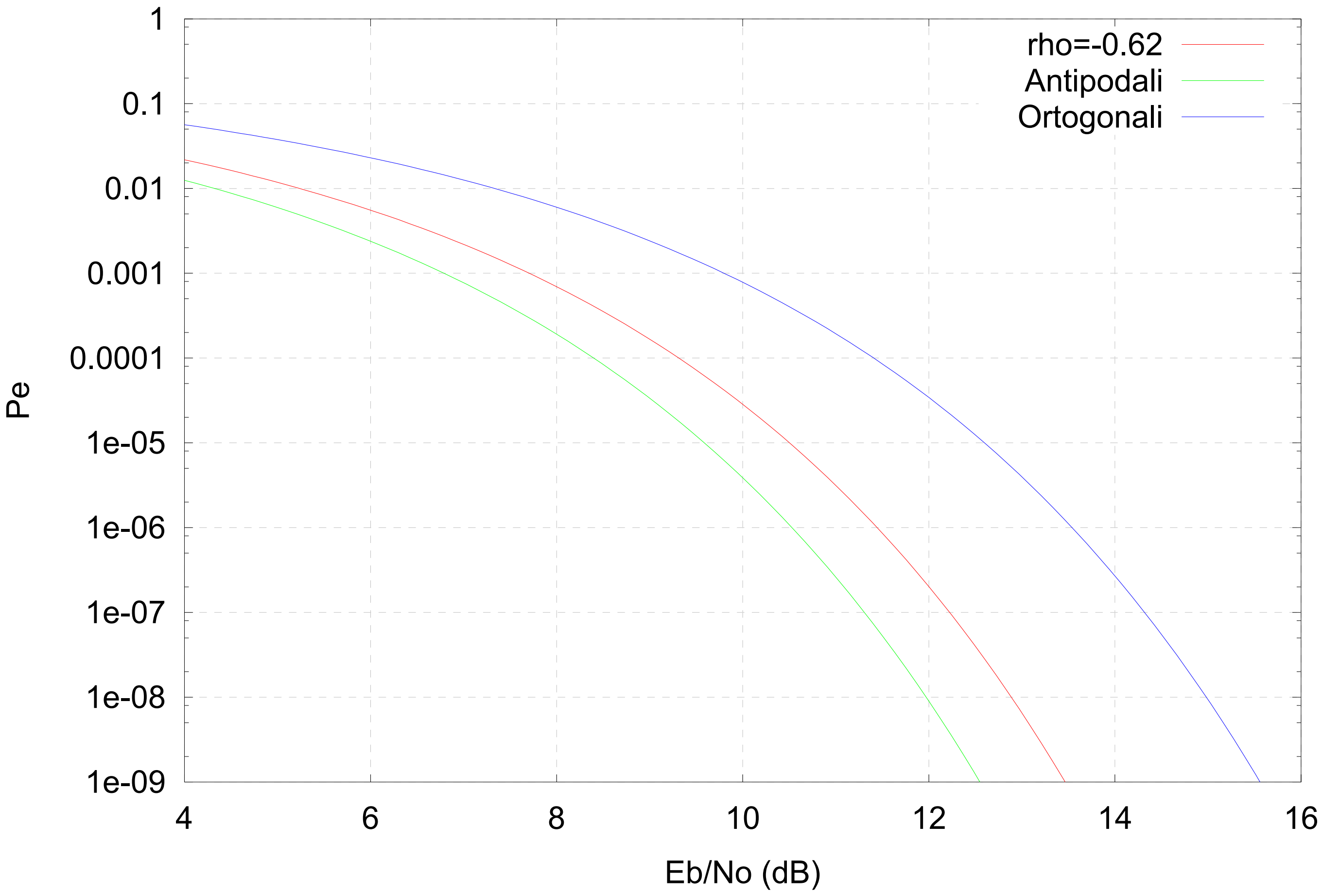
Example: pulse with duration *t_p= 0.4472 ns (Gaussian monocycle)*

$\Rightarrow$ *δ_{opt}= 0.2419 ns ; ρ= - 0.6183*

$$\Rightarrow \quad P_e = \frac{1}{2}\mathrm{erfc}\sqrt{\frac{E_b \cdot 0.81}{N_0}}$$

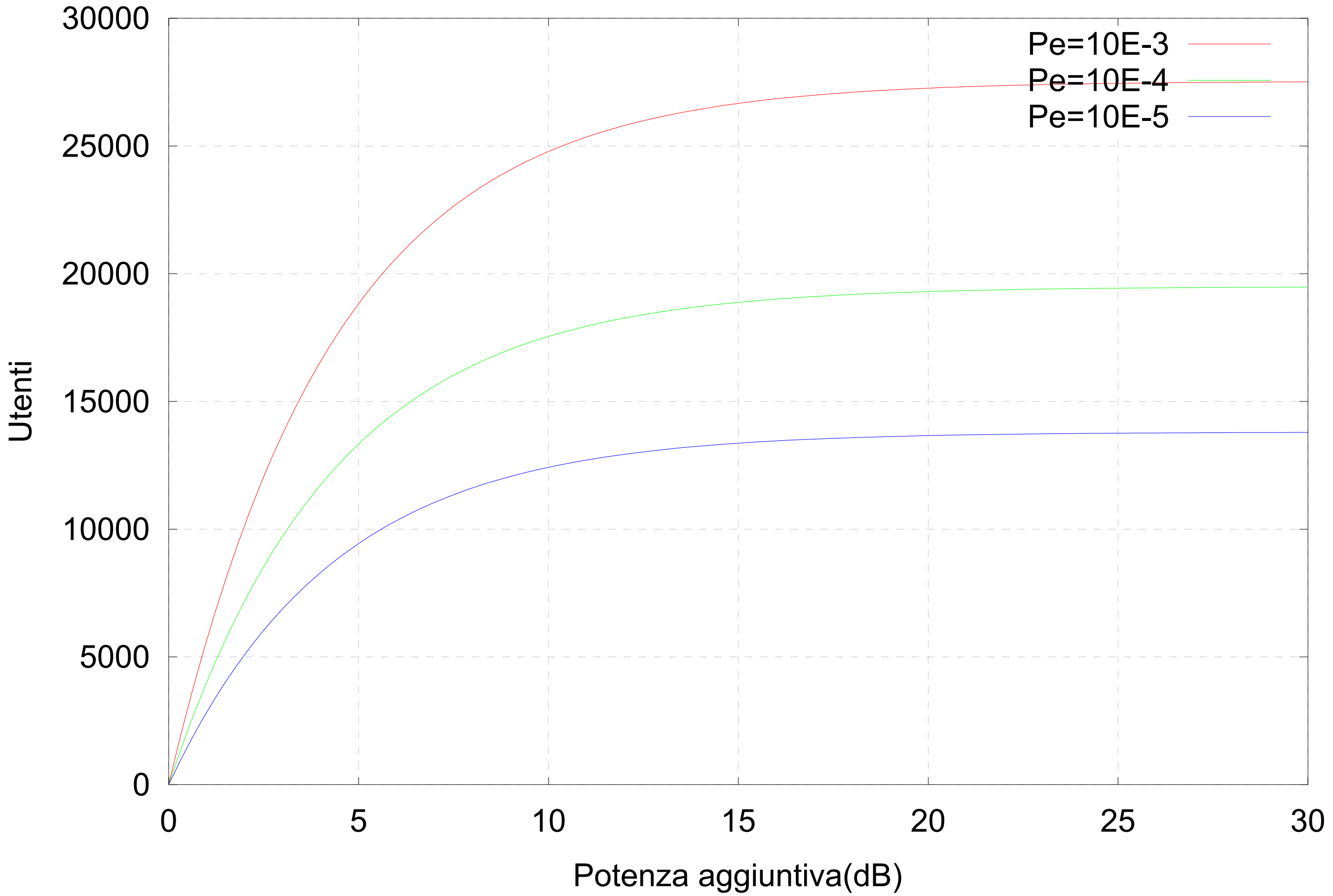
TH-PPM: optimum receiver in AWGN

Performance comparison between antipodal and orthogonal waveforms



TH-PPM: performance in a multi-user scenario

Number of users as a function of power degradation in AWGN



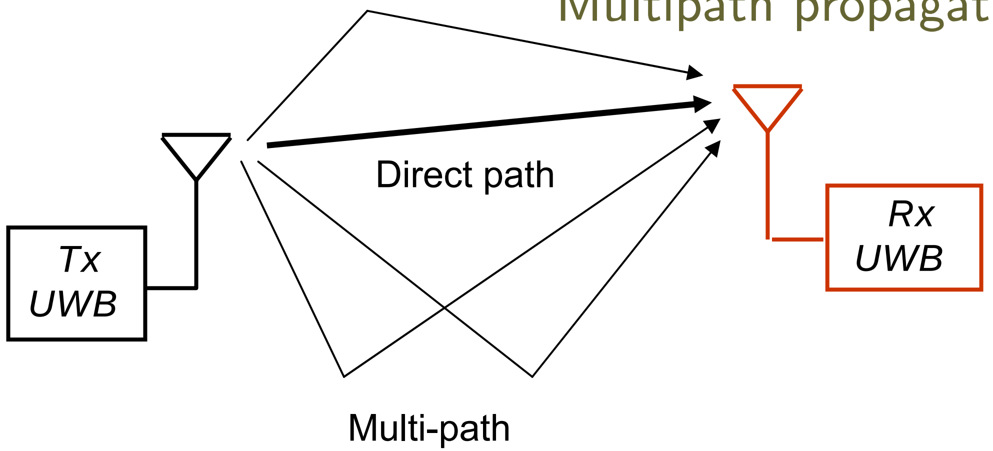
Bit rate 19.2Kbit/s, Tf=100ns

UWB propagation and channel models

The UWB channel

Multipath propagation

$g(t)$: channel gain
$h(t)$: channel impulse response
$s(t)$: transmitted signal
$r(t)$: received signal



Narrowband channel:

$$r(t) = g(t) \cdot s(t)$$

Fading → large link budget margin

Wideband channel

$$r(t) = h(t) \otimes s(t)$$

Echoes → signal distortion

Single paths are typically not resolvable, i.e., echoes amplitudes exhibit fading

Ultra wideband channel

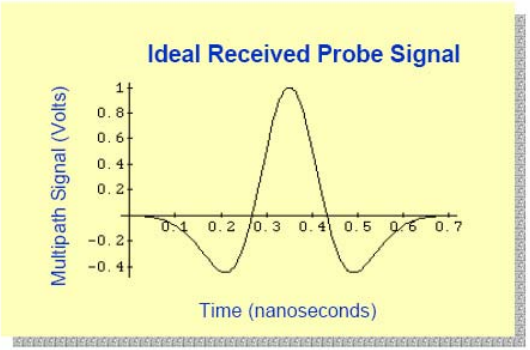
$$r(t) = h(t) \otimes s(t)$$

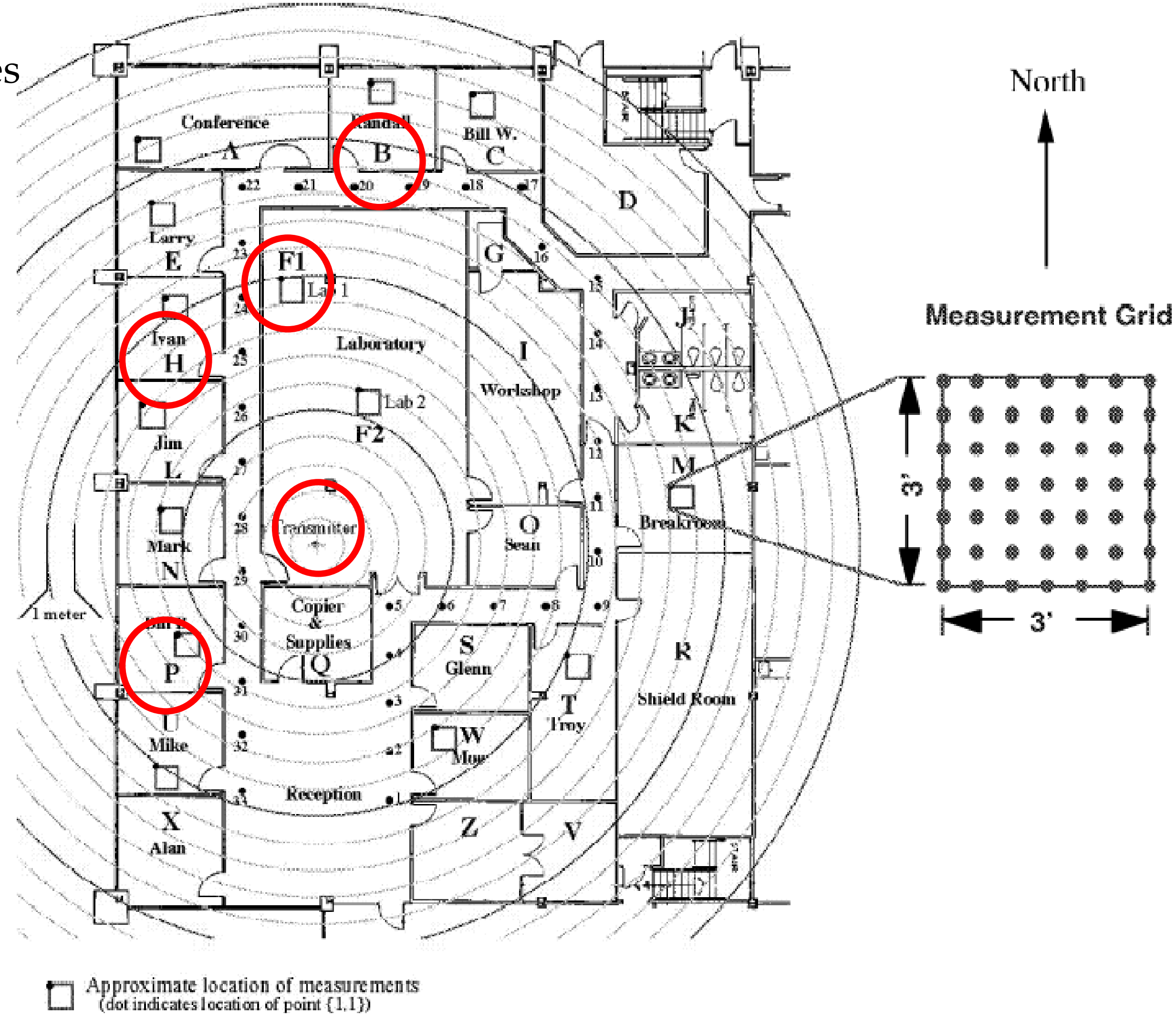
Echoes → signal distortion

Single paths may be resolved → potential diversity gain

UWB Propagation Experiment

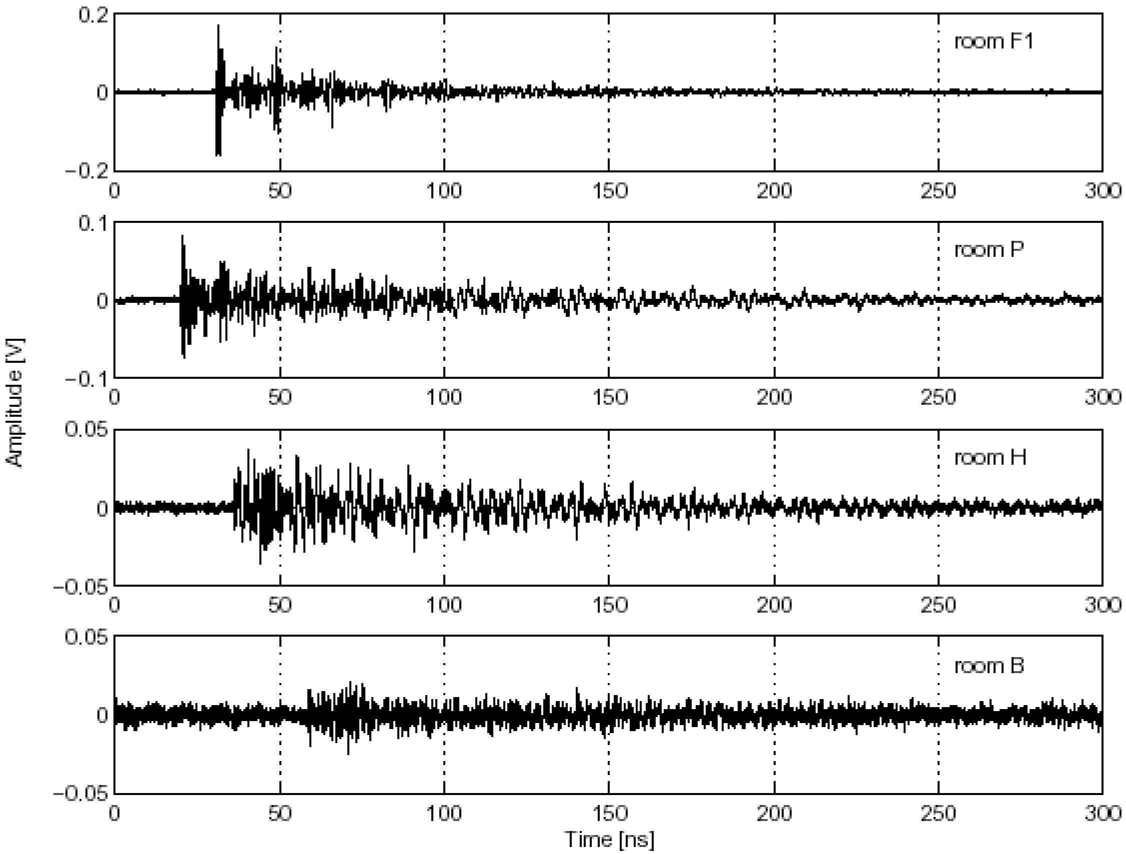
- Modern building with offices and labs
- *Multipath profiles*
  T = 300ns
- 14 rooms
  49 equidistant points
- 7 x 7 measurement grid
  with 90 cm side





Moe Z. Win, and Robert A. Scholtz, “Characterization of Ultra-Wide Bandwidth Wireless Indoor Channels: A Communication-Theoretic View”, IEEE Journal On Selected Areas In Communications, Vol. 20, No. 9, December 2002

Example of channel impulse responses



Room F1

LOS high SNR

Room P

NLOS high SNR

Room H

NLOS medium SNR

Room B

NLOS low SNR

In general, dense multipath is present composed of tens or hundreds paths

Channel model for dense multipath: IEEE 802.15.4a

The IEEE 802.15.4a UWB channel model is based on an extended version of the classical Saleh-Valenzuela (SV) indoor channel model, where multipath components arrive at the receiver in groups (clusters) following the Poisson distribution. According to the SV model, the complex baseband channel impulse response is given as

$$h_0(t) = \sum_{k=0}^{K} \sum_{l=0}^{L} a_{k,l} e^{\jmath \phi_{k,l}} \delta\left(t - T_k - \tau_{k,l}\right) \ ,$$

$a_{k,l}$: amplitude of the lth path in the kth cluster
T_k: delay of the kth cluster
$\tau_{k,l}$: delay of the lth path relative to the kth cluster arrival time T_k
$\phi_{k,l}$ are uniformly distributed in the range $[0, 2\pi)$
The number of clusters K is assumed to be Poisson distributed.
The ray arrival times $\tau_{k,l}$ are modeled with mixtures of two Poisson processes
The small-scale fading, which characterizes the path amplitudes $a_{k,l}$, follows a Nakagami-m distribution

The Power Delay Profile (PDP) is assumed exponential negative within each cluster

$$\Lambda_{k,l} = \mathbb{E}\left\{|a_{k,l}|^2\right\} \propto \exp(-\tau_{k,l}/\epsilon_k)$$

ϵ_k is the intra-cluster decay time constant.

Simplified channel model for lower frequencies

Another widely adopted model is the dense multipath model with a single cluster composed of L independent equally spaced paths and exponential PDP. In this case the real impulse response is given by

$$h(t) = \sum_{l=0}^{L} a_l \, p_l \, \delta\left(t - \tau_l\right)$$

$\tau_l = \tau_1 + (l-1)\,\Delta$
Δ: resolvable time interval
a_l: path amplitude with Nakagami-m statistics
p_l is a r.v. which takes, with equal probability, the values $\{-1, +1\}$

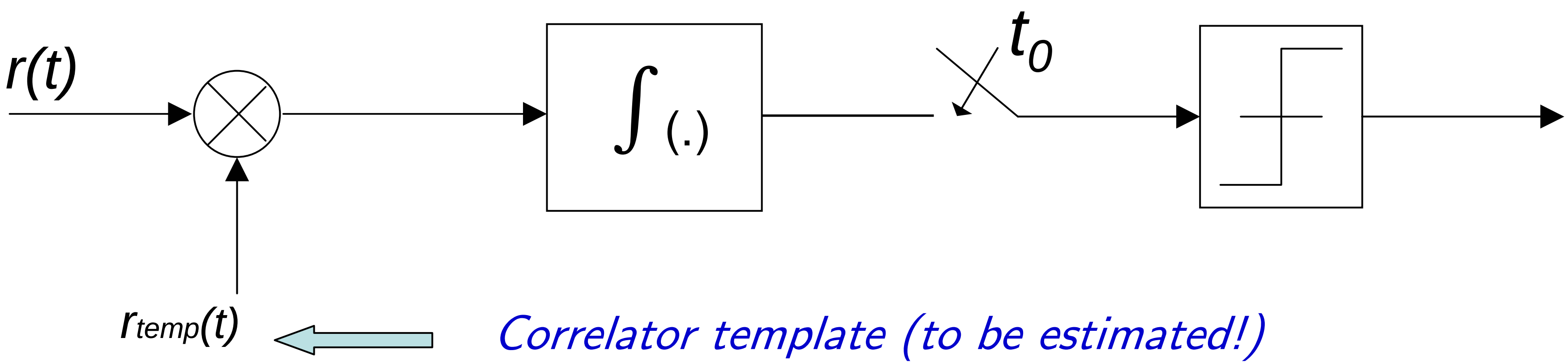
Exponential negative PDP

$$\Lambda_l = \mathbb{E}\left\{|a_l|^2\right\} = \frac{(e^{\Delta/\epsilon}-1)e^{-\Delta(l-1)/\epsilon}}{e^{\Delta/\epsilon}(1-e^{L\,\Delta/\epsilon})} \qquad \epsilon\text{: decay time constant.}$$

A. F. Molisch, D. Cassioli, C.-C. Chong, S. Emami, A. Fort, B. Kannan, J. Karedal, J. Kunisch, H. Schantz, K. Siwiak, and M. Z. Win, "A comprehensive standardized model for ultrawideband propagation channels," *IEEE Trans. Antennas Propag.*, vol. 54, no. 11, pp. 3151–3166, Nov. 2006, Special Issue on Wireless Communications.

UWB receivers for multipath propagation

Receivers for multipath propagation: ideal MF Receiver



Correlator template (to be estimated!)

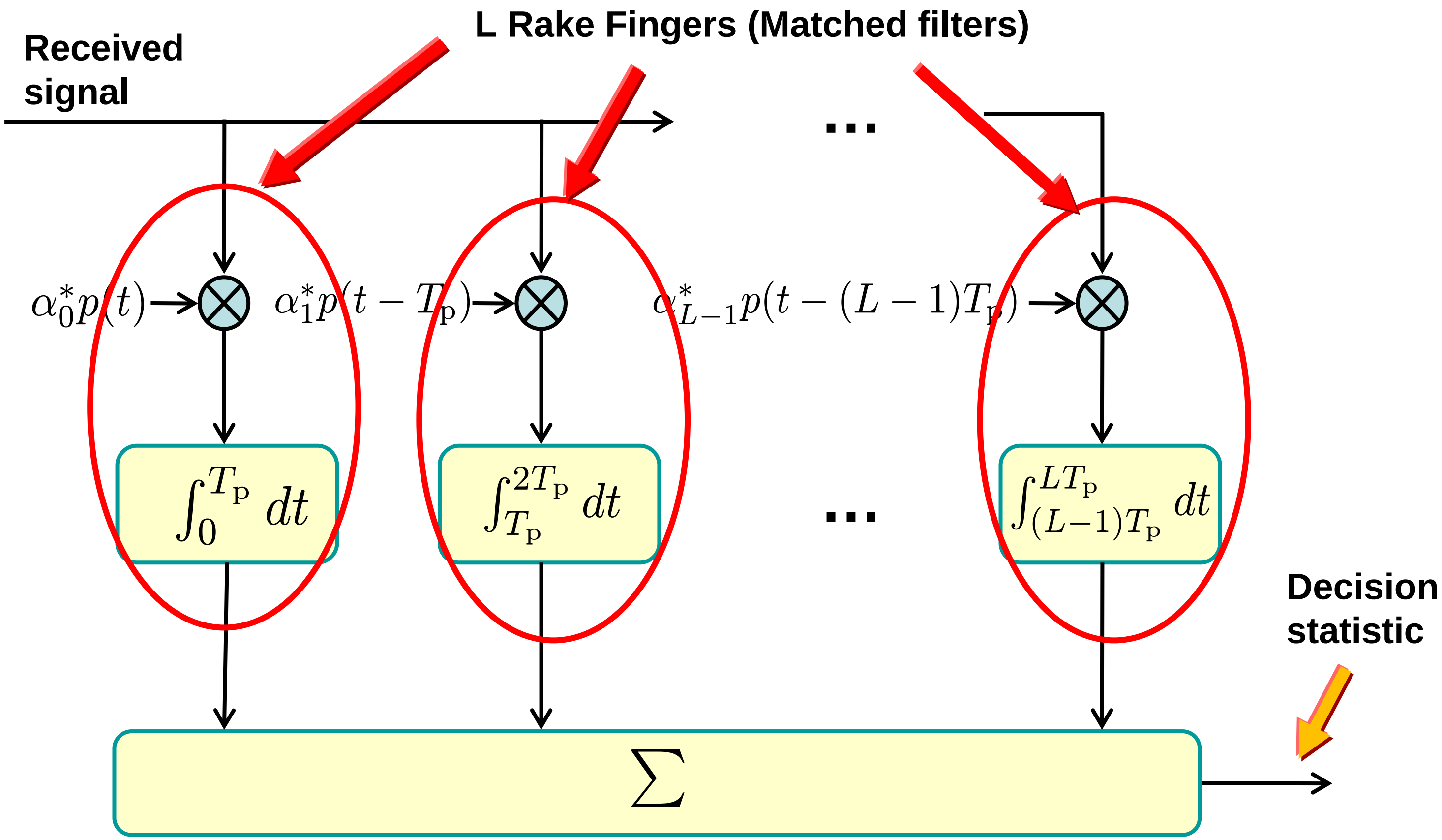
In case of antipodal signaling the error probability is $P_{\mathsf{e}} = \frac{1}{2}\operatorname{erfc}\sqrt{\frac{E_{\mathsf{b}}\eta_{\mathsf{cap}}}{N_0}}$

$$\eta_{\mathsf{cap}} = \frac{\left[\int_{-\infty}^{\infty} r(t)\, r_{\mathsf{temp}}(t)\, dt\right]^2}{\int_{-\infty}^{\infty} r^2(t)\, dt \int_{-\infty}^{\infty} r_{\mathsf{temp}}^2(t)\, dt}$$

Energy capture efficiency

The Rake receiver

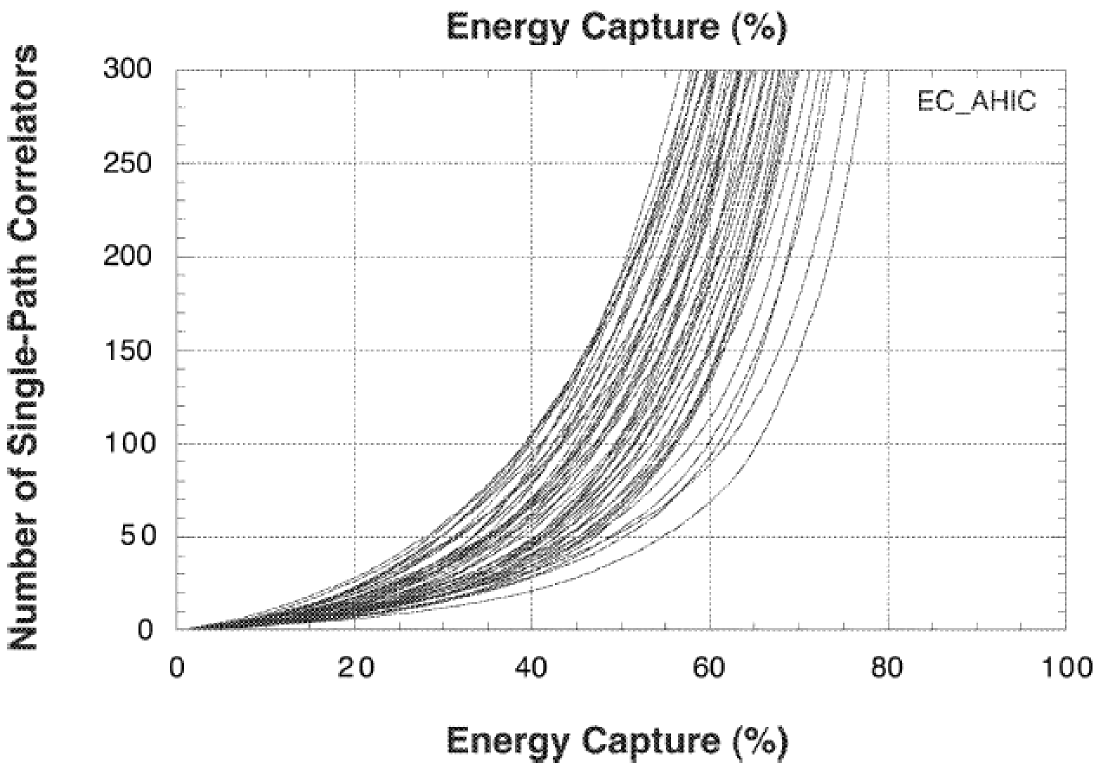
The RAKE (baseband) receiver combines the signals coming over resolvable propagation paths in a way that maximizes the energy-per-bit-to-noise density ratio



Multipath energy captured depends on number of Rake fingers

Energy capture: experimental results

The number of single-path signal correlators in a UWB Rake receiver as a function of percentage energy capture for received waveforms in an office P representing typical "high SNR". 49 measurement waveforms are used.



Moe Z. Win, and Robert A. Scholtz, "Characterization of Ultra-Wide Bandwidth Wireless Indoor Channels: A Communication-Theoretic View", IEEE Journal On Selected Areas In Communications, Vol. 20, No. 9, December 2002

Simplified Rake receivers

Due to the huge number of echoes, the implementation of an ideal Rake receiver (All Rake) could be prohibitive (requires a perfect channel estimator)

Partial Rake (PRake): only the first K echoes are estimated

Selective Rake (SRake): only the strongest K echoes are estimated

PRake and SRake receivers have reduced complexity since only a few echoes have to be estimated.

Theoretical performance of PRake with Uniform PDP

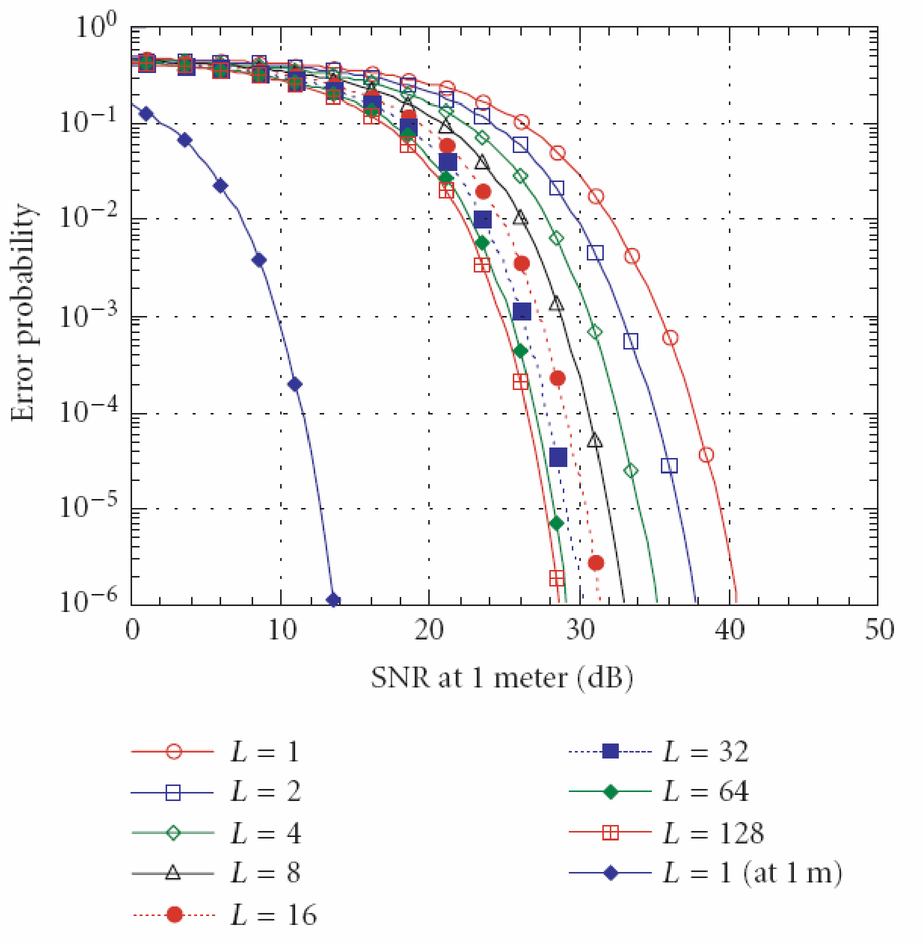
Bit error probability with Nakagami fading and uniform PDP

$$P_{\mathrm{e,PRake}} = \frac{1}{\pi} \int_0^{\frac{\pi}{2}} \left(1 + \frac{\bar{\gamma}}{m \sin^2 \theta}\right)^{-mL_{\mathrm{p}}} d\theta, \qquad \bar{\gamma} = \frac{E_s}{LN_0}.$$

L_p: number of fingers
L: number of echoes
E_s: received energy per symbol
m: Nakagami-m parameter

Performance of Selective Rake Receiver

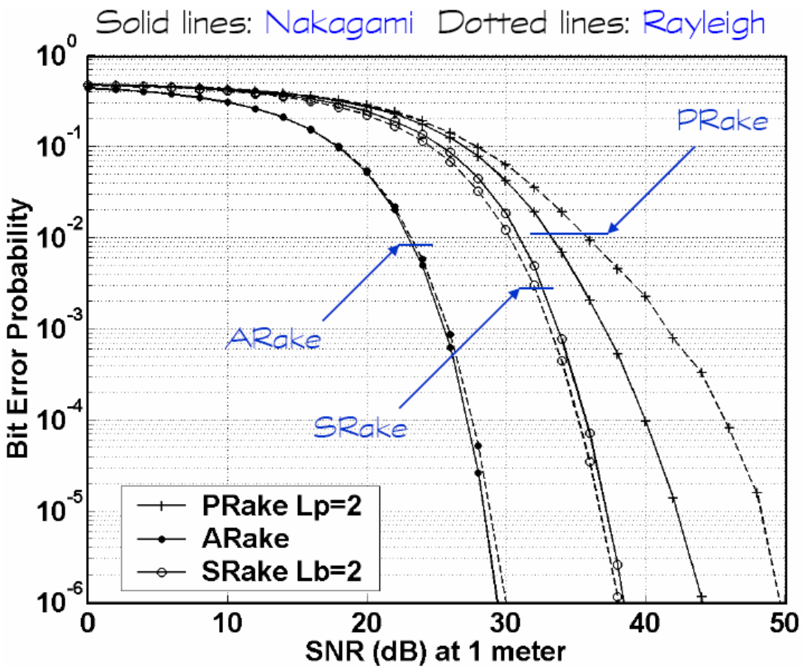
BEP performance of optimal selective Rake receiver in office P representing typical "high SNR", as a function of the number L of signal components combined. Experimental results



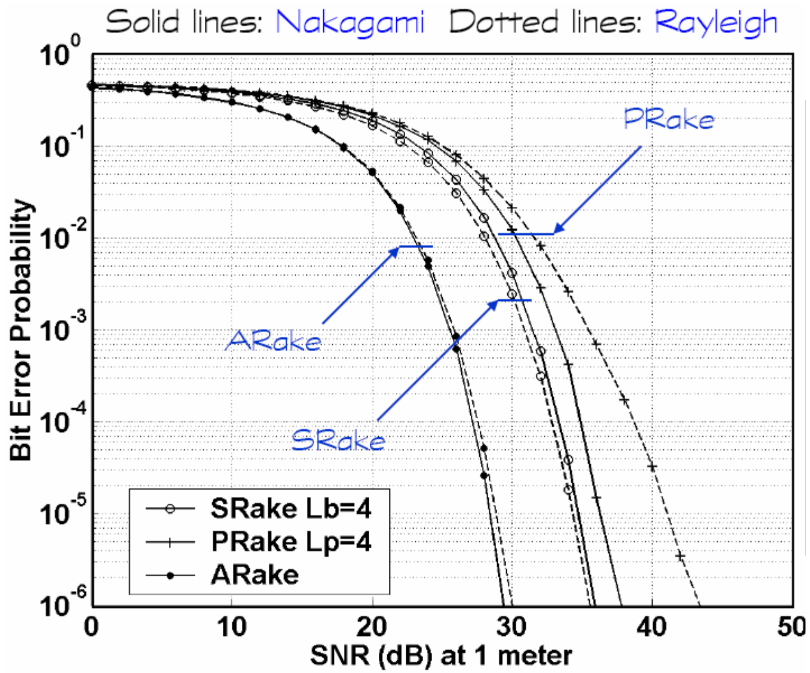
Moe Z. Win, and Robert A. Scholtz, "Characterization of Ultra-Wide Bandwidth Wireless Indoor Channels: A Communication-Theoretic View", IEEE Journal On Selected Areas In Communications, Vol. 20, No. 9, December 2002

Comparison using Statistical Channel Models

L=2



L=4



ARake and SRake not sensitive to channel model
PRake performs better in Nakagami channel models

Remarks

Ultra-wide bandwidth provides robust performance in multipath environment

Less severe signal fading due to multipath propagation means fade margin of only a few dB (lower TX power)

Extremely short pulses enable resolution and constructive use of multipath energy using RAKE receiver techniques (diversity gain)

Excellent candidate for low-cost, short-range, high speed (greater than 100Mbit/s) wireless communications in indoor environments

Low-complexity UWB receivers

Low-Complexity Receiver schemes

Rake Receivers

- Require a large number of fingers to capture most of the multipath energy
- Require accurate acquisition and channel estimation
- Highly complex due to large number of multipath components
- Best performance

Towards lower complexity schemes

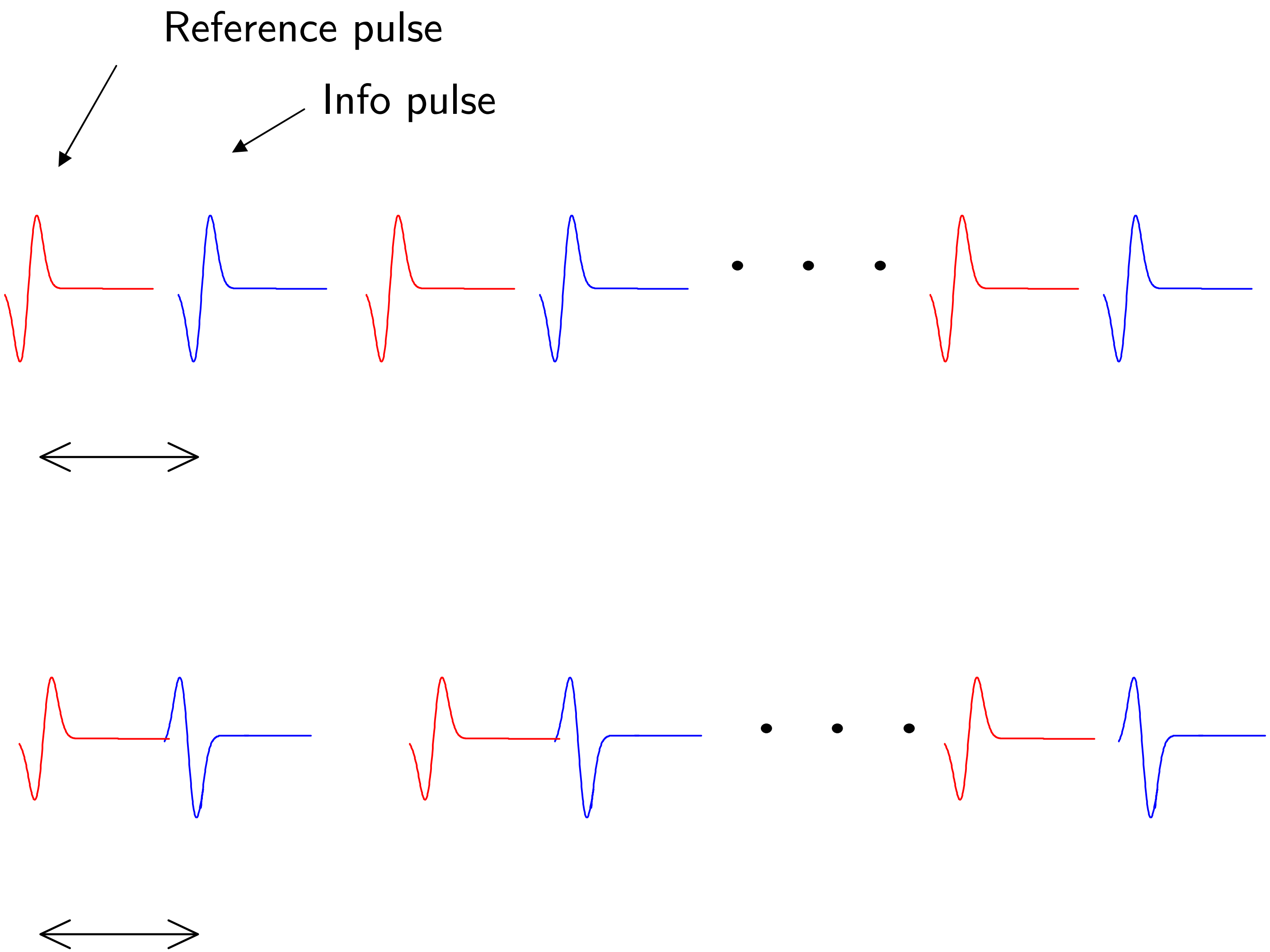
Transmitted Reference (TR) Receiver

- Reference signal is transmitted along with the data
- Receiver is simply an autocorrelation receiver (AcR)
- Can exploit multipath diversity inherent in the environment without the need for channel estimation and stringent acquisition.
- Performance loss

Energy Detector (ED)-based Receiver

- Based on energy detector
- Very simple scheme (no channel estimation neither stringent acquisition)
- Performance loss

Transmitted Reference (TR) Signaling



$$a_j = \{+1 \quad +1 \quad \cdots \quad +1\}$$

$$d_i = +1$$

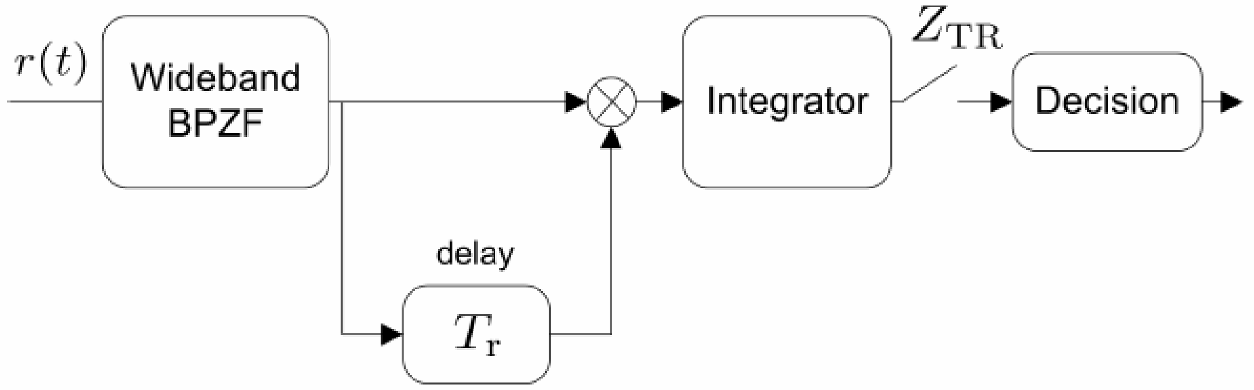
$$a_j = \{+1 \quad +1 \quad \cdots \quad +1\}$$

$$d_i = -1$$

+1

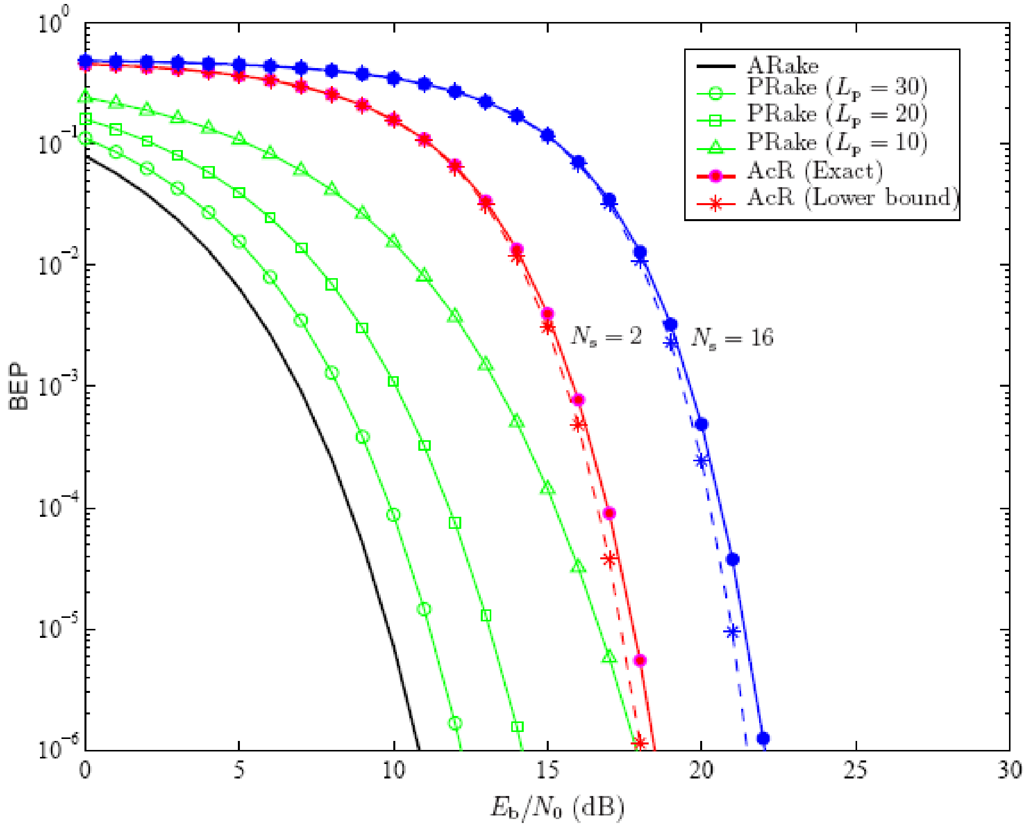
Transmitted Reference Receiver

Autocorrelation receiver (AcR)



T: integration time
W: signal bandwidth

Performance comparison between different schemes



BEP performance comparison between TR signaling with AcR, PRake and ARake receivers with constant PDP, Nakagami-m fading ($m = 2.0$) and $WT = L$.

L_p: number of Rake fingers

L: number of paths

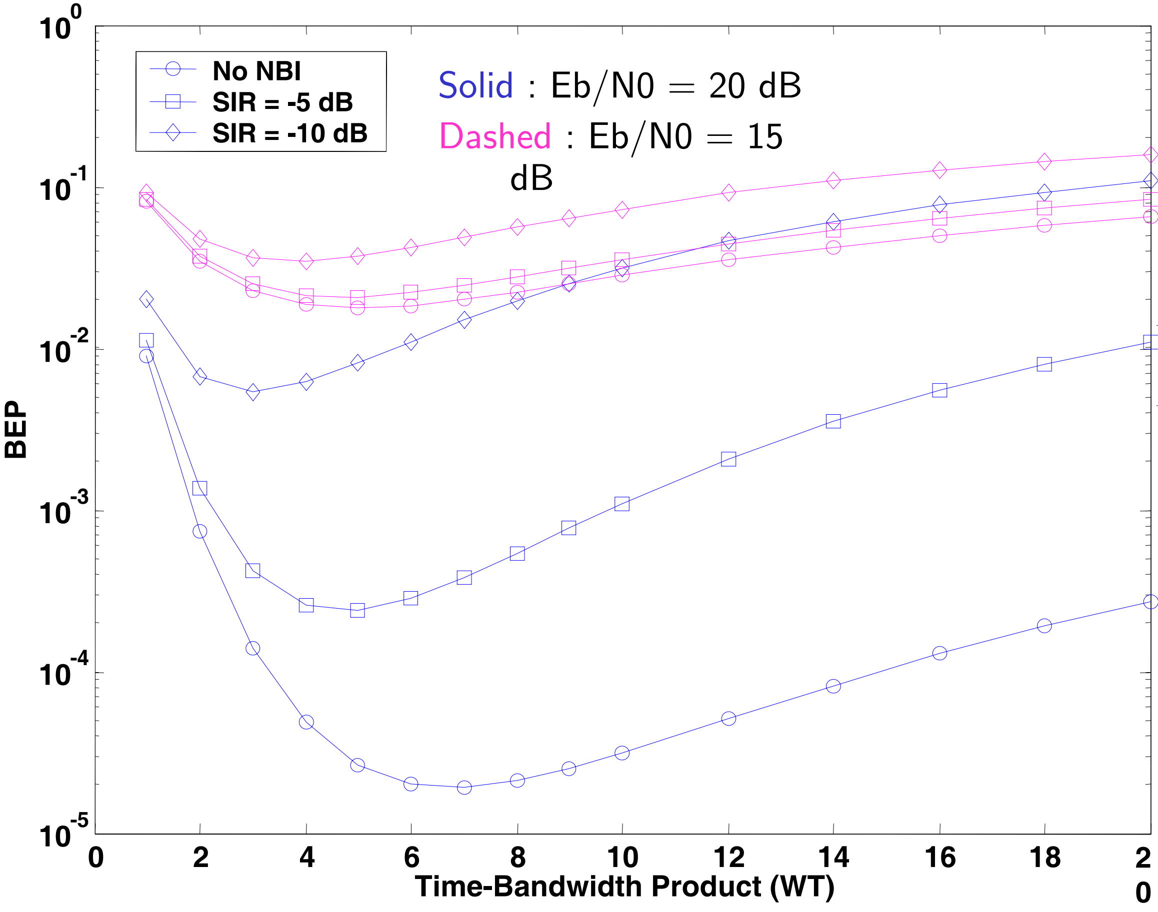
Main issues

- Subject to degradation due to *S x N* and *N x N* terms
  - Can perform noise averaging of reference signals at the AcR (such a receiver is referred to as Modified AcR)
  - How to choose the integration time *T ?*
- Wastage of communication resource
  - Can exploit differential encoding (this alternative signaling is referred to as Differential Transmitted Reference (DTR) signaling)

T. Q. S. Quek and M. Z. Win, “Analysis of UWB transmitted-reference communication systems in dense multipath channels,” *IEEE J. Select. Areas Commun.*, vol. 23, pp. 1863–1874, Sept. 2005.

Effect of T on Performance of TR Signaling

With and without narrowband interference – exponential PDP



- Optimum T depends on channel PDP
- Optimum T increases as E_b/N_0 and SIR increases

T. Q. S. Quek, M. Z. Win, and D. Dardari, "Unified analysis of UWB transmitted-reference schemes in the presence of narrowband interference," *IEEE Trans. Wireless Commun.*, vol. 6, no. 6, pp. 2126–2139, jun 2007.

The choice of the integration interval T is critical

Problems

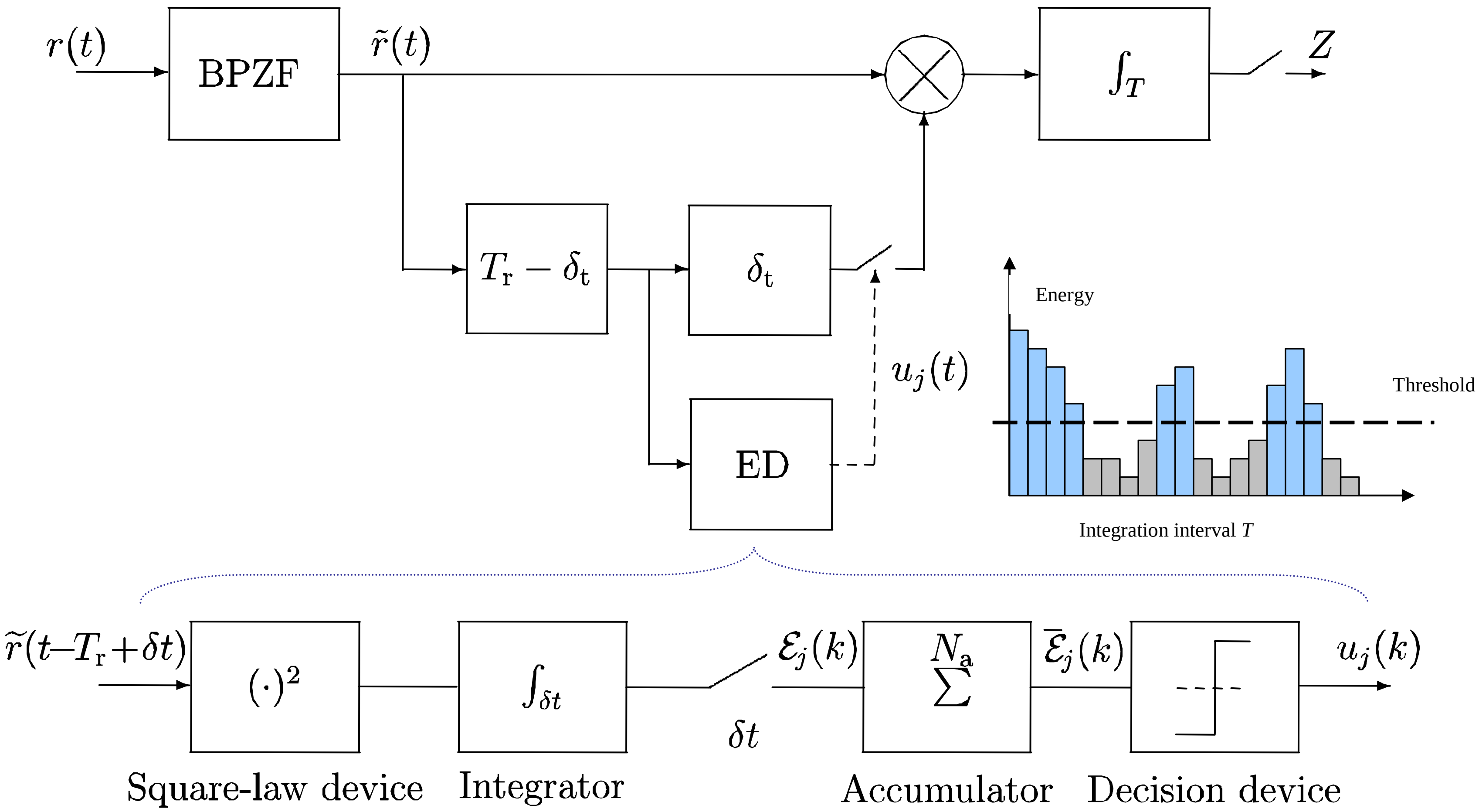
- the integration interval T must be optimized

  small $T \rightarrow$ part of useful energy not collected
  large $T \rightarrow$ excessive noise collection

- the optimal choice of T depends on the channel PDP (need to be estimated $\rightarrow$ complexity increase)

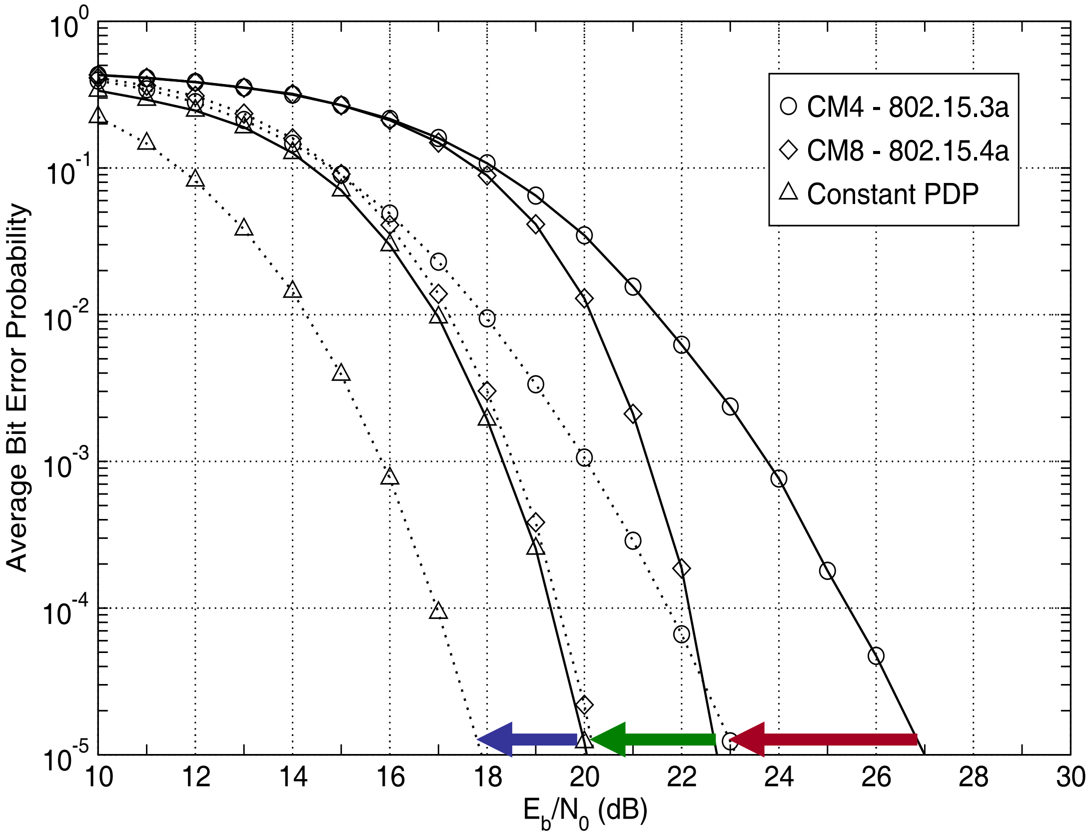
- when the channel PDP involves clusters, the collection of noise is unavoidable regardless the choice of T

The Stop-and-Go AcR



D. Dardari, A. Giorgetti, M. Chiani, and M. Z. Win, "A stop-and-go transmitted-reference UWB receiver," in *IEEE International Conference on Ultra-Wideband, ICUWB 2006*, Waltham, MA, USA, Sept. 2006, pp. 309–314.

Stop-and-Go vs Conventional AcR



Ns=2 pulses per bit
Tp=0.192 ns
W=1/Tp (BPZF bandwidth)
fc=7.2 GHz
WT=600

Advantage of the SaG-AcR on the performance with the optimal threshold λ/No=-1.5dB.

The IEEE 802.15.4a standard

Overview of IEEE 802.15.4 (ZigBee)

Features:

- Low Data Rate
- Low Power Consumption
- Low Cost
- Self-Organization and Flexible Topology

Property	Range
Raw Data Rate	868 MHz: 20 kb/s; 915 MHz: 40 kb/s; 2.4 GHz: 250kb/s
Range	10-20 m
Latency	< 40 ms
Channels	868/915 MHz: 11 channels; 2.4 GHz: 16 channels
Frequency Band	868 MHz/915 MHz and 2.4 GHz
Channel Access	CSMA-CA and slotted CSMA-CA

The IEEE 802.15.4a

As an amendment to 802.15.4 for an **alternative PHY** to provide (2007):

- High precision **ranging/location** capability
- Ultra **low power**
- **Lower cost**
- High aggregate throughput
- Scalability to data rates
- Longer range

Home automation

and.. WSNs, health care monitoring…

Asset tracking

Physical layers

The amendment adds two new PHYs:

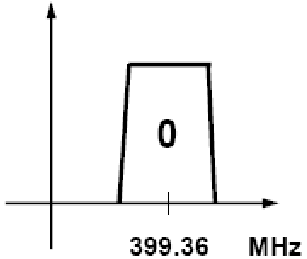
- **150 - 650 MHz** and **3.1 - 10.6 GHz** **Ultra-Wide Band (UWB)**
  - **Impulse Radio (IR)** based signaling
  - Mandatory nominal data rate of 1 Mbps
  - Modulation: Combination of BPM (burst position mod.) and BPSK
- 2450 MHz Chirp Spread Spectrum (CSS)

Property	Characteristics
Raw Data Rate	1 Mb/s
Range	Several hundred meters
Latency	< 10 ms
Channels	UWB: 16 channels CSS: 14 channels
Frequency Band	UWB: 150-650 MHz and 3.1-10.6 GHz CSS: 2450 MHz
Channel Access	UWB: ALOHA CSS: CSMA-CA

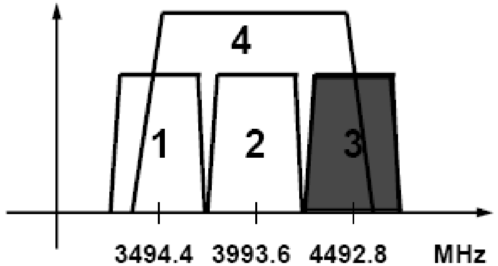
UWB PHY: Channels

A compliant UWB device shall be capable of transmitting in at least one of three specified bands.

- Sub-GHz Band: **150 – 650 MHz**

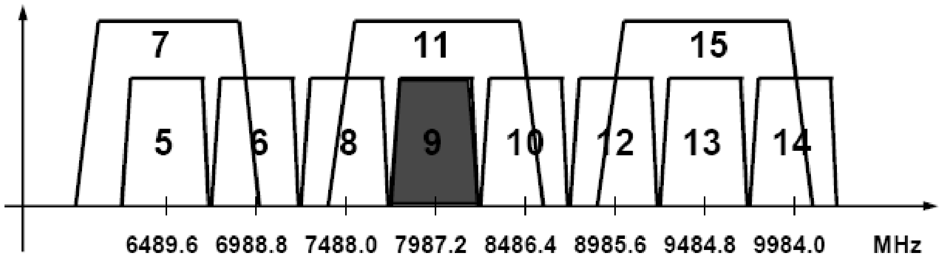


- Low Frequency Band (LFB): **3244 - 4742 MHz**



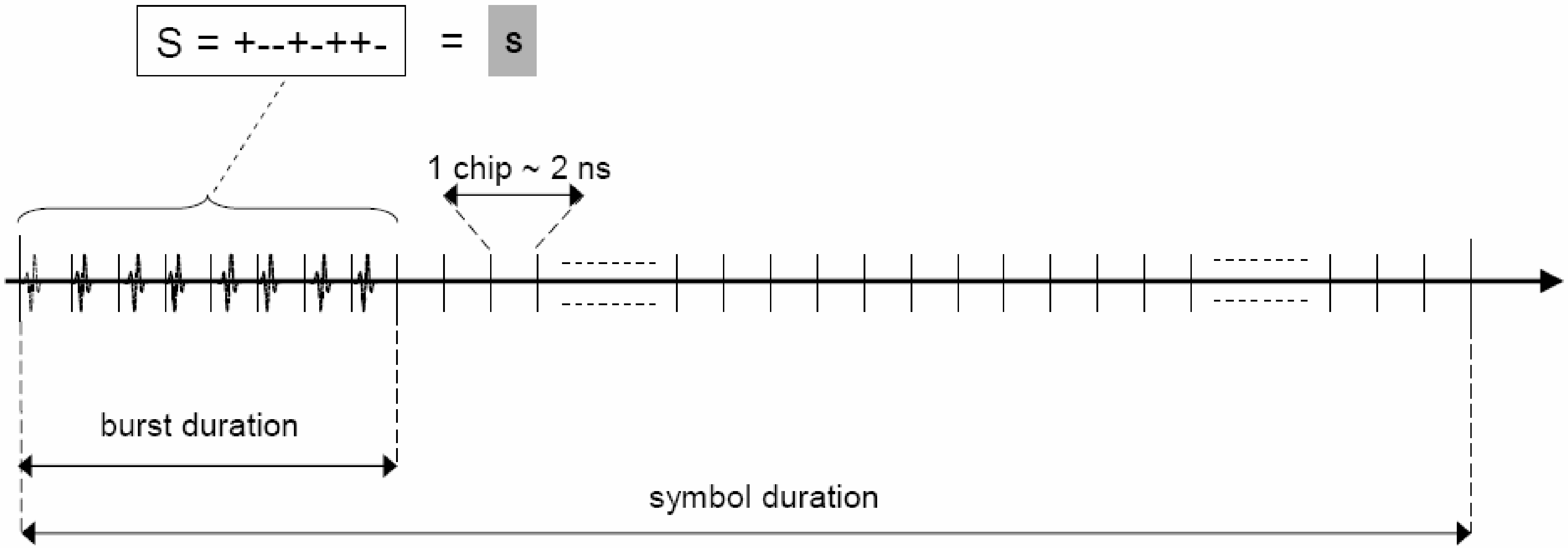
- High Frequency Band (HFB): **5944 – 10234 MHz**

: Mandatory channel



UWB-PHY: Bursts

- Each information-bearing symbol is represented by a **burst** of short time duration pulses
- The duration of an individual pulse is nominally considered to be the length of a **chip**
- Chip duration is equal to **2.02429 ns** (Bandwidth > 494MHz)

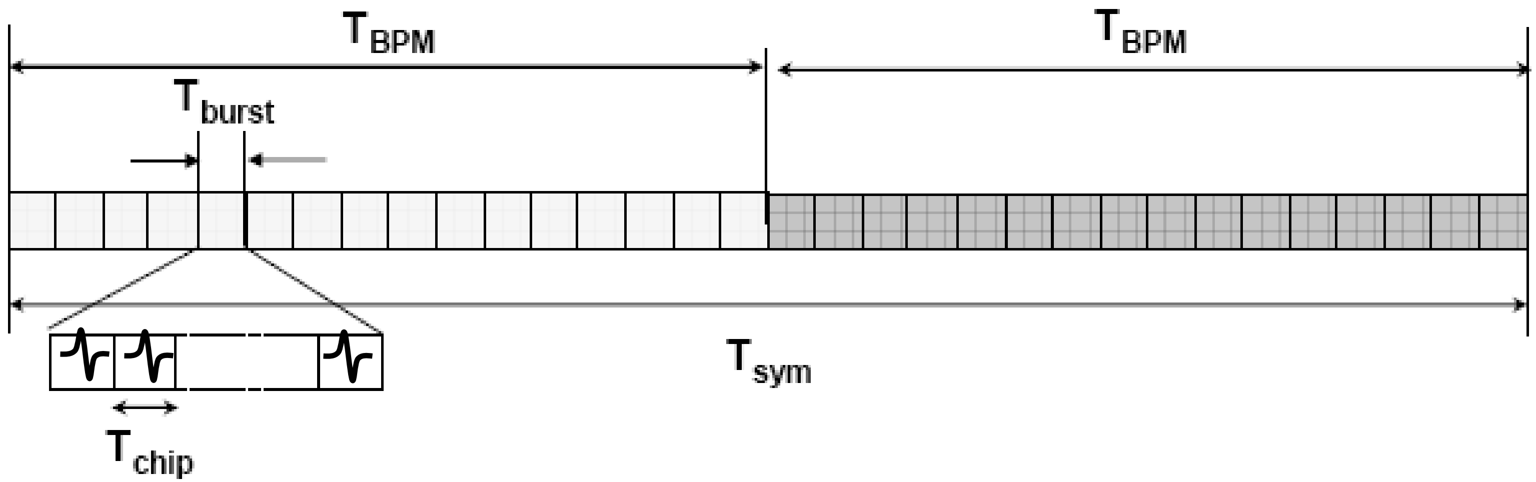


UWB PHY: Modulation

Combination of **burst position modulation (BPM)** and **binary phase shift keying (BPSK)**

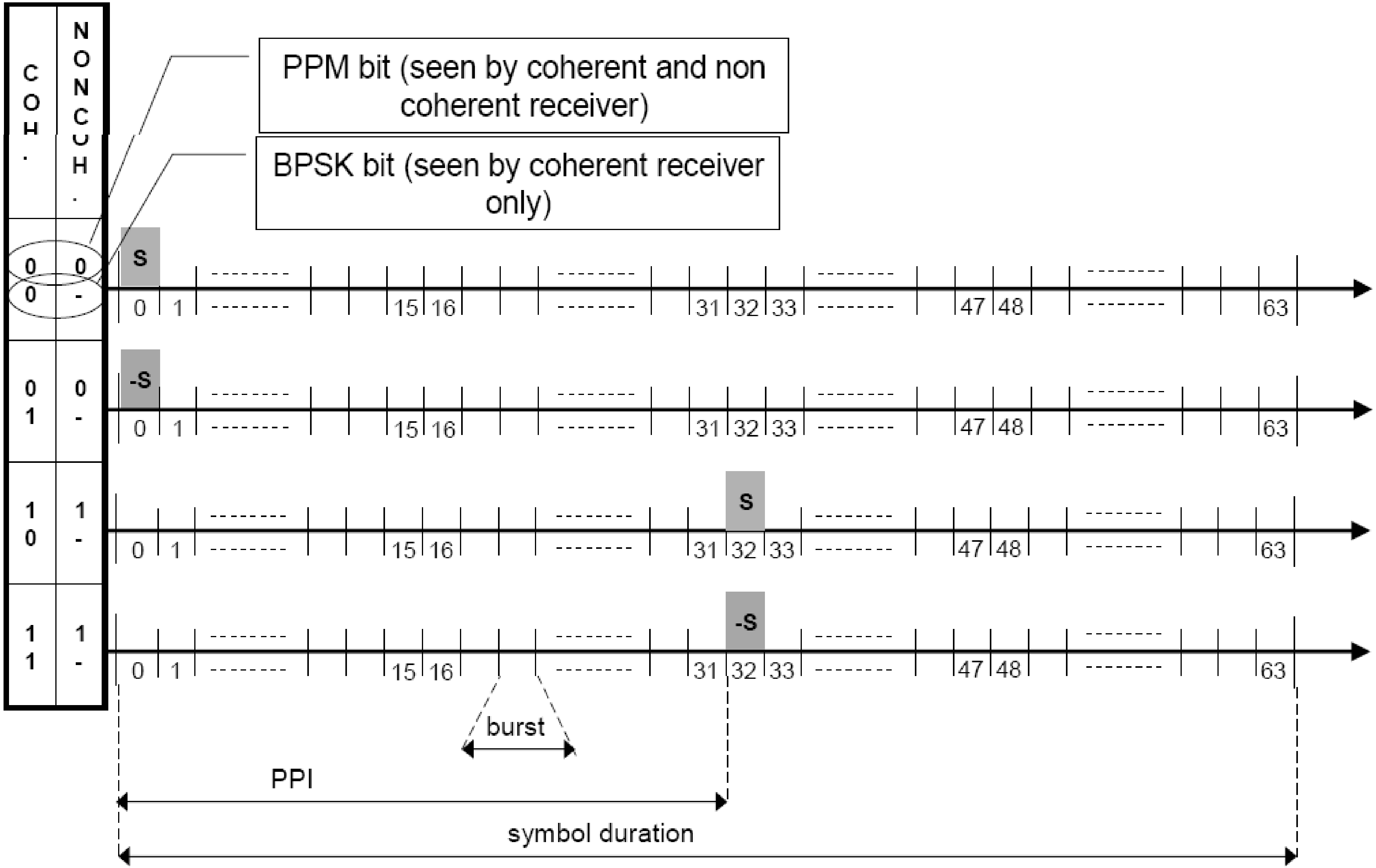
A UWB PHY symbol carries two bits of information: one bit for the position of a burst and the other bit for the phase (parity) of the burst.

- Each symbol can have 8, 16, 32, 64, and 128 possible slots for a burst.
- A symbol period is divided into two BPM intervals, and a burst occurs one of two intervals.
- A burst is formed by grouping 2^n, n=0, 1, 2, ..., 9 consecutive chips.



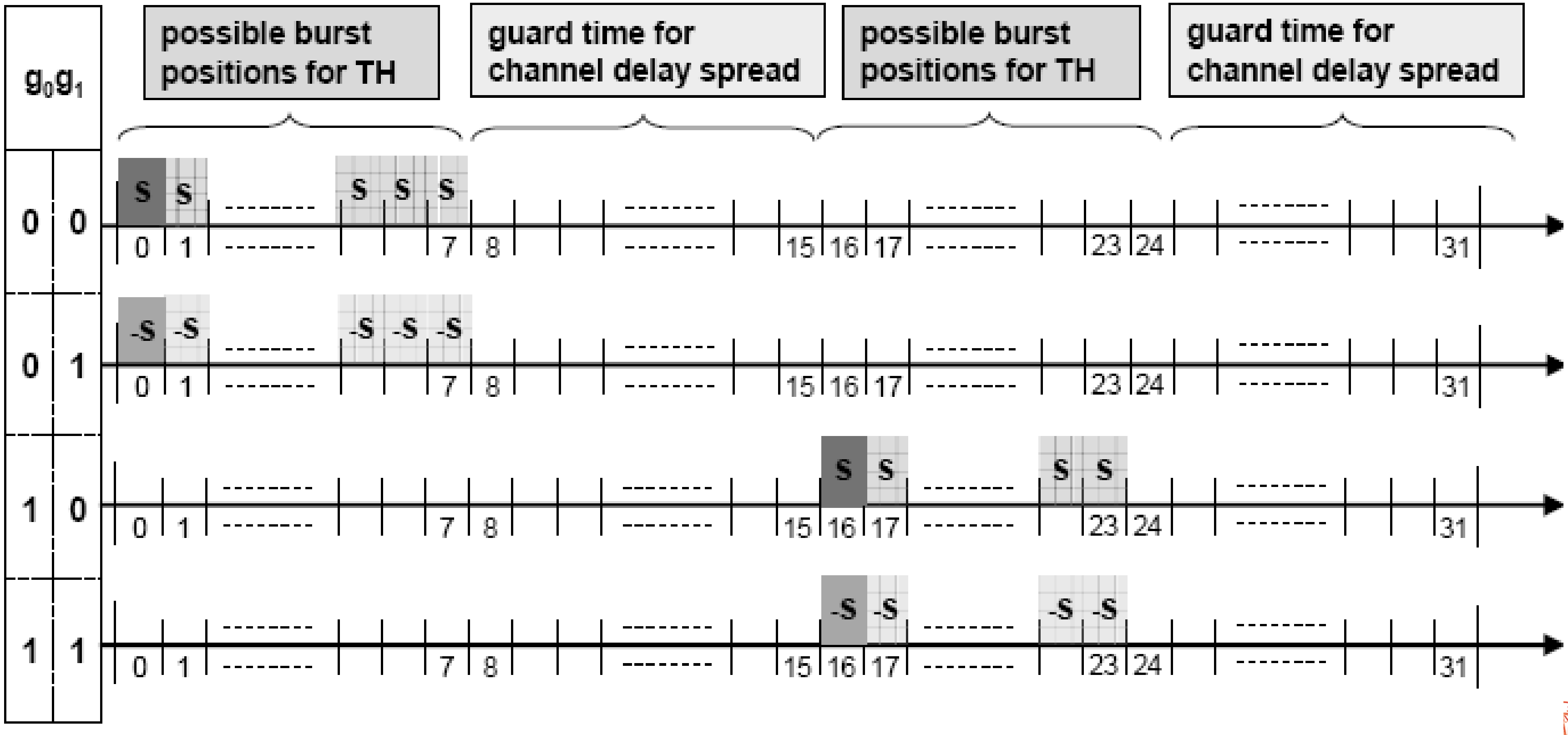
The symbol structure

The UWB-PHY supports both coherent and non-coherent receivers.



UWB-PHY: Spreading

- The UWB PHY provides interference suppression through **scrambling** and **time-hopping**.
- *Scrambling:* each symbol contains a single burst of pulses, which are scrambled by a time-varying scrambling sequence.
- *Time Hopping:* each burst position varies from one symbol to the next according to a time hopping code.



UWB-PHY: Pulse shape

- The transmitted pulse shall have a cross correlation with a reference pulse *r(t),* whose main lobe is greater or equal to 1 to 0.8 for a duration of at least 0.5 ns and any side lobe shall be no greater that 0.3.

- The reference pulse *r(t)* is a root raise cosine pulse with roll-off factor of $\beta = 0.6$

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

- Optional pulse shapes are: Chirp on UWB (CoU) pulses, Continuous Spectrum (CS) pulses, Linear combination of pulses (LCP)

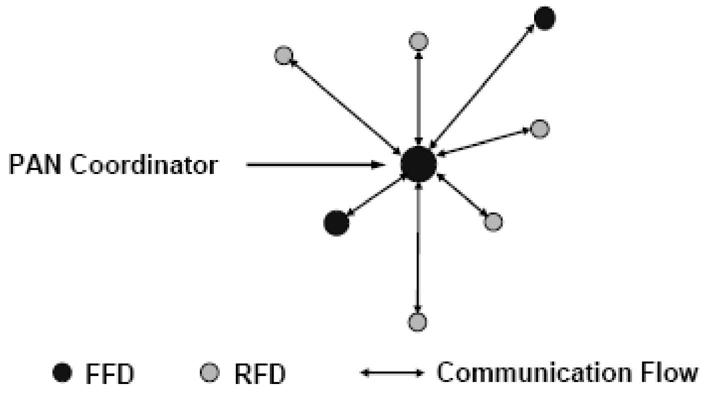
Device Types

- **Fully-function device (FFD)**
  - Any topology
  - PAN coordinator
  - Talks to any other device
  - Capable of perform energy detection (ED) and active scans

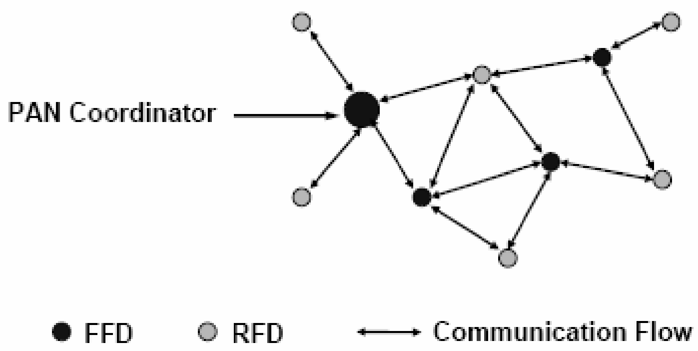
- **Reduced-function device (RFD)**
  - Limited to star topology
  - Talks only to an FFD
  - Simple implementation and application

Topology

- Star topology: Communication is established between devices and a single central controller,called the PAN coordinator.



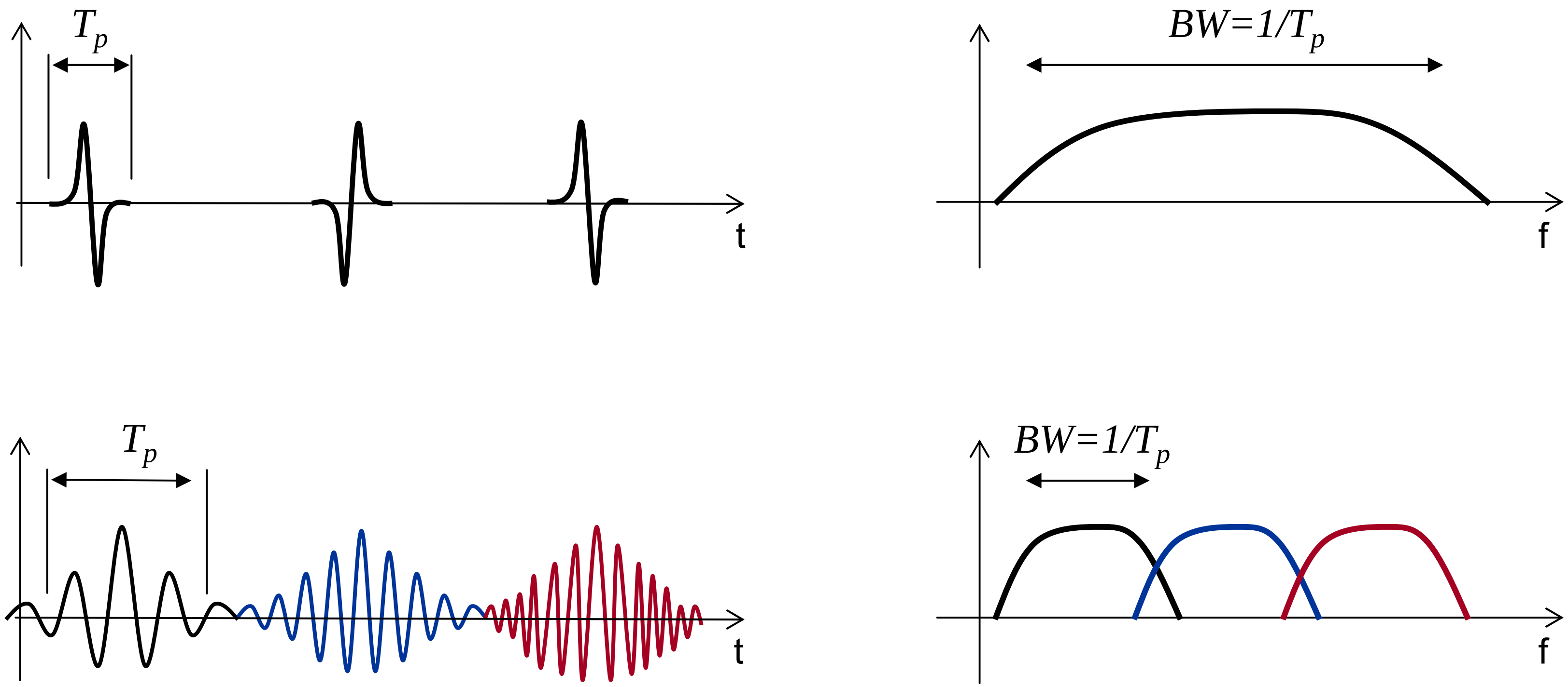
- Peer-to-Peer Topology: Any device can communicate with any other device as long as they are in range of one another.



MultiBand – OFDM:
a different approach to UWB

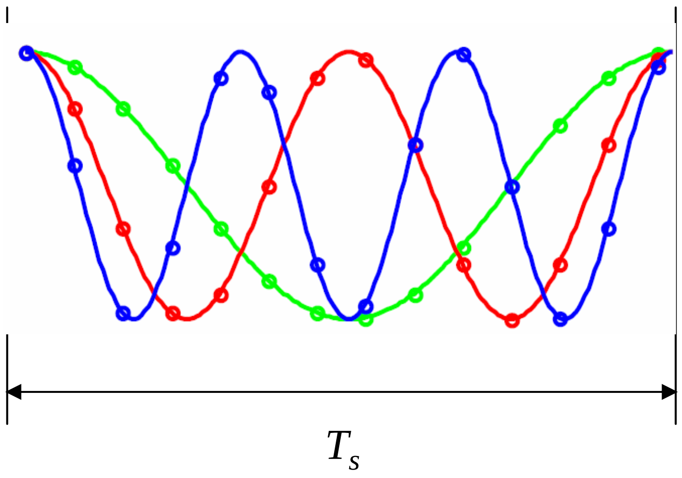
From Impulse Radio to Pulsed Multiband...

Worldwide UWB regulation does not specify the technology, just PSD limits! We can think in a big way!



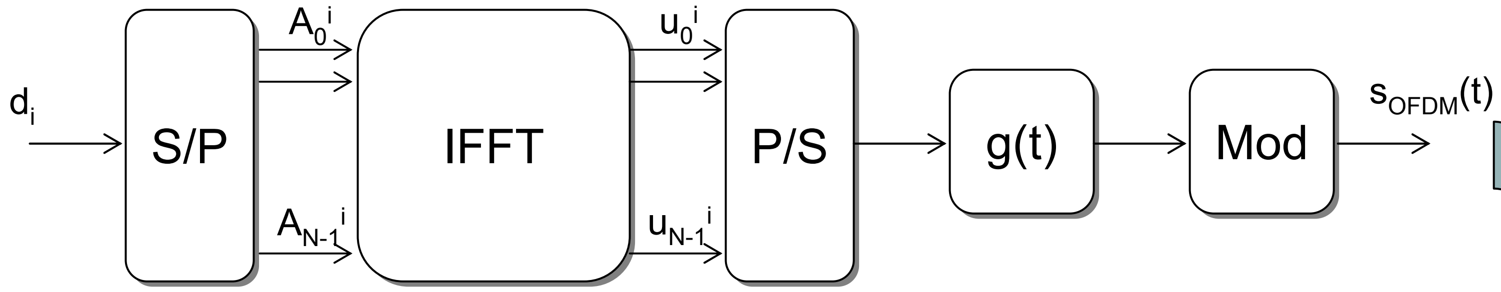
…to Orthogonal Frequency Division Multiplexing (OFDM)

- Each subcarrier has a different frequency
- Frequencies chosen so that an integral number of cycles in a symbol period
- Signals are mathematically orthogonal

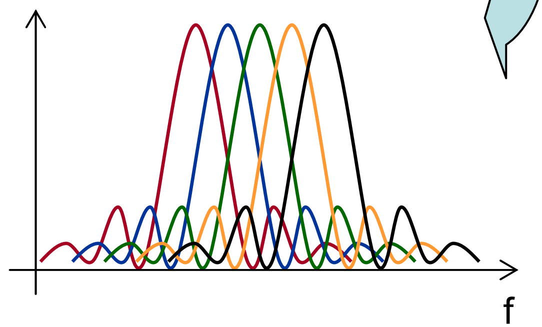


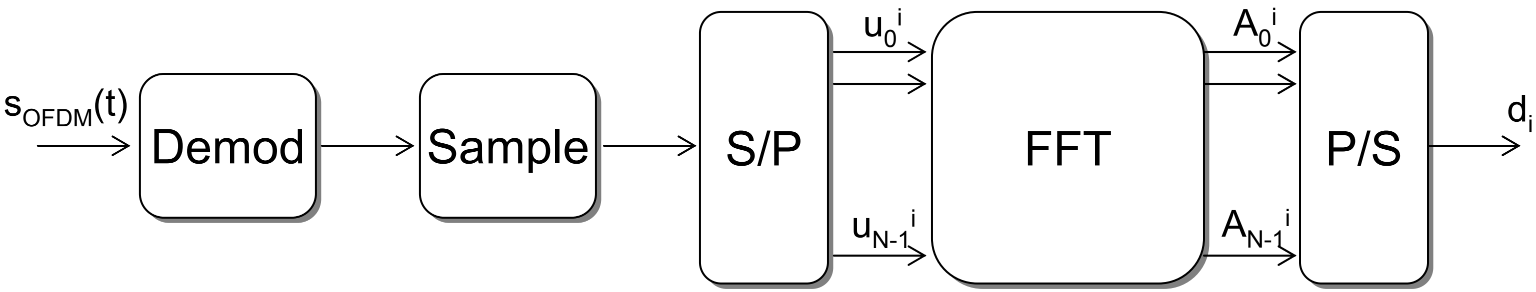
- Data is carried by varying the phase or amplitude of each subcarrier: BPSK, QPSK, 4-QAM, 16-QAM, 64-QAM..

OFDM



$$s_{\text{OFDM}}(t) = \mathcal{R}_e \left\{ \sum_{i=-\infty}^{+\infty} \sum_{n=1}^{N} A_n^i \, g(t - iT_s) \, e^{j2\pi f_n (t-\tau)+\psi} \right\}$$



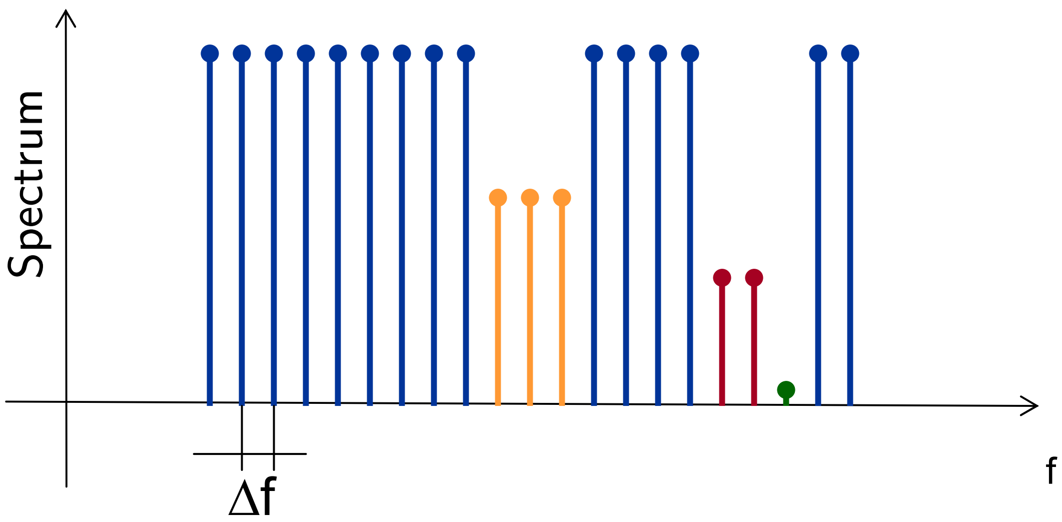


Why OFDM? 1/4

- Invented many years ago
- It is a successful technology adopted in many standards:
  - IEEE 802.11a/g/n, WiMax, Digital Audio Broadcasting (DAB), Digital Video Broadcasting (DVB), xDSL…
- Spectral efficiency: sub-carriers do not interfere even they are overlapped
- Can cope with multipath (neither Rake nor complex equalization)
- Can cope with narrowband interference (NBI)

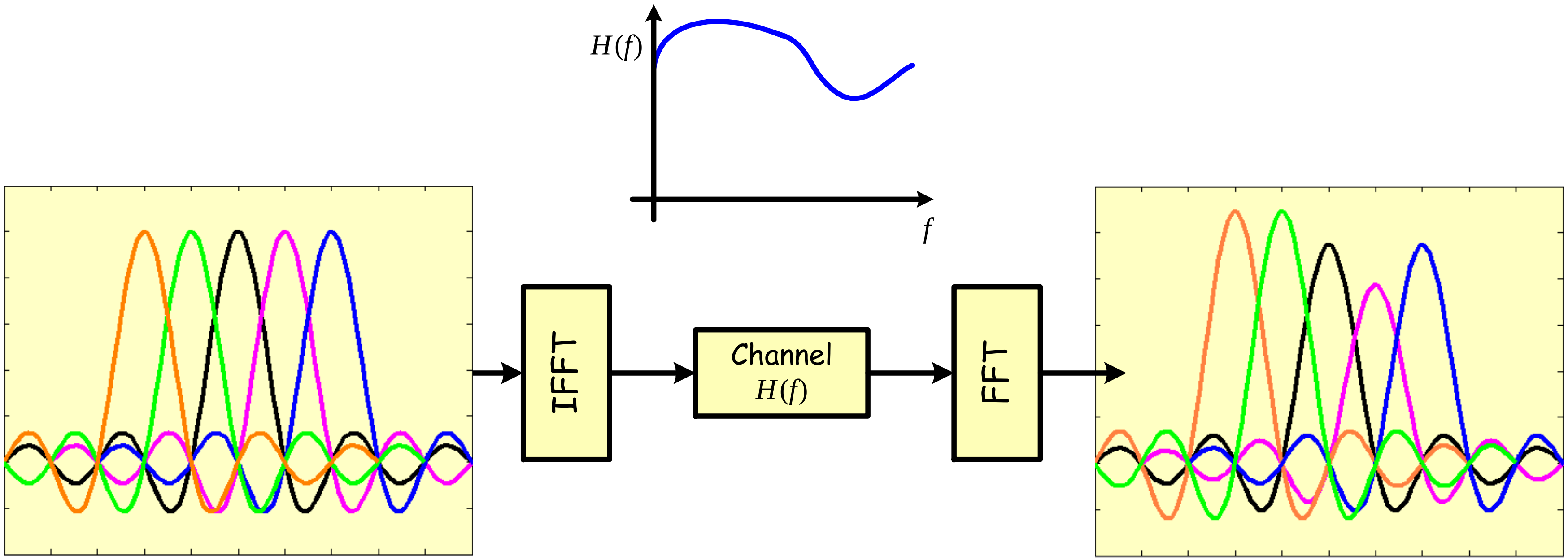
Why OFDM 2/4

- Ability to comply with worldwide regulations:
  - Channels and tones can be turned on/off dynamically to comply with changing regulations.
- Can arbitrarily shape spectrum in software with a resolution of subcarrier spacing Δf. → ***coexistence with existing systems***



Why OFDM 3/4

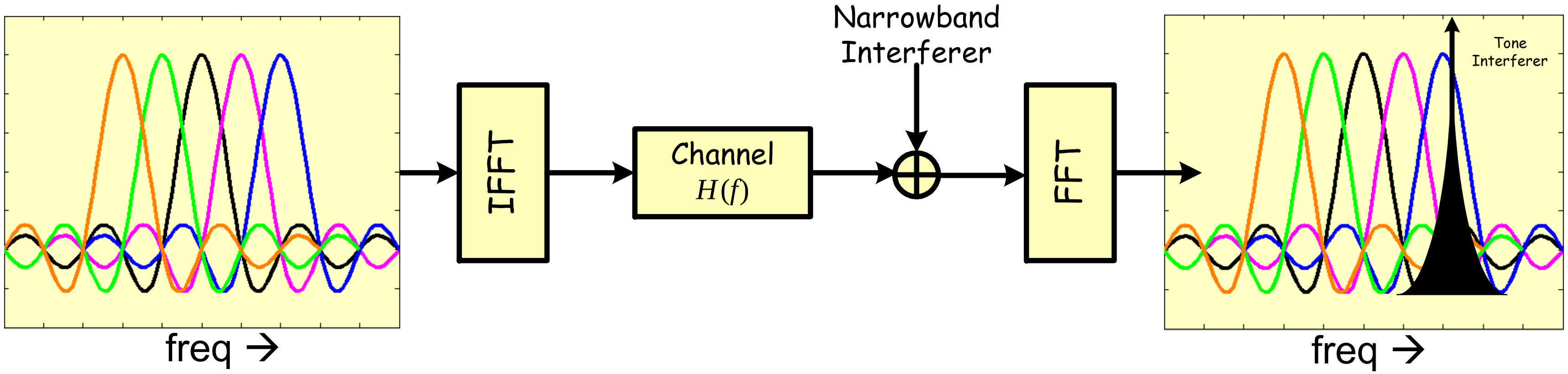
- OFDM has excellent robustness to multipath



from Dave Leeper, Overview of MB-OFDM, WiMedia™ Alliance, Intel Corporation

Why OFDM? 4/4

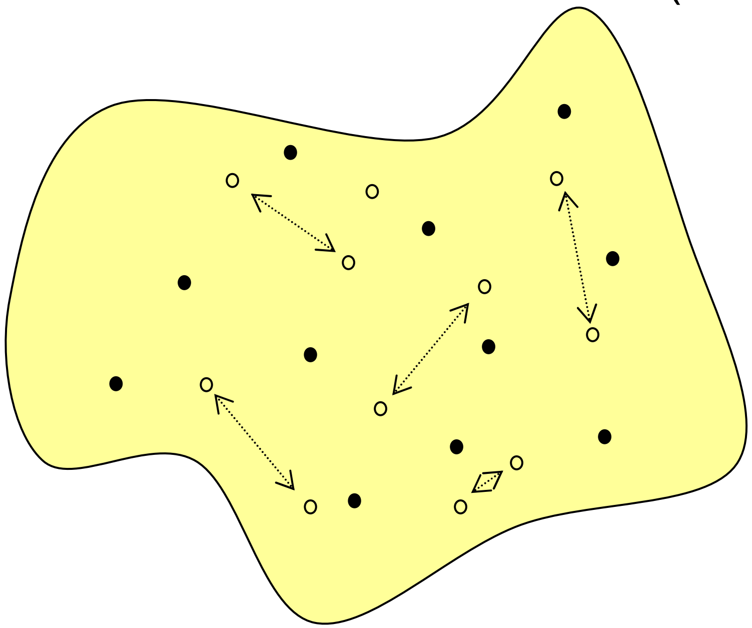
- OFDM is robust against narrowband interference:
  - Narrowband interference will affect at most a couple of tones.
  - Do not have to drop the entire band because of narrowband interference.
  - Erase information from the affected tones, since they are known to be unreliable. Already-present FEC recovers lost information.



from Dave Leeper, Overview of MB-OFDM, WiMedia™ Alliance, Intel Corporation

Why not OFDM? The revenge of Impulse Radio

For instance if we are dealing with complexity and/or energy consumption constraints such as in wireless sensor networks (WSNs) ….



… probably OFDM is not the best choice

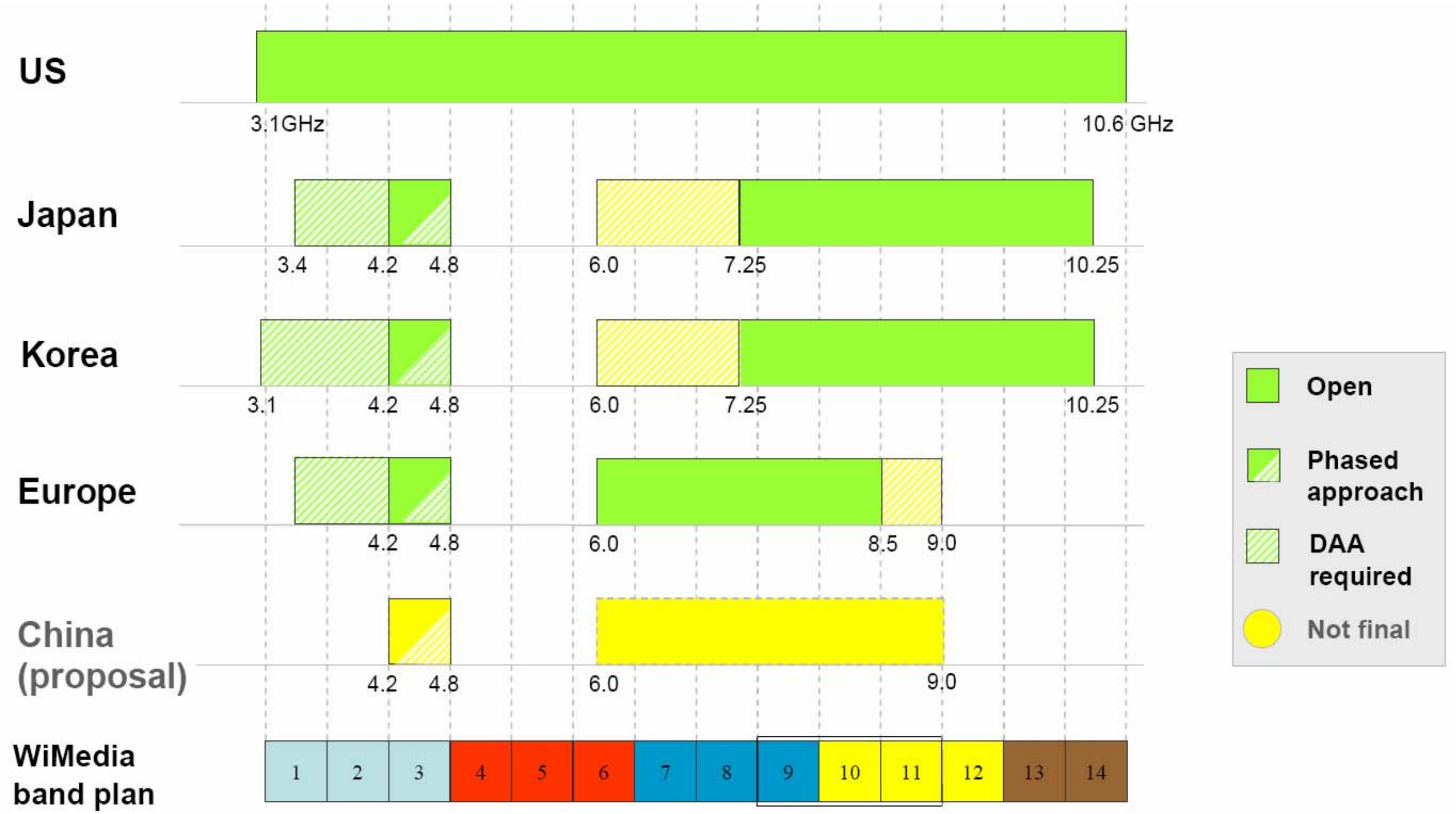
Impulse Radio could require less hardware and thus it can be suitable too meet these requirements!

These are the main motivations behind the IEEE 802.15.4a standard

Is OFDM enough?

- Even with OFDM it is cumbersome to deal with **7.5 GHz free bandwidth (FCC 3.1-10.6 GHz) → too complex with hardware, consumption and cost constraints**

- Furthermore worldwide regulations (FCC, Europe, Japan…) are different



Turi Aytur, WiMedia Technical Overview, Realtek Semiconductor

Multiband OFDM (MB-OFDM)

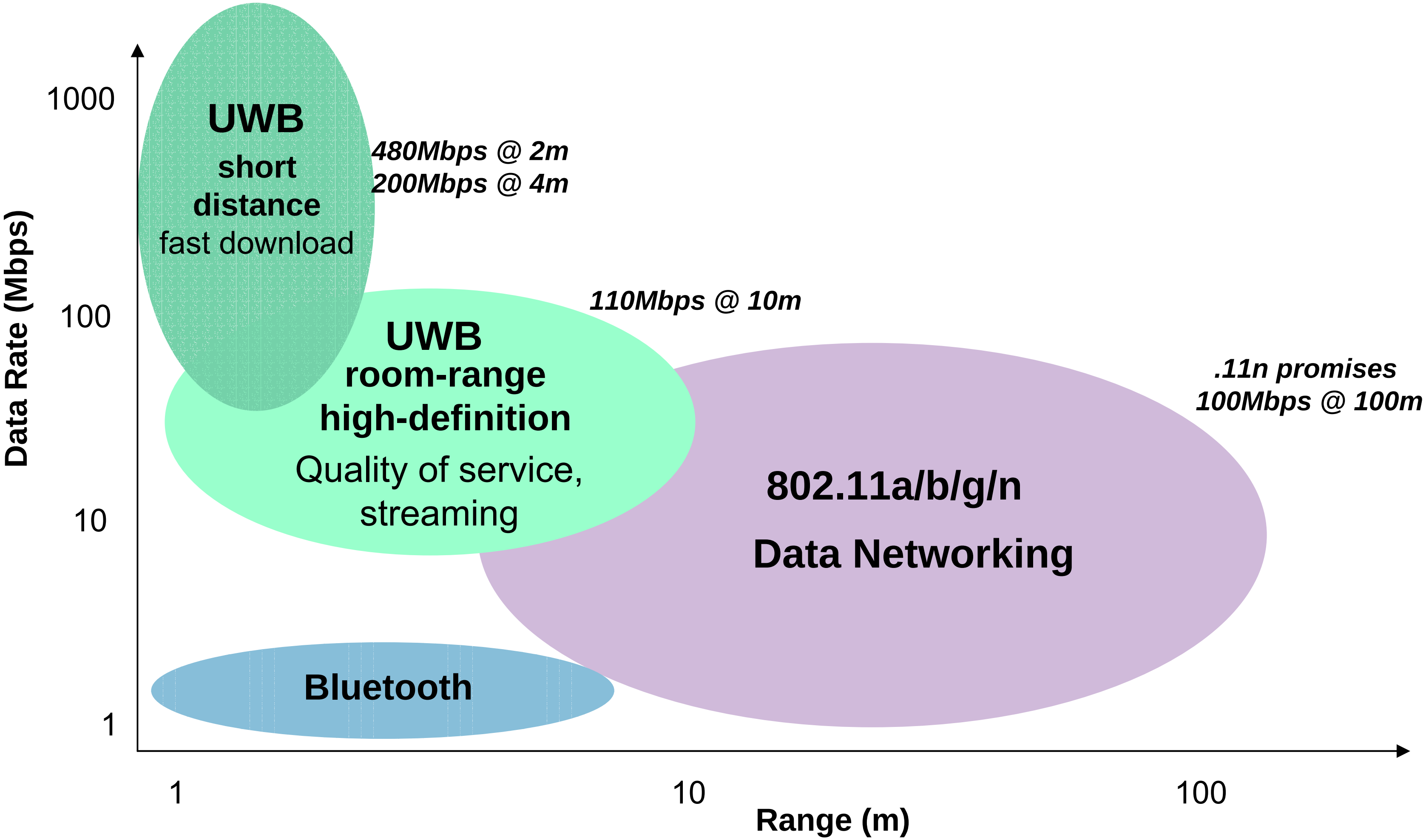
- The key idea is to divide the spectrum in 528 MHz-wide bands
- Transmitter and receiver process smaller baseband bandwidth signals (528 MHz)….
- The TX signals in each band are OFDM based
- Each band satisfy the (>500 MHz) FCC requirement to say that the signal is UWB

14 bands in 5 groups

Source: Turi Aytur, WiMedia Technical Overview, Realtek Semiconductor

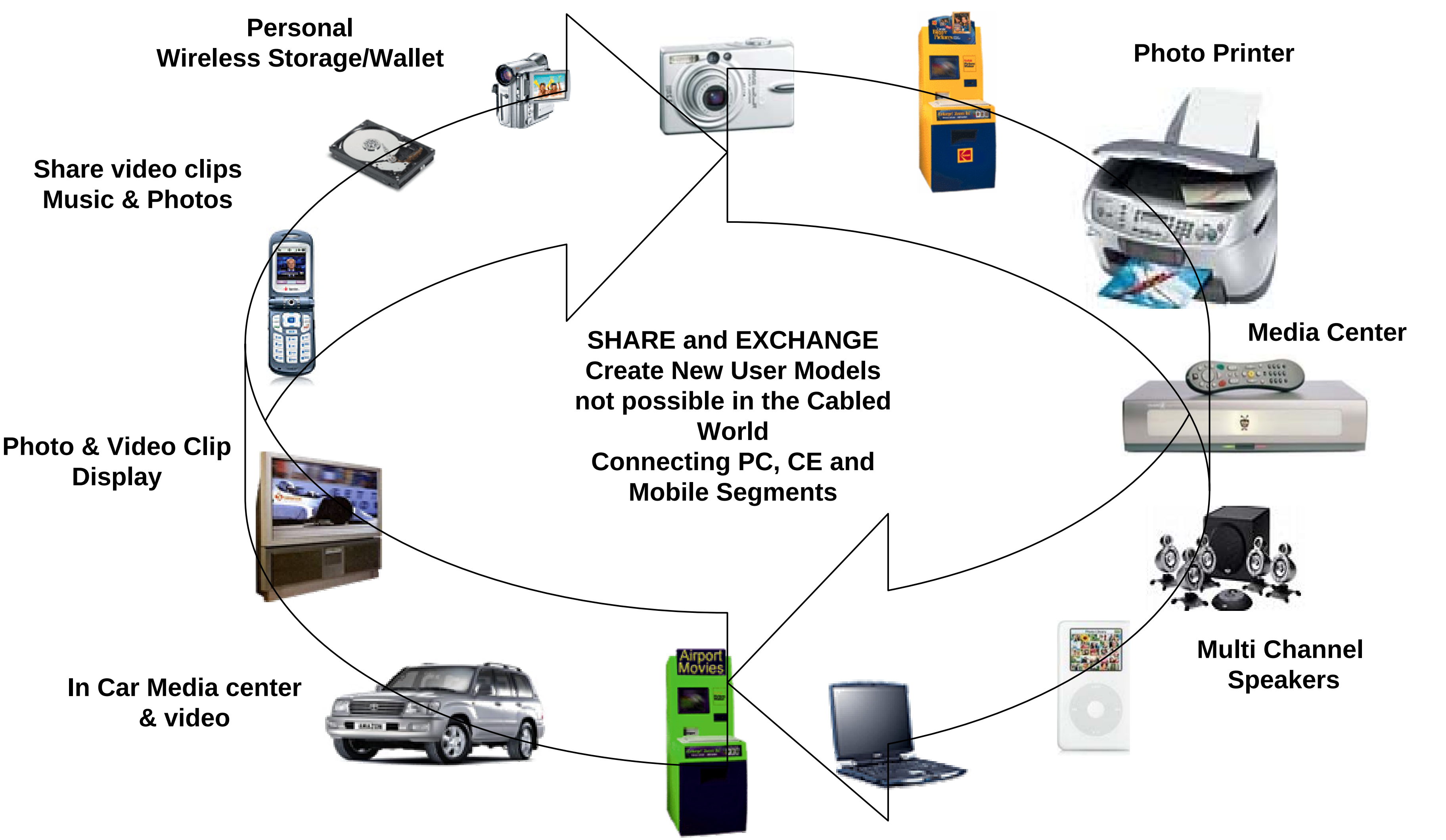
WiMedia

High speed WPANs: UWB WiMedia



Source: Texas Instruments

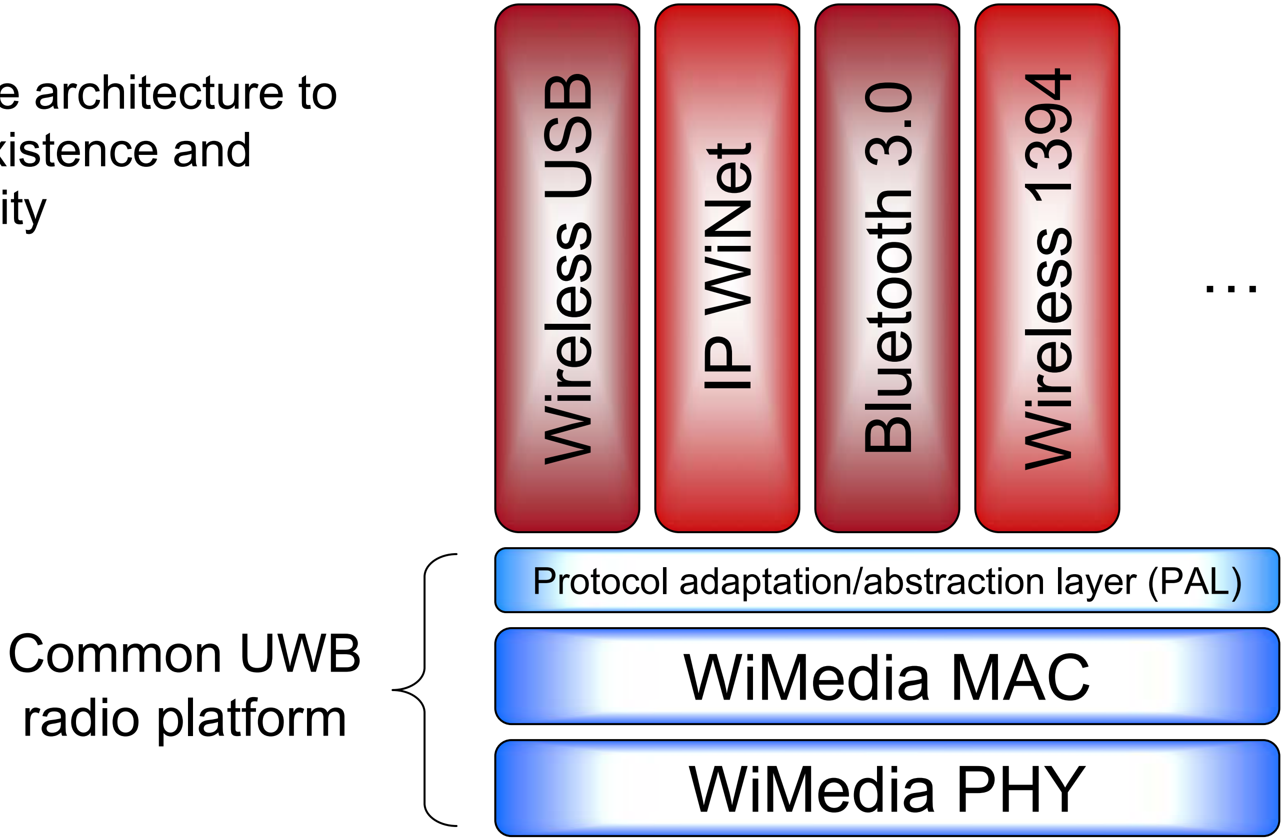
UWB for cable replacement



WiMedia

WiMedia is an ISO-published radio platform standard for high-speed ultra wideband (UWB) wireless connectivity. WiMedia UWB has been selected by the Bluetooth SIG and the USB Implementers Forum as the foundation radio of their high-speed wireless specifications for use in next generation consumer electronics, mobile and computer applications.

Convergence architecture to provide coexistence and interoperability



WiMedia, ECMA & ISO

ECMA

On December 8, 2005 **ECMA** released two international ISO-based specifications (**ECMA-368 and ECMA-369**) for UWB technology based on the WiMedia Ultra-Wideband (UWB) Common Radio Platform.

ETSI

ECMA-368 is also an **ETSI** standard (**ETSI TS 102 455**).

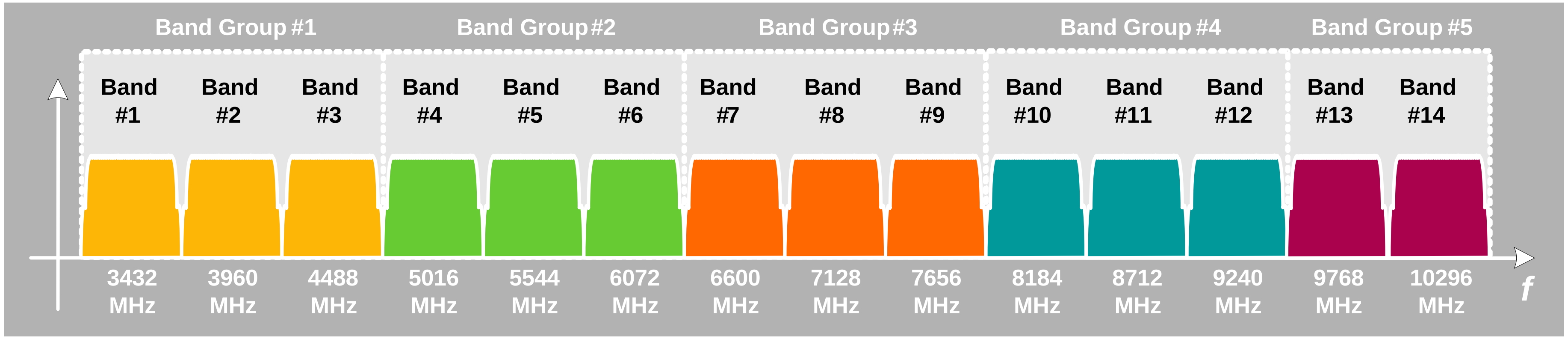
ISO

The Ecma 368 and 369 standards were approved as **ISO/IEC** standards in 2007 respectively with numbers:

ISO/IEC 26907:2007 - Information technology -- Telecommunications and information exchange between systems -- High Rate Ultra Wideband PHY and MAC Standard

ISO/IEC 26908:2007 - Information technology -- MAC-PHY Interface for ISO/IEC 26907

WiMedia



WiMedia is based on a Multiband-OFDM technology

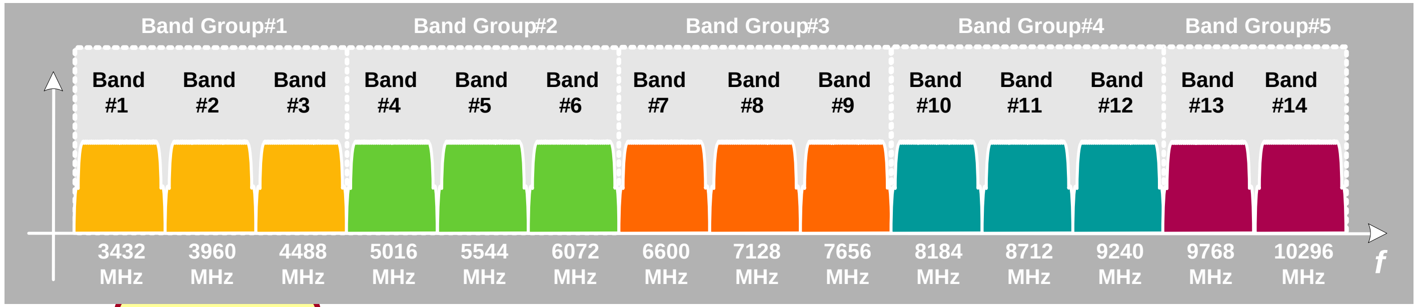
Frequency Allocation

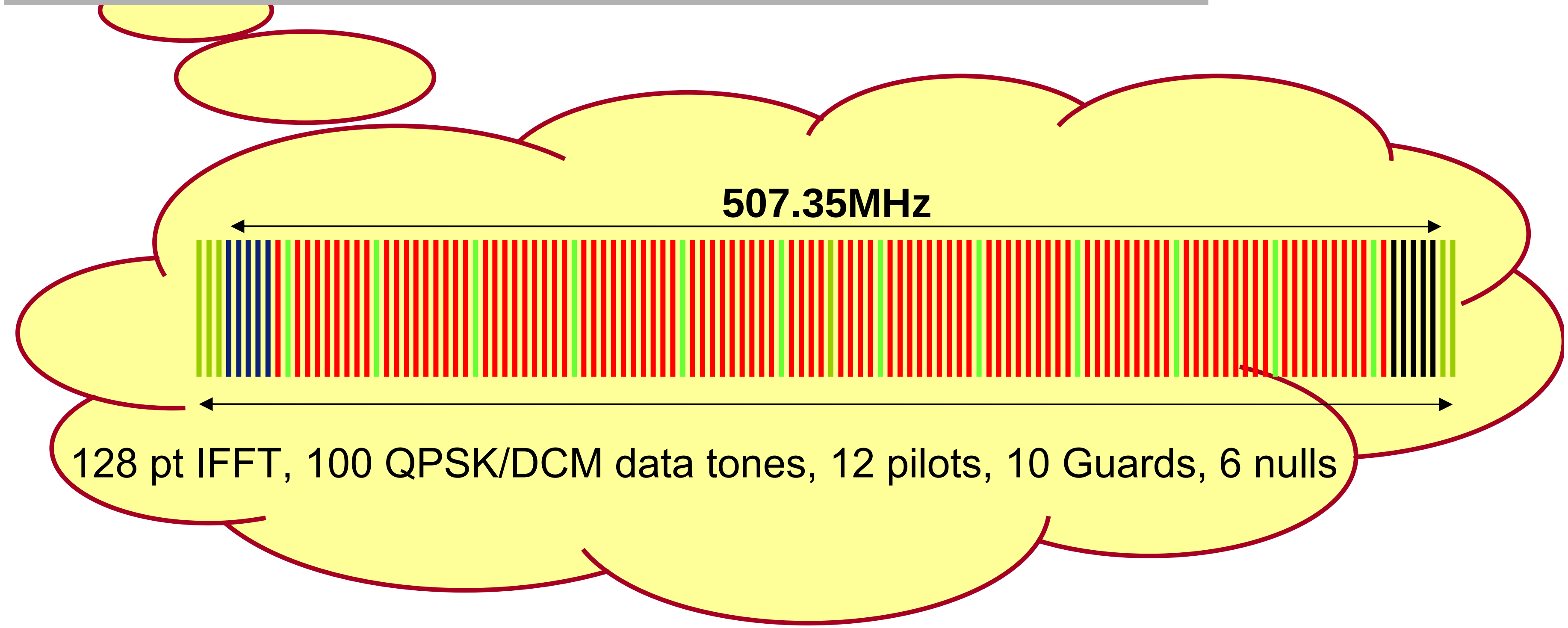
- 3100 - 10600 MHz
- 14 Bands of BW 528 MHz
- 5 Groups

Data rate

- Mandatory 53.3, 106.7, and **200 Mb/s**
- 80, 160, 320, 400, and **480 Mb/s**

WiMedia





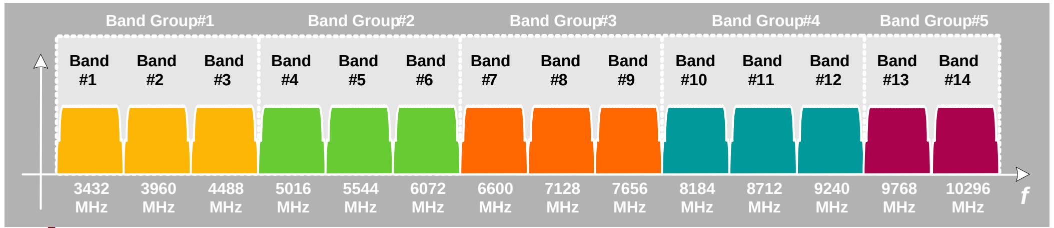
OFDM Symbol:

Total 165 points: 128 points + 37 ZPS (Zero Padded Suffix)

T_{OFDM}=312.5 ns long

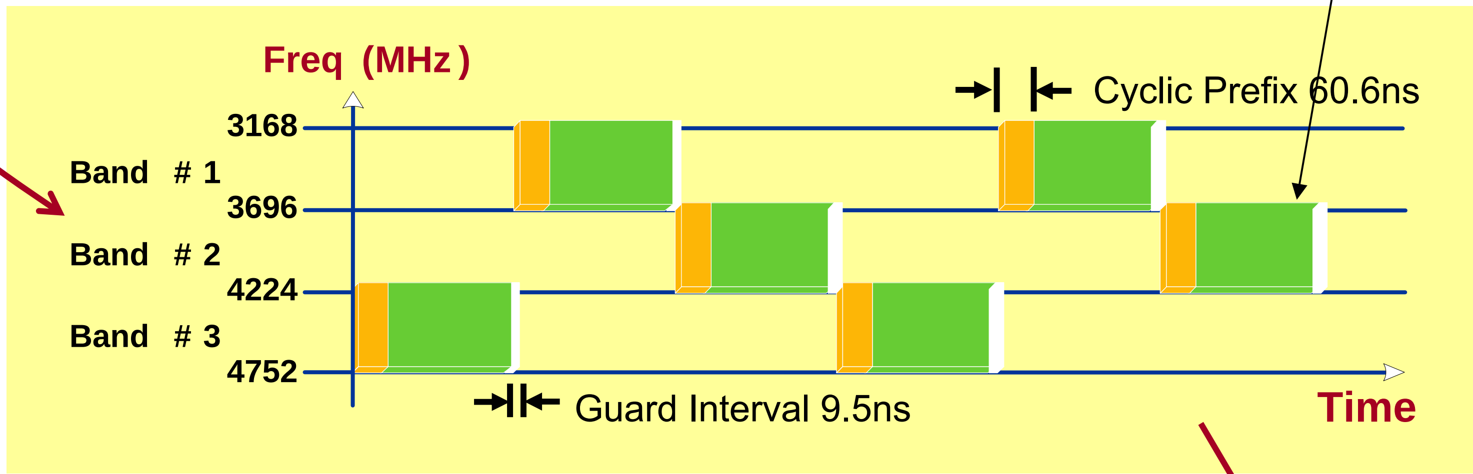
WiMedia

More bandwidth can be exploited through **frequency hopping (slow)**



OFDM symbol
312.5 ns long

Band Interleaving, Zero Prefixes and Guard Intervals



Advantages:

– Frequency diversity, multiple access, piconets…

Source: Turi Aytur, WiMedia Technical Overview, Realtek Semiconductor

Time-Frequency Codes (TFC)

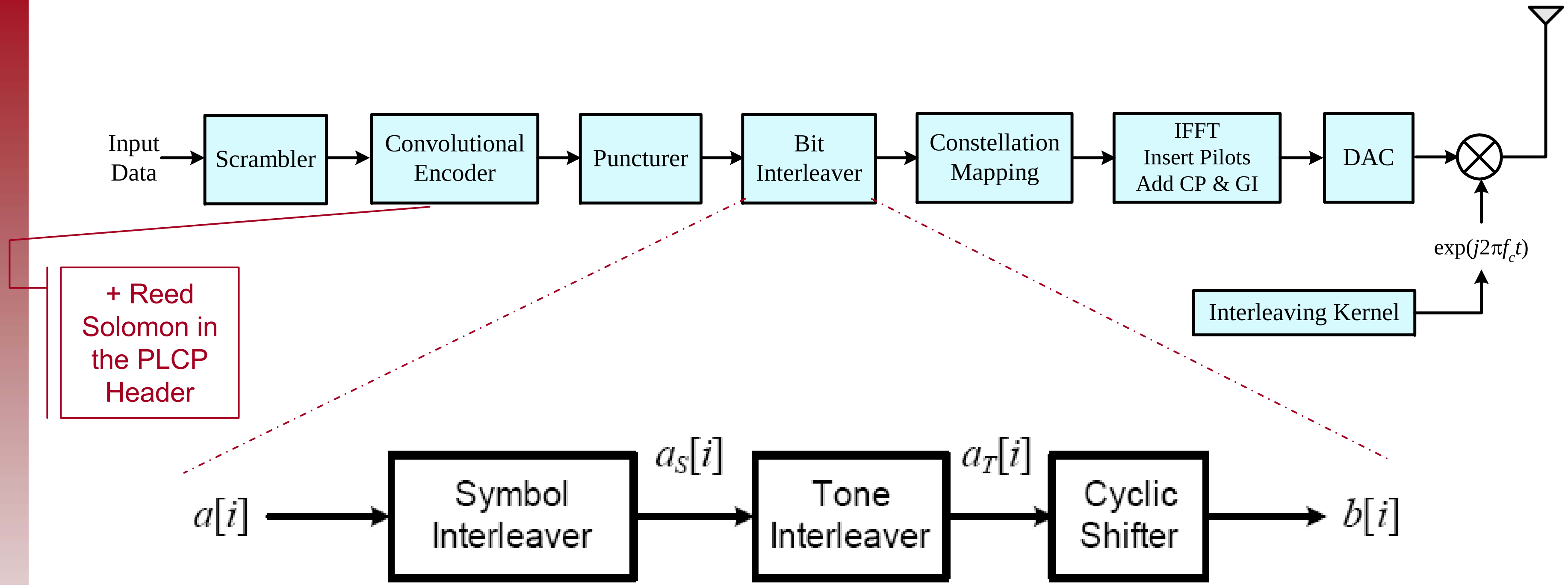
WiMedia: Time-frequency Codes

- TFI=Time-Frequency Interleaving
- FFI=Fixed Frequency Interleaving
- 4 Groups of 3 Bands (7 TF codes : 4 TFI + 3 FFI)
- 1 Group of 2 Bands (2 TF codes : 2 FFI)
- Total 30 Channels (4 Grps x 7 TF codes + 2 TF codes)

TFC Number	Type	Preamble	BAND_ID					
1	TFI	1	1	2	3	1	2	3
2	TFI	2	1	3	2	1	3	2
3	TFI	3	1	1	2	2	3	3
4	TFI	4	1	1	3	3	2	2
5	FFI	5	1	1	1	1	1	1
6	FFI	6	2	2	2	2	2	2
7	FFI	7	3	3	3	3	3	3

6 OFDM symbols are the atoms of the packets

WiMedia: Interleaving



- Symbol interleaving, which permutes the bits across 6 consecutive OFDM symbols, enables the PHY to exploit frequency diversity within a band group.
- Intra-symbol tone interleaving, which permutes the bits across the data subcarriers within an OFDM symbol, exploits frequency diversity across subcarriers and provides robustness againstnarrow-band interferers.
- Intra-symbol cyclic shifts, which cyclically shift the bits in successive OFDM symbols by deterministic amounts, enables modes that employ time-domain spreading and the fixed frequency interleaving (FFI) modes to better exploit frequency diversity.

WiMedia: parameters

Parameter	Description	Value
f_s	Sampling frequency	528 MHz
N_{FFT}	Total number of subcarriers (FFT size)	128
N_D	Number of data subcarriers	100
N_P	Number of pilot subcarriers	12
N_G	Number of guard subcarriers	10
N_T	Total number of subcarriers used	122 (= $N_D + N_P + N_G$)
D_f	Subcarrier frequency spacing	4,125 MHz (= f_s / N_{FFT})
T_{FFT}	IFFT and FFT period	242,42 ns (Δ_f^{-1})
N_{ZPS}	Number of samples in zero-padded suffix	37
T_{ZPS}	Zero-padded suffix duration in time	70,08 ns (= N_{ZPS} / f_s)
T_{SYM}	Symbol interval	312,5 ns (= $T_{FFT} + T_{ZPS}$)
F_{SYM}	Symbol rate	3,2 MHz (= T_{SYM}^{-1})
N_{SYM}	Total number of samples per symbol	165 (= $N_{FFT} + N_{ZPS}$)

WiMedia: data rates

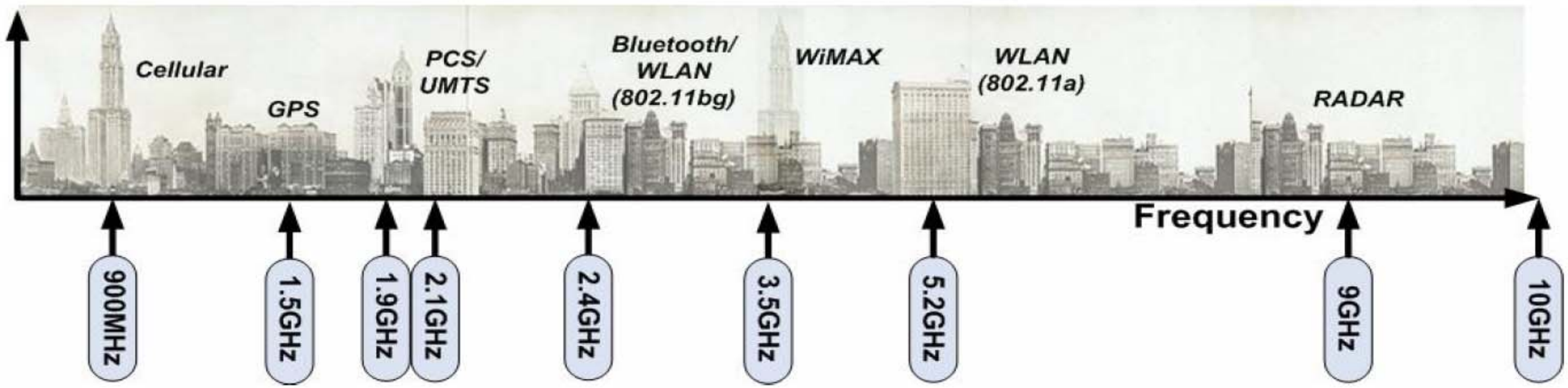
- FDS=Frequency-domain spreading
- TDS=Time-domain spreading

Data Rate (Mb/s)	Modulation	Coding Rate (R)	FDS	TDS	Coded Bits / 6 OFDM Symbol (N_{CBP6S})	Info Bits / 6 OFDM Symbol (N_{IBP6S})
53,3	QPSK	1/3	YES	YES	300	100
80	QPSK	1/2	YES	YES	300	150
106,7	QPSK	1/3	NO	YES	600	200
160	QPSK	1/2	NO	YES	600	300
200	QPSK	5/8	NO	YES	600	375
320	DCM	1/2	NO	NO	1 200	600
400	DCM	5/8	NO	NO	1 200	750
480	DCM	3/4	NO	NO	1 200	900

Dual Carrier Modulation

Coexistence

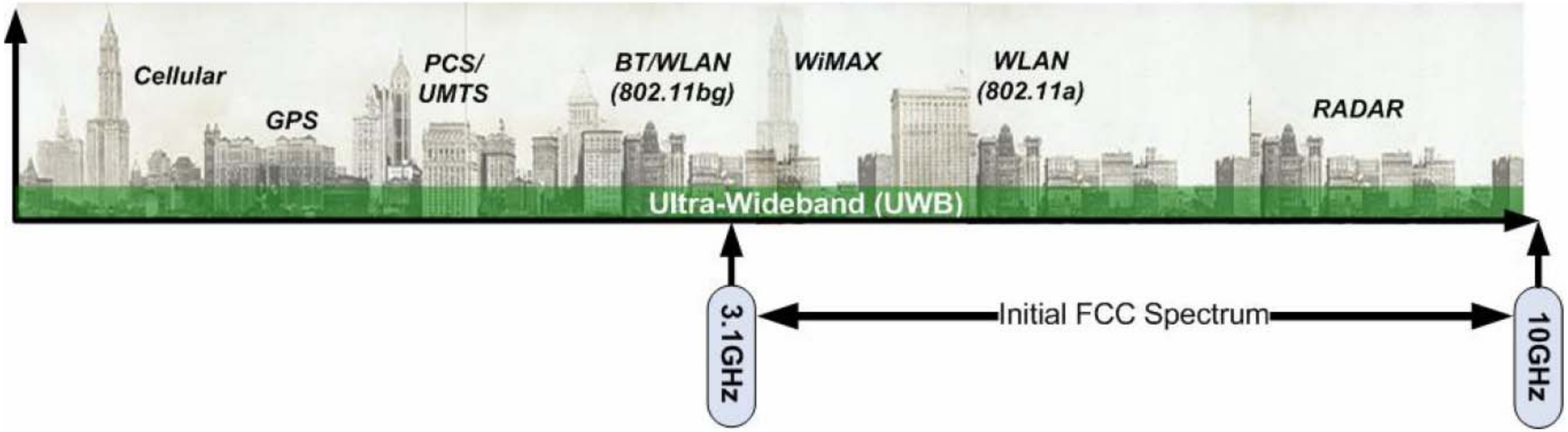
Spectral Skyline



- Total Congestion
- No room to build new high-bandwidth services

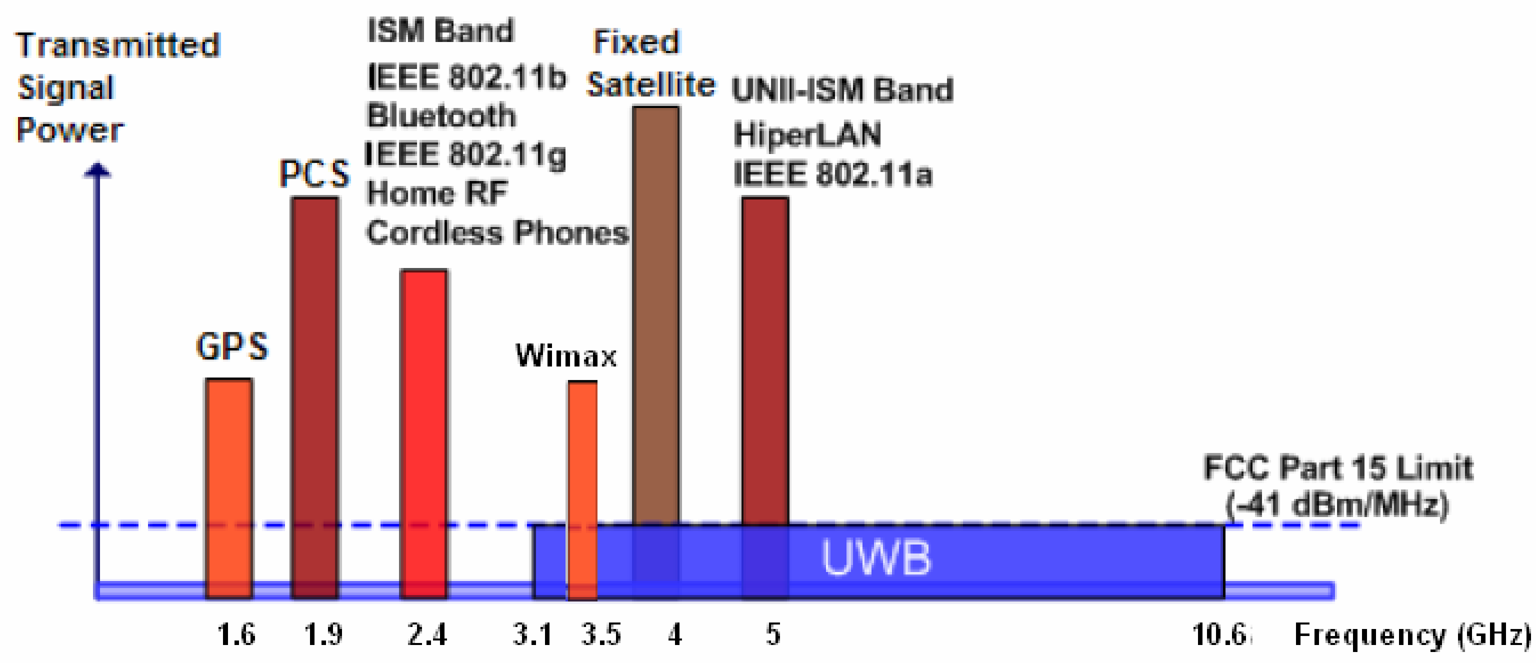
Source: Turi Aytur, WiMedia Technical Overview, Realtek Semiconductor

UWB: the quiet neighbor



- Wide bandwidth and very low power spectral density
- "Underlay" technology coexists with other services

Narrow Band Interference (NBI)



- UWB system operate over extremely wide frequency bands, where various narrow band technology operate with much higher power levels.
- The narrowband system are affected from the UWB signal only at a negligible level.
- The influence of NBI on the UWB system may jam the UWB receiver.

Coexistence

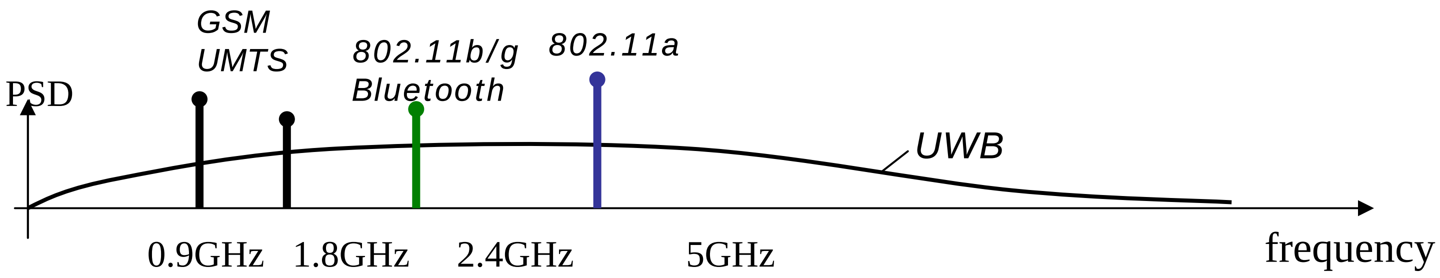
It turns out necessary to study the mutual interference between UWB and NB systems *(GSM, Bluetooth, UMTS, Zigbee ...)* in order to evaluate a possible coexistence.

The goals are:

evaluate the impact of
Narrowband interferers on **UWB** systems

and then

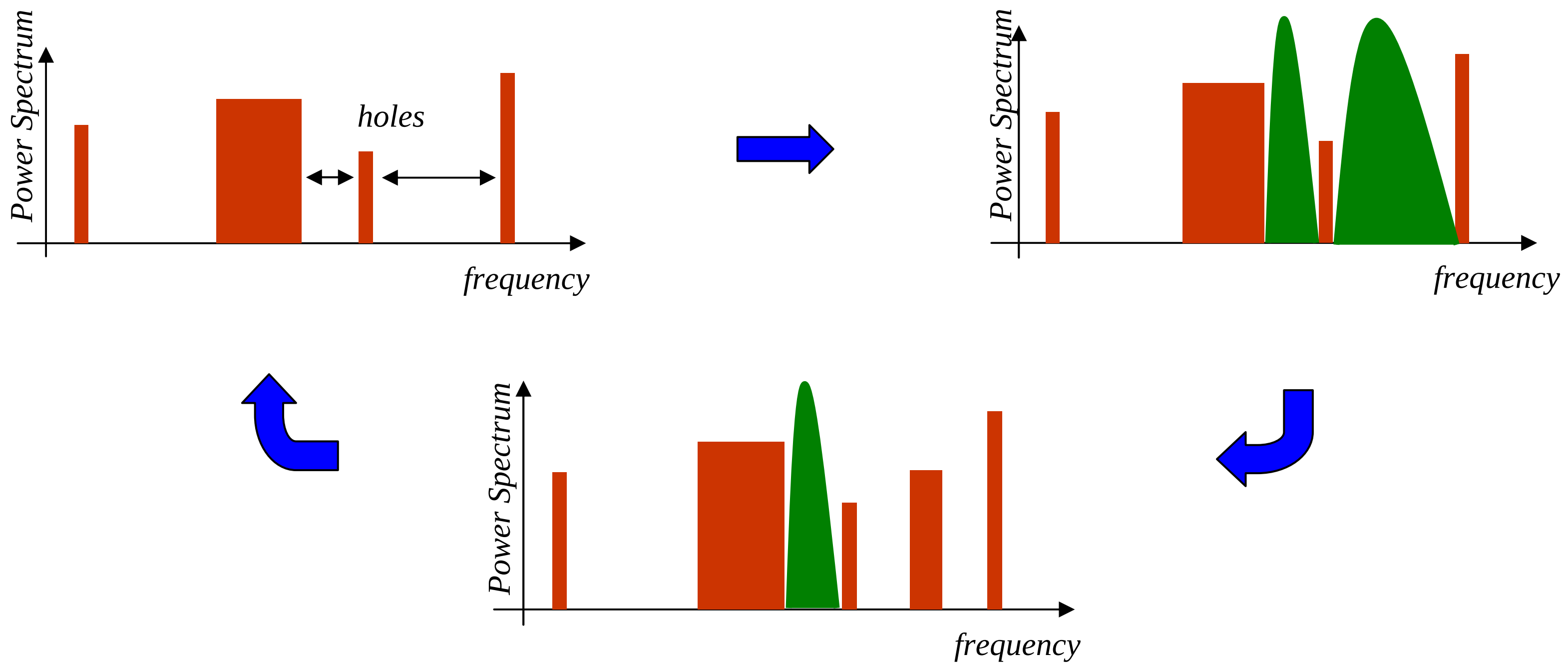
adapt the UWB spectrum
to guarantee a possible coexistence



UWB towards Cognitive Radio paradigm

In this line, **CR based on UWB** could represent a more complete solution as it:

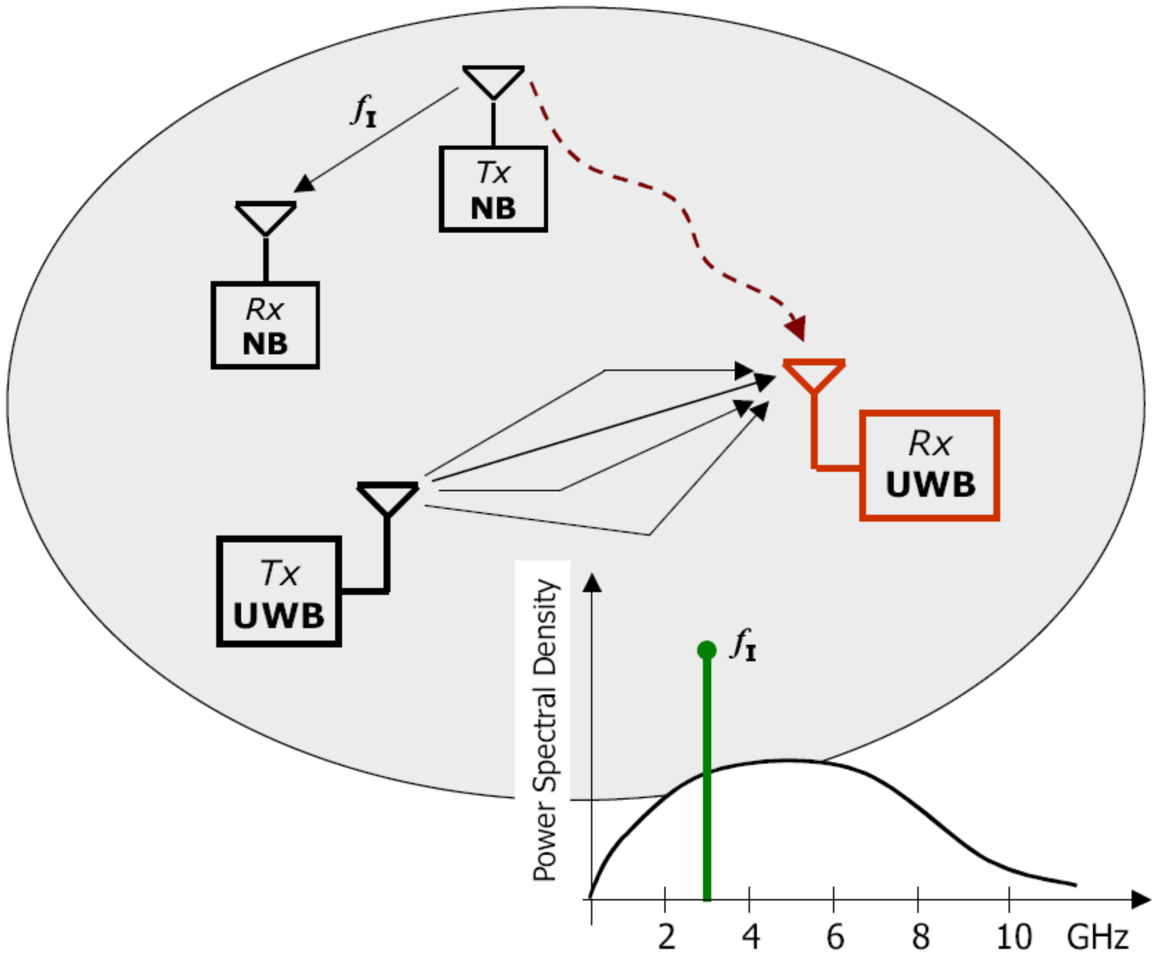
- ***actively looks for unused spectrum*** *(Spectrum sensing)*
- ***begins to transmit inside those bands*** *(Agile spectrum generation)*
- *eventually* ***being get out if needed*** *when the primary users show up*



A. Giorgetti, M. Chiani, and D. Dardari, "Coexistence issues in cognitive radios based on ultra-wide bandwidth systems," in *1st International Conference on Cognitive Radio Oriented Wireless Networks and Communications, CROWNCOM 2006*, Mykonos Island, GREECE, June 2006, pp. 1–5.

Coexistence: WLAN/WPAN scenario

A possible scenario (the fourth in the FCC vision) consists of ***UWB Cognitive Radio*** *systems that contend the spectrum with existing wireless systems...*



Problem formulation with CR-IR-UWB

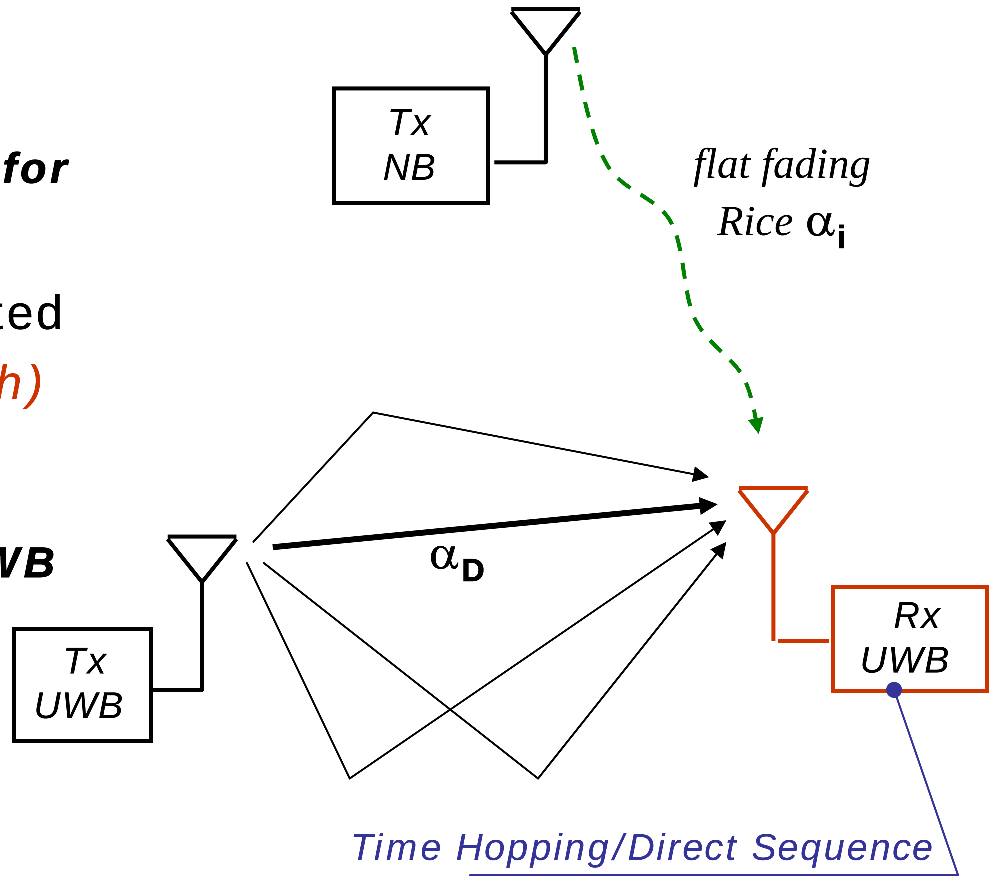
Propagation scenario:

Frequency-Selective channel for the UWB link

- α_D is Nakagami-m distributed *(D.Cassioli, M.Z.Win, A.Molish)*

Ricean channel for the NB-UWB link

- α_i is Rice distributed



A. Giorgetti and D. Dardari, "The impact of OFDM interference on TH-PPM/BPAM transmission systems," in *Proc. IEEE Vehicular Tech. Conf. (VTC 2005-Spring)*, Stockholm, SWEDEN, May 2005.

A. Giorgetti, M. Chiani, and M. Z. Win, "The effect of narrowband interference on wideband wireless communication systems," *IEEE Trans. Commun.*, vol. 53, no. 12, pp. 2139–2149, Dec. 2005.

Performance with MF reception

The **closed-form expression** for the **BEP** of the **UWB system** in this scenario is:

$$P_e = \frac{1}{2} - \frac{1}{\pi}\int_0^{\infty} J_0\left(|\omega|\sqrt{\frac{I}{C}\frac{K}{K+1}\frac{2|H_0(f_\mathrm{I})|^2}{T_\mathrm{b}(1-\rho)^2}}\right)$$
$$\times \exp\left(-\frac{\omega^2}{2}\left[\frac{I}{C}\frac{1}{K+1}\frac{|H_0(f_\mathrm{I})|^2}{T_\mathrm{b}(1-\rho)^2} + \frac{N_0}{E_\mathrm{b}}\frac{1}{1-\rho}\right]\right)$$
$$\times \frac{\Gamma\left(m+\frac{1}{2}\right)}{\sqrt{m}\,\Gamma(m)}\,{}_1F_1\left(m+\frac{1}{2};\frac{3}{2};-\frac{\omega^2}{4\,m}\right)d\omega$$

K: *Rice factor*

m: *Nakagami param.*

E_b/N_0: *Signal-to-Noise r.*

C/I: *Signal-to-interf. r.*

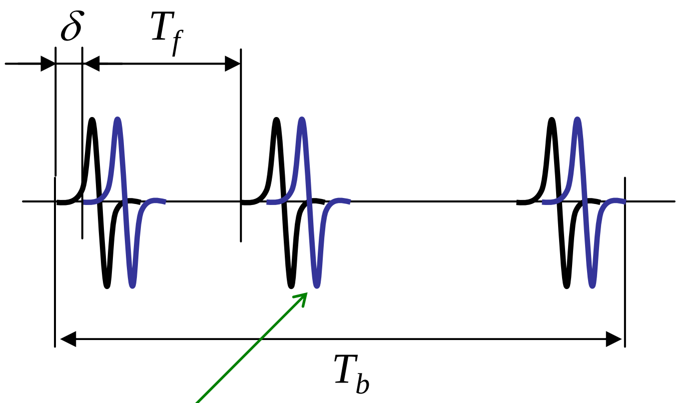
$|H_0(f_I)|$: *MF transf. funct.*

f_I **:** *freq. of interferer*

The impact of the interferer on the reception is strongly dependent on the **transfer function of the Matched Filter** at f_I

Receiver transfer function

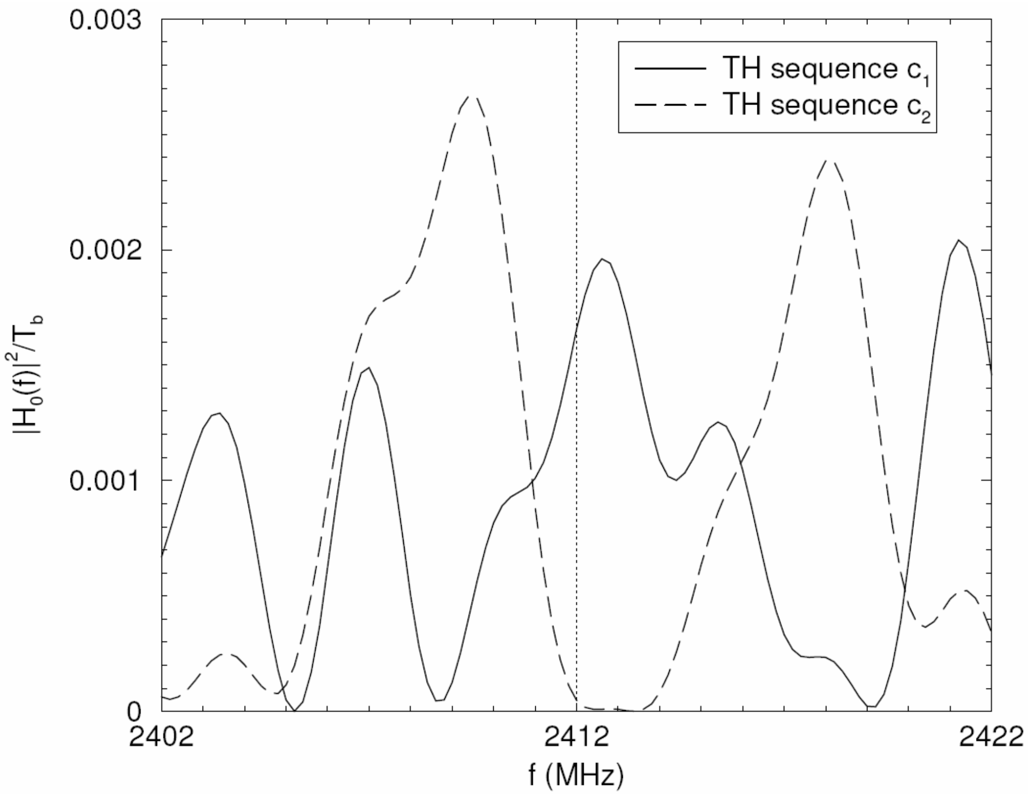
TH-PPM system



$$w(t) = \sqrt{\frac{1}{N_s E_w}} \left[1 - 4\pi \left(\frac{t}{\tau_w} \right)^2 \right] e^{-2\pi (t/\tau_w)}$$

$$W(f) = \sqrt{\frac{1}{N_s E_w}} \frac{\pi}{\sqrt{2}} \tau_w^3 f^2 e^{-\frac{\pi}{2} f^2 \tau_w^2}$$

$$\boxed{|H_0(f)| = 2|W(f)||\sin(\pi f \delta)| \left| \sum_{k=0}^{N_s-1} e^{j2\pi f (kT_f + c_k T_c)} \right|}$$



Example: performance

TH-PPM system parameters

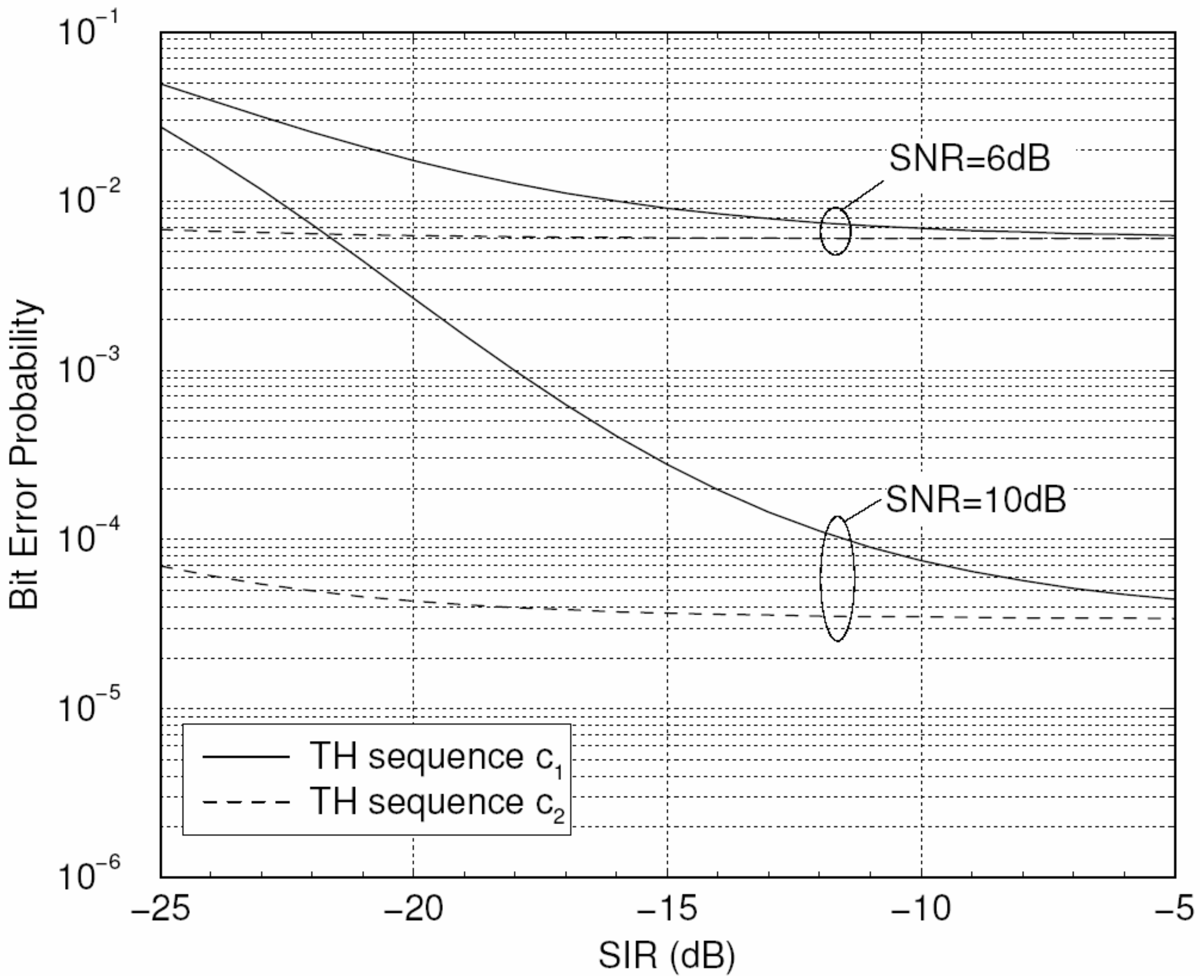
- *pulse duration* τ_w=0.5 ns
- *frame duration* T_f=40 ns
- *ppm offset* δ=0.3 ns
- *pulses per bit* N_s=10
- *TH chip duration* T_c=1.5 ns
- *TH sequences*:

c_1={15,1,11,17,3,7,10,2,0,14}

c_2={18,12,19,16,15,11,9,18,3,9

The Narrowband Interferer

- BPSK
- rectangular pulse shaping
- R_b=1Mbit/s
- f_I=2.412 GHz



Example: the spectrum

If we look at the UWB spectrum (in this case the spectrum of a TH-PPM system) **at the transmitter**

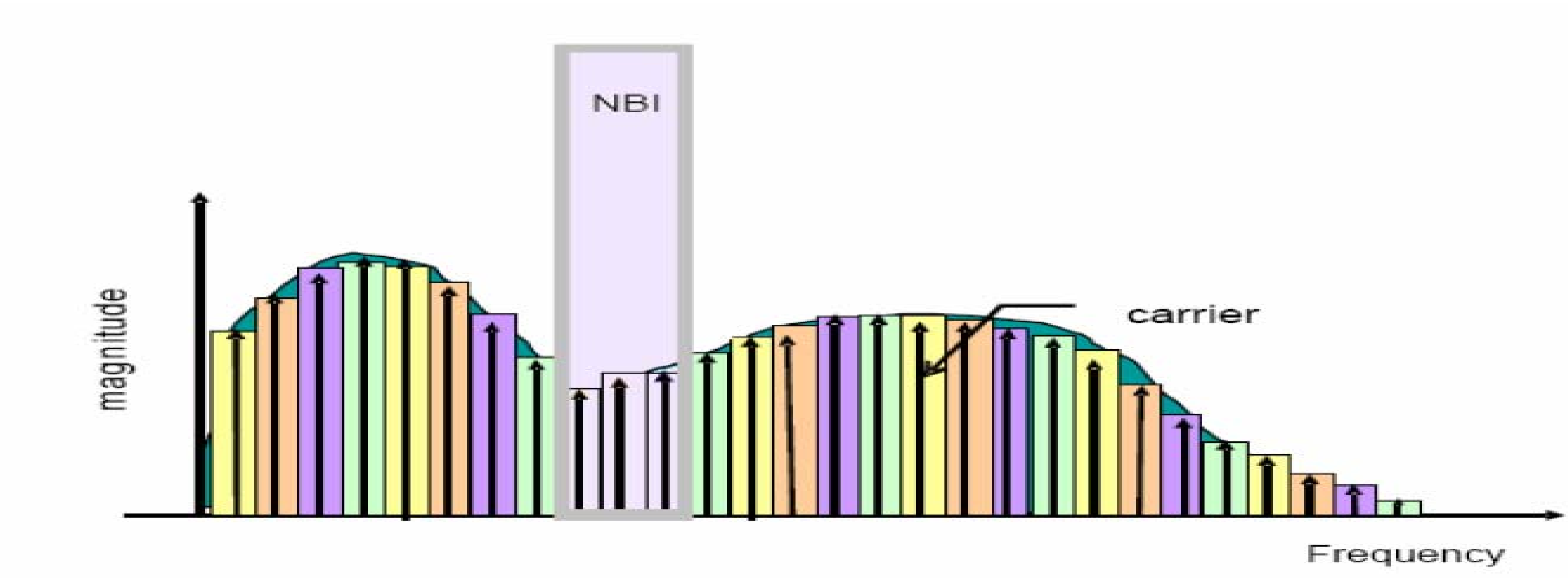
Power Spectral Density: $S(f) \propto |W(f)|^2 \left| \sum_{k=0}^{N_s-1} e^{j2\pi f(kT_f + c_k T_c)} \right|^2$

we can note that this is proportional to the transfer function of the matched filter **at the receiver**

$$|H_0(f)| = 2|W(f)||\sin(\pi f \delta)| \left| \sum_{k=0}^{N_s-1} e^{j2\pi f(kT_f + c_k T_c)} \right|$$

Therefore, we can reduce the **mutual interference!!!**

Coexistence with CR-MB-OFDM-UWB



Cognitive UWB – OFDM system must detect the NBI, than, we have 2 different ways to coexist:

- Mitigate the interference by using an analog notch filter.
- Avoid the transmission of the UWB signal over the frequencies of possible strong NBI, for example, using MB – OFDM system or by nulling the OFDM tone affected.

Potential UWB applications

The role of the UWB technology

- UWB as a promising technology for both robust communication and accurate localization mainly due to large transmission bandwidth

- Sub-nanosecond time resolution leads to precision ranging and imaging capabilities

UWB applications (1/2)

- Communications
  - Short range communication links
  - Wireless sensor networks
  - Wireless Local Area Networks
  - Ad hoc networks
- Radar
  - Ground penetrating radars
  - Through-wall radars
  - Imaging and ranging
  - Buried victim rescue
  - Landmine detection

UWB applications (2/2)

- Intelligent Sensors
  - Collision avoidance, proximity and altitude sensors
  - Telemetry
  - Motion detection
  - RF tags (Inventory tracking)
  - Fluid level monitoring
  - Reverse driving and parking aids
  - Intelligent Transport Systems
- Others
  - Geolocation
  - Medical applications: e.g. radio stethoscope, breath, heart and speech studies etc.

UWB-based standards

- WiMedia (ex IEEE 802.15.3a)
  - d ≤10 m, data-rate larger than 100Mbit/s
  - Applications: Wireless Video Projection, Image Transfer, High-speed Cable Replacement (Wireless USB)

- IEEE802.15.4a
  - d=10-50m, data-rate 850-27Mbit/s, low energy consumption
  - Applications: WPAN and wireless sensor networks

Contacts

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