# Ultra Wide Band Radio Fundamentals

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# Course Presentation


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# Course Presentation

**Mailing List**

**https://groups.google.com/a/uniroma1.it/g/uwb**

**Course Website**

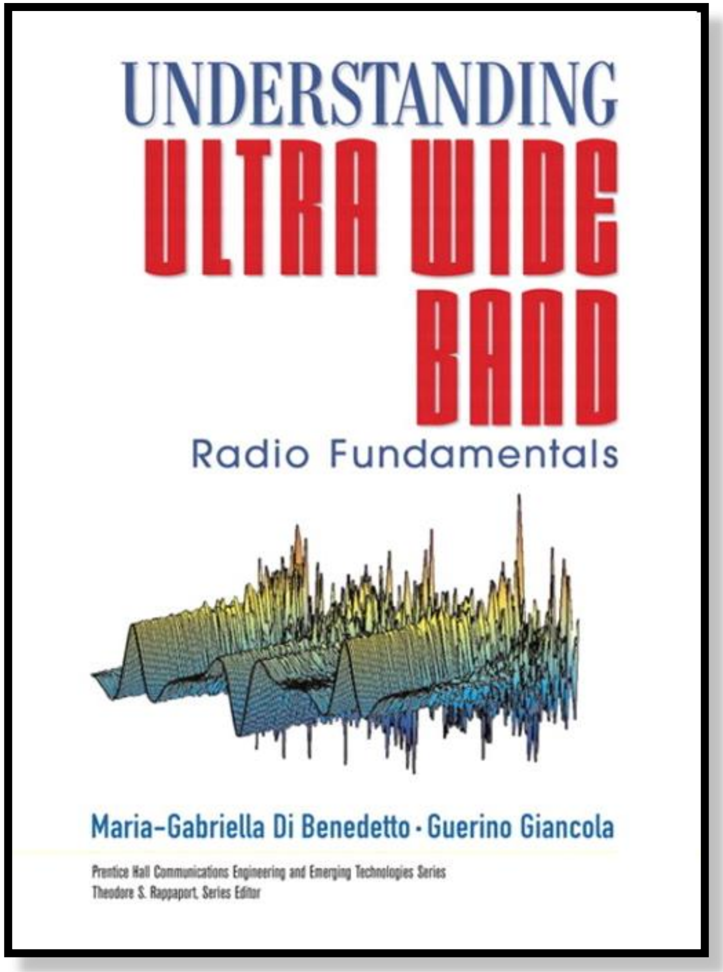
**http://acts.ing.uniroma1.it/uwb.php**

**Google Classroom code**

**xeuttmq**

**Zoom link**

**https://uniroma1.zoom.us/j/84865896881?pwd=Uy9uVlZONUpreUtYaHlpYnQwZ3lmdz09**




**Understanding Ultra Wide Band Radio Fundamentals**

by Maria-Gabriella Di Benedetto & Guerino Giancola

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# Course Organization

- **UWB Basics**
  - Introduction to UWB Communications
  - Generation of UWB radio signals
  - Spectral characteristics of UWB radio signals
- **UWB single user communications**
  - Link Budget for an UWB radio link
  - RX structures for AWGN channels
  - RX structures for multipath-channels: IEEE 802.15.3a channel and Rake RXs
- **UWB multi user communications**
  - MUI models for Impulse Radio
- **UWB special features**
  - Pulse Shaping in UWB
  - Localization and Positioning with UWB
  - UWB in 5G and 6G and THz communications
- **UWB experiments**
  - The Decawave DWM-1001DEV development board
  - MAC and positioning experiments

# Practice Work

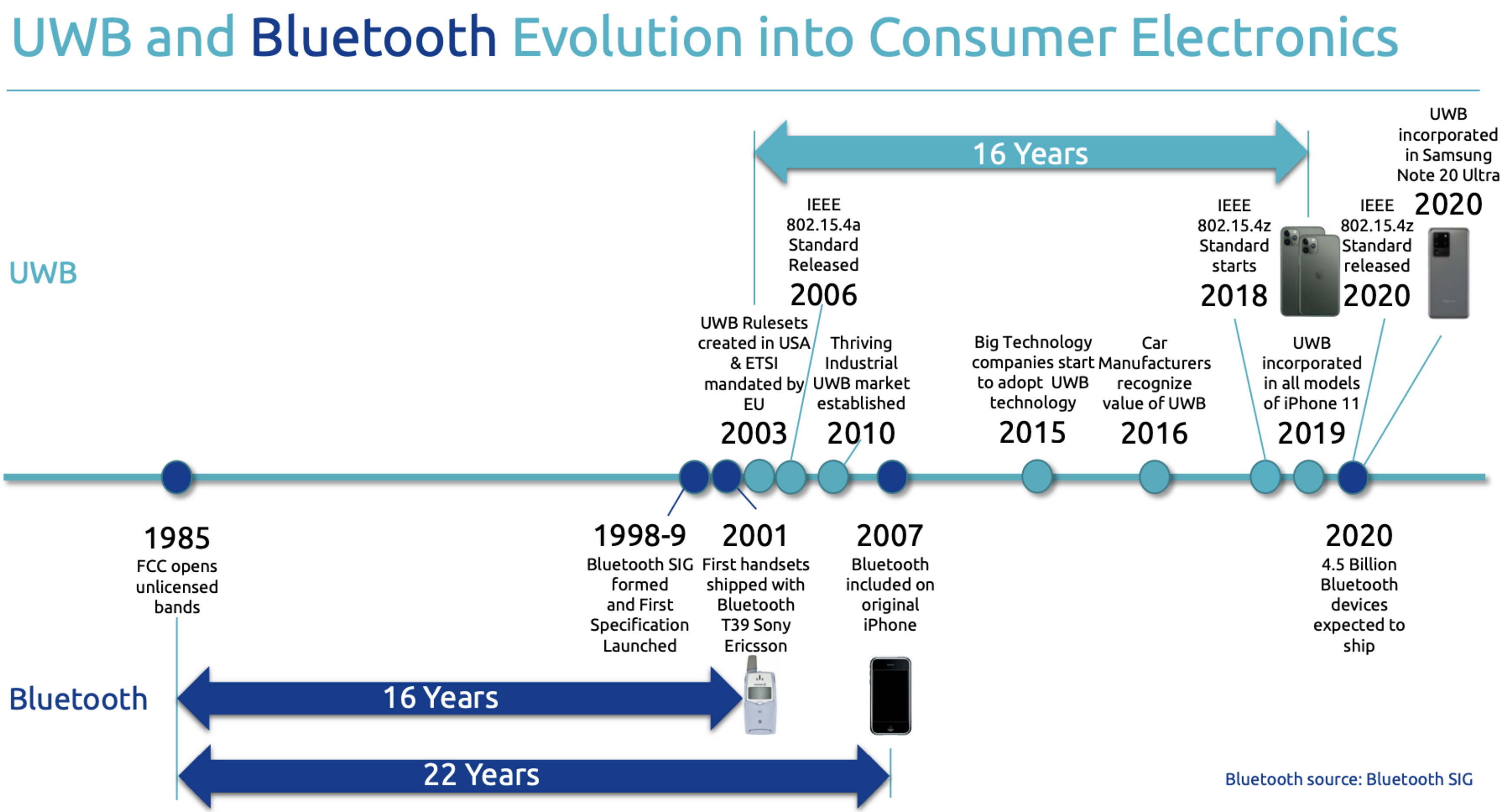
**Practice work sessions that will be developped during the course (Adopted simulation tool: MATLAB®)**

- Introduction to Matlab
- Introduction to UWB
- Generation of UWB signals
- Spectral characteristics of UWB signals
- Link Budget for UWB links
- UWB receiver in AWGN channels
- UWB receiver in multipath-affected channels
- MUI models for IR-UWB
- UWB pulse shaping
- UWB-based positioning

# Lesson 1

Introduction to UWB

# UWB in wireless communications




Source: UWB Alliance

# UWB NOW

- Positioning and tracking are becoming increasingly central in the deployment of cyber-physical systems and sensor networks

- UWB can play a key role, and a new forum pushing for interoperable UWB devices was recently launched:

  https://uwballiance.org/

- Supported by several companies, including large players such as Apple and Samsung

- A group with great impact to push UWB into the mainstream market

# UWB NOW

## Breaking News

### UWB Alliance Supports European Regulatory Vision

*ECC Report Completing Public Consultation Supports Potential UWB Rule Amendments*

Washington D.C., 5th August 2021 – Significant progress was made in the world of ultra-wideband (UWB) technology in Europe in August with the release of results from the Public Consultation of ECC Report 327, which contains sharing and compatibility studies in preparation for an update of the UWB Rulesets in Europe.

"The industry-wide support received from UWB partners boosts the accelerating adoption of ultra-wideband in the consumer market and paves the way for many new innovative UWB use cases," commented Tim Harrington, UWB Alliance Chairman. The UWB Alliance has worked in concert with ETSI, national administrations, liaison partners and top consumer electronic companies around the globe and continues to assist in the process.

UWB Alliance supports European Vision to expand UWB (Web)

Washington D.C., 5th August 2021 – Significant progress was made in the world of ultra-wideband (UWB) technology in Europe in August with the release of results from the Public Consultation of ECC Report 327, which contains sharing and compatibility studies in preparation for an update of the UWB Rulesets in Europe.

# UWB in the context of wireless communications

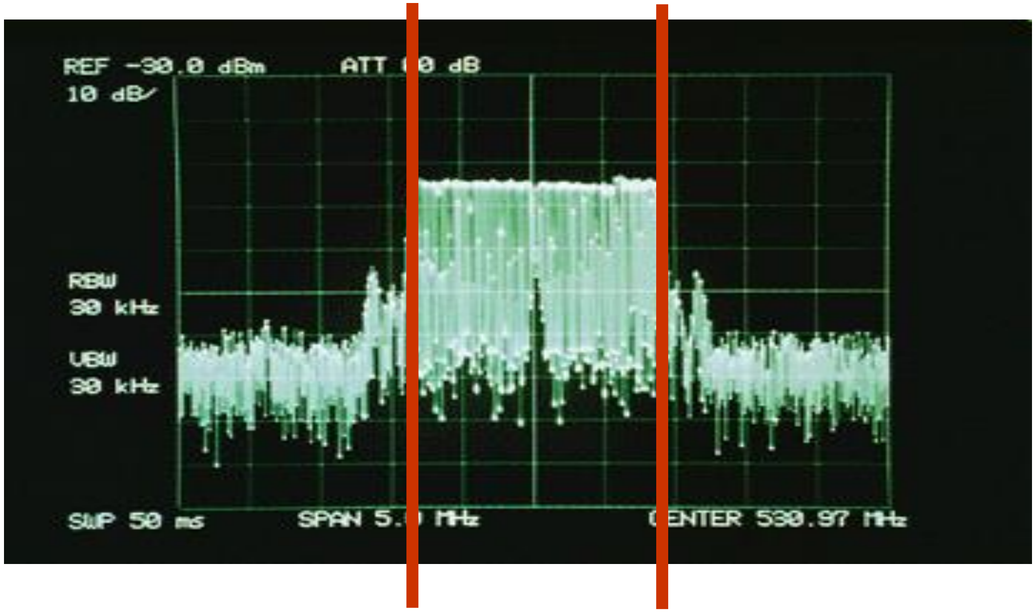
## UWB features:

1. **High data rate**
   - Instantaneous bandwidths of 500 MHz or more enable data rates in the order of hundreds of thousands of Mb/s
2. **Accurate distance and position estimation**
   - Distance estimation errors in the order of 10 cm or below are feasible (vs. e.g. 2-3 m in WiFi)
3. **Hard to intercept**
   - Without prior knowledge on transmission codes, detecting and intercepting UWB communications can be rather tricky

## Main challenges for UWB:

1. **Acquisition and synchronization of UWB signals**
   - Impulse Radio (IR) UWB signals are composed by *very short* pulses (~ nanoseconds), thus acquisition and TX-RX synchronization is challenging.
2. **Power constraints**
   - UWB operates on *very large* bandwidth (~ hundreds of MHz), thus the emission power should be limited, in order to make coexistence with other systems possible.
3. **Lack of accurate propagation models**
   - Need for channel models for impulsive rather than continuous signal propagation
4. **Lack of accurate interference models**
   - Modeling UWB communications is not a simple task
5. **Efficiency of implementation**

- A signal is UWB if its bandwidth is large with respect to the carrier or center frequency of the spectrum, that is, if its Fractional Bandwidth (FB) is high.




$f_L$ $f_H$

$$FB = \frac{f_H - f_L}{\left(\frac{f_H + f_L}{2}\right)}$$

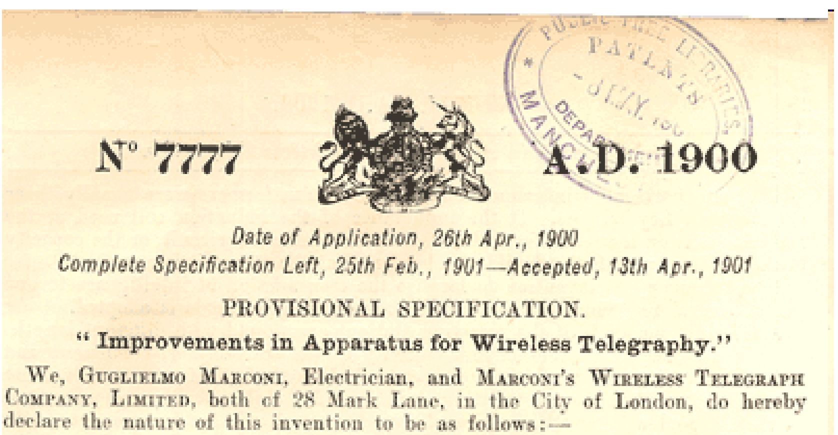
# What is UWB? (2/5)

- The common adoption of the term UWB comes to us from the radar community, and refers to electromagnetic waveforms with an instantaneous fractional bandwidth greater than about **0.20–0.25**
- Traditionally, UWB signals have been obtained by transmitting **very short pulses** with typically no Radio Frequencies modulation
  - In communication systems, “very short” refers to a duration of the pulse that is typically about a few hundred picoseconds
- This technique goes under the name of **Impulse Radio (IR)**

# What is UWB? (3/5)

- Impulse Radio was the primal technique for transfering information over the wireless medium

In Guglielmo Marconi's first experiments, back in **1894-1896**, Morse Code messages were transmitted over two miles using **pulsed transmission.**



Nº 7777 A.D. 1900

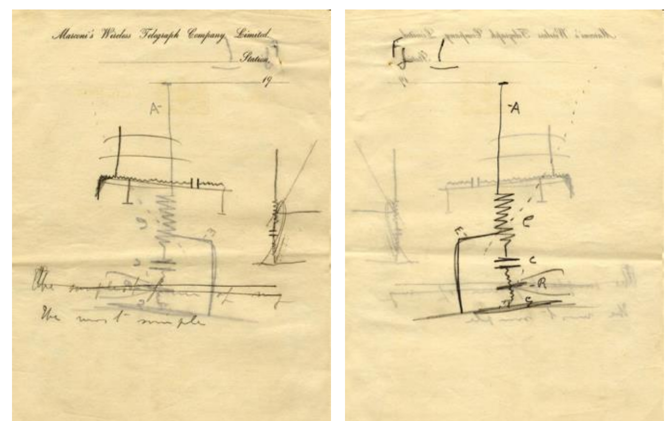
*Date of Application, 26th Apr., 1900*
*Complete Specification Left, 25th Feb., 1901—Accepted, 13th Apr., 1901*

PROVISIONAL SPECIFICATION.

"**Improvements in Apparatus for Wireless Telegraphy.**"

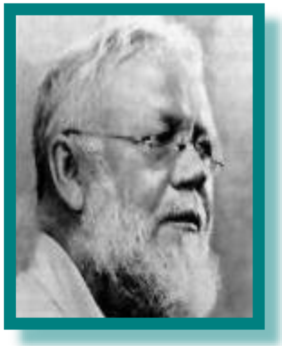
We, Guglielmo Marconi, Electrician, and Marconi's Wireless Telegraph Company, Limited, both of 28 Mark Lane, in the City of London, do hereby declare the nature of this invention to be as follows:—

Marconi's "7777" Patent

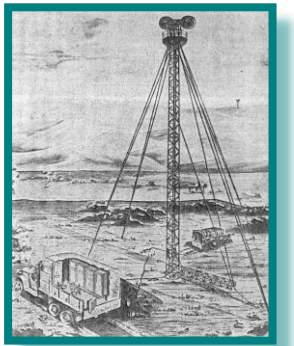


Marconi's handwritten notes for the specifications for the '7777' Patent

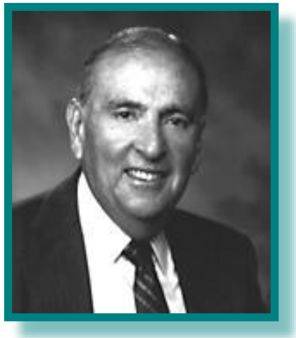
# What is UWB? (4/5)



In December **1900**, Reginal Fessenden used impulse radio signals for transmitting speech over one mile



In **1946** a remarkable microwave radio relay system was developed by Black, Beyer, Grieser, and Polkinghorn. This system was based on the transmission of pulses that were **position-modulated** and ensured two-way voice transmission over radio links totalling 1600 miles, and one-way over 3200 miles



During the **1970**s, the first patent for an impulse radio receiver to be used in communication systems is filed by Gerald F. Ross.

# What is UWB? (5/5)

The term **Ultra Wide Band** was coined by the U.S. Department of Defense in **1989**

During the **1990**s, relevant researches about Impulse Radio are carried out at the University of Southern California by Scholtz and Win.

During the **1990**s, a few small and medium-sized enterprises reintroduced the idea of wireless communications based on the impulse radio paradigm

# FCC regulation about UWB emissions (1/6)

- In order to verify the possibility for UWB systems to coexist with other existing systems, several measurement campaigns were performed in the United States by research institutes and agencies.
  - Measurement reports were commissioned to the National Telecommunications and Information Administration (**NTIA**) by the Federal Communication Commission (**FCC**)
  - The final report was released by NTIA in March 2001.

NTIA Report 01-384

**Measurements to Determine Potential Interference to GPS Receivers from Ultrawideband Transmission Systems**

# FCC regulation about UWB emissions (2/6)

- The most influential milestone in the history of UWB was set in 2002, when the FCC approved in the U.S. the first guidelines allowing the intentional emission of UWB signals and specified emission masks

**NEWS**

Federal Communications Commission
445 12th Street, S.W.
Washington, D. C. 20554

News media Information 202 / 418-0500
TTY 202 / 418-2555
Fax-On-Demand 202 / 418-2830
Internet: http://www.fcc.gov
ftp.fcc.gov

This is an unofficial announcement of Commission action. Release of the full text of a Commission order constitutes official action. See MCI v. FCC. 515 F 2d 385 (D.C. Circ 1974).

FOR IMMEDIATE RELEASE
February 14, 2002

NEWS MEDIA CONTACT:
David Fiske at (202) 418-0513

**NEW PUBLIC SAFETY APPLICATIONS AND BROADBAND INTERNET ACCESS AMONG USES ENVISIONED BY FCC AUTHORIZATION OF ULTRA-WIDEBAND TECHNOLOGY**

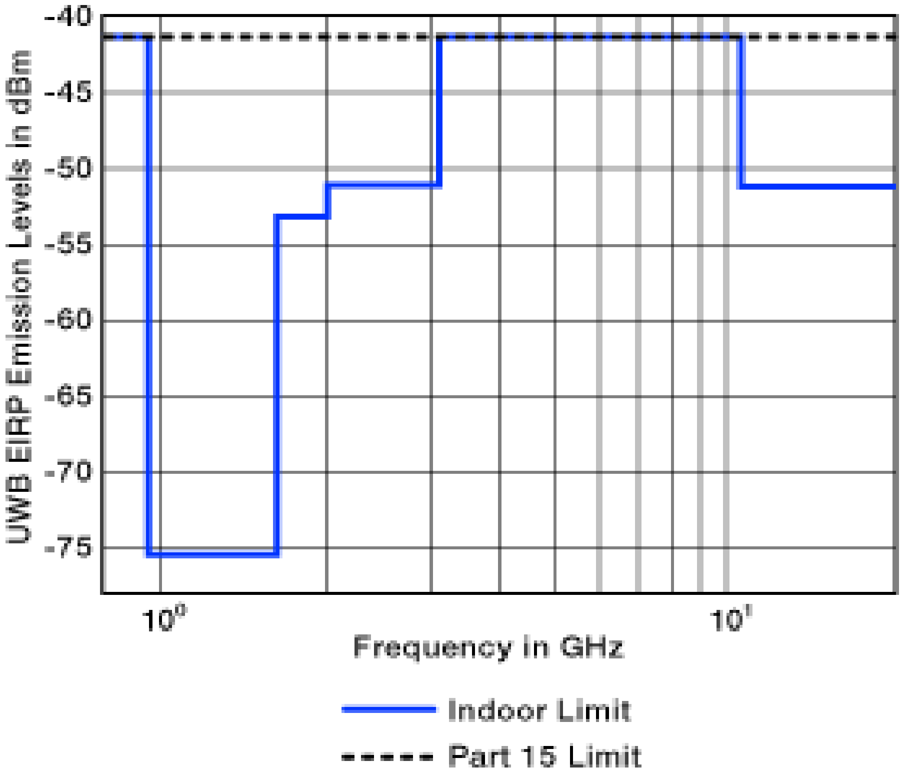
# FCC regulation about UWB emissions (3/6)

- In the FCC document, UWB is presented as a technology with enormous potentials
- In the same report, however, we find explicit concern about the need for emission masks, due to the unknown effects that UWB transmissions may have on other communication systems.

> 65. *Indoor UWB Systems*. Devices operating under this category must demonstrate that the system units will fail to operate if they are removed from the indoor environment. One acceptable procedure may be to show that the transmitting unit requires AC power to function. Based on the concerns expressed by NTIA and others regarding operation below 3.1 GHz, we are requiring that –10 dB bandwidth of indoor UWB systems must lie between 3.1 GHz and 10.6 GHz. We are adopting a very conservative out of band emission mask to address the concerns of companies which make or market indoor electronic equipment. In the frequency band below 960 MHz these devices are permitted to emit at or below the § 15.209 limits, and emissions appearing above 960 MHz will conform to the following emissions mask:

# FCC regulation about UWB emissions (4/6)

## FCC indoor emission mask




## FCC outdoor emission mask

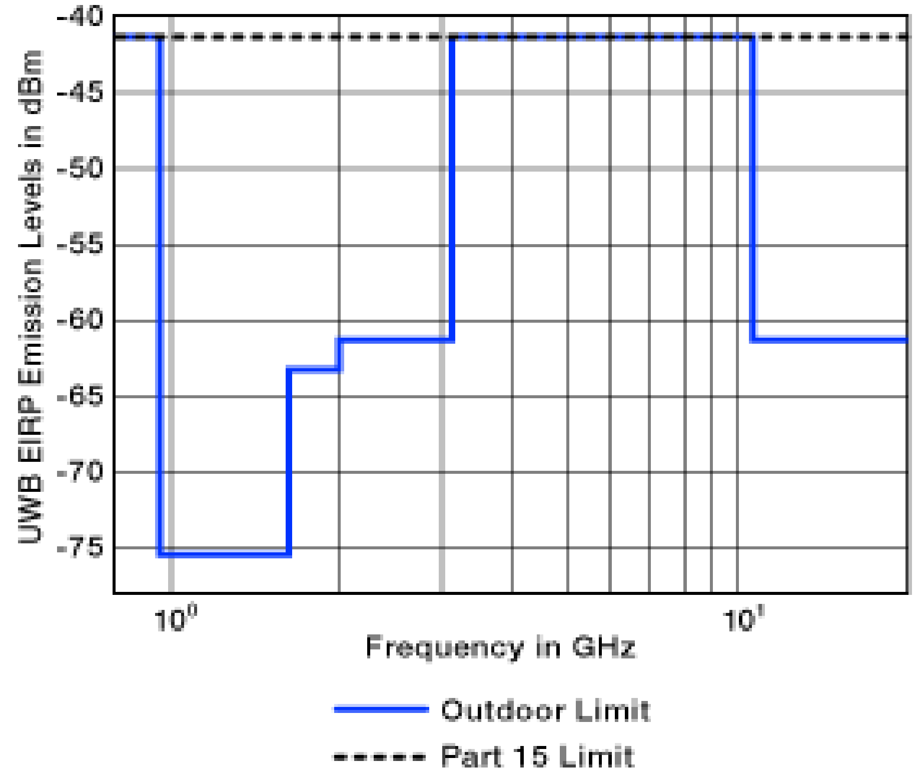


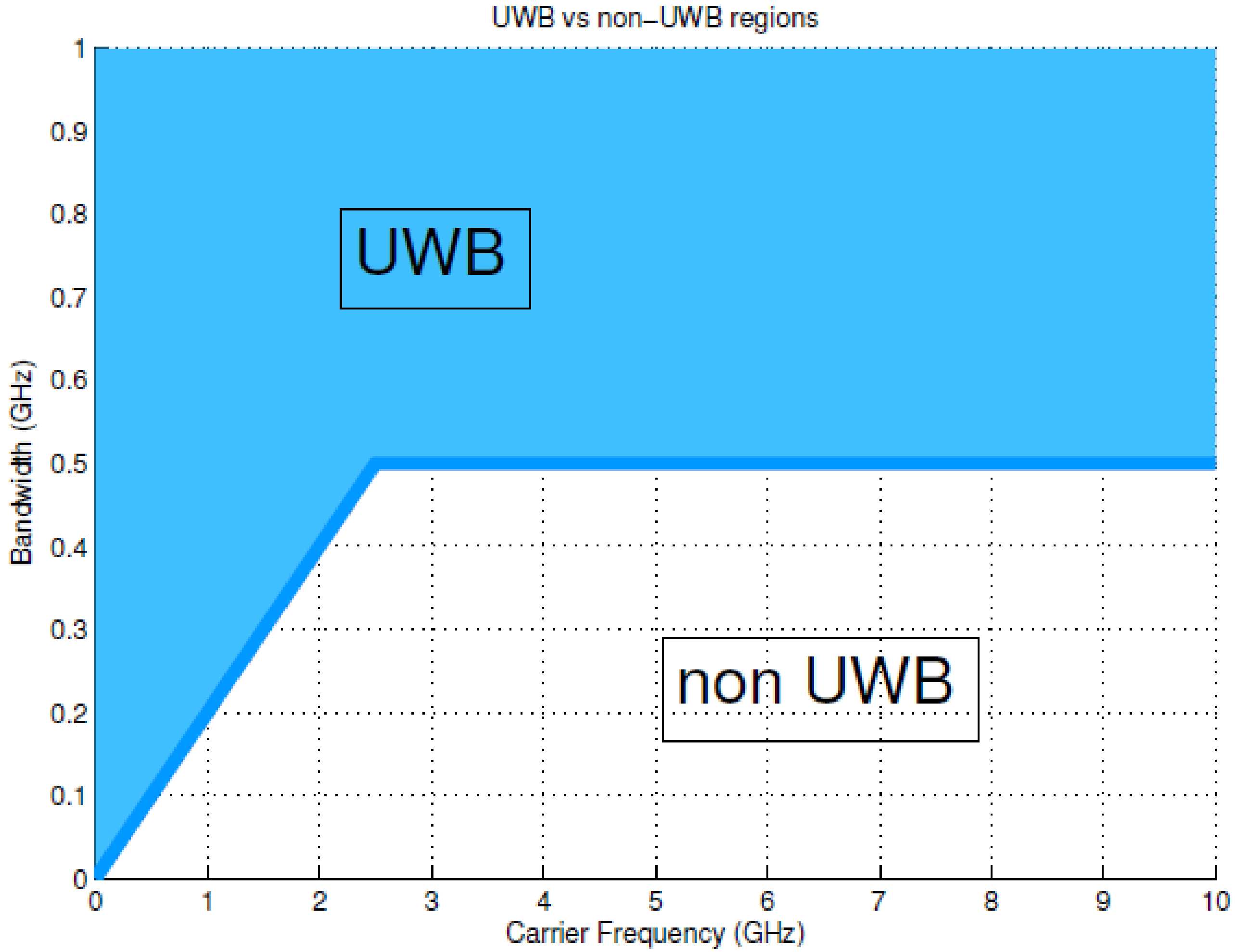

Figure 1. FCC Part 15 Spectral Mask

**FCC Part 15**: Allowed emitted PSD of **unintentional emitters** (TV set, electronic devices, …)

# FCC regulation about UWB emissions (5/6)

- According to the FCC rules, the UWB concept is not limited to Impulse Radio
- Any signal is UWB provided that **its fractional bandwidth is greater than 0.2** or **its occupied bandwidth is greater than 500 MHz**.
- The 500 MHz minimum bandwidth limit sets a threshold at 2.5 GHz
  - Below the threshold signals are UWB if their fractional bandwidth exceeds 0.20
  - Above the threshold signals are UWB if their bandwidth exceeds 500 MHz

# FCC regulation about UWB emissions (6/6)



# IEEE UWB standardization activities (1/4)

- FCC rules extended the UWB definition beyond Impulse Radio
- The dichotomy between impulsive and non-impulsive UWB was reflected in the debate on UWB standardization, in particular in the framework of the IEEE 802.15 High Rate Alternative PHY Task Group (**IEEE 802.15.3a Task Group** )

The **IEEE 802.15.3a Task Group** aimed at providing a higher speed PHY enhancement amendment to 802.15.3 for applications involving imaging and multimedia

High Rates over Short Ranges

# IEEE UWB standardization activities (2/4)

- Two different proposals for a physical layer based on UWB were under discussion for several years:
  - a **Multi-Band** (MB) approach combining frequency hopping with Orthogonal Frequency Division Multiplexing (OFDM)
  - a second approach using **Direct-Sequence UWB**, or DS-UWB, which preserved the original pulsed nature of UWB
- In the minutes of a **IEEE 802.15.3a Task Group** meeting held in November 2004, the DS-UWB obtained a majority of votes
- A final agreement was however never reached, and the group was eventually disbanded in 2007.

# UWB standards for high-rate data networks (3/4)

The Register

The Register » Enterprise » Data Networking »

UWB standards battle remains unresolved

By Wireless Watch

Published Friday 26th Septe

TECHWORLD

The UK's infrastructure & network knowledge centre

07 September 2004

UWB wars may let Wi-Fi win

While you're fighting, guys, someone else will steal your market!

By Peter Judge, Techworld

InfoWorld

Standards deadlock looms over UWB

Impasse could derail efforts to create a standard for the short-range wireless technology

By Sumner Lemon, IDG News Service

May 17, 2005

Part of the TechWeb Bus

mobilepipeline

December 12, 2003

UWB Contenders Take Their Fight To The Market

The marketplace, not the IEEE, will probably decide which UWB

By Rick Merritt, EE Times

TECHWORLD

The UK's infrastructure & network knowledge centre

17 May 2005

Standards deadlock hits UWB

The market will have to decide.

By Sumner Lemon, IDG News Service

USA TODAY

Posted 8/24/2004 11:25 PM Updated 8/25/2004 3:37 AM

Fight over ultrawideband standards turns into morass

# UWB standards for high-rate data networks (4/4)

- Each proposal was backed as an industrial standard by its own consortium:
  - **WiMedia Alliance** (for MB-OFDM)
    - Was adopted in the Certified Wireless USB standard, but failed to gain market share
  - **UWB Forum** (for DS-UWB)
    - Short lived: created in 2004, and dissolved in 2006
- To sum up: given the simultaneous dramatic increase in data rates of competing technologies (WiFi, in particular) the window of opportunity for UWB in high rate applications was missed

# UWB standards for low-rate data networks (1/2)

- Regarding the introduction of UWB in low-rate, location-enabled applications, standardization took its first steps within the **IEEE 802.15.4a** Task Group

Standard for **low-rate** WPANs with multi-month to multi-year battery life.

- Original IEEE 802.15.4 (Zigbee) features included data rates of 20-250 kbps, power management to ensure low power consumption, and low complexity.

# UWB standards for low-rate data networks (2/2)

- Within the 802.15.4, the Low Rate Alternative PHY Task Group (**TG4a**) focused on high precision ranging / location capability (1 meter accuracy) and ultra low power consumption.
- In March 2005, TG4a selected two optional PHYs consisting of:
  - a **UWB Impulse Radio** (operating in unlicensed UWB spectrum)
  - a Chirp Spread Spectrum (operating in unlicensed 2.4 GHz spectrum).
- The results of the work carried out in the TG4a were integrated in the revised IEEE 802.15.4-2011 standard

# IEEE standards on UWB after 2007

- The standard was further revised in 2015, adding support for new PHY layers, including:
  - TV White Spaces
  - Smart Utility Networks
- The 2015 revision redefined the UWB PHY by splitting it into two different UWB PHYs:
  - High Rate Pulse Repetition Frequency (HRP)
  - Low Rate Pulse Repetition Frequency (LRP)
- A new revision of the standard was released in 2020 (new PHYs and corrections)
- Next step: 802.15.4z , just approved:
  - enhanced ranging robustness and accuracy
  - encrypted ranging

# IEEE 802.15.4 UWB HRP PHY

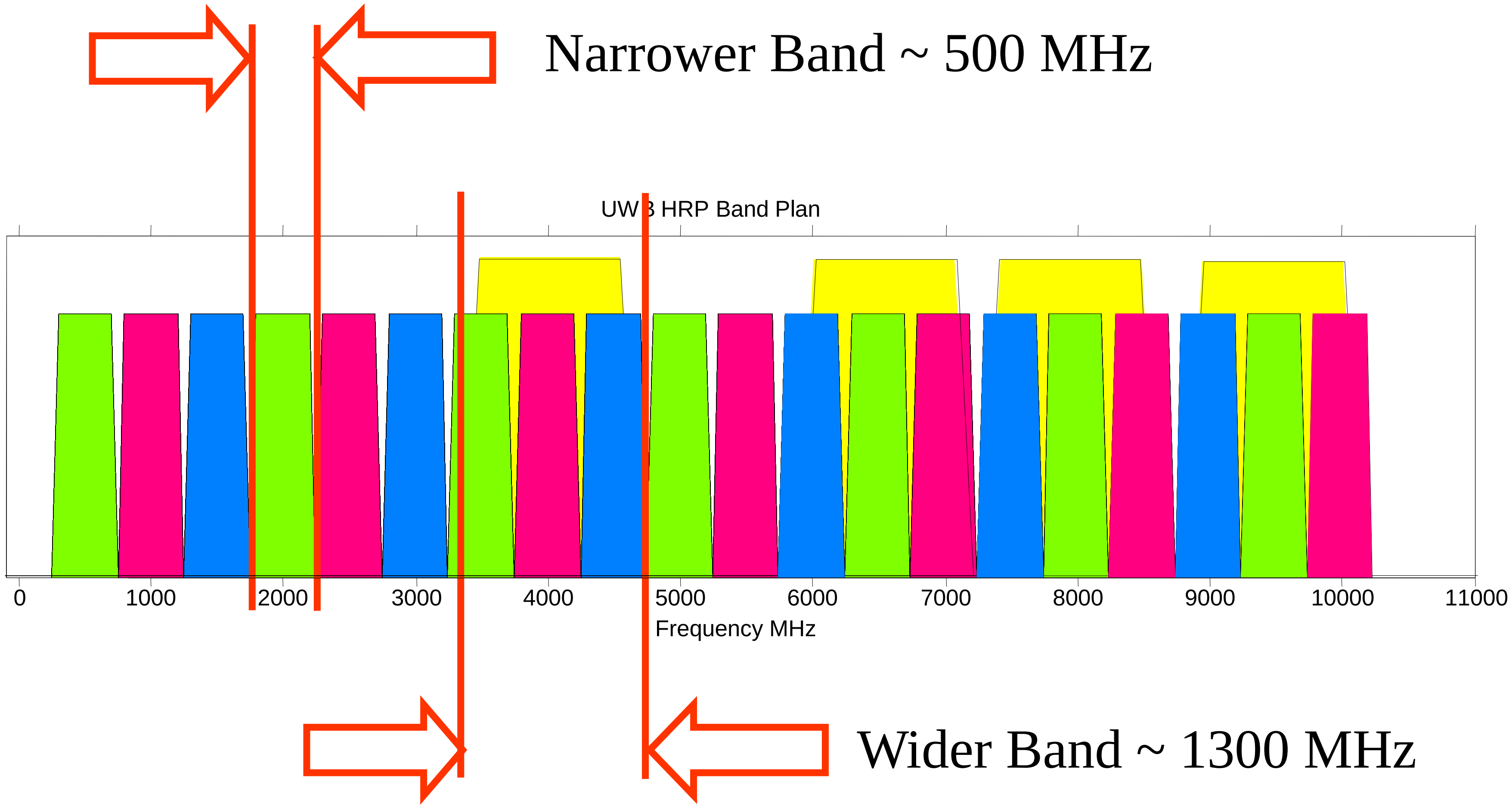
Table 15-3—HRP UWB PHY rate-dependent and timing-related parameters

| Channel Number | Peak PRF MHz | Bandwidth MHz | Preamble Code Length | Modulation & Coding | | | Data Symbol Structure | | | | | | Data | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | Viterbi Rate | RS Rate | Overall FEC Rate | #Burst Positions per Symbol $N_{burst}$ | # Hop Bursts $N_{hop}$ | # Chips Per Burst $N_{cpb}$ | #Chips Per Symbol | Burst Duration $T_{burst}$ (ns) | Symbol Duration $T_{dsym}$ (ns) | Symbol Rate (MHz) | Bit Rate Mb/s | Mean PRF (MHz) |
| {0:3, 5:6, 8:10, 12:14} | 499.2 | 499.2 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 128 | 4096 | 256.41 | 8205.13 | 0.12 | 0.11 | 15.60 |
| | 499.2 | 499.2 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 16 | 512 | 32.05 | 1025.64 | 0.98 | 0.85 | 15.60 |
| | 499.2 | 499.2 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 2 | 64 | 4.01 | 128.21 | 7.80 | 6.81 | 15.60 |
| | 499.2 | 499.2 | 31 | 1 | 0.87 | 0.87 | 32 | 8 | 1 | 32 | 2.00 | 64.10 | 15.60 | 27.24 | 15.60 |
| {0:3, 5:6, 8:10, 12:14} | 499.2 | 499.2 | 31 | 0.5 | 0.87 | 0.44 | 128 | 32 | 32 | 4096 | 64.10 | 8205.13 | 0.12 | 0.11 | 3.90 |
| | 499.2 | 499.2 | 31 | 0.5 | 0.87 | 0.44 | 128 | 32 | 4 | 512 | 8.01 | 1025.64 | 0.98 | 0.85 | 3.90 |
| | 499.2 | 499.2 | 31 | 0.5 | 0.87 | 0.44 | 128 | 32 | 2 | 256 | 4.01 | 512.82 | 1.95 | 1.70 | 3.90 |
| | 499.2 | 499.2 | 31 | 1 | 0.87 | 0.87 | 128 | 32 | 1 | 128 | 2.00 | 256.41 | 3.90 | 6.81 | 3.90 |
| {0:3, 5:6, 8:10, 12:14} | 499.2 | 499.2 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 512 | 4096 | 1025.64 | 8205.13 | 0.12 | 0.11 | 62.40 |
| | 499.2 | 499.2 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 64 | 512 | 128.21 | 1025.64 | 0.98 | 0.85 | 62.40 |
| | 499.2 | 499.2 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 8 | 64 | 16.03 | 128.21 | 7.80 | 6.81 | 62.40 |
| | 499.2 | 499.2 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 2 | 16 | 4.01 | 32.05 | 31.20 | 27.24 | 62.40 |
| {4, 11} | 499.2 | 1331.2 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 128 | 4096 | 256.41 | 8205.13 | 0.12 | 0.11 | 15.60 |
| | 499.2 | 1331.2 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 16 | 512 | 32.05 | 1025.64 | 0.98 | 0.85 | 15.60 |
| | 499.2 | 1331.2 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 2 | 64 | 4.01 | 128.21 | 7.80 | 6.81 | 15.60 |
| | 499.2 | 1331.2 | 31 | 1 | 0.87 | 0.87 | 32 | 8 | 1 | 32 | 2.00 | 64.10 | 15.60 | 27.24 | 15.60 |
| {4, 11} | 499.2 | 1331.2 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 512 | 4096 | 1025.64 | 8205.13 | 0.12 | 0.11 | 62.40 |
| | 499.2 | 1331.2 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 64 | 512 | 128.21 | 1025.64 | 0.98 | 0.85 | 62.40 |
| | 499.2 | 1331.2 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 8 | 64 | 16.03 | 128.21 | 7.80 | 6.81 | 62.40 |
| | 499.2 | 1331.2 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 2 | 16 | 4.01 | 32.05 | 31.20 | 27.24 | 62.40 |
| 7 | 499.2 | 1081.6 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 128 | 4096 | 256.41 | 8205.13 | 0.12 | 0.11 | 15.60 |
| | 499.2 | 1081.6 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 16 | 512 | 32.05 | 1025.64 | 0.98 | 0.85 | 15.60 |
| | 499.2 | 1081.6 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 2 | 64 | 4.01 | 128.21 | 7.80 | 6.81 | 15.60 |
| | 499.2 | 1081.6 | 31 | 1 | 0.87 | 0.87 | 32 | 8 | 1 | 32 | 2.00 | 64.10 | 15.60 | 27.24 | 15.60 |
| 7 | 499.2 | 1081.6 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 512 | 4096 | 1025.64 | 8205.13 | 0.12 | 0.11 | 62.40 |
| | 499.2 | 1081.6 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 64 | 512 | 128.21 | 1025.64 | 0.98 | 0.85 | 62.40 |
| | 499.2 | 1081.6 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 8 | 64 | 16.03 | 128.21 | 7.80 | 6.81 | 62.40 |
| | 499.2 | 1081.6 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 2 | 16 | 4.01 | 32.05 | 31.20 | 27.24 | 62.40 |
| 15 | 499.2 | 1354.97 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 128 | 4096 | 256.41 | 8205.13 | 0.12 | 0.11 | 15.60 |
| | 499.2 | 1354.97 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 16 | 512 | 32.05 | 1025.64 | 0.98 | 0.85 | 15.60 |
| | 499.2 | 1354.97 | 31 | 0.5 | 0.87 | 0.44 | 32 | 8 | 2 | 64 | 4.01 | 128.21 | 7.80 | 6.81 | 15.60 |
| | 499.2 | 1354.97 | 31 | 1 | 0.87 | 0.87 | 32 | 8 | 1 | 32 | 2.00 | 64.10 | 15.60 | 27.24 | 15.60 |
| 15 | 499.2 | 1354.97 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 512 | 4096 | 1025.64 | 8205.13 | 0.12 | 0.11 | 62.40 |
| | 499.2 | 1354.97 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 64 | 512 | 128.21 | 1025.64 | 0.98 | 0.85 | 62.40 |
| | 499.2 | 1354.97 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 8 | 64 | 16.03 | 128.21 | 7.80 | 6.81 | 62.40 |
| | 499.2 | 1354.97 | 127 | 0.5 | 0.87 | 0.44 | 8 | 2 | 2 | 16 | 4.01 | 32.05 | 31.20 | 27.24 | 62.40 |

- Bit rate: 0.11 – 27.24 Mb/s
- Bandwidth: 499.2 – 1354.97 MHz

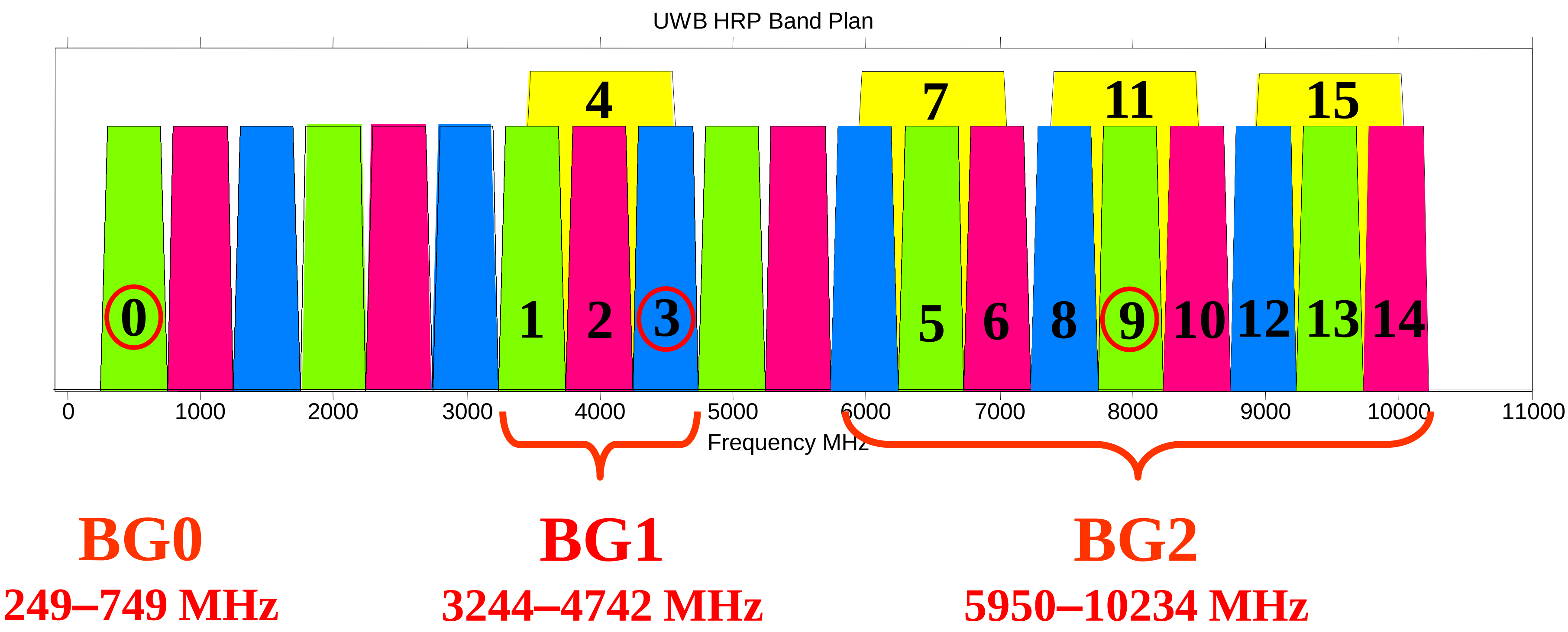
# IEEE 802.15.4 UWB HRP PHY Band Plan (1/2)

- IEEE 802.15.4 UWB HRP PHY adopts a dual band plan



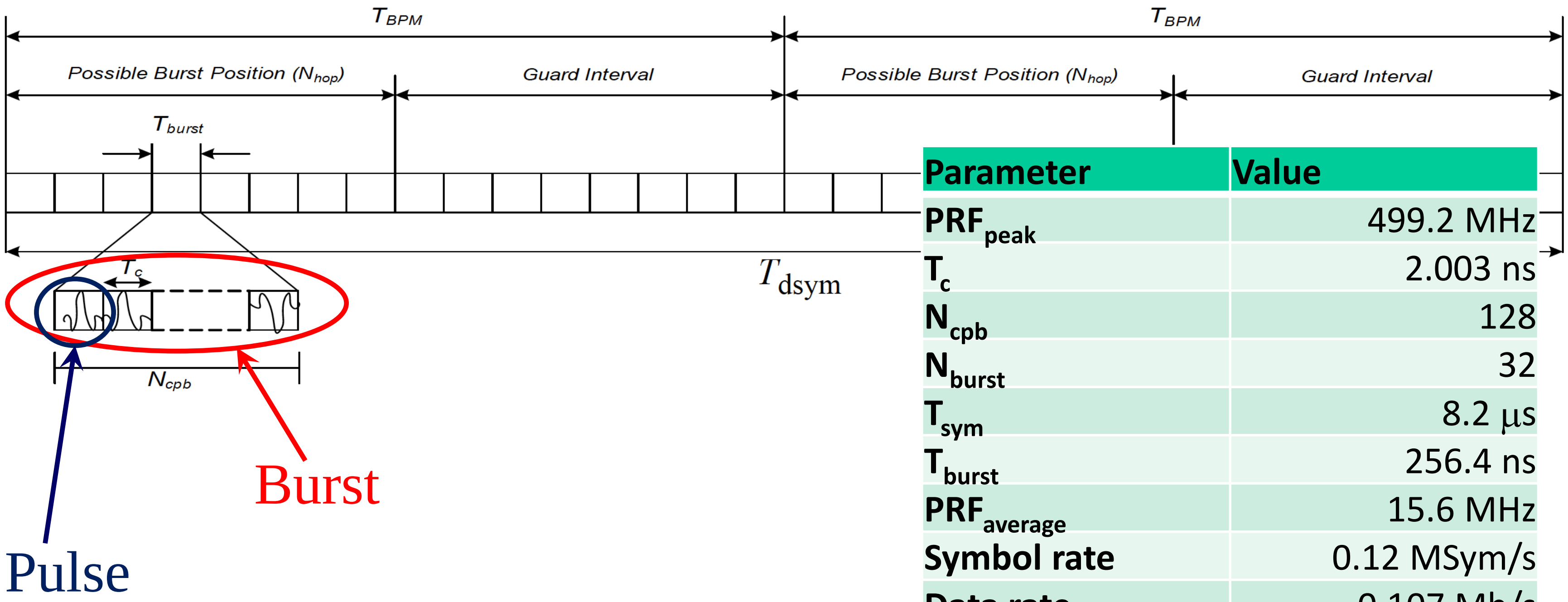
# IEEE 802.15.4 UWB HRP PHY Band Plan (2/2)

- Not all bands are used
- 15 channels were defined, divided in Band Groups (BGs)
- 1 mandatory channel was identified in each BG



# IEEE 802.15.4 UWB HRP PHY Modulation

- HRP UWB PHY adopts bursts of pulses at high Pulse Repetition Frequency (PRF)
- Information is encoded by combining
  - Burst Position Modulation (BPM)
  - Binary Phase Shift Keying (BPSK)



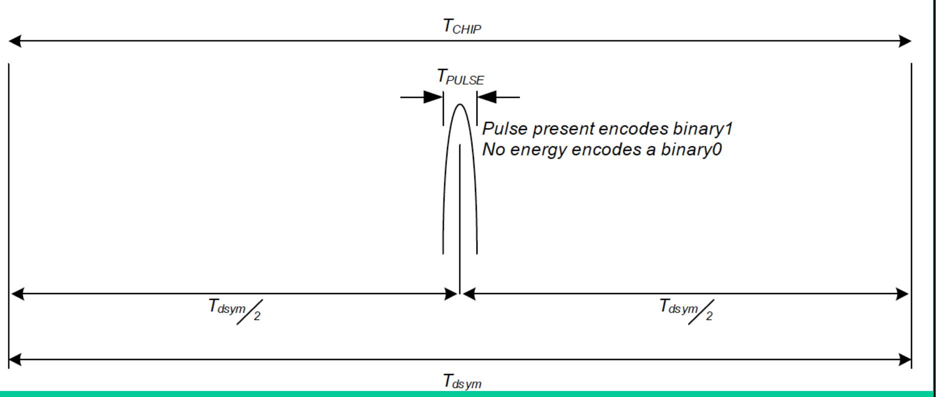

| Parameter | Value |
|---|---|
| $PRF_{peak}$ | 499.2 MHz |
| $T_c$ | 2.003 ns |
| $N_{cpb}$ | 128 |
| $N_{burst}$ | 32 |
| $T_{sym}$ | 8.2 µs |
| $T_{burst}$ | 256.4 ns |
| $PRF_{average}$ | 15.6 MHz |
| Symbol rate | 0.12 MSym/s |
| Data rate | 0.107 Mb/s |

# IEEE 802.15.4 UWB LRP PHY

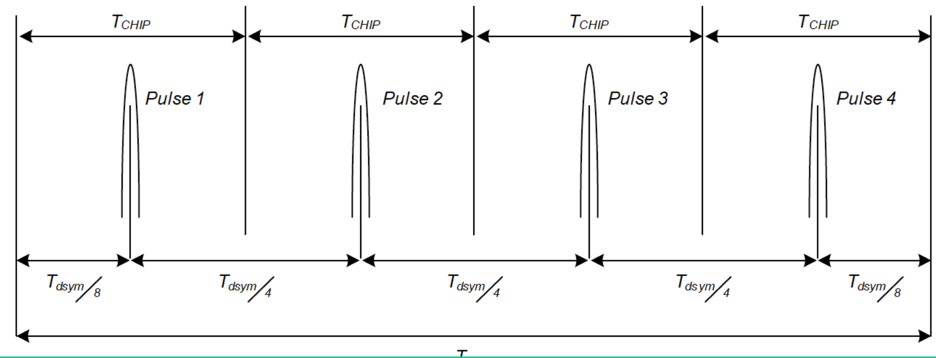
- LRP UWB PHY does not use bursts.
- A low Pulse Repetition Frequency (< 2 MHz) is used
- Modulation scheme is either On Off Keying (OOK) or Pulse Position Modulation (PPM)
- Three operation modes are defined:

| Mode | PRF | Pulses per bit | Data rate | Modulation |
|---|---|---|---|---|
| **Base** | 1 MHz | 1 | 1 Mb/s | OOK |
| **Extended** | 1 MHz | 4 | 250 kb/s | OOK |
| **Long-range** | 2 MHz | 64 (32 off) | 31.25 kb/s | PPM |

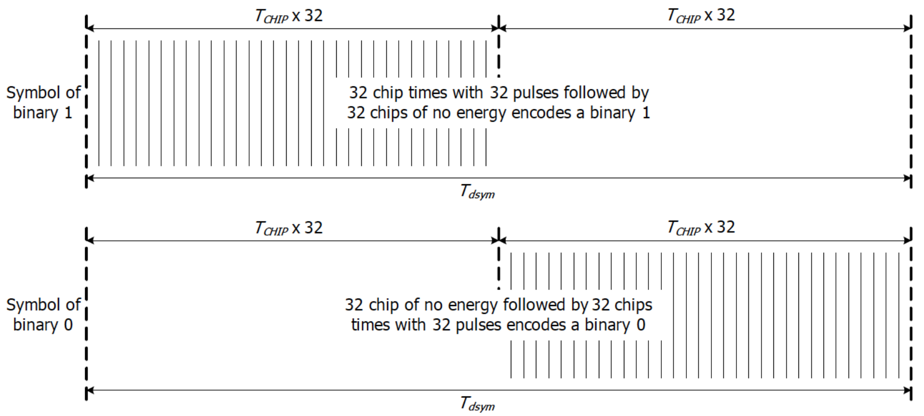
# IEEE 802.15.4 UWB LRP PHY




Base mode symbol structure




Extended mode symbol structure



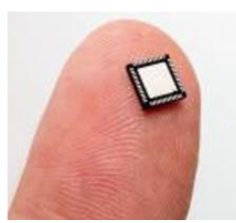

Long range mode symbol structure

# UWB on the market

- Several companies released UWB products (mostly for low rate tracking applications).

- *nanotron Technologies*, recently aquired by Sensera (Sept. 2017), focused on UWB modules adopting Chirp Spread Spectrum (CSS), mostly used for indoor localization.
- *DecaWave* (now owned by Qorvo) develops UWB chips based on Impulse Radio, mostly used for indoor localization.
- *Multispectral Solutions*, now owned by Zebra Enterprise Solutions also focused on IR UWB for positioning since the early 2000s
- *Time Domain*, now owned by 5D Robotics developed several IR-UWB modules for positioning/tracking

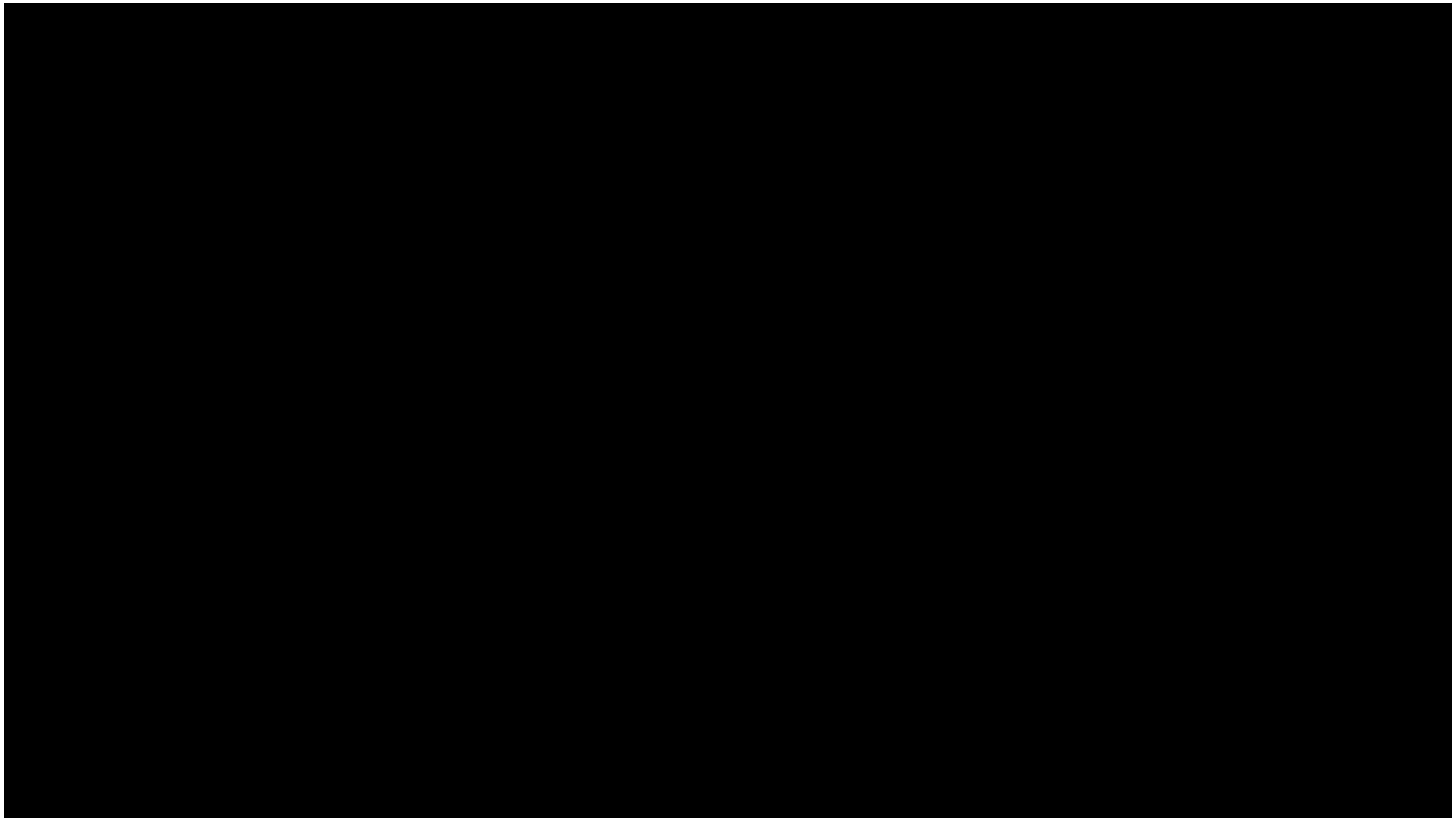
nanotron *swarm* chip


Decawave *DW1000* chip


Time Domain *PulsON* 440

# UWB devices

5D Robotics *Virtual Rail* (using Time Domain UWB technology)



# UWB devices

Peer to peer distance estimation and security distance violation detection (using Decawave DWM1001-DEV chips)