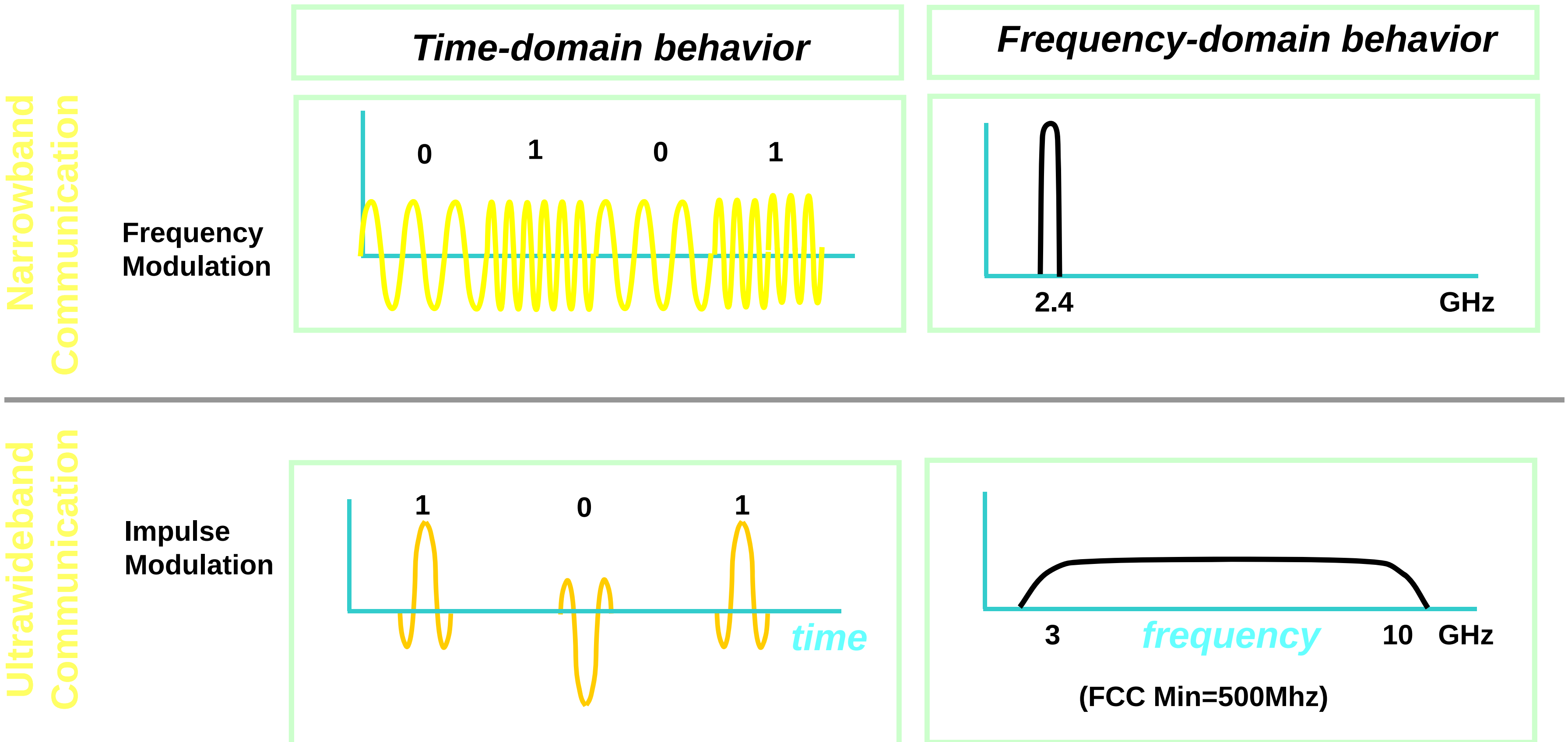
UWB: Technology and implications for sensor networks

Ali Medi

Outline

- Technical background
- Why is it good? Applications of UWB
- Standards activities
- Implications for sensor networks
- Resources and Conclusions

What is UltraWideBand?



- Communication that occupies more than 500 MHz of spectrum
- Communication with fractional bandwidth of more than 0.2
- More possibilities than pulses

UWB Signals

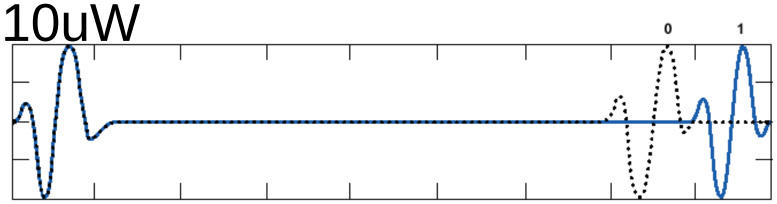
- Earliest form of radio communication – Hertz, 1870s
- Impulse followed by shaping filter and Chirp signals
  - Best suited for non-coherent pulse transmissions
- Synchronous pulse synthesis
  - Best suited for frequency/time-agile systems and synchronous systems
- OFDM and COFM
  - Best suited for fine PSD tailoring

Basic Impulse Information Modulation

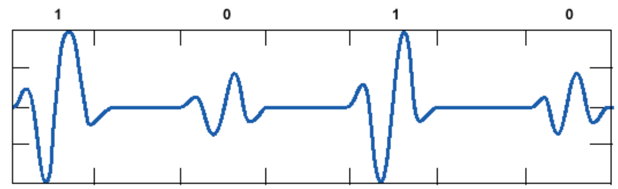
Pulse length ~ 200ps; Energy concentrated in 2-6GHz band;

Voltage swing ~100mV; Power ~ 10uW

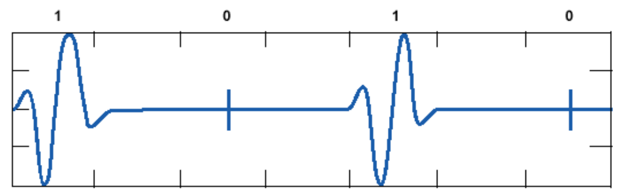
- **Pulse Position Modulation (PPM)**



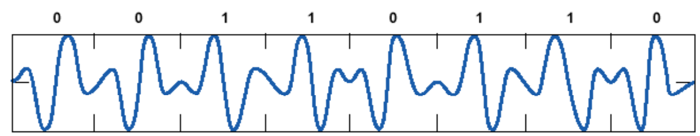
- **Pulse Amplitude Modulation (PAM)**



- **On-Off Keying (OOK)**

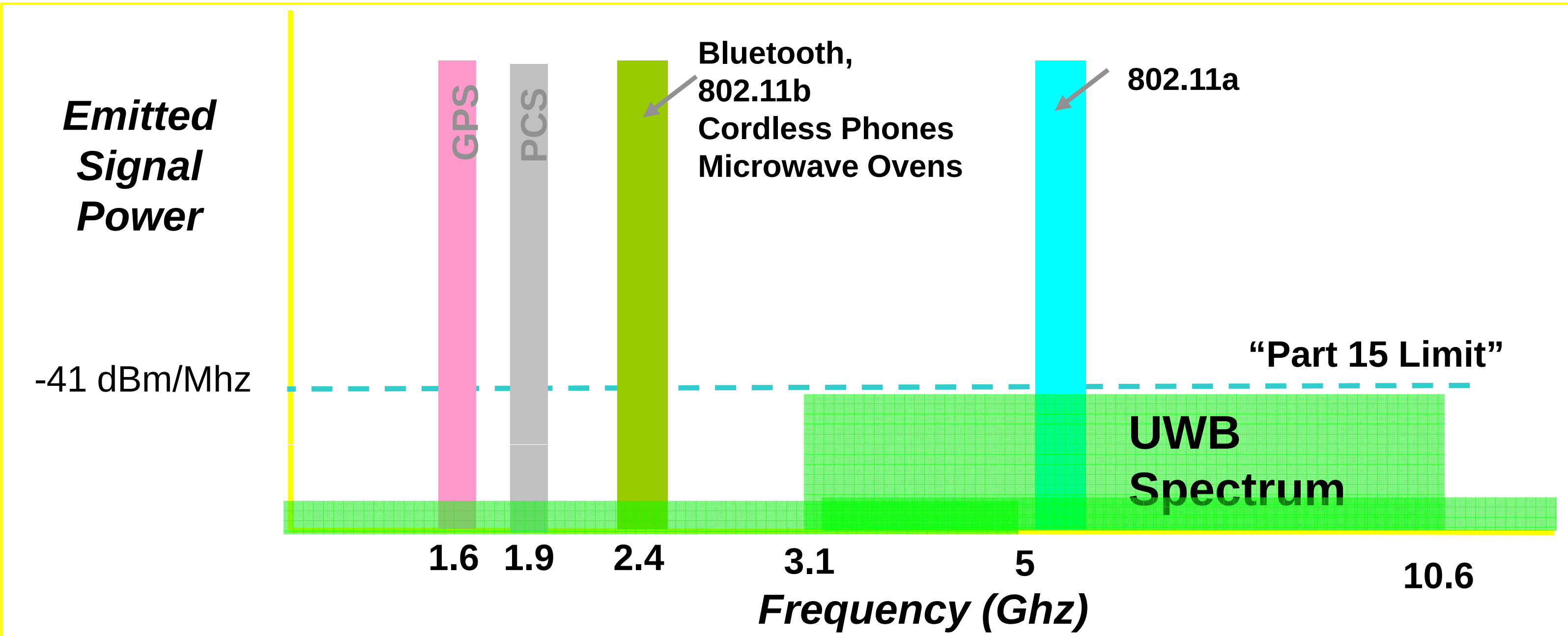


- **Bi-Phase Modulation (BPSK)**



UWB Spectrum

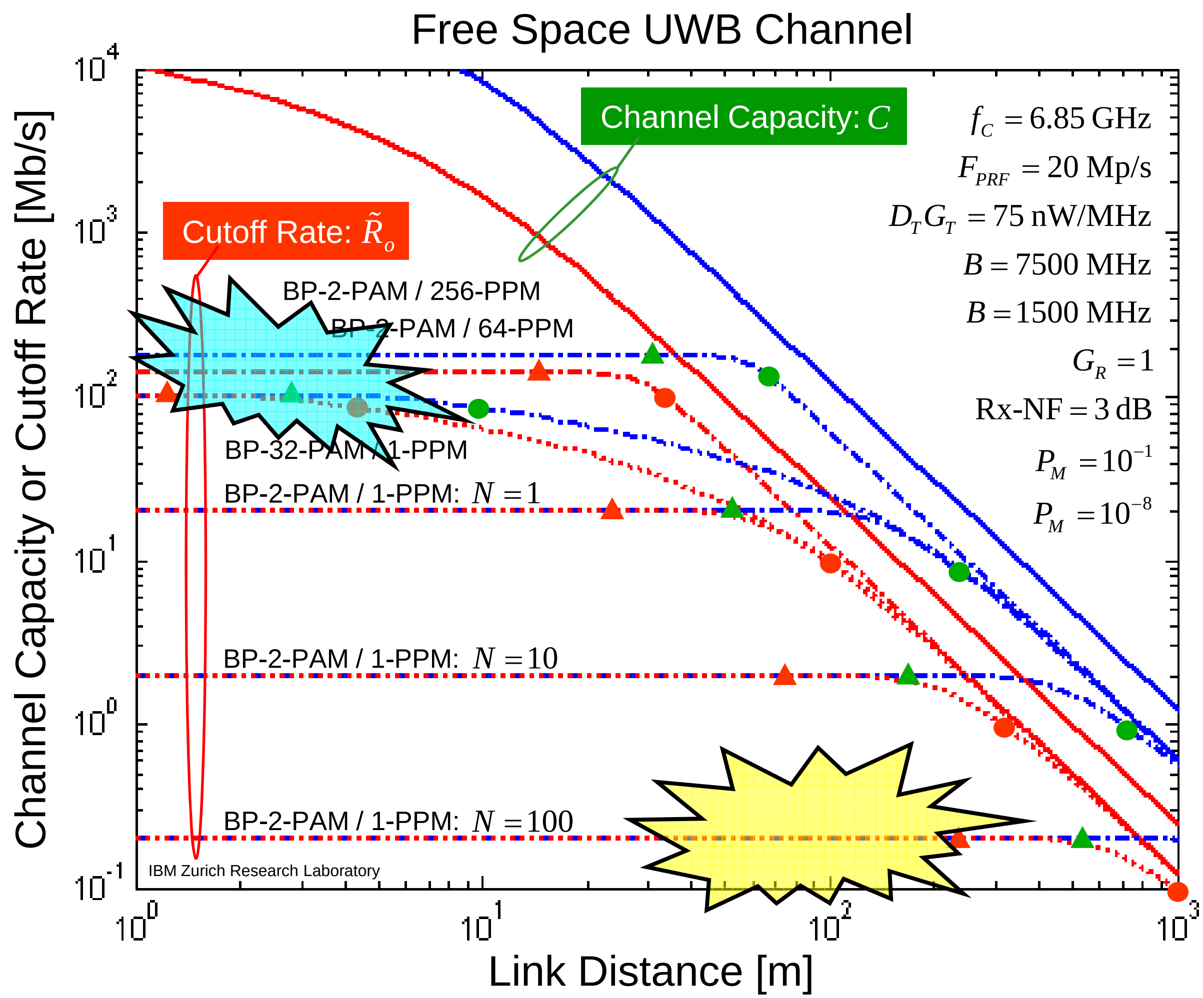
- FCC ruling permits UWB spectrum overlay



- FCC ruling issued 2/14/2002 after ~4 years of study & public debate
- FCC believes current ruling is conservative
- Worldwide regulations differ – Japan, EU, Asia…

Theoretical capability & application spaces

Very High Data Rate Applications



Low Data Rate and/or Location Tracking Applications

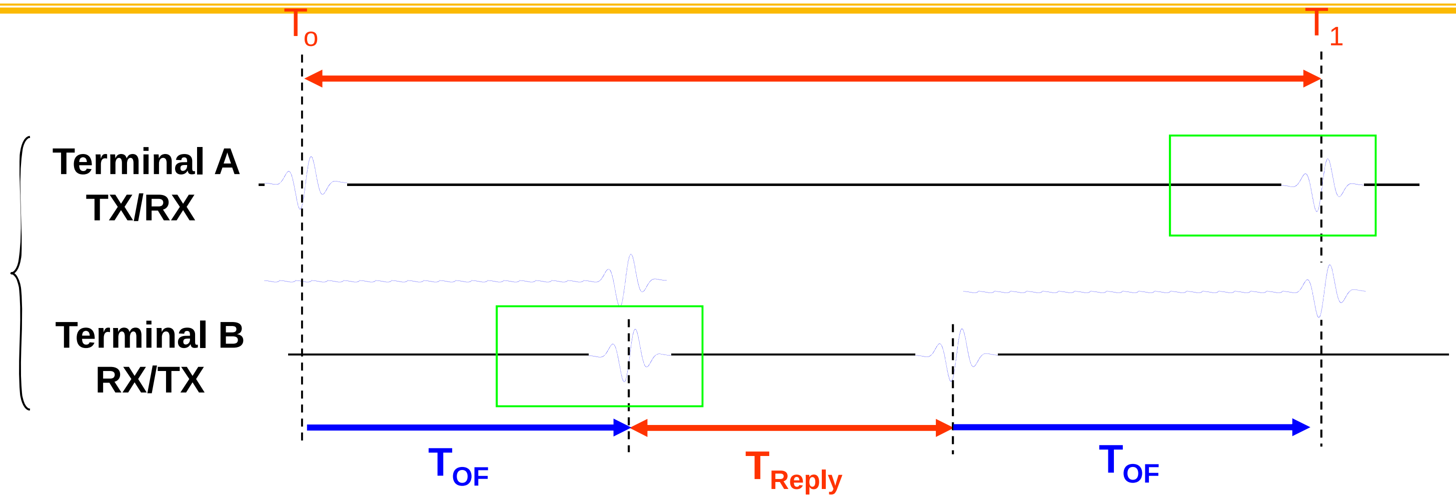
So why is UWB so interesting?

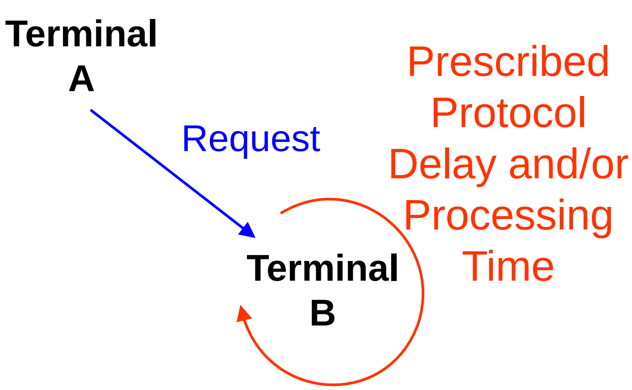
- **7.5 Ghz of "free spectrum" in the U.S.**
  - FCC recently legalized UWB for commercial use
  - Spectrum allocation overlays existing users, but its allowed power level is very low to minimize interference
- **Very high data rates possible**
  - 500 Mbps can be achieved at distances of 10 feet under current regulations
- **Simple CMOS transmitters at very low power**
  - Suitable for battery-operated devices
  - Low power is CMOS friendly
  - "Moore's Law Radio" --Data rate scales with the shorter pulse widths made possible with ever faster CMOS circuits
- **Low cost**
  - Nearly "all digital" radio ?
  - Integration of more components on a chip (antennas?)

Advantages

- **Range/bitrate scalability**
  - **Extremely good W/Mbit communication**
- **Localization**
  - **Sub-centimeter resolution using pulse leading edge detection**
  - **passes through building blocks, walls, etc. (LOS not required)**
- **Robustness to interference and multipath**
  - **Path delay >> pulse width => possible to resolve different signal paths**
  - **Use a RAKE receiver to turn multipath into a consistent advantage**
  - **Consistent range**
- **Radio as a sensor (radar)**
  - **Localization and multipath robustness are a consequence of this**
  - **Channel characterization reveals absorptive/reflective sources and their positions**
- **Difficult to intercept in traditional ways**
  - **Low interference (that's why we allow it, after all)**
  - **Very low spectral energy density**
- **Size**
  - **4.5 mm^2 in 90 nm process for high data rate designs**
  - **integration of more components onto a single chip**

Time Of Arrival (TOA) & Two Way Ranging (TWR)





T_{OF} Estimation

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

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

Time Of Arrival (TOA) & Two Way Ranging (TWR)

Main Limitations / Impact of Clock Drift on Perceived Time

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

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

Range estimation is affected by :

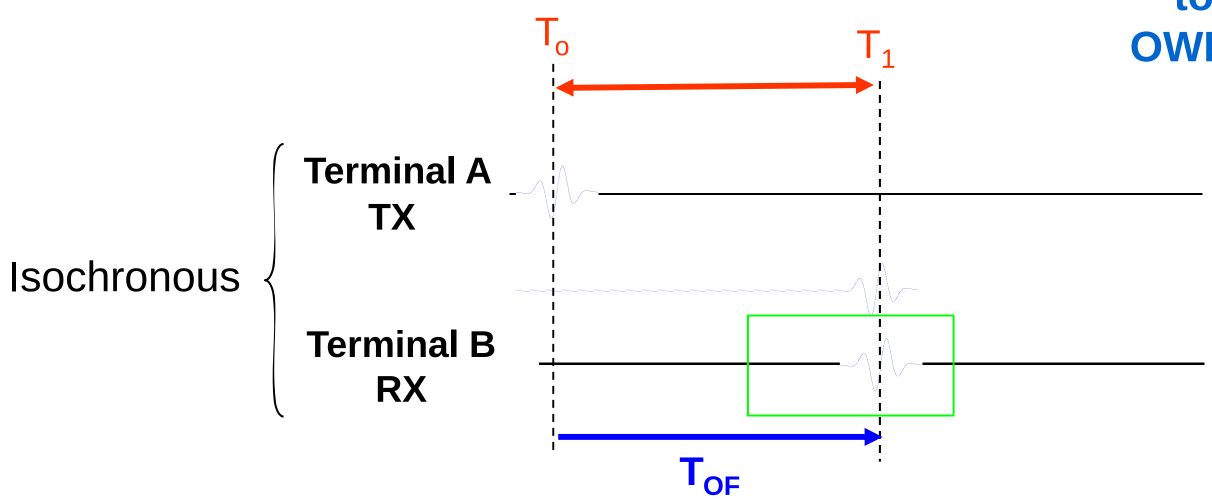
- Relative clock drift between A and B
- Clock accuracy in A and B
- Prescribed response delay

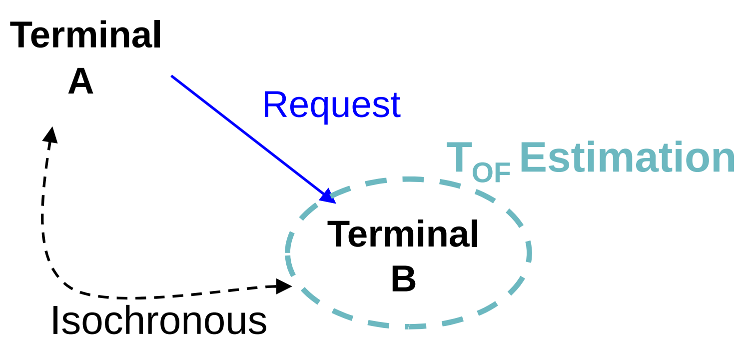
Relaxing constraints on clock accuracy by

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

Time Of Arrival (TOA) & One Way Ranging (OWR)

If Terminals are synchronized to a common clock, direct OWR can be used for Ranging





T_{OF} Estimation

$$\tilde{T}_{OF\,B} = (T_1 - T_0)$$

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

Time Of Arrival (TOA) & One Way Ranging (OWR)

Main Limitations / Impact of Synchronization and Clock Drifts on Perceived Time

$$\tilde{T}_{OF\,B} = T_{OF}\left(1 + \Delta_B\right) + \Delta_{synchro}$$

Δf_0 Is the frequency offset relative to the nominal ideal frequency f_0

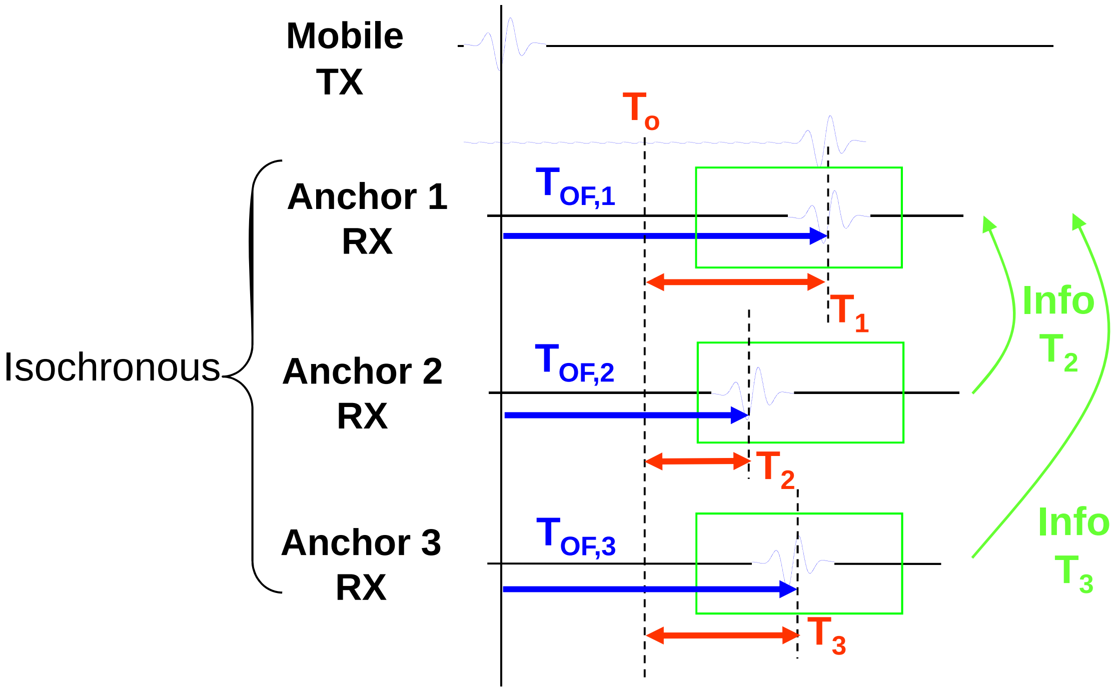
Range estimation is affected by :

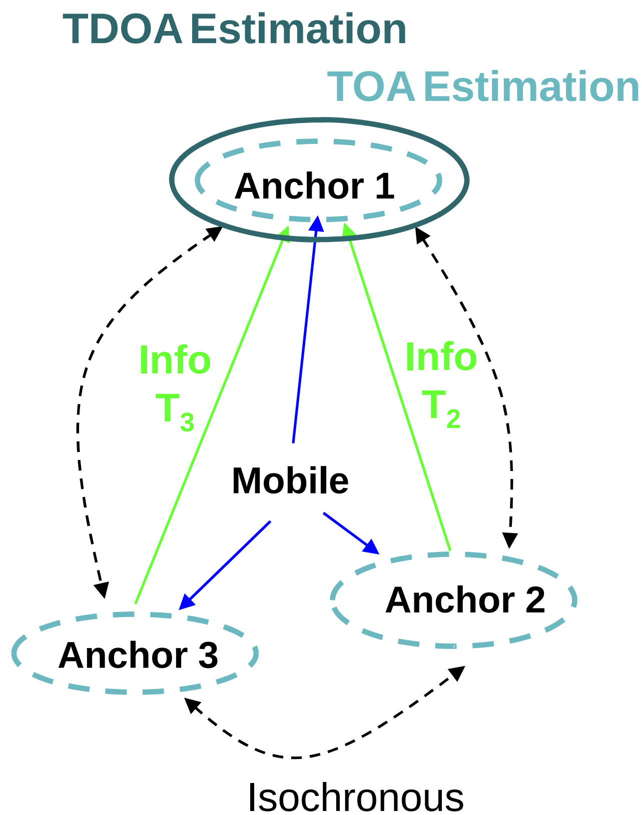
- Clock accuracy
- Uncertainty on the reference start times (synchronization)

Requirements

- Achieving fine synchronization between terminals prior to ranging

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





Passive Location

TOA Estimation → **TDOA Estimation**

$$T_1, T_2, T_3$$

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

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

Received Signal Strength Indicator (RSSI)

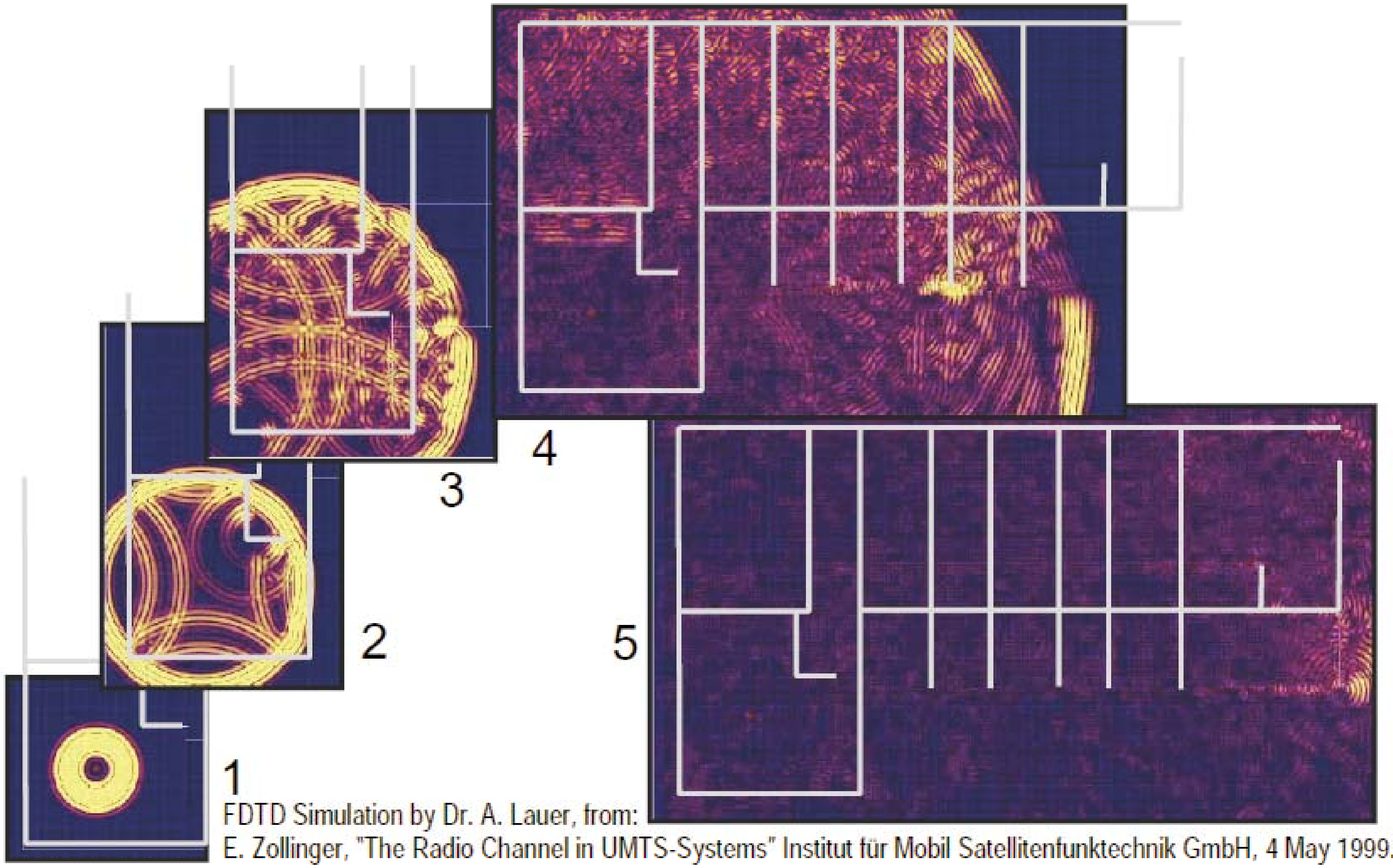
Power Strength could be an alternative solution to TOA/TDOA in the UWB Context

- Lower requirements in terms of synchronization and clock precision

But

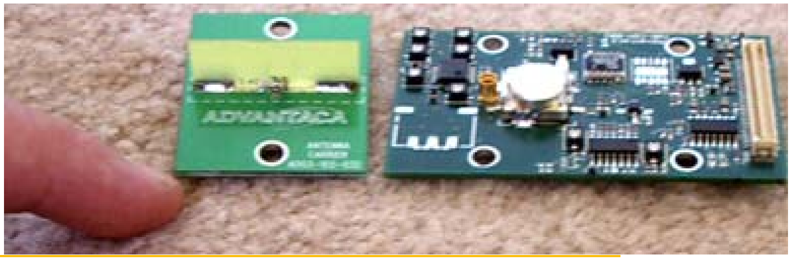
- RSSI requires precise channel behavioral model
- RSSI is sensitive to channel inconstancy and non-stationarity
- RSSI does not benefit from UWB high resolution

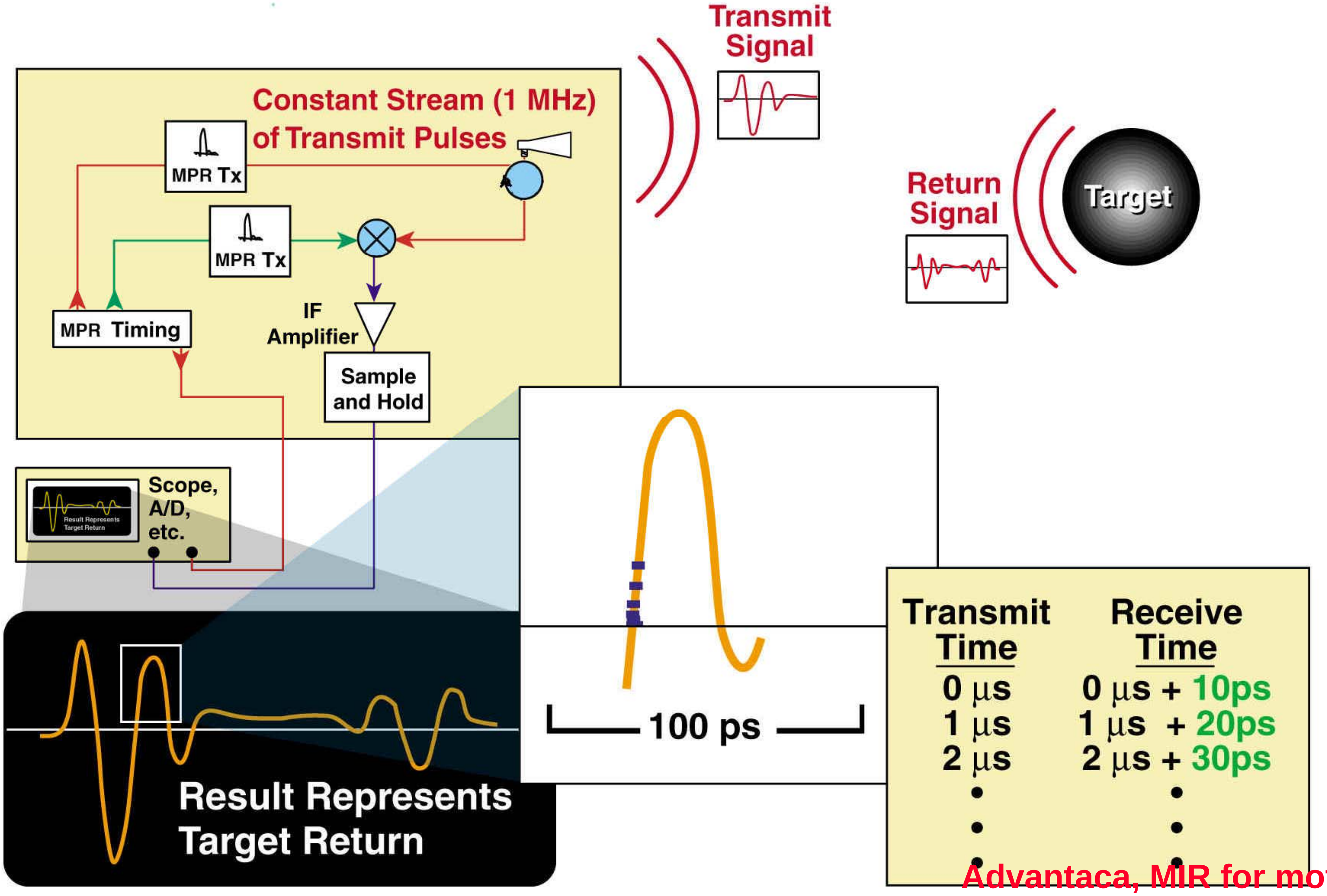
Isolated Pulse Propagation Indoors



FDTD Simulation by Dr. A. Lauer, from:
E. Zollinger, "The Radio Channel in UMTS-Systems" Institut für Mobil Satellitenfunktechnik GmbH, 4 May 1999.

UWB & radar

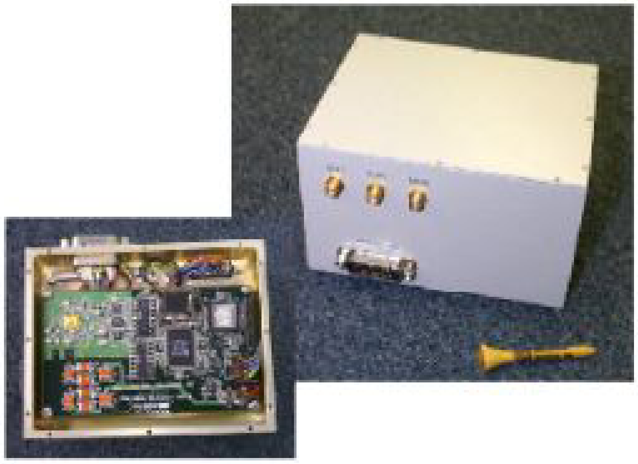




Advantaca, MIR for motes!

UWB Radar

UWB Altimeter & Obstacle Avoidance Radar

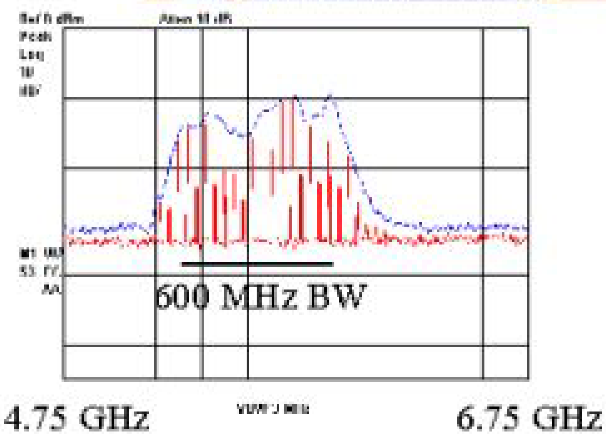


Design Characteristics

- UWB altimeter & obstacle avoidance system
- Spectrally shaped waveform design
- L-band altimeter
  - 1.0W peak, 400 MHz instantaneous BW
  - 1.3-1.7 GHz, 27% fractional BW
  - 25 μW average power @ 10kpps
  - ~5000 feet range, < 1 foot resolution
- C-band collision/obstacle avoidance sensor
  - 0.25W peak, 500 MHz instantaneous BW
  - 5.4-5.9 GHz, 8.9% fractional BW
  - 5 μW average power @ 10kpps
  - High sensitivity – 1/4" diam. wire @ 300'

UWB Radar

UWB Collision Avoidance Backup Sensor



Design Characteristics

- C-band UWB backup sensor
  - 0.25W peak, 500 MHz instantaneous BW
  - 5.25-5.85 GHz, 10.8% fractional BW
  - 5 μW average power
- High-speed, dual tunnel detector
- Range
  - 1 - 50 feet against human target
  - 1 - 200 feet against pickup truck
- Clutter resistant
- Extremely low false alarm rate – range gate cutoff

"Smart" license plate

- C-band collision avoidance radar
- L-band tag (vehicle-to-vehicle & vehicle-to-roadside)

MULTISPECTRAL SOLUTIONS, INC.

UWB Radar
UWB Intrusion Detection

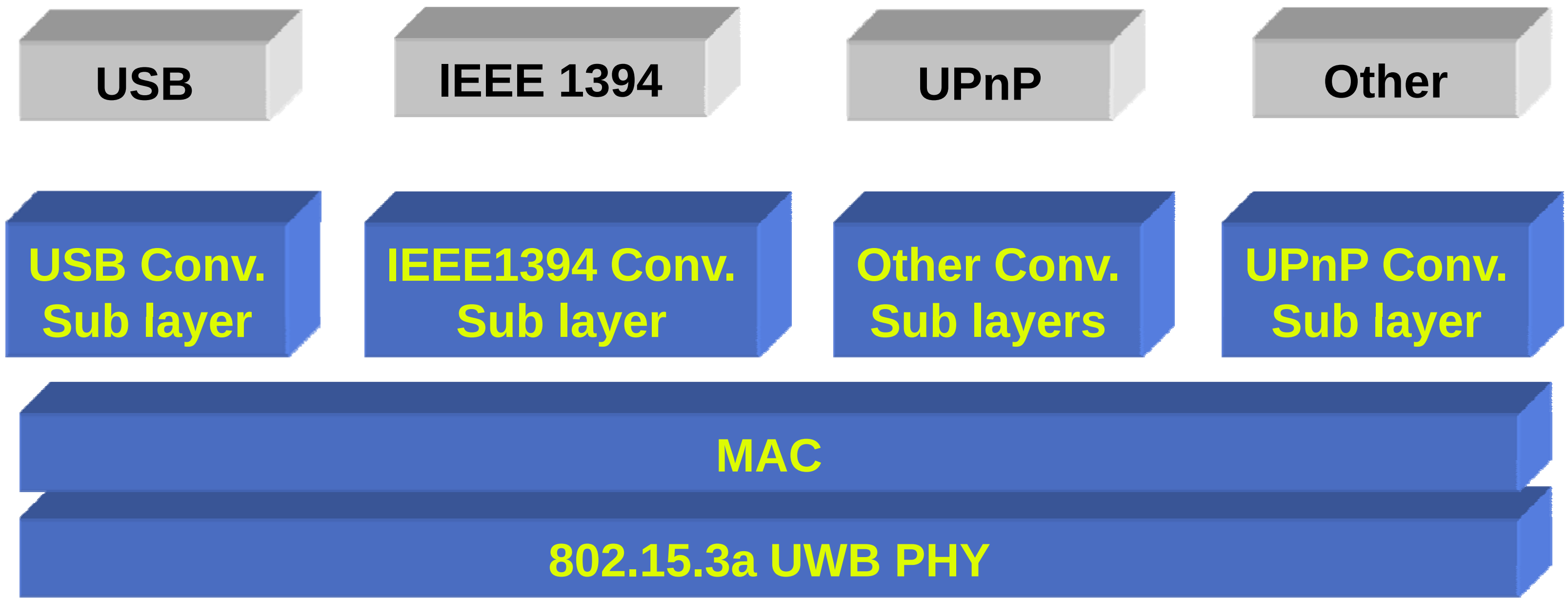
Design Characteristics

- L-band Through-the-wall sensor
  - 1.0W peak, 400 MHz instantaneous BW
  - 1.3-1.7 GHz, 27% fractional BW
  - 25 μW average power @ 10kpps
  - 0-200 feet (through wall)
- L-band Intrusion Sensor
  - 4.0W peak, 400 MHz instantaneous BW
  - 1.3-1.7 GHz, 27% fractional BW
  - 100 μW average power @ 10kpps
  - 1000 feet against human target

802.15.3a – high data rate WPAN standard

- **Direct sequence (DS-UWB)**
  - **Championed by Motorola/XtremeSpectrum**
  - **Classic UWB, simple pulses,**
  - **2 frequency bands: 3.1-4.85GHz, 6.2-9.7GHz**
  - **CDMA has been proposed at the encoding layer**
  - **Spectrum dependent on the shaping filter – possible differing devices worldwide**
- **Multiband Orthogonal Frequency Division Multiplexing (OFDM)**
  - **Intel/TI/many others**
  - **Similar in nature to 802.11a/g**
  - **14 528MHz bands (simplest devices need to support 3 lowest bands, 3.1GHz – 4.7 GHz)**
  - **Spectrum shaping flexibility for international use**

MBOA: vision for wire replacement



- **Big players backing MBOA**
- **Inclusion in many consumer electronic devices as wire replacement**
  - **Cameras, MP3 players, etc.**
  - **Chipsets & motherboard support**
- **Split from IEEE process**
  - **Will become an industry standard**
  - **Perhaps post-facto IEEE ratification**

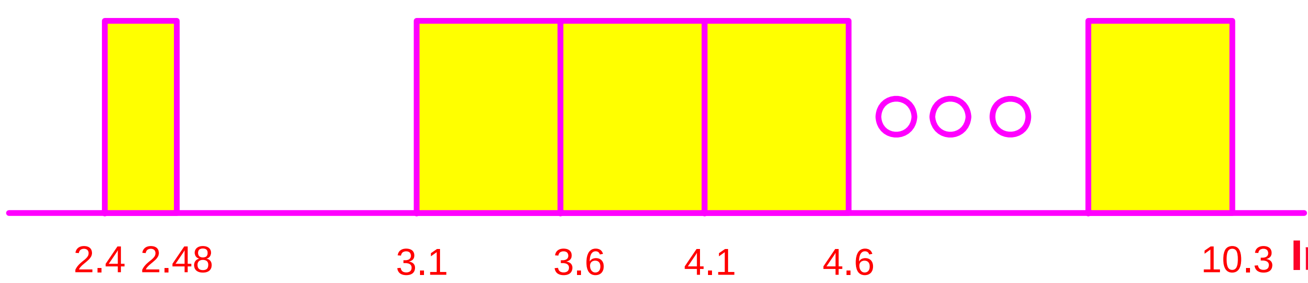
802.15.4a – alternate PHY for 802.15.4

- **Addresses the following**
  - Globally deployable
  - Compatible / interoperable with 802.15.4
  - Longer range
  - Higher reliability
  - Ranging/localization support
  - Lower latency & support for mobility
  - Low cost
- **Current UWB systems not quite suitable**
  - 90 nm CMOS is expensive, 200 mW is a lot of power
- **Still in early stages**
  - Proposals due Jan. 2005!
  - DS-UWB a major contender (Motorola)
  - Chirp Spread Spectrum another cool tech (Nanotron)
  - Many axes for diversity: Basic tech (2.4 v. UWB), ranging (UWB v. CSS v. Phase-based ranging), pulse shapes, channel arbitration (CSMA v. CDMA)

Comparison of 2.4G and “UWB band”

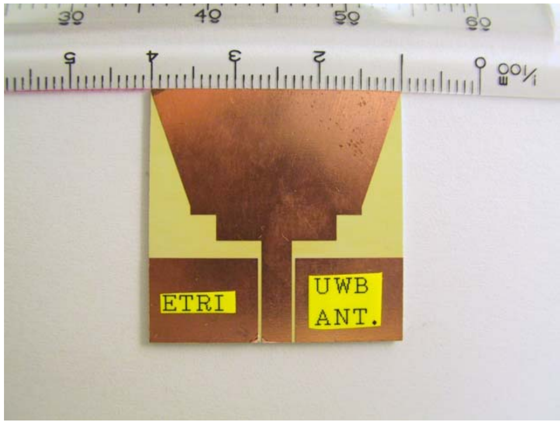
2.4	UWB
• Lot of potential interferers	•Currently cleaner
• BW=80MHz, max error 1.5m	•BW>500MHz, max error <0.3m
• One channel	•Several channels
• High power allowed	•Low power allowed
• Worldwide regulation	•US only (currently)
• Outdoor, no use restriction	•Outdoor, handheld only + more
• Easier implementation	•Tougher implementation

- **We may have both… We may define one PHY in two bands (see 15.4 as an example)**
- **The 2.4 band will be different than the other only by some parameters (e.g. pulse shape if one uses impulse radio)**



Antennas

- Generally omnidirectional
- Mass producible
- Challenges
  - Size
  - Gain
  - Efficiency
- Smallest currently described antenna: 16x13.6x3mm
- For size may need to go to higher frequencies (24 and 60 GHz)
  - Range suffers



ETRI, 30x30mm,
3.1-8.3 GHz, omni

Hitachi, 30x30mm,
3.1-6.5 GHz

Power characteristics

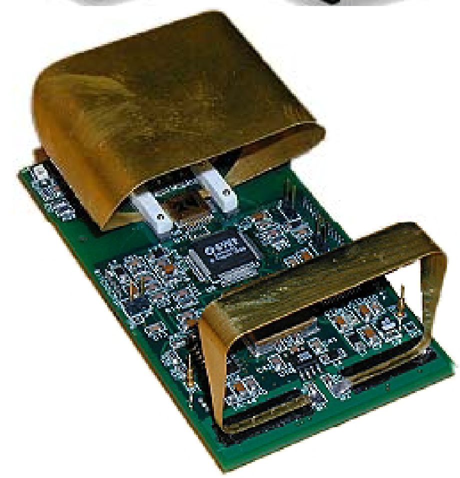
- High data rate designs (MBOA)

Block	90 nm	130 nm
TX AFE (110Mb/s)	76 mW	91 mW
TX Total (110 Mb/s)	93 mW	117 mW
RX AFE (110Mb/s)	101 mW	121 mW
RX Total (110 Mb/s)	155 mW	205 mW
RX Total (200 Mb/s)	169 mW	227 mW
Deep Sleep	15 μW	18 μW

- Power efficient per bit, but…
  - Receive ~ 2x transmit
  - Unclear startup times
  - Receiver: unclear scaling with data rate
    - » Linear extrapolation – 60-130 mW data rate independent power consumption
  - Passive wakeup schemes not applicable
    - » Cf. low probability of detection

Existing Products/Eval kits

- **Wisair UB501 RF/UB 531 BB (MB-OFDM, April 2004)**
- **Freescale(Motorola)/XtremeSpectrum XS110**
  - **FCC certified**
- **PulsON 200 - UWB Evaluation Kit**
- **AEtherWire localizer (do they still exist??)**
- **A slew of MIR applications**
  - **Collision avoidance, fluid level detection**
- **Intel/TI are not shipping anything yet**



Commercial UWB

Æther Wire & Location (USA) (http://www.aetherwire.com)
- Low power, miniature, distributed position location ("Localizers") and communication devices.
- DARPA Projects (Defense Advanced Research Projects Agency)

Intel (USA) (http://www.intel.com/technology/itj/q22001/articles/art_4.htm)
- UWB for communicating between devices, instead of networking PCs (wireless USB);

Pulse-Link (USA) (Fantasma Networks IP) (http://www.pulselink.net/default.htm)
- Very active on patents and IP;
- Development of UWB platform for wireless video, short and long (km) range communication, positioning.

Time Domain (USA) (Pulse-ON technology) (http://www.time-domain.com)
- Wireless Communications (Home WLAN), Precision Location and Tracking and High Definition Portable Radar
- Already a 5-chip chipset: PulseONÆÊ chipset (IBM foundry)

MultiSpectral Solutions, Inc (MSSI) (USA) (http://www.multispectral.com)
- High-speed communications networks and data links, collision and obstacle avoidance radars, precision geolocation systems for personnel location and mapping, intelligent transportation systems.

XtremeSpectrum (USA) (http://www.xtremespectrum.com)
- First product announced for middle 2002

McEwan Techologies (USA) (http://www.mcewantechnologies.com)
- McEwan Technologies licenses its wideband and ultra-wideband (UWB) radar sensor technology to industry. Thomas McEwan is the inventor of the MIR Rangefinder UWB radar developed at the Lawrence Livermore National Laboratories (LLNL).

Wisair (Israel) (http://www.wisair.com)

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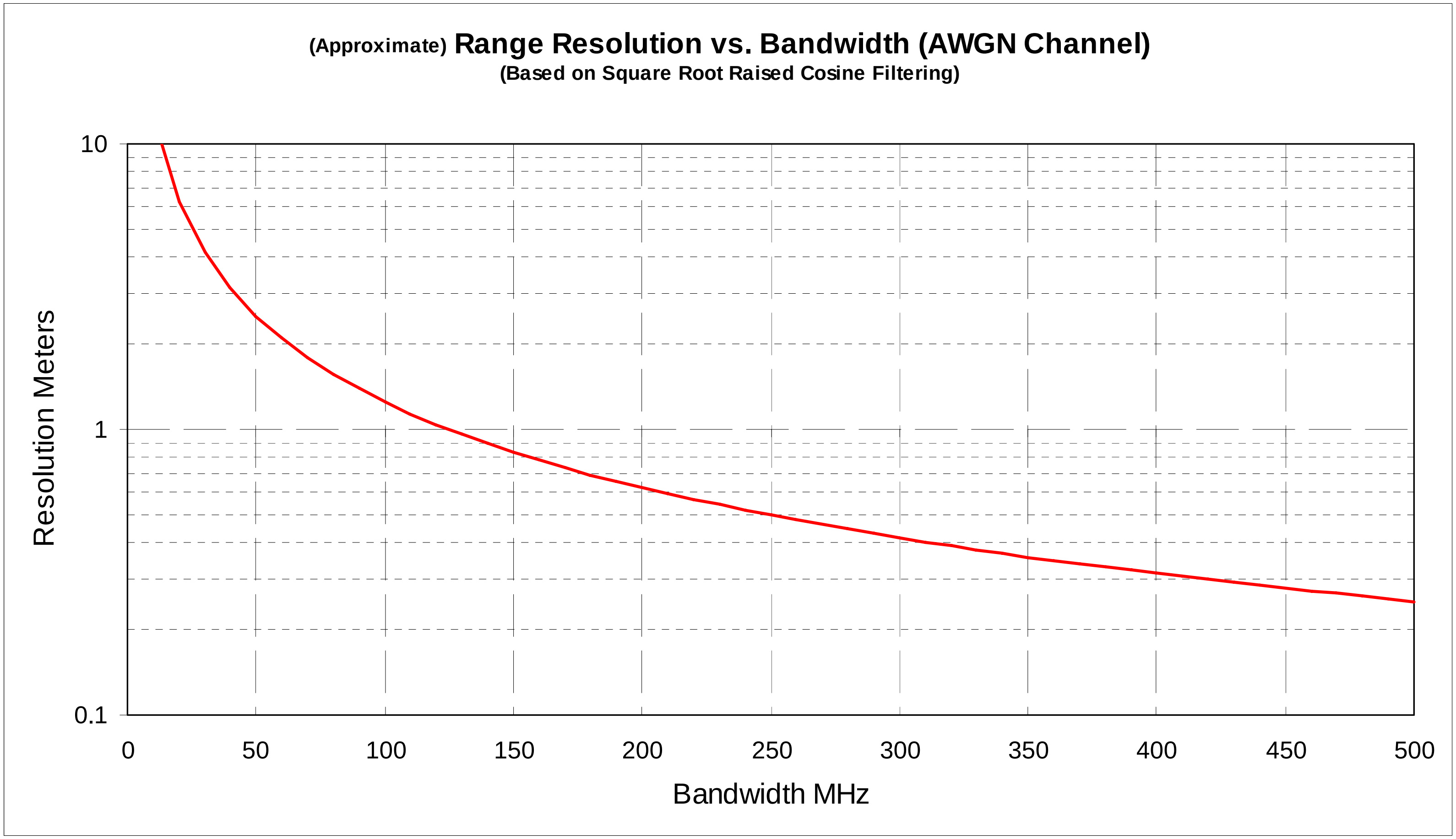
Bandwidth: key to ranging



125 MHz for 1m resolution

Heisenberg at work