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

Submission Title: [***Understanding UWB - Principles and Implications for Low-Power Communications - A Tutorial***]

Date Submitted: [10 March 2003]

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Re: [Tutorial: Introduction to UWB-RT.]

Abstract: [This is an introduction to UWB Radio Technology applications prepared for TG4. The tutorial is based partially on material presented at ICWLHN and ICN 2002, Atlanta, GA.]

Purpose: [Tutorial contribution.]

Agenda for tonight

- A little background to what's been happening in the UWB world
- A very brief look at the current status of the regulations and what we think is likely to happen
- Presentation explaining what UWB is
- Presentation on location capabilities
- Presentation on implementation implications for low power
- Panel with questions from the floor
  - 15.4 point of view
  - Presenters

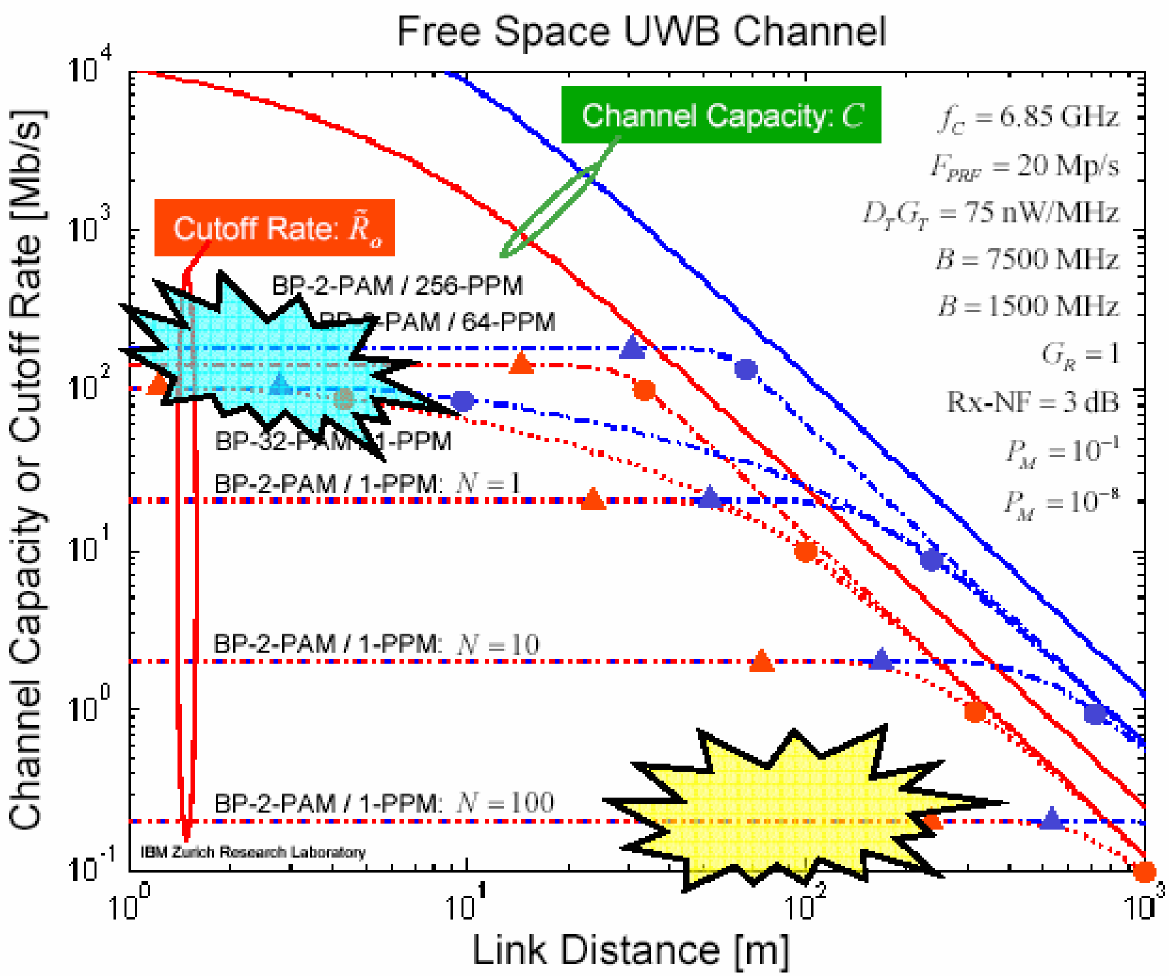
Why are we doing this?

- 15.4 architecture is basically similar to 15.3
  - Coordinator, Superframe, Slotted MAC
- Similar timing constraints & functions to 15.3
  - Tx/Rx, Ack, GTS, Beacon
- 15.3a formed to define Alt PHY to exceed 15.3 performance
  - 100+ Mb/s
  - Similar power consumption to 15.3 to maintain applications in CE & PC
- It is interesting to look at the other end of the spectrum and see what impact UWB techniques have there
  - Low power
  - Other characteristics

Basic Capabilities and Application Spaces

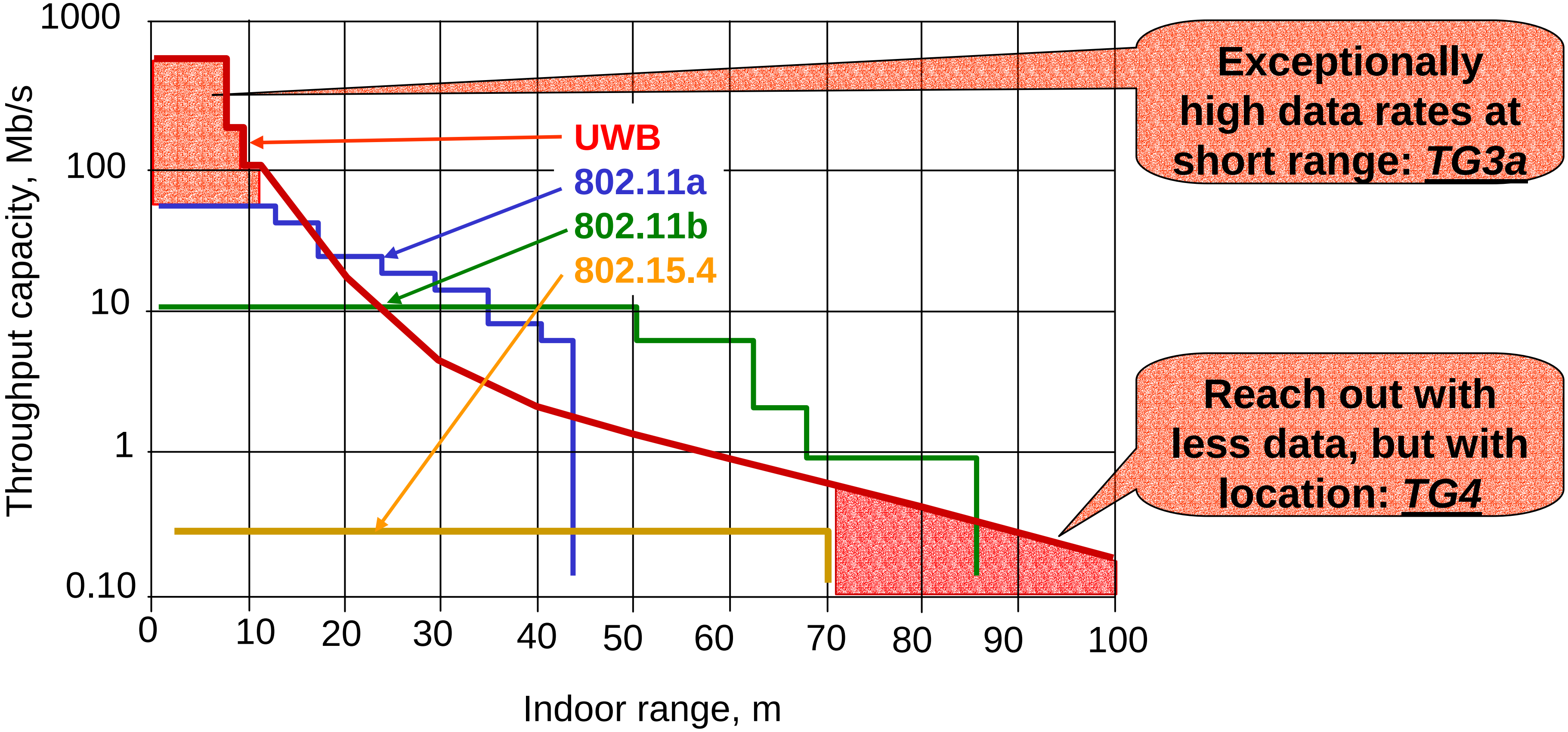
Pervasive Ultra-wideband Low Spectral Energy Radio Systems

Very High Data Rate Applications



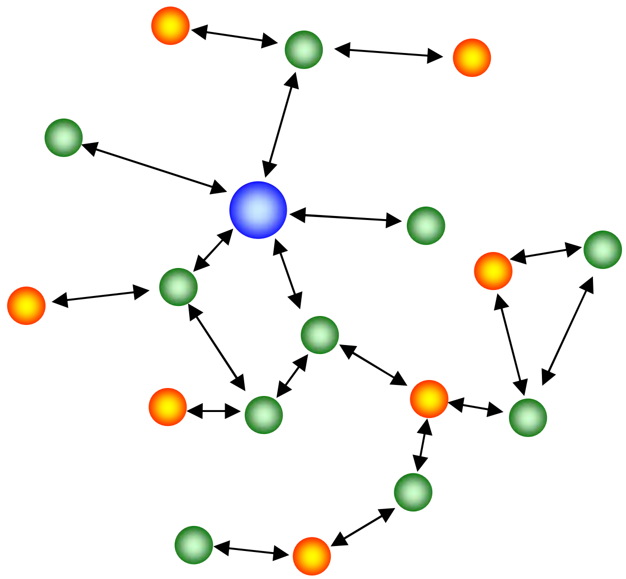
Low Data Rate and/or Location Tracking Applications

Where UWB Fits in PANs

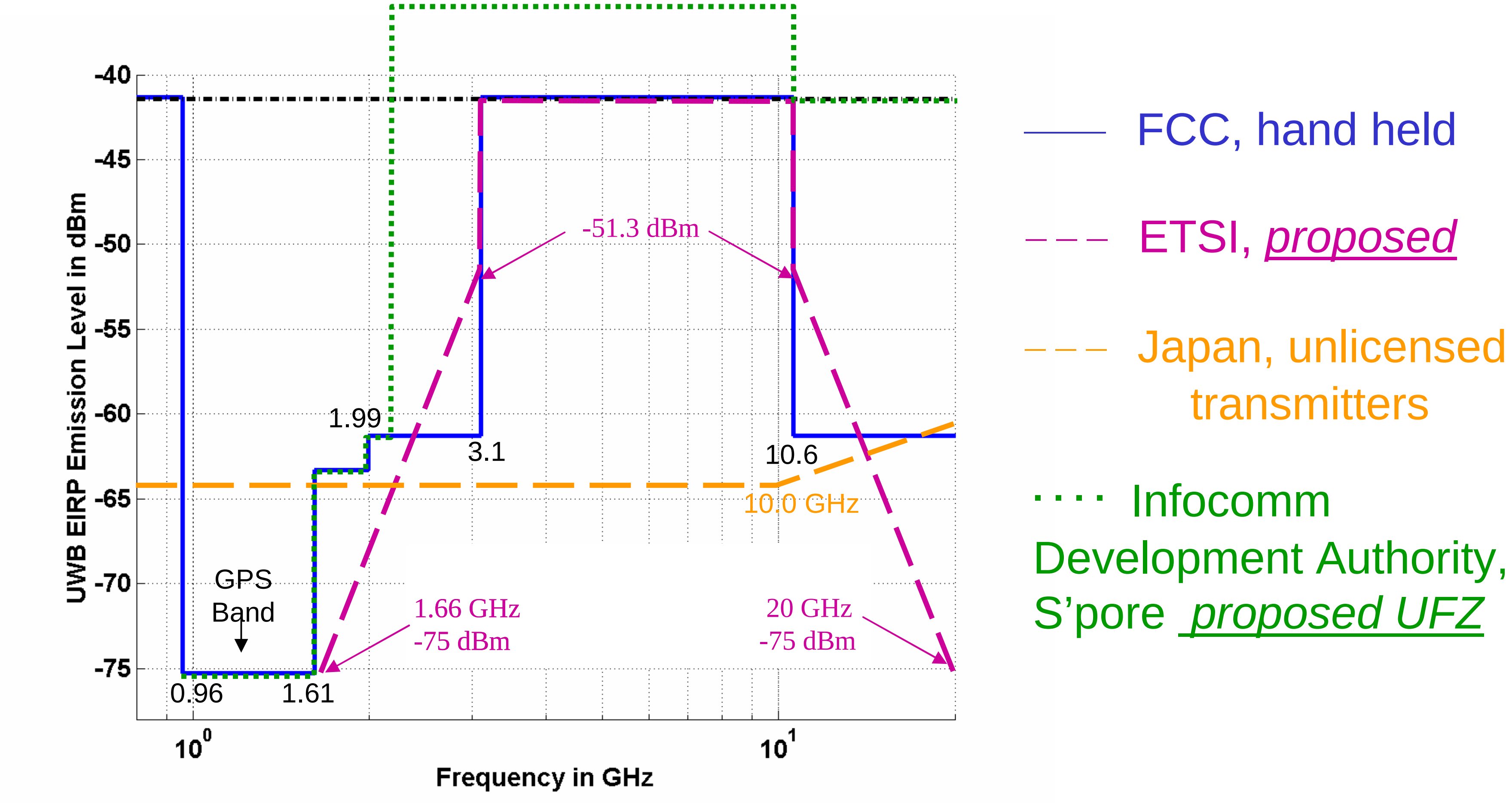


What does 15.4 look like

- 2 Device Roles
  - Full Function
  - Reduced Function
- 2 Configurations
  - Star
  - Peer-Peer
- 3 RF Bands
  - 900 & 2400 ISM (US)
  - 868 & 2400 ISM (Europe)
  - At least 1mW Tx power
- 2 MAC configurations
  - Beacon + Slotted Aloha
  - Unslotted Aloha
  - Acknowledged Data Service



UWB Emissions Masks



Source:
www.fcc.gov,
"Cover Story: UWB arrives in Japan," Nikkei Electronics, 17 Feb., 2003.

Wireless Began as UWB

1870s

– Hertzian experiments were UWB

– Apparatus was spark gap

– Low-Q circuits

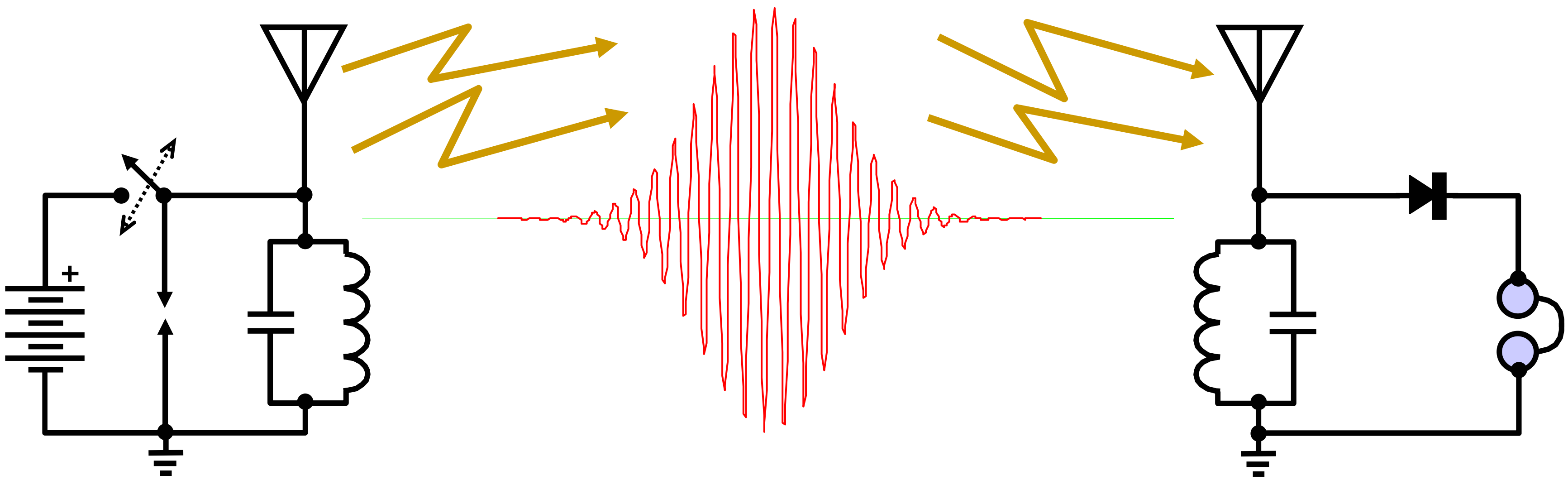
– Large RF bandwidths

– Led to Morse telegraphy (25wpm=20 Hz BW)

– No way to take advantage of *HUGE* bandwidth spreading gain!

1890s

Early Radio



- Q near 5
- "*Class B damped sine waves*"
- $BW = f_0/Q = 0.2f_0$ hence UWB!
- *but … no way to recover the wide band energy efficiently*

Wireless Becomes NB 'Radio'

1900s **Wireless goes 'tuned'**

– Analog processing: filters, resonators

Government Radio Regulations 1912

– Separation of services by wavelength

– Spark outlawed

1920-40s **Wireless becomes 'radio'**

– Era of wireless telephony begins

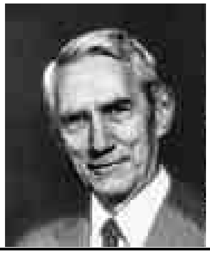
– AM / SSB / FM

– Ionospheric propagation developed

1941

Hedy Kiesler Markey - George Antheil

– Frequency Hopping



1940-50 **Claude Shannon**

–Papers refer to the 'down in the noise' as most efficient communication

UWB Reappears

1950s UWB and 'impulse' technology

– Both heavily investigated for communications, radar & other applications

UWB-like Patents 1960s

– Patents begin appearing using UWB-like techniques

1970s Digital applied

– Digital techniques applied to UWB impulse radios

Publications 1980s

– Publications on UWB start to appear

PulsON®

1990s Commercial system

– First commercial systems emerging (thanks to device technology)

FCC Approval 2002

– UWB approved by FCC for commercialization

Federal Communications Commission

UWB Defined

- UWB signal BW defined by FCC as:

$$2\,\frac{f_u - f_l}{f_u + f_l} \geq 0.20$$

f_u = upper -10 dB point
f_l = lower -10 dB point

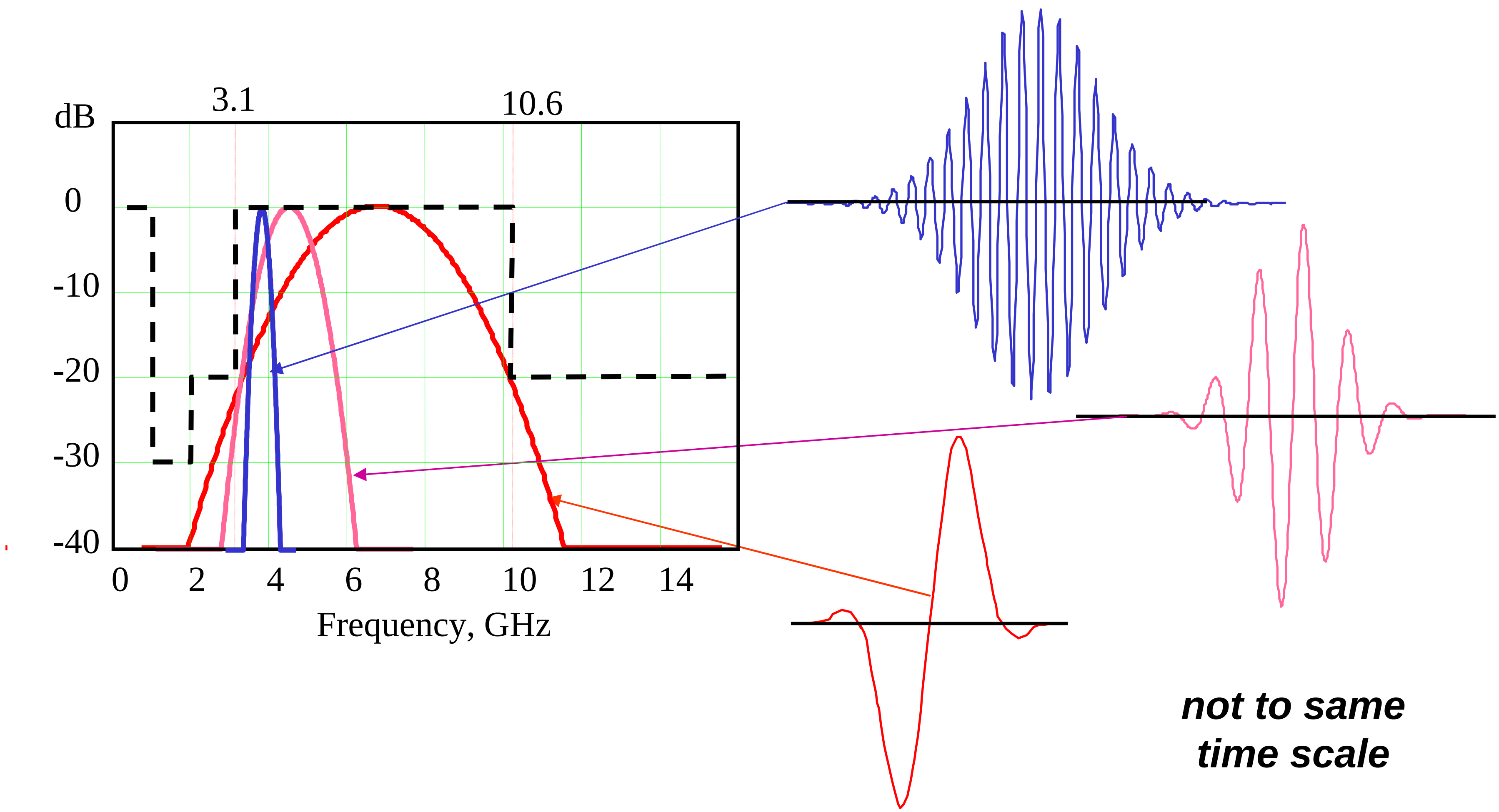
- Or, BW ≥ 500 MHz regardless of fractional BW
- Emissions below –41.3 dBm/MHz
- Put differently - UWB is just a means of accessing 7,500 MHz of unlicensed spectrum!

Source: US 47 CFR Part15 Ultra-Wideband Operations FCC Report and Order, 22 April 2002: http://www.fcc.gov/Bureaus/Engineering_Technology/Orders/2002/fcc02048.pdf

Basics of Signal Generation

- Impulse followed by shaping filter, and Chirp signals
  - best suited to non-coherent pulse transmissions
- Synchronous pulse synthesis
  - best suited for frequency/time-agile and synchronous systems
- OFDM and COFDM
  - best suited for fine PSD tailoring

UWB Signals and Their Spectra



not to same time scale

Pulse Bandwidth and Spectrum

- *Width of pulse* defines the bandwidth, and hence total EIRP
- *Cycles per pulse* defines center frequency
- *Envelope* defines the energy structure outside the main lobe
- ***Other, more complex pulses possible!***
- FCC: Minimum BW above 2.5 GHz is 500 MHz

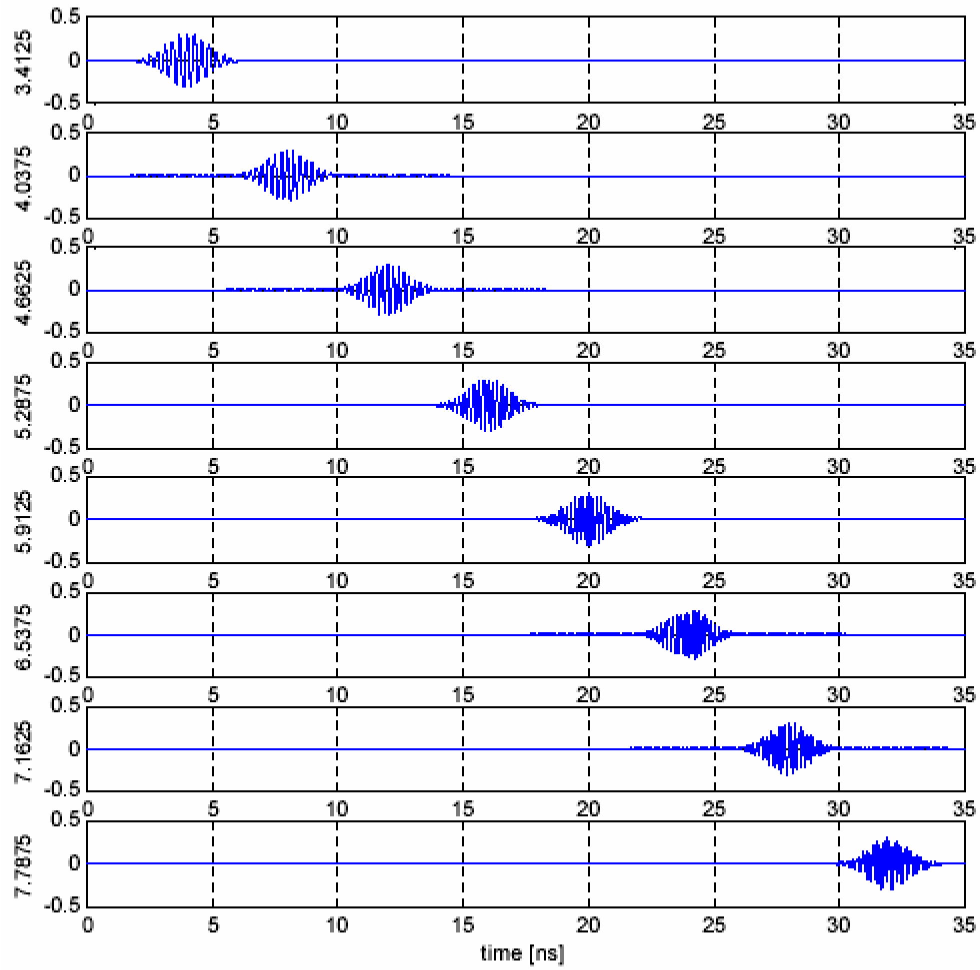
High-Rate Isolated-Impulse Signals

Shaped isolated pulses sent in a combined TD / FD fashion, with BPSK / QPSK / OQPSK / QAM

<u>Various hybrid possibilities</u>:

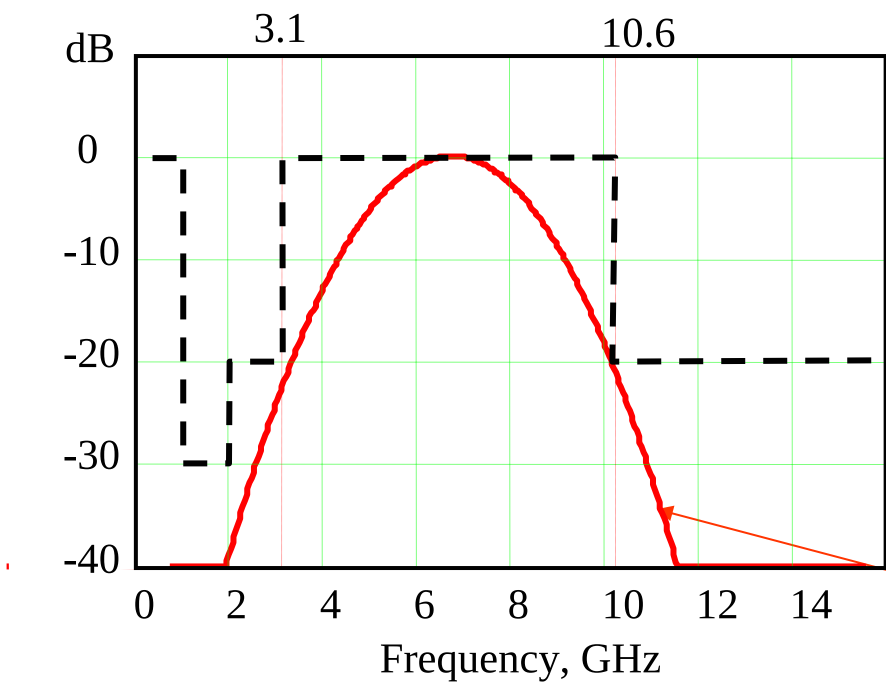
- isolated or sequences

- TD / FD combinations



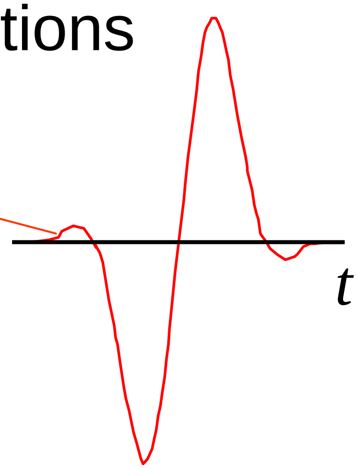
<u>Figure source</u>: “White paper on IEEE 802.15.3a - 480Mbps UWB radio,” [On-line:] 28 Feb. 2003 <http://www.discretetime.com/papers/complex.pdf>.

A Single Band Approach

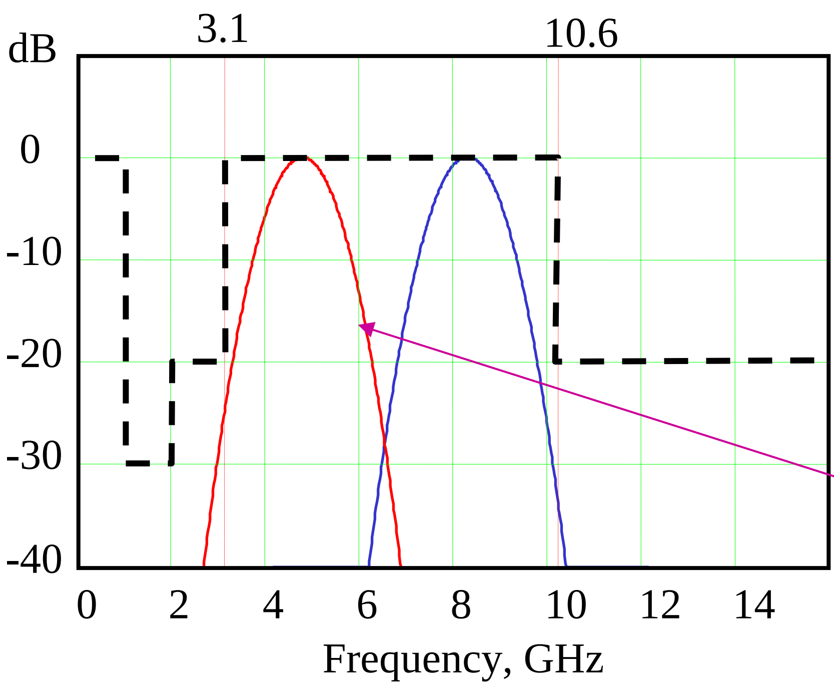


Widest bandwidth, can work well in multipath; can use filtered impulse

... lowest flexibility in spectrum design, shaping
... needs high performance silicon solutions

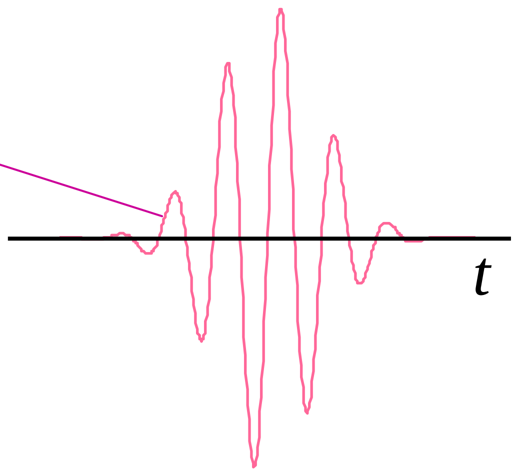


Few-Bands Approach

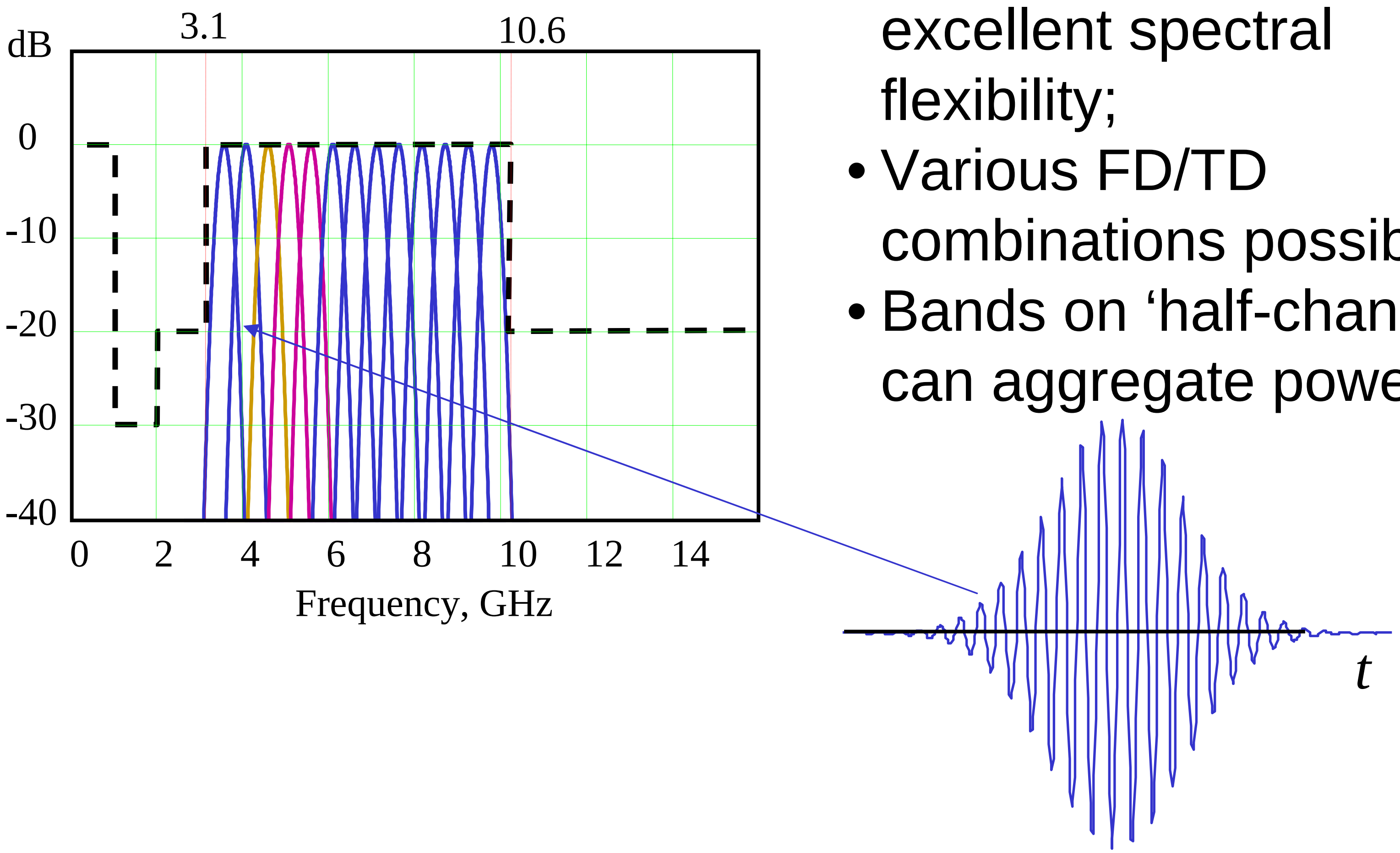


Can use cheaper IC technology in lower band; Use upper band later.

... moderate flexibility

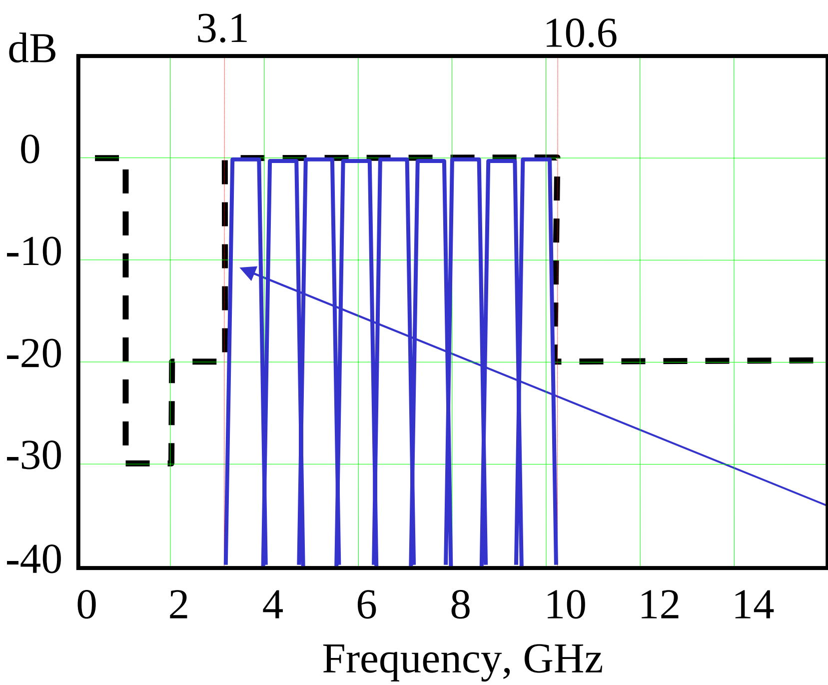


Many-bands Approach



- Banded approach has excellent spectral flexibility;
- Various FD/TD combinations possible;
- Bands on ‘half-channels’ can aggregate power

Many-band OFDM Approach



good multipath characteristics; excellent spectrum control

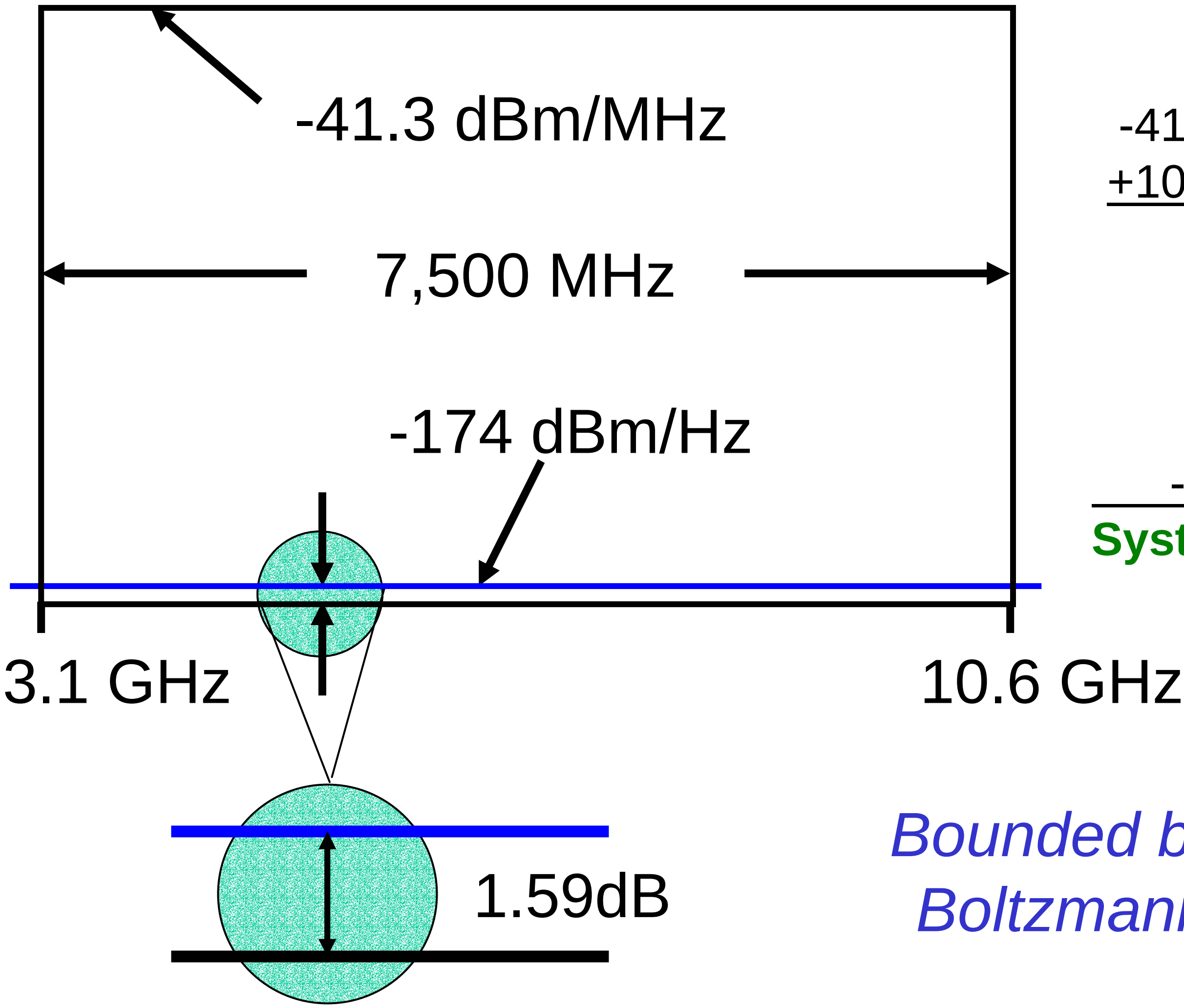
... communications DSP needed

n-point FT of symbol

Radio Systems Limited by ...

- Noise (thermal and other) and interference
- Allowed effective isotropically radiated power (EIRP)
- Available bandwidth
- Implementation efficiency

Fundamental Limit: 173 dB/Bps System Gain



-41.3 dBm / MHz
+10 log($7.5x10^3$) MHz
-2.5 dBm EIRP

-2.5 dBm EIRP
-(-1.59) dB E_b/N_0
-(-174) dBm/Hz .

System Gain = 173 dBm/Bps

Bounded by FCC, Shannon, Boltzmann (thermal noise)

Limit and Parameters

- Limit means 1 b/s has 173 dB path gain available
  - nearly 2,000 km range between unity gain antennas
  - [but let's get *real*!]
- Additional limitations from practical implementations, like desired data rates (much higher than 1 b/s!)
  - EIRP further limited by FCC PSD masks corners, margin, and antenna implementations
  - Practical modulations many dB from Shannon limit
  - Noise figure and losses further limit performance

Example:
UWB at a High Data Rate (TG3a)

Consider: 200 Mb/s system, Antipodal modulation: 10^{-3} BER, 9 dB noise figure+losses, 3.4-4.6GHz Power BW, 0 dBi antennas

System Gain	**System Gain Limit 173 dB/Bps**
10 log(data bandwidth)	-10 log(200×10^6) = -83 dB Hz
E_b/N_0 required by modulation	- E_b/N_0= 6.8 -(-1.59) = -8.4 dB
System losses, (noise figure, implementation loss, ...)	-System losses = -9 dB
10 log(Power BW / 7.5 GHz)	10 log(1.2 / 7.5) = -8 dB
Antenna gain or loss	Antenna: = 0 dBi
Path attenuation	**Left for Path attenuation: 64.6 dB**

0.75 MAC and error correction brings link capacity to **150 Mb/s**

1 m path loss = 44 dB, *leaves 20+ dB for range:* **10+ m** in free space

Example:
UWB at Longer Range (TG4)

Consider: 250 kb/s system, BPSK: 10^{-3} BER, 15 dB noise figure + losses, 3.4-4.6GHz Power BW, 0dBi antennas

System Gain	**System Gain Limit 173 dB/Bps**
10 log(data bandwidth)	-10 log(250,000) = -54 dB Hz
E_b/N_0 required by modulation	- E_b/N_0= 6.8- (-1.59) = -8.4 dB
System losses, (noise figure, implementation loss, ...)	-System losses = -12 dB
10 log(Power BW / 7.5 GHz)	10 log(1.2 / 7.5) = -8 dB
Antenna gain or loss	Antenna: = 0 dBi
Path attenuation	**Left for Path attenuation: 90.6 dB**

200+ m in free space
(75 m in buildings)

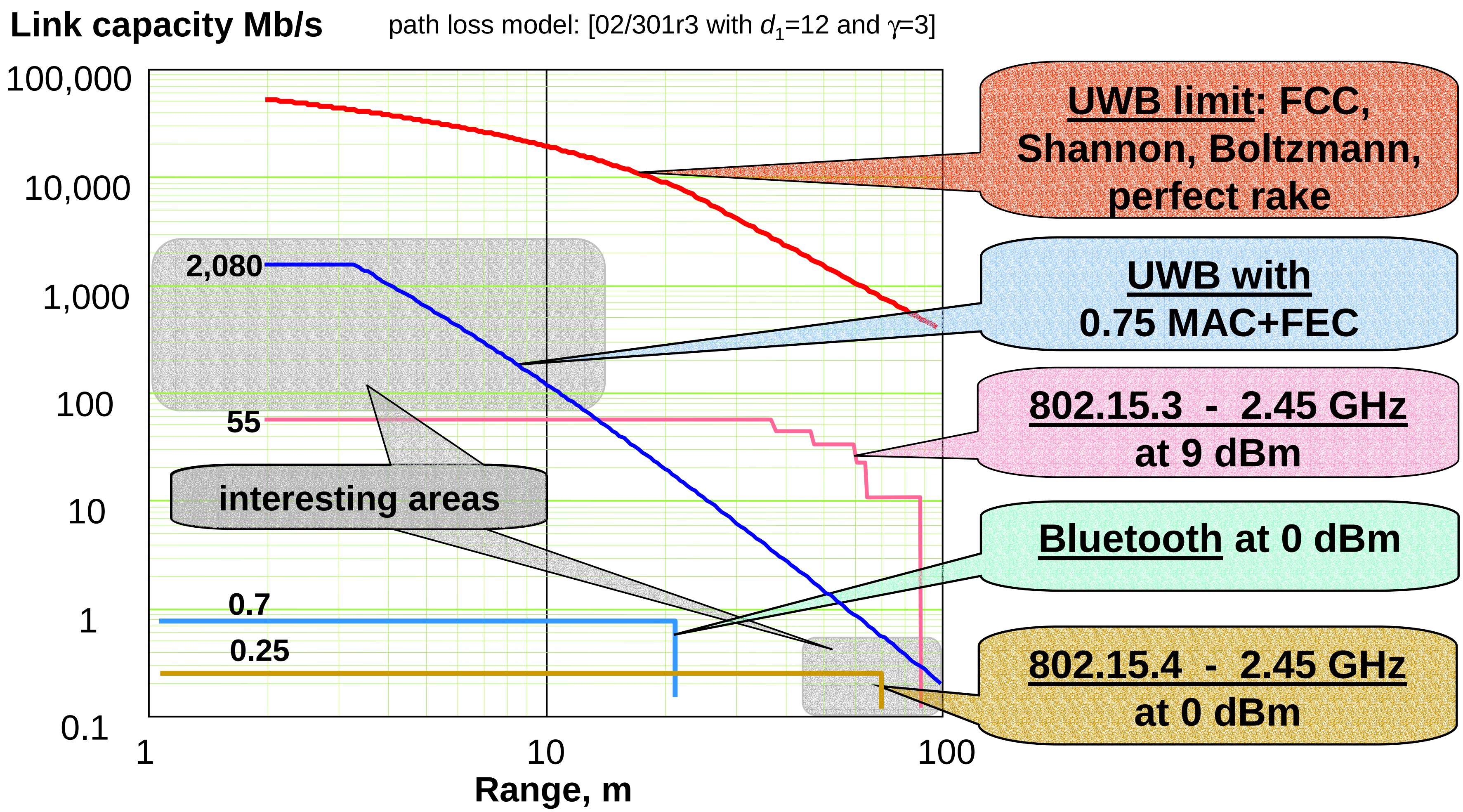
Bandwidth Constraint Can Hurt!

- Conventional radio is bandwidth constrained: ISM band has ***B***~80 MHz BW
- Can fit link capacity ***C*** up to 80 Mbps QPSK signalling (null to null BW): *linearly trade-off BW and system gain in that BW*
- After that, must use higher-level modulation: *requires exponential increase in SNR = γ for same BER:*

$$C = B \log_2(\gamma + 1)$$

- With UWB *C*=7,500 MHz using QPSK! *BW and System Gain trade off linearly*

Link Capacity: UWB and DANs



Talk overview

- Location and UWB
- Multipath Resilience
- UWB Location System Example

Location Systems Introduction

- What are Location Systems?
  - Where am I?
  - Where is an object?
  - Where are the others? (Ad Hoc)
- Difference in requirements leads to different solutions
  - Monitored premises size
  - Number of items
  - Cost
  - Power Consumption
  - Accuracy

High Accuracy: Operational Implications

- Enables additional applications (e.g., document tracking).
- Threshold effects: correct room, aisle, shelf, floor, etc.
- Virtual zones, virtual partitions, Alerts, and Multi-tag RTLS functions become truly useful – security and safety.
- Can dramatically increase efficiency of use.

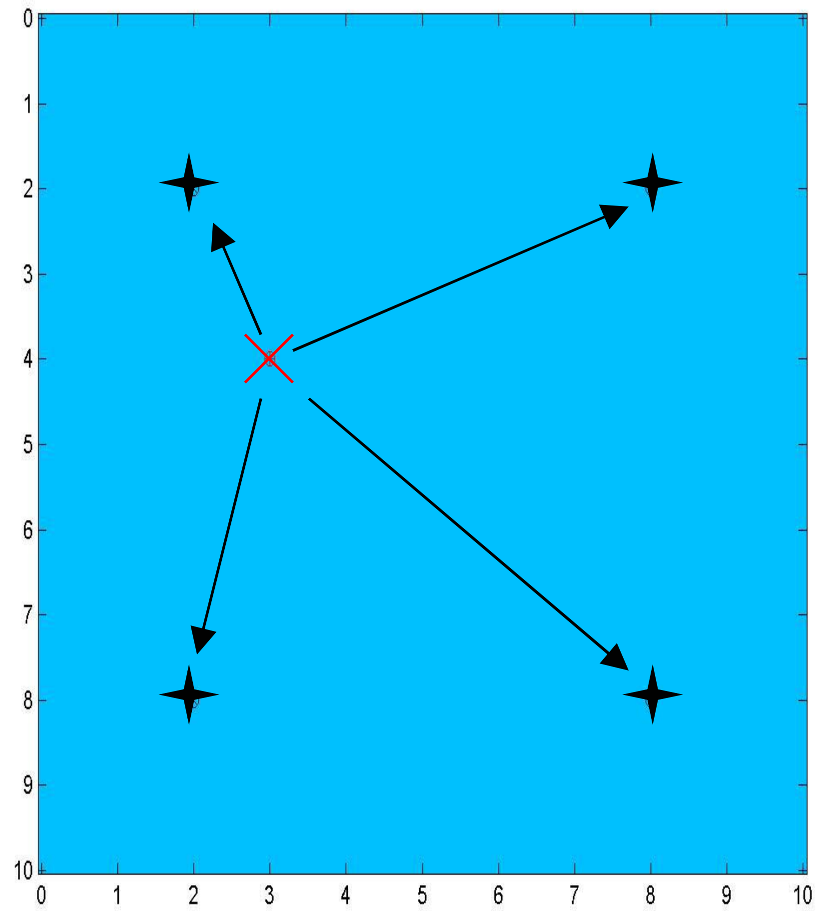
No RTLS	Inaccurate RTLS	Accurate RTLS
↓	↓	↓
Go **LOOK FOR** item	Go **FIND** item	Go **GET** item
	A useful backup system	Effective primary system

Methods for Location Determination

- Angle Of Arrival (AOA)
- Time Of Arrival (TOA)
- Time Difference Of Arrival (TDOA)

TDOA

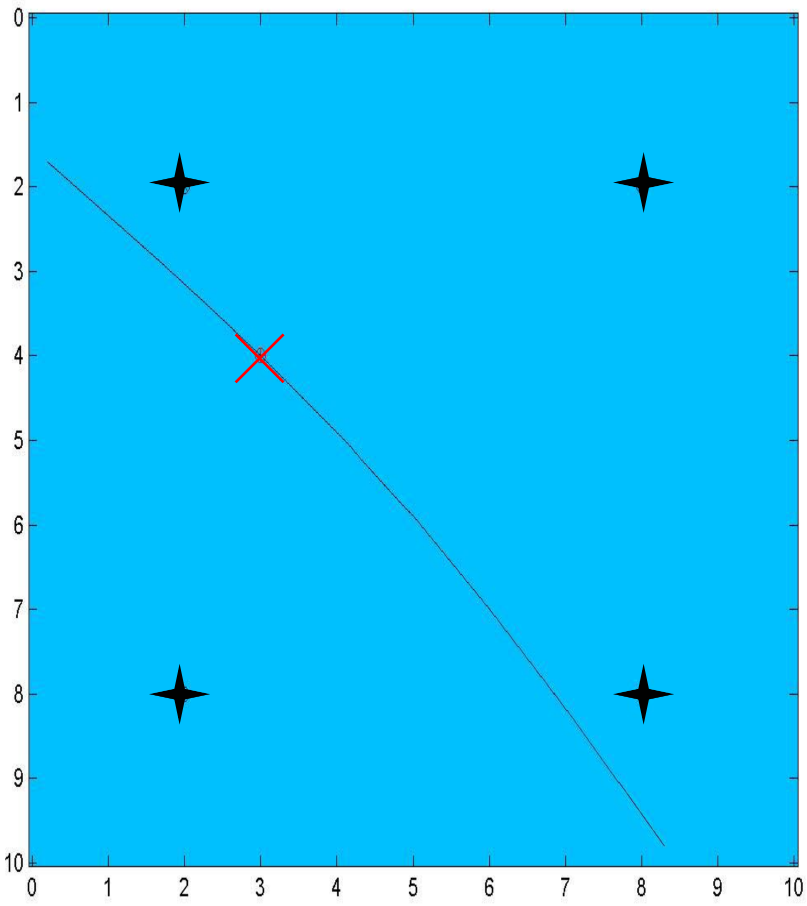
- Tag transmits at t_0 received by other nodes at t_1, t_2, t_3, t_4



TDOA

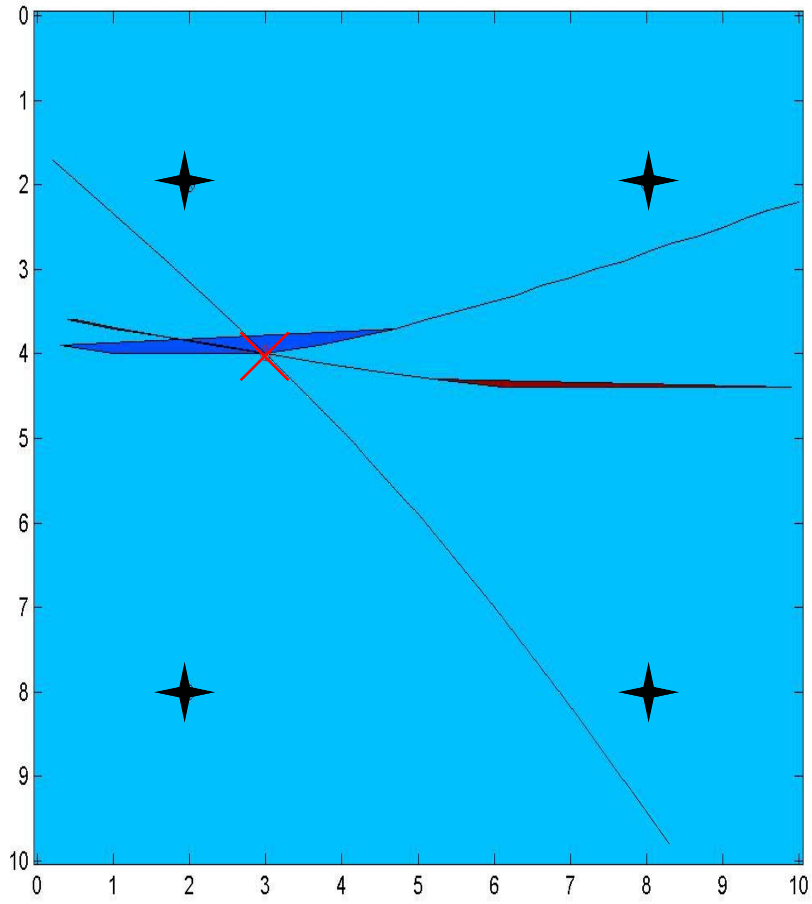
- Tag transmits at t_0 received by other nodes at t_1, t_2, t_3, t_4
- Distance difference:

  d_m-d_n=(t_m-t_n)/C



TDOA

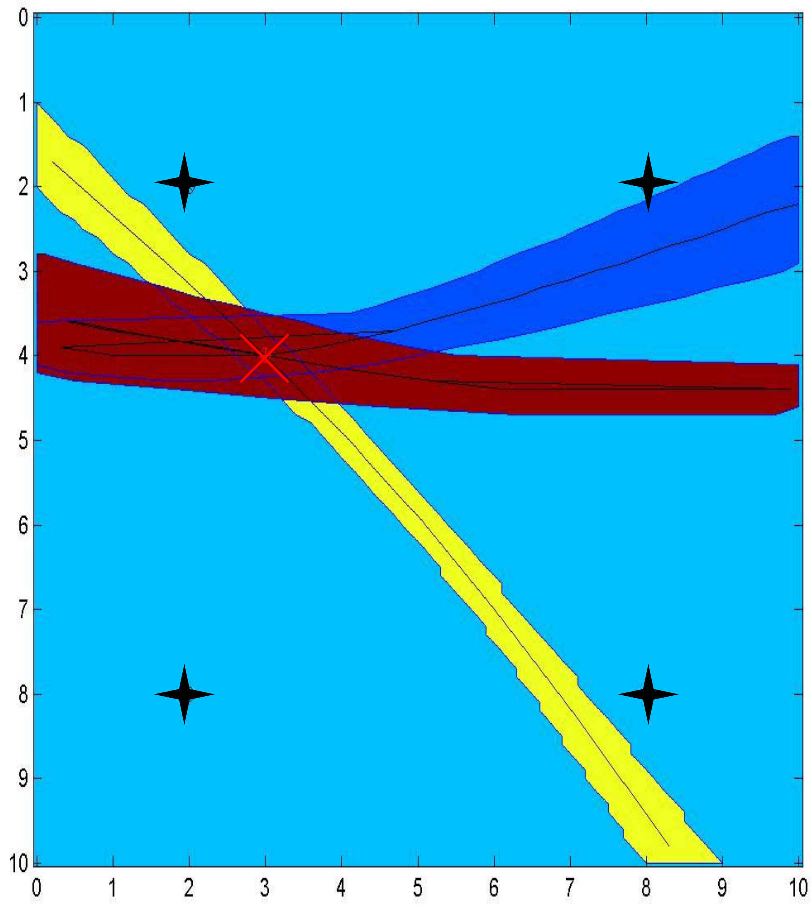
- Tag transmits at t_0 received by other nodes at t_1, t_2, t_3, t_4
- Distance difference: $d_m\text{-}d_n=(t_m\text{-}t_n)/C$
- Location determined by intersection



TDOA

- Node transmits at t_0 received by other nodes at t_1, t_2, t_3, t_4
- Distance difference:

  $d_m - d_n = (t_m - t_n)/C$
- Location determined by intersection
- Bandwidth determines the accuracy



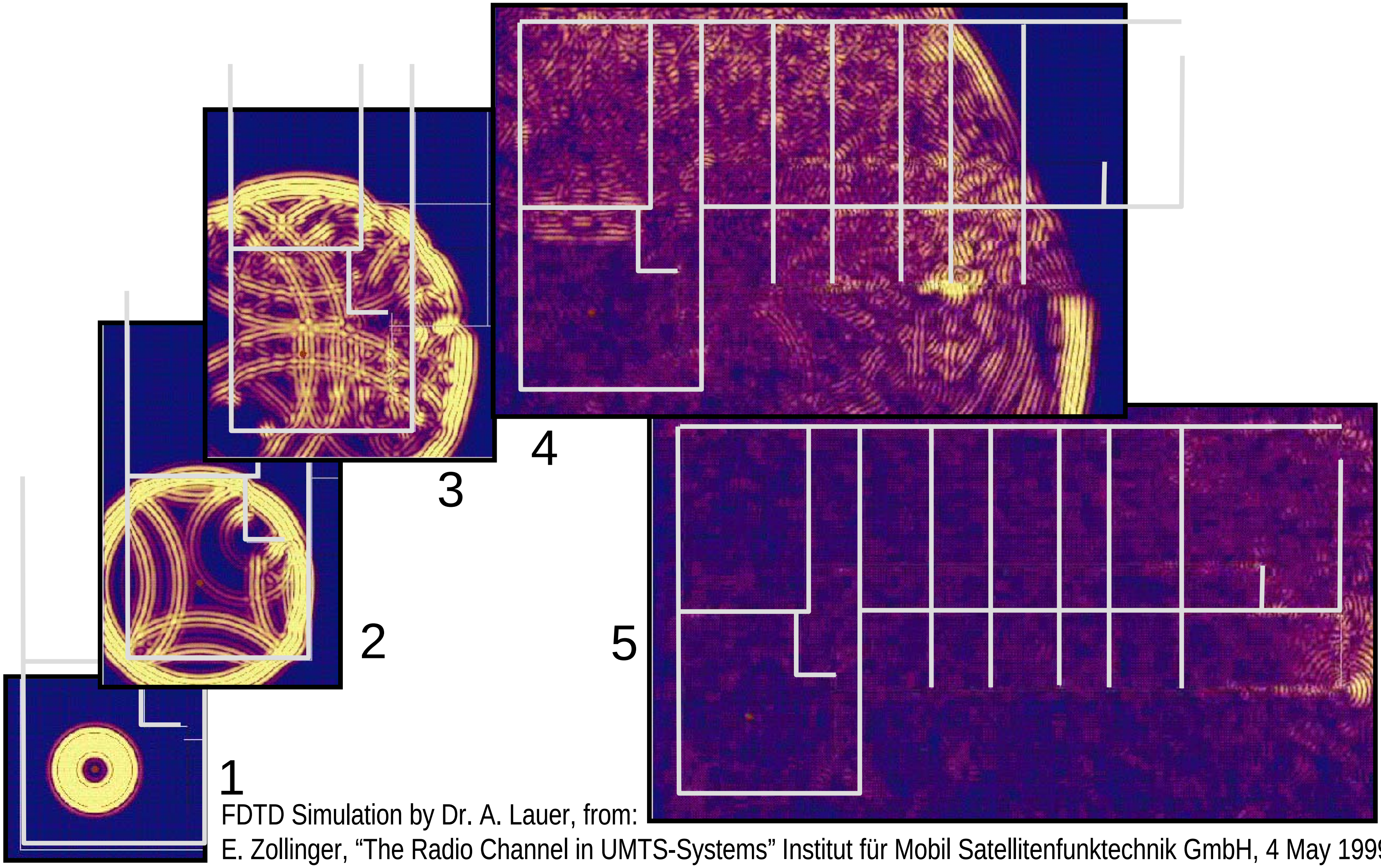
UWB for Location Systems

- Precise, fine-grain measurement of time $\rightarrow$ distance accuracy (inches)
- Combined Communication and Location
- Determination of node location
  - Line of sight unnecessary
  - Low cost
  - Low power

Multipath Fading

- Wide band RF signal propagation
- Narrow band RF signal propagation

Isolated Pulse Propagation Indoors

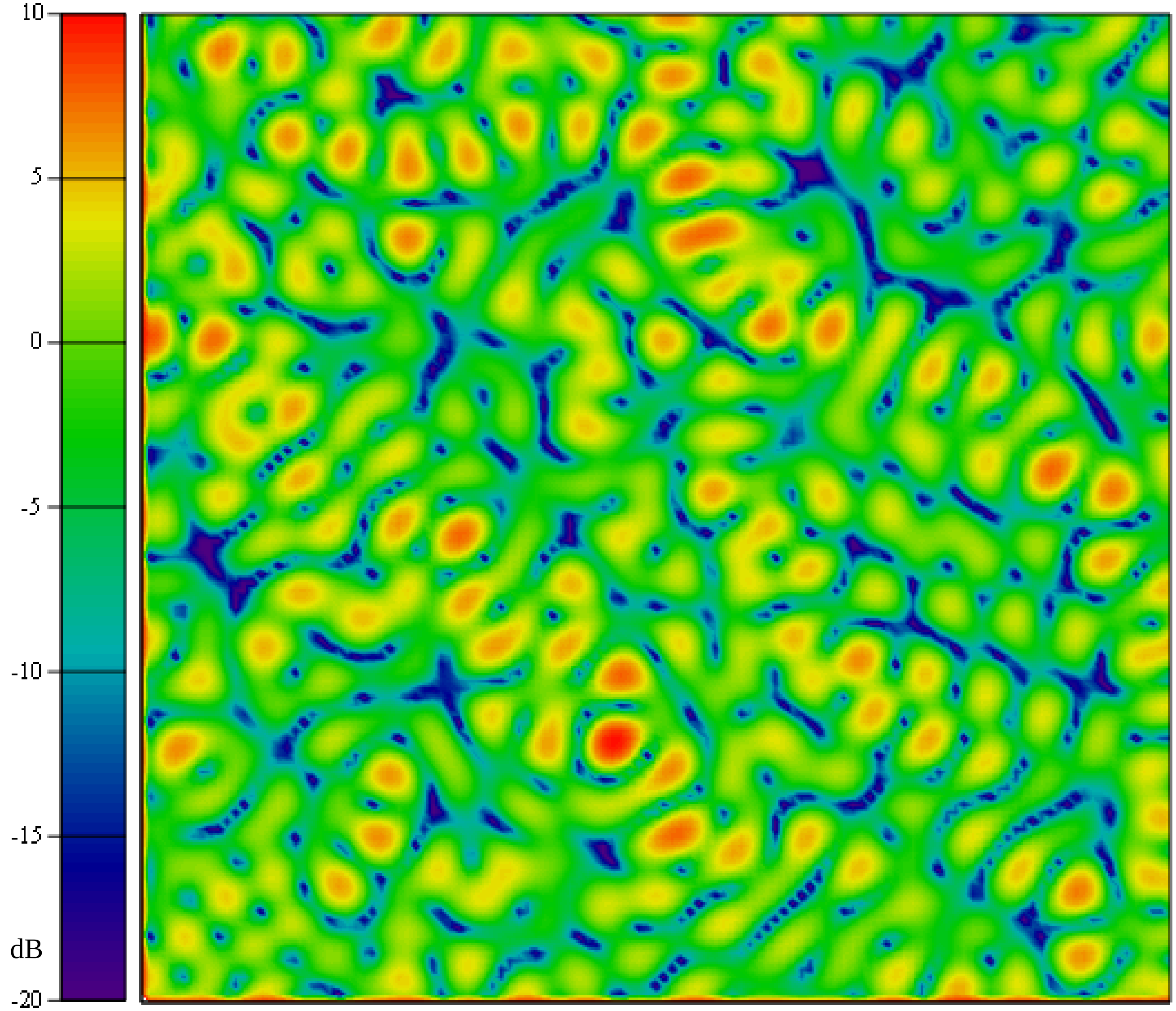


FDTD Simulation by Dr. A. Lauer, from:
E. Zollinger, “The Radio Channel in UMTS-Systems” Institut für Mobil Satellitenfunktechnik GmbH, 4 May 1999.

Sine Wave Multipath in 10λ Square

<u>Conventional Radio Signals in Multipath</u>

Rayleigh faded narrow band signal: 63% of signal is below median level



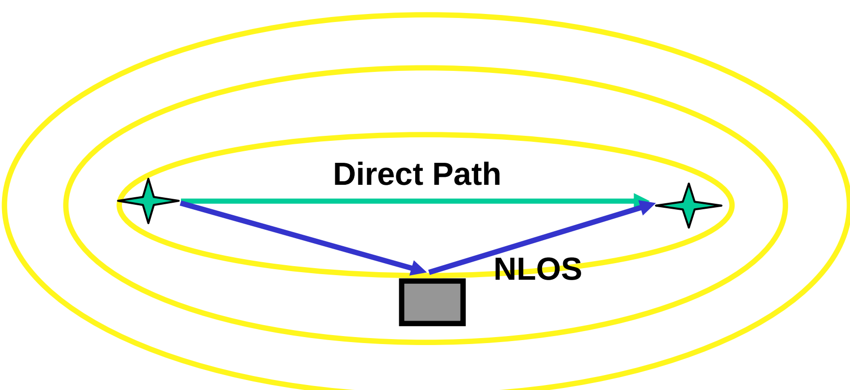
Multipath

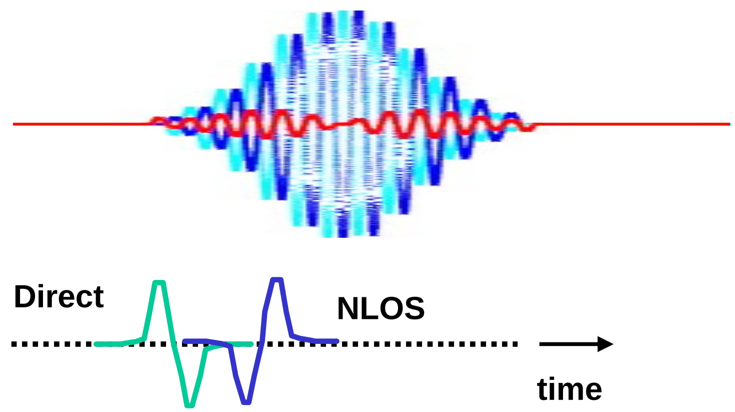
Traditional Multipath
(E.g., rooftop TV Ant.)

- Path-length difference several kilometers
- Power difference usually large
- Change: slow if any
- Result: overlay if linear modulation; inter-symbol interference if non-linear

Short-Distance MP
(Indoor commun.)

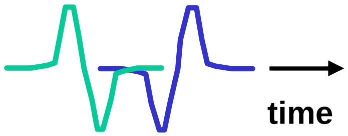
- Path-length diff: ~meter
- Powers may be similar
- Change: can be rapid
- Result: deep fading (destructive self-interference), variable in time and space.

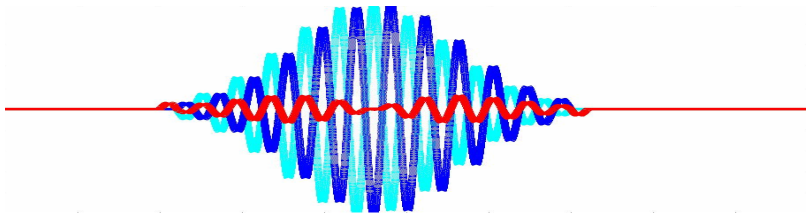




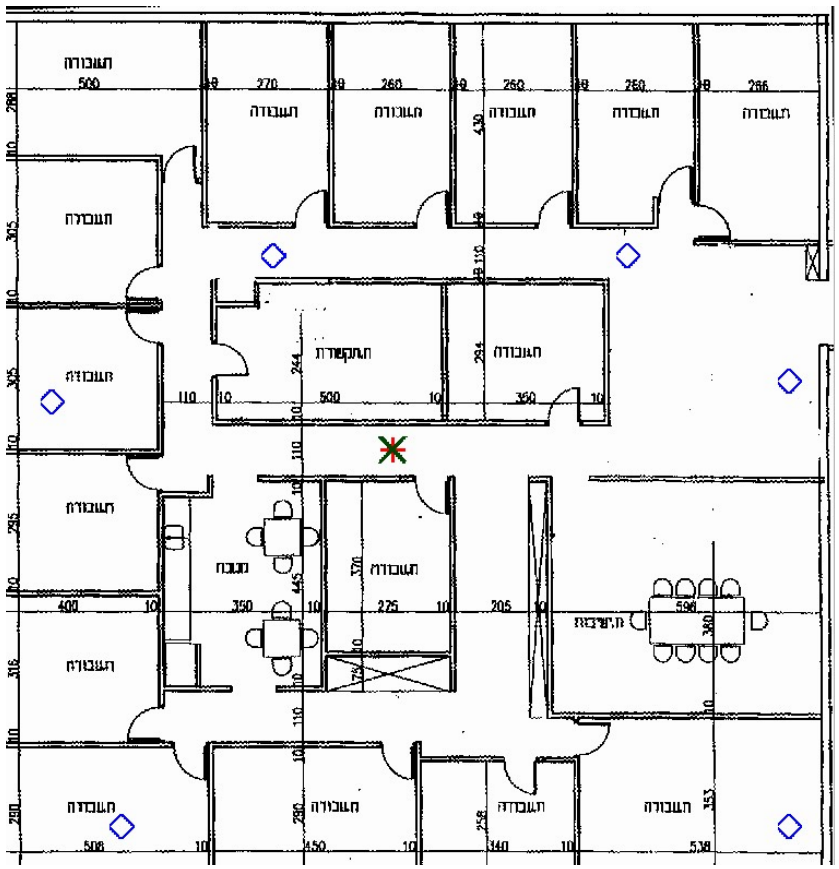
Multipath: Corrective Action

- Traditional Multipath: signal processing
- Short-distance Multipath:
  - Nothing to process
  - Conventional spreading techniques are insufficient
- Short pulses: there is little or no overlap in arrival times of pulse copies following different paths! So, signal processing can be used.

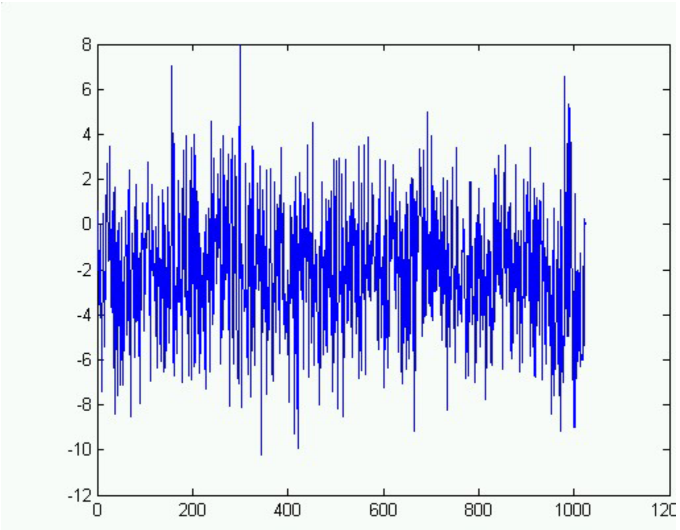


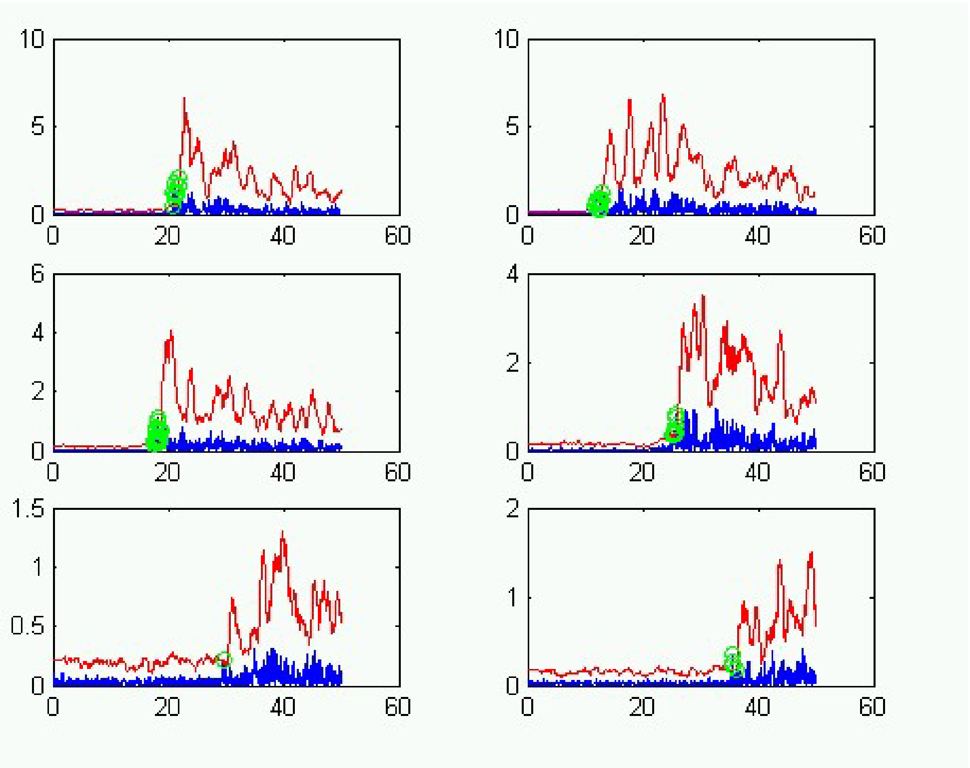


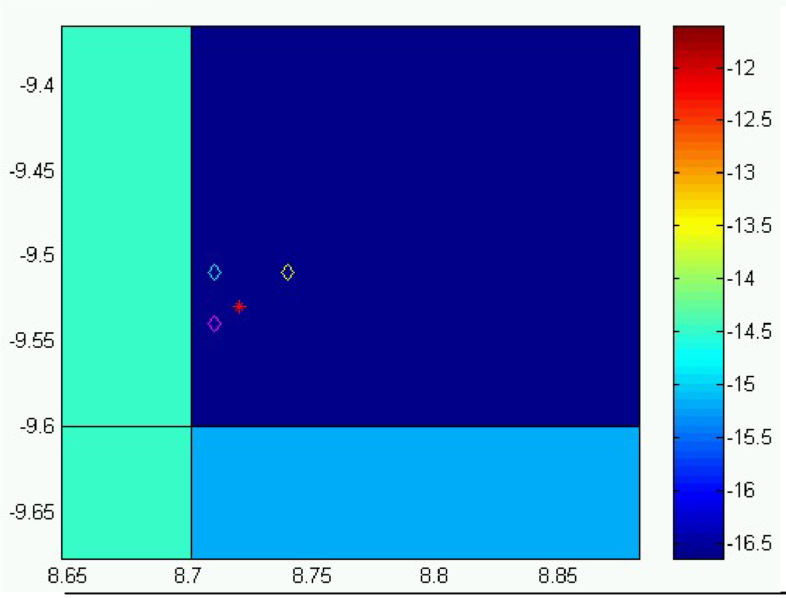
Example - Office Env. Trial – I (Pulsicom Premises)



Example Office Env. Trial – II



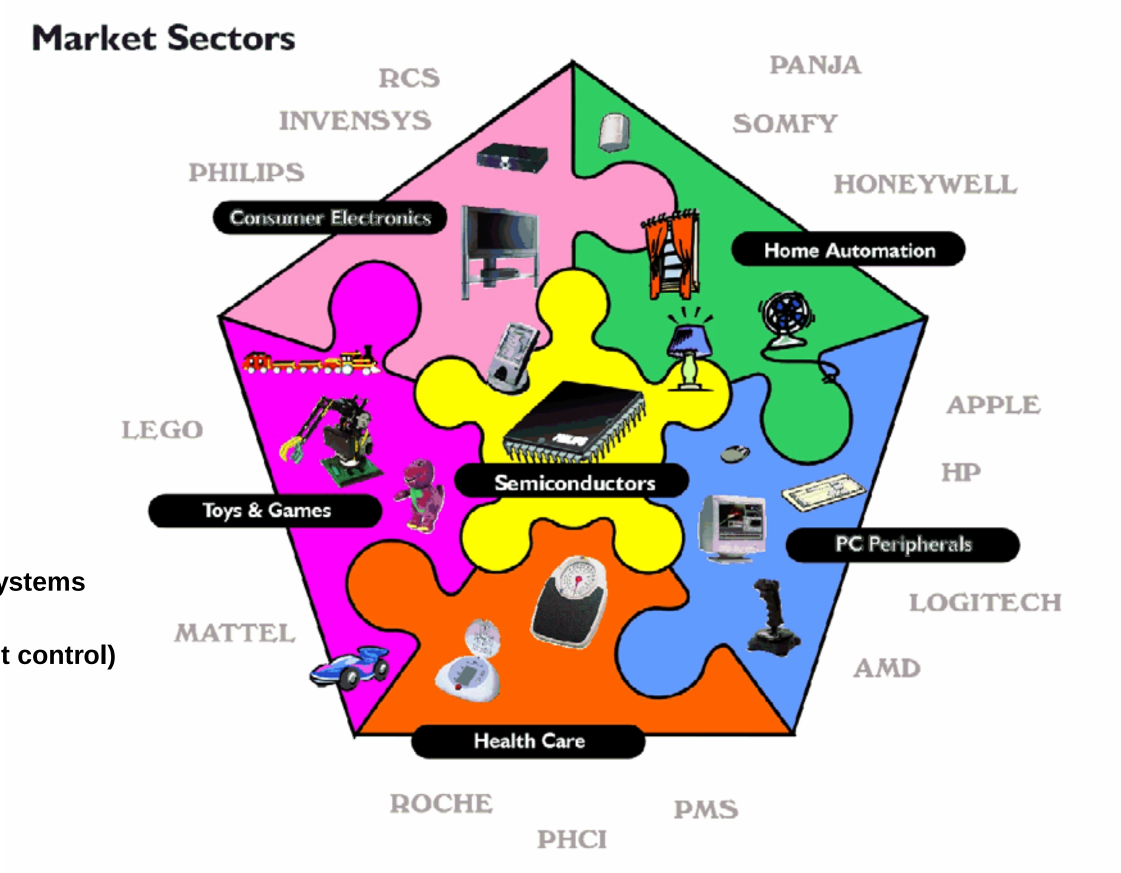




Applications

Single and multi-family dwelling residents who have at least one of the following configurations in their dwellings:

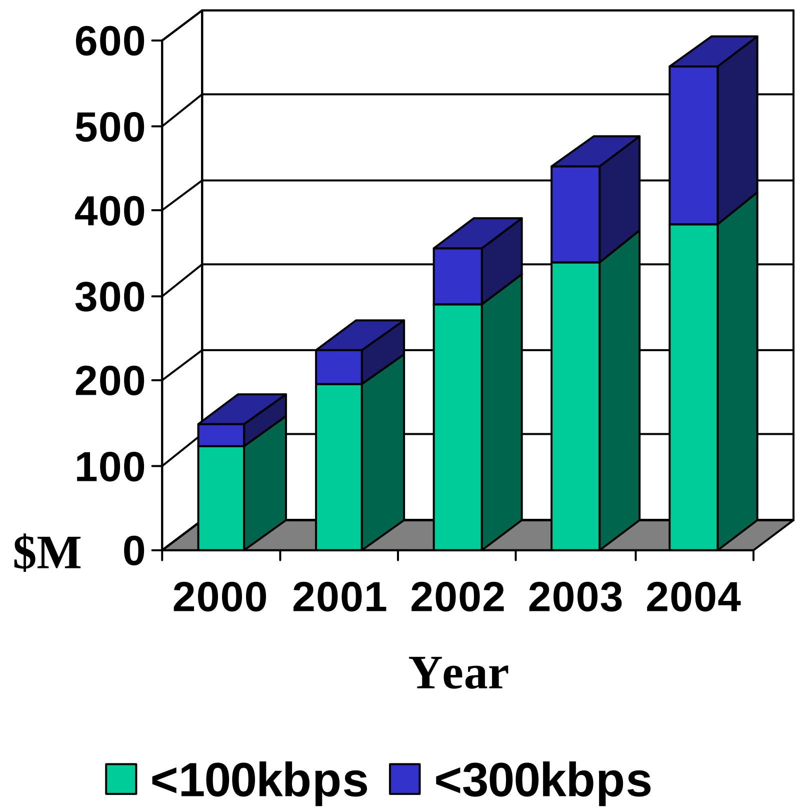
- Remote control for:
  - Multimedia PC with interactive gaming options
  - Consumer devices like,TV (w internet access), Home Theatre, video gaming console, DVD player, STB, DVCR, Home Stereo, TiVo
- Interconnectivity between toys (Tomoguchis, Gameboys, etc.)
- Home security, home automation or HVAC systems (sensors, control units)
- Illumination control (light switches, spot light control)
- Small Office/Home Office (SOHO) control of:
  - multimedia presentations
  - conference rooms
  - training rooms
  - automation or control functions
- Industry applications for control and surveillance
- Healthcare industry for monitoring and wearable sensors, patient monitoring



Source: doc.: IEEE 802.15-01/036r0

Estimated Market Size for Home Applications

- Including
  - White goods
  - Home security
  - HVAC
  - PC peripherals
- Rough estimation based on forecast for goods only, wireless link penetration estimated



Source: doc.: IEEE 802.15-01/036r0

Power consumption issues for 802.15.4

- Power consumption modes
  - Sleep (the device is consuming minimal or no current and is not able to operate on the network before going through a wakeup procedure)
  - Idle (the device is able to operate on the network without going through a wakeup procedure)
  - Device registration (the time between a device wishing to join a network and the time it may operate on the network)

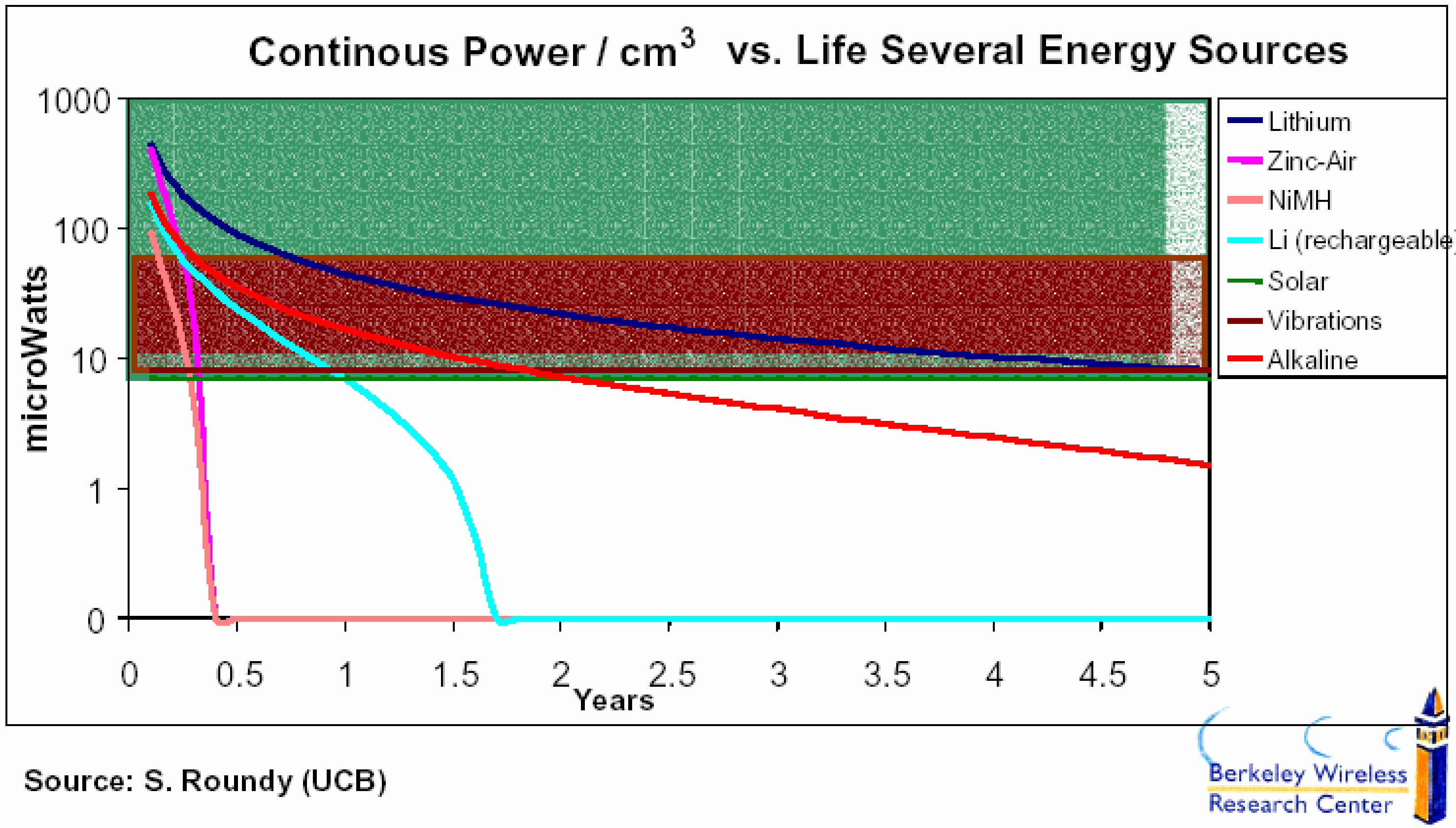
- Supported traffic type scenarios
  - Periodic. For example, a flow meter, transmitting 1 byte every 5 minutes
  - Intermittent. For example, a light switch, transmitting 3 bytes of application payload, 8 times a day and having an expected response time of 250ms
  - Repetitive low latency. For example, a mouse transmitting 4 bytes, 50 times per second and a latency of 30ms.

Battery characteristics

Battery type	Voltage [V]	Capacity [mAh]	Radio power consumption in active state [mW]	Approximate operation time (10% duty cycle)	Approximate operation time (1% duty cycle)	Approximate operation time (0.1% duty cycle)
Button cell (L = 2.7 mm, dia. = 9.5 mm)	1.5	42	1	26 days	239 days	3.6 years
			10	3 days	24 days	131 days
			100	0.3 days	2 days	13 days
Button cell (L = 5.4 mm, dia. = 11.6 mm)	1.5	170	1	105 days	2.6 years	15 years
			10	11 days	97 days	1.5 years
			100	1 days	10 days	53 days
AAA	1.5	1175	1	2.0 years	18 years	101 years
			10	73 days	1.8 years	10 years
			100	7 days	67 days	1.0 years
AA	1.5	2700	1	4.6 years	42 years	231 years
			10	167 days	4.2 years	23 years
			100	17 days	154 days	2.3 years

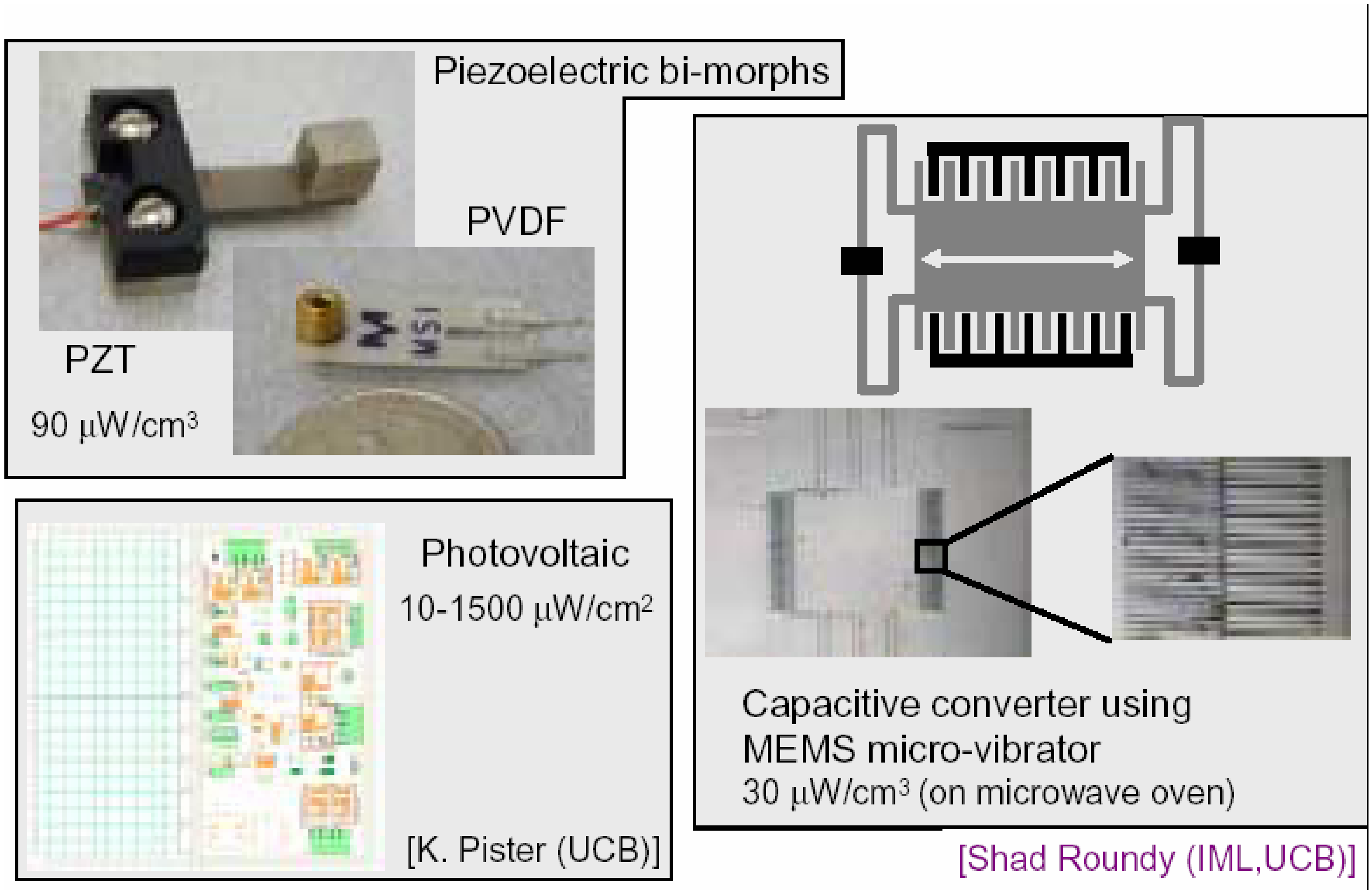
Source: doc.: IEEE 802.15-01/231r2

Power sources' characteristics



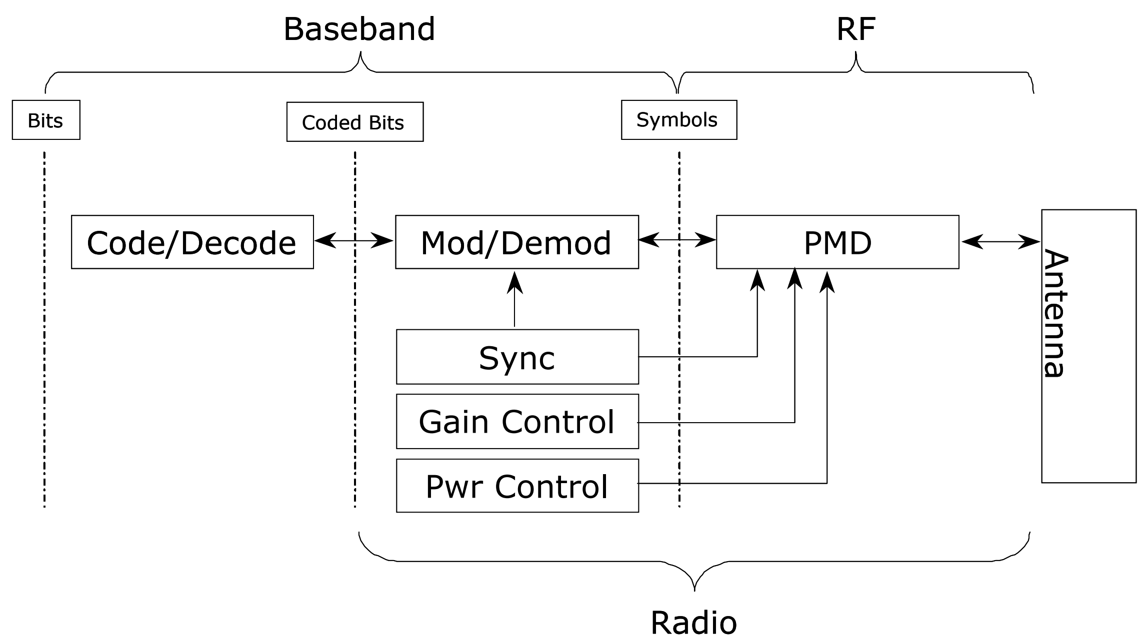
- 100µW is the threshold for energy scavenging

Practical means of energy scavenging



Sources of power dissipation

- Radio transceiver
  - Transmitter
  - Receiver
    - Active
    - Acquisition
    - Sleep
- Protocol stack
- Application



IEEE 802.15.4 modulation/spreading

2.4 GHz PHY

- 250 kbps (4 bits/symbol, 62.5 kBaud)
- Data modulation is 16-ary orthogonal modulation
- 16 symbols are ~orthogonal set of 32-chip PN codes
- Chip modulation is MSK at 2.0 Mchips/s

868 MHz / 915 MHz PHY

- 20 kbps (1 bit/symbol, 20 kBaud)
- Data modulation is BPSK with differential encoding
- Spreading code is a 15-chip m-sequence
- Chip modulation is BPSK at 0.3 Mchips/s

Example UWB link budget

- Negative RX antenna gain
- 500 MHz bandwidth
- 2 MHz chip rate (10 chips/bit)
- 200 kbps raw bit rate, ½ coding

- 30 dB link margin at 10m
- 300 m path loss d = 2
- 30 m path loss d = 3.5

Parameter	**Value**	**Unit**
Throughput (Rb)	100	kbps
Average Transmit Power	-14.3	dBm
Tx antenna gain (Gt)	0.0	dB
Geometric center frequency Fc	4.0	GHz
Path loss at 1 meter (L1=20Log(4πFc/c))	44.5	dB
Path loss at 10 meters (L2=20log(10))	20.0	dB
Rx antenna gain (Gr)	-3.0	dBi
Rx power at 10m (Pr =Pt+Gt+Gr-L1-L2)	-81.7	dBm
Average noise power per bit (N=-174 +10*log(Rb))	-124.0	dBm
Rx Noise Figure Referred to the Antenna Terminal (Nf)	15.0	dB
Average noise power per bit (Pn=N+Nf)	-109.0	dBm
Minimum Eb/No (S)	3.6	dB
Implementation Loss(I)	3.0	dB
No of Bands	1	
Chip Rate	2	MHz
Processing gain (PG)	10	dB
3 dB Bandwidth per band	0.50	GHz
Bits per symbol	1.0	
Raw Bit rate	200.0	kbps
Code rate	0.5	
Pulse Tx power (Pt)	9.7	dBm
Antenna Impedance	50.0	ohm
Transmit p-p voltage at PA	1.9	Volt
Link Margin at 10 m (M=Pr-Pn-S-I+PG)	**30.7**	**dB**

Radio transmitter

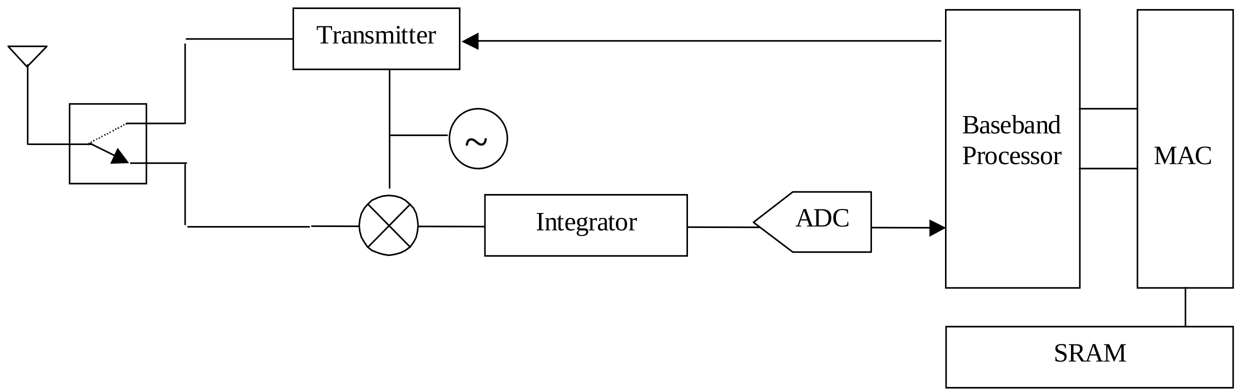
- Minimum UWB bandwidth allowed: 500 MHz
- UWB transmit power
  - PSD = -41.3 dBm/MHz
  - Average power: -14.3dBm => 38 μW
- Energy/bit (@100 kbps) = 0.38 nJ/bit

Radio receiver

- Analog section power typically dominated by oscillators and mixers
- Digital section power driven by clock rate

- Low power UWB radio: not a software radio!
  - Analog section
    - No LNA: increase transmit power, allow higher noise figure
    - No oscillator at the receiver: envelope detector
    - Low power oscillator: low Q and relaxed phase noise requirement, low power reference oscillator
  - Digital section
    - Circuits running at symbol rate (kHz or MHz), not at RF rate (GHz)

Transceiver architecture



Receiver power budget

Component	Active	Sleep
Oscillator	5mW	50µW
Integrator	100µW	0
ADC	100µW	0
Baseband	1mW	10µW
Total	6.2mW	60µW

- Fast wake-up
  - 1ms acquisition time => 6.2µJ per first bit acquired
- Transmit/receive accurate synchronization
  - Requires correct system architecture
  - Adaptive periodic polling (application dependent)

Network protocol

- Ad hoc architecture
  - Reduces range requirements
  - Reduces overall network power consumption
- Location information
  - Reduces networking overhead

Conclusions

- 7,500MHz of available spectrum for unlicensed use
- Spectrum regulation in progress in the ROW
- UWB is a means of accessing the spectrum
  - High data rate, short range
  - Low power, low data rate
- Enables new applications based on precision location

- Batteries not included

- Back to Larry…..