Ultra Wide Band (UWB) Communications Systems

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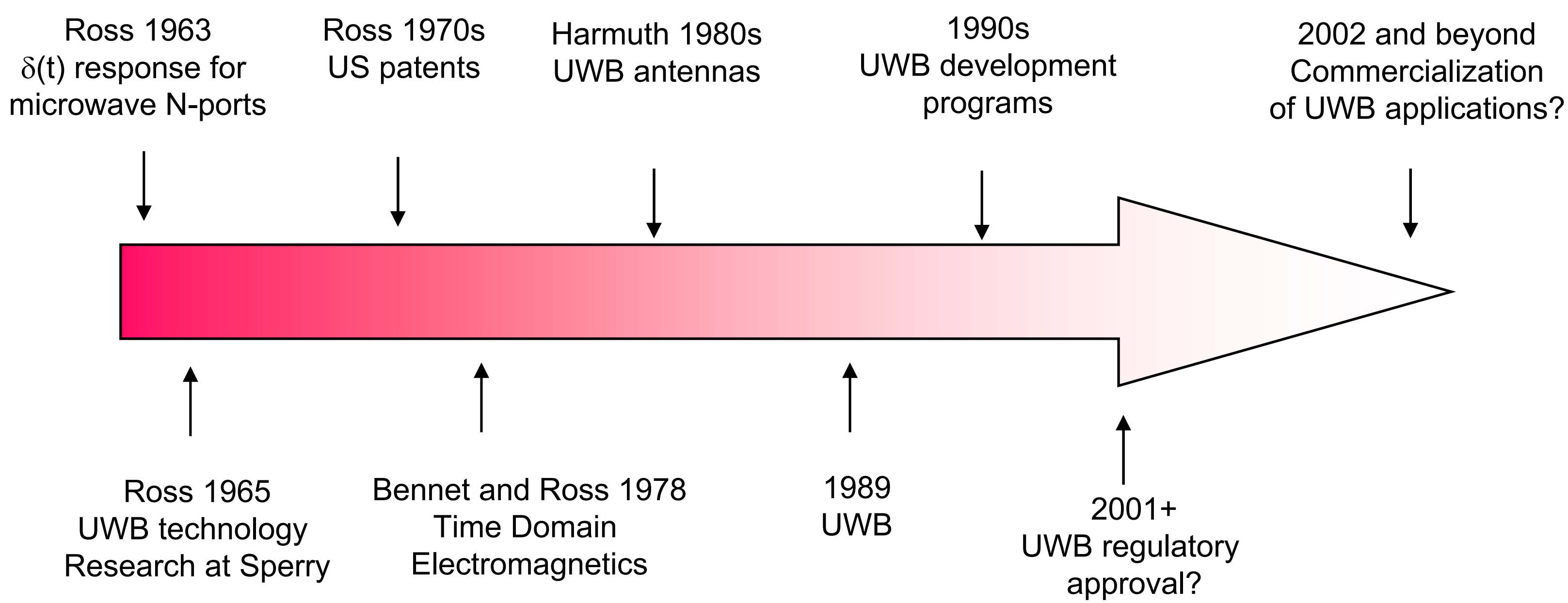
OUTLINE

- Introduction to UWB (JRF)
- The UWB channel, propagation and antennas (JRF)
- Frequency domain solutions, advantages and limitations (JGe)
- Time Domain impulse solutions, advantages and limitations (JAy)
- Summary and concluding remarks (JRF)

OUTLINE

- Introduction to UWB (30 min)
  - Historical perspectives
  - Basics of UWB systems
  - Regulatory issues
  - Applications and services
  - Design alternatives and standards
  - Key issues for UWB systems
- The UWB channel, propagation and antennas
- Frequency domain solutions, advantages and limitations
- Time Domain solutions, advantages and limitations
- Summary and concluding remarks

NOTIONAL UWB TIMELINE



Alternative terms ⇒
- Impulse radar, impulse radio, time domain
- Pulsed radar, short pulse radar, short pulse techniques
- Baseband carrierless, carrier-free, non-sinusioidal

Source: MSSI, Barrett

ORIGINS

- Origins of UWB [Scholtz, MSSI, Barrett]
  - UWB techniques have existed for over 3 decades.
  - Origins can be traced to work in time-domain electromagnetics circa ‘62.
  - Initial studies describing μwave networks via impulse response (Ross ’63, ’66).
  - The design of wideband radiating antenna elements dates to 1968 (Ross).
  - Commercial UWB radar systems have available since the 1970’s .
  - UWB for radar is not new, but the application to communication is relatively new.

- The term Ultra Wideband came in to use in around 1989 [Barrett]
  - Time Domain Impulse Radio UWB (IR-UWB)
  - Alternative terms [Barrett, MSSI]
    - Impulse radar, impulse radio, time domain
    - Pulsed radar, short pulse radar, short pulse techniques
    - Baseband carrierless, carrier-free, non-sinusoidal

- A wide range of UWB systems and applications exist today

OVERVIEW OF POTENTIAL UWB APPLICATIONS

- **Communication**
  - Low power, short range
    - HDR, MDR, LDR
  - Environment and system
    - Fixed indoor-outdoor (e.g. WLAN)
    - Portable systems (e.g. WPAN)
  - Networking and security
    - Point-to-point or multipoint
    - LPI/LPD
- **Vehicular**
  - Proximity radar
  - Self-driving vehicles
- **Localization services**
  - Distance and localization
  - Remote sensing of objects
- **Imaging and sensing**
  - Medical imaging
  - Ground penetration
- **Security services**
  - Motion detection radar

Communication is only one application of UWB and maybe not even be the biggest. UWB is a mulipurpose technology, well suited to short range wireless systems requiring high coexitence, worldwide operation and low power operation, such as, future WSNs

WHAT IS UWB?

- **UWB signal**
  - Radar history
  - UWB communication made possible by DSP advances
  - A sequence of pulses referred to as moncycles
  - Sinusoidal carrier not required

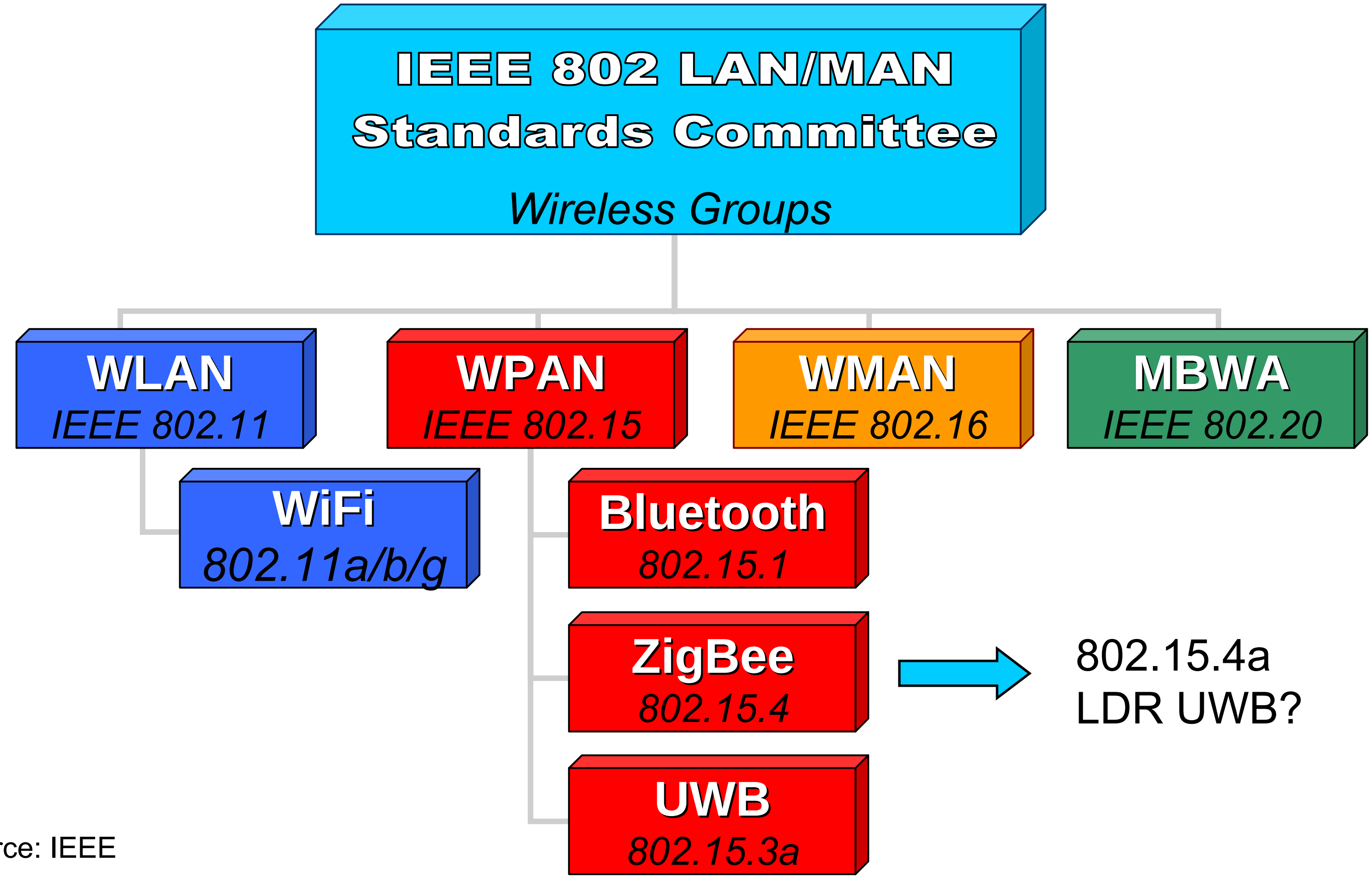
- **UWB bandwidth**
  - Fractional bandwidth (FBW) of at least 20% of f_c *or at least 500 MHz* ($B_{-10\,dB}$)
  - Example: f_c = 4.0 GHz, f_H = 4.5 GHz, f_L = 3.5 GHz → FBW ≅ 25%

$$FBW = 2\frac{f_H - f_L}{f_H + f_L} = \frac{f_H - f_L}{f_c}$$

The definition of UWB remains relatively loose – open standard

Sources: Harmuth, Baum, Win, FCC, ETSI

OVERVIEW OF STANDARDS



Source: IEEE

TYPES OF UWB SYSTEMS

- A plurality of UWB systems are possible each with relative advantages and disadvantages
  - Time and frequency domain implementations
  - High Data Rate (HDR), but also Low and Medium (LDR/MDR)

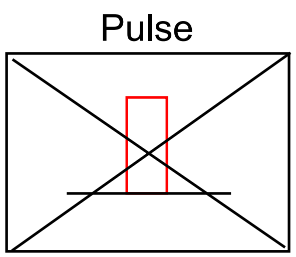
- UWB communication systems
  - Time Hopped (IR-UWB)
    - Analog impulse radio multiple access (AIRMA) [Scholtz, Win]
    - Digital impulse radio multiple access (DIRMA) [Scholtz, Win]
  - OFDM based (e.g. Multi-Band OFDM)
  - DS-CDMA based (e.g. Multi-carrier CDMA)
  - FM based, swept frequency and others

- UWB standards
  - IEEE802.15.3.a is the dominant standard for hotspot UWB
  - IEEE802.15.4.a is emerging as the standard for low data rate transmission

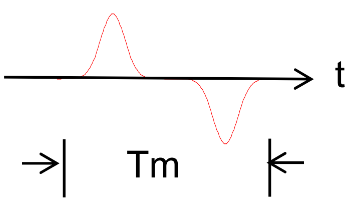
IR-UWB was the first and remains important. Multiple options exist today and choice depends on the application, system requirements and future standards.

IR-UWB REFERENCE AND TERMINOLOGY

- UWB pulse
  - Nominally, pico seconds to nano seconds
  - The pulse shape is typically Gaussian (doublet)
- Binary symbol rate
  - $R_s = 1/T_s = 1/(N_s T_f)$, T_f is the pulse repetition interval
  - $N_s = (B_s/B_p)$ frames per symbol
  - $B_s = 1/T_m$, where $T_m \cong$ UWB pulse width
- Pulse repetition frequency
  - B_p = peak pulse frequency (PRF)
  - Nominally, measured in a 0.1 s interval
- Processing gain (PG)
  - $PG_{CDMA} = 10\log(W/R)$
  - $PG_{UWB} = 10\log(N_s)$



√ Gaussian doublet



UWB obeys Shannon's laws and the capacity is comparable to DS-CDMA systems of the same spread BW (W)

Source: Foerster, Scholtz, Win

ENVELOPE OF THE POWER SPECTRAL DENSITY (PSD) FOR IR-UWB USING GAUSSIAN PULSES

$$f(t) = G(t)$$

Gaussian Tx pulse

$$\frac{dG(t)}{dt} = A\frac{t}{T_m}\exp\left[-(t/T_m)^2\right]$$

Tx waveform
(after the Tx antenna)

$$f(at) \rightarrow \frac{1}{|a|}X\left(\frac{\omega}{a}\right)$$

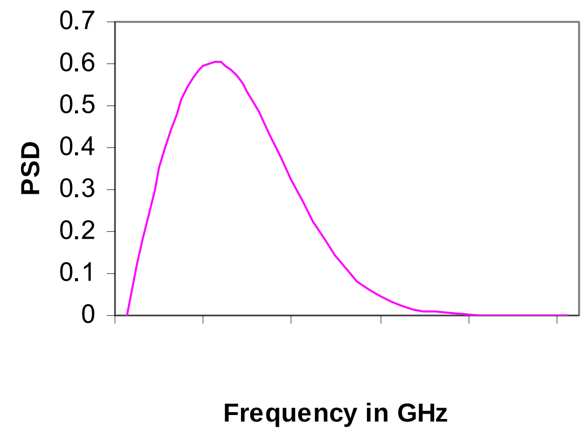
$$G(f) = A\omega T_m^2\sqrt{2\pi e}\,\exp\left[-\frac{\omega^2 T_m^2}{2}\right]$$

PSD
(Tx waveform)

$$\frac{dG(f)}{df} = -(2\pi)^2\sigma^2 fG(f)$$

Rx template
(after the Rx antenna)

PSD envelope of the Tx waveform



T_m = 1 ns and A = 1.

Source: Fullerton

COEXISTENCE AND THE NEED TO MAINTAIN UWB EMMISSIONS WITHIN ACCEPTABLE LIMITS

- Noise aggregation and co-existence
  - Co-existence with existing systems must be maintained within acceptable limits.
  - Radiation in some bands should be avoided, or VERY limited (e.g. astronomy, GPS, UMTS and aeronautical bands (65 restricted bands of operation))
  - Complicated by potential noise aggregation of UWB systems over multiple bands.

- GPS interference example
  - Rx space-to-earth signal power: ≈ –134 dBm (10^{-16} W) [Enge, NTIA]
  - Typical GPS Rx sensitivity: -135 dBm @ 1575.42 MHz [Garmin]
  - Interference from UWB signals can occur at to 30-100 m [Enge, NTIA]
  - Potentially large restriction range or Tx modifications (e.g., filters) [Enge]

- Astronomy case (K.Ruf, IUCAF ETSI)
  - Definition 1 Jansky (Jy) = -260 dBW/m^2Hz
  - Radio astronomical sources : ~ a few mJy

Source: Hurt

UWB REGULATORY STATUS AND INTERNATIONAL RECOMMENDATIONS

- US
  - FCC granted *limited approval* for operation of UWB devices 14.2.02 (Part 15).
  - Memorandum of Opinion and Order largely affirming the approval 13.2.03.
- Europe
  - ETSI TG31a initiated standards development and has proposed a spectral mask
  - CEPT SE24 is dealing with regulatory issues (spectrum sharing study for < 6 GHz)
- Japan and Asia starting
  - Ministry of Posts and Telematics (MPT) started the regulatory process with industry issuing experimental licenses.
  - First experimental license granted for operation of a UWB transmitter in Japan.
  - In Singapore, IDA UWB-FZ has allowed UWB systems to operate locally.
- ITU preparing recommendations
  - ITU-R Study Group 1 (SG 1), Spectrum Management, Task Group 1/8 (GA 1/8) - Compatibility between UWB devices and radiocommunication services.

Source: FCC, ETSI, IST Prodemis

FCC LIMITED APPROVAL

- Imaging Systems
  - Ground Penetrating Radar Systems (GPRs):- < 960 MHz or in the frequency band 3.1-10.6 GHz.
  - Wall Imaging Systems – location of objects: < 960 MHz or in the frequency band 3.1-10.6 GHz.
  - Through-wall Imaging Systems, location or movement of persons: < 960 MHz or, 1.99-10.6 GHz.
- Medical Systems
  - Variety of health applications (e.g. to see inside the body of a person): 3.1-10.6 GHz.
- Surveillance Systems
  - Surveillance systems operate as “security fences” (e.g. detecting of intruders): 1.99 – 10.6 GHz.
  - Operation is limited to law enforcement, fire and rescue, public utilities and to industrial entities.
- Vehicular Radar Systems
  - Vehicular radar systems (e.g.collision avoidance, improved airbag activation): > 24.075 GHz
- Communications and Measurement Systems
  - Wide variety of other UWB devices (e.g. high-speed networking): 3.1-10.6 GHz.
  - Indoor operation or hand-held devices employed for such activities as peer-to-peer operation.

Source: FCC

FCC PART 15 LIMITS FOR COEXISTENCE WITH OTHER SYSTEMS

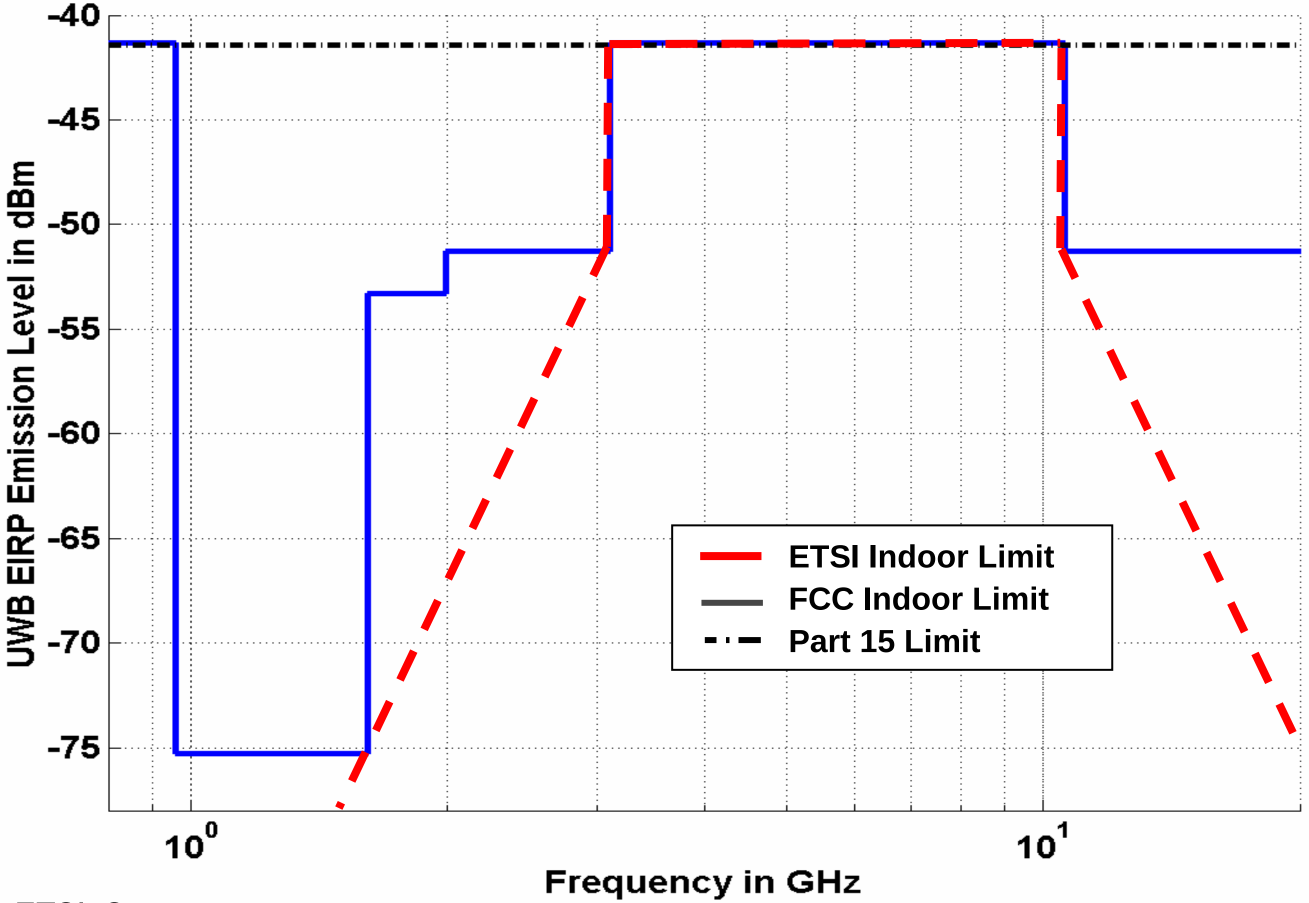
- Unlicensed intentional radiator emission limits [FCC]
  - f < 960 MHz: 12 nW/MHz → -49.3 dBm/MHz
  - f > 960 MHz: 75 nW/MHz → -41.3 dBm/MHz

- Unintentional radiator emission limits [FCC]
  - Class A devices: commercial, industrial or business markets
  - Class A limits: f < 960 MHz: 147 nW/MHz → -38.3 dBm/MHz
  - Class B devices are targetted for the home or residential market
  - Class B limits: same as for unlicensed intentional radiators

- Peak power
  - For example, the maximum transmitted power of an UWB transmitter with a 1 GHz bandwidth operating at 4 GHz could not exceed –11.3 dBm.

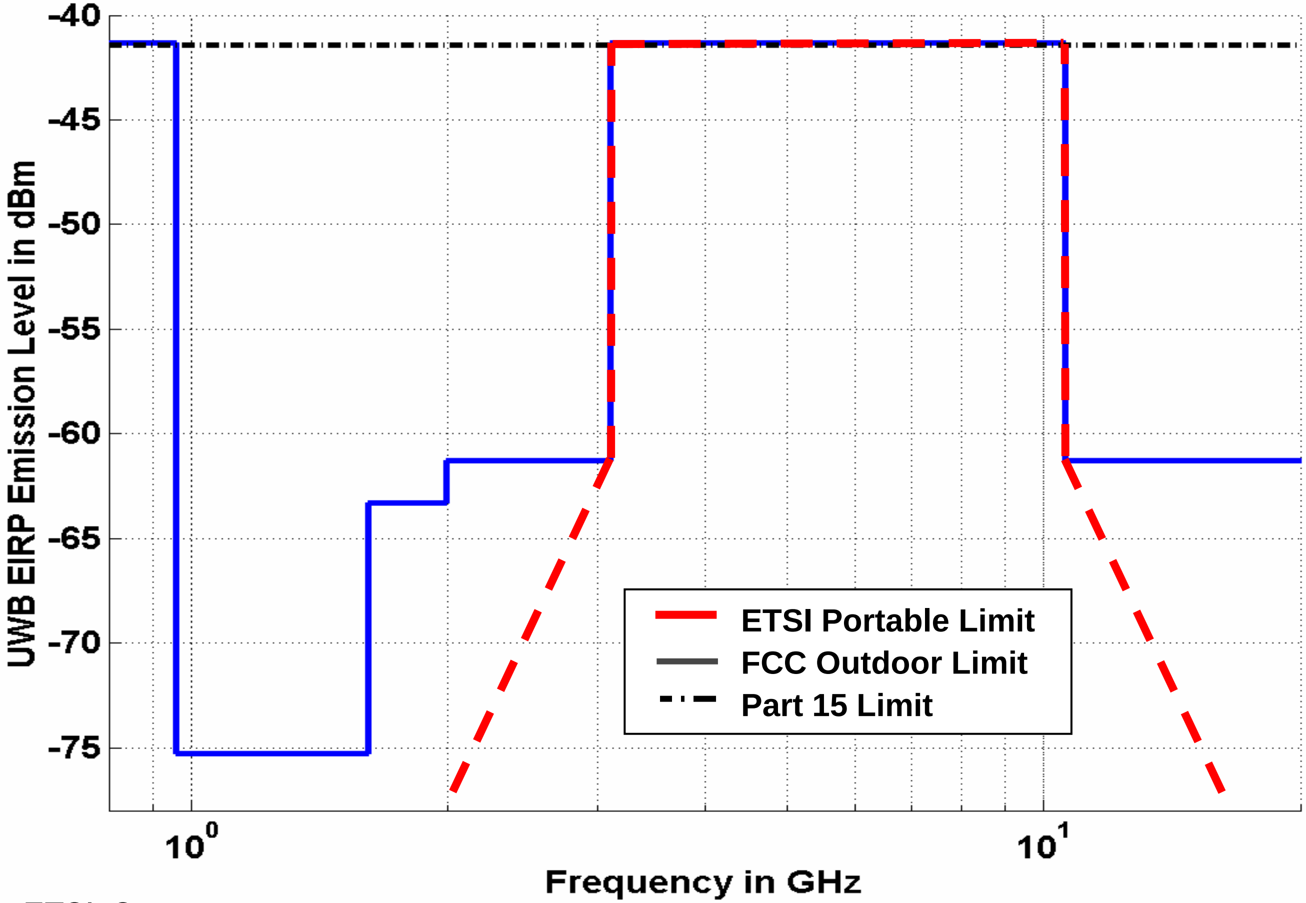
- Other limitations/constraints
  - In addition to peak power and power spectral density (PSD), other potentially important parameters may include: field strength, duty cycle, pulse repetition frequency (PRF), modulation, antenna gain, density of radiators…

FCC AND DRAFT ETSI UWB EMISSION LIMITS FOR INDOOR SYSTEMS



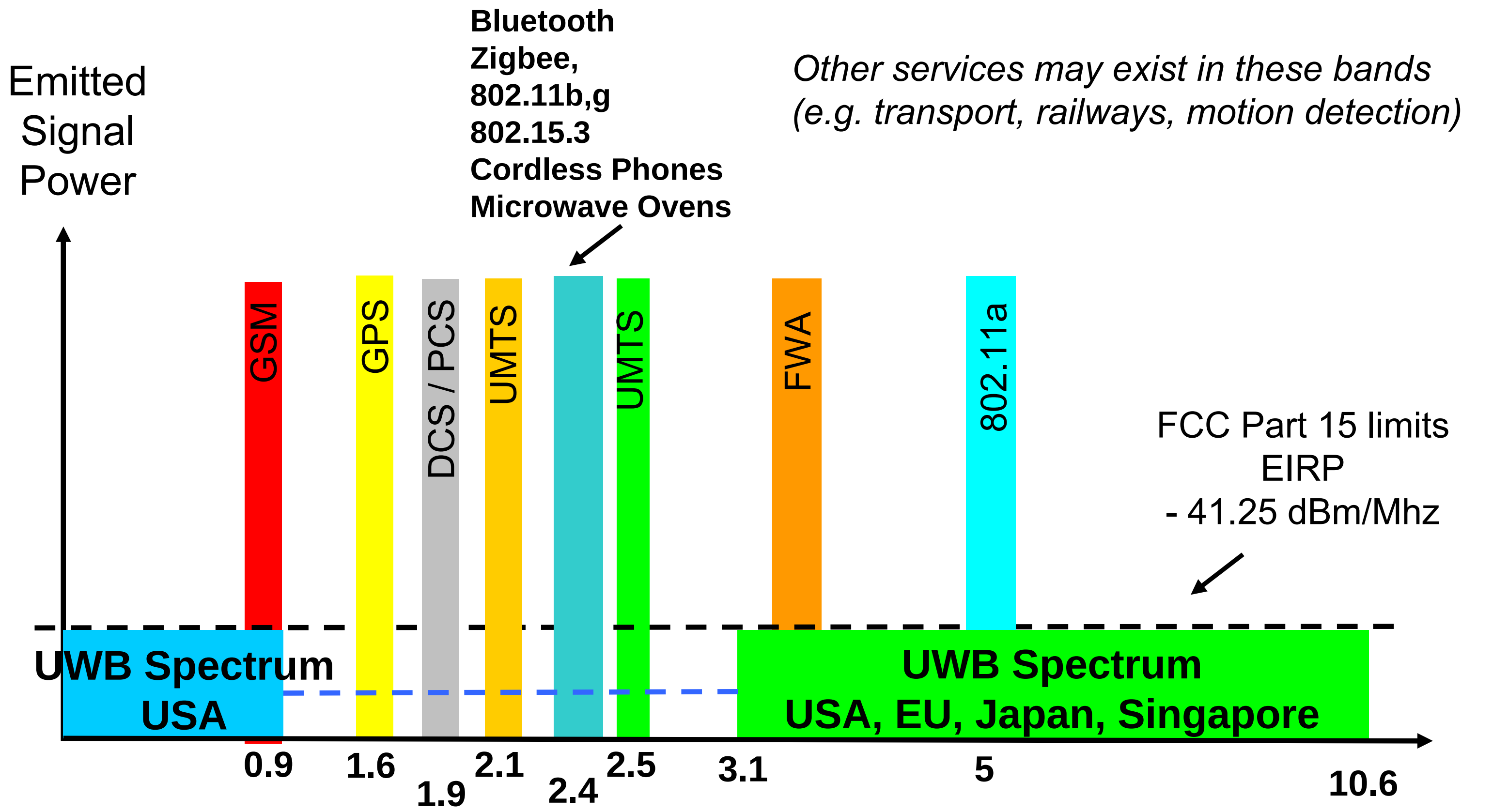
Source: FCC, ETSI, Sony

ETSI DRAFT UWB EMISSION LIMITS FOR PORTABLE SYSTEMS



Source: FCC, ETSI, Sony

COEXISTENCE: OVERVIEW OF UWB EMISSION LIMITS FOR INDOOR AND OUTDOOR SYSTEMS



Source: IST PULSERS

WORLDWIDE OPERATION

Region, system and frequency bands

Region	Bluetooth (1) 100 mW 83.5 MHz 721 kbps FHSS (GHz)	IEEE802.11a 40-800mW 300 MHz 54-72 Mbps OFDM (GHz)	IEEE802.11b/g 100 mW 83.5 MHz 11/54 Mbps DSSS (GHz)	Narrow band ISM (3)			UWB <100µW 7.5 GHz (GHz)
				433.05-434.79 MHz 10 mW 1.74 MHz (MHz)	868-870 MHz 5-500 mW 2 MHz (MHz)	902-928 MHz 1W 26 MHz (MHz)	
Europe	2.400 – 2.4835	5.15 - 5.25 5.25 - 5.35 5.725 - 5.825	2.412 - 2.472 (2)	X	X		3.1 – 10.6
France (1)	2.4465 – 2.475		2.457 - 2.472	X	X		
Spain (1)	2.445 – 2.475		2.412 - 2.462	X	X		
US	2.400 – 2.4835		2.412 - 2.462			X	
Japan (1)	2.471 – 2.497		2.412 - 2.484	(4)			

1. 79 hops, 1 MHz/hop, from 2.402 – 2.480 GHz. However, in a few countries the number of hops is reduced to 23.
2. Europe ETSI.
3. Representative examples. Multiple sub-bands and limits may apply (e.g. 868 MHz).
4. 426 MHz in Japan.

UWB offers a potential worldwide solution for nomadic users.

LINK ANALYSIS 1: RECEIVED POWER GIVEN ISOTROPIC ANTENNAS

$P_R(f) = \dfrac{P_T(f)G_T(f)G_R(f)c^2}{(4\pi d)^2 f^2}$	Received power as a function of frequency
$P_T(f)$	Average transmit spectral density
$P_{ave} = \int_{-\infty}^{\infty} P_T(f)G_T(f)df$	Total average transmit power
c	Speed of light
$G_T(f)$	Transmit antenna frequency response
$G_R(f)$	Receive antenna frequency response

Based on narrowband model, basically the same as for any wireless link

Source: Intel, IEEE P802.15-02/279r0-SG3a

LINK ANALYSIS 2. FLAT FREQUENCY RESPONSE, CONSTANT GAIN ANTENNA MODEL

$$P_{Rave} = \int_{f_c - W/2}^{f_c + W/2} P_R(f)df = \frac{P_{ave} G_R c^2}{W(4\pi d)^2}\left[\frac{1}{f_c - W/2} - \frac{1}{f_c + W/2}\right] = \frac{P_{ave} G_R c^2}{(4\pi d)^2 f_c^2}\left[\frac{1}{1-(W/2f_c)^2}\right]$$

$$P_{Rave} = P_{ave}^{NB}\left[\frac{1}{1-(W/2f_c)^2}\right]$$

Wideband adjustment factor

$$P_{ave}^{NB} = \frac{P_{ave} G_R c^2}{(4\pi d)^2 f_c^2}$$

Narrowband (NB)

$G_R = \text{constant}$ Constant gain accross the whole bandwidth (G_R = 1 ideal isotropic)

Narrowband path loss model, with an adjustment factor for wideband

Source: Intel, IEEE P802.15-02/279r0-SG3a

LINK ANALYSIS 3: GENERAL, FREQUENCY DEPENDENT GAIN MODEL FOR UWB

$$P_{Rave} = \frac{P_{ave} 4\pi A_R}{(4\pi d)^2} = \left(\frac{P_{ave} c^2}{(4\pi d)^2 f_c^2} \right) \left(\frac{4\pi A_R f_c^2}{c^2} \right) = P_{ave}^{NB} G_R(f_c)$$

Average received power

$G_R(f) = 4\pi A_R f^2 / c^2$ Receive antenna response

A_R Effective area of the antenna

$G_R(f_c)$ Antenna gain at center frequency

This more general model yields higher gain at higher frequencies

Source: Intel, IEEE P802.15-02/279r0-SG3a

EXAMPLE IR-UWB LINK BUDGET ANALYSIS

Item	*Parameter*	*Value*	*Units*	*Comments*
1	Center frequency (f_c)	3750.0	MHz	ISM band
2	Bandwidth (B)	2500.0	MHz	67% FBW
3	Peak transmit power (P_{peak})	750.0	nW	
4	Pulse duration (T_m)	0.4	ns	$T_m = 1/B$
5	Frame duration (T_f)	4.0	ns	PRF = 250 MHz
6	Pulse repetiton rate (*PRF*)	250.0	Mpps	$B_p = PRF = 1/T_f$
7	Duty factor (ρ)	0.1	N/A	
8	Transmit power (P_{ave})	- 7.0	dBm	-41 dBm/MHz (FCC part 15), B = 2500 MHz
9	Antenna gain (G_{tx})	- 0.0	dBi	Ideal dipole
10	Terminal EIRP	- 7.0	dBm	
11	Path loss (P_L)	63.9	dB	L = 10 m
12	Antenna gain (G_{rx})	- 0.0	dBi	Ideal dipole
13	Received signal power (S)	- 70.9	dBm	At the receiver input
14	Miscellaneous losses	0.0	dB	Shadowing, absorption, etc…
15	Receiver noise (T)	- 29.1	dB	T = 819° K (NF = 6 dB)
16	Boltzman's constant	- 198.6	dBm/K·Hz	$1.38 \cdot 10^{-23}$
17	Noise density (N_0)	- 169.5	dBm·Hz	$N_0 = kT$
18	Signal-to-Noise ratio (S/N)	11.6	dB	$N = 2kTB_p$
19	Signal-to-noise-density (S/N_0)	93.6	dB·Hz	
20	Data rate (R)	84.0	dB	R = 250 Mbit/s = PRF, binary modulation
21	System margin (M)	5.0	dB	5 dB margin for implementation losses
22	E_b/N_0	6.6	dB	BPPM, AWGN, BER = 10^{-3}

Reference IR-UWB link analysis provided for illustration purposes. Ideal operating assuptions (e.g., channel, antenna efficiency, losses, etc…).

Source: Foerster, see also Intel, IEEE P802.15-02/279r0-SG3a

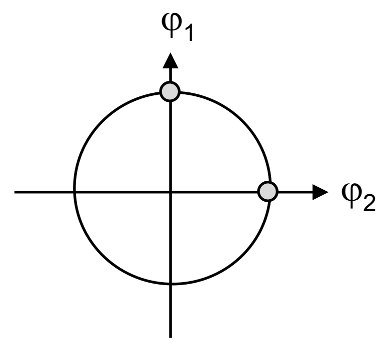
UWB MODULATION SCHEMES

UWB modulation schemes:

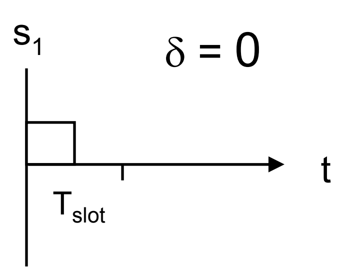
- *Pulse Position Modulation (PPM)*
- On Off Keying (OOK)
- Amplitude Shift Keying (ASK)
- Frequency Shift Keying (FSK)
- Frequency sweep (CHIRP)

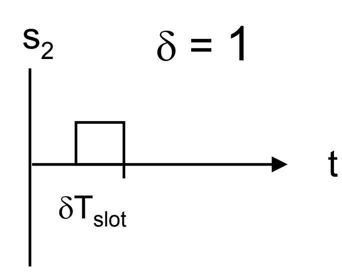
BPPM ≈ BFSK

Binary PPM

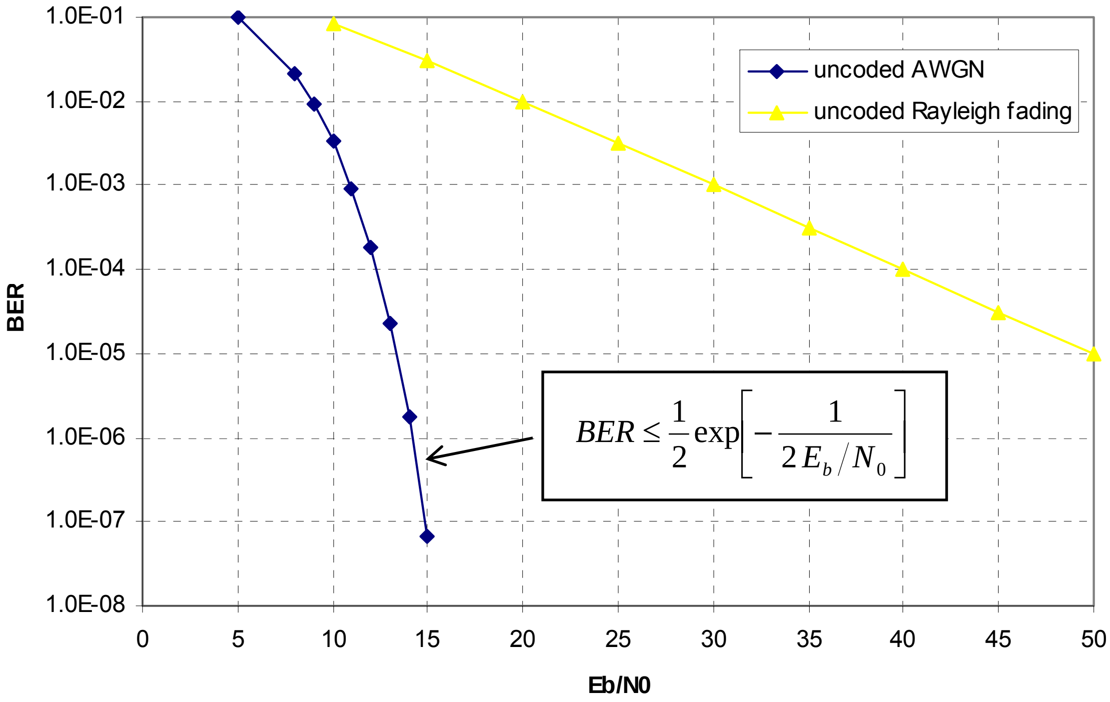


- N = 2 (axis)
- Orthonormal
- Axes $\underline{\varphi}_1$ and φ_2
- $s_j = \sqrt{E_s}\varphi_j$; j = 0,1,…M-1
- M equally likely signals
- $M = 2^k = N$ (orthogonal)
- $\delta = (N-1) = 1$ for BPPM





PERFORMANCE BOUNDS OF IR-UWB USING BINARY PPM

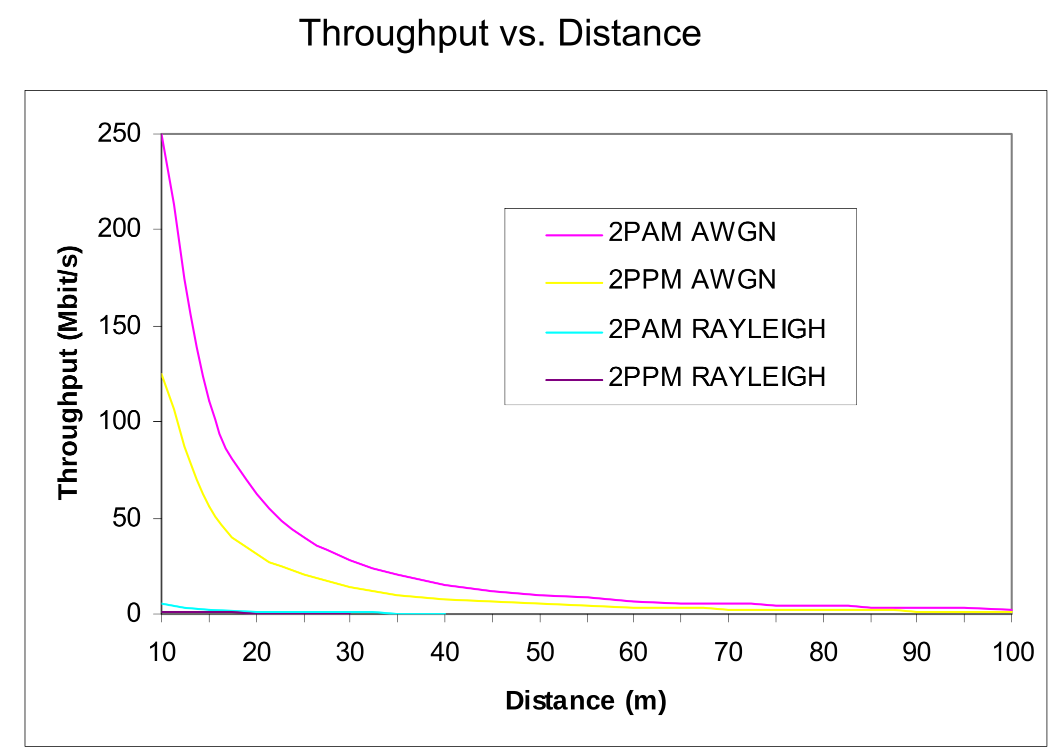


$$BER \le \frac{1}{2}\exp\left[-\frac{1}{2\,E_b/N_0}\right]$$

$$BER \le \frac{1}{2 + E_b/N_0}$$

Given robustness to multipath fading, the performance of UWB is expected to be closer to that of AWGN than Rayleigh fading.

TIME HOPPED IR-UWB THROUGHPUT ANALYSIS



Example single link throughput curves based on [Foerster] for uncoded 2PPM and 2PAM, BER = 10^{-3}, AWGN and Rayleigh fading channels.

OUTLINE

- Introduction to UWB
- The UWB channel, propagation and antennas (30 min)
  - Channel and propagation
  - Coexistence and interference
  - UWB antennas
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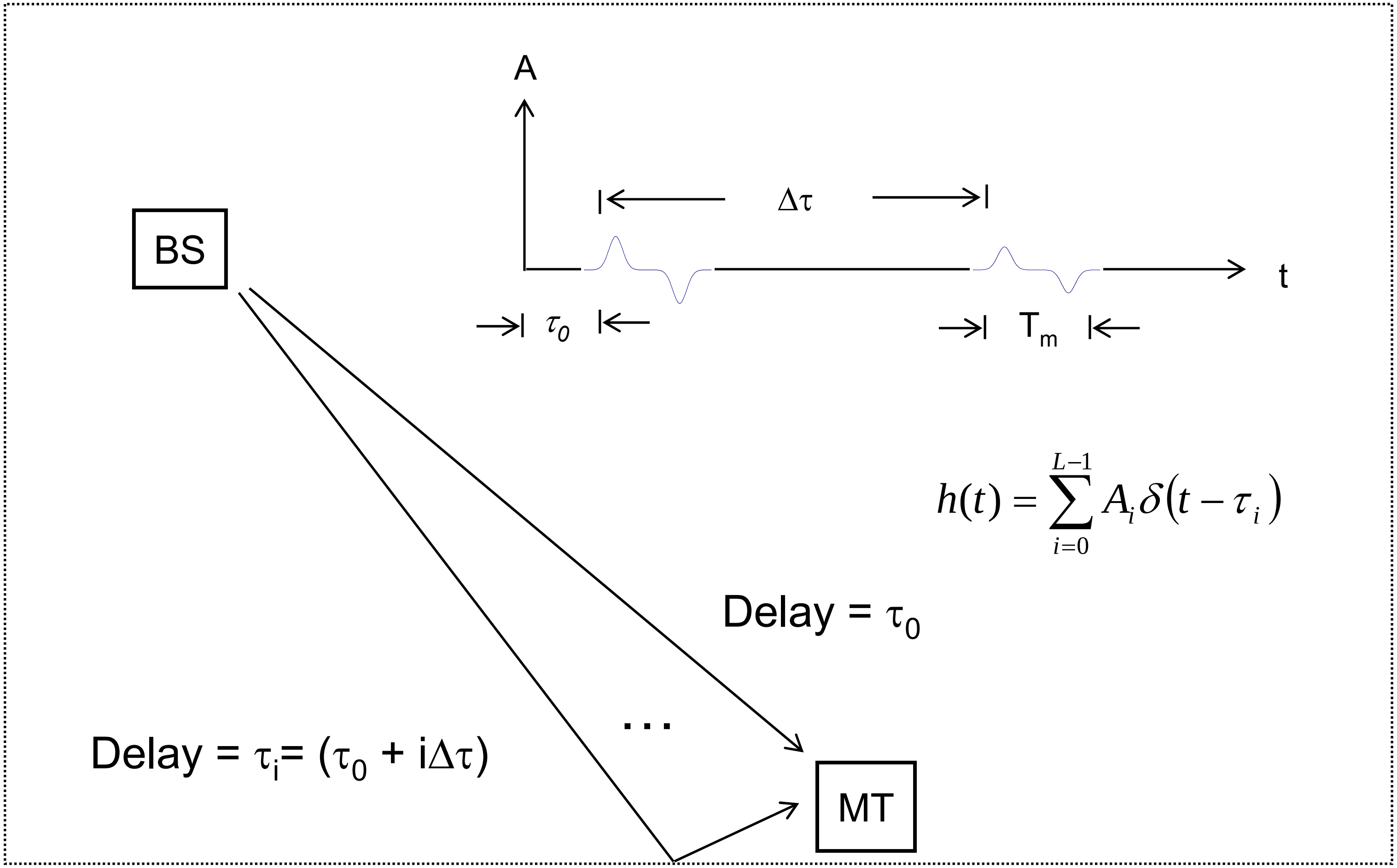
ILLUSTRATIION OF A MULTIPATH IR-UWB CHANNEL



$$h(t) = \sum_{i=0}^{L-1} A_i \delta(t - \tau_i)$$

IR-UWB MULTIPATH MODEL

- The UWB channel may be defined in terms of a finite number (*Lp*) of dominant multipath components [Win] (e.g. LOS, specular and diffuse components).

$$h(t) \approx \sum_{i=0}^{Lp} A_i \delta(t - \tau_i)$$

- A good IR-UWB receiver is able to capture at least the dominant components. *Lp* = no. single-path (SP) signal correlators needed (Rx and channel model).

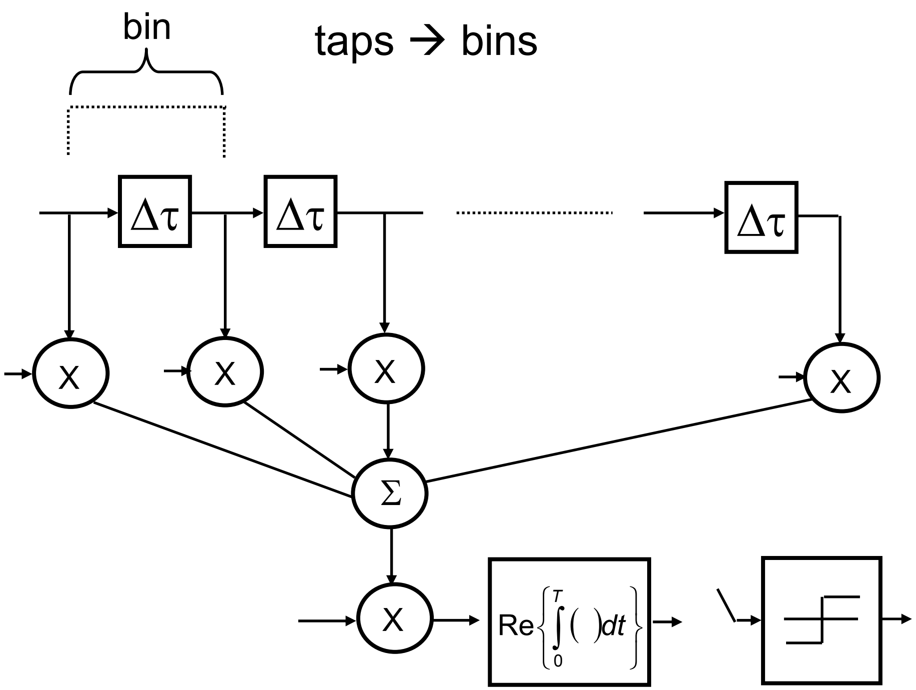
- The IR-UWB receiver is typically a RAKE with discrete bins of $\Delta\tau$ seconds. If the power in the i^{th} bin is greater than the min signal detection threshold (T), then a multipath component is considered to exist at $\tau_i = i\Delta\tau$ [Win].

- Complexity scales with the number of components to be captured (e.g *Lp* = 5).

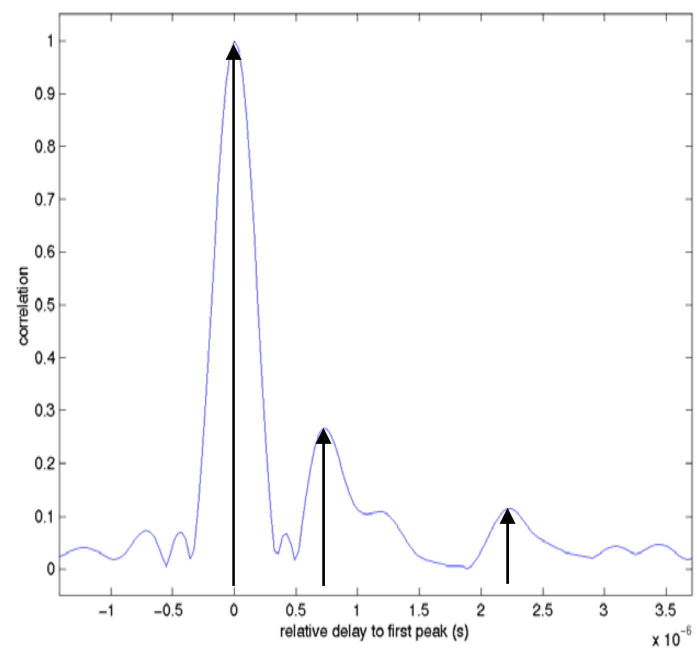
- Although the first arriving path is not always the strongest, it is easier to discern the individual paths with UWB than other wireless systems (sinusoidal carrier).

IR-UWB RAKE RECEIVER

taps → bins



Continuous → Discrete correlation



INDOOR MULTIPATH FADING AND DELAY SPREADS

RMS delay spread

$$\sigma_\tau = \sqrt{\overline{\tau^2} - (\overline{\tau})^2}$$

$$\sigma_\tau = \sqrt{\frac{\sum_k a_k^2 \tau_k^2}{\sum a_k^2} - \left[\frac{\sum a_k^2 \tau_k}{\sum a_k^2}\right]^2}$$

a_k = relative amplitude of the k[th] component

τ_k = relative delay of the k[th] component

Conventional wireless

- Minimum: approx. 10 ns [1]
- Typical: 50 -100 ns [1]
- Maximum: over 1000 [1]

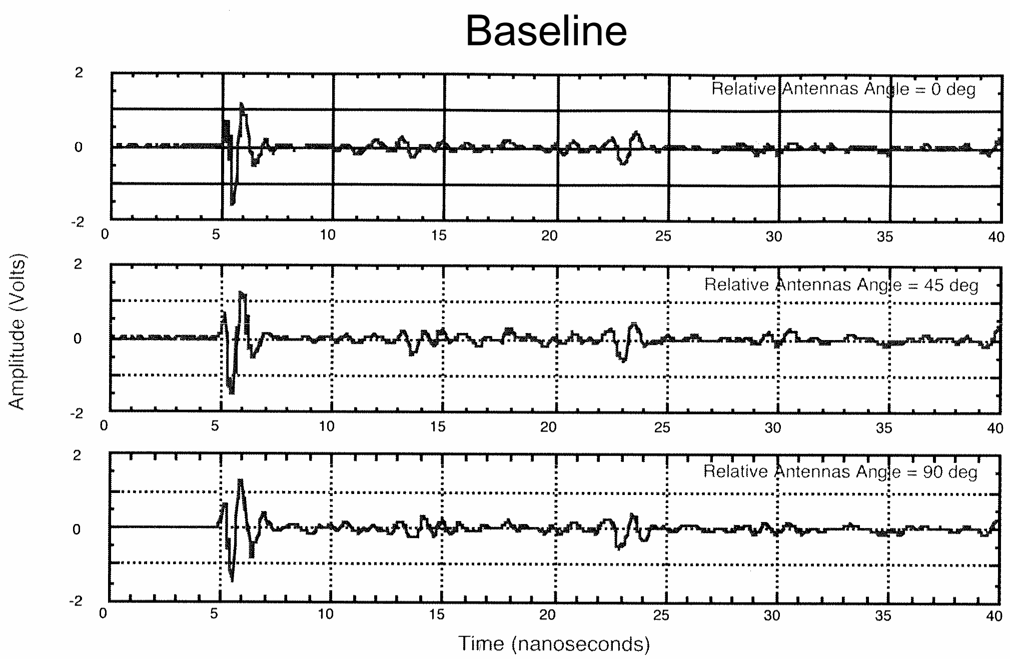
UWB

- Typical: 50-100 ns [Win]

It is not the delay spread that changes, but rather receiver dependent perception.

1. For more information on the delay spread, refer to [Proakis, Rappaport]

IR-UWB MEASUREMENTS

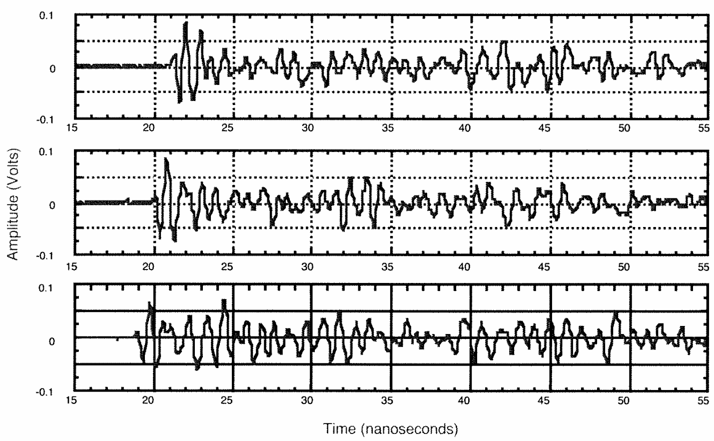


Source: [Scholtz, Win]

- Measurements of Tx UWB pulses made with the Rx antenna 1 m from the emmitter
- Vertically polarized antenna rotated about it's axis (i.e., 0, 45 and 90 degrees)

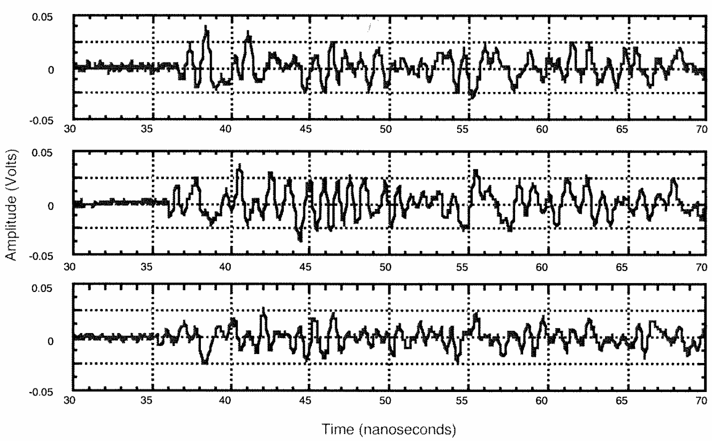
IR-UWB MEASUREMENTS CONTINUED

High SNR
(Room P – 6 m from emmitter)



Source : [Scholtz, Win]

Low SNR
(Room H 10 m from emmitter)

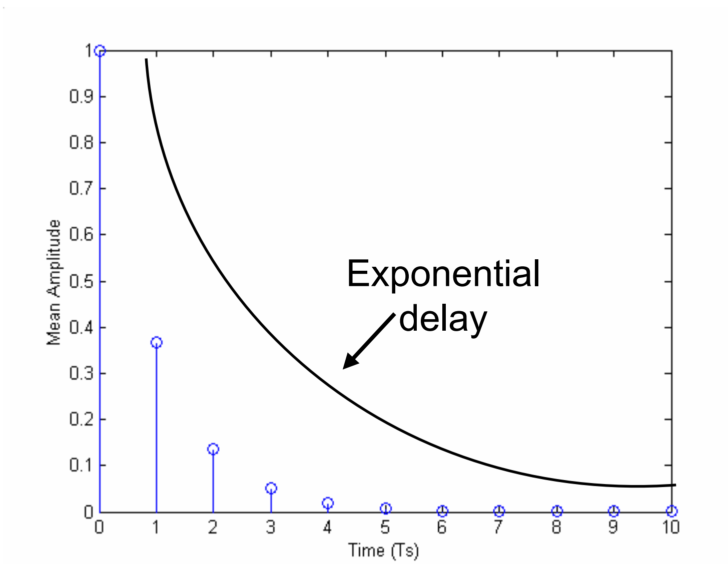


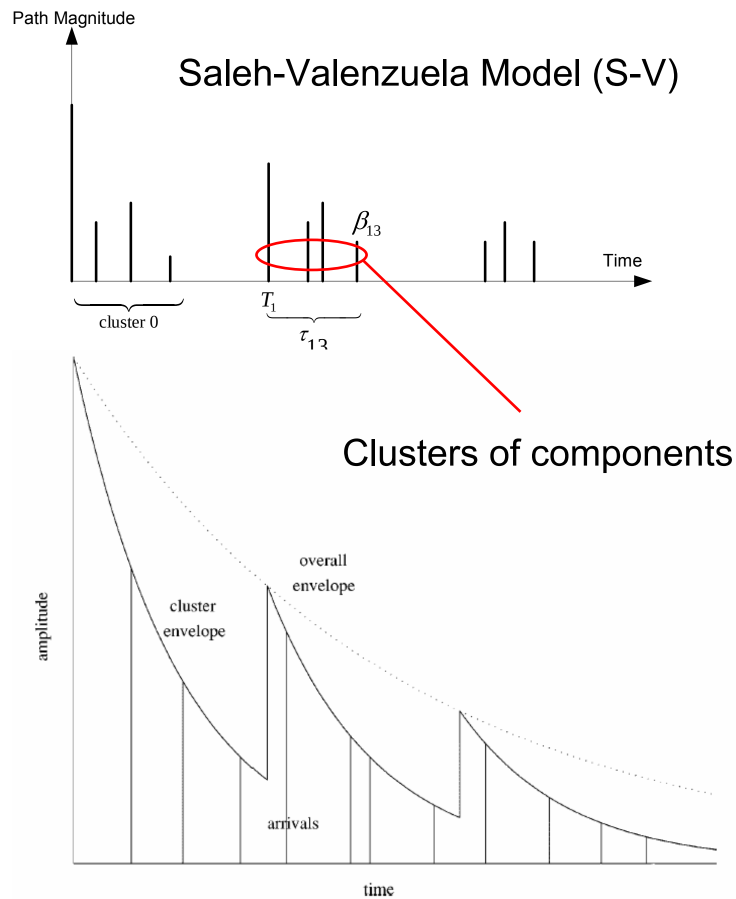
Source : [Scholtz, Win]

- Periodic sub-nanosecond UWB pulses are emmitted every 500 ns
- Measurements made in different rooms corresponding to high and low SNR
  - 49 measurements were taken per room
  - 3 foot-by-3 foot grid (7 x 7 matrix), 6 inches between measurement points
  - 300 ns long measurement windows in each room

IEEE802.15 CHANNEL IMPULSE RESPONSE

IEEE802.11 model





Source: Intel, IEEE P802.15-02/279r0-SG3a

TYPICAL FADE LEVELS

Distance (m)	Fade level		
	Minimum	Maximum	Mean
6.0 (1)	-15.5	-12.2	-14.2
10.0 (2)	-21.1	-16.2	-18.7

1. Win and Scholtz measurements case 1 (Room P)
2. Win and Scholtz measurements case 2 (Room H)

- Fading occurs, but multipath variations appear to be relatively moderate.
- For example, by comparison to Rayleigh fading, which is common indoors, the minimum signal would be 0 (i.e., for the case where *A* = *B* and ϕ = 180°).

$$A\cos(wt+\theta)+B\cos(wt+\theta+\phi)=0$$

Reduced potential for deep fades!

FREQUENCY DOMAIN MEASUREMENTS 1

- An ideal free space (FS) path (no ground reflection, no multipath) has a path loss that is proportional to the square (α=2) of the separation *d,* and with λ the wavelength:

$$PL_{dB}(d) = \alpha \cdot 10\log_{10}\left(\frac{4\pi d}{\lambda}\right) = \alpha \cdot 10\log_{10}(d) + c$$

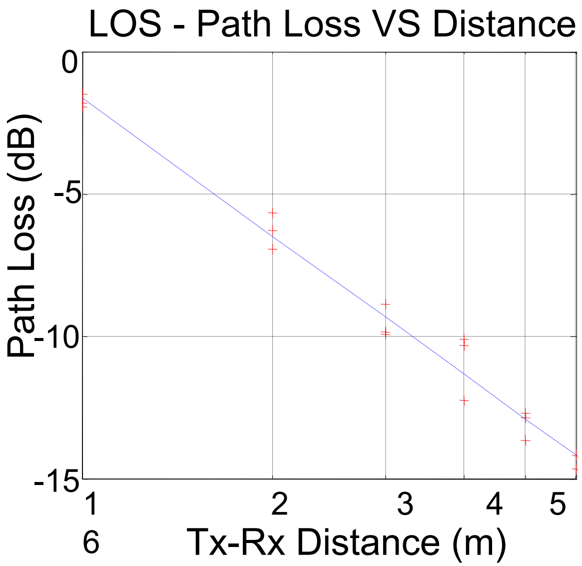
where α is the path loss exponent and c is a power scaling constant included in calibration

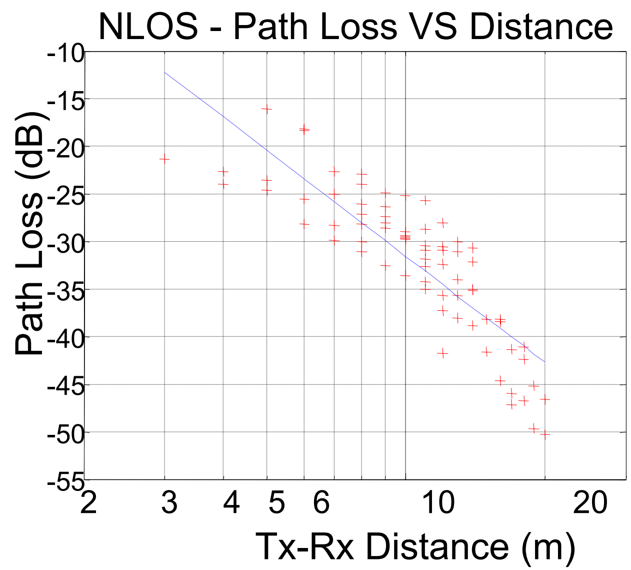
- Friis formula suggest a 1m path loss equal to 44.5 dB at 4GHz center frequency.

- Attenuation has been directly calculated from the total received power in frequency domain.

Source: CEA-LETI, IEEE802.15.4

FREQUENCY DOMAIN MEASUREMENTS 2





- Path loss results for office/laboratory environment
  - LOS path loss factor: α = - 1.6319
  - NLOS path loss factor: α = - 3.6822

Source: CEA-LETI, IEEE802.15.4

TIME DOMAIN MEASUREMENTS

- Three parameters from channel impulse response are analysed for a bin size of 250ps obtain from complex baseband IFFT
- Number of paths within 10dB corresponds to multipath with an amplitude higher than 10dB under the maximum path.

	Environment	Mean Excess Delay (ns)	RMS Delay Spread (ns)	Number of paths within 10dB
LOS (0-4m)	Flat	6.53	11.45	3.4
	Lab/office	6.42	10.07	2
NLOS(4-10m)	Lab/office	16.01	14.78	46.8
NLOS(10-20m)	Lab/office	18.85	17.64	75.8

SUMMARY OF UWB CHANNEL AND PROPAGATION IMPLICATIONS

- IR-UWB robustness
  - No sinusoidal carrier (no constructive and destructive interference)
  - Distortion of pulses must be avoided though
- IR-UWB resolution of multipath components
  - Resolution of delays on the order of 1ns or less (1 GHz BW → 1 ns resolution)
  - This implies resolution of path differentials to a foot, or few cm (in principle)
  - Potentially reduced multipath fading margins (no destructive interference)
- Diversity
  - Potential frequency diversity, added robustness, lower fading margins (lower power)
- Localization
  - In principle, the accuracy is inversely related to the bandwidth (1/GHz → few cm)
  - Potential implementation dependent advantages (e.g. IR-UWB)
- Penetration of materials
  - Low signal power is sensitve to attenuation and absorption
  - Highest bandwidth, lowest frequency, offers potential advantages (e.g. GPR)

UWB EMMISSION FIELD STRENGTH AND COEXISTENCE CONSIDERATIONS

- The actual FCC limts are defined in terms of the electric field strength of the radiator (E_0) in microvolts per meter (μV/m) [FCC, Scholtz, Foerster].

- The emmitted power from a radiator is given by

$$P = \frac{E_0^2 4\pi R^2}{\eta}$$

η = the intrinsic impedance of free space = 377 ohms
R = the radius of the sphere in which the field strength is measured

- Example: E_0 = 500 μV/m at 3 m (FCC Part 15.109 of section 47 for undesireable emmissions at f > 960 MHz). PSD = –41.3 dBm/MHz.

Source: FCC, Intel, IEEE P802.15-02/279r0-SG3a

GPS INTERFERENCE EXAMPLE CASE

- From [Homier, Scholtz], the degradation in C/N_0 of the GPS receiver may be estimated from

$$[C/N_0]_{Degradation} \cong -10\log\left[1+\frac{P_T G_T G_R \lambda^2}{2BN_0(4\pi L)^2}\right]$$

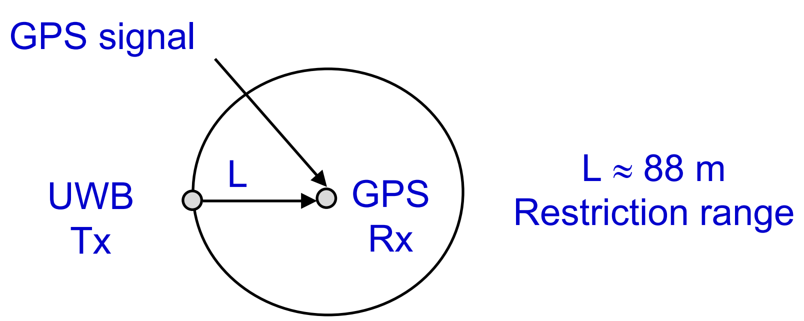
P_T = the transmit UWB power (i.e., in the GPS receive band)
G_T = the transmit antenna gain (UWB)
G_R = the receive antenna gain (GPS)
B = GPS receiver bandwidth (1.023 MHz for the C/A code)
N_0 = the noise power density (300 °K for a GPS receiver)
L = the distance between the UWB transmitter and the GPS receiver

- This is only an estimate, based on white noise equivalent UWB interference power, but it serves as an intuitive point of reference

RESTRICTION RANGE?

- As a UWB transmitter becomes close to a GPS receiver, it may interfere with reception leading to performance degradation and, ultimately, loss of lock.
- Relative to a given threshold, the minimum tolerable distance between a UWB transmitter and a GPS receiver is referred to as the restriction range.
- Consider the example below, with a nominal degradation threshold of 1 dB in terms of C/N_0, a restriction range of about 88 meters between the UWB transmitter and the GPS receiver is estimated! Although this is subject to interpretation, it is consistent with calculations in the literature [NTIA, Enge].

P_T = 75 nW
G_T = 0 dBi
G_R = 0 dBi
B = 1.023 MHz (C/A code)
N_0 = kT (T = 300 °K)



An important reason why UWB operation was shifted to 3.1 – 10.6 GHz!

RF EMMITTERS AND POTENTIAL UWB INTERFERERS

Emmiter category		Emmitter type
Licensed		Radars Broadcasting Microwave Land mobile Cellular/PCS
Unlicensed	Intentional	Garage openers Wireless alarms Cordless phones
	Unintentional	Computers Digital services Radio TV receivers
	Incidental	Electrical devices
ISM		Microwave ovens

- Millions of RF emmitters
- Some relatively high power
- Various frequency bands
- Interference to UWB systems
- Mitigation is possible
- May complicate UWB design

Source: Hurt

j1

IEEE802.15.4 INTERFERENCE SUSCEPTIBILITY

	Microwave Oven	Bluetooth & IEEE 802.15.1 Interferer	IEEE 802.11b & IEEE 802.15.3 Interferer	IEEE 802.11a Interferer	IEEE 802.15.4 Interferer (2.45 GHz)
Max. tolerable interferer power at the encoder	-82.3 dBm	-82.3 dBm	-82.3 dBm	-82.3 dBm	-82.3 dBm
Processing gain[1] (coding rate of 11/32)	4.6 dB	4.6 dB	4.6 dB	4.6 dB	4.6 dB
Minimum base-band filter attenuation	35.4 dB	36.9 dB	36.9 dB	30.7 dB	35.6 dB
Front-end pre-select filter attenuation	35 dB	35 dB	35 dB	30 dB	35 dB
Max. tolerable interferer power at the antenna	-7.3 dB	-5.8 dB	-5.8 dB	-17 dB	-7.1 dB
Interferer power at 1m separation	-23.2 dBm	-40 dBm	-20 dBm	-31.9 dBm	-40.2 dBm
Minimum margin	15.9 dB	34.2 dB	14.2 dB	14.1 dB	33.1 dB
Tolerable separation	≅ 0.16 m	≅ 0.02 m	≅ 0.2 m	≅ 0.2 m	≅ 0.02 m

1. This is a pessimistic analysis performed for the sub-band closest to the interferer and does not include the processing gain of 10log10(3) dB that arises from the use of Time-Frequency Codes across the 3 bands

Source: IEEE802.15.4

Slide 44

j1 jrf; 14.07.2004

UWB ANTENNAS

- UWB antenna issues
  - Antenna size and complexity
    - Small, electrically efficient, wideband antennas (e.g. for mobile users)
  - Pulse distortion
    - In IR-UWB, the antenna, as well as the channel, can distort the pulses

- UWB antenna options
  - Many options are possible, but designs must be tailored to the application
  - IR-UWB examples:
    - Linear phaseTEM or TEM-like horns
    - Spiral antennas with both wideband amplitude and phase
    - Wideband tapered slot antennas designed to operate in large arrays have been suggested, but size may be an issue for mobile applications [Carlberg]
    - The use of sparse arrays have been proposed to reduce complexity and cost

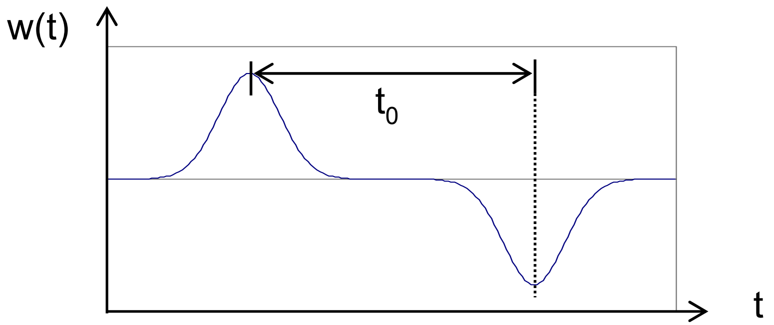
GAUSSIAN DOUBLET PULSES

- An impulse sequence can be generated by stepping the current up or down through the transmit antenna [Aetherwire]

- Generation of impulses of the same polarity incrementally increases the current, resulting in higher power consumption, regardless of TH code
  - DC current is related to the delta between the no. of +/- pulses

- Doublets are employed to alleviate this problem. A doublet is a pair of positive and negative impulses. It is analogous to a DSSS chip

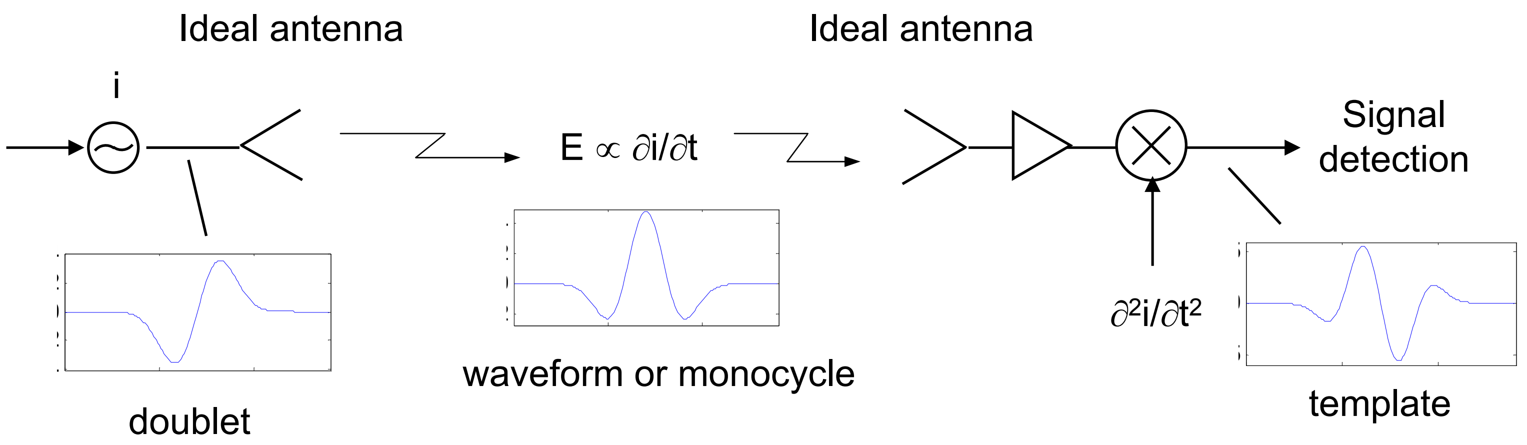
- The separation between pulses can be adjusted to create spectrum nulls (e.g., nulls at $1/t_0$ help avoid interference)



Source: Aetherwire

UWB ANTENNAS AND PULSE DIFFERENTIATION

- In general case, antennas differentiate the signal, which is not usually noticed since wireless communication systems employ sinusoids for which differentiation simply results in a phase shifted signal.
  - However, it can be shown that the electric field strength in UWB systems is proportional to the time derivative of the drive current regardless of the waveform (i.e., assuming ideal antennas).



Source: Carlberg, Chalmers

BROADBAND ANTENNA OPTION: NON-DISPERSIVE ANTENNAS

- Non-dispersive antennas: phase linear
  - TEM or TEM-like horn

    Large bandwidth, directive, large size.

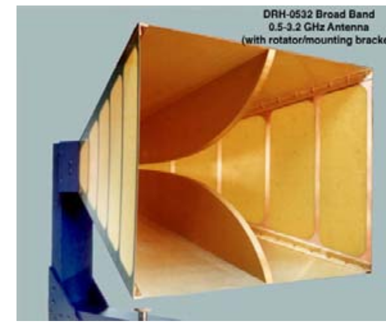
  - Bicone or bowtie antenna

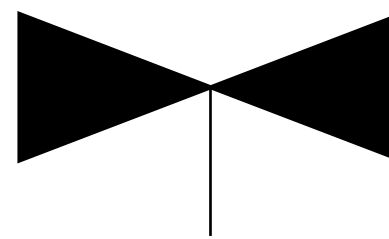
    Relative large bandwidth.

  - Resistive or lumped element loaded antenna

    Resistive loading: small size, large bandwidth, low gain, low radiation efficiency.

    ⇨ Solution: capacitive loading.

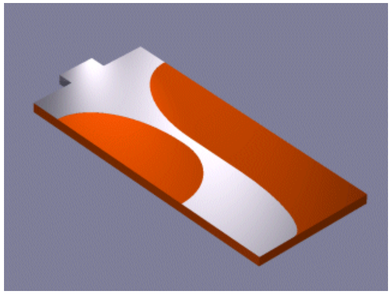




Source: Q. Xu, CSEM

BROADBAND ANTENNA OPTION: DISPERSIVE ANTENNAS

- Dispersive antennas: phase non-linear
  - Exponential spiral, Archimedean spiral.
  - Log-periodic antenna
  - Vivaldi antenna
  - Slot antenna
    - Wideband tapered slot antennas designed to operate in large arrays have been suggested, but size may be an issue for mobile applications [Carlberg].
    - Size is an issue, as well as, complexity. The use of sparse arrays have been proposed to reduce complexity.



Source: Q. Xu, CSEM

ANTENNA SIZE CONSIDERATIONS

- For electrically small antennas, the efficiency can be poor due to the fact that bandwidth, quality factor (Q) and losses are closely related.

- Q is typically 10 to 200 for small antennas. In the absence of other filters, the UWB antenna may be a filter. In either case, the bandwidth is also roughly proportional to the inverse of Q.

- An antenna may be defined as electrically small if it is constrained in size to the volume of a sphere that is significantly smaller than $r = \lambda/2\pi = 1/k$.
  - $k = 2\pi/\lambda$ = the wave number
  - r = antenna radius (e.g., circular aperture)
  - η = radiating efficiency
  - BW = maximum fractional bandwidth

$$BW = \frac{2(kr)^3}{\eta}$$

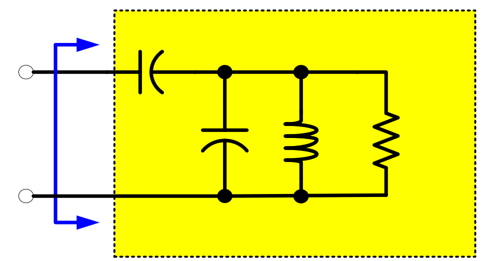
Example: f_c = 5 GHz, BW = 1.25 GHz, r = 1cm → η = 0.0022 or –26.4 dBi

Source: Siwiak

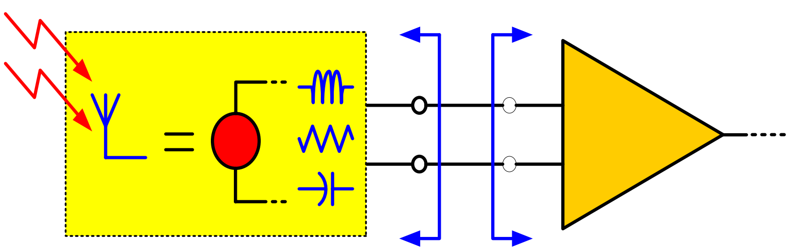
UWB ANTENNA EQUIVALENT CIRCUITS AND CO-DESIGN

- We may consider the antenna as a filter then co-design the antenna and circuits
- The antenna may be modelled using equivalent circuits
  - Resitance, capacitance, inductance
- Transmit
  - Voltage-drive antennas→ capacitor-dominant
  - Current-drive antennas → inductor-dominant
- Receive
  - Optimize by antenna/LNA co-design
  - The impedance seen by the LNA (Z_{LNA}) = Zant
  - v-driven antennas ~ prefer large Z_{LNA}
  - i-driven antennas ~ prefer small Z_{LNA}

Simple dipole antenna model



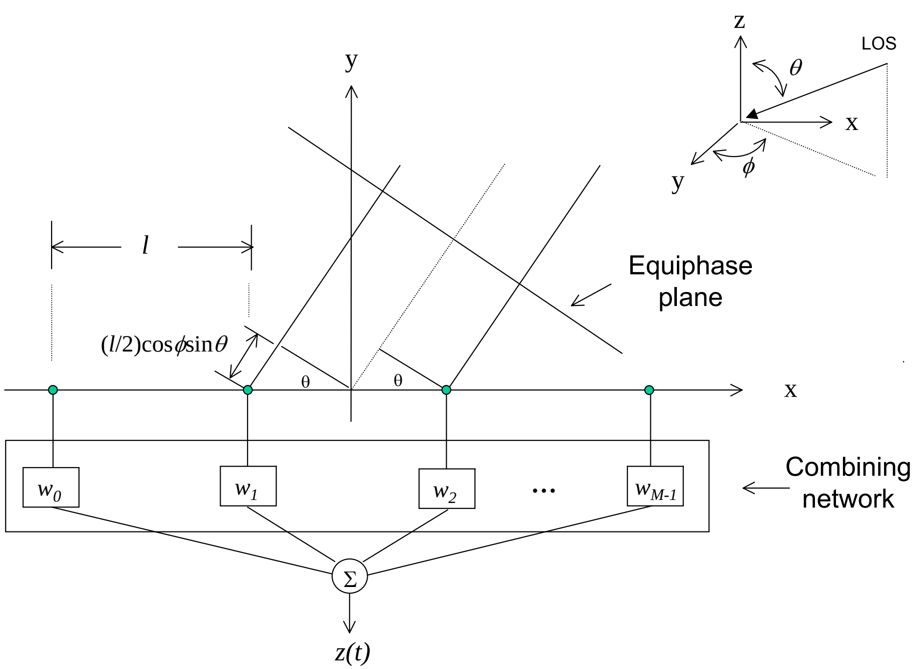
Antenna/LNA co-design



Source: B. Broderson, U. Cal. Berkeley

SPARSE UWB LINEAR ANTENNA ARRAY

$l > T_p$ → ultrasparse



Non interfereing UWB time pulses lead to reduced build-up of sidelobe energy and lower side radiation levels [Baum] (e.g., $1/N^2$ vs. $1/N$)

- UWB affords improved time resolution relative to narrow band.
- Time is essentially an added dimension → very thin or sparse antenna arrays are possible.
- The number of elements N may be reduced, relative to a conventional array with $l = \lambda/2$ element spacing
  - lower complexity and cost
  - larger aperture for the same N
  - improved resolving power
  - lower absolute gain
  - higher sidelobe radiation
- Reduction of approx. $\sqrt{N}$, where N = no. elements in conventional array.

Source: Baum

OUTLINE

- Introduction to UWB
- The UWB channel, propagation and antennas
- Frequency domain solutions, advantages and limitations (50 min)
  - Motivation for frequency domain UWB approaches
  - How to optimally use the spectral mask
  - The HDR challenge
  - The MBOFDM approach
  - The LDR UWBFM approach and localization
- Time Domain solutions, advantages and limitations
- Summary and concluding remarks

MOTIVATION FOR FREQUENCY-DOMAIN (= NON TIME-DOMAIN) APPROACHES

Pulses that have been optimized for radar-like applications have not necessarily the best characteristics for a communiciations system.

Realization of low power and fully integrated pulse generation circuits is not trivial.

Since the definition of a UWB signal does not specify a particular air interface or modulation scheme, many different techniques may be applicable to a UWB signal.

More conventional modulation schemes may/should be used to generate a UWB signal.

ADDITIONAL MOTIVATION FOR LDR FREQUENCY-DOMAIN APPROACH

Find an alternative UWB radio architecture without

pulse generation

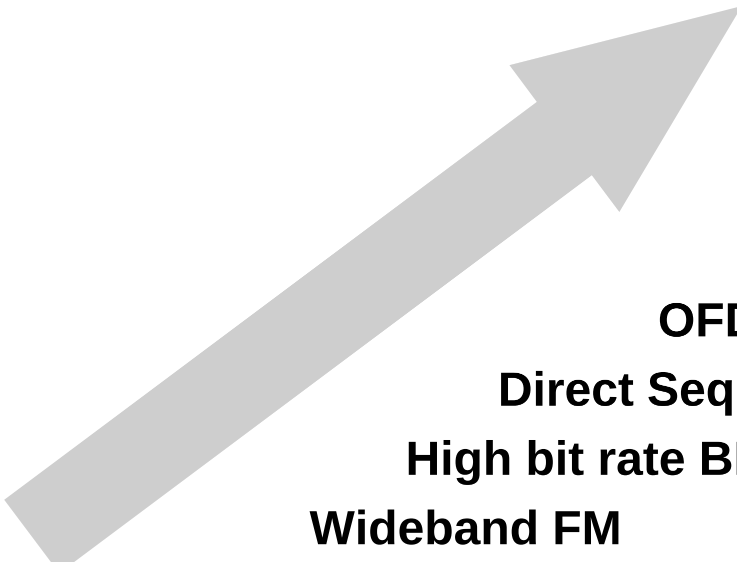
low duty cycle

pulse synchronization

slow spectral roll-off

A straightforward-to-implement low-power LDR scalable, communication system.

ALTERNATIVE UWB APPROACHES



Increasing complexity

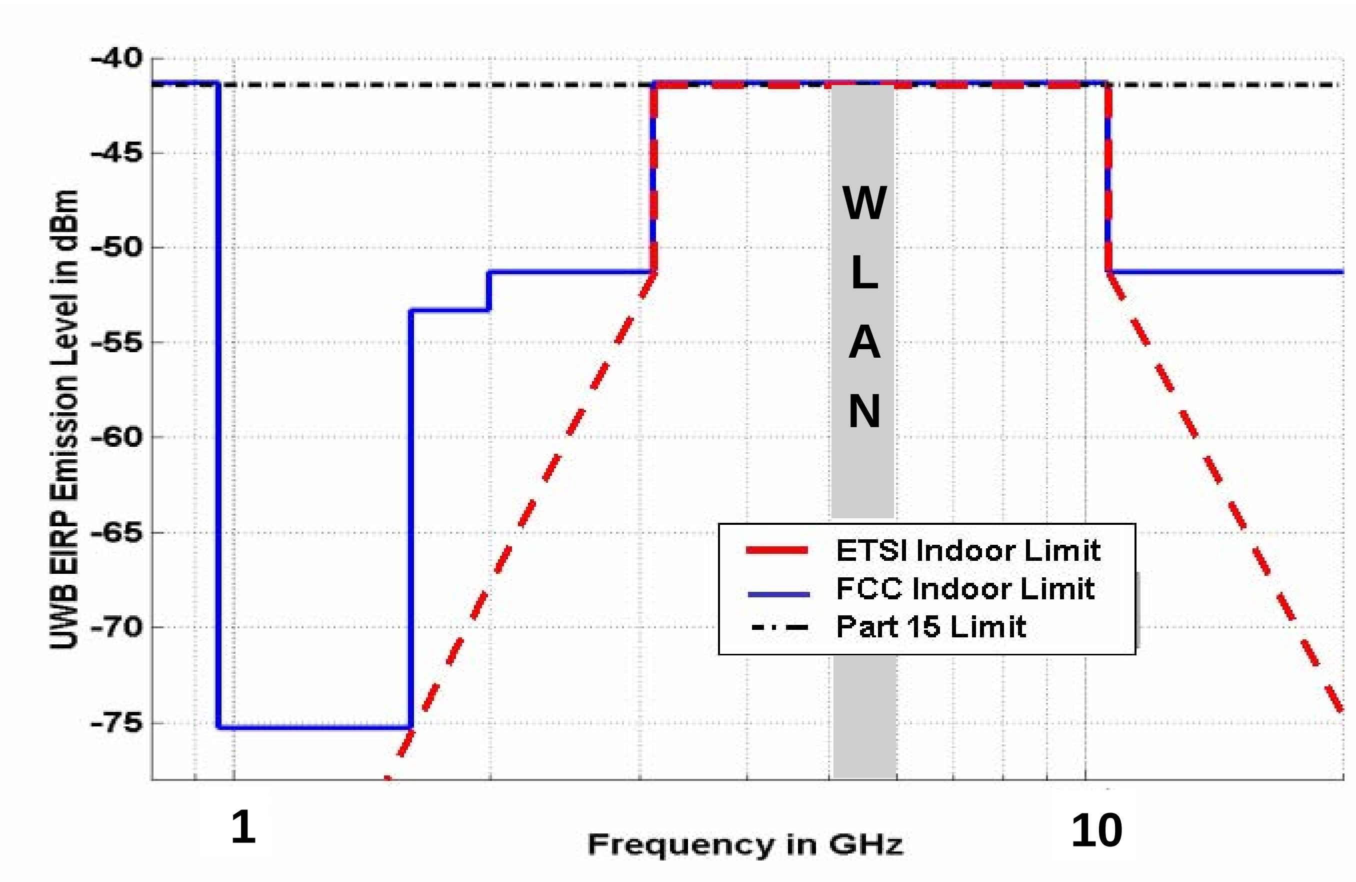
OFDM

Direct Sequence Spread Spectrum

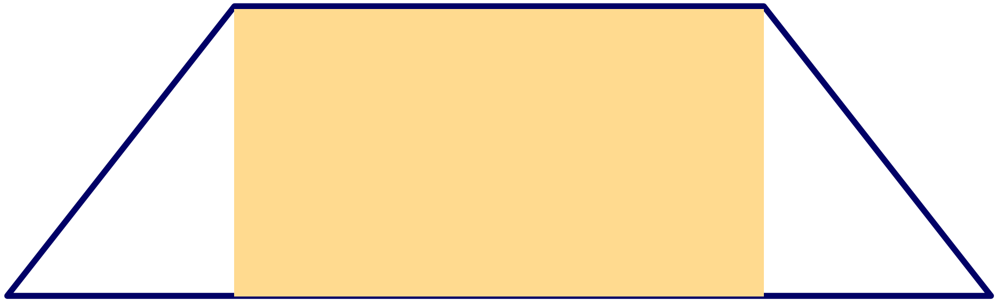
High bit rate BPSK, QPSK

Wideband FM

HOW TO OPTIMALLY USE THE UWB SPECTRAL MASK



THE JIGSAW PUZZLE PROBLEM



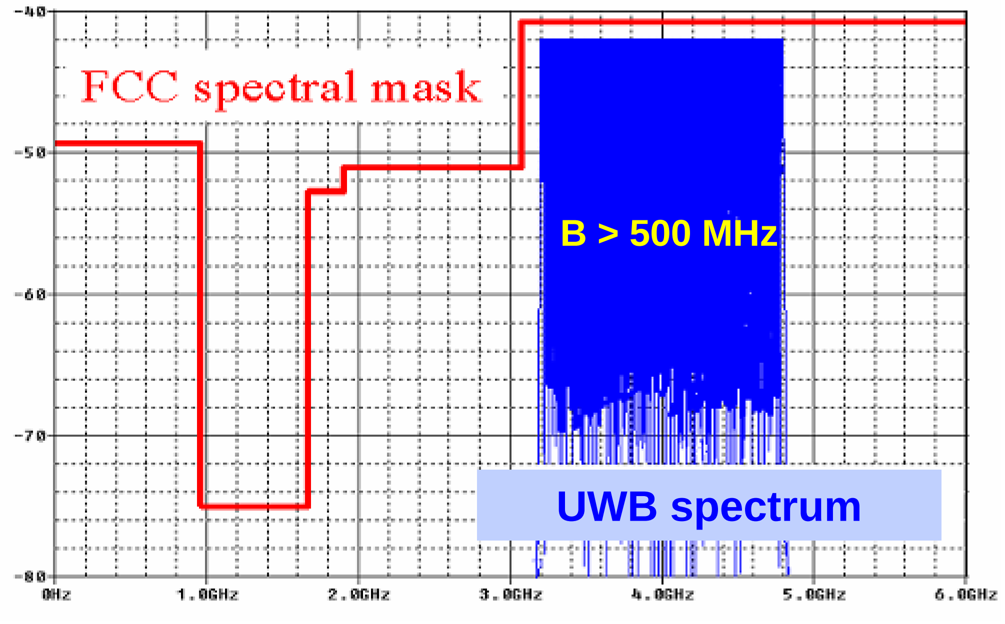
<u>Ideal filling of the 3 – 10 GHz range</u>:

Brick wall constant power spectral density with steep roll-off on both sides resulting in maximum power -41 dBm/MHz + 10log10(7000) = - 2.5 dBm

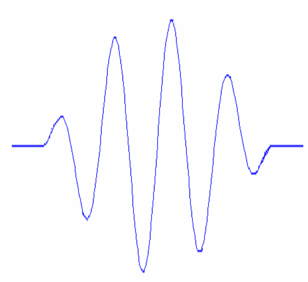
In reality what kind of Jigsaw pieces are available?

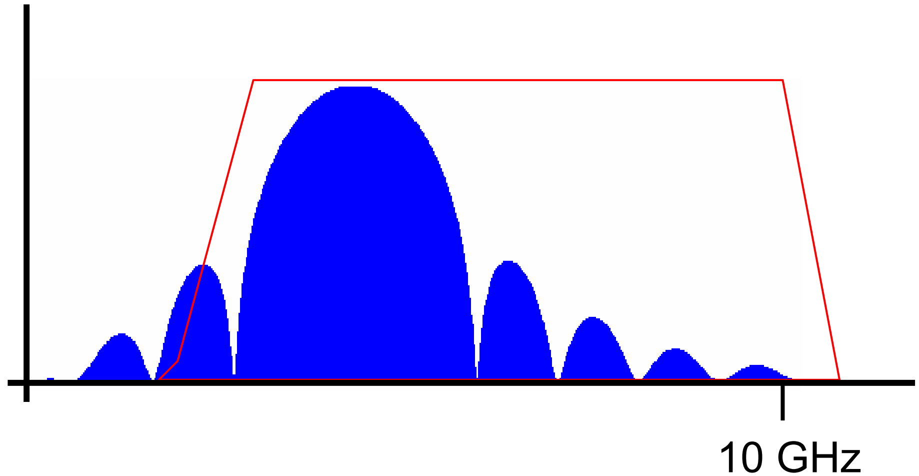
THE IDEAL CASE

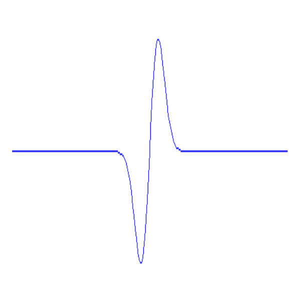
A signal of the appropriate bandwidth with brick-wall roll-off in the frequency domain.

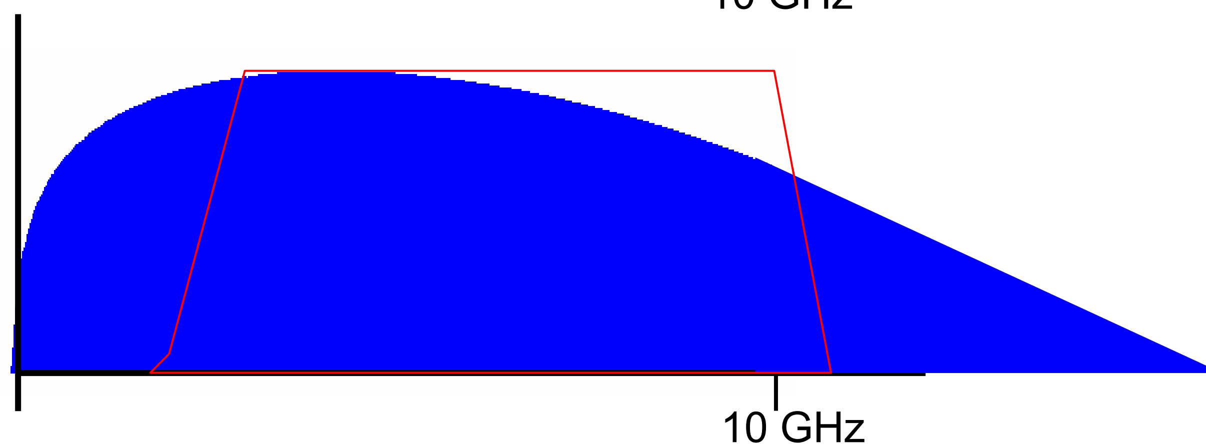


EXAMPLES FOR IMPULSE RADIO





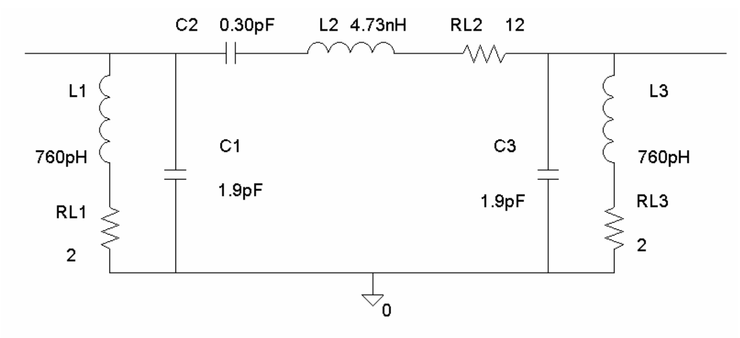


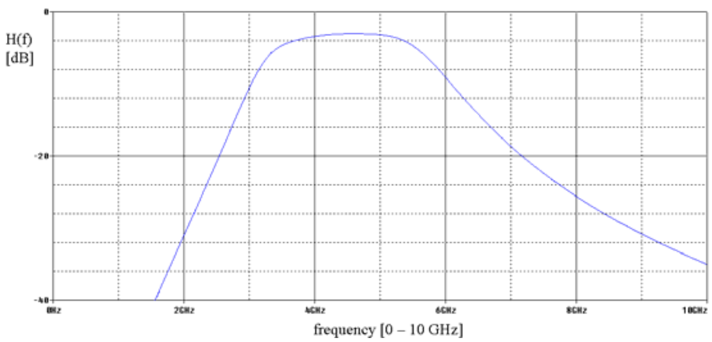


ADDITIONAL FILTERING IS REQUIRED TO COMPLY WITH THE SPECTRAL MASK

In order to comply with the spectral mask, additional bandpass filtering is usually required. Part of the filtering can be implemented by the antenna.

However, there is no free lunch: filtering of pulses also alters their shape and creates pulse distortion.





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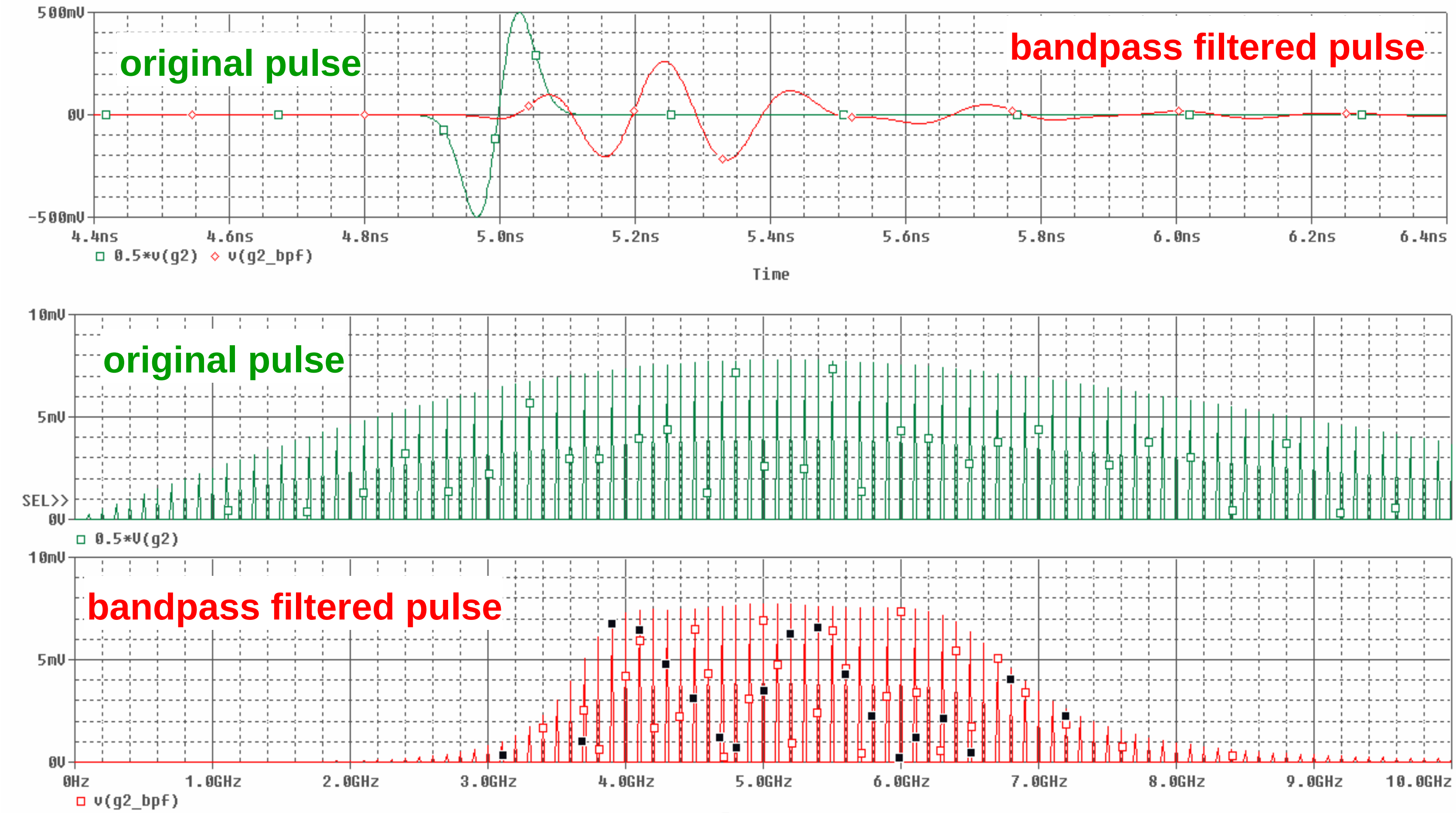
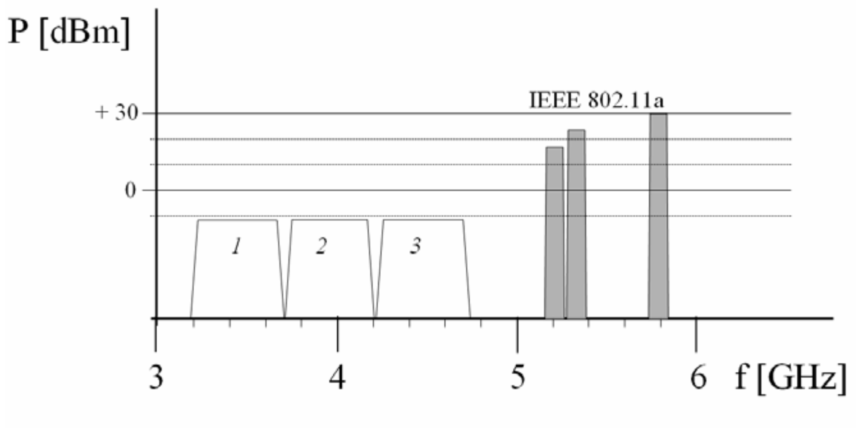
ADDITIONAL FILTERING YIELDS PULSE DISTORTION



ANOTHER CHALLENGE: INTERFRENCE

It is not wise to use the complete band from 3 to 10 GHz, since strong interfering signals are present between 5 and 6 GHz. These originate from IEEE802.11a systems with power levels that can be 30 dB higher than the UWB signal. A UWB system should avoid the 5 – 6 GHz part of the spectrum!



Solution: use several smaller Jigsaw pieces: multi-band approach

POTENTIAL SOLUTIONS TO COMPLY WITH THE SPECTRAL MASK

HDR OFDM

Fill up the available space using a multi-carrier approach

MDR UWBIR

Use properly designed pulses and filter the output signal with analog filters.

LDR UWBFM

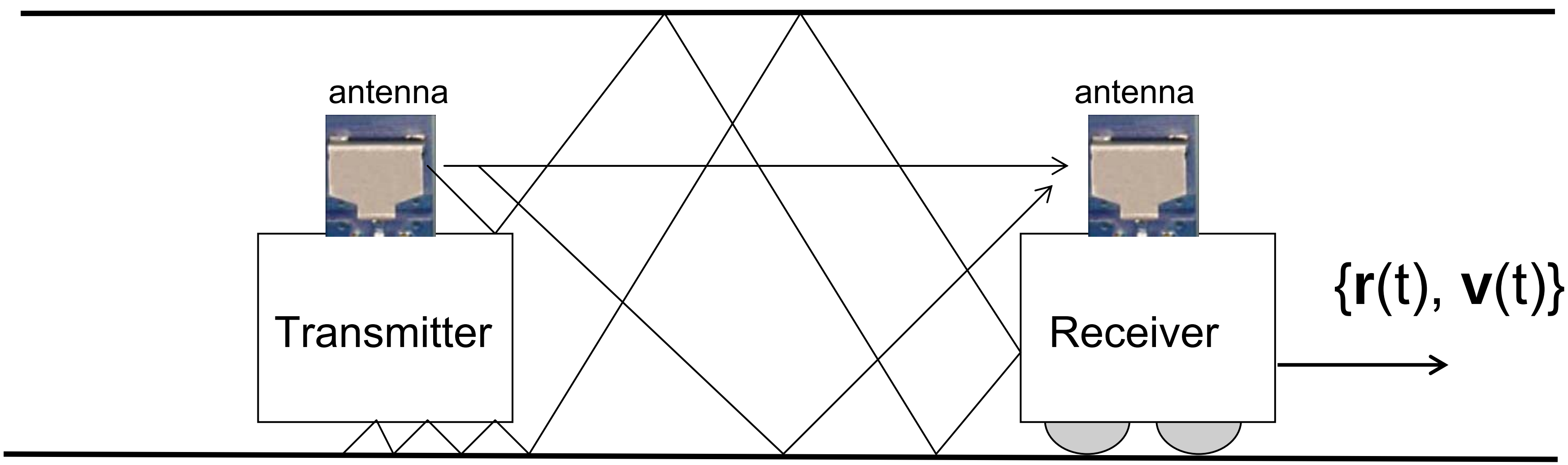
Generate a wideband FM signal with steep roll-off that fits inside the bandwidth.

We will now illustrate the OFDM and UWBFM approach in more detail.

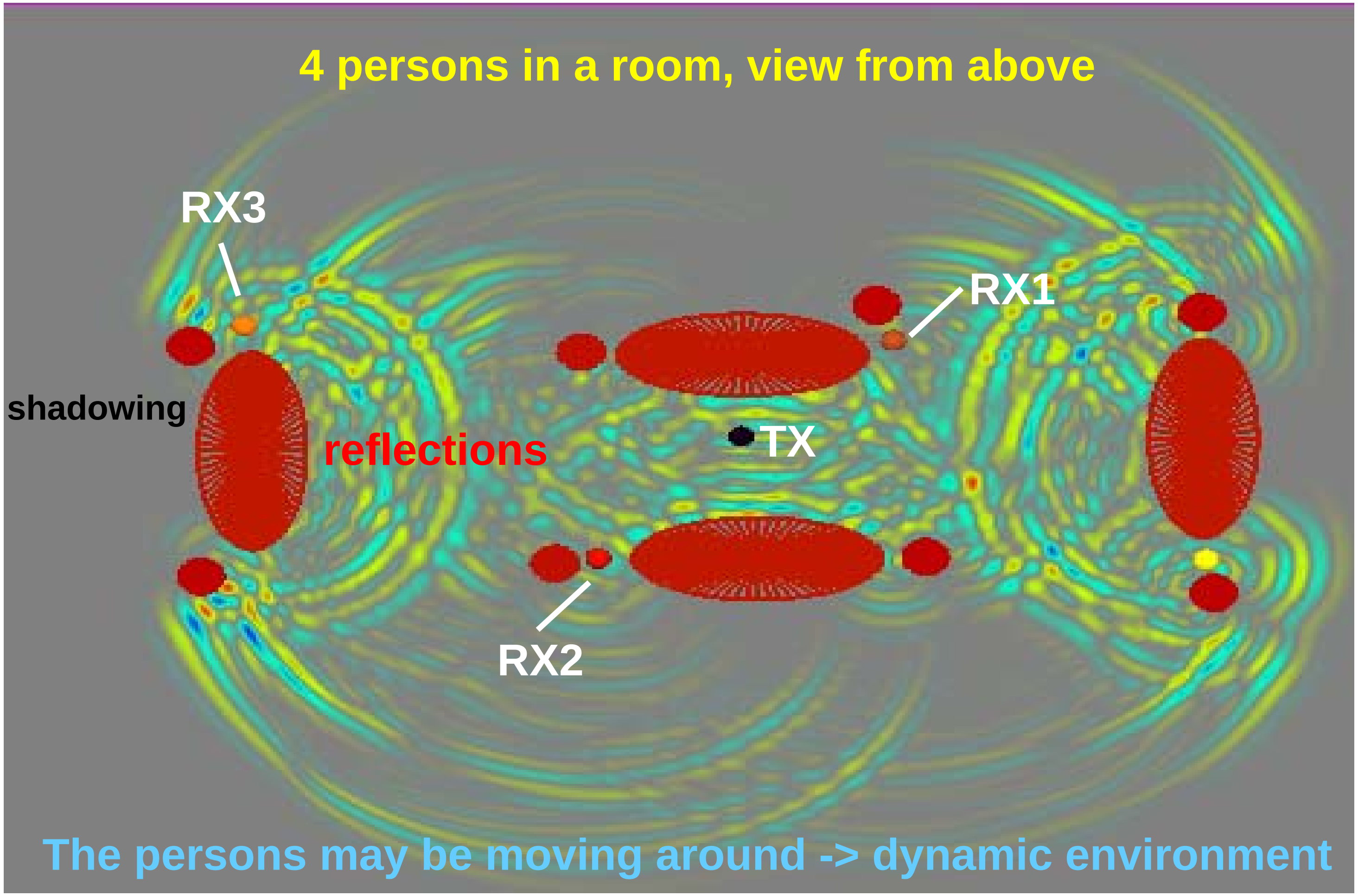
THE HDR CHALLENGE

What changes in a wireless communications system when the data rate increases?
Why can't we easily implement a 100 Mbit/s BPSK or GFSK system?

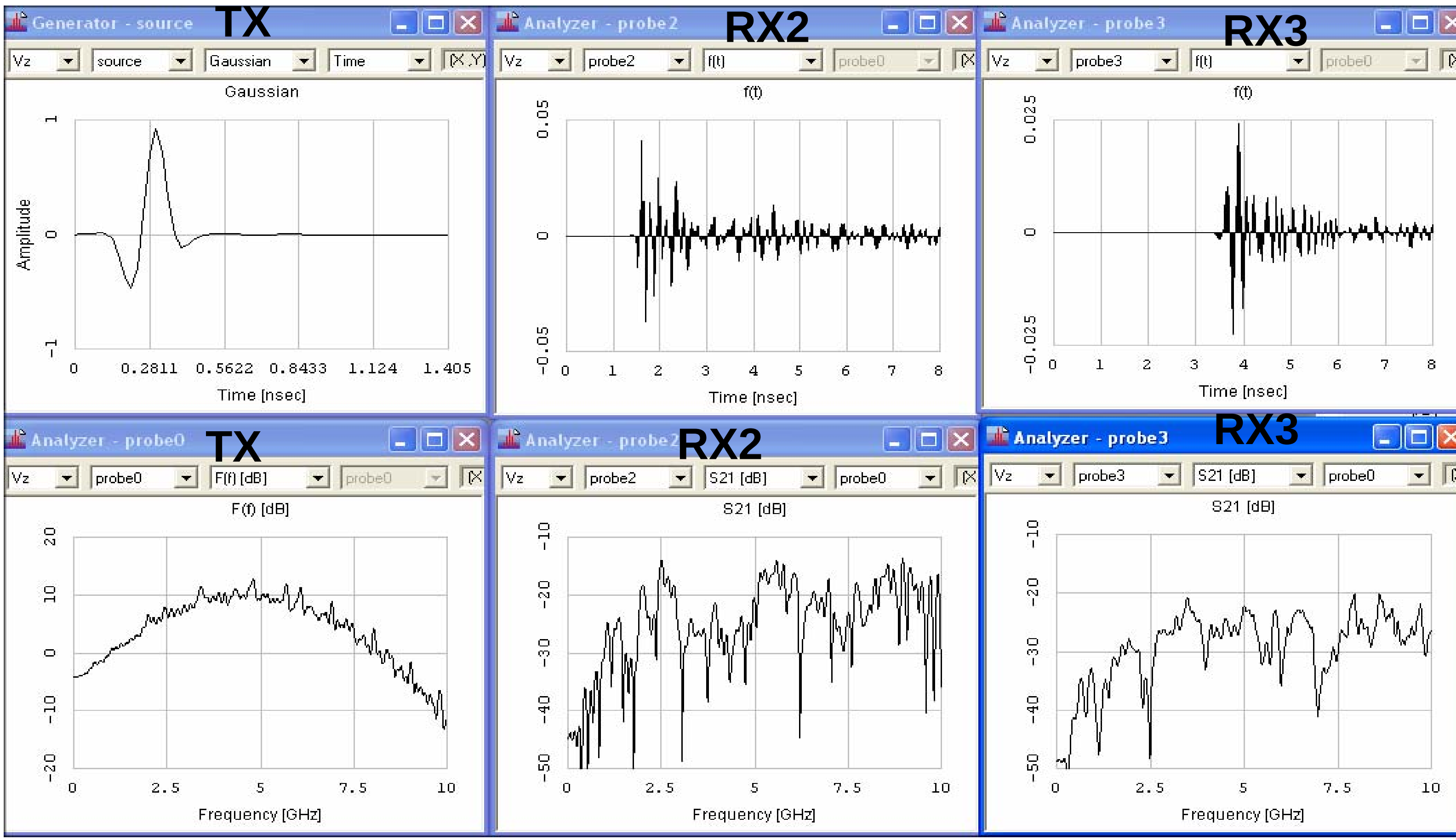
The big difference w.r.t. to a wired connection is the channel:
strong multipath and shadowing, and depending on the speed, Doppler shift.



THE WPAN ENVIRONMENT



TIME AND FREQUENC-DOMAIN RESULTS



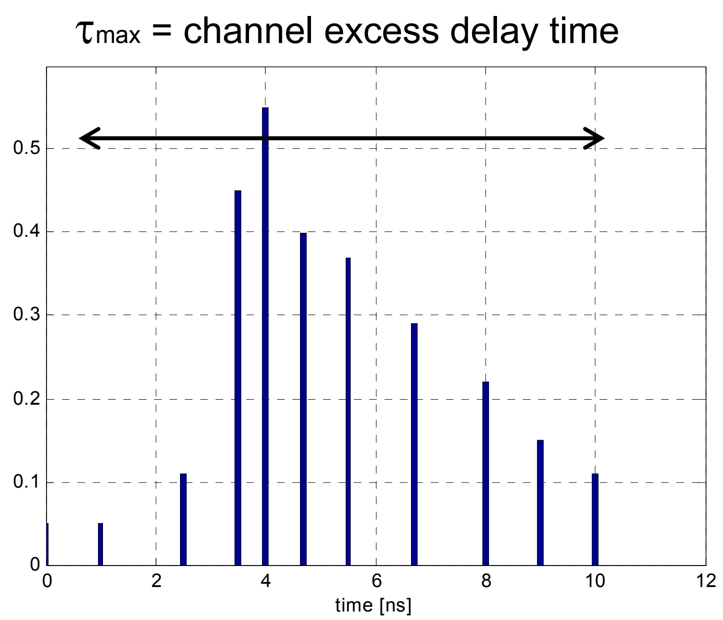
MEFiSTo-3D Pro TLM simulation results

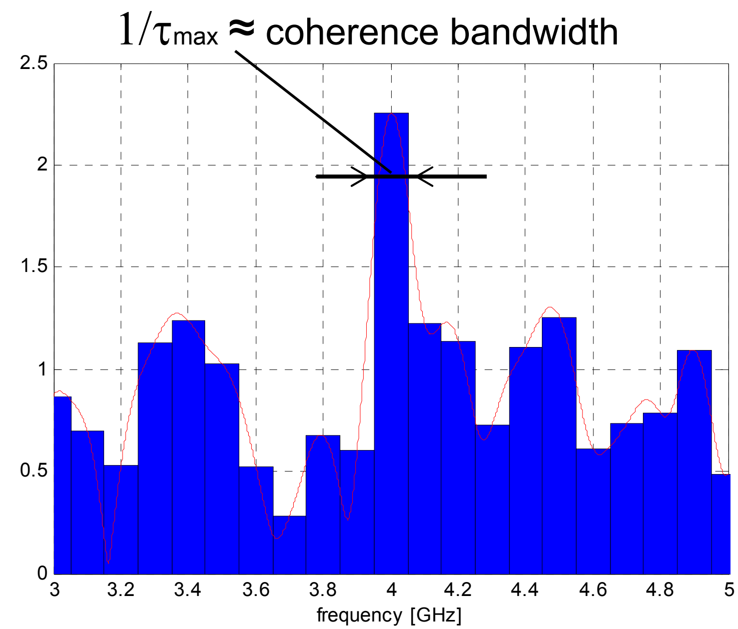
THE CHANNEL TRANSFER FUNCTION

Due to the multipath the impulse response contains many components.

As a result, the frequency transfer H(f) is not flat.

A simplilfied case simulated in MATLAB:

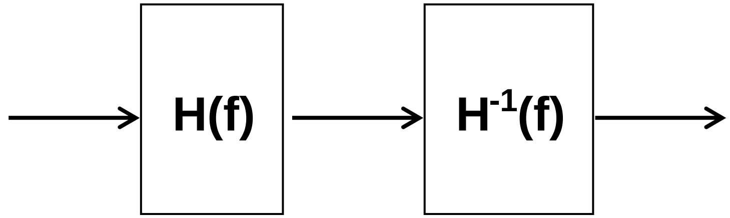




INTER-SYMBOL INTERFERENCE (ISI)

When the excess delay time gets as large as the symbol duration, inter symbol interference will occur, resulting in detection errors.

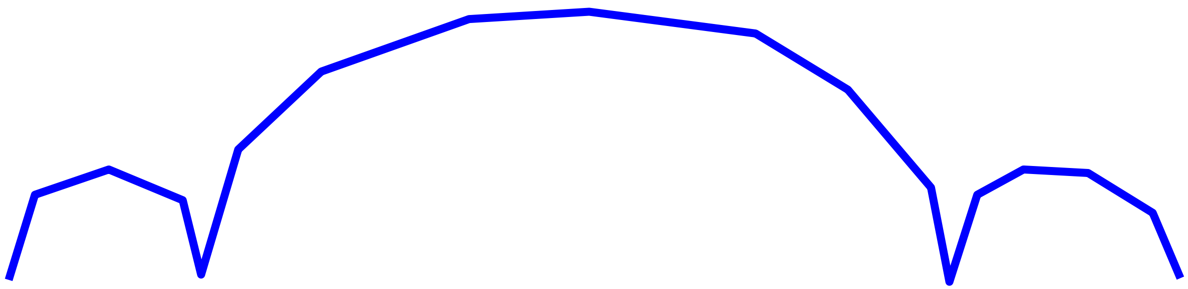
***Solution 1*: *channel equalization* undoing the channel transfer function H.**
This can only be done to a certain extent (zeros can't be undone).



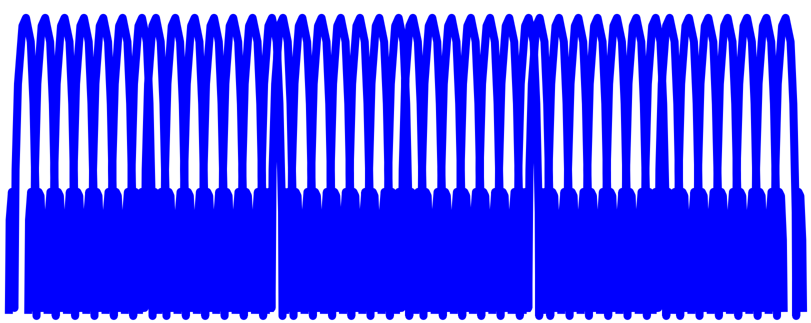
Equalizer complexity rapidly increases when $\tau_{max} > T_{symbol}$.

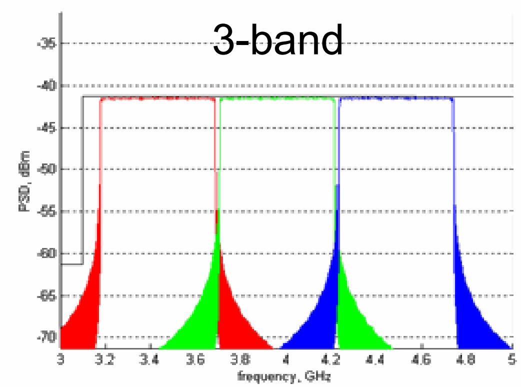
***Solution 2*: use a *multi-carrier* approach to increase the symbol time.**

THE HDR OFDM APPROACH



Instead of a single modulated carrier at data rate R with slow roll-off, use N carriers at reduced data rate R/N. This yields fast roll-off and also resistance to narrowband jamming and multipath.



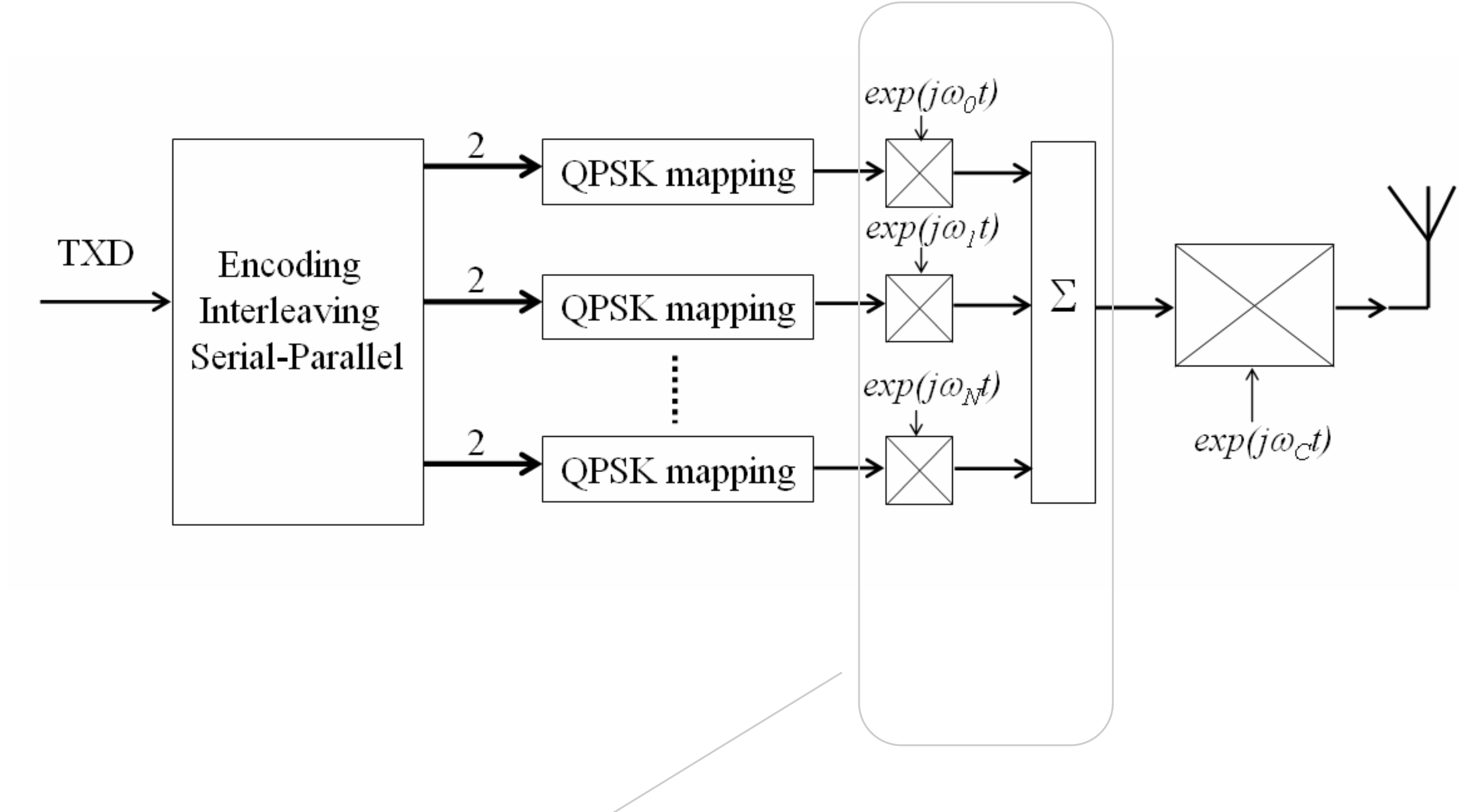


OFDM PRINCIPLES

Multi-carrier approach where the input data is split into multiple (e.g., 100) lower rate data signals that are modulated on individual carriers that each experience a flat channel without need for equalization. The realization uses digital IDFT techniques to simplify the hardware realization.

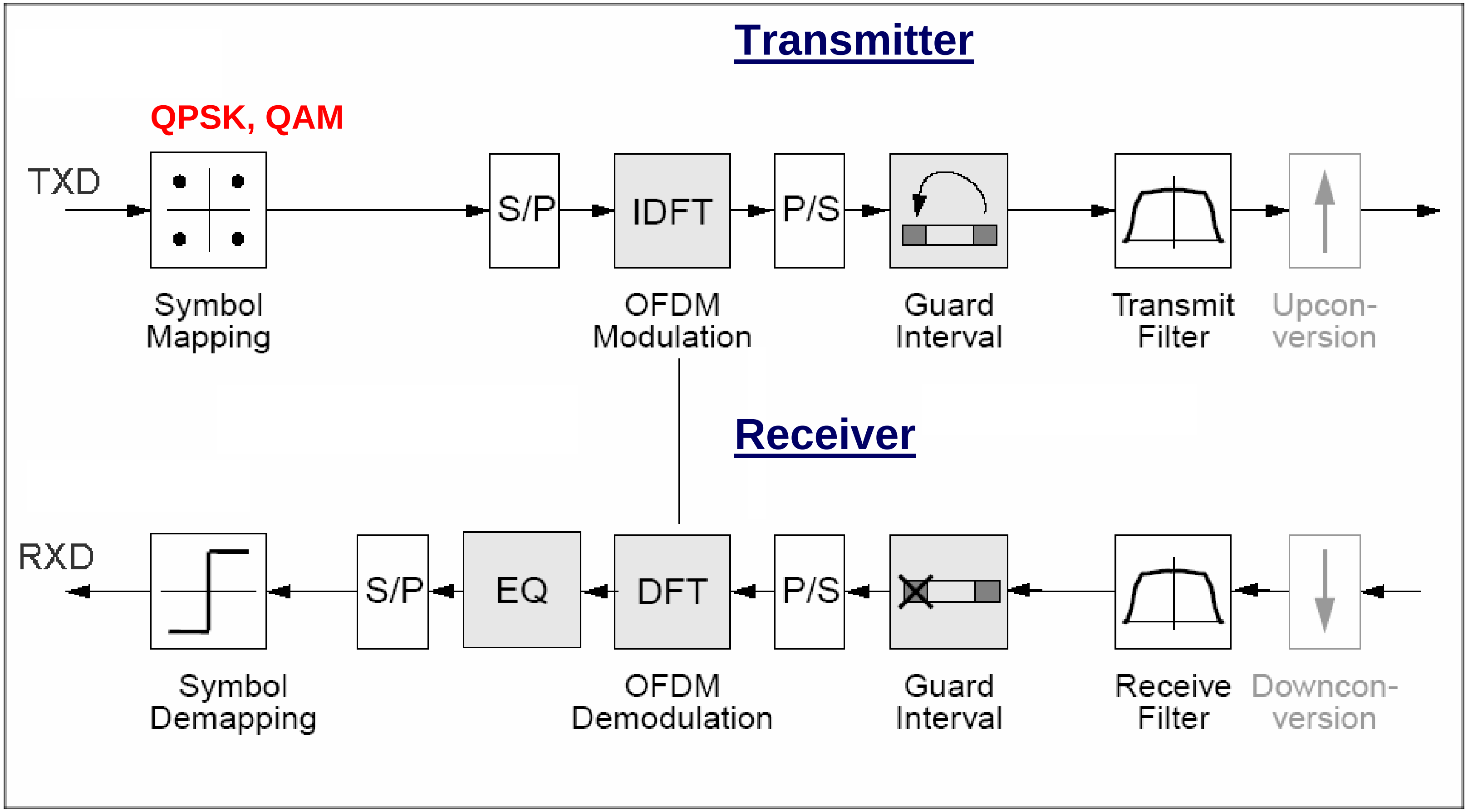
Channel coding is required to compensate for the carriers that have a too low SNR (due to multipath or narrowband interference).

MULTI-CARRIER APPROACH



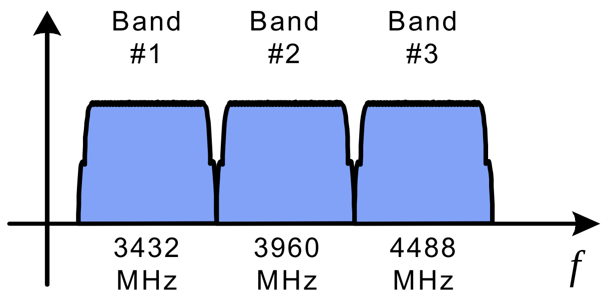
How can we realize this part in an efficient way?

IMPLEMENTATION OF OFDM

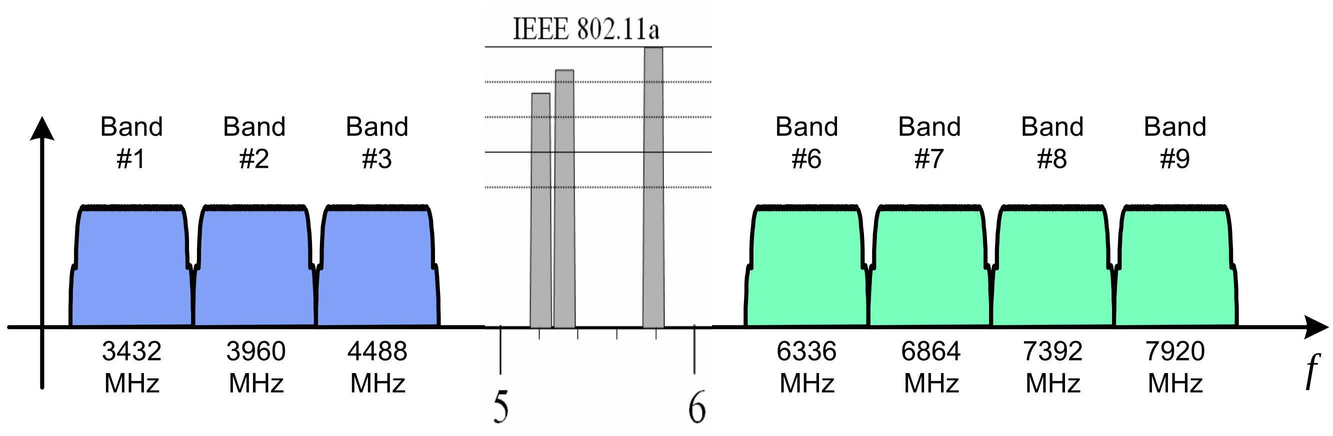


MULTI-BAND OFDM APPROACH: 528 MHz SUB-BANDS

Mode 1 device operating in 3 bands



Mode 2 device operating in 7 bands



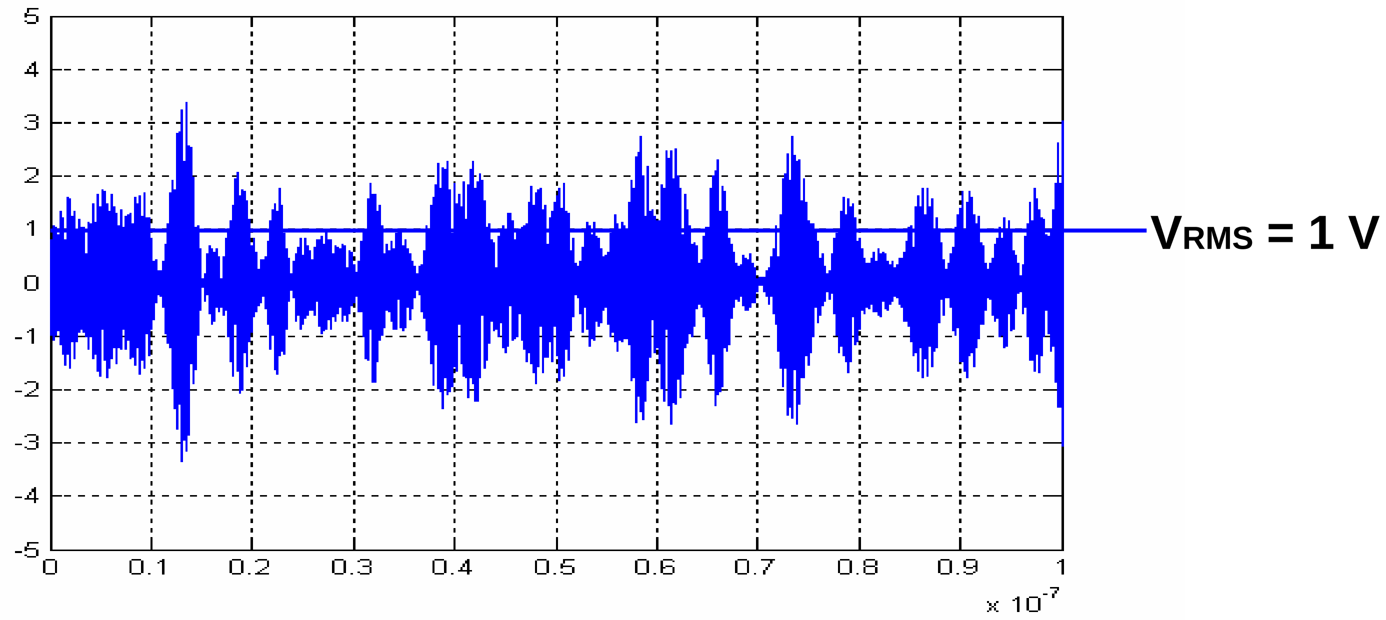
PERFORMANCE OF MB-OFDM MODE 1

Parameter	Value	Value	Value
Information Data Rate	110 Mb/s	200 Mb/s	480 Mb/s
Average TX Power	-10.3 dBm	-10.3 dBm	-10.3 dBm
Total Path Loss	64.2 dB (@ 10 meters)	56.2 dB (@ 4 meters)	50.2 dB (@ 2 meters)
Average RX Power	-74.5 dBm	-66.5 dBm	-60.5 dBm
Noise Power Per Bit	-93.6 dBm	-91.0 dBm	-87.2 dBm
CMOS RX Noise Figure	6.6 dB	6.6 dB	6.6 dB
Total Noise Power	-87.0 dBm	-84.4 dBm	-80.6 dBm
Required Eb/N0	4.0 dB	4.7 dB	4.9 dB
Implementation Loss	2.5 dB	2.5 dB	3.0 dB
Link Margin	6.0 dB	10.7 dB	12.2 dB
RX Sensitivity Level	-80.5 dBm	-77.2 dBm	-72.7 dB

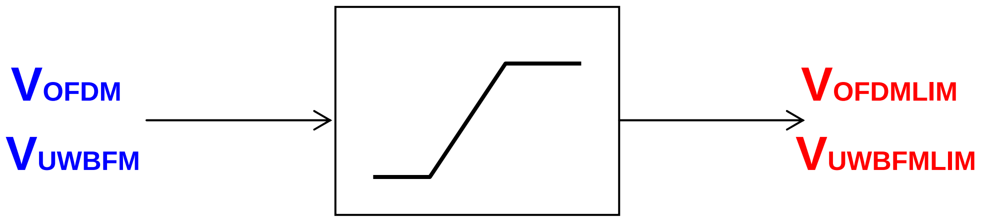
ENVELOPE VARIATIONS OF OFDM SIGNALS

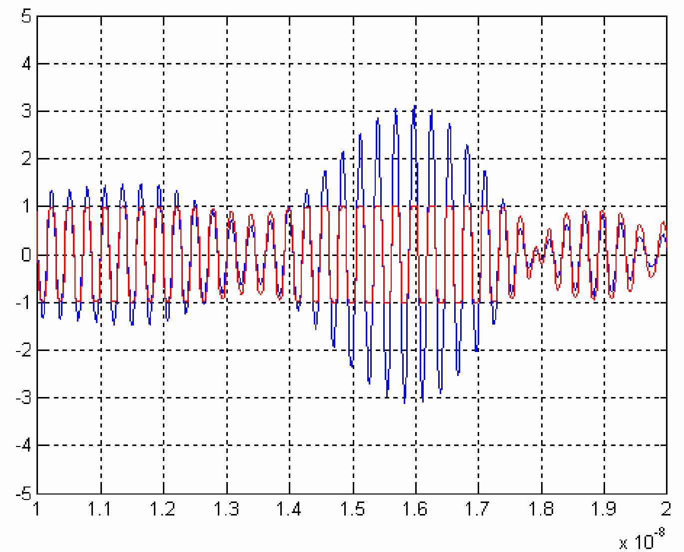
OFDM signals have a strongly varying envelope.

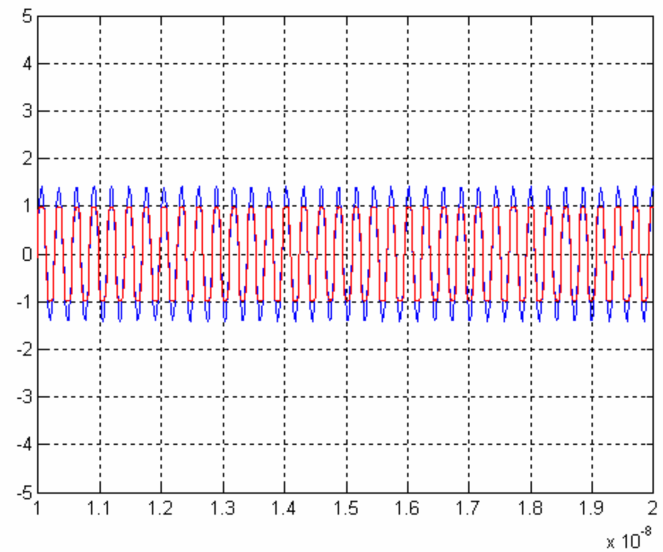
This puts constraints on the linearity of upconversion and RF amplification and may cause harmful interference to other UWB systems.



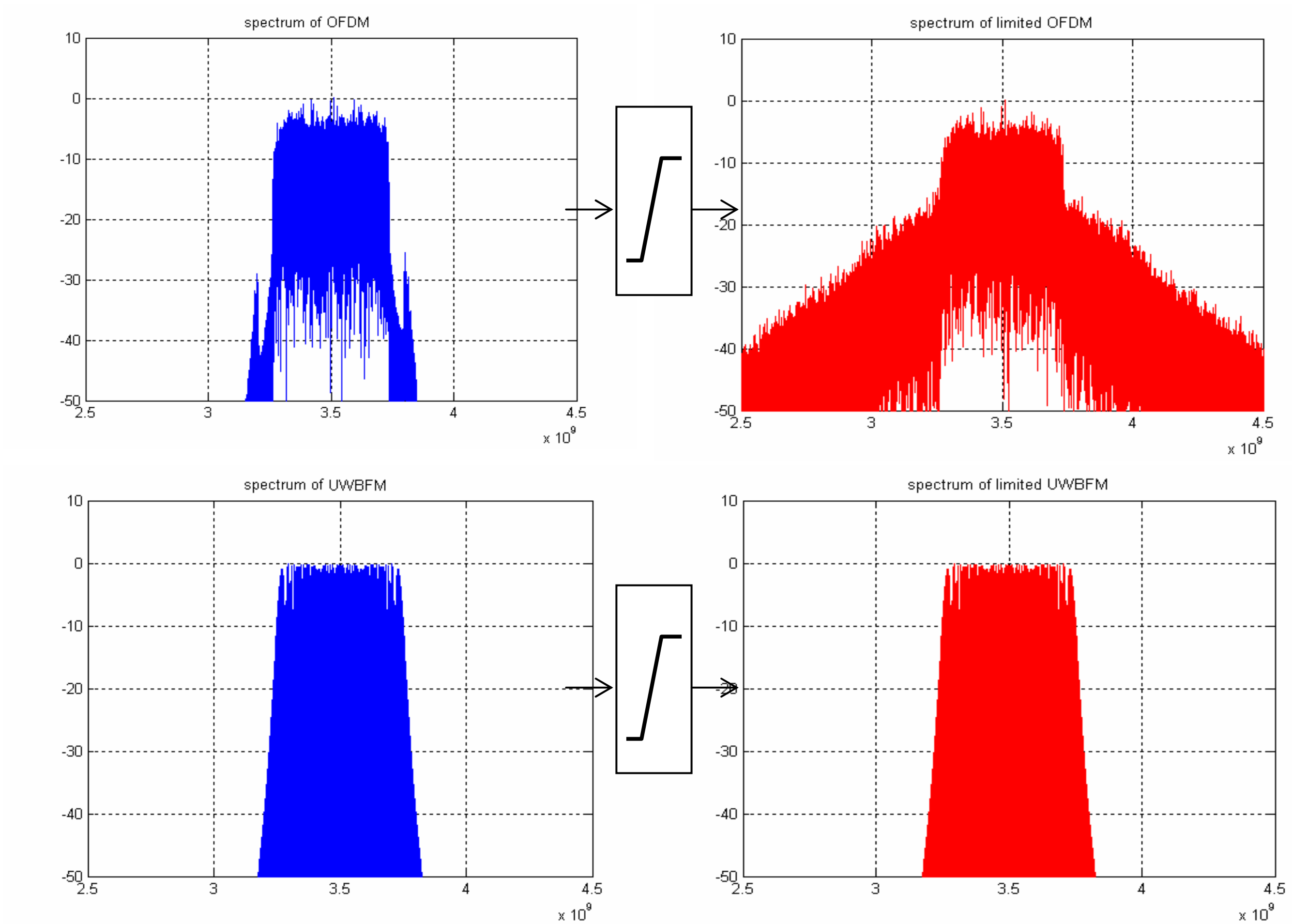
EFFECT OF NON-LINEARITIES







RESULTS IN THE FREQUENCY-DOMAIN



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HARDWARE CHALLENGES FOR OFDM

- Time and frequency synchronization
- Amplifier linearity (peak-to-average ratio)
- Oscillator phase noise

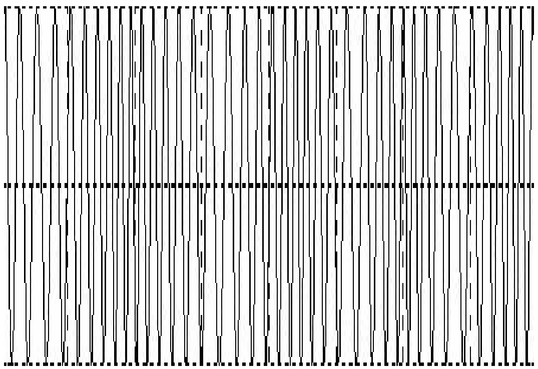
↓

The price to be paid for the HDR performance is hardware complexity and power consumption.

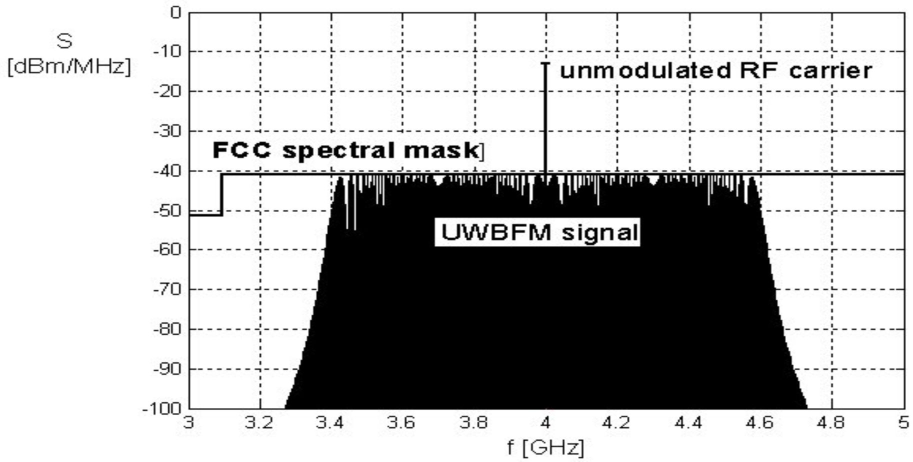
THE LDR ULTRA WIDE BAND FM APPROACH

An analog FM signal can have any bandwidth (as long as you can design the VCO) independent of modulation frequency and has a very steep roll-off. Moreover, it has a constant envelope relaxing the constraints on the hardware.

$$B_{RF} = 2(\beta + 1) f_m = 2(\Delta f + f_m)$$

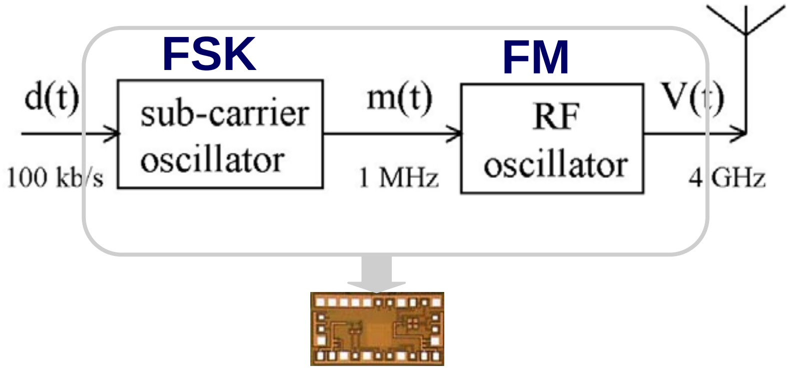


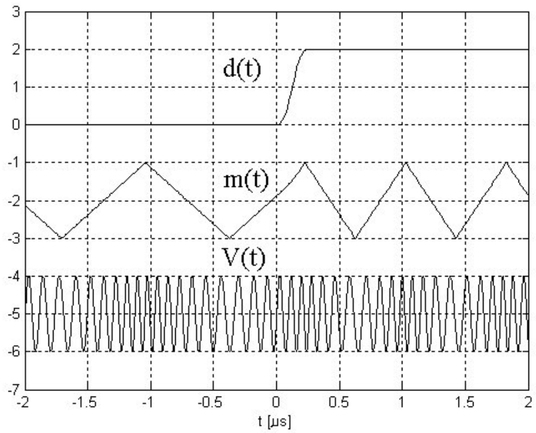
time domain

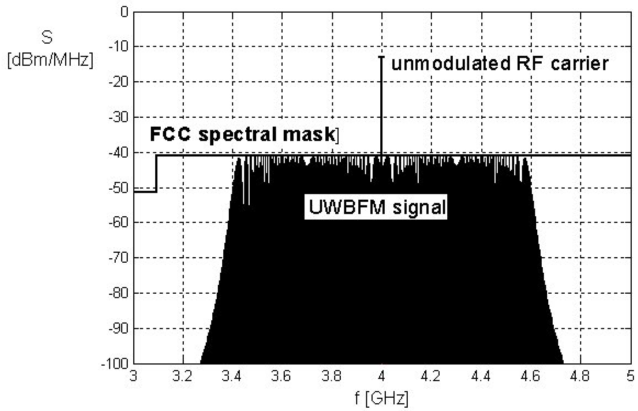


frequency domain

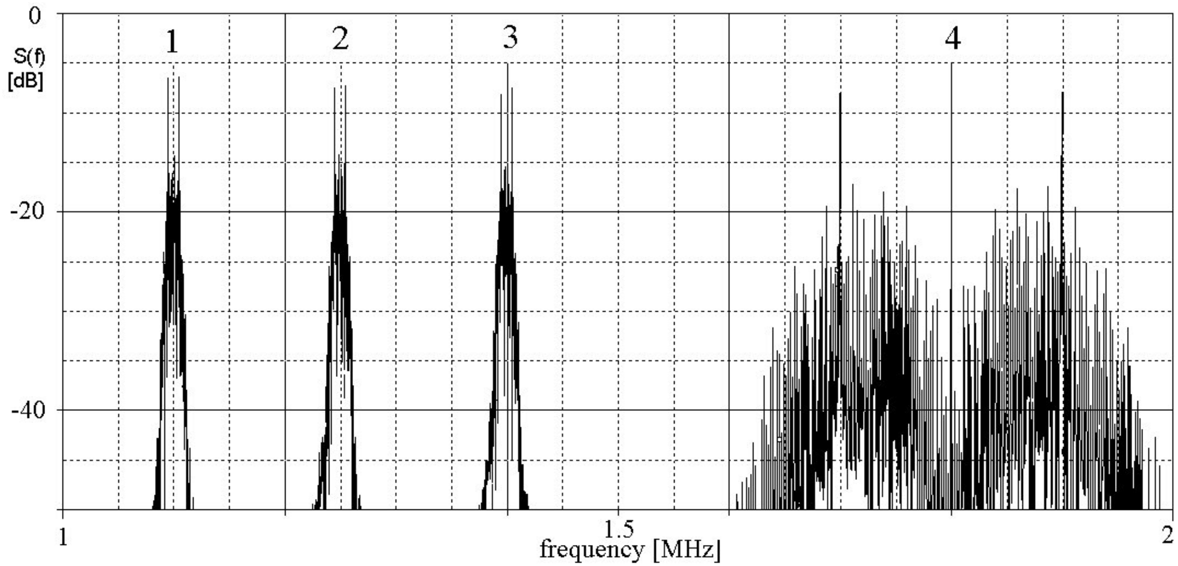
UWBFM TX


FSK
FM
d(t)
sub-carrier oscillator
m(t)
RF oscillator
V(t)
100 kb/s
1 MHz
4 GHz


d(t)
m(t)
V(t)
t [μs]

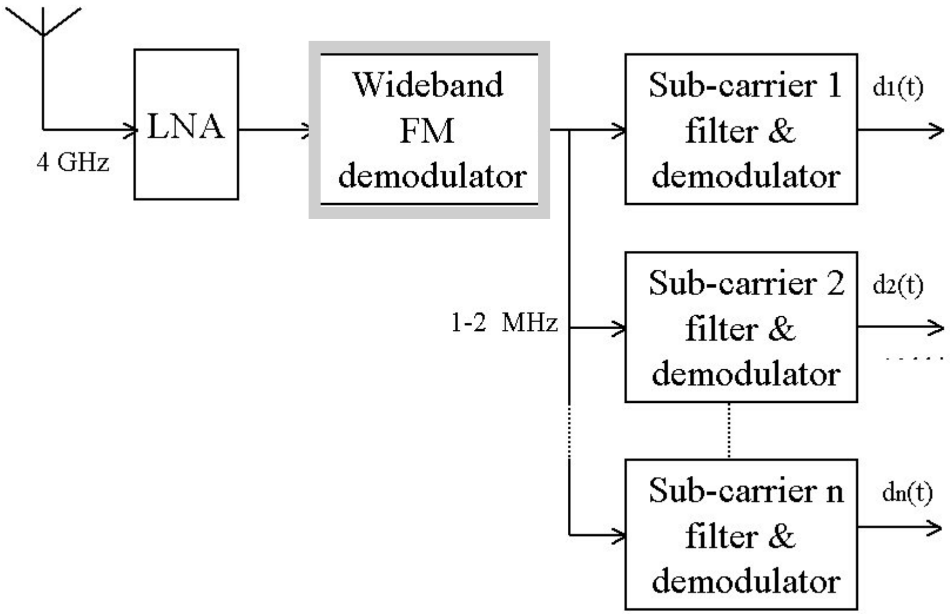

S [dBm/MHz]
unmodulated RF carrier
FCC spectral mask
UWBFM signal
f [GHz]

DIFFERENT USERS HAVE DIFFERENT SUB-CARRIER FREQUENCIES



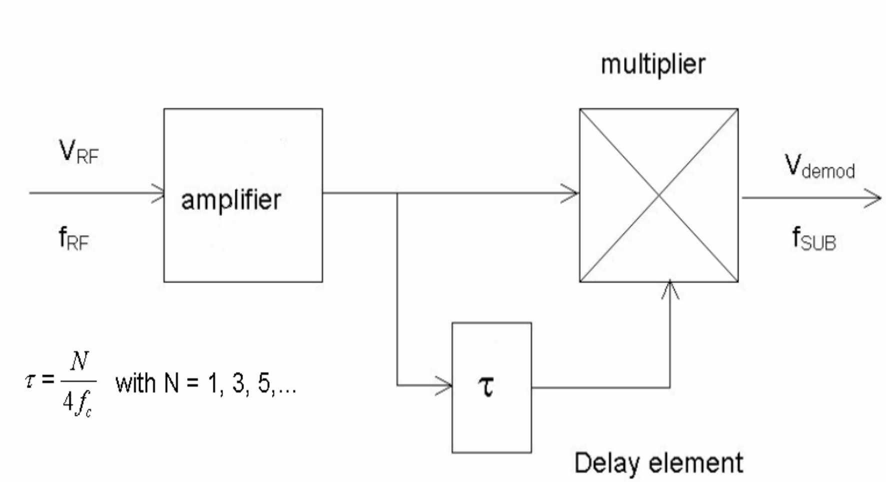
When the users share the same RF carrier frequency, simultaneous demodulation of multiple signals must be performed in the receiver.

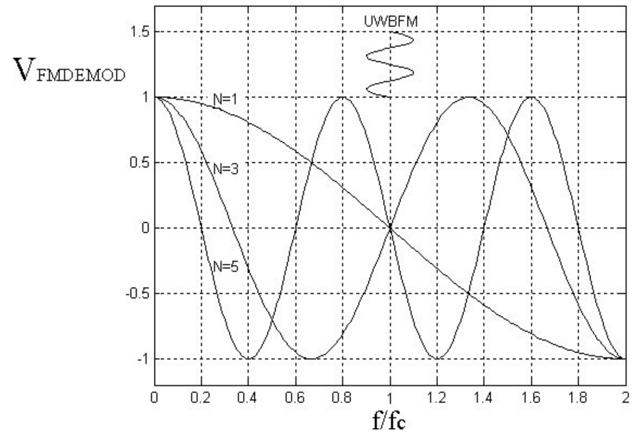
UWBFM RX



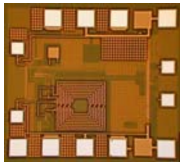
When no hard limiting is done prior to FM demodulation, simultaneous demodulation of multiple FM signals is possible As in a DSSS system, the limit is multiple-access interference.

WIDEBAND FM DELAY LINE DEMODULATOR

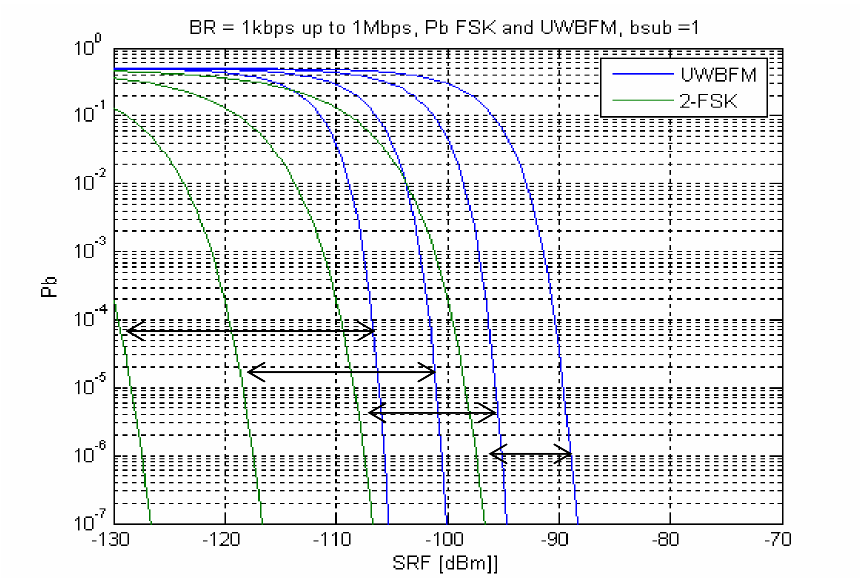


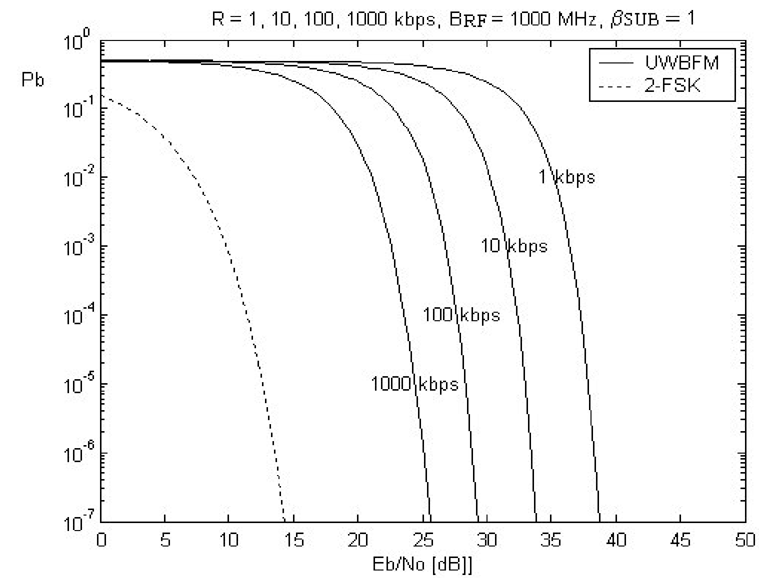


This demodulator has been fully integrated on silicon.



UWBFM PERFORMANCE WITH AWGN





B_{RF} = fixed ⇨ BER performance depends on the bit rate.

Data rate R [kbit/s]	*SNR_{RF} [dB]*	*PL [dB]*	*d_{FS} [m]*
1	**-22**	**90**	**183**
10	**-17**	**85**	**106**
100	**-11**	**79**	**52**
1000	**-5**	**73**	**25**

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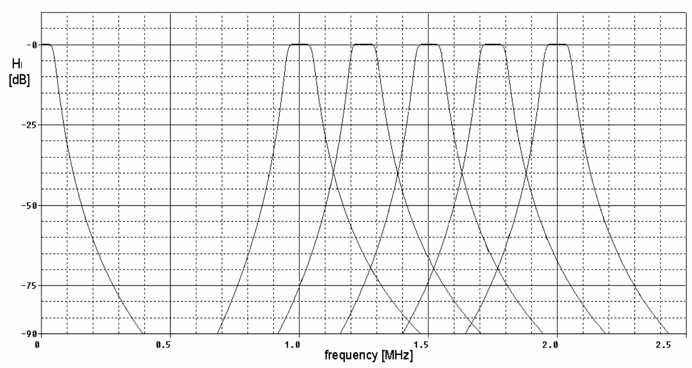
MULTI-USER LIMITATIONS

Removing the hard limiter makes it possible to demodulate multiple FM signals on the same frequency at the same time.

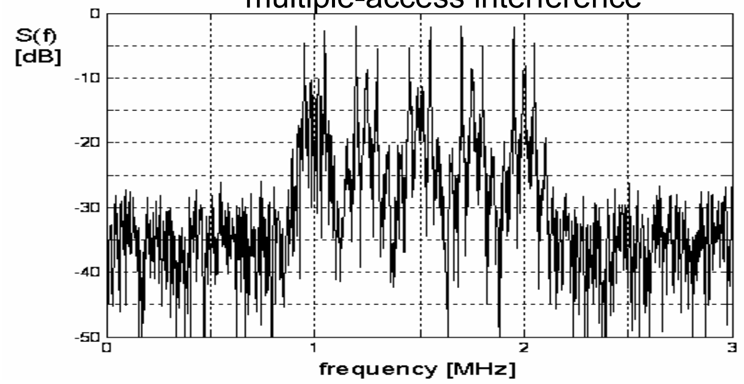
The number of simultaneous users is limited by the quality of the frequency domain filtering used to separate the individual sub-carriers and by the multiple-access interference.

A five 100 kbit/s user system is feasible with f_{sub} = 1 – 2 MHz
Capacity can be further increased by using multiple RF carrier frequencies.

subcarrier filtering (zero-IF)



multiple-access interference

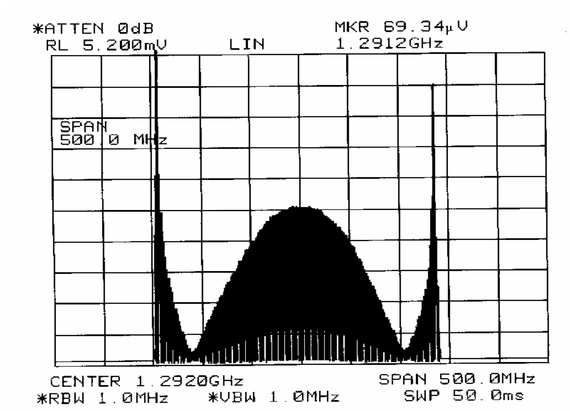


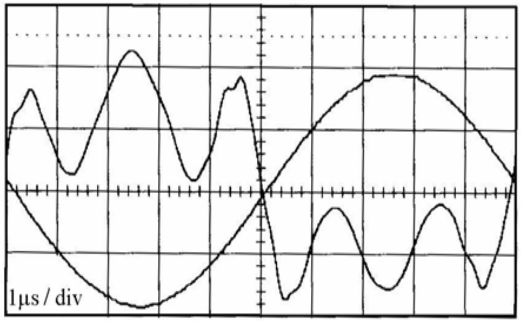
UWBFM ROBUSTNESS

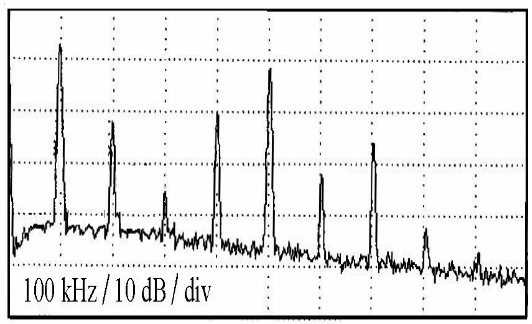
UWBFM can be seen as an analog implementation of a spread-spectrum system with a spreading gain equal to the FM signal's modulation index β.

Narrow-band interference is spread in the wideband FM demodulator.

Multipath creates harmonic distortion of the sub-carrier signal, that by itself can be easily dealt with, but that may limit the number of users.







UWBFM ADVANTAGES

Simple hardware implementation

The solution can be fully integrated

Receiver requires no local oscillator

No carrier synchronization (as in impulse radio)

Antennas are not critical

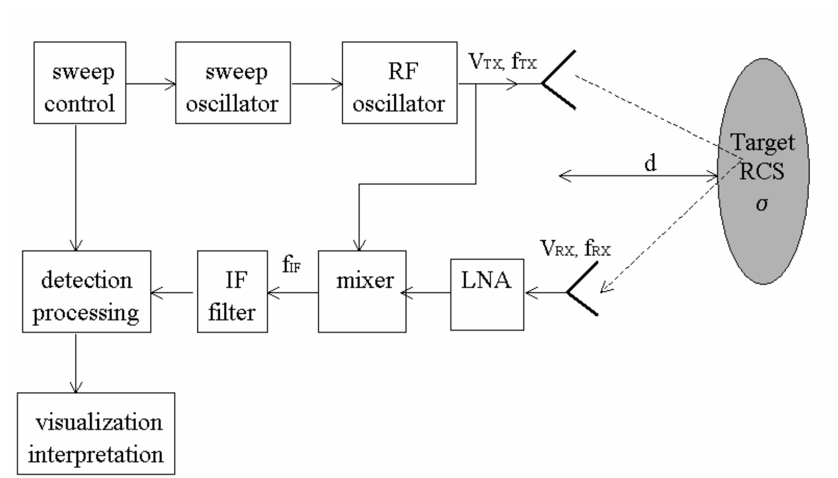
Steep spectral roll-off

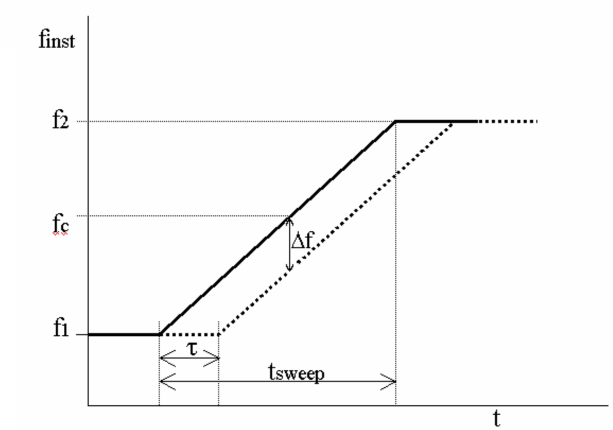
Robustness to MBOFDM interference and multipath

CSMA techniques can enhance performance

Localization compatibility

FREQUENCY-DOMAIN LOCALIZATION





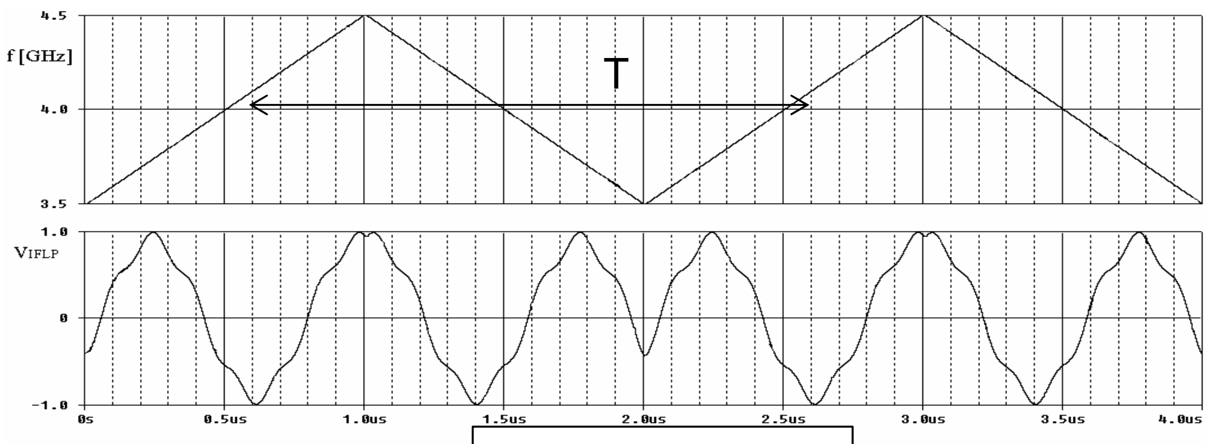
$$\Delta f = \frac{\partial f_{inst}}{\partial t}\tau = 2\frac{f_2 - f_1}{t_{sweep}}\frac{d}{c} = 2\frac{B_{RF}}{t_{sweep}}\frac{d}{c} \rightarrow 6.67\text{ MHz}$$

1 GHz — 1 m — 1 µs — $3\text{x}10^8$ m/s

LOCALIZATION ACCURACY

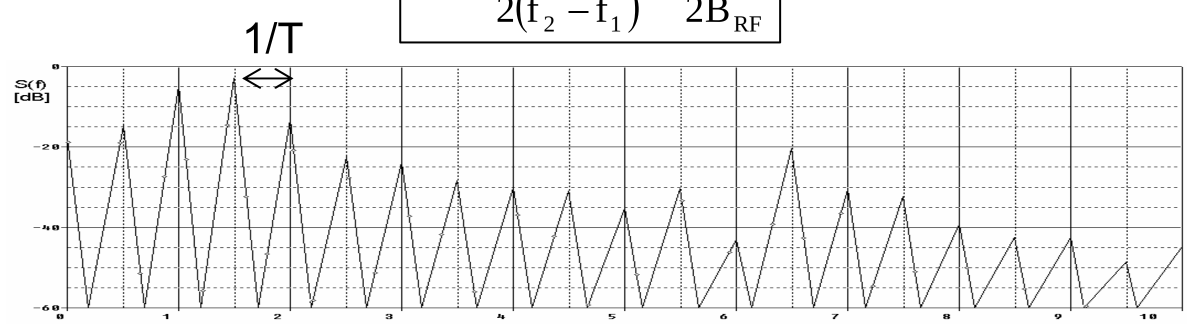
Instantaneous frequeny f(t)

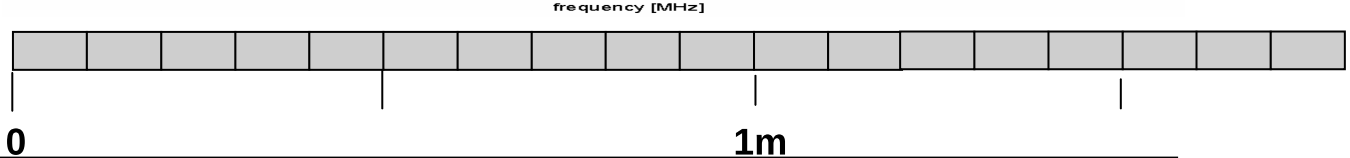
IF signal $V_{IF}(t)$



$$\Delta d = \frac{c}{2(f_2 - f_1)} = \frac{c}{2B_{RF}}$$

DFT of IF signal $V_{IF}(f)$





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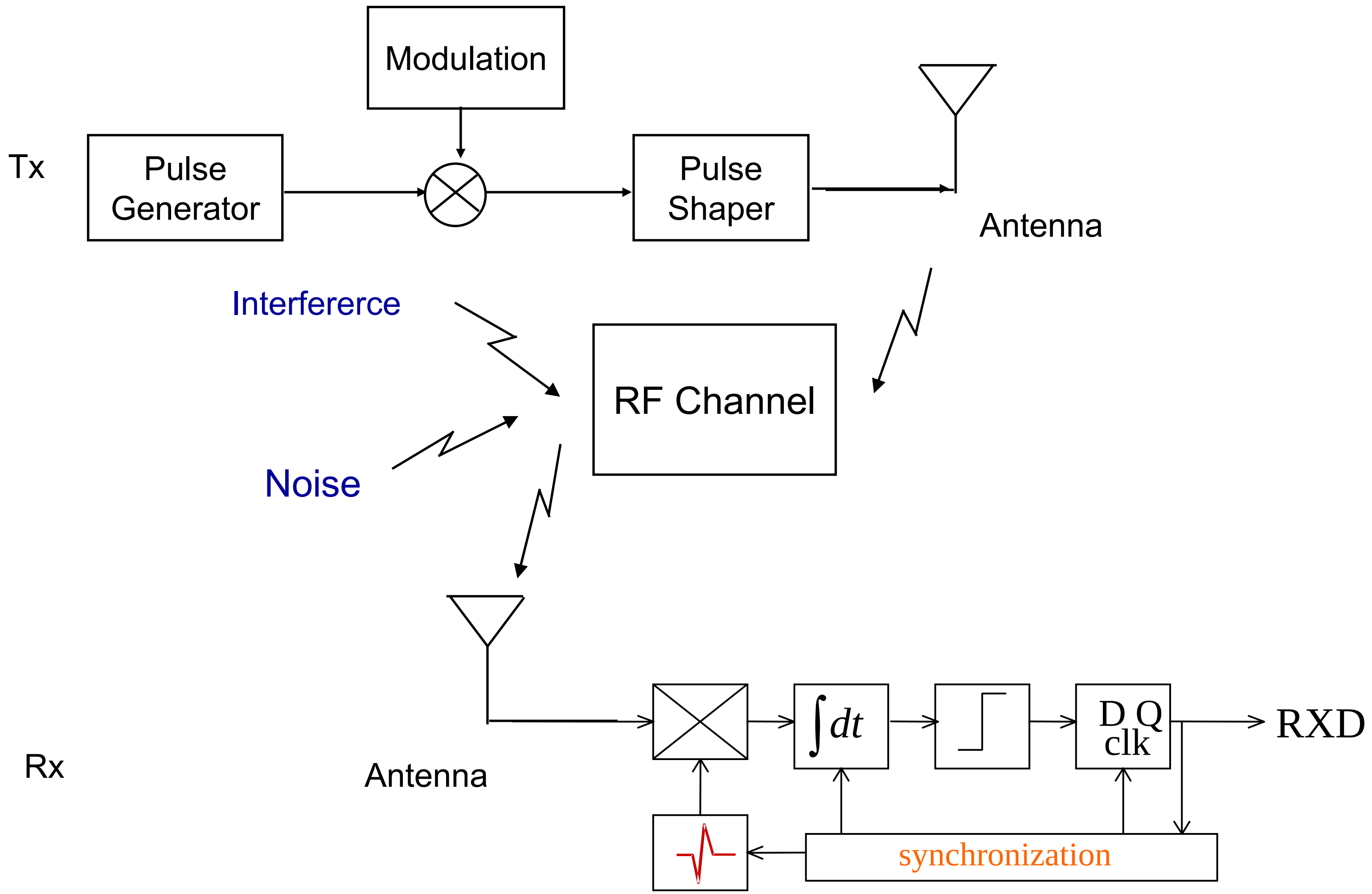
OUTLINE

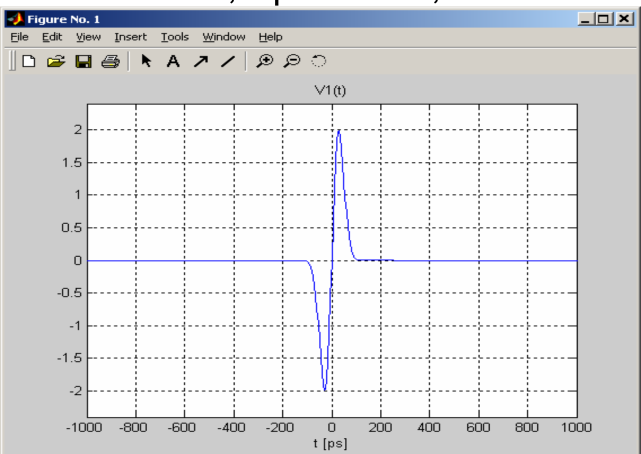
- Introduction to UWB
- The UWB channel, propagation and antennas
- Frequency domain solutions, advantages and limitations
- Time Domain solutions, advantages and limitations (50 min)
  - Introduction to Time Domain approaches
  - Impulse Radio UWB
  - Implementation challenges
  - HDR solutions: IEEE802.15.3a (proposal 2)
  - LDR/MDR solutions:
    - IEEE802.15.4a,
    - IST-PACWOMAN approach
  - Other issues
- Summary and concluding remarks

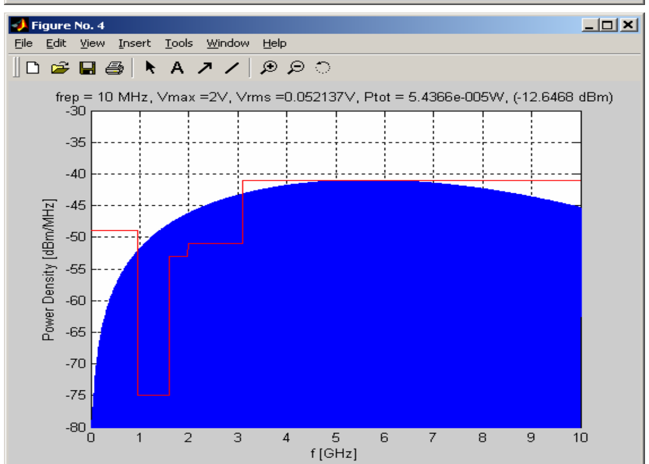
OVERVIEW OF A SIMPLE PULSED UWB SYSTEM



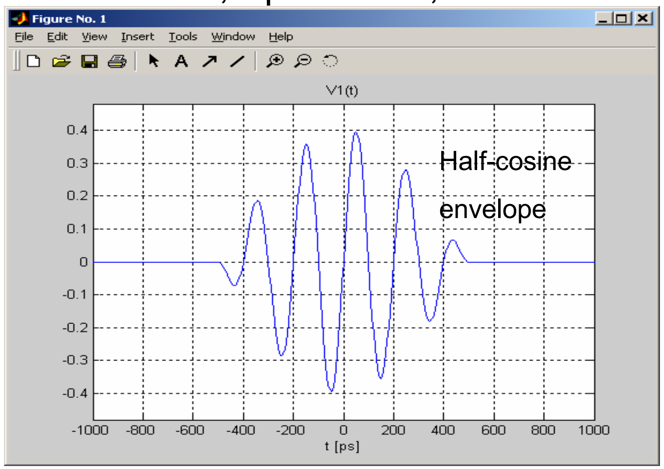
WAVELET CHOICE

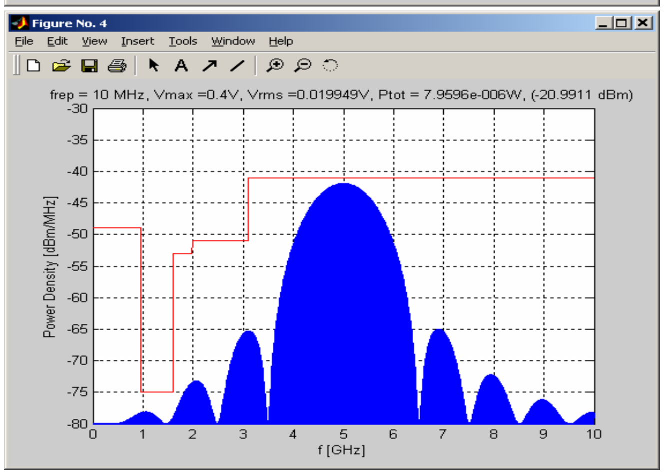
Gaussian, Vpeak =2V, CF = 40



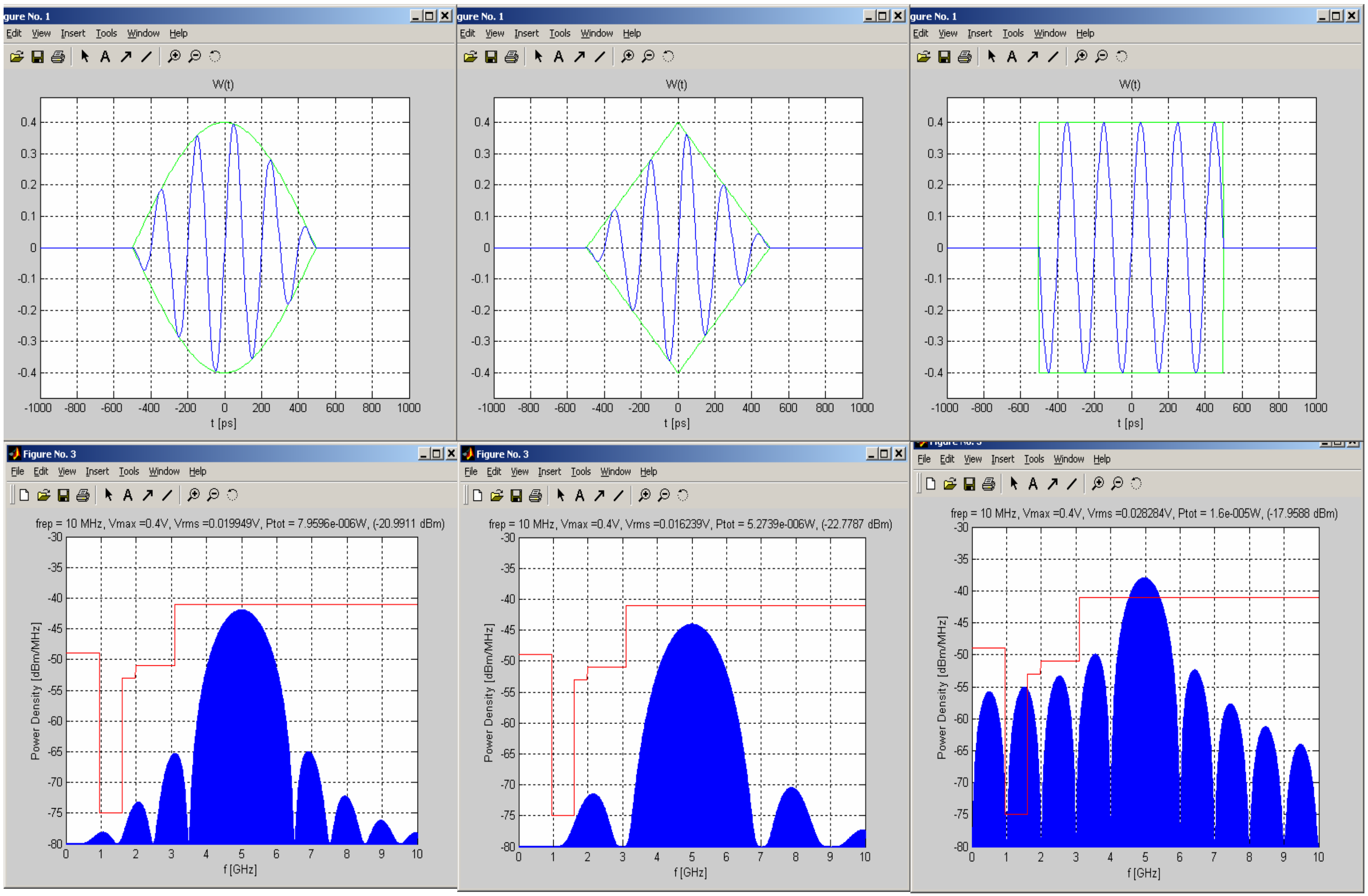


Sinewave, Vpeak =0.4, CF = 20

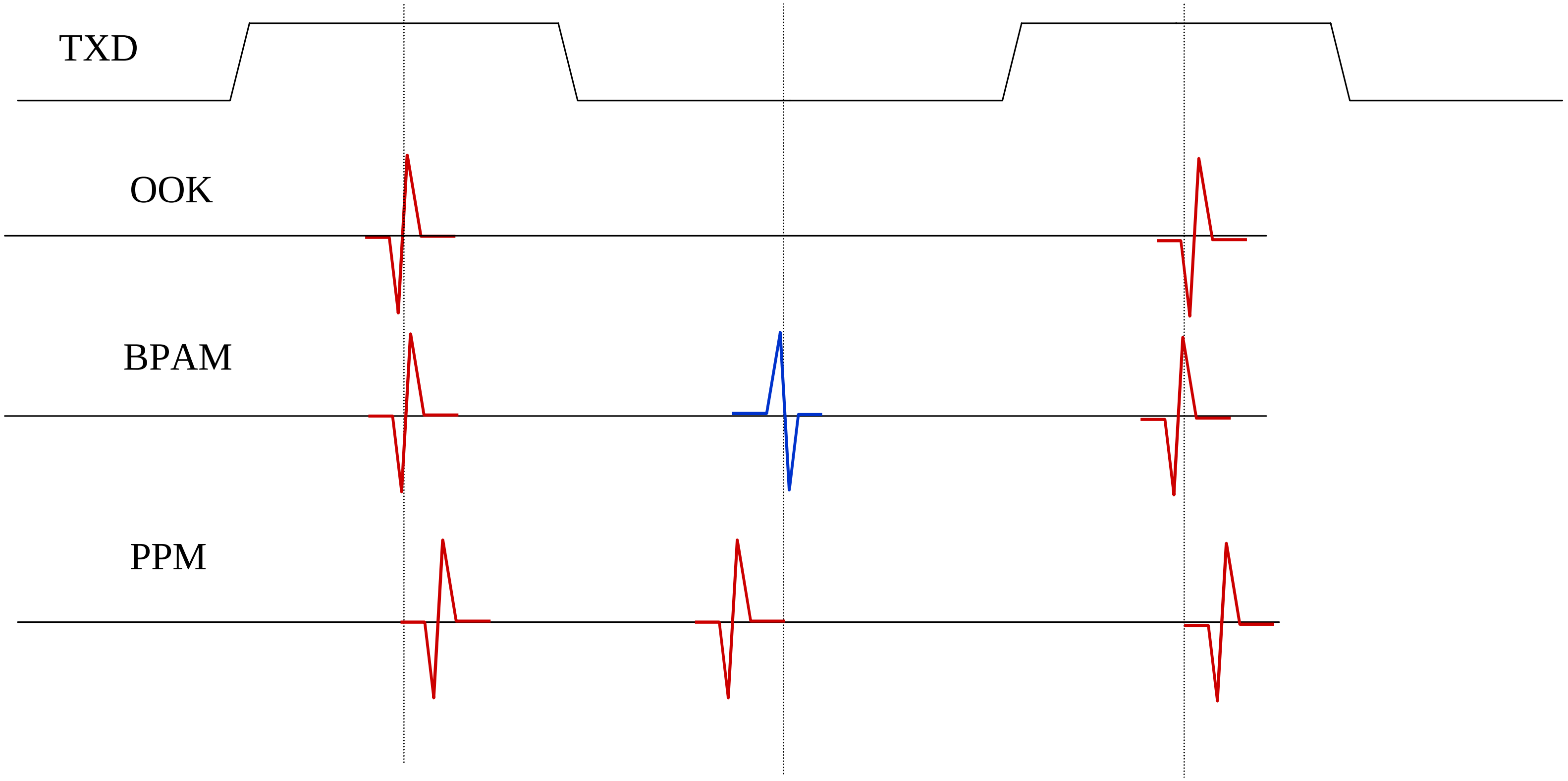




ENVELOPE CHOICE



MODULATION TECHNIQUES



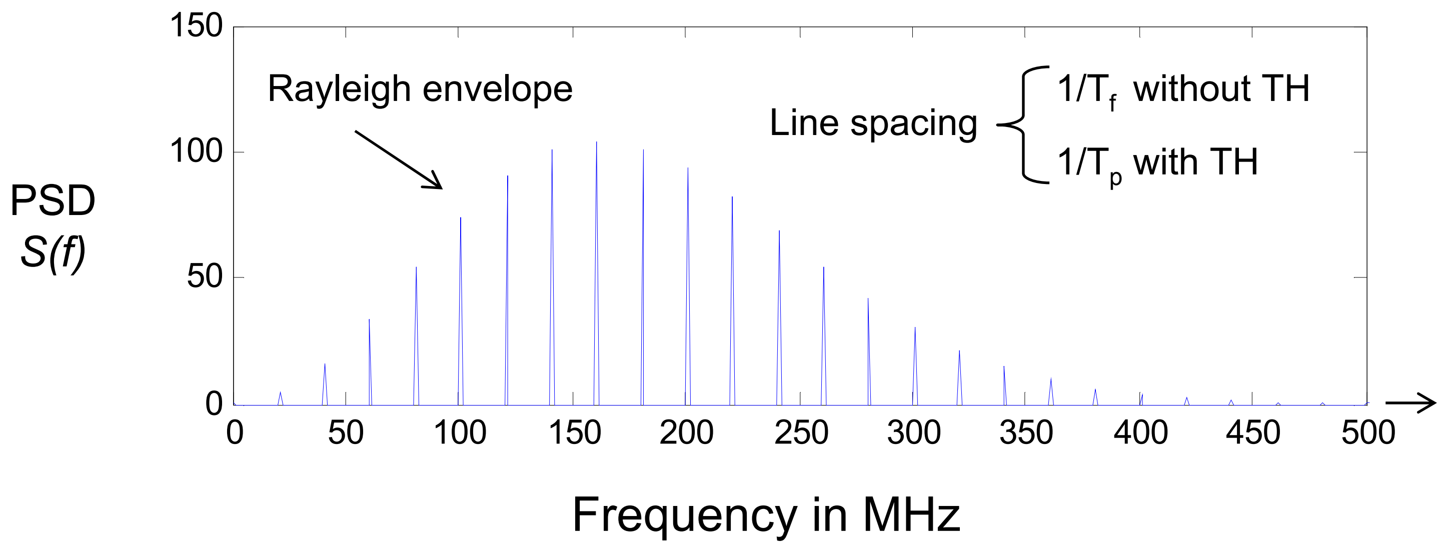
IMPULSE RADIO UWB TRANSMIT SIGNAL

$$s_{tr}^{(k)}\left(u,t^{(k)}\right)=\sum_{j=-\infty}^{\infty} w_{tr}\left(t^{(k)}-jT_f-c_j^{(k)}(u)T_c-d_j^{(k)}(u)\right)$$

u = a random variable
k = k^th impulse radio transmitter (user)
$t^{(k)}$ = the transmitter clock time
w_{tr} = the transmitted monocycle waveform (starting at time zero)
j = j^th monocycle
$c(u)$ = a TH pulse shift (integer shift), $0 \leq c(u) < N_h$
T_f = frame or pulse repetition time (time between monocycles)
$d(u)$ = modulation sequence sampled at a rate $1/T_f$
T_c = TH unit time shift, where $T_c N_h \leq T_f$
N_p = period of the pseudorandom TH sequence
$T_p = N_p T_f$ = period of the monocycle waveform

[Win1, Scholtz]

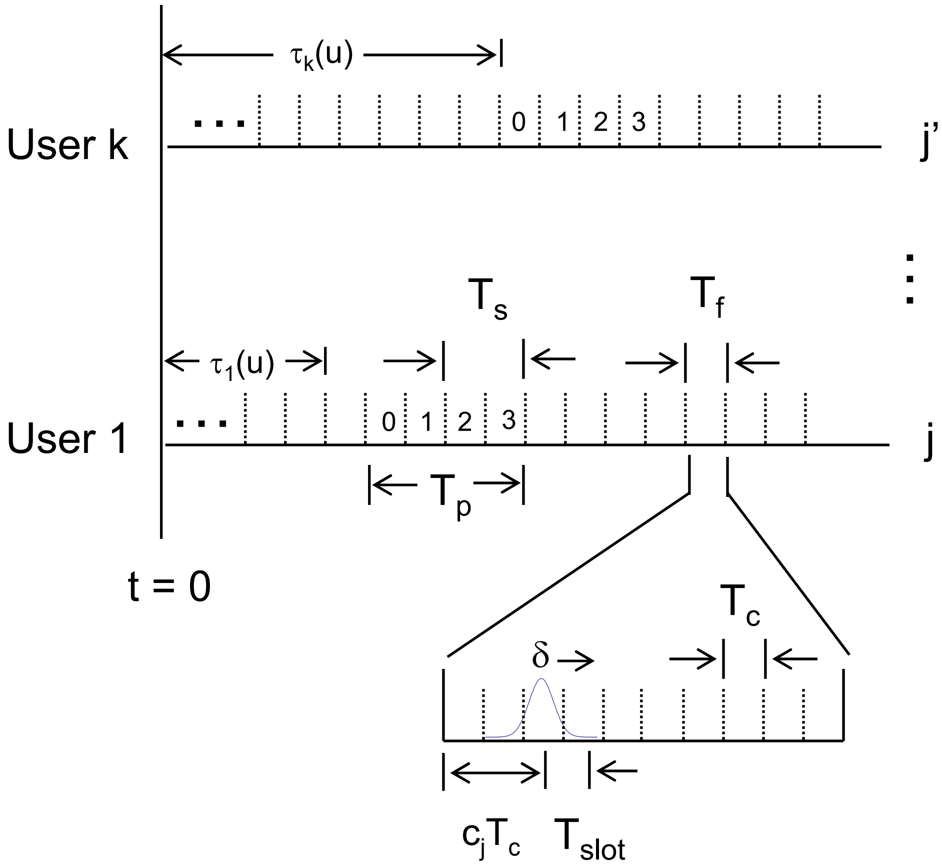
POWER SECTRAL DENSITY (PSD)



$$S(f)=\frac{|W(f)|^2}{T_p^2}\left|\sum_{n=0}^{N_p-1}\exp\left[-j2\pi f\left(nT_f+c_nT_c\right)\right]\right|^2\sum_{k=-\infty}^{\infty}\delta\left(f-k/T_p\right)$$

- N_p = period of the TH PN code
- $T_p = N_p T_f$ = period of the waveform

OVERVIEW OF TH-UWB: TIMING DIAGRAM WITH PSEUDO RANDOM PULSE SEQUENCES



T_f = UWB frame duration (typically >> T_m)

$T_m \cong$ pulse width (e.g., doublet)

$T_s = N_s T_f$ = symbol period

N_s = Impulses per symbol

$N_h T_c$= a random shift $\leq T_f$

T_c = unit TH code time shift

$T_p = N_p T_f$ = period of TH waveform

T_{slot} = slot (e.g., BPPM)

j = j[th] instant in time

τ = timing offset between users

As shown, $T_c \approx T_m$. It may not be [Win1].

[Win1, Scholtz]

UWB CAPACITY AND SHANNONS LAW

- Shannon's law applies to UWB [Barrett, Leeper]

$$C = B\log_2\left(1+\frac{P}{N}\right)$$

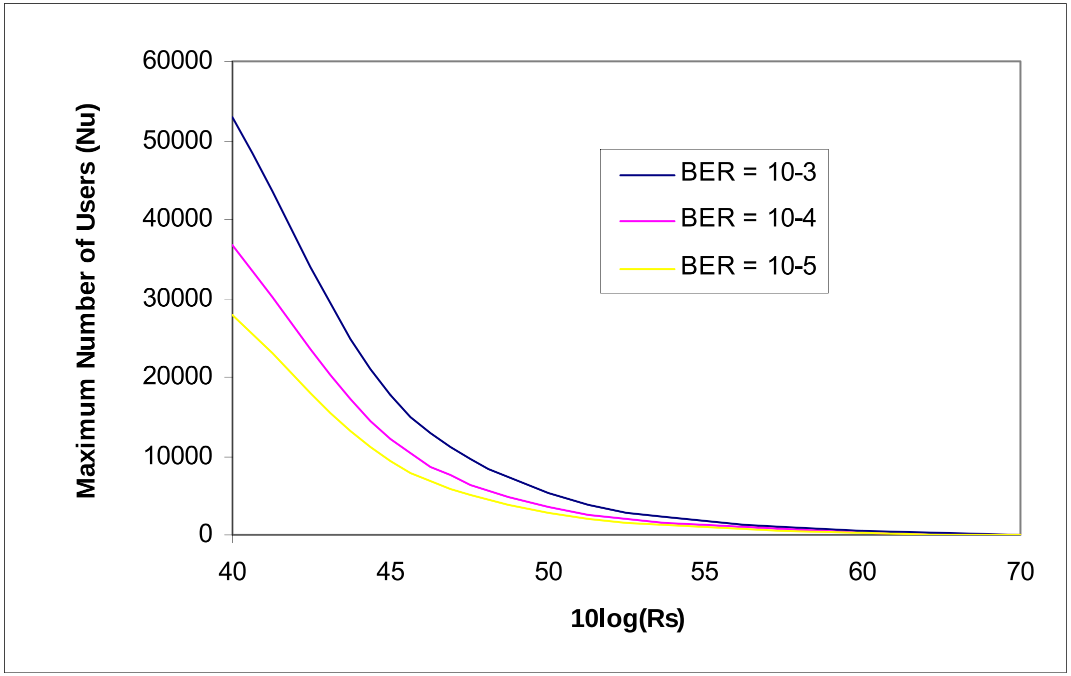
$$C = Max\ channel\ capacity\ in\ bits/s$$
$$B = Channel\ bandwidth\ in\ Hertz$$
$$P = Signal\ \ power\ in\ Watts$$
$$N = Noise\ \ power\ in\ Watts$$

- UWB system capacity is comparable to that of DS-CDMA systems given the same bandwidths. From [Foerster]

$$P_{ave} = B_s P_{sd}\ \ and\ \ N = B_p N_0$$
$$P_{sd} = average\ power\ spectral\ density$$

DIGITAL TH IR-UWB MULTIPLE ACCESS CAPACITY

Maximum Number of Users vs. Modulation Rate



Example based on [Win, Scholtz], uncoded BPPM, AWGN, ΔP = 20 dB.

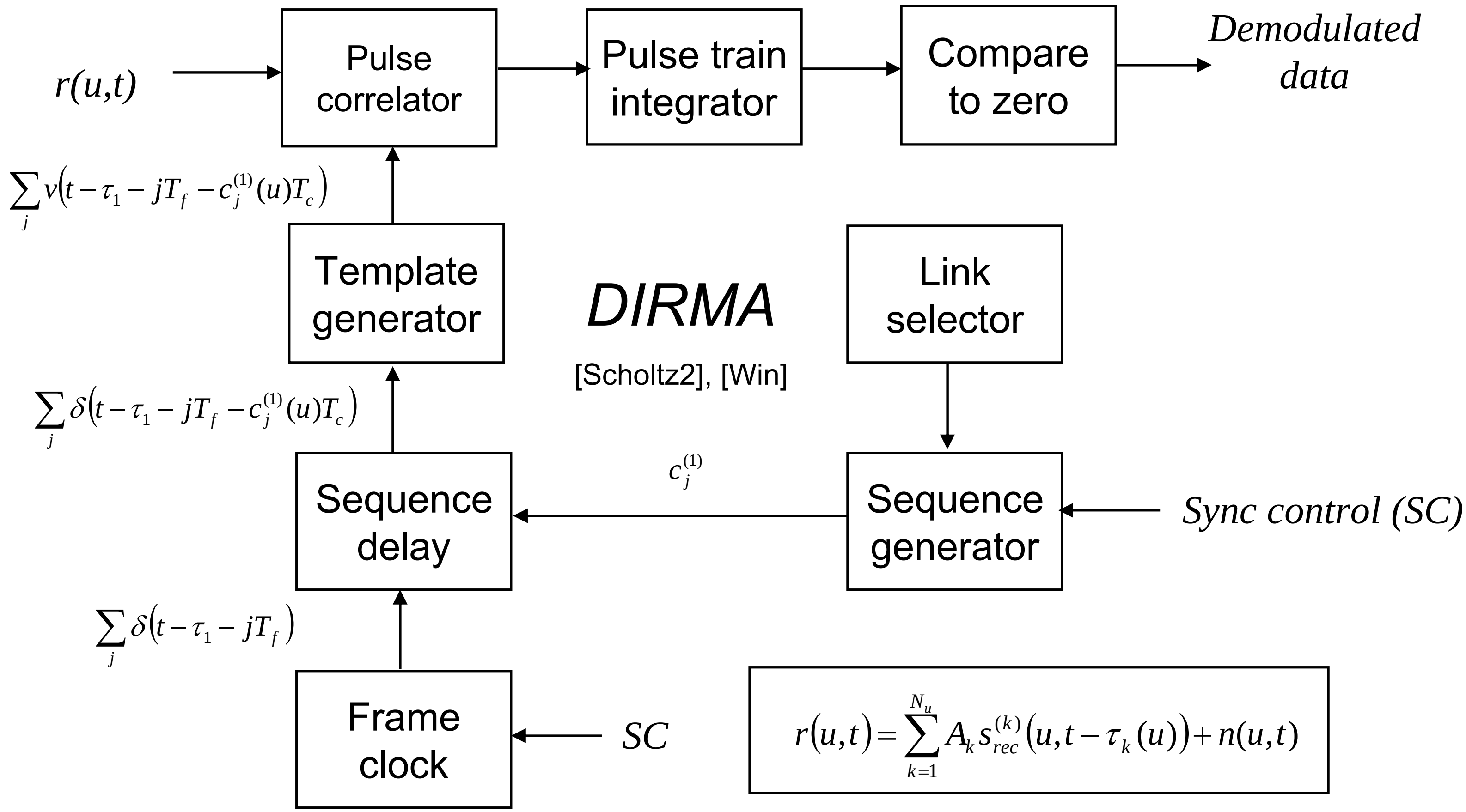
Note: TH-UWB is soft capacity limited, like DS-CDMA: the number of users at a given performance (BER as a function of SNR) can not exceed N_{max}.

IR-UWB AND TIME HOPPING

- Until recently, TH-UWB was the dominant technique in the literature
  - Analog impulse radio multiple access (AIRMA) [Scholtz, Win]
  - Digital impulse radio multiple access (DIRMA) [Scholtz, Win]

- The major elements of an IR-UWB communication system include [Barrett, Ross, Harmuth]
  - Techniques for generating and and modulating pulse trains
  - Techniques for switching to generate RF pulse train signals
  - Techniques for detection, reception and synchronization
  - Acceptably efficient antennas

SIMPLIFIED MODEL OF A DIGITAL UWB RECEIVER FOR TH-UWB MULTPLE ACCESS



TH-UWB RECEIVER DECISIONS

The optimum receiver for binary impulse radio in AWGN is the correlation receiver [Scholtz1].

Decisions are made over N_s correlations between the received signal *r(t)* and the correlation template signal $v(t) = w_{rec}(t) - w_{rec}(t-\delta)$.

pulse correlator = α_j

$$\text{decide } d_0^{(1)} = 0 \Leftrightarrow \underbrace{\sum_{j=0}^{N_s-1} \overbrace{\int_{\tau_1 + jT_f}^{\tau_1 + (j+1)T_f} r(t)\, v\left(t - \tau_1 - jT_f - c_j^{(1)} T_c\right) dt}^{\alpha_j}}_{\alpha} > 0$$

test statistic = α

Optimal detection in a multi-user environment, with knowledge of all TH sequences, is complex. However, multiple access interference may be approximated as a Gaussian random process [Scholtz, Win].

IR-UWB CORRELATION MATRIX

$$R = \begin{bmatrix} R(\tau_1 - \tau_1) & R(\tau_1 - \tau_2) & \dots & R(\tau_1 - \tau_{Lp}) \\ R(\tau_2 - \tau_1) & R(\tau_2 - \tau_2) & \dots & R(\tau_2 - \tau_{Lp}) \\ \vdots & \vdots & \ddots & \vdots \\ R(\tau_{Lp} - \tau_1) & R(\tau_{Lp} - \tau_2) & \dots & R(\tau_{Lp} - \tau_{Lp}) \end{bmatrix}$$

$$R(\tau_i - \tau_j) = E\{r(\tau_i)\, r(\tau_i - \tau_j)\}$$

$\Downarrow$

$$R = \begin{bmatrix} R(0) & 0 & \dots & 0 \\ 0 & R(0) & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & R(0) \end{bmatrix}$$

The UWB multipath channel components are separable (i.e., provided the pulses are shorter than the echoes).

[Win, Scholtz]

TH IR-UWB MULTIPLE ACCESS CHANNEL

For N_u active users in a multiple access impulse radio system, the received signal at the output of the antenna may be modeled by [Scholtz1]

$$r(t) = \sum_{k=1}^{N_u} A_k s_{rec}^{(k)}(t - \tau_k) + n(t)$$

N_u is the number of transmitters on-air, A_k is the signal attenuation over the propagation path, s_{rec} is the received signal from the k^{th} transmitter, τ_k is the asynchronism between transmit and receive clocks and $n(t)$ is the noise

IR-UWB IMPLEMENTATION CHALLENGES

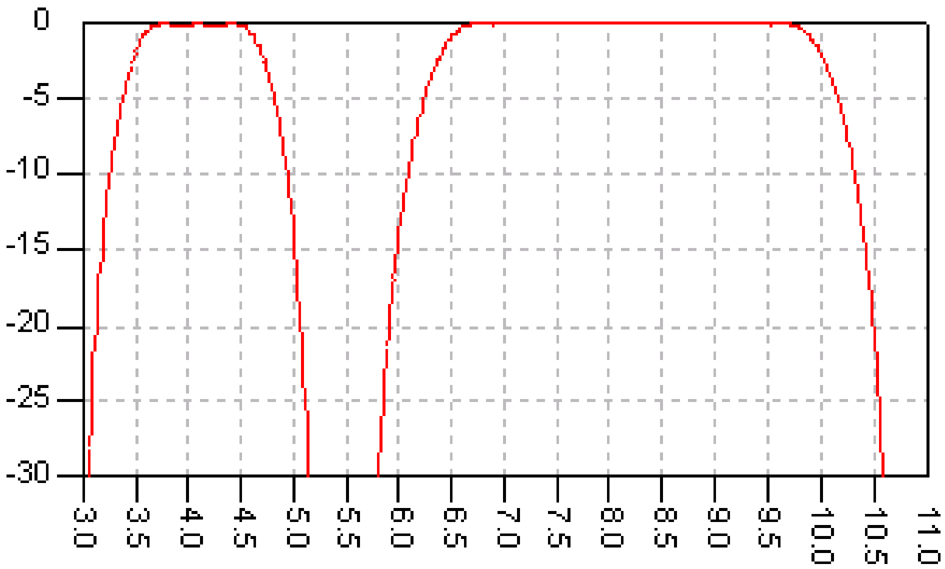
- Transmitter
  - Simple, high-speed pulsed waveform generation
  - Spectral co-existence with other systems
  - Reducing potential system noise aggregaion
  - Avoidance of certain bands (e.g., UMTS, GPS, astronomy)
- Receiver
  - Simple, high-speed pulse detection
  - Fast ADC and high-speed sampling (e.g. 2 Giga samples per second is required to satisfy the Nyquist criteria for a 1 GHz waveform (1 ns pulse)).
  - Circuits (e.g., CMOS) capable of high dynamic range (i.e., strong interferers)
  - Synchronisation (e.g. resolution of timing uncertainty and jitter)
  - Simple techniques feducing the potential susceptibility to interference
- Antennas
  - Small, efficient, inexpensive, highly-linear UWB antennas
  - Antenna filtering in combination with pulse generation
  - Possible UWB antennas integrated with the chip

TECHNICAL CHALLENGES: THE SAMPLING RATE ISSUE

- UWB systems require very high speed sampling rates.
- The sampling interval is typically a fraction of a pulse duration (e.g., a fraction of a 1 ns pulse).
- The sampling rate may be even higher dependent on the accuracy required and whether oversampling is employed to increase the effective processing gain.
- For example, sampling at the rate of 2 Giga samples per second (Gsps) is required to satisfy the Nyquist criteria for a 1 GHz waveform (1 ns pulse).
- This is not possible today and, for this reason, parralel architectures have been proposed, but this tends to increase complexity and cost.

HDR SOLUTIONS: IEEE802.15.3a (PROPOSAL 2) - OVERVIEW

- Direct Sequence (DS) UWB proposal for the PHY layer
- Supports two independent bands of operation:
  - **lower band: 3.1 GHz to 4.85 GHz**
  - **upper band: 6.2 GHz to 9.7 GHz**



[Kohno, Mc Laughlin]

HDR SOLUTIONS: IEEE802.15.3a (PROPOSAL 2) - MODULATIONS

- The DS-UWB proposal supports data communication using both BPSK (mandatory) and 4-BOK (optional)
- For some applications it is useful to use 4-BOK to improve performance
- Every device is required to support the *transmission* of 4-BOK modulated signals
- It is *optional* for devices to support the capability to receive and demodulated 4-BOK modulated waveforms.
- Goals of requiring 4-BOK support for transmit *only:*
  - very low additional device complexity (generation of 4-BOK signals requires little additional complexity relative to BPSK)
  - allows implementers to incorporate the additional complexity required to receive 4-BOK signals for specific situations

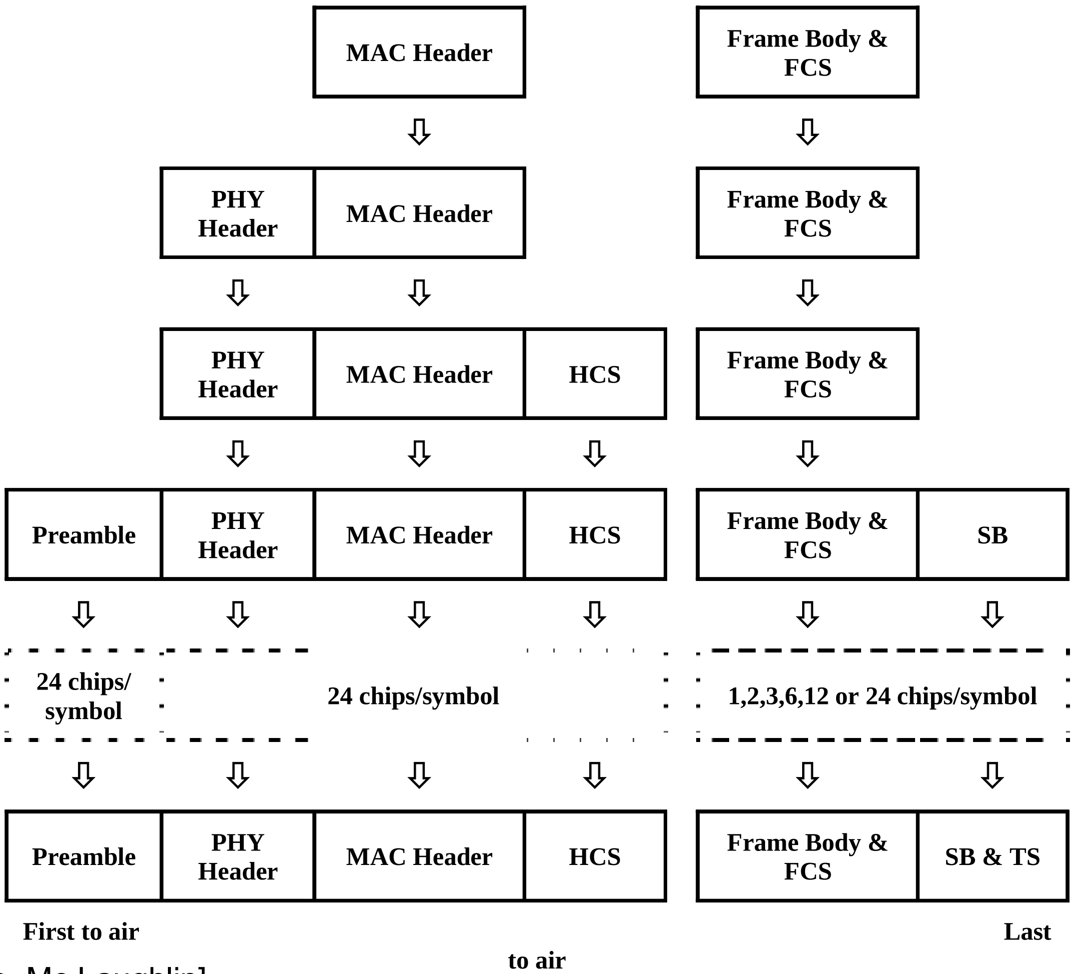
[Kohno, Mc Laughlin]

HDR SOLUTIONS: IEEE802.15.3a (PROPOSAL 2) – BASEBAND

- Communication capabilities of 28, 55, 110, 220, 500, 660,1000 and 1320 Mbps
- Forward error correction coding (convolutional coding) is used with a coding rate of ½ and ¾
- The baseband reference pulse is a root raised cosine low pass filter with 30% excess bandwidth
- For both the low and high frequency bands the filter cutoff frequency (-3 dB point) is Fchip/2
- The implemented baseband impulse response must have a normalized peak cross-correlation within 3 dB of this reference pulse

[Kohno, Mc Laughlin]

HDR SOLUTIONS: IEEE802.15.3a (PROPOSAL 2) - PHY FRAME FORMAT



[Kohno, Mc Laughlin]

LDR/MDR SOLUTIONS: IEEE 802.15.4a

- Formed in November 2002
- Alternative PHY Specification for 802.15.4
- Principle goals
  - Communications with high precision location capability
    - Location within centimeter accuracy
    - Robustness even in multipath rich environments
  - High agregate throughput (many thousands of collocated nodes)
  - Ultra low power (battery life from months to years)
  - Very low cost
  - Data rate less than 1Mbps
  - Operates with little change compared to 802.15.4 Medium Acces Control
- Extension of PHY capabilities to enable significant new applications and market opportunities

LDR/MDR SOLUTIONS: IST-PACWOMAN APPROACH

- The IST-2001-34157 project “Power Aware Communications for Wireless OptiMised personal Area Networks” investigates low-power and low-cost solutions for WPAN applications
- One of the project deliverables is an Impulse Radio UWB demonstrator for LDR applications, typically 10 – 100 kbit/s
- Ways to lower complexity and power consumption:
  - fully digital transmitter (reproducable)
  - straightforward receiver
  - simple modulation scheme
  - simple or no pulse synchronization
  - IC implementation

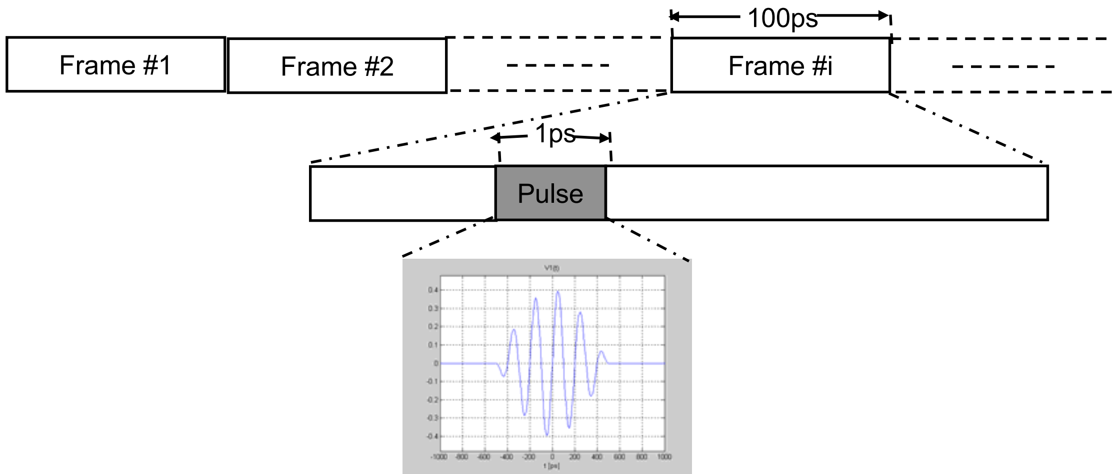
[PACWOMAN - D4.1.1]

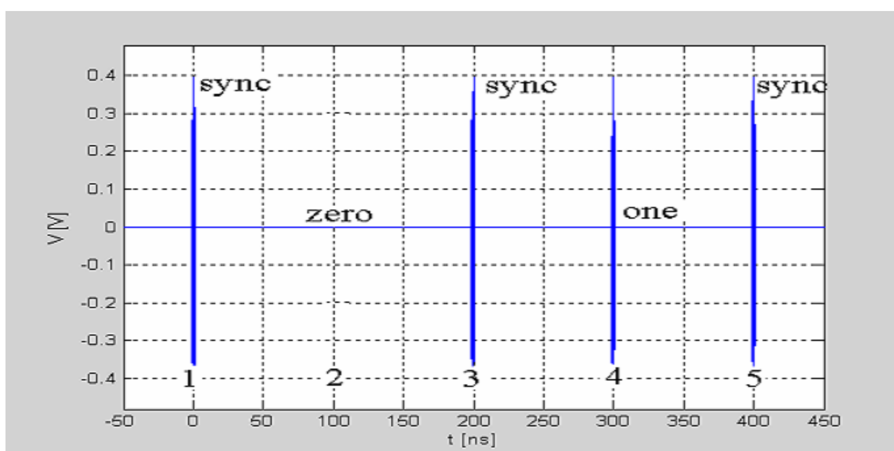
LDR UWB PACWOMAN SYSTEM PARAMETERS

System parameter	value	unit
Modulation scheme	On-Off Keying	
Center frequency	4	GHz
Bandwidth –20 dB	2.5	GHz
Peak power	+2	dBm
Average power	-21	dBm
Duty cycle	0.01	
Pulse repetition frequency	10	MHz
Pulse envelope	half period cosine	
Maximum bit rate	5	Mbit/s

[PACWOMAN - D4.1.1]

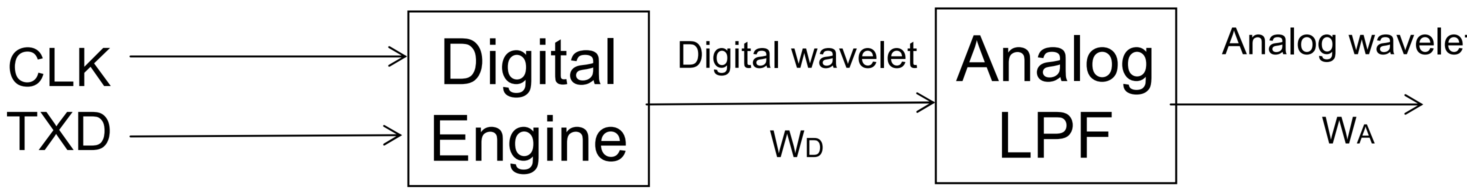
LDR UWB PACWOMAN FRAME STRUCTURE

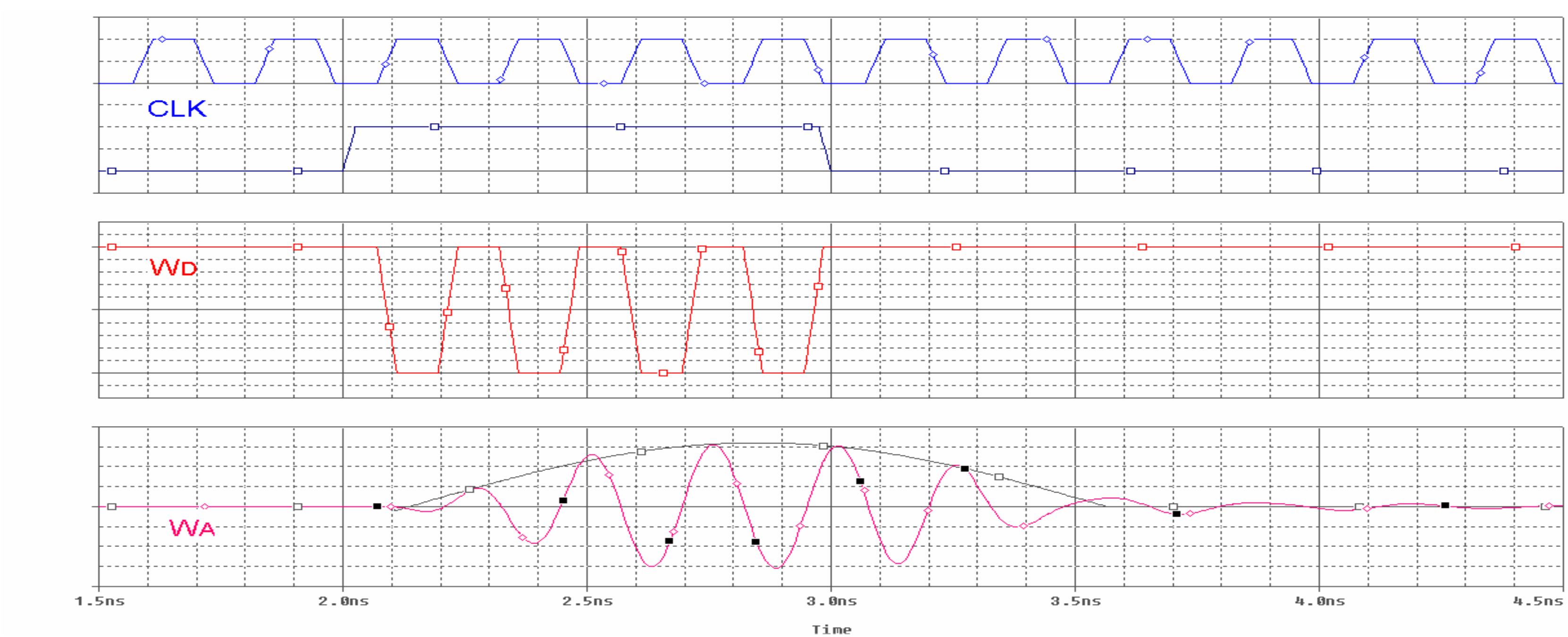




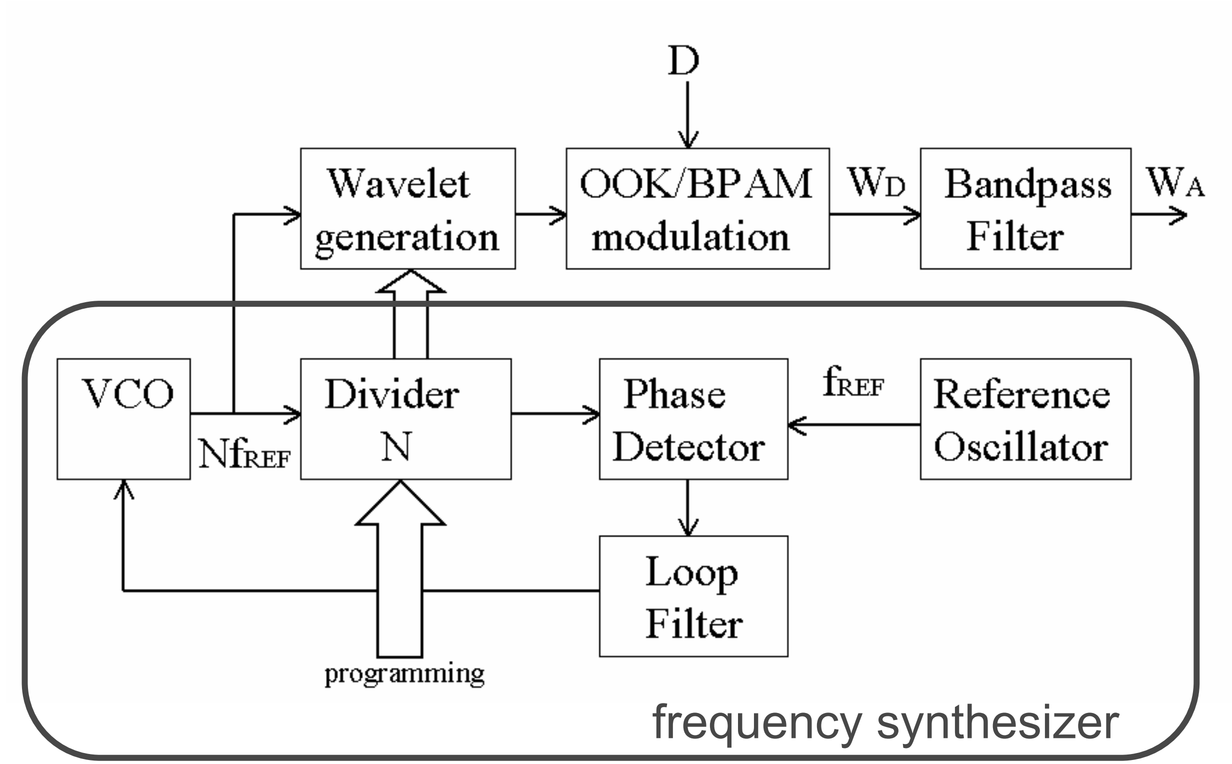
[John Gerrits, Jaouhar Ayadi, John Farserotu, CSEM's Patent, 2004]

DIGITAL TRANSMITTER CONCEPT





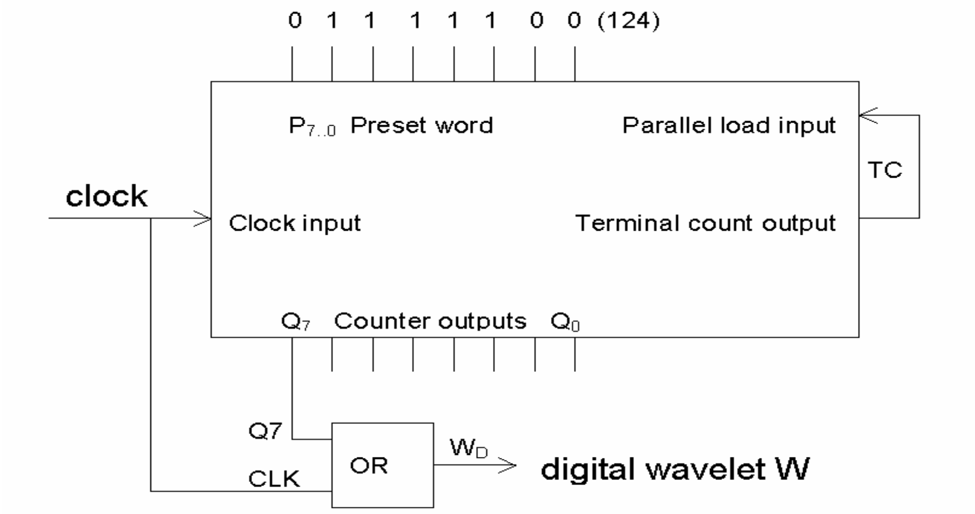
DIGITAL TRANSMITTER CIRCUIT IMPLEMENTATION

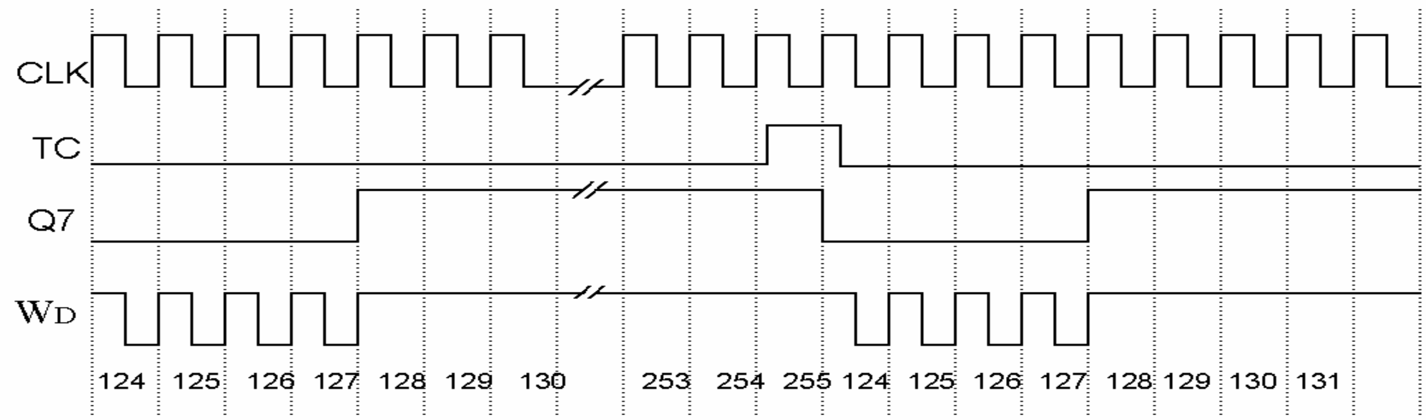


fc = N fref

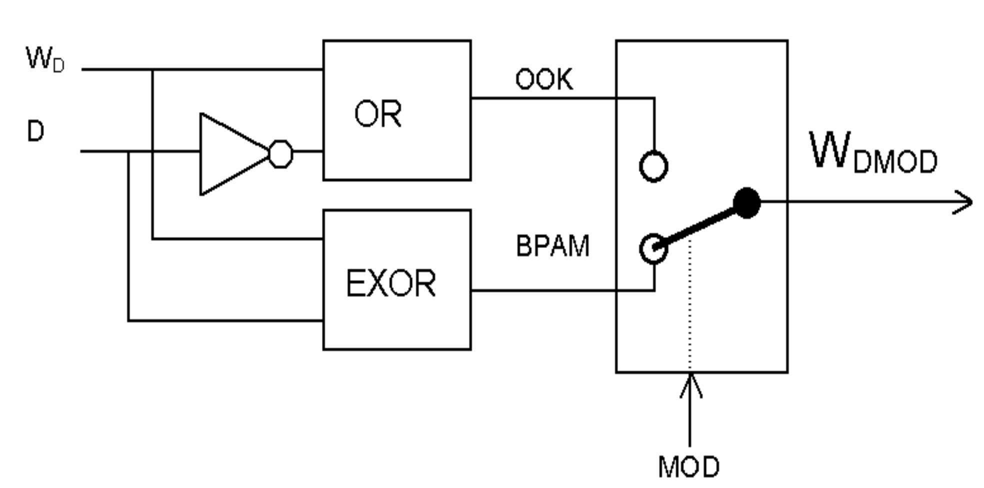
proven technology, programmable and reproducible results

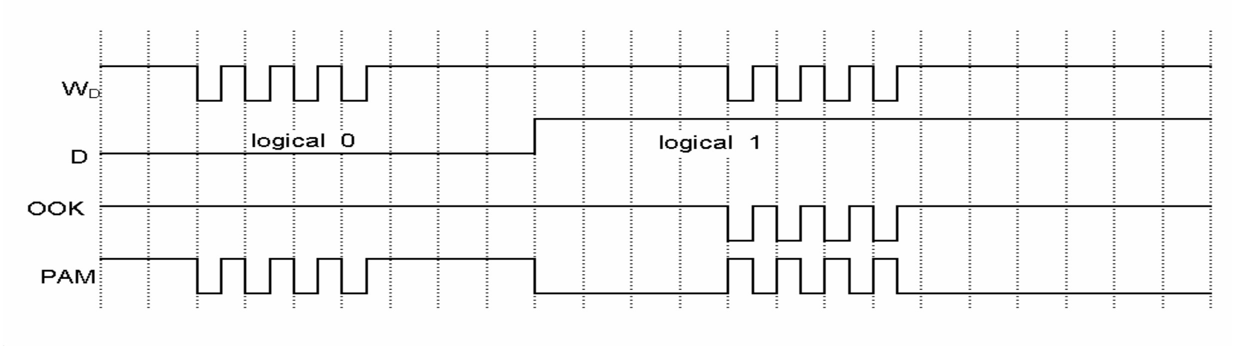
WAVELET GENERATION CIRCUIT





MODULATION CIRCUIT





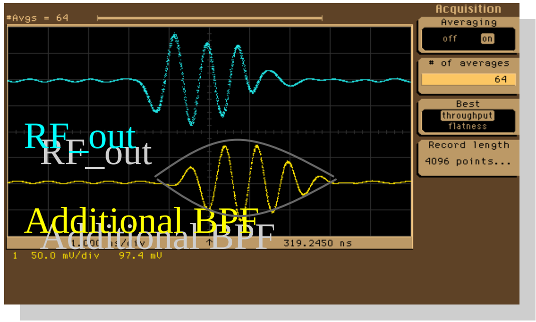
TRANSMITTER LABORATORY PROTOTYPE

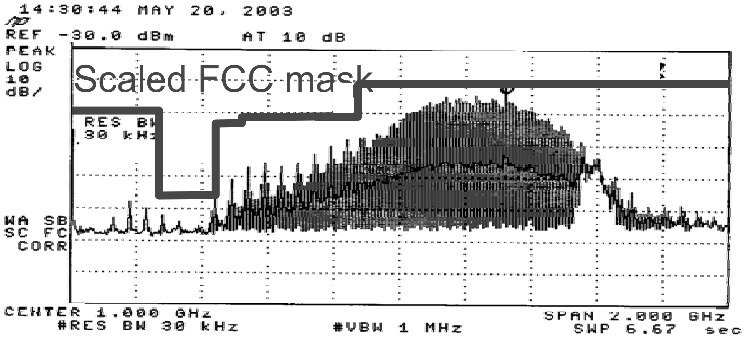
- Downscaled version (f/3) at fc = 1.32 GHz
- using off-the-shelf components from

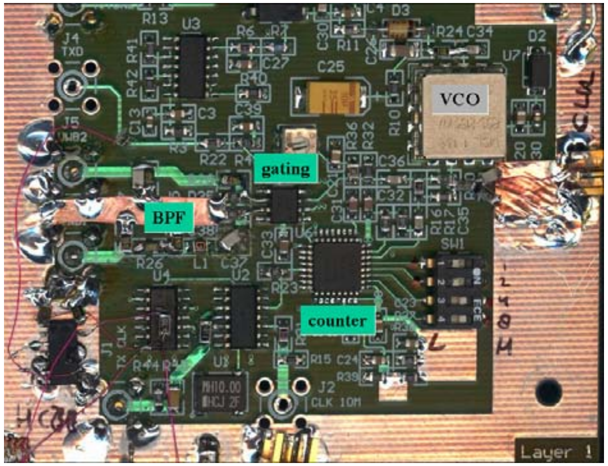
- ON-Semiconductor: fast PECL counter and logic
- Mini-Circuits: clock VCO

- The purpose of this prototype was to show the feasibility of the concept of the digital transmitter.

TRANSMITTER MEASUREMENT RESULTS

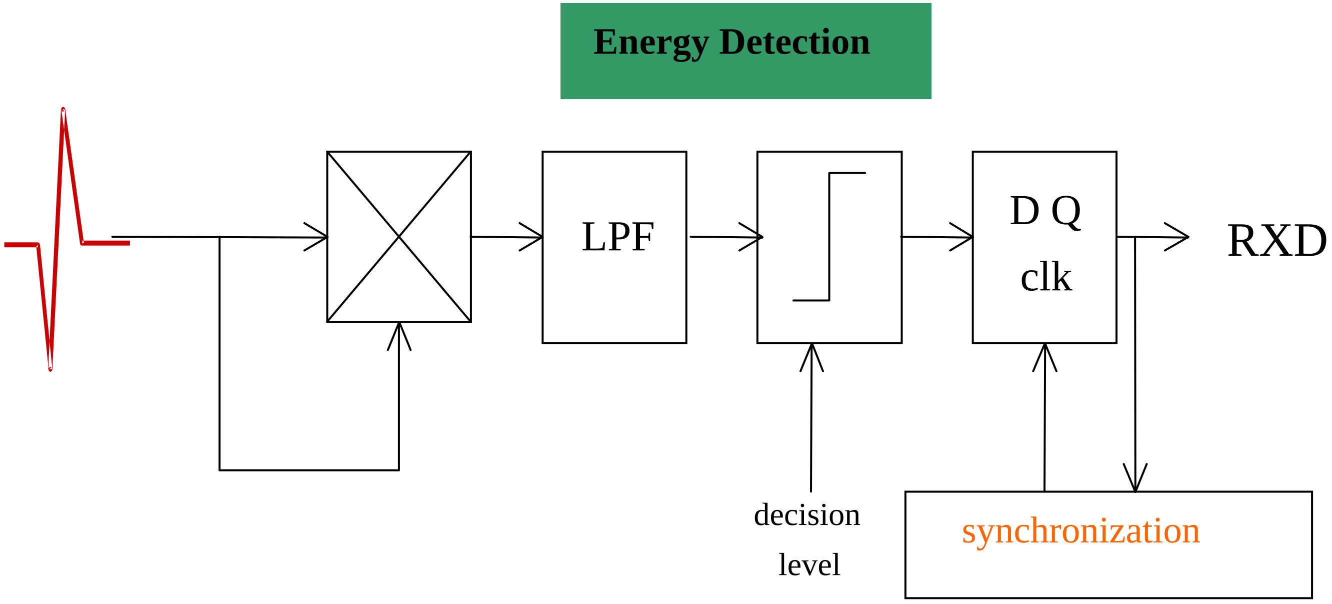






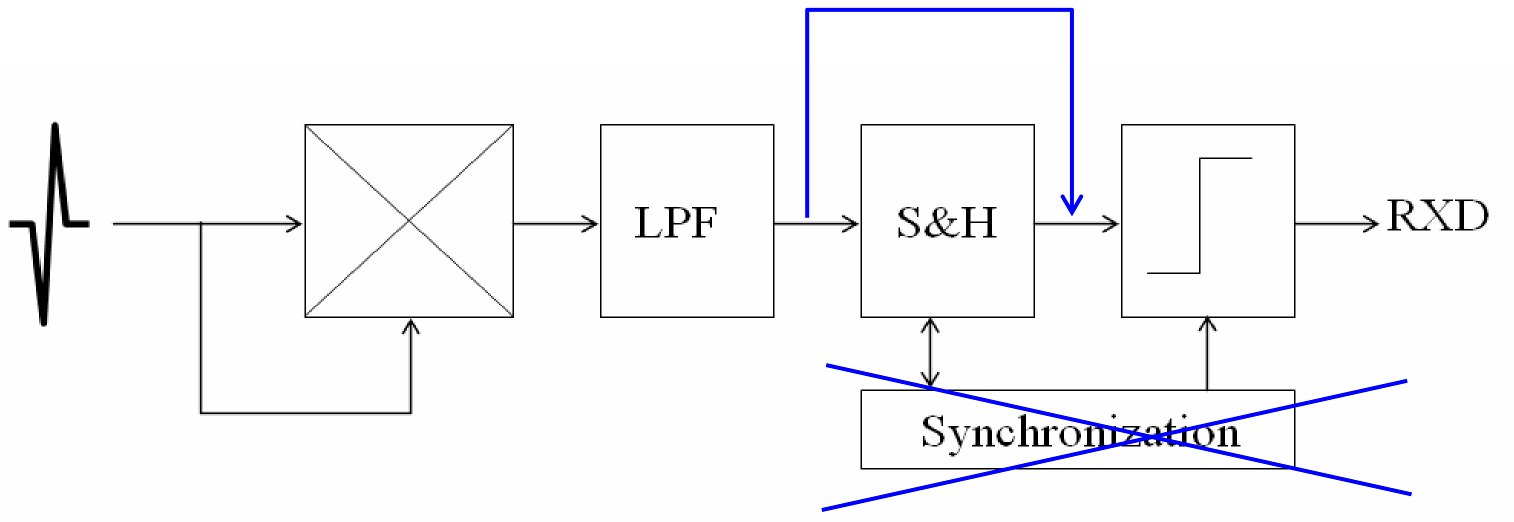
And 800 mW of power consumption!

BASIC RECEIVER TECHNIQUE



SYNCHRONIZATION ISSUES

- Another aspect is the simplicity of the UWB receiver
- Asynchronous energy detection with only bit synchronization



IST-PACWOMAN RESULTS

- A physical layer for UWB based WPAN communication system has been presented
- Transmitter is fully digital circuit + analog LPF
- Receiver uses simple square-law detector
- Receiver performs well in channels with LOS component
- Demonstrator: downscaled version (f/3) at fc = 1.32 GHz

OTHER ISSUES: TH-UWB MAC PROTOCOL CONSIDERATIONS

- Operation
  - Each user is assigned a unique TH sequence
  - TH-SSMA operation is asynchronous
  - Any user can transmit at any time (i.e., via the unique TH sequence)

- TH-UWB MAC parameters
  - TH code, T_f, T_p
  - Number of pulses per bit
  - Link quality measures
  - Other parameters describing pulse shape and duration…

- TH-UWB code parameters
  - Code allocation process
  - Code length or period (N_p)
  - N_h shift ($N_h T_c \leq T_f$)

The codes are important for user detection, as well as identification

Source: Iacobucci, Foerster, Win

OTHER ISSUES: TO ADOPT OR DEVELOP AN UWB MAC PROTOCOL?

- UWB MAC questions
  - Are standard MAC protocols applicable to UWB (e.g., 802.11b)?
  - What, if any, UWB specific features may be required within the MAC?
  - Can the UWB MAC facilitate coexistence with other systems (e.g., WLAN) and how?
- Special TH-UWB MAC design considerations
  - Synchronization of received packets at different receivers in a multicast network based on localization capabilities of UWB [Foerster]
  - The ability to trade range for throughput (PRF and peak power can vary inversely providing for constant average power) enables signalling of different data rates on a per packet or link basis based on the range [Foerster]

Source: Iacobucci, Foerster, Win

OUTLINE

- Introduction to UWB
- The UWB channel, propagation and antennas
- Frequency domain solutions, advantages and limitations
- Time Domain solutions, advantages and limitations
- Summary and concluding remarks

SUMMARY OF POTENTIAL BENEFITS

- Low cost, low power
  - Carrierless, direct baseband signal
  - Minimal RF, no mixers or filters
  - Low complexity design
  - Low duty cycle operation
- Potential for high capacity
  - Large effective processing gain
  - Share the spectrum with many users
- Low interference
  - Low noise power spectral density
  - Large effective processing gain
- Frequency planning
  - Ideally, not required…
- Potential resistance to interference
  - Large effective processing gain
- Good multipath resistance
  - Enables simpler designs
  - Improved TOA resolution
  - Location to within a few cm
- Low frequency/high bandwidth
  - High penetration

Not a revolution, but a technology whose time has come.

SUMMARY OF KEY ISSUES AND LIMITATIONS

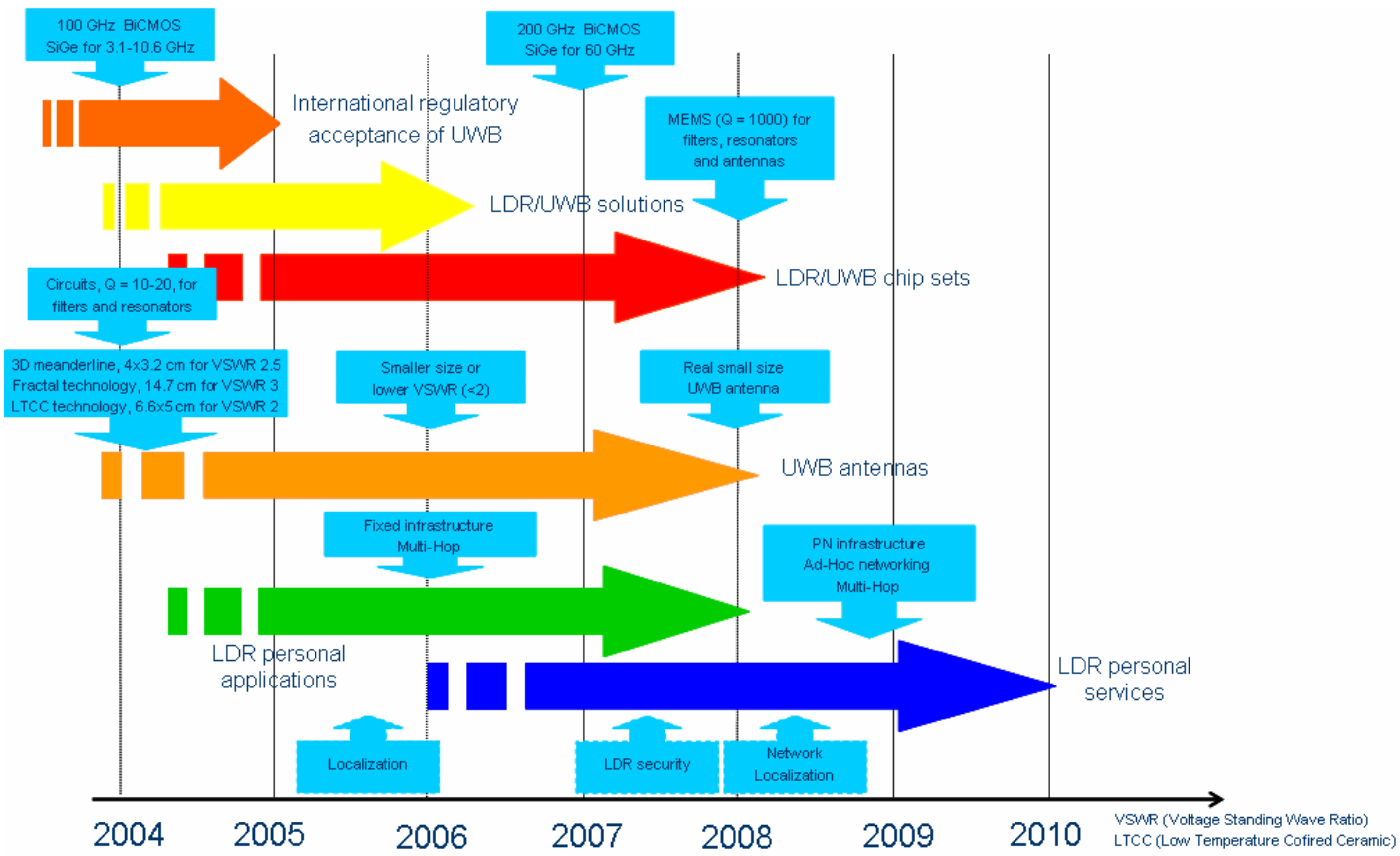
- Regulatory
  - Limits and thresholds
  - System aggregation
  - Frequency bands
  - Wireless internet connectivity
- Standardization
  - Standards remain in development…
  - Process may be lengthy
- Performance
  - Synchronization/timing jitter
  - Guard time and overhead
  - Susceptibility to interference
- Short range
  - Typically, a few meters to a few km
  - Low power direct pulse operation
  - Low antenna transmit efficiency (BW ~ 1/QF)

Regulatory issues still remain to be resolved.

CONCLUDING REMARKS

- UWB is a very promising technology!
  - Low cost, low power
  - LDR/MDR as well as HDR communications
  - More than just communication though
- UWB applications and products can have a substantial impact on a wide range of markets
  - Communication, localization, automotive (radar)…
- Practical considerations, such as interference and the need to avoid certain bands can have a non-trivial impact on the actual performance and cost of UWB systems
- Regulatory approval is required before the potential benefits of UWB can be commercially realized

WHERE ARE WE GOING? A TECHNOLOGY ROADMAP FOR LDR UWB



Source: IST Prodemis