System design considerations for high speed UWB wireless communications

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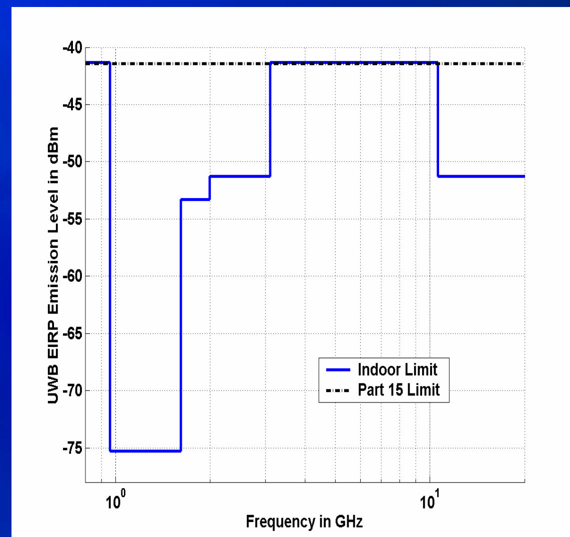
Outline of Talk

- Introduction to UWB
  - Definition
  - Capacity considerations
  - Applications and usage models
- The UWB Propagation Channel
  - Channel Measurements and Modeling
  - Implications for System Design
- UWB architectural options and design trade-offs
  - Impulse radio
  - Multi-carrier
- Other design challenges – e.g., coexistence
- Conclusion

Introduction to UWB

UWB for Communication – A First Definition

- **Bandwidth definition:**
  - occupied fractional BW > 0.2 or
  - absolute BW > 500 MHz
- **Power spectral density limited**
- **FCC R&O opens up 3.1 to 10.6 GHz frequency band for UWB communications systems**



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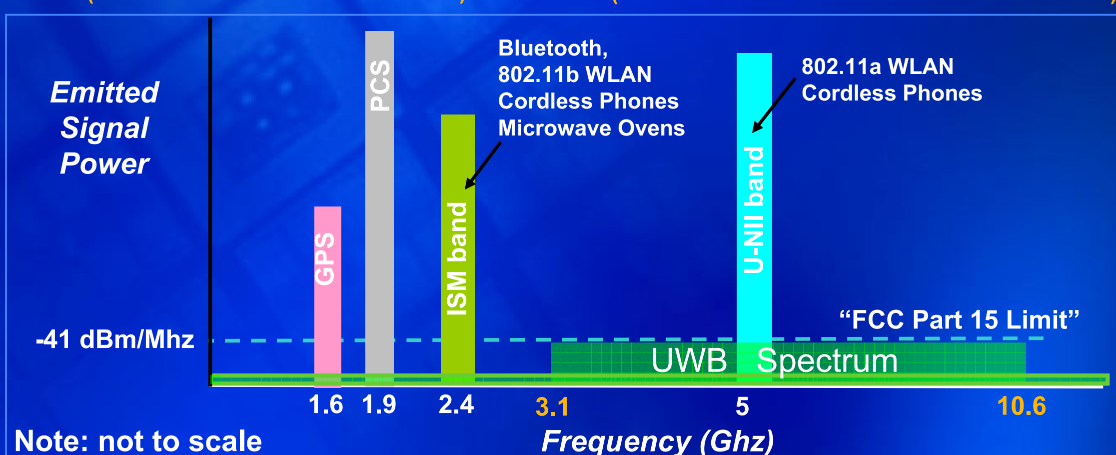
UWB spectrum regulations

- **FCC ruling permits UWB spectrum overlay**
  - GPS (Global Positioning System)
  - PCS (Personal Communication Services)
  - ISM band (Industry Scientific Medical)
  - U-NII band (Unlicensed National Information Infrastructure)



- **UWB is presently legal only in the US**
  - Regulatory activity underway in Europe, Japan, and China
- **Consistent "rules of the game"**
  - Open standardization is critical for worldwide market adoption

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Very Low Power Spectral Density (PSD)

- FCC limits ensure that UWB emission levels are exceedingly small
  - Part 15 limits: –41.25 dBm/MHz
  - At or below spurious emission limits for <u>all</u> radios and unintentional emitters
  - Limits the Power Spectral Density [W/Hz] and *not* total average transmit power as is typical with other unlicensed bands [e.g. 5 GHz];
    - Avg. transmit power scales with BW
- Total emitted power over several gigahertz of bandwidth is a fraction of a milliwatt

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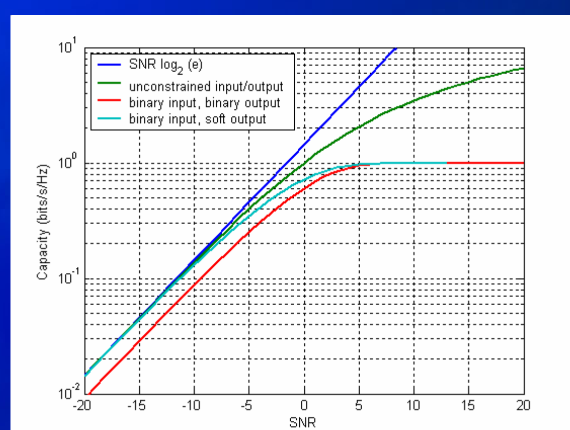
UWB Channel Capacity

- Capacity in AWGN (bits/s/Hz)

$$C = \log_2(1+SNR)$$

- High SNR regime: SNR > 0 dB or C > 1 bit/s/Hz
  - $C = \log_2(SNR)$: capacity increases logarithmically with SNR
    - 1 bit/s/Hz for every 3 dB increase in SNR
  - Use higher order modulations to increase rate - e.g. narrowband, bandwidth efficient systems such as 802.11a/g, etc.



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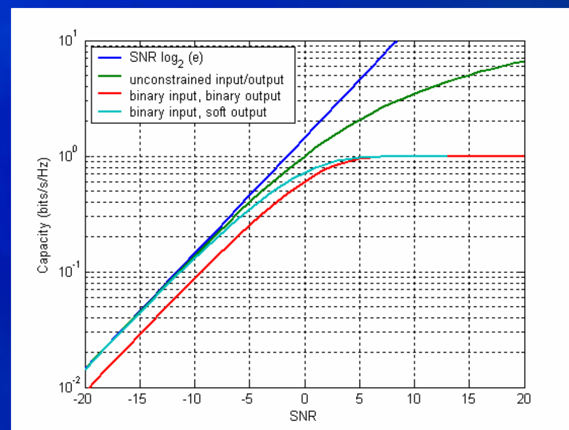
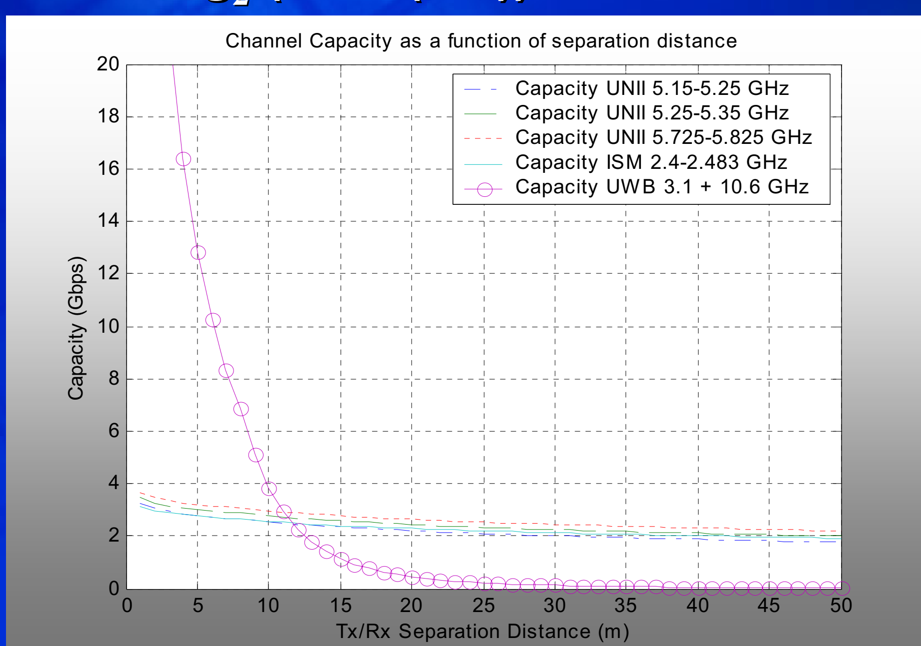
UWB Channel Capacity

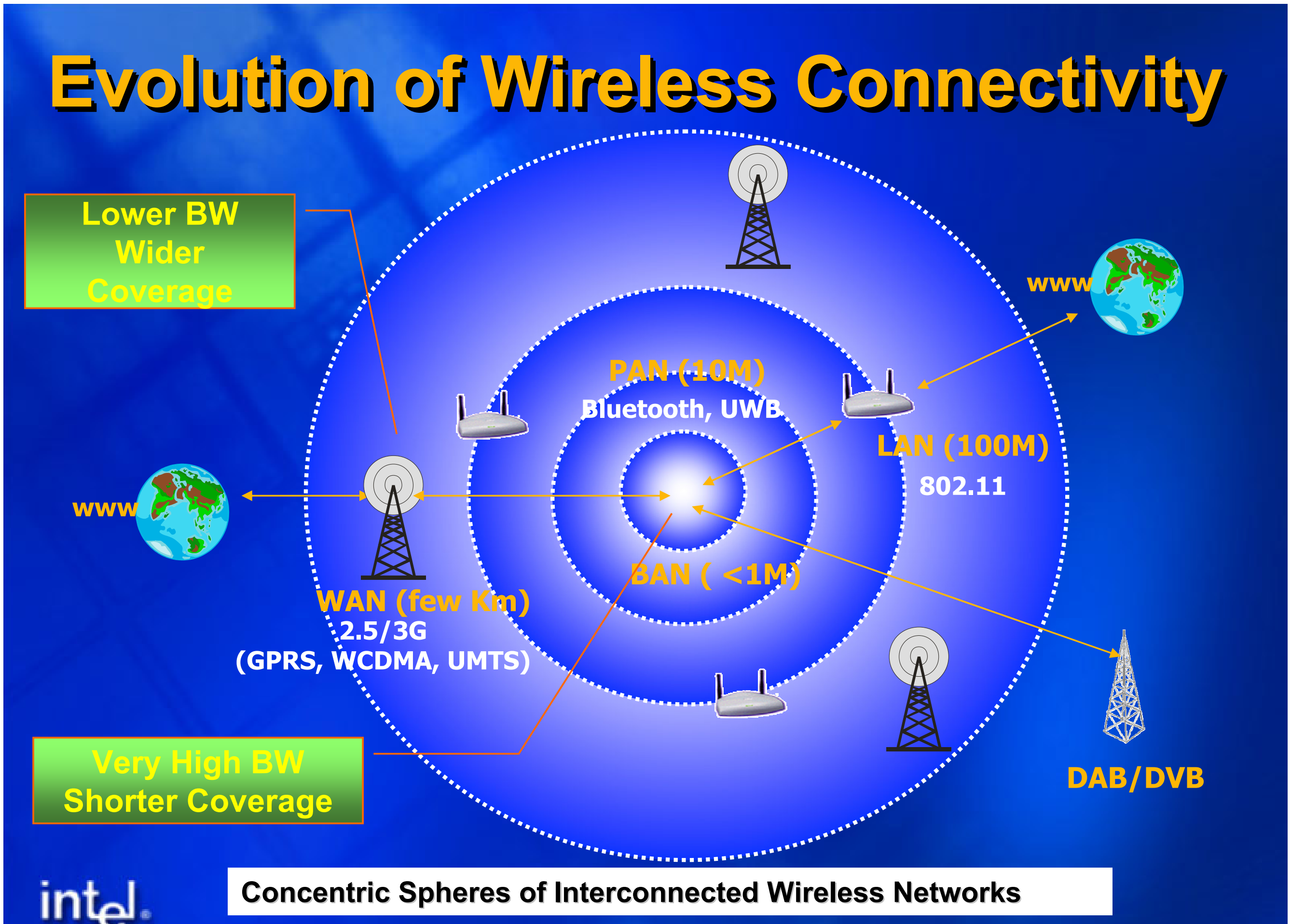
- Low SNR regime: SNR < 0 dB or C < 1 bit/s/Hz
  - C = SNR $\log_2 e$: capacity increases linearly with SNR
    - Coding gain plays much bigger role than in high SNR regime
  - Binary modulation gets us close to optimality – no gains from using higher order modulation
  - Use bandwidth to increase rate: e.g., *UWB*



UWB Channel Capacity

- Capacity at 10 meters vs. UWB BW
  - $C = B \log_2 (1+ P/(BN))$




Evolution of Wireless Connectivity
Lower BW
Wider
Coverage
www
PAN (10M)
Bluetooth, UWB
LAN (100M)
802.11
www
BAN (<1M)
WAN (few Km)
2.5/3G
(GPRS, WCDMA, UMTS)
Very High BW
Shorter Coverage
DAB/DVB
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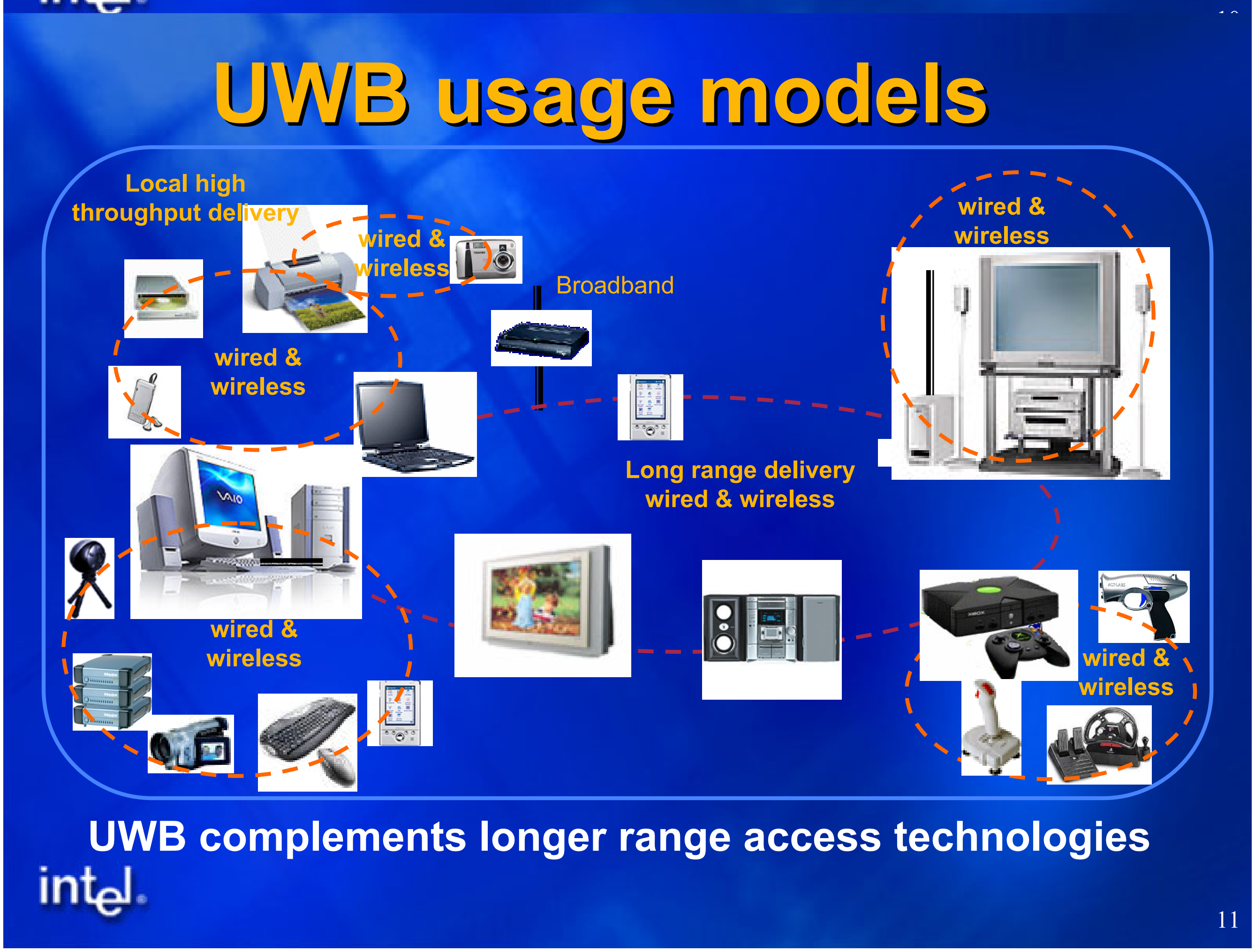
Concentric Spheres of Interconnected Wireless Networks


UWB usage models
Local high
throughput delivery
wired &
wireless
Broadband
wired &
wireless
wired &
wireless
Long range delivery
wired & wireless
wired &
wireless
wired &
wireless
UWB complements longer range access technologies
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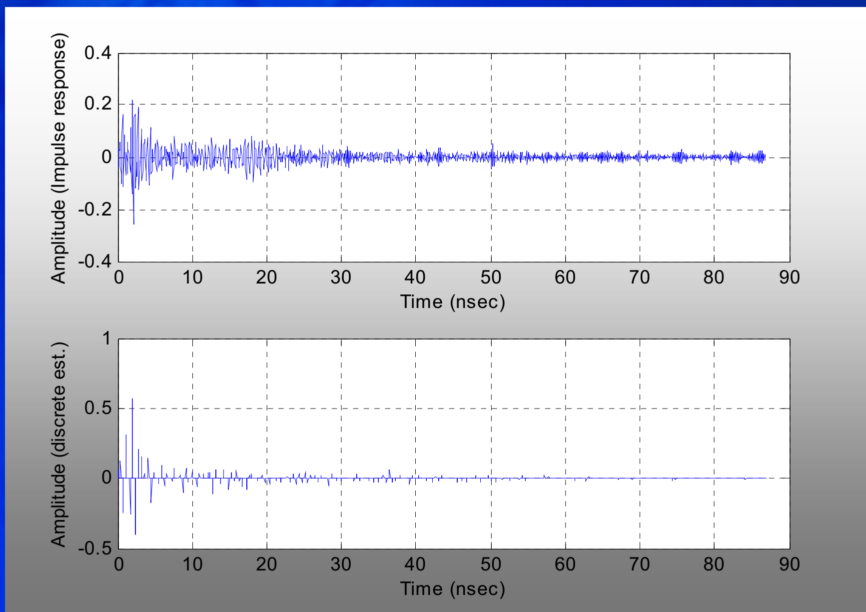
UWB Indoor Multipath Channel

Indoor Multipath Propagation

- Channel model is essential for evaluating different PHY approaches
- IEEE 802.15.3a Channel modeling sub-committee formed to come up with a model to use in evaluation of proposals
- Sub-committee received many contributions from AT&T, IMST, Intel, Mitsubishi, Time Domain, and others
  - Multiple sets of measurements that span home and office settings
  - Some sets cover 3-10 GHz frequency range

Indoor Multipath Propagation

- Example NLOS Multipath Realization



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Multipath Channel Characteristics

Target Channel Characteristics[5]	**CM 1**[1]	**CM 2**[2]	**CM 3**[3]	**CM 4**[4]
Mean excess delay (nsec) τ_m	5.05	10.38	14.18	
RMS delay (nsec) τ_{rms}	5.28	8.03	14.28	25
NP_{10dB}			35	
NP (85%)	24	36.1	61.54	
Model Characteristics[5]				
Mean excess delay (nsec) τ_m	5.0	9.9	15.9	30.1
RMS delay (nsec) τ_{rms}	5	8	15	25
NP_{10dB}	12.5	15.3	24.9	41.2
NP (85%)	20.8	33.9	64.7	123.3
Channel energy mean (dB)	-0.4	-0.5	0.0	0.3
Channel energy std (dB)	2.9	3.1	3.1	2.7

* Times expressed in nano-seconds

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Multipath Channel Characteristics

- High-level observations based on measurements
  - RMS delay spread smaller at the shorter ranges (< 10 meters)
    - 5-25 nsec vs. 50+ nsec for WLANs
  - Number of resolvable paths increases as bandwidth increases
    - Channel energy spread over a large number of paths
  - Clustering of arrival times observed in several measurements
    - Saleh-Valenzuela (S-V) model, Δ-K model, Deterministic echo modeling, etc. as proposed models
  - Best fit to per path fading amplitude follows log-normal distribution

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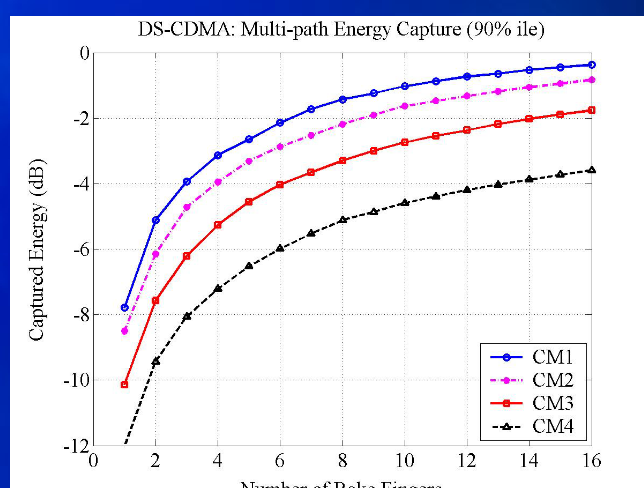
Multipath Channel Characteristics

Efficient multipath energy capture critical to system design

- Example using DSSS UWB system:
  - Optimal timing information.
  - Perfect channel estimation.
  - Largest RAKE fingers over the entire span of the channel impulse response are selected.
  - No shadowing
  - Does not reflect degradation due to ICI/ISI.
  - Loss in captured energy averaged over all 100 channel realizations.
- Observations:
  - 90th %-ile channel realization has a loss of 3.8 dB with a 16 finger RAKE for CM4 channel environment.
  - 90th %-ile channel realization has a loss of ~2 dB with a 16 finger RAKE for a CM3 channel environment.



*J. Balakrishnan, et. al. , Texas Instruments

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Multipath Channel Modeling

- Mathematical model
  - Poisson point process used to determine arrival times of both clusters and rays within a cluster (following S-V model)
  - Amplitudes modeled as product of a log-normal shadowing and log-normal fading term
  - Model parameters can be found in IEEE 802.15.3a channel modeling sub-committee final report

$$h_i(t) = X_i \sum_{l=0}^{L} \sum_{k=0}^{K} \alpha_{k,l}^{i} \delta(t - T_l^{i} - \tau_{k,l}^{i})$$

X_i = shadowing

$\alpha_{k,l}$ = multipath amplitudes

T_l = the arrival time of the first path of the *l*-th cluster;

$\tau_{k,l}$ = the delay of the *k*-th path within the *l*-th cluster relative to

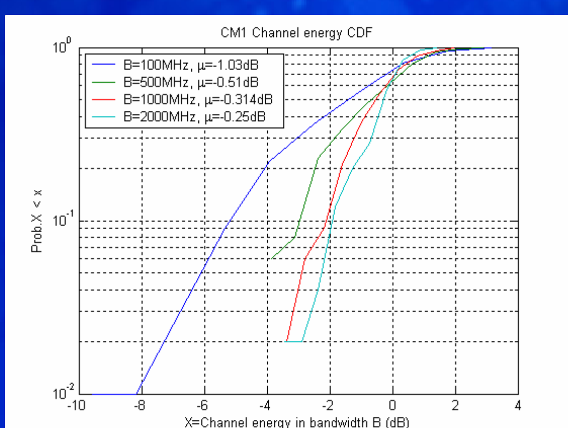
UWB System Bandwidth

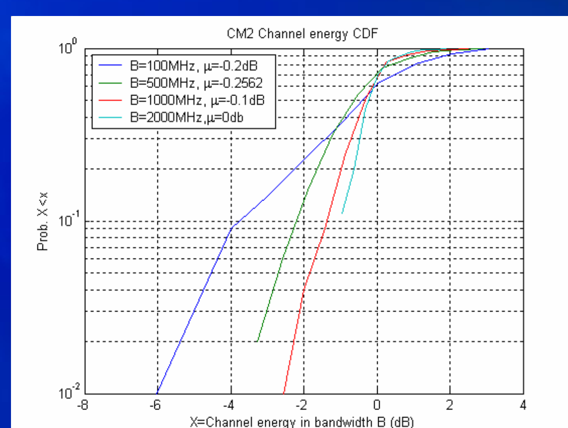
- Advantages for wider bandwidth:
  - FCC's UWB regulations are p.s.d. based : transmit power increases with the bandwidth.
    - But higher propagation losses at high frequencies limit benefit to link
  - Multiple access performance:
    - Link throughput is proportional to the bandwidth.
    - Multiple access isolation, d_{ref}/d_{int} ~ sqrt (bandwidth)
  - Better Immunity to Frequency-Selective Fading
- Disadvantages of wider bandwidth:
  - typically results in higher cost, power.

UWB System Bandwidth

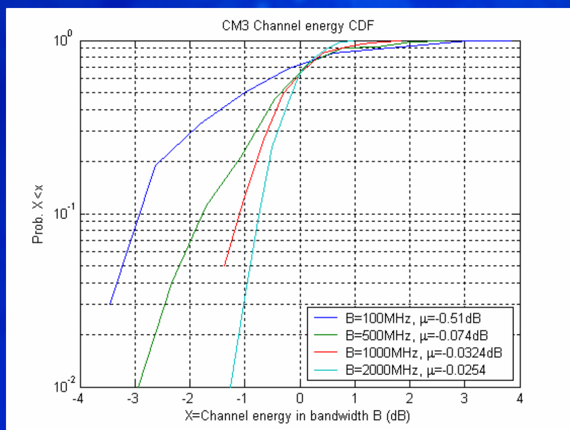
- One of the key advantages to Ultra-Wide-Band technology is its inherent immunity to frequency-selective fading.
  - function of the ratio of bandwidth to center frequency.
- Narrowband signals cannot resolve multipath components.
  - the entire frequency band could fall in a deep spectral null.
- Impact of channel bandwidth on multipath characteristics:
  - Consider 100 normalized channel impulse responses for each CM environment
  - Filter the channel responses at specified bandwidth B, centered at f_c = 5 GHz
  - Plot CDF of energy in filtered channel

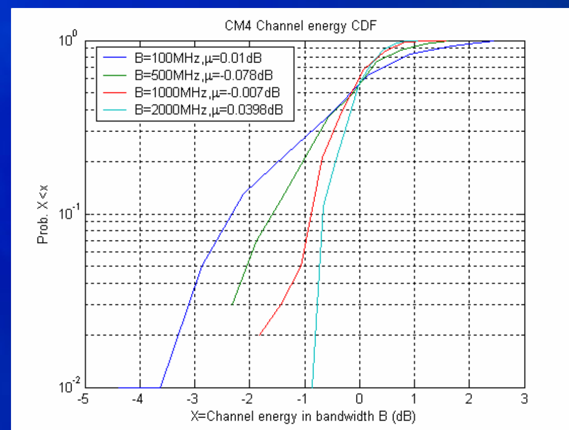
Effect of channel bandwidth





Effect of channel bandwidth





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Effect of channel bandwidth

- Based on these data, it appears there's relatively little difference between the 500 MHz curves and the 2GHz bandwidth curves
  - 500 MHz channels should offer reasonable immunity from fading

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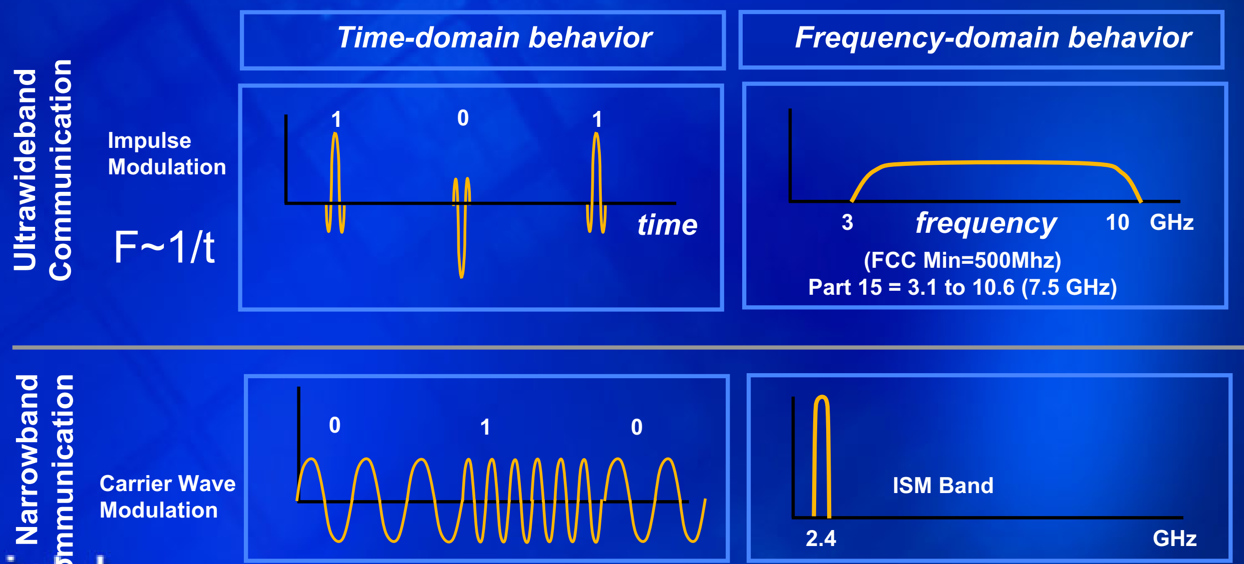
UWB Architectural Options and Design Space

Possible architectures for high-rate UWB systems

- Starting point for communications systems
  - 7.5 GHz of new, unlicensed spectrum
    - Spectral mask from 3.1-10.6 GHz
      - Different indoor/outdoor masks
  - 500 MHz minimum instantaneous BW per transmission
  - Power spectral density limit (- 41.3 dBm/MHz)
  - Peak power limits
  - No legacy limitations or backward compatibility requirements

Impulse Radio…the first UWB design

- Radio technology that modulates impulse based waveforms instead of continuous carrier waves



UWB System Architectures

- But…many other options are available
  - (1) Impulse radio based
    - Single impulse occupies 3.1-10.6 GHz or some subset
  - (2) Continuous single-carrier based
    - Direct sequence spread spectrum techniques extended to GHz chip rates
  - (3) Multi-carrier based
    - Divide spectrum into a number of 'carriers'
    - Multi-carrier CDMA, OFDM, multi-banding (frequency hopping)
  - (4) Hybrid approaches
    - MB-OFDM, pulsed multi-banding, pulsed DS-CDMA

UWB System Architectures

- **Key challenges:**
  - Multipath energy capture
  - Robustness to NBI
  - Tx spectrum flexibility
    - Adapt to future international regulations
    - Adapt to current and future narrowband services
  - Multiple access and near-far effects
    - Peer-to-peer and ad hoc usage will result in near-far problems
  - Low cost and low power consumption
    - Desire systems which are CMOS friendly

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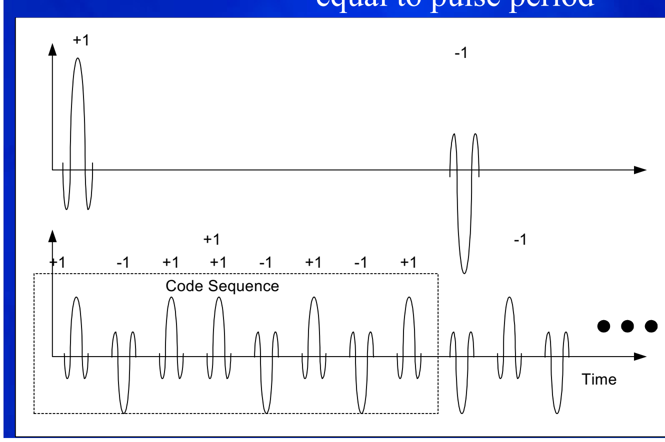
Design Parameters

- **Spreading / coding / *pulsing* / equalization**
  - Similar trade-offs for high-rate CDMA systems + new design parameter: *pulsing*
  - When is it better to spread vs. pulse?
    - In multipath…
      - Spreading (non-zero chips) will experience inter-chip interference (ICI) due to non-zero autocorrelation with delays
      - Pulsing (zeros between pulses) is orthogonal to multipath spreads not equal to pulse period



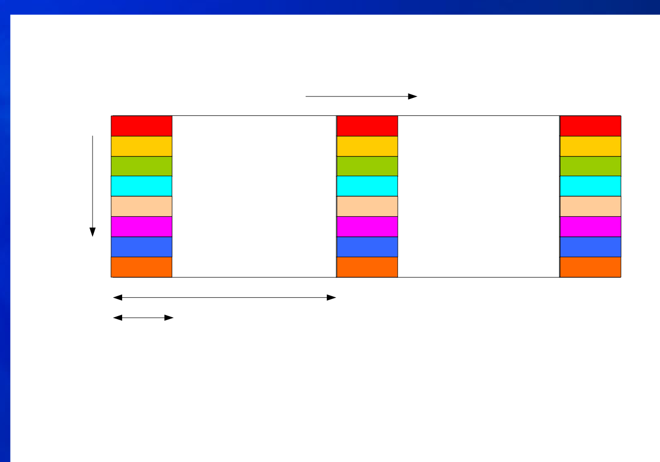
- In multi-user environment…
  - Spreading results in processing gain which reduces multiple access interference (MAI) after de-spreading
    - Multipath components from interferer increases level of MAI
  - Pulsing experiences collisions and error probability ~ collision rate ~ 1 / pulse separation period

Design Parameters

- Comments on pulsing / spreading trade-offs
  - Pulsing offers good performance in multipath
    - Non-overlapping paths are orthogonal to each other
  - Spreading offers good multiple access interference mitigation
  - Performance of both are comparable when multipath and MAI are considered
    - Not losing anything by pulsing
- Comments on coding / equalization trade-offs
  - Treat ISI as noise, and mitigate through low-rate code, spreading, and rake
  - Equalize ISI with linear equalizer (use preamble to estimate channel coefficients or as training sequence)
  - Joint decoding/non-linear equalizer (use decoded bits in DFE)
  - Use OFDM waveform with FFT in receiver to capture energy with cyclic prefix which mitigates ISI

UWB System design approaches

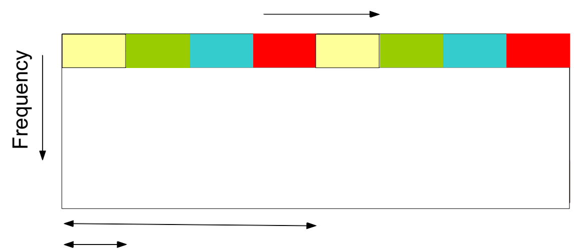
- "Carrier" or wavelet based approaches dictated by
  - FCC spectral mask
  - Overlay of NB interfering systems
- Combine spreading and pulsing for
  - Good range in multipath
  - Good MAI performance
  - Ease NBI suppression complexity
- One approach – pulsed multi-carrier CDMA (MC-CDMA):
  - Spreading / coding in the frequency domain
  - Pulsing in the time domain



UWB System design approaches

•Stagger bands in time to relax receiver requirements

•avoid wideband ADC/DACs, mixers etc.

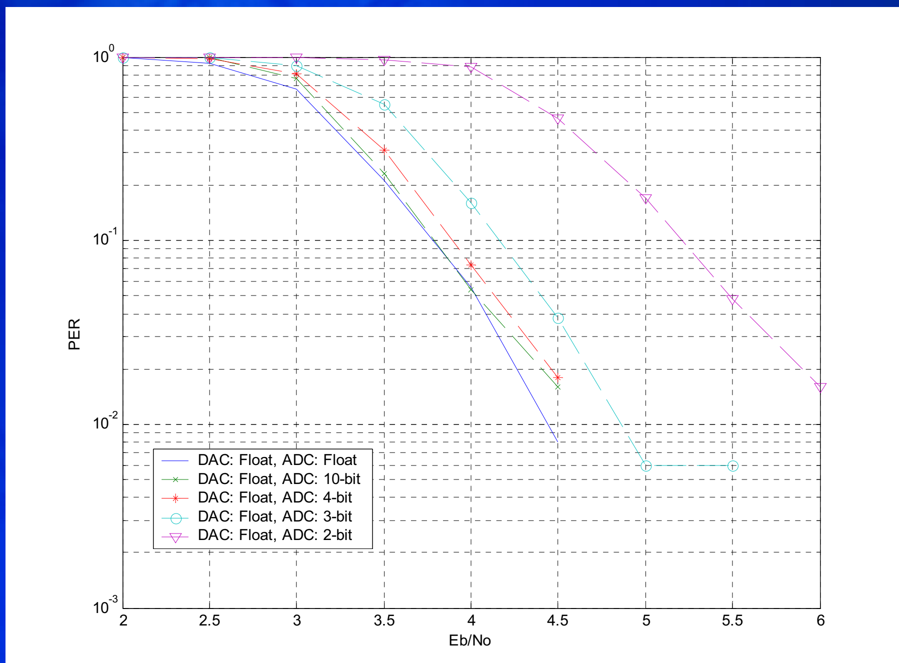


Receiver Architectures

- Analog correlation
  - Pros: Simple implementation, removes NBI before sampling
  - Cons: Inefficient energy capture…need several rake arms
- Direct RF sampling
  - Pros: Reduces number of RF components, single-bit sampling possible
  - Cons: Requires high rate sampler and could be sensitive to strong interferers when single-bit sampling used
- Direct down-conversion with Nyquist sampling
  - Pros: Enables digital energy capture techniques (FFT with OFDM, digital rake)
  - Cons: Requires moderately high-rate ADC, power consumption depends on number of bits in ADC
- Need to efficiently capture multipath energy steers towards a highly digital receiver
- Spectral flexibility dictated by need to co-exist with different narrowband systems, cope with uncertain direction of worldwide regulatory proceedings
- Unique receiver components for UWB:
  - ADC requirements
    - Modulation typically limited to QPSK
    - High spreading factor allows low number of bits in ADC (<4-5 bits possible)
    - Small number of bits allows more power efficient flash ADC architectures
  - Low Peak Tx power (no external PA required)
  - Relaxed phase noise requirements due to low order modulation

Receiver Architectures

- ADC bit trade-offs for UWB systems
  - Example results: MB-OFDM system, 110 Mbps mode, 2x oversampling (1056 MHz), low order baseband filters (CMOS friendly)



IEEE Standards Status

- 2 proposals remain
  - Single-carrier, MBOK, DS-CDMA
  - Multiband OFDM (MB-OFDM)
- Technology Trends
  - Highly digital implementations necessary for efficient multipath energy capture
  - DS-CDMA can use rake + equalizer (either RF sampling or chip-rate sampler expected)
  - MB-OFDM uses FFT + low-rate code using baseband sampler
  - Fundamental architectural differences which yield different implementation challenges and performance characteristics
  - MB-OFDM currently facing regulatory challenges due to frequency hopping nature of waveform and potential interference into wideband receivers
    - However, important to note that differences in the interference caused by the two systems is much smaller than the differences compared to FCC UWB limits being argued in world-wide regulatory bodies for UWB in general.

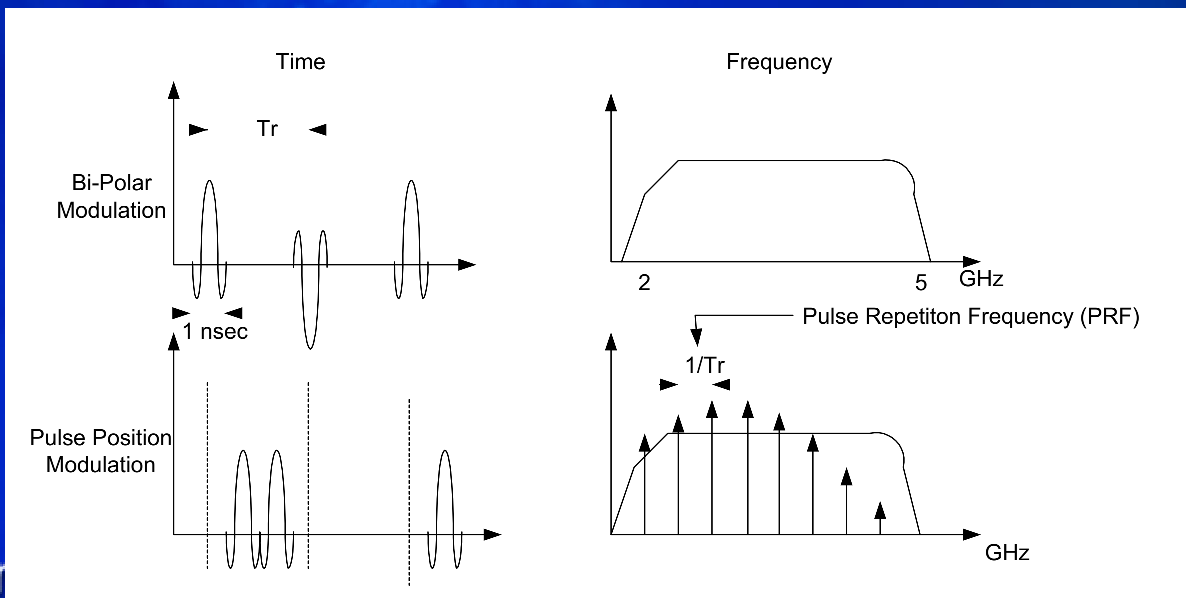
UWB Coexistence

UWB Coexistence

- UWB shall NOT cause harmful interference to other wireless systems
  - UWB (as overlay approach) needs to be proven not to cause harmful interference
    - Regulatory challenges still exist (inside/outside US)
  - Needs to adapt to future spectrum allocations and new spectrum usage models
- Robust to interference from other wireless systems
  - Close proximity operation with 802.11a/b/g/n WLAN systems
    - Home and office
  - Receiver issues to consider
    - Number of ADC bits and non-linear impacts of clipping
    - Dynamic range of LNA and following RF components (mixer, LPF)
    - DSP techniques

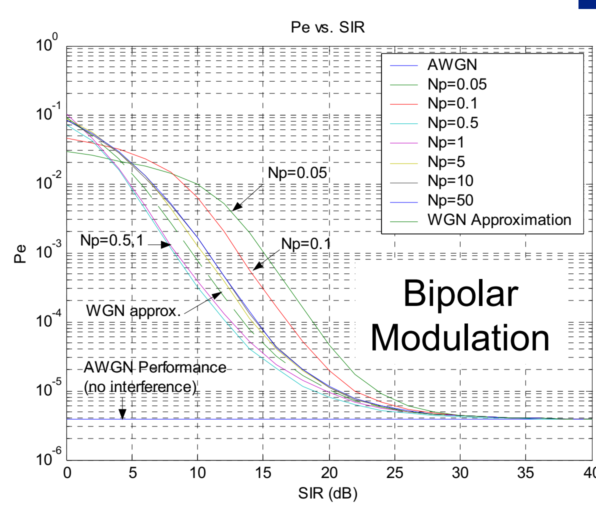
UWB Coexistence

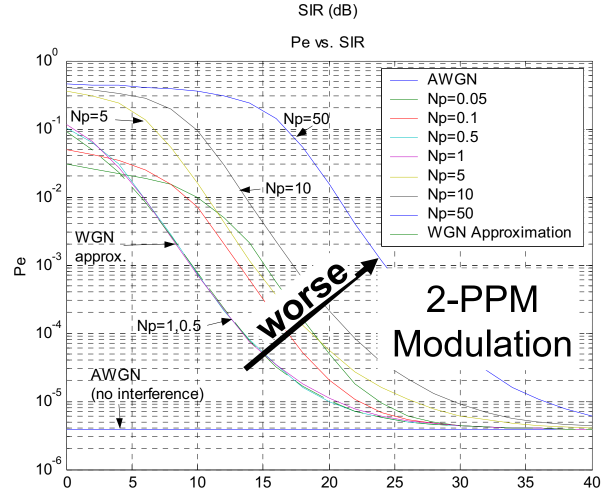
- **Impact of modulation on interference**
  - Need to ensure spectral flatness of waveform
  - Limit spectral line content



UWB Coexistence

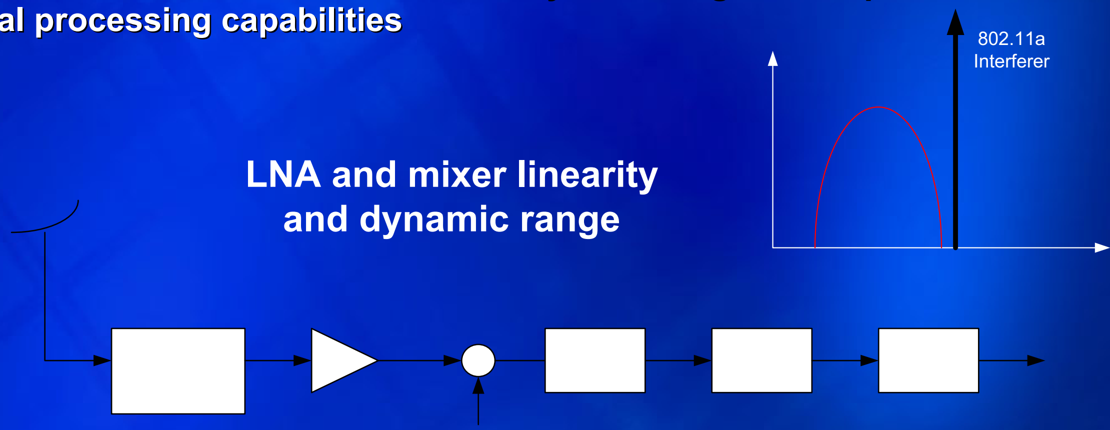
- **How can UWB interference be modeled?**
  - WGN works in most cases
  - Factors that may effect WGN model: modulation, PRF, f_0, and narrowband waveform (bandwidth) and receiver signal processing (coding, interleaving)
  - $N_p = B_p/B_s$: ratio of PRF to symbol rate of narrowband system





Impact of 802.11a on UWB Rx AFE

- Undesired (802.11a interferer) signal level at the antenna:
  - P_{INT} = 16 – 20*log10(4π * 5.15e9 * 0.3/ c) = -20.2 dBm
- Requires a total of ~60 dB attenuation in the 802.11a band
  - Target 20-30 dB attenuation in RF BPF
  - Target 30-40 dB attenuation in LPF in baseband
  - Want to minimize external filters and desire low order baseband filters for easier implementation in CMOS
- Required attenuation can be reduced by balancing ADC requirements and signal processing capabilities



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Conclusions

- A number of interesting architectures exist for high-rate UWB systems
  - UWB uniqueness: achieve high rates using low order modulation and low rate coding / spreading
    - Allows novel implementations which take advantage of waveform robustness
- Area is ripe for future research
  - Adaptive interference detection, avoidance, and suppression techniques
  - Multi-radio design and integration
    - How to integrate UWB and 802.11a into same chip and operating simultaneously?
  - Cognitive radio enabling
    - Select "best" available in space and time: UWB / 802.11a/b/g/n / 802.16 / W-CDMA
    - "best" could be a function of peak throughput, power consumption, QoS, etc.

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Accessing the Ultrawideband Channel

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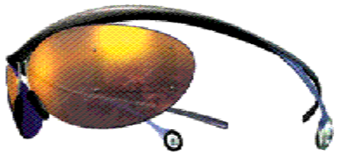
May 23 2004

Outline

- **Introduction**
- **The UWB link**
- **Antennas**
    - ***- definitions***
    - ***- broadband antennas and their characteristics***
    - ***- planar antennas***
- **Circuits**
    - ***- broadband amplifiers***
    - ***- pulse generation and detection***
    - ***- high-speed circuit issues***

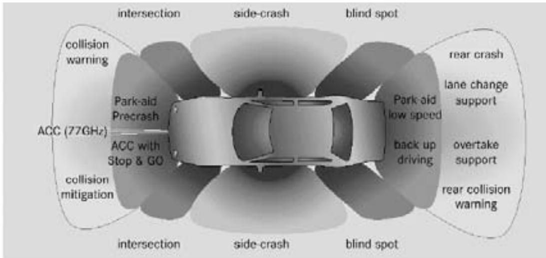
Expanding RF IC Applications

Peer-to-Peer/Ad Hoc Networks

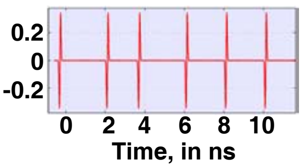


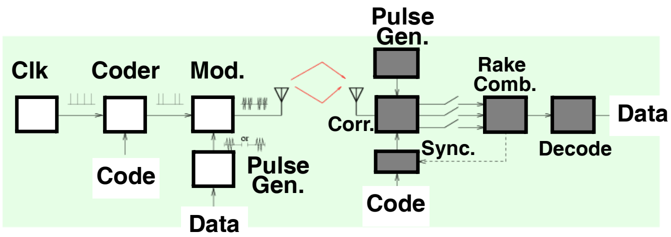
WPAN/Wearable Devices

Ranging and Position Finding



Ultrawideband (time-domain) Radio



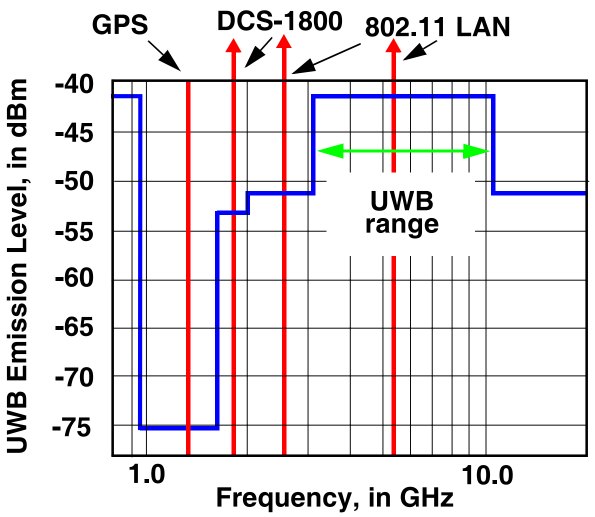


- Radio transmission of coded pulse train at μW/MHz with potential for high data rates (Mb/s) over short distances.
- Unregulated, use of 3-10GHz band approved by FCC.
- Compatible with digital computing technology, simple air interface electronics.
- Antennas and synchronization are scientific challenges.

Ultrawideband (multi-carrier) Radio

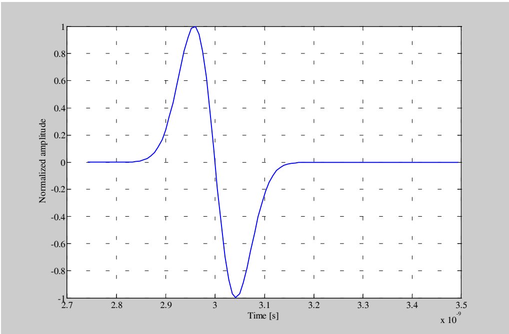
- A multi-carrier system using multiple OFDM carriers in the 3 to 10 GHz band.
- Antennas must also be capable of broadband operation if a single antenna is used, but phase restrictions may be relaxed.
- Can leverage existing narrowband radio hardware in the design.
- Synthesizers must be capable of fast switching in order to hop from one carrier to another efficiently.

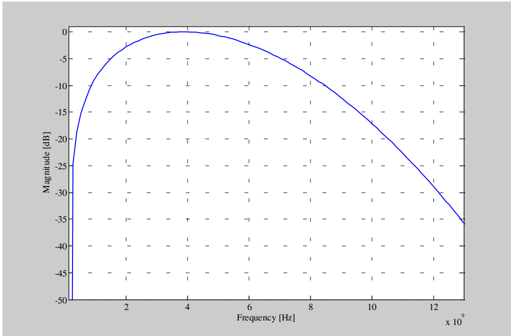
Ultrawideband Power Limits



- Equivalent isotropic radiated power (EIRP) for UWB is -41 dBm from 0-700 MHz and 3.1-10.6 GHz indoors (802.11 permits +16 dBm to +29 dBm in 5.3-5.8 GHz band).

Pulse Shape





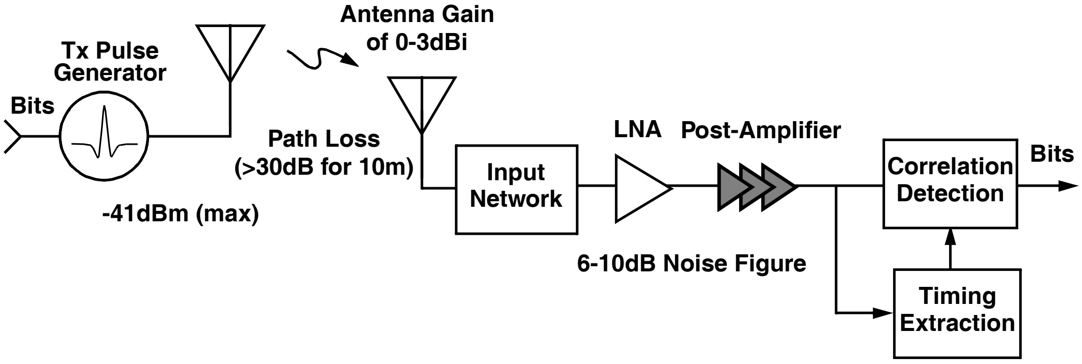
Time Response
0.3ns Gaussian monocycle

$\Im$ ⟷

Normalized Spectrum
-40dB bandwidth is 0.13-13GHz

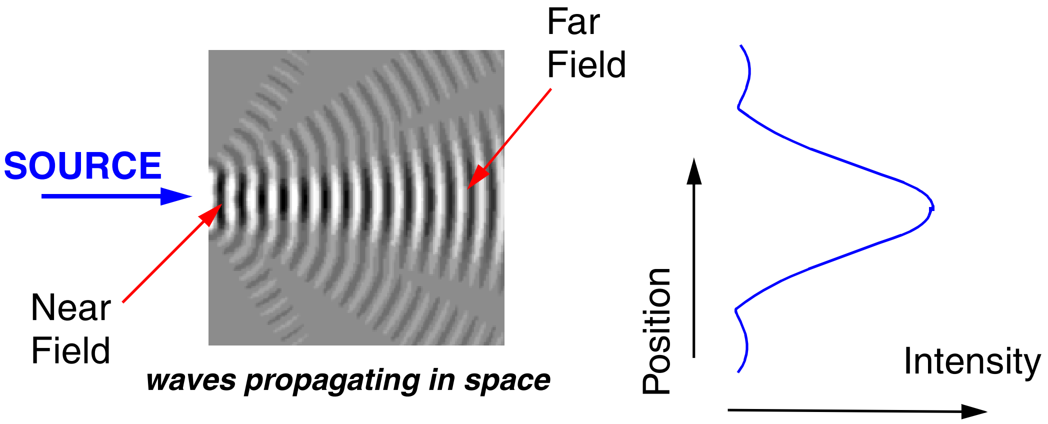
- Using a less bandwidth and sharpening the cut-off (e.g., to meet 802.15 transmit mask and avoid the 802.11a band) requires a damped sinusoidal pulse.

UWB Link



- Max transmit power is -41 dBm between 3.1 and 10.7 GHz. This translates to pulse amplitudes on the order of 100 mV.
- Antenna gain is low for an omnidirectional design, and received power is proportional to $1/f^2$ (2 omni antennas). Path loss can be much greater when obstructions are present.

Antennas

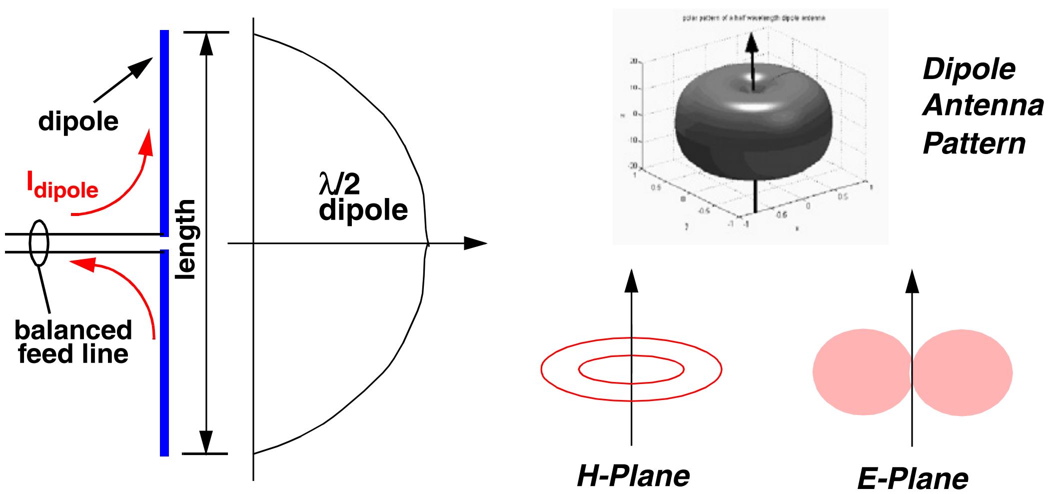


waves propagating in space

pattern from amplitude vs. position

- Antenna connects an RF source to free space. Important parameters are field intensity vs. position (the “pattern), total power radiated, impedance, bandwidth and efficiency.

The Dipole Antenna

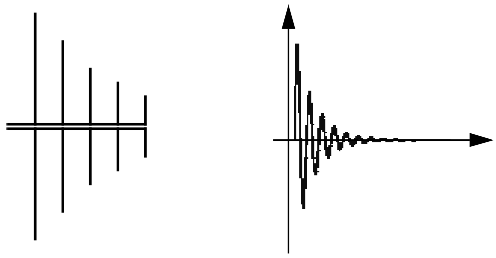


Current Distribution

- Antenna pattern depends upon signal wavelength but electric and magnetic fields are perpendicular (TEM). Gain, bandwidth and input Z are also frequency dependent.

Broadband Antennas

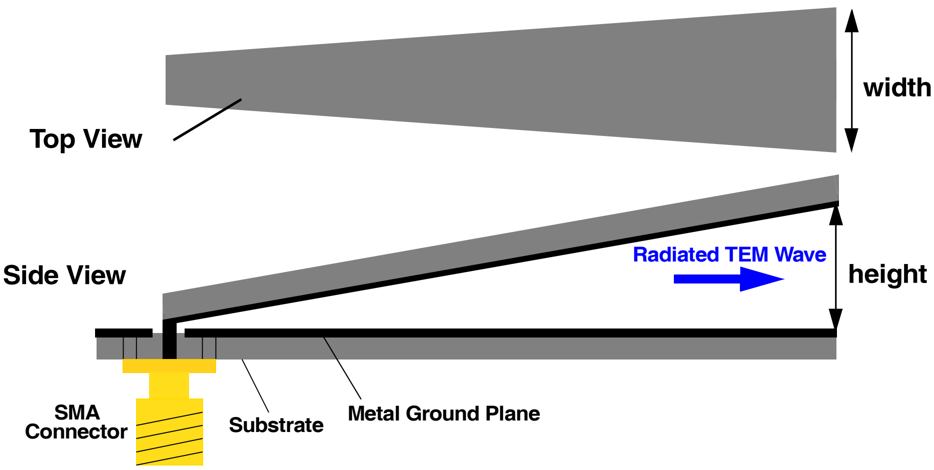
Yagi Antenna (top view)



Butterfly Antenna (elliptical dipole)

- AM band (540-1700 kHz) is UWB since Δf is > f_c. However antenna is tuned to a particular channel (1-2% bandwidth).
- Multi-element antennas (e.g., Yagi-Uda) have broadband amplitude response, but phase response is dispersive.

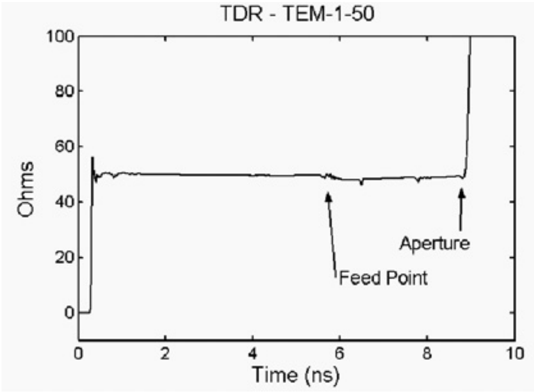
The TEM Horn

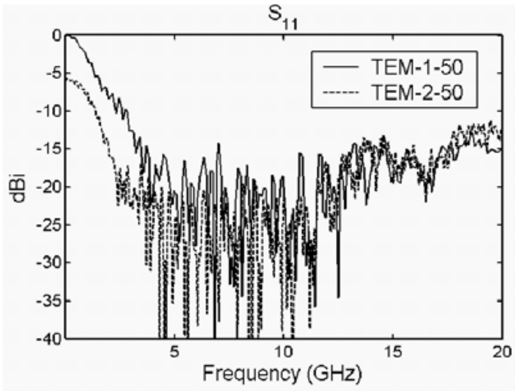


- An open ended transmission line is inherently broadband. Height to width ratio is constant to maintain a near constant impedance. Absorber at end needed to damp reflections.

TEM Horn Receive Antenna

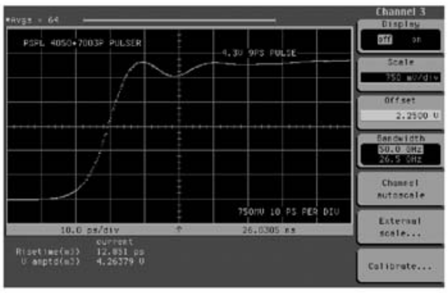
TEM-1-50 TEM_Horn Antenna
(Farr Research Inc.)



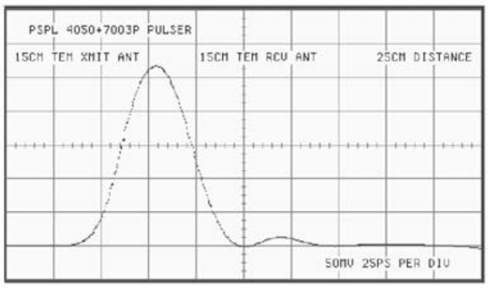


- TEM horn received signal is proportional to the incident field strength. TDR shows a consistent 50Ω input impedance to the aperture; input impedance is ~50Ω from 4-20GHz.

TEM Horn Tx Step Response



4V, 9ps risetime input step*

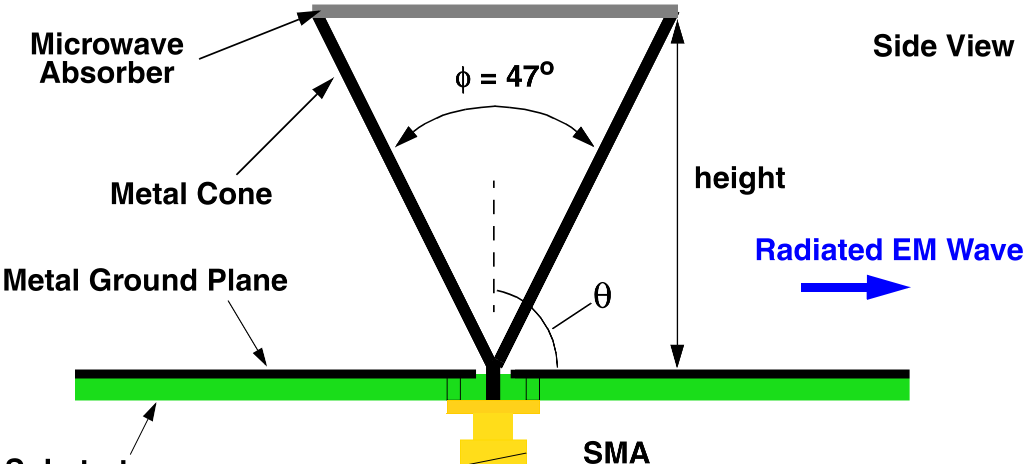


Transmission (l = 25cm) between identical 15cm long TEM horns*

- Response of a tx antenna (time domain) is proportional to the derivative of the response of the same antenna used as a receiver. TEM horn output is the first derivative of electrical signal driving it as shown in plot on right.

*** After J.R. Andrews, 2003 IEEE Conf. on Wireless Communication Technology.**

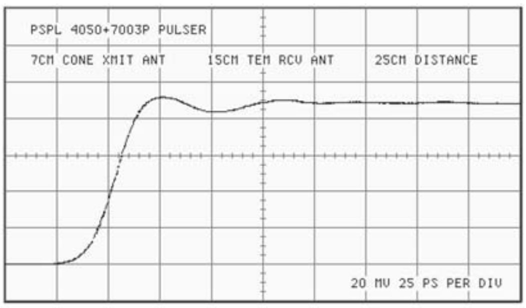
The Conical Antenna



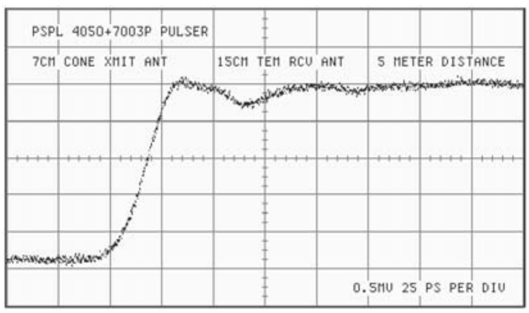
$$Z_0 = \left(\frac{377}{2\pi}\right)\ln\left[\cot\left(\frac{\phi}{2}\right)\right]$$

- Absorber at end damps reflections and ringing caused by finite length. Signals transmitted by the antenna are proportional to sin(θ) and the applied signal.

Conical Antenna Tx Step Response



Transmission (l = 25cm) between 7cm cone and 15cm TEM horn*

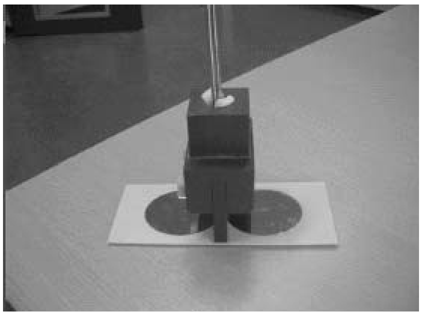


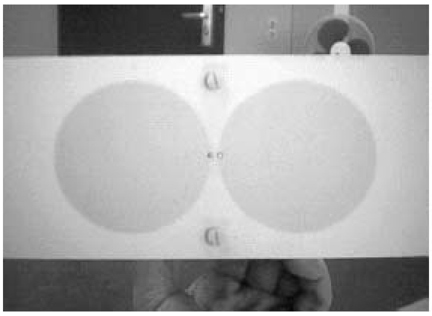
Transmission (l = 5m) between 7cm cone and 15cm TEM horn*

- Conical antenna scales the transmit signal; TEM horn scales the received signal. The received signal is therefore a faithful representation of the transmitted step, and extra path length just attenuates the signal.

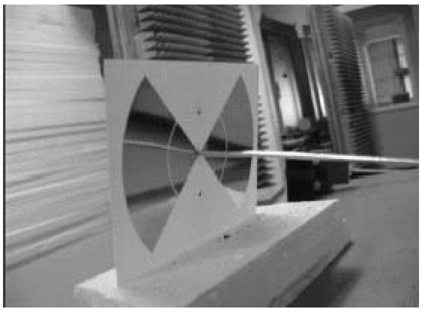
*** After J.R. Andrews, 2003 IEEE Conf. on Wireless Communication Technology.**

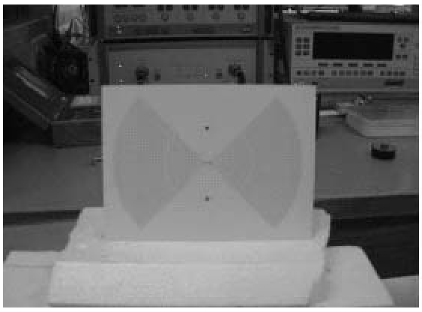
Planar Broadband Antenna Prototypes





Butterfly (3x size)

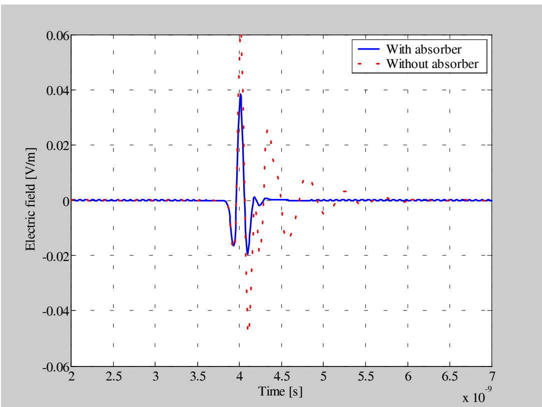


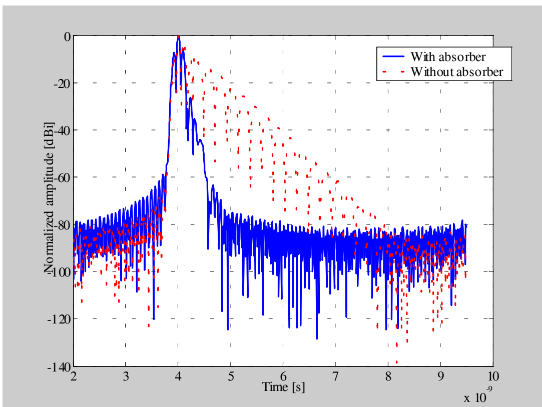


Bowtie (3x size)

*Courtesy of A. Yarovoy, IRCTR/TU DELFT

Time Domain Response



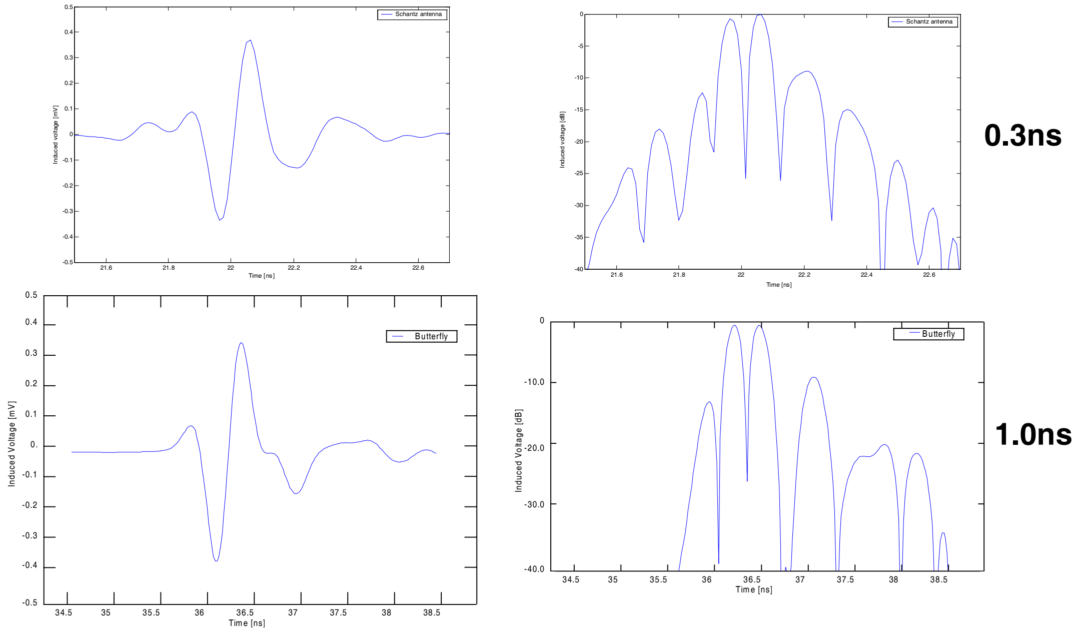


Time Response of Butterfly Antenna (2x2.2cm elliptical flares)

- 0.058 Vp-p amplitude with 57% efficiency.

*Courtesy of A. Yarovoy, IRCTR/TU DELFT

Antenna Comparison

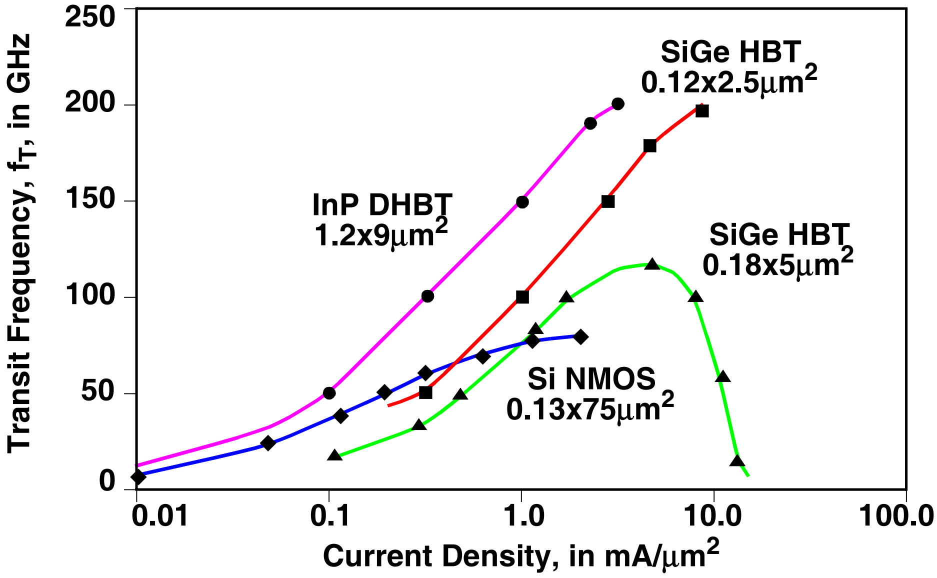


*Courtesy of A. Yarovoy, IRCTR/TU DELFT

Silicon RFIC Technology Evolution

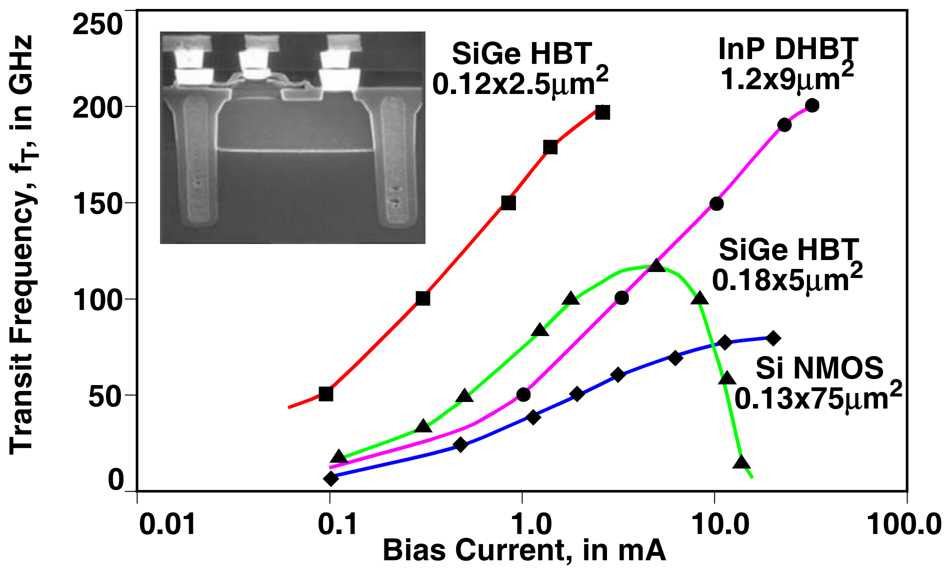
- 1985: polysilicon emitter bjt (10GHz f_T) and scalable models
- 1989: sub-micron bipolar/BiCMOS (mobile phone)
- 1990: TLM backend with 5µm thick IMD oxide (RF passives)
- 1992: UHV epitaxial-base SiGe bjt (50GHz f_T)
- 1995: 0.35µm CMOS with 5LM, 25GHz f_T (Bluetooth)
- 2001: 0.13µm CMOS-SOI, 140GHz f_T (broadband/low power)
- 2002: 0.12µm SiGe BiCMOS+Cu (207GHz f_T/285GHz f_{max})

Active Device Comparison



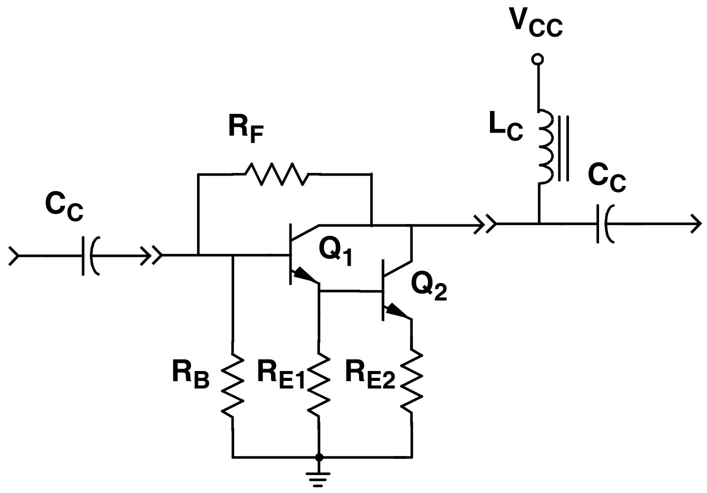
- Strong improvement in active device performance with raw speed of SiGe now comparable with best III-V's.

Active Device Bias Current



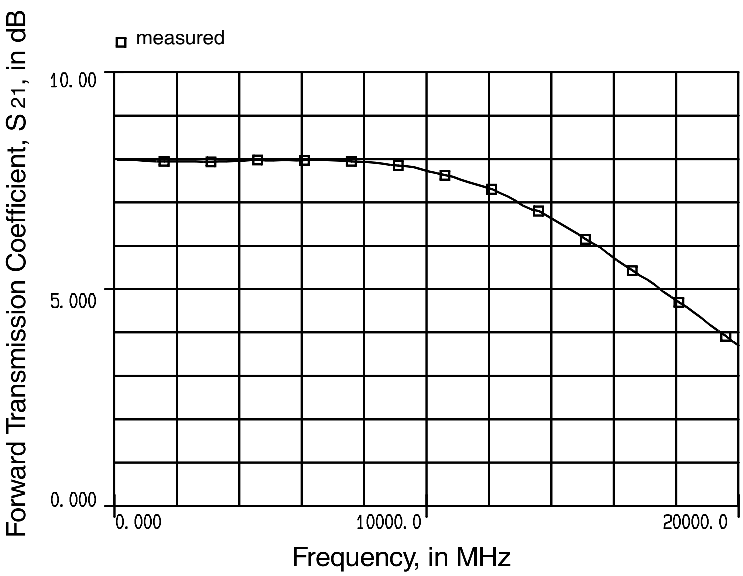
- Silicon devices now outperform III-V's in absolute terms. Opportunity for higher frequency/speed, or to reduce power.

Broadband Gain Block



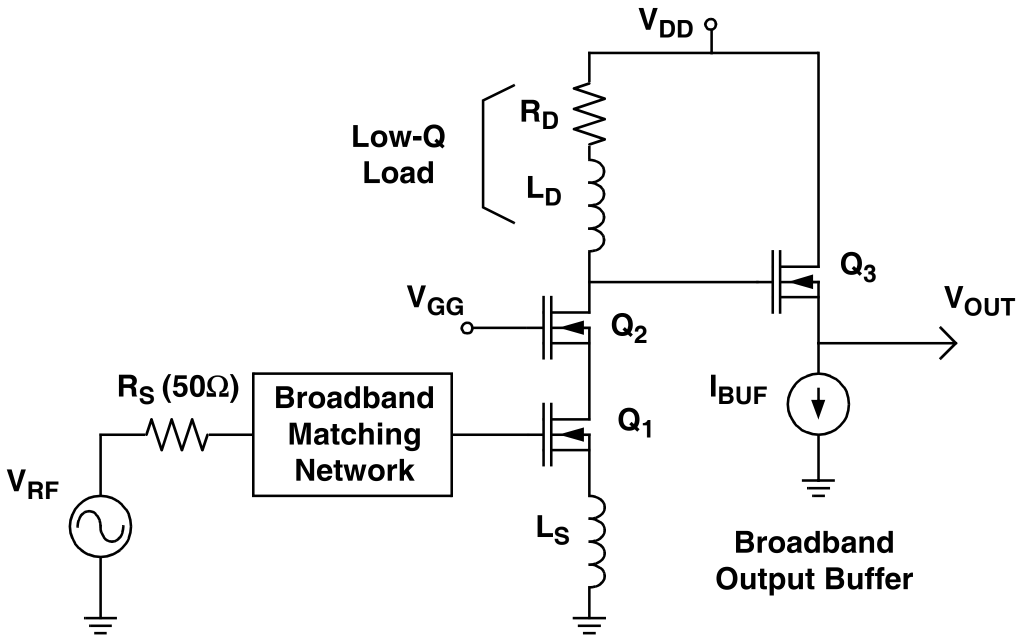
- Cascadable 50 Ohm gain block
- Darlington-connected transistors with compound feedback

Measured Performance (0.5μm SiGe)



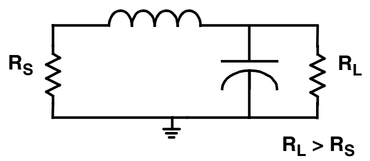
- Noise Figure of 6dB, IIP_3 = +10dBm, P_D of 25mW from a 3V supply.

Broadband Low-Noise Amplifier

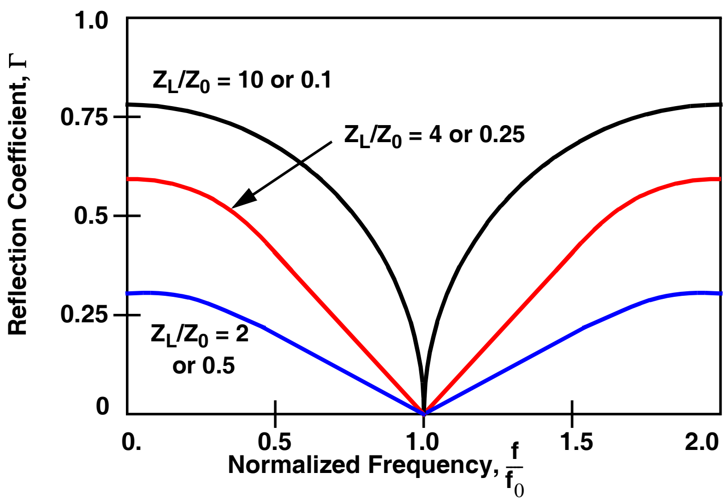


TUDelft RF/MMIC Group ISCAS 2004 Tutorial

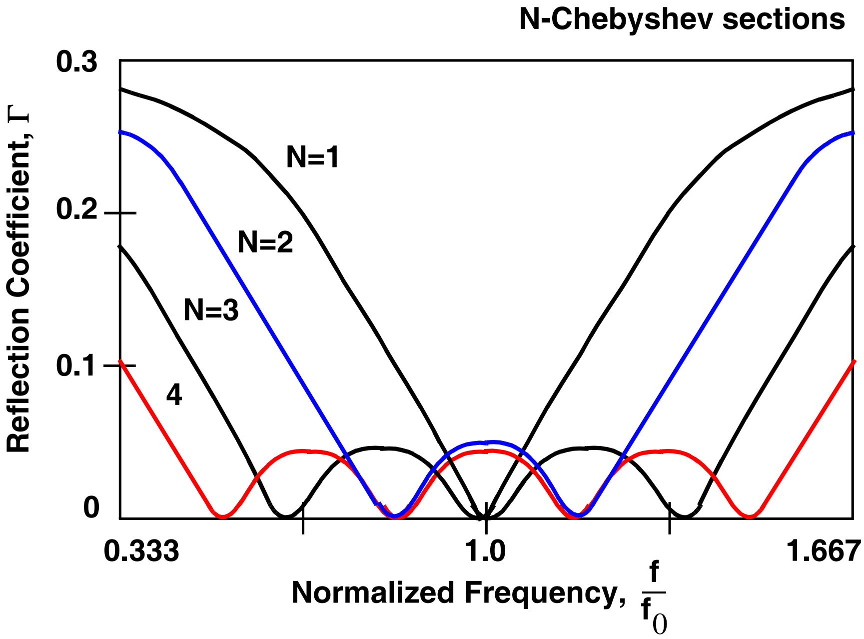
Single Section Matching



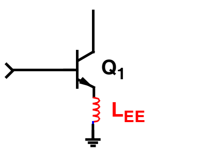
$$\Gamma = \frac{V_{reflected}}{V_{incident}} = \frac{Z_L - Z_0}{Z_L + Z_0}$$



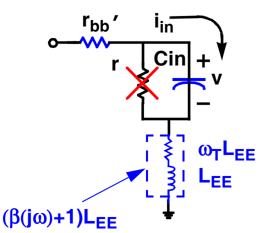
Multi-Section Matching



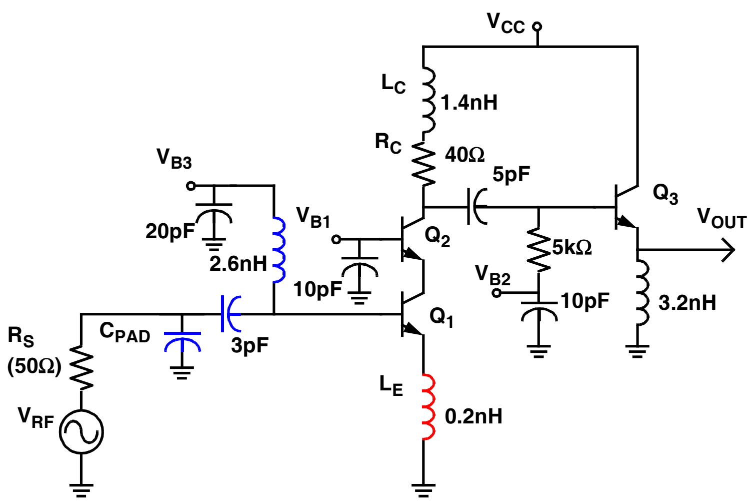
3-10GHz SiGe Bipolar LNA



C-E Amplifier with Emitter Degeneration

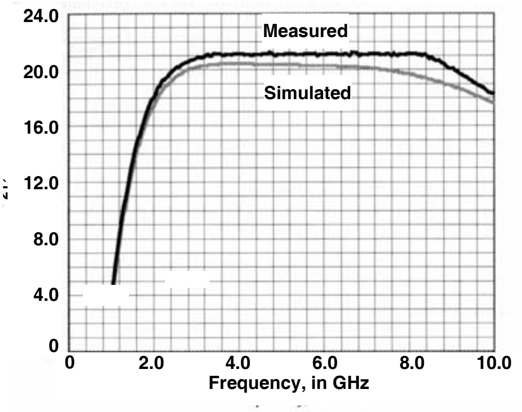


Equivalent Small-Signal Model of Input Loop

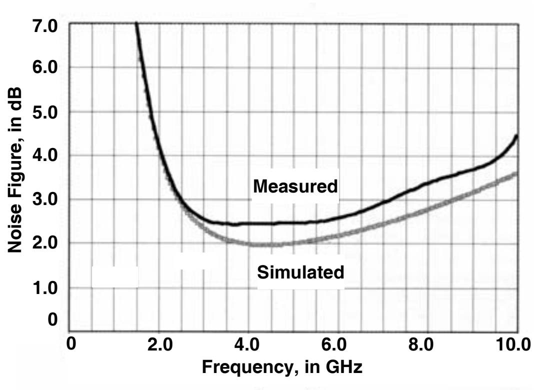


- Gyration of emitter inductance forms series LC network and input termination (**Ismail and Abidi, ISSCC 2004**)

3-10GHz SiGe Bipolar LNA



Measured Gain*

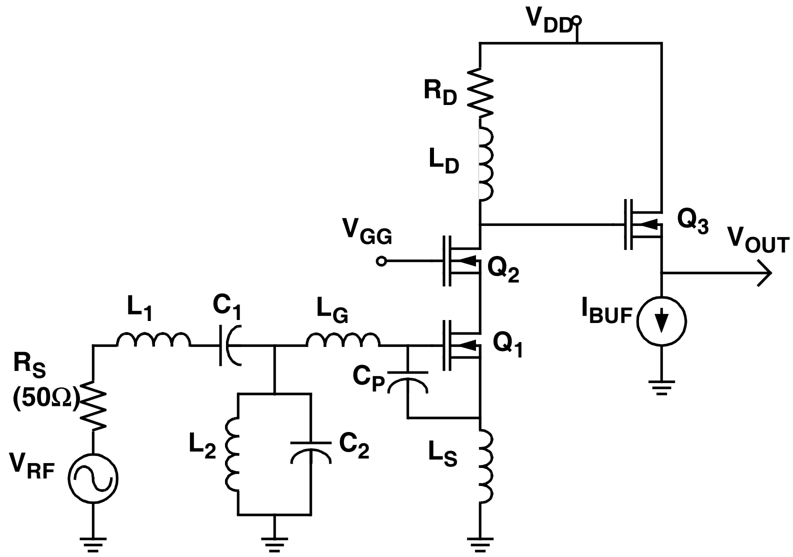


Measured Noise Figure*

- 0.18µm SiGe, S_{11} < -10dB, IIP_3 = -5.5dBm (3.5GHz), P_D = 27mW (2.7V).

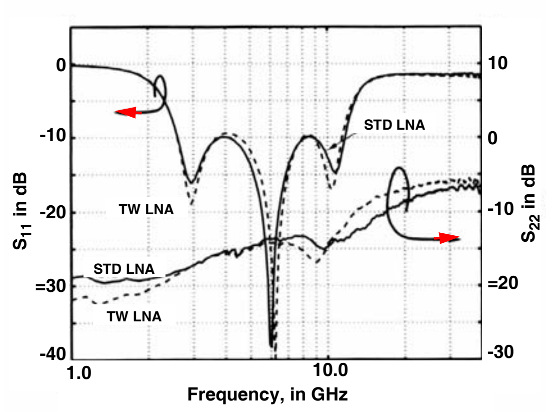
***Ismail and Abidi, ISSCC 2004.**

3.1-10.6GHz CMOS LNA

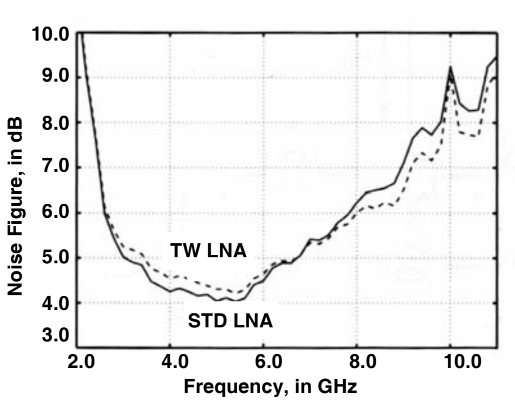


- 3-section bandpass filter embedded at input. Series on-chip inductors drive up the noise figure. (Bevilacqua and Niknejad, ISSCC 2004).

3.1-10.6GHz CMOS LNA



Measured I/O_Impedances*

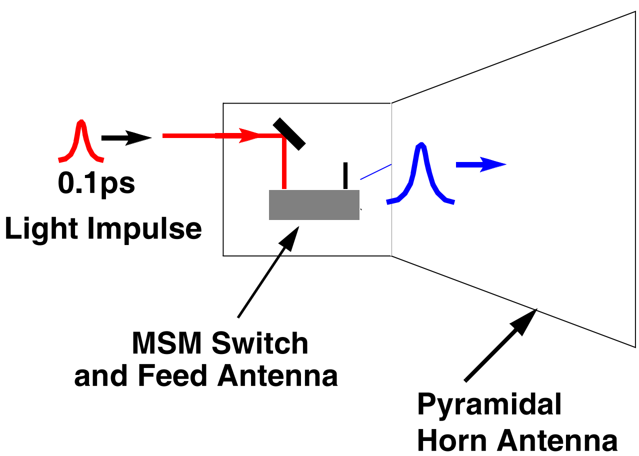


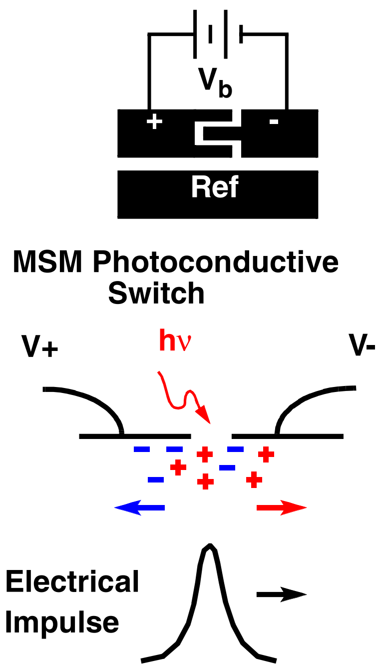
Measured Noise Figure*

- 0.18µm CMOS, G = 9.3dB, IIP_3 = -6.7dBm (6GHz), P_D = 9mW (1.8V).

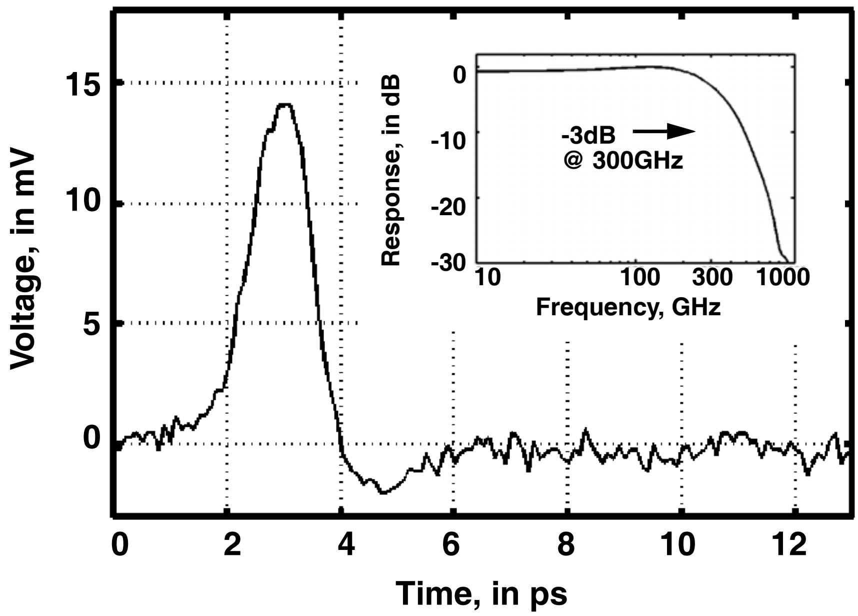
***Bevilacqua and Niknejad, ISSCC 2004. STD is standard process flow, TW is twin well process.**

Electro-Optic Impulse Generation

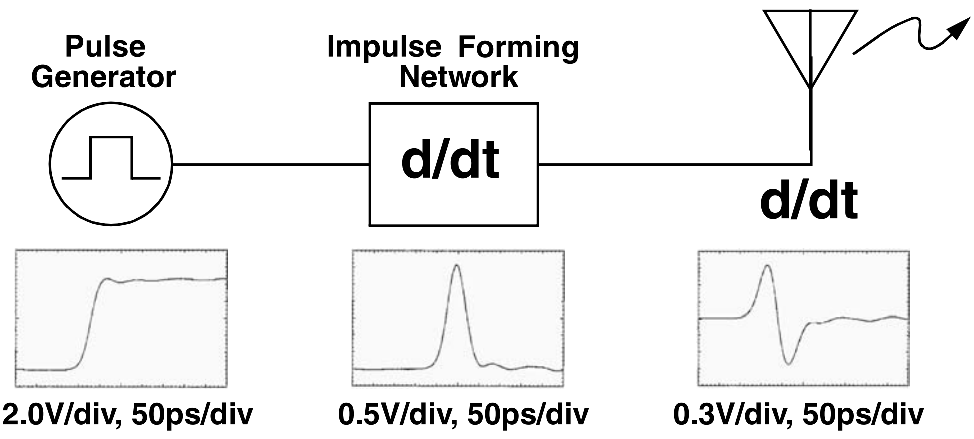




Electrical Impulse

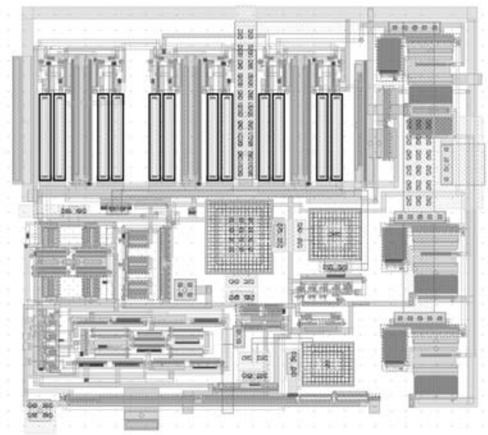


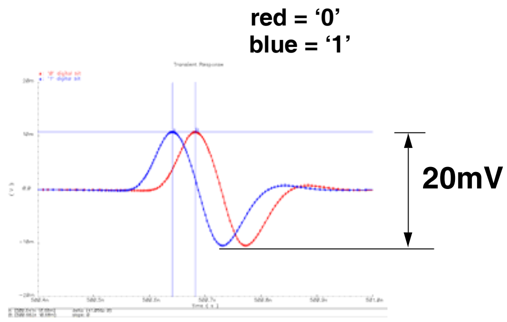
Electronic Pulse Generation



- High speed pulse (10 V amplitude, 45ps risetime) generated using tunnel diodes, Differentiating the step using a passive network forms a 3 V-pk impulse. Second differentiation in antenna give 1.8 Vp-p monocycle.

CMOS Monocycle Generator

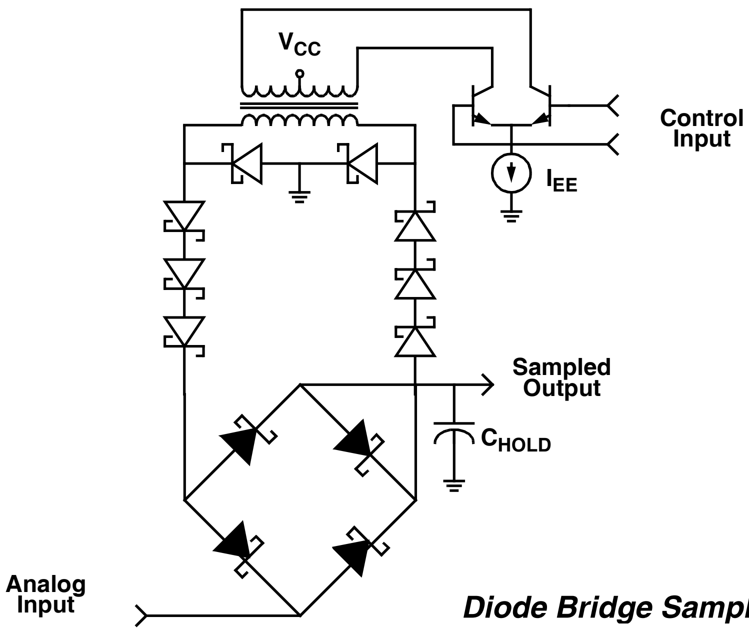




250ps Gaussian monocycle

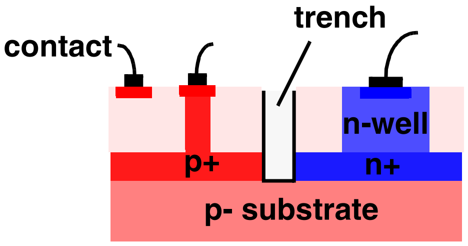
- FIltered impulse produces monocycle, 0.03mm^2 circuit implemented in 0.18μm CMOS consumes 46mW from a 1.8V supply.

High-Speed Sampling/Detection

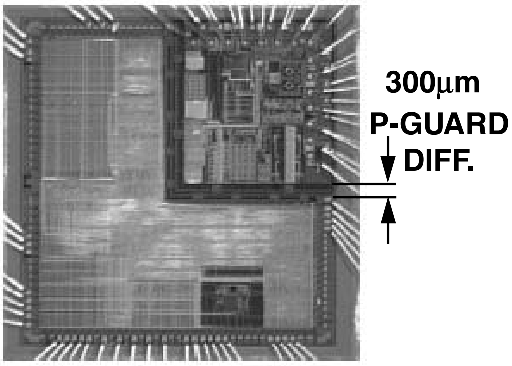


Diode Bridge Sampler

Substrate Coupling



p+ and n+ buried layer isolation

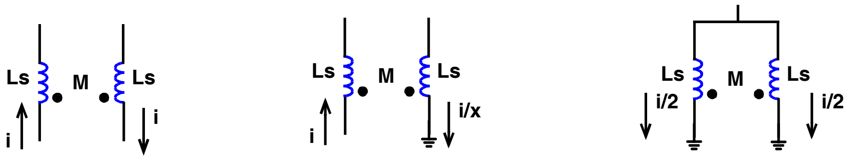


0.18µm Bluetooth
(Ericsson, 2002)

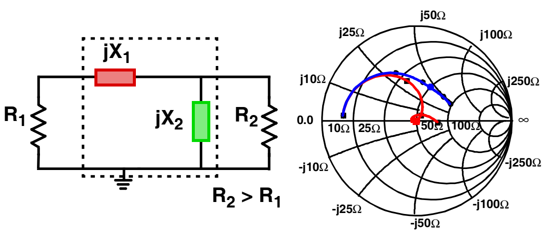
- Effectiveness depends on doping, number/width of isolating diffusions, frequency, grounding scheme and package.

Bondwire Interfaces

$L_{diff} = L_s - M$ $\quad L_{se} = L_s - \frac{M}{x}$ $\quad L_p = (L_s + M)/2$

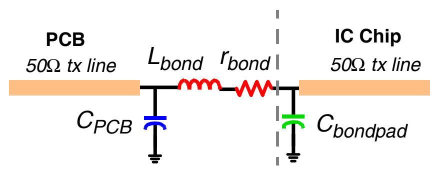


DIfferential drive *Single-ended drive* *Parallel bondwires*



Narrowband Matching

$Z_0 \approx \sqrt{\frac{L}{C}}$ $\quad BW \approx \frac{1}{\pi\sqrt{LC}}$



Broadband Matching

Summary

- Existing technology developed for radar applications is not easily portable to a UWB WPAN design. New solutions must be found for integrated circuits and compact broadband antenna designs.
- Pulse forming to meet FCC restrictions requires careful co-design of the pulse generator and the transmit and receive antennas. The entire chain must be considered.
- Broadband circuits cannot realize the same level of performance of their narrowband counterparts (NF, P_D, etc.). Realizing high efficiency in the transmitter and receiver circuitry one of the greatest challenges in UWB circuit design.

Achieving High Speed Wireless Communications Using a Multi-Band OFDM UWB System

Anuj Batra
Member, Group Technical Staff

DSPS R&D Center
Texas Instruments, Dallas

May 23, 2004

Outline

- Motivation for Ultra-wideband Systems.
- Challenges for Designing Ultra-wideband Systems:
  - Overlay of UWB spectrum with licensed and unlicensed bands.
  - Operating bandwidth for initial devices.
  - Worldwide compliance.
- Overview of Multi-band OFDM:
  - Band plan and frequency synthesis.
  - Transmitter and receiver architectures.
  - Systems parameters and system details.
  - Link budget and system performance.
  - Complexity.
- Multi-band Advantages and Conclusions.

Exploiting Shannon's Theorem To Achieve High Data Rates (1)

- Shannon's Theorem: $C = W \log_2(1 + S/N)$
- For the high S/N regime: $C \cong W \log_2(S/N)$
  - Capacity (C) is linearly related to the Bandwidth (W).
  - Capacity (C) is logarithmically related to S/N.
- For the low S/N regime: $C \cong W\,(S/N)$
  - Capacity (C) is linearly related to both S/N and Bandwidth (W).
  - More bang for your buck!
- Two mechanisms for achieving higher data rates:
  - Increasing effective S/N: decreasing the range of the system, or adding an advanced FEC code.
  - Increasing bandwidth.

Exploiting Shannon's Theorem To Achieve High Data Rates (2)

- For bandwidth constrained system using a single antenna, the only way to achieve higher data rates is to increase the effective S/N:
  - Increasing the effective $S/N \Rightarrow$ larger constellation sizes can be supported.
  - Can add advanced FEC codes, but at the expense of increased complexity.
  - Can decrease the range of the system (no one wants this).

- For an average PSD limited system that operates in the low S/N regime, the only way to achieve higher data rates is to increase the bandwidth:
  - By restricting the average PSD, the received power S is essentially constrained at a given distance d.
  - The typical operating S/N is low, on the order of 0 dB, for these systems.
  - Increasing bandwidth is a relatively easy way to achieve higher data rates.
  - Can also add advanced FEC codes by increasing complexity.

- The relative easy of increasing BW has generated a push to explore the potential of Ultra-wideband Systems.

Promise of UWB

- Data rates:
  - Scalable data rates from 55 Mb/s to 480 Mb/s.
  - 110 Mb/s at 10 meters in realistic multi-path environments.
  - 200 Mb/s at greater than 4 meters in realistic multi-path environments.
  - 480 Mb/s at 2 meters in realistic multi-path environments.

- Low cost solutions.

- Low power solutions (PHY: TX $\leq$ 130 mw, RX $\leq$ 160 mW).

- Integrated CMOS solution $\Rightarrow$ Single chip solutions.

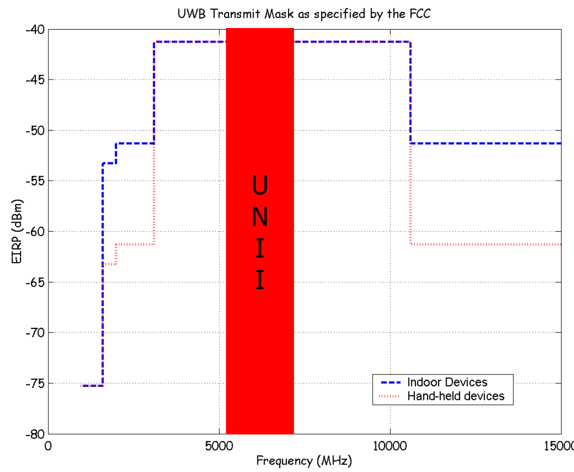
- Small form factors.

- Coexistence with current and future devices.

- Quality of Service – can support multimedia applications.

Challenges for Design of UWB Systems

- On Feb. 14, 2002, FCC amended the Part 15 rules to allow operation of devices incorporating UWB technology.
- Unprecedented allocation of spectrum.
- Indoor and handheld devices must operate in the frequency band 3.1 – 10.6 GHz.
- The challenge when designing a system is that the UWB spectrum allocation cuts across previously allocated spectrum; both licensed and unlicensed.



What Operating Bandwidth to Use?

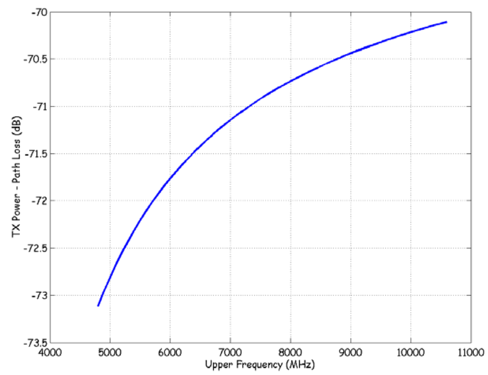
- Given that we have 7.5 GHz to use, what should the operating bandwidth be?
- Look at Received Power = TX Power – Path Loss, as a function of upper frequency.
- Assume that the TX signal occupies the BW from f_L to f_U.
  - Assume that f_L is fixed at 3.1 GHz. Vary upper frequency f_U between 4.8–10.6 GHz.
  - Assume that the transmit spectrum is flat over entire bandwidth.
  - TX power = –41.25 dBm + 10log10($f_U - f_L$).
- IEEE 802.15.3a has specified a free-space propagation model:

$$P_L(d) = 20\log_{10}\left[\frac{4\pi f_g d}{c}\right] \quad \text{(dB)}$$

  - f_g is the Geometric mean of lower/upper frequencies (10-dB points)
  - d is the UWB transmitter-receiver separation distance (assume d = 10 m)
  - c is the speed of light

Small Gains From Increasing Upper Frequency

- Increasing the upper frequency to 7.0 GHz (10.5 GHz) gives at most a 2.0 dB (3.0 dB) advantage in total received power.
- On the other hand, increasing the upper frequency, results in an increased noise figure:
  - For f_u = 7.0 GHz, by at least 1.0 dB.
  - For f_u = 10.5 GHz, by at least 2.0 dB.
- Result: using frequencies larger than 4.8 GHz increases the overall link margin by *at most* 1.0 dB with the current RF technology, but at the cost of higher complexity and higher power consumption.



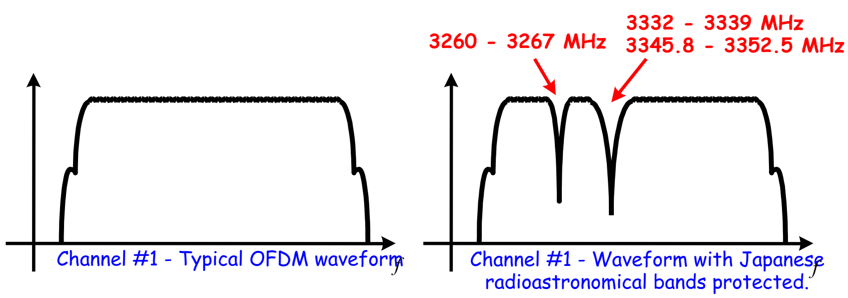
- Conclusion: only minimal gains can be realized in the link budget by using frequencies above 4.8 GHz. Link budget translate directly into range.
- Note: using larger operating bandwidth is useful from a multiple access point of view.

The Benefits of OFDM

- OFDM was invented almost 50 years ago.
- OFDM is a mature technology
- Currently used in several products available today:
  - ADSL, 802.11a/g, 802.16, European Digital TV, Digital Audio Broadcast
- OFDM is also being considered in the following technologies:
  - 4G, 802.11n, 802.16a, 802.20
- High spectral efficiency
- Excellent robustness against multi-path
- Robustness against narrowband interferers

Worldwide Compliance

- By using OFDM, small and narrow bandwidths can easily be protected by turning off tones near the frequencies of interest.
- In addition, tones can be dynamically turned on and off via software in order to comply with changing world-wide regulations.
- For example, consider the radio-astronomy bands allocated in Japan. Only need to zero out a few tones in order to protect these services.



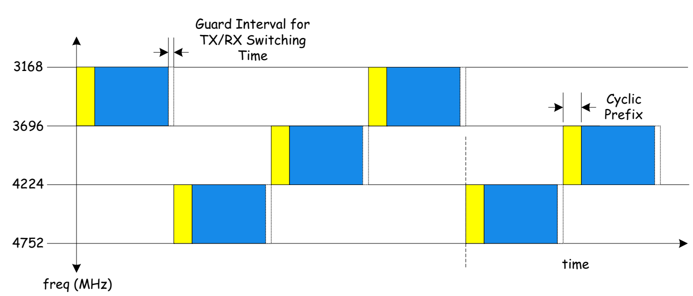
Overview of Multi-band OFDM

Authors and Supporters of Multi-band OFDM

Authors

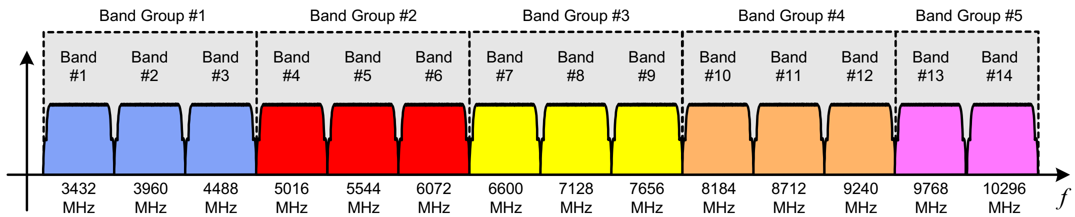
Overview of Multi-band OFDM

- Basic idea: divide the spectrum into bands that are 528 MHz wide.
- Interleave OFDM symbols across all bands to exploit frequency diversity and provide robustness against multi-path and interference.
- Transmitter and receiver process smaller bandwidth signals (528 MHz).
- Prefix provides robustness against multi-path even in the worst case channel environments.
- Insert a guard interval between OFDM symbols in order to allow sufficient time to switch between channels.



Band Plan

- Group the 528 MHz bands into 5 distinct groups.



- Band Group #1: Intended for 1st generation devices (3.1 – 4.9 GHz).
- Band Group #2 – #5: Reserved for future use.

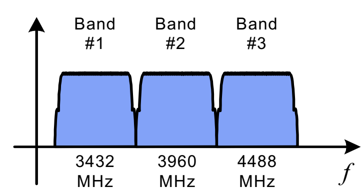
- Because of path loss, the range that is supported by each Band Group will be different, i.e.,

$$R_{max,1} > R_{max,2} > R_{max,3} > R_{max,4} > R_{max,5}$$

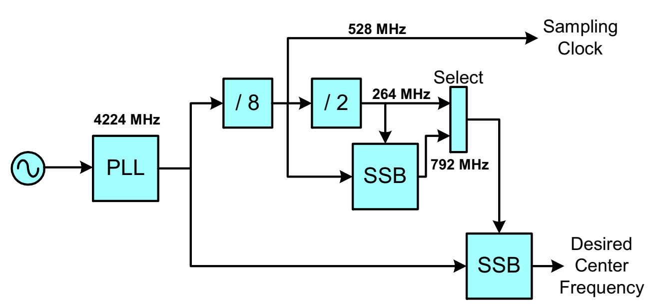
- Range differential turns out to be an advantage!
  - Can use range differential to help address multiple access.
  - Example: for applications, such as DVD to HDTV, use Band Group #1 or #2.
  - Example: for applications, such as DSC to laptop, use Band Group #3 or #4.

Frequency Synthesis (1)

- Center frequencies for the sub-bands:
  - f_1 = 4224 – 792 = 3432 MHz
  - f_2 = 4224 – 264 = 3960 MHz
  - f_3 = 4224 + 264 = 4488 MHz

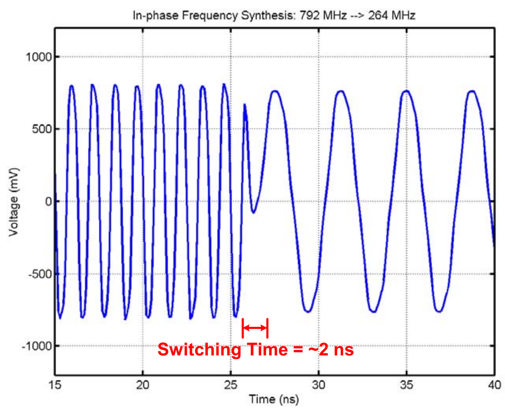


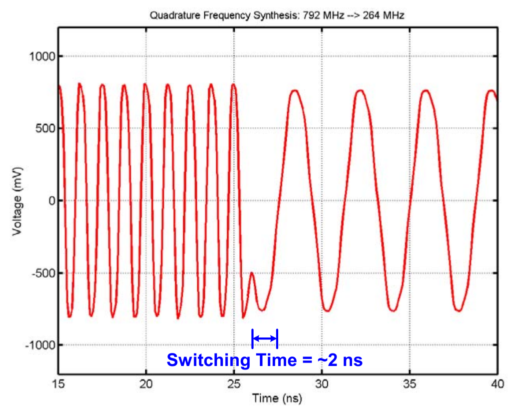
- Example: Frequency synthesis circuit for Band Group #1:



Frequency Synthesis (2)

- Circuit-level simulation of frequency synthesis:

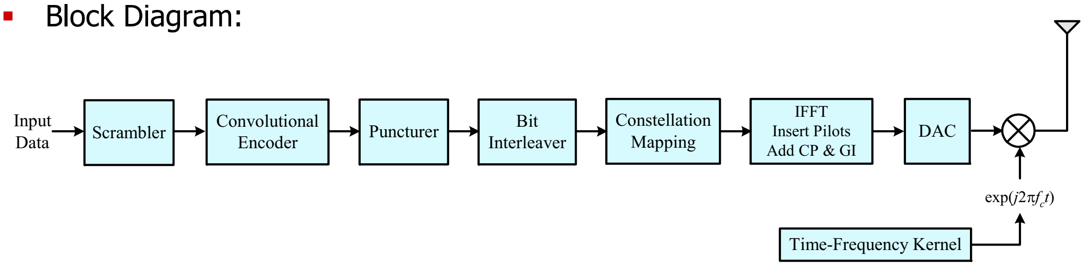




- Nominal switching time = ~2 ns.
- Need to use a slightly larger switching time to allow for process and temperature variations.

Multi-band OFDM Transmitter Architecture

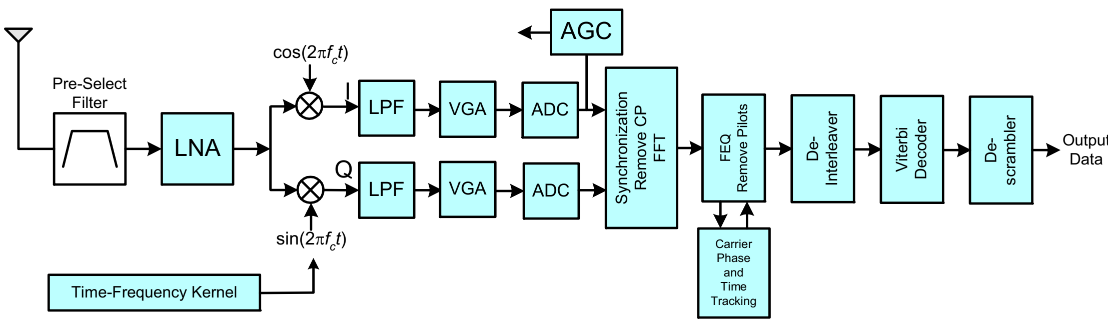
- Block Diagram:



- Architecture is similar to that of a conventional and proven OFDM system.
- Major Differences:
  - Time-Frequency kernel specifies the frequency for next OFDM symbol.
  - Constellation size is limited to QPSK (limits size of IFFT/FFT, DAC/ADC).
  - For rates less than 80 Mb/s, we force the input to the IFFT to be conjugate symmetric.
    - Need to only implement the "I" portion of TX analog chain.
    - As a result, only half the analog die size of a full "I/Q" transmitter is needed.
  - Zero-padded prefix limits power back at the transmitter.

Multi-band OFDM Receiver Architecture

- Block diagram:



- Architecture is similar to that of a conventional and proven OFDM system.
- Can leverage existing OFDM solutions for the development of the Multi-band OFDM physical layer.

Multi-band OFDM System Parameters

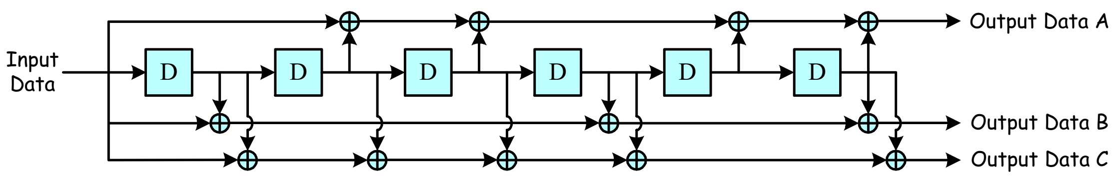
- System parameters for mandatory and optional data rates:

Info. Data Rate	55 Mbps	80 Mbps	110 Mbps	160 Mbps	200 Mbps	320 Mbps	400 Mbps	480 Mbps
Modulation/Constellation	OFDM QPSK	OFDM QPSK	OFDM QPSK	OFDM QPSK	OFDM QPSK	OFDM QPSK	OFDM QPSK	OFDM QPSK
FFT Size	128	128	128	128	128	128	128	128
Coding Rate (K=7)	R = 11/32	R = 1/2	R = 11/32	R = 1/2	R = 5/8	R = 1/2	R = 5/8	R = 3/4
Frequency-domain Spreading	Yes	Yes	No	No	No	No	No	No
Time-domain Spreading	Yes	Yes	Yes	Yes	Yes	No	No	No
Data Tones	100	100	100	100	100	100	100	100
Zero-padded Prefix	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns
Guard Interval	9.5 ns	9.5 ns	9.5 ns	9.5 ns	9.5 ns	9.5 ns	9.5 ns	9.5 ns
Symbol Length	312.5 ns	312.5 ns	312.5 ns	312.5 ns	312.5 ns	312.5 ns	312.5 ns	312.5 ns
Channel Bit Rate	640 Mbps	640 Mbps	640 Mbps	640 Mbps	640 Mbps	640 Mbps	640 Mbps	640 Mbps
Multi-path Tolerance	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns	60.6 ns

* Mandatory information data rate, ** Optional information data rate

Convolutional Encoder

- Assume a mother convolutional code of R = 1/3, K = 7. Having a single mother code simplifies the decoder implementation.
- Generator polynomial: $g_0 = [133_8]$, $g_1 = [165_8]$, $g_2 = [171_8]$.



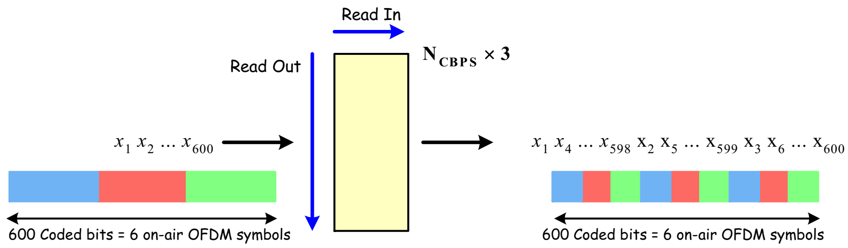
- Higher rate codes are achieved by optimally puncturing the mother code. Code rates supported via puncturing are: 11/32, 1/2, 5/8, 3/4.

Bit Interleaver

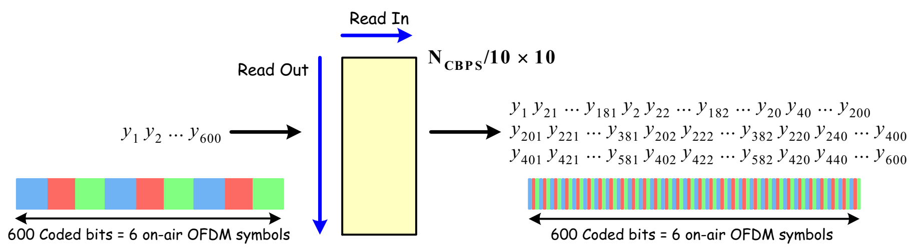
- Bit interleaving is performed across the bits within an OFDM symbol and across six OFDM symbols.
  - Exploits frequency diversity.
  - Randomizes any interference ⇒ interference looks nearly white.
  - Latency is less than 2 μs.
- Bit interleaving is performed in three stages:
  - Initially, $(6/T_{SF})N_{CBPS}$ coded bits are grouped together.
  - First stage: the coded bits are interleaved using $N_{CBPS} \times (6/T_{SF})$ block symbol interleaver.
  - Second stage: the output bits from 1st stage are interleaved using $(N_{CBPS}/10) \times 10$ block tone interleaver.
  - The end results is that the data is spread across 6 on-air OFDM symbols; spanning three different frequency bands.
- If there are less than $(6/T_{SF})N_{CBPS}$ coded bits, the data is padded out to align with the interleaver boundary.

Bit Interleaver

- Ex: Second stage (symbol interleaver) for a data rate of 110 Mbps (T_{SF} = 2).

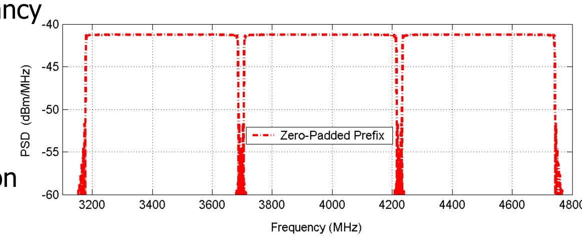


- Ex: Third stage (tone interleaver) for a data rate of 110 Mbps.



Zero-Padded Prefix (1)

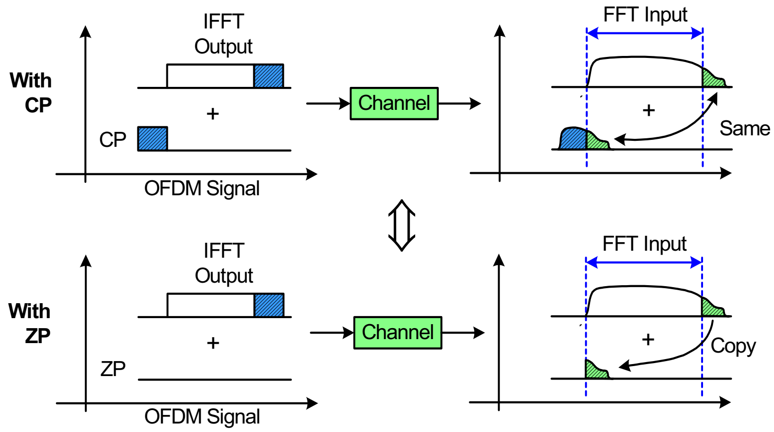
- In conventional OFDM system, a cyclic prefix is added to provide multi-path protection.
- Cyclic prefix introduces structure into the transmitted waveform ⇒ structure in the transmitted waveform produces ripples in the PSD.
- In an average power-limited system, any ripples in the transmitted waveform will results in back-off at the transmitter (reduction in range).
- Ripple in the transmitted spectrum can be eliminated by using a zero-padded prefix.
  - Zero-padded prefix eliminates redundancy in the transmitted waveform.
  - Results in almost no ripple in PSD.
  - Provides the same multi-path protection if a cyclic prefix were present.



- Using a zero-padded (ZP) prefix instead of a cyclic prefix is a well-known and well-analyzed technique.

Zero-Padded Prefix (2)

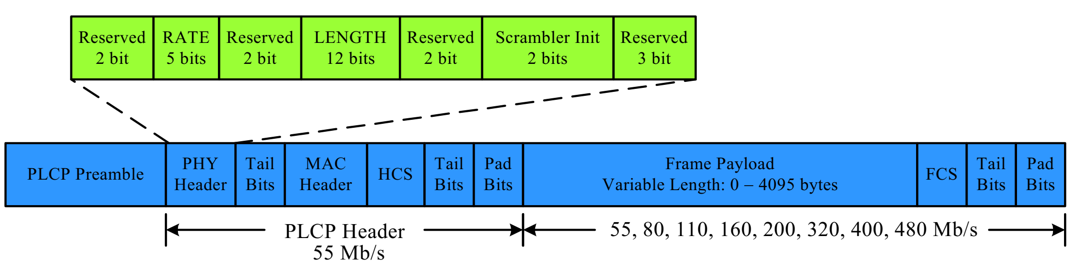
- A Zero-Padded Multi-band OFDM has the same multi-path robustness as a system that uses a cyclic prefix (60.6 ns of protection).
- The receiver architecture for a zero-padded multi-band OFDM system requires ONLY a minor modification (less than < 200 gates).



- Added flexibility to implementer: multi-path robustness can be dynamically controlled at the receiver, from 1.9 ns up to 60.6 ns.

Multi-band OFDM: PLCP Frame Format

- PLCP frame format:



- Rates supported: 55, 80, 110, 160, 200, 320, 400, 480 Mb/s.
  - Support for 55, 110, and 200 Mb/s is mandatory.
- Preamble + Header = 13.125 ms.
- Burst preamble + Header = 9.375 ms.
- Header is sent at an information data rate of 55 Mb/s.
- Maximum frame payload supported is 4095 bytes.

Multiple Access

- Multiple piconet performance is governed by the bandwidth expansion factor.
- Bandwidth expansion can be achieved using any of the following techniques or combination of techniques:
  - Spreading, Time-frequency interleaving, Coding
  - Ex: Multi-band OFDM obtains its BW expansion by using all 3 techniques.
- Time Frequency Codes:

Channel Number	Preamble Pattern	Mode 1 DEV: 3-band Length 6 TFC					
1	1	1	2	3	1	2	3
2	2	1	3	2	1	3	2
3	3	1	1	2	2	3	3
4	4	1	1	3	3	2	2

PLCP Preamble (1)

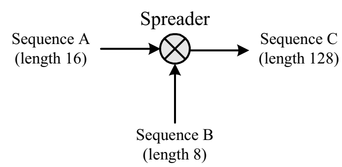
- Multi-band OFDM preamble is composed of 3 sections:
  - Packet sync sequence: used for packet detection.
  - Frame sync sequence: used for boundary detection.
  - Channel estimation sequence: used for channel estimation.
- Packet and frame sync sequences are constructed from the same hierarchical sequence.
- Correlators for hierarchical sequences can be implemented efficiently:
  - Low gate count.
  - Extremely low power consumption.
- Sequences are designed to be the most robust portion of the packet.

PLCP Preamble (2)

- In the multiple overlapping piconet case, it is desirable to use different hierarchical preambles for each of the piconets.
- Basic idea: define 4 hierarchical preambles, with low cross-correlation values.
- Preambles are generated by spreading a length 16 sequence by a length 8 sequence.

Preamble Pattern	Sequence A															
1	1	1	1	1	-1	-1	1	1	-1	-1	1	-1	1	-1	1	1
2	1	-1	-1	-1	-1	-1	1	-1	1	-1	-1	1	1	-1	-1	1
3	1	1	-1	-1	-1	1	-1	-1	-1	1	-1	-1	1	-1	1	1
4	1	-1	-1	1	-1	1	-1	-1	1	1	-1	-1	-1	-1	-1	1

Preamble Pattern	Sequence B							
1	1	-1	-1	-1	1	1	-1	1
2	1	-1	1	1	-1	-1	-1	1
3	1	1	-1	1	1	-1	-1	-1
4	1	1	1	-1	-1	1	-1	-1



Link Budget and Receiver Sensitivity

- Assumption: 3-band Device, AWGN, and 0 dBi gain at TX/RX antennas.

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

System Performance (3-band)

- The distance at which the Multi-band OFDM system can achieve a PER of 8% for a 90% link success probability is tabulated below:

Range*	AWGN	LOS: 0 – 4 m CM1	NLOS: 0 – 4 m CM2	NLOS: 4 – 10 m CM3	RMS Delay Spread: 25 ns CM4
110 Mbps	20.5 m	11.4 m	10.7 m	11.5 m	10.9 m
200 Mbps	14.1 m	6.9 m	6.3 m	6.8 m	4.7 m
480 Mbps	8.9 m	2.9 m	2.6 m	N/A	N/A

* Includes losses due to front-end filtering, clipping at the DAC, ADC degradation, multi-path degradation, channel estimation, carrier tracking, packet acquisition, etc.

Signal Robustness/Coexistence

- Assumption: Received signal is 6 dB above sensitivity.
- Values listed below are the required distance or power level needed to obtain a PER ≤ 8% for a 1024 byte packet at 110 Mb/s and operating in Band Group #1.

Interferer	Value
IEEE 802.11b @ 2.4 GHz	$d_{int} \cong 0.2$ meter
IEEE 802.11a @ 5.3 GHz	$d_{int} \cong 0.2$ meter
Modulated interferer	SIR ≥ -9.0 dB
Tone interferer	SIR ≥ -7.9 dB

- Coexistence with IEEE 802.11b and Bluetooth is relatively straightforward because they are out-of-band.
- Multi-band OFDM is also coexistence friendly with both GSM and WCDMA.
  - MB-OFDM has the ability to tightly control OOB emissions.

PHY-SAP Throughput

- Assumptions:
  - MPDU (MAC frame body + FCS) length is 1024 bytes.
  - SIFS = 10 ms.
  - MIFS = 2 ms.

Number of frames	Throughput @ 110 Mb/s	Throughput @ 200 Mb/s	Throughput @ 480 Mb/s
1	Mode 1: 83.2 Mb/s	Mode 1: 126.8 Mb/s	Mode 1: 194.9 Mb/s
5	Mode 1: 97.8 Mb/s	Mode 1: 150.5 Mb/s	Mode 1: 257.2 Mb/s

- Assumptions:
  - MPDU (MAC frame body + FCS) length is 4024 bytes.

Number of frames	Throughput @ 110 Mb/s	Throughput @ 200 Mb/s	Throughput @ 480 Mb/s
1	Mode 1: 101.3 Mb/s	Mode 1: 174.4 Mb/s	Mode 1: 354.9 Mb/s
5	Mode 1: 104.6 Mb/s	Mode 1: 184.6 Mb/s	Mode 1: 399.6 Mb/s

Complexity

- Unit manufacturing cost (selected information):
  - Process: CMOS 90 nm technology node in 2005.
  - CMOS 90 nm production will be available from all major SC foundries by early 2004.

- Die size for a device operating in Band Group #1:

Process	Complete Analog*	Complete Digital
90 nm	3.0 mm^2	1.9 mm^2
130 nm	3.3 mm^2	3.8 mm^2

* Component area.

- Active CMOS power consumption for a device operating in Band Group #1 :

Process	TX (55 Mb/s)	TX (110, 200 Mb/s)	RX (55 Mb/s)	RX (110 Mb/s)	RX (200 Mb/s)
90 nm	85 mW	128 mW	147 mW	155 mW	169 mW
130 nm	104 mW	156 mW	192 mW	205 mW	227 mW

Comparison of OFDM Technologies

- Qualitative comparison between Multi-band OFDM and IEEE 802.11a OFDM:

Criteria	Multi-band OFDM Strong Advantage	Multi-band OFDM Slight Advantage	Neutral	802.11a Slight Advantage	802.11a Strong Advantage
PA Power Consumption	✓				
ADC Power Consumption	✓[3]				
FFT Complexity			✓[1]	✓[2]	
Viterbi Decoder Complexity				✓	
Band Select Filter Power Consumption		✓			
Band Select Filter Area		✓			
ADC Precision	✓				
Digital Precision		✓			
Phase Noise Requirements	✓				
Sensitivity to Frequency/Timing Errors	✓				
Design of Radio	✓				
Power / Mbps	✓				

1. Assumes a 256-point FFT for IEEE 802.11a device.
2. Assumes a 128-point FFT for IEEE 802.11a device.
3. Even though the Multi-band OFDM ADC runs faster than the IEEE 802.11a ADC, the bit precision requirements are significantly smaller, therefore the Multi-OFDM ADC will consume much less power.

Multi-band OFDM – Advantages

- Inherent robustness to multi-path in all expected environments.
- Excellent robustness to U-NII and other generic narrowband interference.
- Ability to comply with worldwide regulations:
  - Channels and tones can be turned on/off dynamically to comply with changing regulations.
- Enhanced coexistence with current and future services:
  - Channels and tones can be turned on/off dynamically to coexist with other devices.
- Scalability:
  - More channels can be added as RF technology improves and as capacity requirements increase.
  - Multi-band OFDM is digital heavy. Digital section complexity and power scales with improvements in technology node (Moore's Law).

Conclusion

- The proposed system is specifically designed to be a low power, low complexity CMOS solution.
- Expected range for a device operating in Band Group #1 and transmitting at 110 Mb/s:
  - 20.5 meters in AWGN.
  - Nearly 11 meters in heavy multi-path environments.
- Expected power consumption for a device operating in Band Group #1 and transmitting at 110 Mb/s (90 nm CMOS process):
  - TX = 128 mW
  - RX = 155 mW
  - Deep Sleep = 15 μW
- Multi-band OFDM is coexistence friendly and can complies with worldwide regulations.
- Multi-band OFDM provides the best trade-off among the various system parameters.

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May 23, 2004

Waveform Design, Channel Estimation and Multiple Access for UWB Radios

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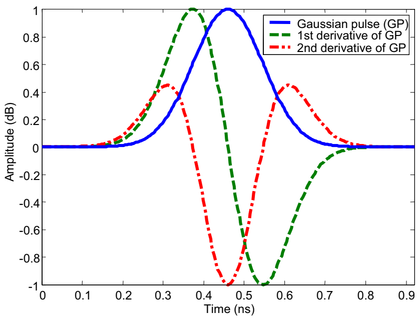
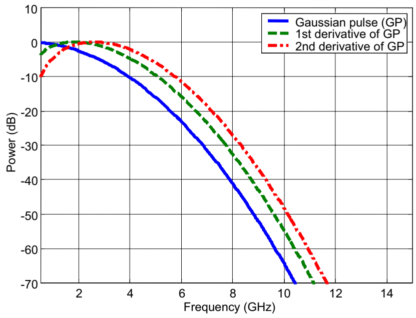
Acknowledgments: ***Liuqing Yang***
ARL/CTA Grant No. DAAD 19-01-2-0011
NSF Grant No. EIA-0324864

Outline

- Optimal UWB pulse shapers
- Timing synchronization for UWB
- UWB channel estimation
- UWB multiple access
- Summary

Baseband UWB





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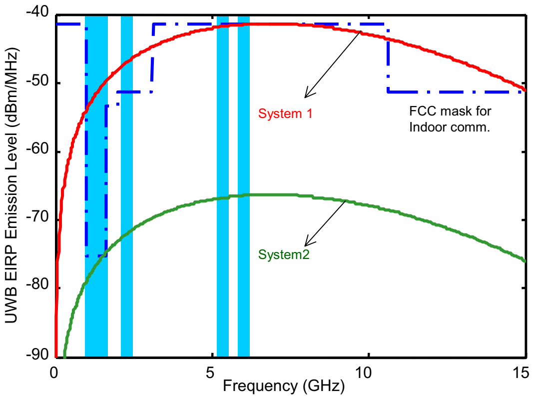
Baseband UWB vs. FCC Mask



System 1:

✓ to maximize Tx power, G-monocycle

✘ violates the FCC spectrum mask

System 2:

✓ to respect the FCC mask, G-monocycle

✘ does not exploit the mask efficiently

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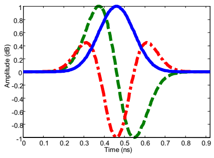
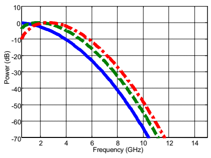
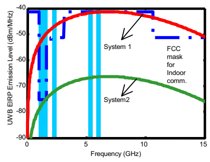
Should we go Baseband ? Single band?







- ❑ Pros:
  - ✓ carrier-free ⇒ low-cost RF components
  - ✓ low duty-cycle ⇒ prolonged battery life
  - ✓ low power ⇒ covert communications
- ❑ Cons:
  - ➢ single band inflexible with narrowband interference (NBI)
  - ➢ power-inefficient use of FCC mask

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Better Pulse-Shapers?

- ❑ Gaussian monocycle:
  - ✘ does NOT optimally exploit FCC mask
  - ✘ does NOT avoid interference with co-existing RF systems
  - ✘ does NOT facilitate Frequency-Hopping (FH) to gain LPI-LPD
- ❑ Possible alternatives:
  - ➢ analog filtering of the G-monocycle ⇒ lacks flexibility & repeatability ✘
  - ➢ carrier-modulation of the G-monocycle ⇒ carrier frequency offset/jitter ✘

Optimal Pulse-Shapers for UWB

Idea: digitally filter the antenna generated pulse $g(t)$ [LYG'03]

$$p(t) = \sum_{k=0}^{M-1} w[k] g(t - kT_0)$$

Step 1: Select digital filter tap spacing T_0

Step 2: Find *M* tap coefficients $\{w[m]\}_{m=0}^{M-1}$, so that:

$$|W(e^{j2\pi f})| := \left| \sum_{m=0}^{M-1} w[m] e^{-j2\pi f m T_0} \right| : \begin{cases} \approx \frac{P_d(f)}{|G(f)|}, & f \in [0, \frac{1}{2T_0}] \\ < \frac{\mathcal{M}(f)}{|G(f)|}, & f \in [\frac{1}{2T_0}, +\infty] \end{cases}$$

$P_d(f)$: desired FT magnitude

$\mathcal{M}(f)$: normalized sqrt (ERIP FCC mask)

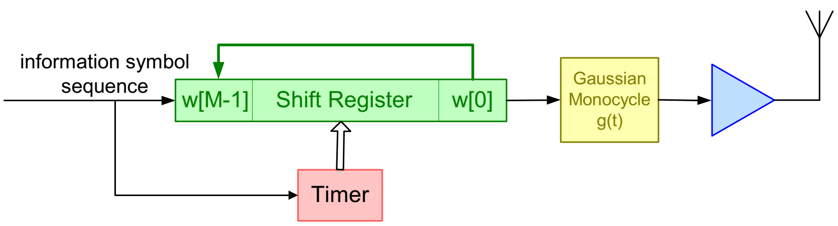
Algorithm and Implementation

- Solution: *Parks-McClellan* digital filter design algorithm
- Optimality: $\{w[m]\}_{m=1}^{M} = \arg\min_{\{w[m]\}_{m=1}^{M}} \{\max_{F \in \mathcal{F}} |e(F)|\}$

$\mathcal{F} \in [0, 0.5]$: $\cup$ prescribed disjoint intervals

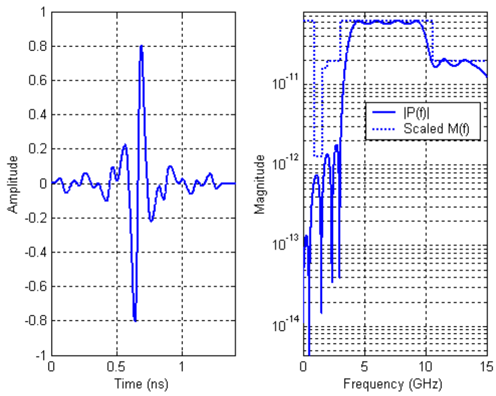
$e(F) = \lambda(F) \left[W(e^{j2\pi F}) - D\left(\frac{F}{T_0}\right) \right]$: weighted error

- Implementation:



Single-Band UWB: Example I

- G-monocycle with Tp = 0.37ns
- Select $T_0 = 35.7\text{ps}$ to gain full control over 0~10.6GHz
- Design $\{w[m]\}_{m=0}^{M-1}$, M=33



Pulse Duration 1.3 ns

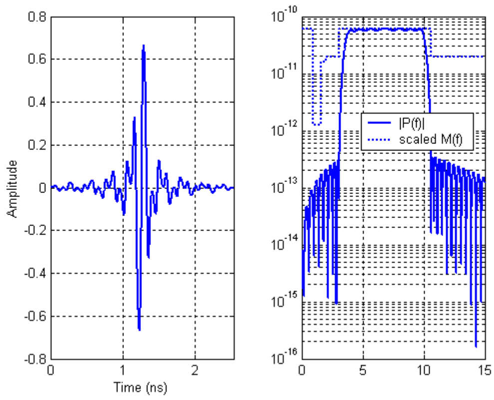
Maximum Power 0.91 mW

Optimal approximation over the entire bandwidth

High clock rate

Single-Band UWB: Example II

- G-monocycle with Tp = 0.37ns
- Select $T_0 = 73\text{ps}$ to exploit the symmetry
- Design $\{w[m]\}_{m=0}^{M-1}$, M=33



Pulse Duration 2.4 ns

Maximum Power 0.88 mW

Sub-optimal approximation over the entire bandwidth

Lower clock rate

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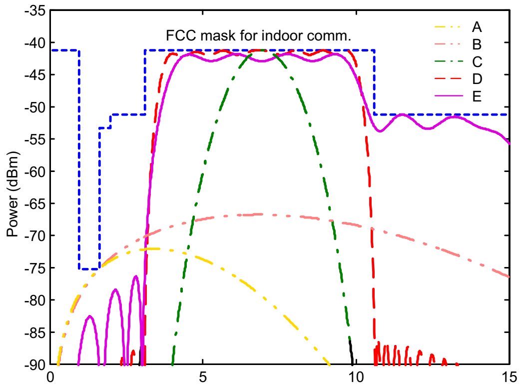
Comparison I: Maximum Tx Power



- A & B:
  Gaussian monocycles
- C:
  pulse shaper in [Parr etal '03]
- D & E:
  pulse shapers in [LYG'03]

	A	B	C	D	E
Pulse duration (ns)	0.37	0.19	1.3	2.4	1.3
Tx power (μW)	0.506	3.43	250	880	910

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Multi-Band UWB: Example

- G-Monocycle with *Tp* = 0.37ns
- Select $T_0 = 35.7\text{ps}$ to gain full control over 0~10.6GHz
- For the *n*th sub-band, design $\{w_n[m]\}_{m=0}^{M-1}$ such that:

$$\left|\sum_{m=0}^{M-1} w_n[m]e^{-j2\pi f m T_0}\right| \approx \begin{cases} 0 & f \in [0, 3.1 + n\cdot\frac{7.5}{N}]\text{GHz} \\ \frac{P_d(f)}{|G(f)|} & f \in [3.1 + n\cdot\frac{7.5}{N}, 3.1 + (n+1)\cdot\frac{7.5}{N}]\text{GHz} \\ 0 & f \in [3.1 + (n+1)\cdot\frac{7.5}{N}, 10.6]GHz \end{cases}$$

- Tradeoffs:
  - T_0 ↑ ⇒ complexity ↓, number of *independent* sub-bands ↓
  - number of sub-bands ↑ ⇒ complexity ↑, flexibility ↑

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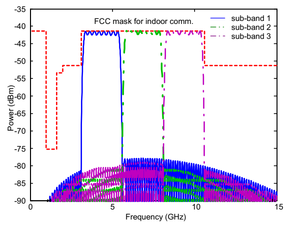
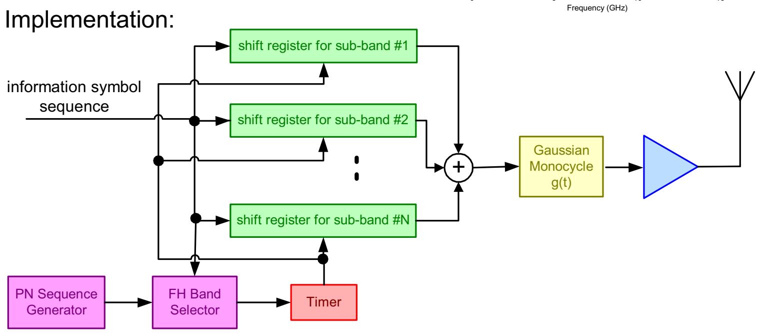
Carrier-Free Multi-Band UWB

- Attractive features:
  - ✓ Optimal FCC mask exploitation
  - ✓ Flexible NBI avoidance
  - ✓ Baseband FH

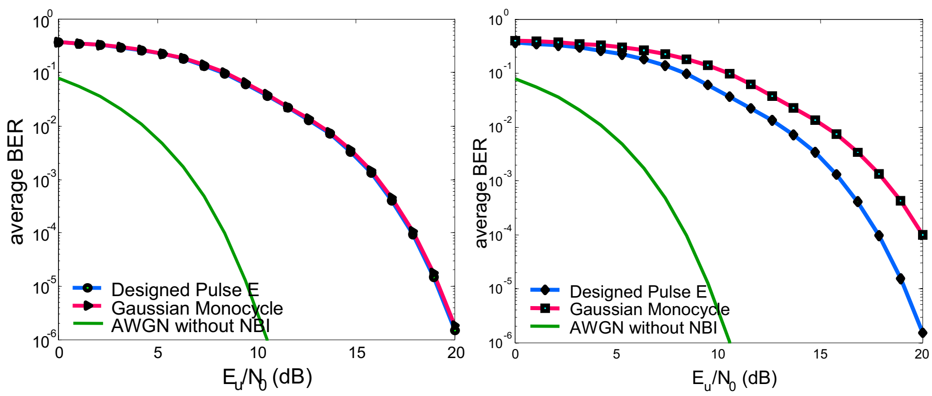


- Implementation:



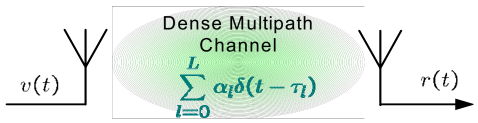
Comparison II: Average BER

✓ In the absence of NBI ✓ In the presence of NBI



Narrowband interference between 0.99GHz and 3.1 GHz,
Power of NBI is 10 times AWGN variance

Timing Synchronization for UWB



$$v(t) = \sqrt{\mathcal{E}} \sum_{n=-\infty}^{\infty} s(\lfloor n/N_f \rfloor) p(t - nT_f - c(n)T_c)$$

$$r(t) = \sum_{l=0}^{L} \alpha_l v(t - \tau_{l,0} - \tau_0) + noise$$

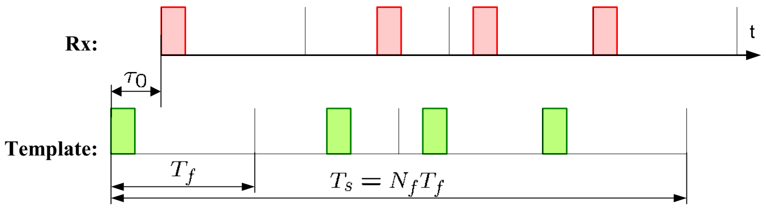
- First arrival time τ_0
- Timing synchronization: finding τ_0
- **Acquisition**: coarse timing
- **Tracking**: fine timing

Prior Art

- Coarse bin reversal search in the absence of noise
  [Homier-Scholtz'02]
- Coded beacon sequence in the absence of multipath
  [Fleming'02]
- Ranging system requiring strongest path knowledge
  [Lee-Scholtz'02]
- Non-data aided timing for UWB in dense multipath
  [Yang-Tian-Giannakis'02]
- Data-aided Generalized Likelihood Ratio Tests (GLRT)
  [Tian-Giannakis'03]

Timing with a Clean Template (1)

- When multipath is absent but TH is present



- Need to search $T_s/T_p\ (> 1{,}000)$ bins

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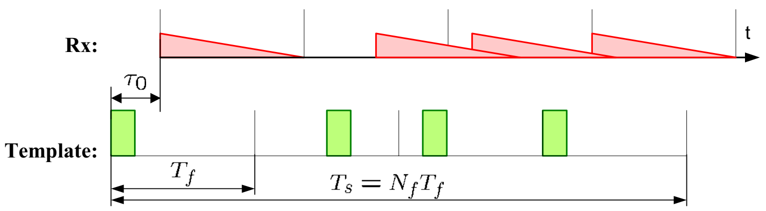
Timing with a Clean Template (2)

- When multipath is also present



✓ Tracking possible with fast TH [H-S'02,T-Y-G'02]

✘ Acquisition only with slow/no TH [Yang-Tian-GG'03, Tian-GG'03]

✘ Poor energy capture ⇒ synchronization performance affected

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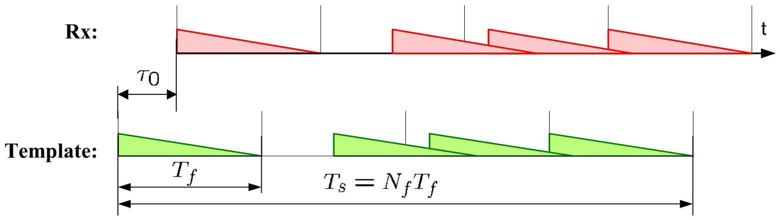
If we knew the channel …



$\Rightarrow$ Maximum Likelihood (ML) & sub-opt. Early-Late gate

Idea: Timing with "Dirty" Templates (TDT) !

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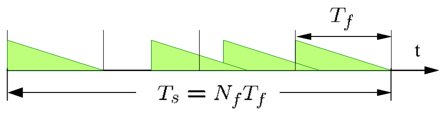
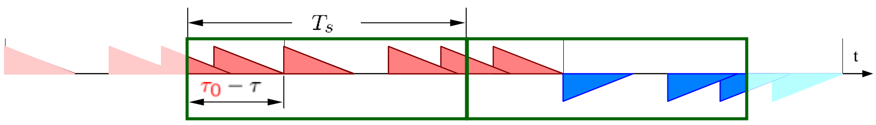
"Dirty" Templates

- Aggregate pulse: $p_R(t) = \sum_{l=0}^{L} \alpha_l p_T(t - \tau_{l,0})$



- Rx waveform: $r(t) = \sqrt{\mathcal{E}} \sum_{k=-\infty}^{\infty} s(k) p_R(t - kT_s - \tau_0) + noise$



- "Dirty" Templates:

$\forall t \in [0, T_s)$ $\quad r(t + (k-1)T_s + \tau)$ $\quad r(t + kT_s + \tau)$

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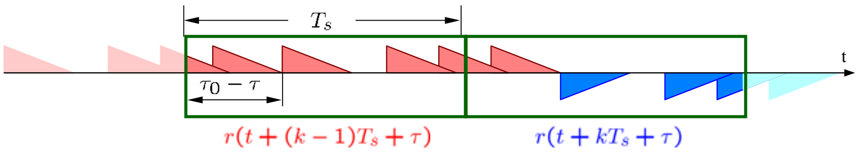
Our Key Observation



- Symbol-rate samples:

$$x_k(\tau) = \int_0^{T_s} r(t+(k-1)T_s+\tau)r(t+kT_s+\tau)dt, \quad \forall\tau \in [0, T_s)$$

- Cauchy-Schwartz's inequality (noise absent):

$$\bar{x}_k^2(\tau) \leq \int_0^{T_s} \bar{r}^2(t+(k-1)T_s+\tau)dt \int_0^{T_s} \bar{r}^2(t+kT_s+\tau)dt$$

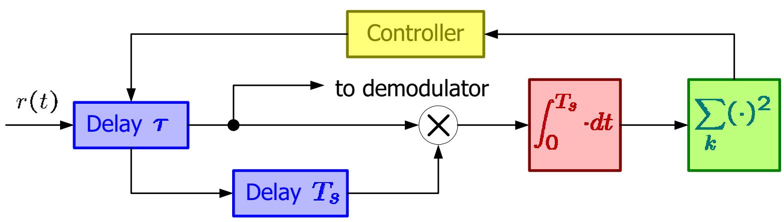
  - Equality holds $\forall k$ iff

$$\bar{r}(t+(k-1)T_s+\tau) = \lambda\bar{r}(t+kT_s+\tau), \ \forall t \in [0, T_s) \ \Leftrightarrow \ \tau = \tau_0$$

Timing with "Dirty" Templates (TDT)

Theorem [Yang-GG'03,04]**:** Consistent timing offset estimation can be accomplished in the absence of ISI even when TH codes are present and the UWB multipath is unknown, using "dirty" Ts-long segments of the received waveform as follows:

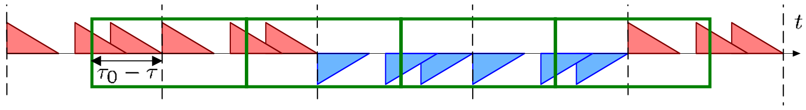
$$\hat{\tau}_0 = \arg \max_{\tau\in[0,T_s)} \frac{1}{K}\sum_{k=1}^{K}\left(\int_{kT_s}^{(k+1)T_s} r(t+\tau)r(t+\tau-T_s)dt\right)^2$$



The Beauty of the Training Pattern

Training Pattern: **... s, s, -s, -s, s, s, -s, -s, ...**

Rx:



$$x_k(\tau) = (-1)^k s^2 \left[\mathcal{E}_B(\tau_0 - \tau) - \mathcal{E}_A(\tau_0 - \tau)\right] + \xi(k)$$

- $K^{-1} \sum_{k=1}^{K} x_k^2(\tau)$ converges faster to

$$\mathrm{E}\{x_k^2(\tau)\} = s^4 [\mathcal{E}_B(\tau_0 - \tau) - \mathcal{E}_A(\tau_0 - \tau)]^2 + \sigma_\xi^2$$

- **K=1** pair suffices ⇒ rapid acquisition
- Enables multi-user TDT

Why is this result neat?

- A distinct criterion for timing synchronization:
  - *Auto*-correlation vs. *Cross*-correlation
  - *Clean* vs. *Dirty* templates and the noise-noise issue
- Features:
  - ✓ TDT with both *training* and *blind* modes
  - ✓ Simple integrate-and-dump operations
  - ✓ Acquisition and tracking at *any* desirable resolution!
  - ✓ With or without TH & With or without multipath
  - ✓ VCC implementation possible

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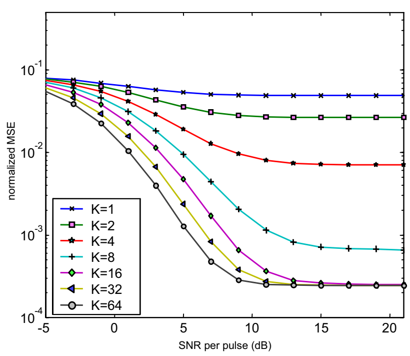
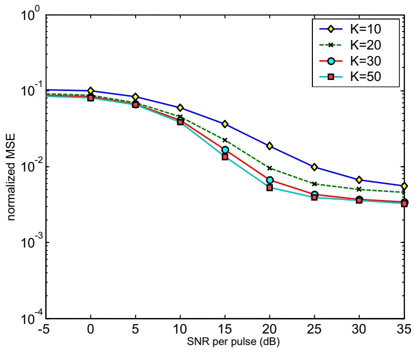
TDT Acquisition: Blind Mode

➢ $N_f = 32$ ➢ N_ϵ uniform over $[0, N_f - 1]$

- Dirty template:



- Clean *p(t)* template:



✓ Good energy capture ⇒ good performance
✓ Simple integrate-and-dump operations ⇒ low complexity

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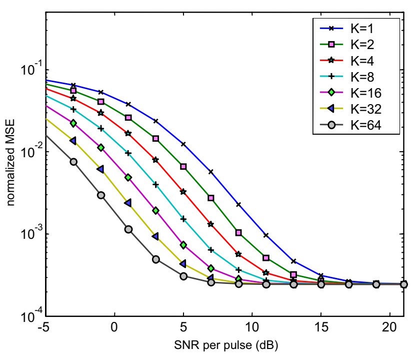
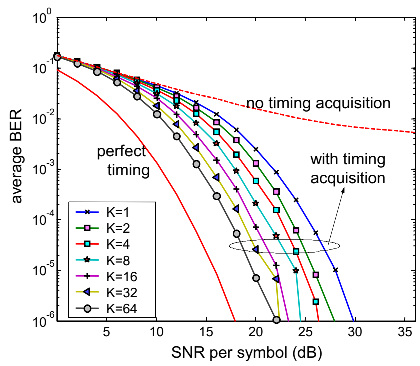
TDT Acquisition: Training Mode

➢ $N_f = 32$ ➢ N_ϵ uniform over $[0, N_f - 1]$

- Synchronization MSE:



- Detection BER:



✓ Data-aided TDT operational with K=1 ⇒ rapid acquisition
✓ Considerable BER improvement

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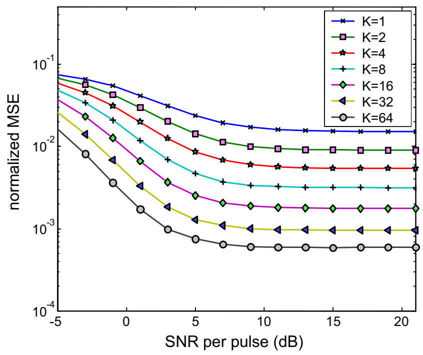
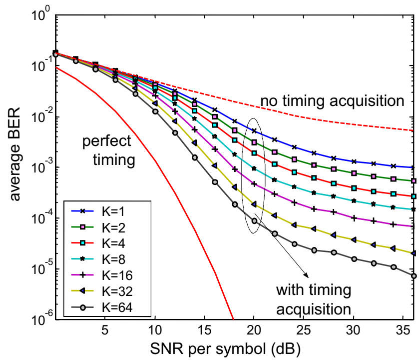
TDT in Multi-User Settings

- ➢ two interfering asynchronous users

- Timing acquisition MSE:



- BER performance:



✓ Rapid acquisition in ad hoc networks
✓ Operational without modification
✓ Improvement possible

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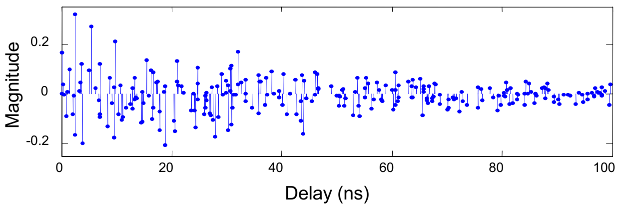
Channel Estimation



Parameters:

$\Gamma = 33ns$
$\gamma = 5ns$
$1/\Lambda = 2ns$
$1/\lambda = 0.5ns$

- ❑ Needed for Rake reception

Q: Can we estimate the baseband-equivalent sampled channel?

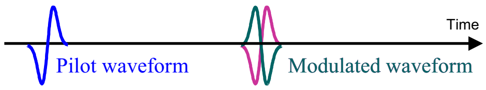
- ➢ Pulse duration ***Tp=0.7ns*** ⇒ sampling rate ***14.3-35.7GHz***

  [Lottici et al '02] samples 10-25 times per pulse

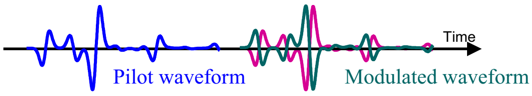
A: Only for sub-band channels in “multi-band UWB”

Transmitted Reference (TR)

Tx: $v(t) = p(t) + s \cdot p(t - T_f), \quad s = \{\pm 1\}$



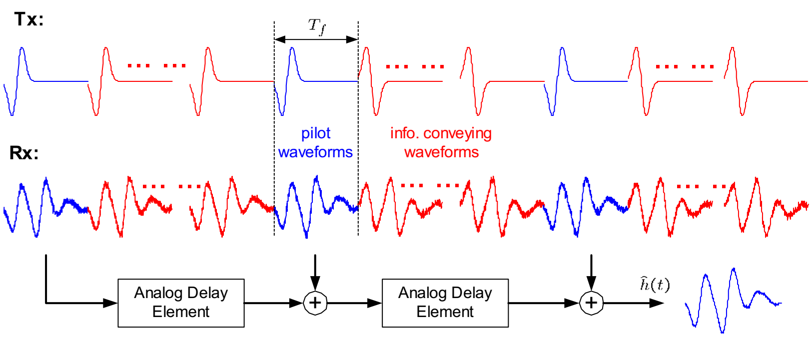
Rx: $r(t) = h(t) + s \cdot h(t - T_f), \quad h(t) := \sum_{l=0}^{L} \alpha_l p(t - \tau_l)$



Idea: Rx pilot waveform as correlator template [Hoctor-Tomlinson'02]

$$\hat{s} = \text{sign}\left\{\int r(t) r(t - T_f) dt\right\} = \text{sign}\left\{s \int h^2(t) dt\right\} = s$$

Pilot Waveform Assisted Modulation (PWAM)



- PWAM [Yang-GG'02]
  - ✓ Error performance similar to differential decoding
  - ✓ Low complexity (just frame-rate integrate-and-dump)
  - ✓ Performance-rate tradeoffs, and robustness to timing jitter

PWAM Optimality

Theorem [Yang-GG'02]: Given T_f, N_f, and channel coherence time τ_c, equi-spaced pilot waveforms every $\lfloor \tau_c / T_f \rfloor$ pulses, and equi-powered with $\mathcal{E}\sqrt{N_f}/(\sqrt{\lfloor \tau_c/T_f \rfloor - N_f} + \sqrt{N_f})$ achieve the channel CRLB and maximize average capacity.

PWAM Relatives

- Transmitted reference (TR) signaling [Hoctor-Tomlinson'02, Choi-Stark'02]:

  When $N = 2N_f$, PWAM yields:

  - Optimal number of pilot waveforms: $N_p = N_f$
  - Optimal energy allocation factor: $\alpha = \frac{1}{2}$

  TR

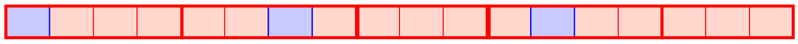
  $\Rightarrow$ **TR is optimal only when $N = 2N_f$**

- Pilot symbol assisted modulation (PSAM) [Cavers'91, Ohno-Giannakis'02]:

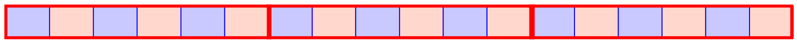
  - ***discrete***-time channel taps vs. ***continuous***-time channel waveform (*pulse-rate sampling vs. frame-rate integrate-and-dump*)
  - narrowband with inter- symbol interference (ISI) vs. UWB without ISI
  - one ***digital*** pilot symbol vs. multiple ***analog*** pilot pulses across frames

Placement of Pilot Waveforms

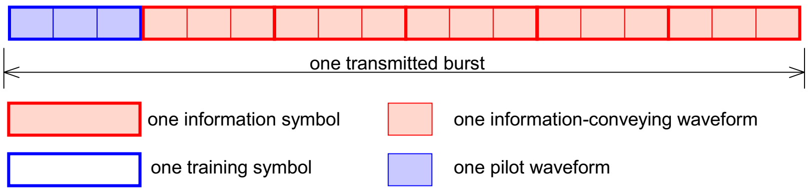
- PWAM with distributed pilot waveforms:



- Transmitted reference: special case of PWAM when $N = 2N_f$



- Preamble:



Equi-SNR (ES-)PWAM

- nominal SNR:

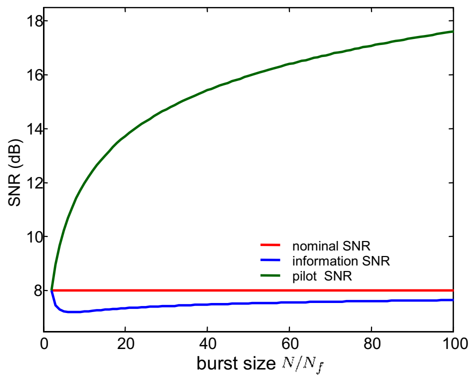
$$\rho = \frac{N_f \mathcal{E}}{N \sigma^2}$$

- information SNR:

$$\rho_s = \frac{\mathcal{E}_s}{N_s \sigma^2} = \frac{N}{N_s N_f} \alpha \rho$$

- pilot SNR:

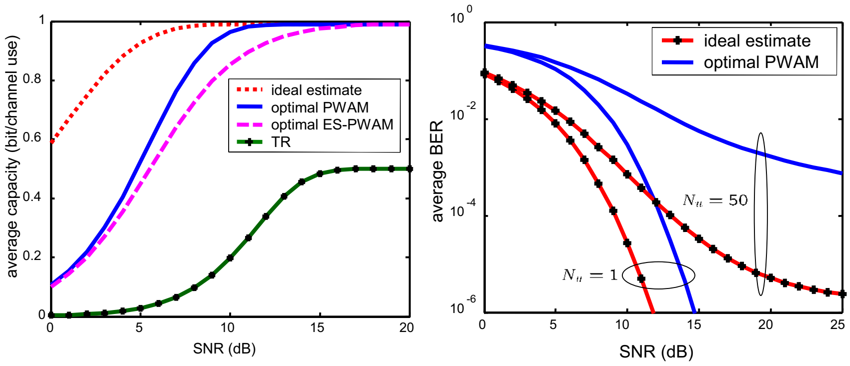
$$\rho_p = \frac{N_f \mathcal{E}_p}{N_p \sigma^2} = \frac{N}{N_p} (1 - \alpha) \rho$$



✓ Facilitates operation of nonlinear power amplifiers

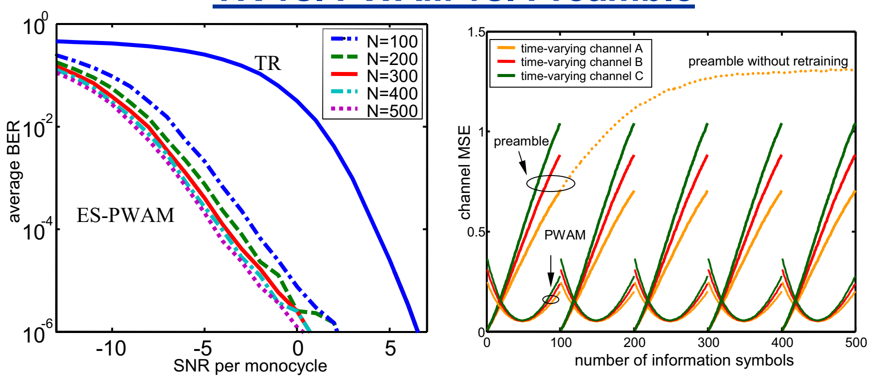
✓ Reduces interference to existing NB systems

Average Capacity and Performance



- ✓ average capacity
- ✓ BER in peer-to-peer and multiple access

TR vs. PWAM vs. Preamble



At high SNR: $250Kbps$ (TR) $495Kbps$ (N=100) $499Kbps$ (N=500)

Types of channels:

- ✓ Quasi-static: PWAM outperforms TR, and offers higher rate
- ✓ Time-varying: PWAM outperforms preamble

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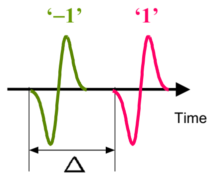
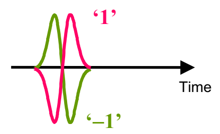
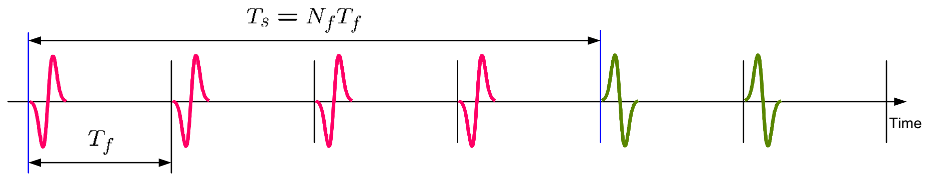
Baseband Modulation for UWB

- Pulse Position Modulation (PPM)
- Pulse Amplitude Modulation (PAM)





- Each symbol is conveyed by N_f pulses $p(t)$



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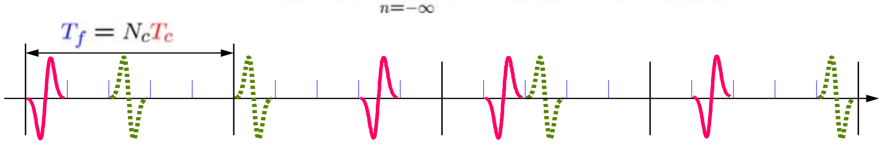
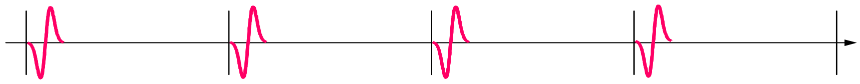
UWB Multiple Access

- Time Hopping (TH): $v_u(t) = \sqrt{\mathcal{E}_u} \sum_{n=-\infty}^{\infty} s_u(\lfloor n/N_f \rfloor) p(t - nT_f - c_u(n)T_c)$ [Scholtz '93]

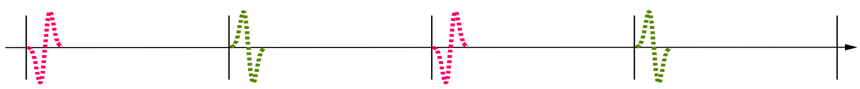


- Direct Sequence (DS): $v_u(t) = \sqrt{\mathcal{E}_u} \sum_{n=-\infty}^{\infty} s_u(\lfloor n/N_f \rfloor) c_u(n) p(t - nT_f)$ [Foerster '03]

DS code for User A: ***1 1 1 1***



DS code for User B: ***1 -1 1 -1***



Baseband UWB-MA

- Tx signal of user u:

$$\nu_u(t) = \sqrt{\mathcal{E}_u/N_f}\sum_{k=0}^{\infty} s_u(\lfloor k/N_f \rfloor)\, c_u(k)\, p(t - kT_f - c_u^{th}(k)T_c)$$

- Existing codes:
  - TH-UWB: $c_u^{th}(k) \in [0, \lfloor T_f/T_c \rfloor)$, and $c_u(k) = 1, \ \forall k$
  - DS-UWB: $c_u(k) \in \{\pm 1\}$, $\sum_{k=0}^{N_f-1} c_u{}^2(k) = N_f$, and $c_u^{th}(k) = 0, \ \forall k$
- Features:
  - ✓ constant modulus
  - ✗ not flexible in handling narrow-band interference (NBI)
  - ✗ not flexible in handling multi-user interference (MUI)

Baseband Single/Multi-Carrier UWB-MA

- $N_u = N_f$ real orthogonal subcarriers:
  - Set I with $f_u = (u + 0.5)/N_f, \ \forall u \in [0, N_f - 1]$

$$[\mathbf{f}_u]_k = \begin{cases} \sqrt{2}\cos(2\pi f_u k), & \forall u \in \left[0, \frac{N_f}{2} - 1\right], \\ \sqrt{2}\sin(2\pi f_u k), & \forall u \in \left[\frac{N_f}{2}, N_f - 1\right], \end{cases} \quad \forall k \in [0, N_f - 1]$$

  - Set II with $f_u = u/N_f, \ \forall u \in [0, N_f - 1]$

$$[\mathbf{f}_u]_k = \begin{cases} \cos(2\pi f_u k), & u = 0, \text{ or, } u = \frac{N_f}{2} \\ \sqrt{2}\cos(2\pi f_u k), & u \in [1, \frac{N_f}{2} - 1] \\ \sqrt{2}\sin(2\pi f_u k), & u \in [\frac{N_f}{2} + 1, N_f - 1] \end{cases}, \quad \forall k \in [0, N_f - 1]$$

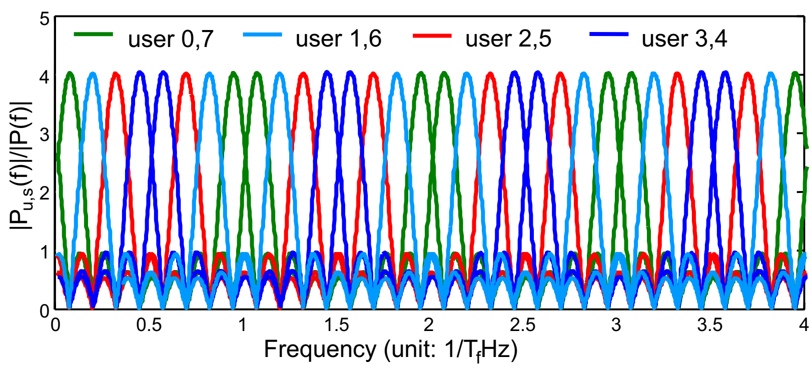
- Baseband single- and multi-carrier (SC/MC) user codes:

$$\mathbf{c}_u = \sum_{k=1}^{N_f-1} \left[\mathbf{c}_u^{(o)}\right]_k \mathbf{f}_k$$

  - $\left\{\mathbf{c}_u^{(o)}\right\}_{u=0}^{N_f-1}$ $\perp$ spreading codes
  - generally MC; SC if $\mathbf{c}_u^{(o)} = \mathbf{e}_u, \ \forall u$

Multi-Band Transmission

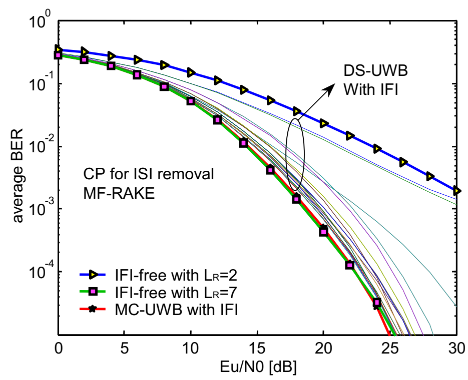
- ✓ Discrete cos/sin functions ⇒ DCT implementation & one RF chain !
- ✓ Digital carriers ⇒ flexibility in handling NBI
- ✓ Multiband transmission full multipath diversity even with SC !



MC-UWB vs. DS-UWB

- ❑ $\tau_L = 90\text{ns},\ T_f = 24\text{ns} \Leftrightarrow$ IFI
- ❑ $L_R = 2,\ N_f = 32,\ T_p \approx 1.0\text{ns}$
- ❑ ISI avoided by:
  - ➢ zero-padding (ZP)
  - ➢ cyclic-prefix (CP)
- ❑ Saleh-Valenzuela Channel Model

  $\left(\frac{1}{\Lambda}, \frac{1}{\lambda}, \Gamma, \gamma\right) = (2, 0.5, 30, 5)\text{ns}$
- ❑ Benchmarks generated using MRC (in the absence of IFI)



	$G_{d,max}$	$G_{c,max}$	code-indep.
MC-UWB	YES	YES	YES
DS-UWB	NO		NO

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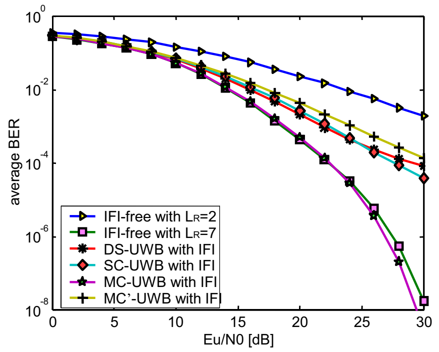
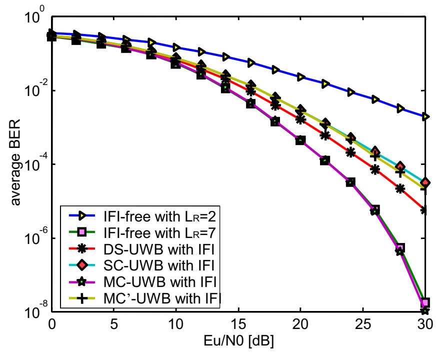
CP vs. ZP

- CP for ISI removal, MF-RAKE
- ZP for ISI removal, MF-RAKE





MC ≫ SC ≈ DS > MC' **MC ≫ DS > MC' ≈ SC**

✓ MC-UWB achieves maximum diversity AND maximum coding gains

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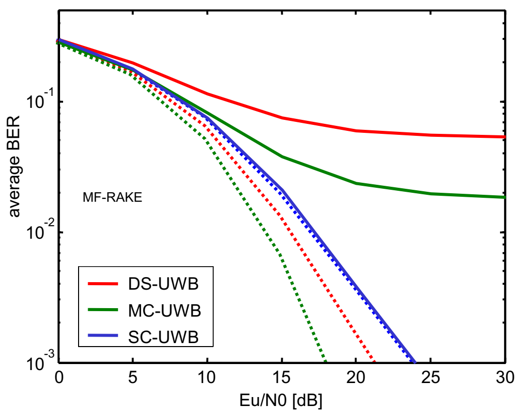
Comparison: Multiple Access

- CP for ISI removal, MF-RAKE



Dotted curves (low load):
$N_u = 1$

MC > DS > SC

Solid curves (medium load):
$N_u = N_f/2 + 1 = 17$

SC ≫ MC ≫ DS

✓ SC-UWB achieves *better* MA performance with *simple* MF-RAKE

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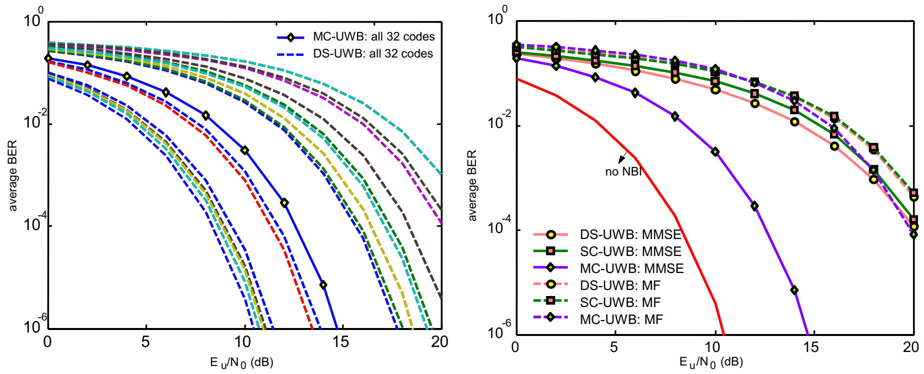
NBI and AWGN

- NBI: GPS (c.f. 1.2GHz, b.w. 20MHz, J_0/N_0=30dB)



- MC-UWB enables user-independent performance
- MC-UWB yields best BER
- SC-UWB similar to DS-UWB

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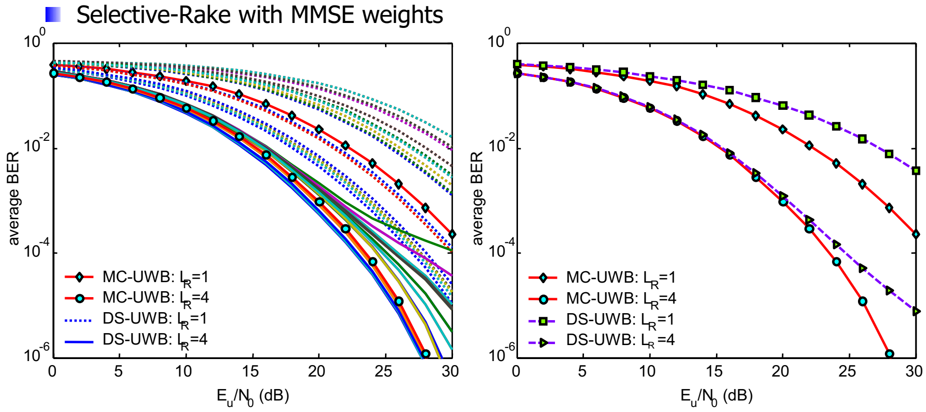
NBI and Multipath

- Selective-Rake with MMSE weights



- MC-UWB: user-independent performance
- MC-UWB outperforms DS-UWB

Summary

- Optimal UWB pulse shapers:
  - Dynamic narrowband interference avoidance
  - Single-band or multi-band
  - Time-hopping and/or frequency-hopping
- Synchronization for UWB communications:
  - In the presence/absence of TH and/or multipath
  - Rapid acquisition with low complexity and good performance
  - Data-aided or blind, single-user or multi-user settings
- UWB channel estimation
  - Transmitted Reference (TR)
  - Optimal Pilot Waveform Assisted Modulation (PWAM)
- Baseband UWB radios
  - Baseband SC/MC codes for multiple access
  - Unifying model for comparison in the presence of NBI

RF/Analog Design Issues for UWB Radio Communications

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Outline

- **Acknowledgements: work of my graduate students**
  - UWB introduction & power considerations: Jackson Harvey
  - Data converters: Shubha Bommalingaiahna-pallya
- **Introduction to UWB**
- **High-rate WPAN**
  - OFDM & MBOA proposal
  - Frequency hopping
  - DSSS XSI/Motorola proposal
  - Circuits for carrier based UWB
- **Low-rate WPAN**
  - Impulse radio based UWB
- **Broadband circuits**
- **Data converters for UWB**
- **Conclusions**

Introduction to UWB

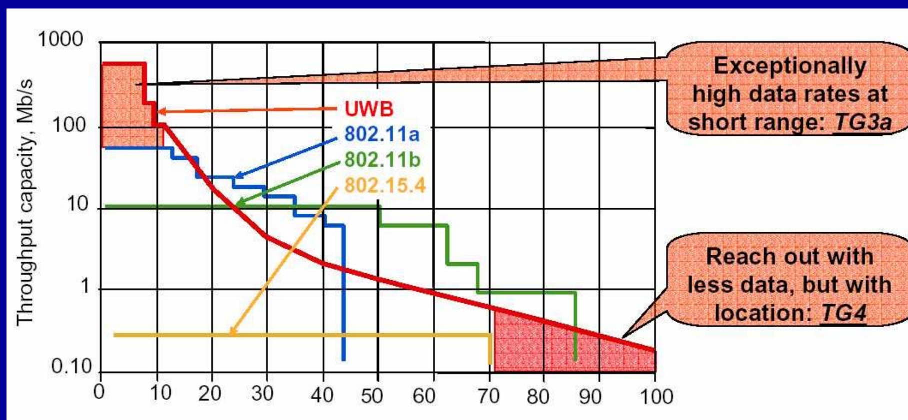
- **7.5 GHz of unlicensed spectrum in the U.S.A**
- **FCC definition of UWB: –10 dB BW > 20% or > 500 MHz**
- **EIRP limit: -41.3 dBm/MHz between 3.1 GHz and 10.6 GHz**
- **Two competing proposals before IEEE 802.15.3a group**
  - MBOA proposal: FHSS OFDM modulation
  - Motorola/XSI proposal: DSSS CDMA PSK
- **802.15.4a task group also exploring UWB**
- **Shannon-Hartley channel capacity theorem**

$$C = BW \cdot \log_2\left(1 + \frac{P_S}{P_N}\right) = BW \cdot \log_2\left(1 + \frac{P_S}{N_0 BW}\right)$$

  - Capacity increases linearly with BW, logarithmically with SNR
  - Large BW allows high throughput at low transmit power

UWB – Where Does It Fit?

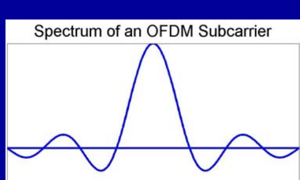
- **High-rate, short distance UWB (802.15.3a) – Carrier-based**
  - High data rate
  - Focused on multi-media (wireless USB/1394)
- **Low-rate, low power UWB (802.15.4) – Impulse radio**
  - Extremely low power consumption
  - Location awareness

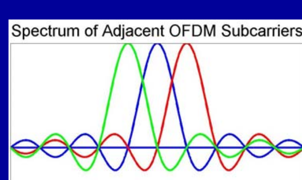


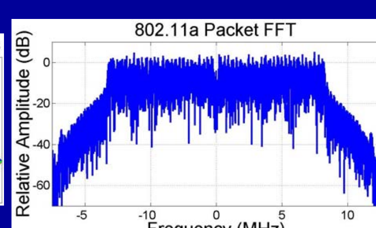
From IEEE 802.15-03/157r1

OFDM

- **Orthogonal Frequency Division Multiplexing (OFDM)**
  - Many carriers, each carrying data
  - May add pilot tones used for signal processing
  - May add unused subcarriers
    - Allows space between channels
    - Allows notches in spectrum to avoid interference
  - Time domain signal generated via FFT
  - Data spread over many subcarriers
    - If one carrier is faded, data can still be decoded
      - Low sensitivity to multipath and tonal interference

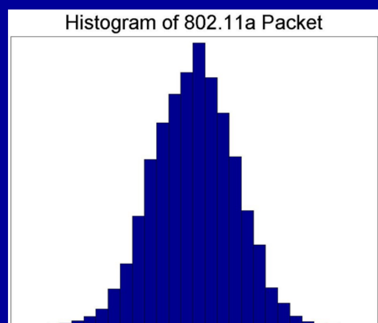


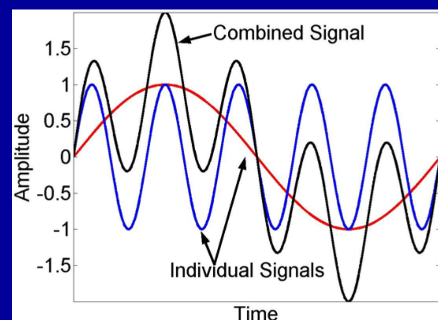




OFDM - PAPR

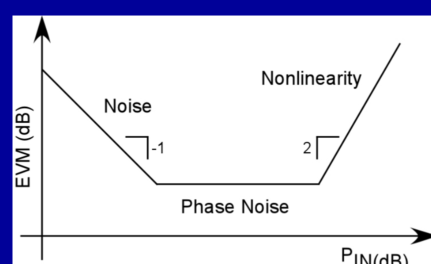
- **Peak-to-average power ratio (PAPR)**
  - Summation of many modulated carriers
  - Central limit theorem predicts normal distribution
  - Normal distribution has infinite peak power
  - PAPR (dB) = 10 * log10 (number of subcarriers)
    - Theoretically 21 dB for MBOA proposal
  - Peak is very rare – Not all PAPR needs to be preserved





OFDM - PAPR

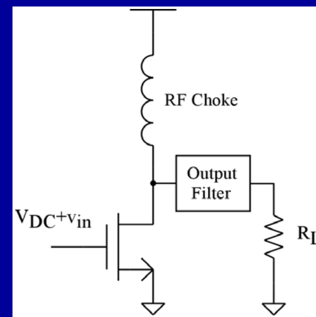
- **Systems must handle large signals**
- **Must have noise performance based on smaller average**
  - Large dynamic range
- **Power Amplifier (PA)**
  - Must be able to handle large peaks
  - Signal handling is set by DC current (linear amplifier)
  - DC current usually "wasted"
  - Leads to "backoff" specification
    - Ratio of P_{1dB} to average power
    - Some signal is still clipped
  - PA power consumption is larger than output power suggests
  - PA peak voltage is larger than output power suggests



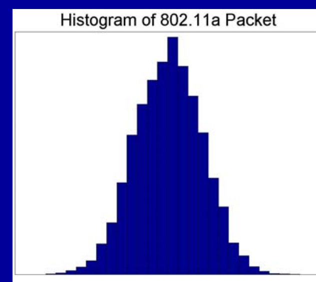
- **Error Vector Magnitude**
- **(N + D + I) to signal ratio**
- **Due to noise at low input**
- **Due to phase noise at moderate input**
- **Due to nonlinearity at high input**
- **Required back-off set by PAPR and required EVM**

Multicarrier PA Power

- **RF power output**
  - -41.3dBm/MHz + 10log(528) = -14.07dBm
- **Example backoff**
  - 6dB (depends on EVM and prefix)
- **Multicarrier requires class A amplifier**
- **Class A power amplifier efficiency @ P1dB**
  - 25% ~ 30%
- **DC power consumption for PA**



$$Pdc(dBm) = Ptotal + Backoff + 10\log\left(\frac{1}{Eff}\right)$$
$$= -2.05dBm$$
$$Pdc(mW) = 10^{Pdc(dBm)/10}$$
$$= 0.623mW$$



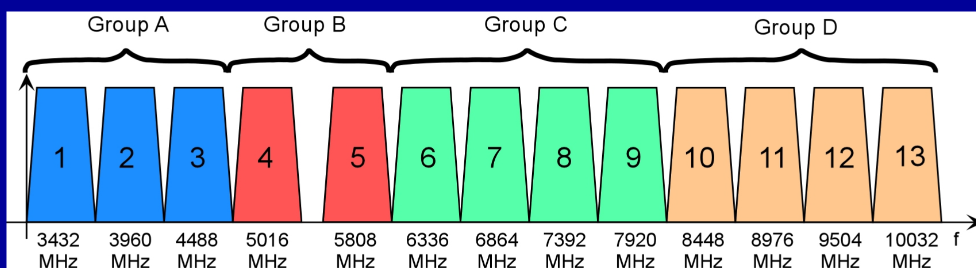
- **Digital & other power likely to swamp power consumpion**

Frequency Hopped Spread Spectrum

- **Narrowband modulation with changing carrier frequency**
  - Spectrum is widened by using many channels
  - “Instantaneous” spectrum is narrow
- **Fast hopping: hopping within packet**
  - At limit, hop after each symbol
- **Slow hopping: hopping between packets**
- **Data is lost if RX and TX hops not synchronized**
- **Multiple access via hopping sequence**
  - Collisions result in loss of data
  - System must be able to handle burst errors
- **Frequency hopping constrains PLL settling time**
  - New LO must be available for each hop
  - Fast hopping requires short settling time
    - May make PLL design very difficult

Multi-Band OFDM Alliance (MBOA) Proposal

- **MBOA includes TI, Philips, Panasonic, Samsung, Intel, Broadcom, HP, Microsoft, Nokia, RFMD, many others**
- **QPSK OFDM**
  - 128 subcarriers: 100 data, 12 pilot, 10 guard , 6 null
    - Guard tones may be null, proprietary data, or used to reduce PAPR
  - Subcarrier width = 528 MHz / 128 = 4.125 MHz
  - 60.6 ns zero padded prefix (ZPP)
    - Reduces ripple in spectrum relative to cyclic prefix
- **Bands: Group A mandatory, C optional, B + D reserved**



MBOA Proposal

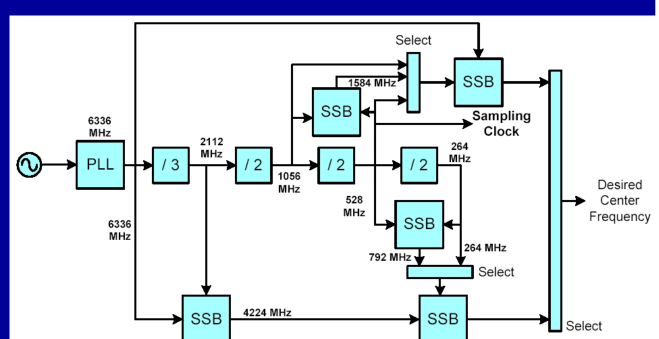
- **Fast frequency hopped (FHSS-OFDM)**
  - 528 MHz channels
  - Information interleaved across all bands
    - Multipath and interference robustness
  - 312.5 ns symbol, 9.5 ns guard interval
  - 3 band (Group A) or 7 band (Group A + C) options
  - Multiple access via hopping sequence
- **55, 110, 200 Mbps mandatory, 80, 160, 320, 480 Mbps optional**
- **Challenges**
  - Fast frequency hopping – 9.5 ns to switch channel
  - ADC requires >= 5 bits at 528 MHz
  - Wide IF bandwidth > 250 MHz (ZIF) or > 500 MHz (LIF)
    - Amplitude and phase variation partially corrected by equalization
- **Backoff: Claim is that with ZPP no backoff is required**

Frequency Hopping

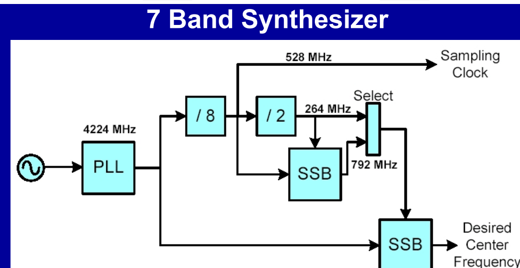
- **Allows wide total bandwidth with narrow channel bandwidth**
  - High instantaneous Q: low signal path power consumption
  - Signal path rings for Q cycles upon frequency change
- **LO frequency must shift in guard interval**
- **PLL hopping rate limited**
  - Loop filter frequency < reference frequency / 10
  - Reference frequency generated by quartz oscillator
    - Limited by reasonable crystal width to < 80 MHz
    - Overtone crystals have higher phase noise, hard to control
  - Bottom line: PLL cannot reasonably settle in 10 ns
- **Disagreement about meaning of FCC rules**
  - Part 15 states that compliance is measured at fixed frequency
  - MBOA claims that issue is interference
  - FCC refused to issue declarative ruling

MBOA Frequency Hopping Proposal

- **Change channels without resettling PLL**
- **PLL frequency constant**
- **Multiple SSB mixers**
  - High phase noise
    - Bad for OFDM
  - High power
  - Spurious products
    - Vestigial sidebands
  - 3 in LO path, 5 total for 7 band
- **Very fast hopping**
  - ~2 ns ideally
  - < 10 ns easily



7 Band Synthesizer



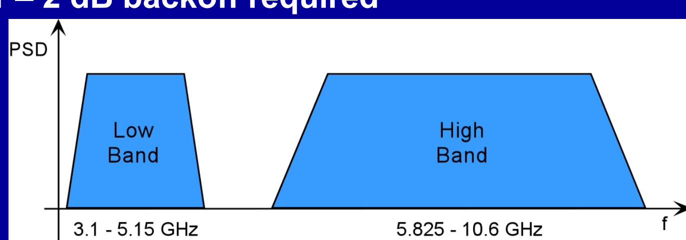
3 Band Synthesizer

Direct Sequence Spread Spectrum (DSSS)

- **Digital signal is XORed with "chip" PRBS before modulation**
  - Chip stream at faster rate
  - Processing gain is chip rate / bit rate
- **TX spectrum is that of modulated chip stream**
  - Wider than that of modulated bit stream by processing gain
  - Spectrum has been "spread"
- **RX XORs received signal by same chip stream**
  - Desired signal is "despread"
    - Synchronization performed via DSP
- **Only small part of signal in narrow frequency band**
  - Good immunity to narrowband interferers
  - Good immunity to fading
- **Data using different code looks like wideband noise**
  - Multiple access through use of different chip streams
  - Security via use of secret chip stream
  - Low probability of intercept / spoof

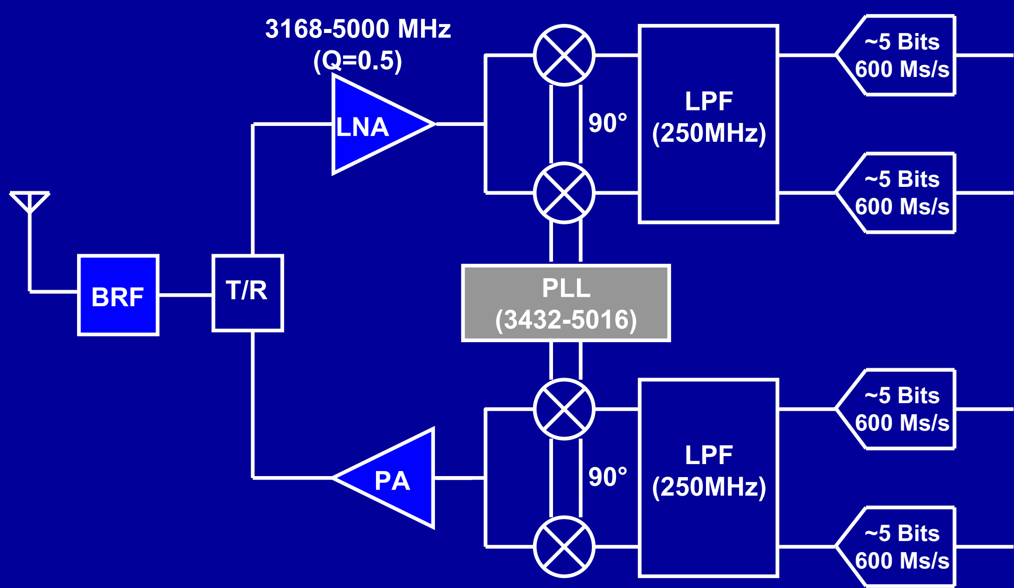
Motorola/XSI Proposal

- **Backed by Motorola/XSI, Parthus, CRL-UWB members**
- **DSSS CDMA (B/Q) PSK – No frequency hopping**
- **Two bands: 3.1 – 5.15 GHz, 5.825 – 10.6 GHz**
- **Multiple access via FDM (2 bands) / CDM (2 codes) / TDM**
- **Data rates: 25, 50, 112, 114, 200, 224, 448, 900 Mbps**
- **ADC requirements depend greatly on implementation chosen**
  - Symbol-rate sampling vs. chip-rate sampling
- **Wide IF required even for low-band**
- **Claims of 1 – 2 dB backoff required**



Potential MBOA Architecture

- **Direct conversion RF architecture for MBOA proposal**

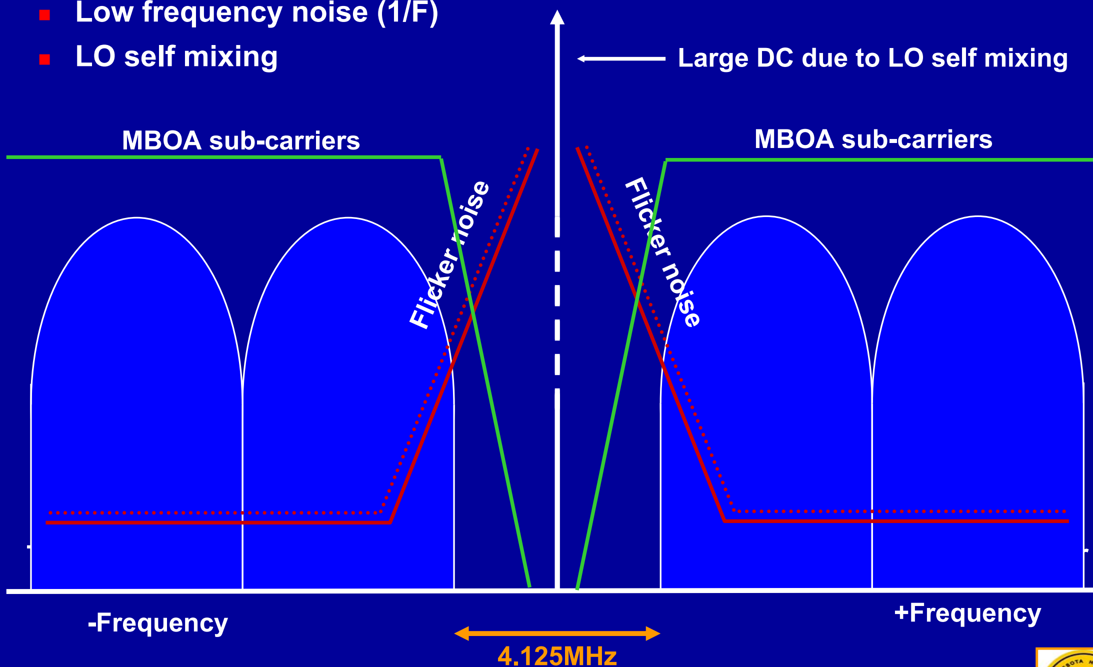


Direct Conversion Issues

- **DC offset**
  - LO leakage & large interferers
    - Leakage much bigger than signal
    - LO signal large ~about 0dBm
    - Leakage ~10mV, signal level ~30uV
  - Can saturate following stages (large gain after LNA 80~100dB)
- **Flicker (1/F) noise**
  - Flicker noise corner is inversely proportional to device area
  - RF devices small to obtain high speed operation
  - I/F noise corner ~MHz
- **LO pulling**
  - Large signal near LO freq will injection pull the internal VCO
- **LO re-radiation**
  - Radiation from LO (0dBm) to antenna
  - Requirements: -50dbm to -80dBm
  - Harder to meet due to lack of isolation
- **I/Q distortion**
  - I/Q gain and phase harder to do at RF
- **Offset can be removed by highpass filtering**
  - Possible for modulation schemes that have no signal at carrier
  - Wideband modulation schemes (e.g. DSSS)
  - Large channel bandwidth, small loss in band causes limited ISI

Flicker Noise & LO Self Mixing

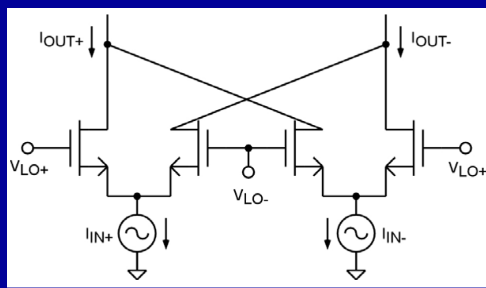
- **Low frequency noise (1/F)**
- **LO self mixing**

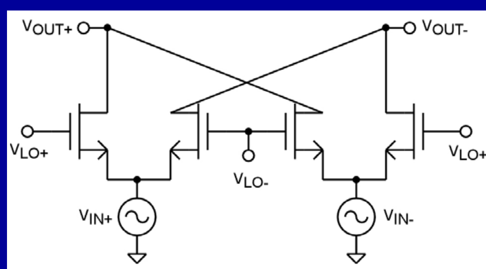


Highpass-Filter for Offset Removal

- **One sub-carrier removed at DC**
  - High-pass pole <= 2MHz (4.125MHz/2)
  - Process variations ? (R & C vary independently)
  - More realistic number is about 1MHz
- **Carrier stability requirement is 20 ppm per TX/RX**
  - Carrier frequency offset (CFO) can be >= 400kHz
  - Easy to accommodate CFO at 25 degree C
  - Increased BER/PER if sub-carrier affected (as for 802.11a/g)
- **Startup & switching time**
  - With 1MHz pole, 3 time constants = 477ns
  - Offset likely to change when switching channels
  - Large slow settling transient
  - Also true for startup times (switching between TX/RX)

UWB Mixer Issues





- **Current switching**
  - Transconductor and load can be analyzed independently
  - Switch resistance not critical
  - Moderate switches
  - Moderate LO drive
- **Voltage switching (aka passive mixer)**
  - Source, switch, and load impedance critical
  - Large switches
  - Large LO drive
- **Power consumption in LO drive**

$$P = \frac{V_{RMS}^2 C \omega_0}{Q}$$

UWB Mixer Issues

- **Downconversion Mixer**
  - Input signal is channel dependent, broadband, bandpass
    - Wideband bandpass load required at LNA
    - Load may be tuned to channel frequency
      - Channel bandwidth must still be accommodated
    - LO frequency depends on channel
      - Bandpass driver requires low Q or tuning
      - Lowpass broadbanding may be suitable
  - Output signal is broadband, lowpass
    - Same frequency regardless of channel
    - Lowpass broadbanding techniques suitable for load
    - Capacitance at output detrimental to bandwidth
      - Voltage switching mixer may be unsuitable
- **Upconversion mixer faces issues in reverse**
  - Channel dependent, broadband, bandpass output signal

Low-Power Carrier-Based RF

- **Largest power consumers in carrier-based digital RX:**
  - Local oscillator
    - Low phase noise, fast switching → high power
    - High frequency, wide frequency range → high power
  - Downconversion mixer
    - High dynamic range, high gain, high frequency → high power
    - LO drive of mixer core capacitance may dominate
  - Analog-to-digital converter
    - High resolution, high speed → high power
- **Largest power consumers in carrier-based digital TX:**
  - Local oscillator
  - Upconversion mixer
    - High frequency, wide frequency range → high power
    - Often requires high linearity (gain is cheaper at IF)
  - Power amplifier
    - High linearity, high frequency, high frequency range → high power
    - Not necessarily true for UWB FCC specs

Low-Power Carrier-Based RF

- **General rules**
  - Reduce dynamic range requirements
    - Reduce PAPR and required SNDR
  - Lower center frequency, bandwidth, and frequency range
- **Simplify local oscillator**
  - Reduce phase noise requirements (reduce required SNDR)
  - Increase allowed switching time (slow hopping, if any)
- **Simplify up- and down-conversion mixers**
- **Simplify (or eliminate) ADC and DAC**
  - Use analog modulation/demodulation when possible
  - Reduce required resolution (required SNDR)
  - Reduce required speed (signal bandwidth)
- **Simplify power amplifier**
  - Reduce required linearity (PAPR and required SNDR)
- **Reduce active duty cycle (TX and RX)**

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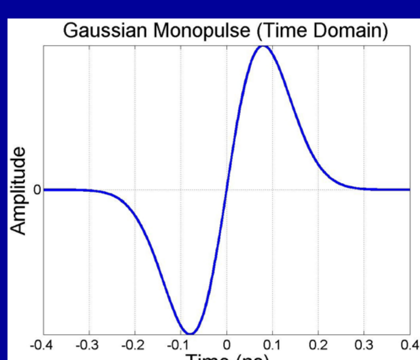
  - Circuits for carrier based UWB
- **Low-rate WPAN**
  - Impulse radio based UWB

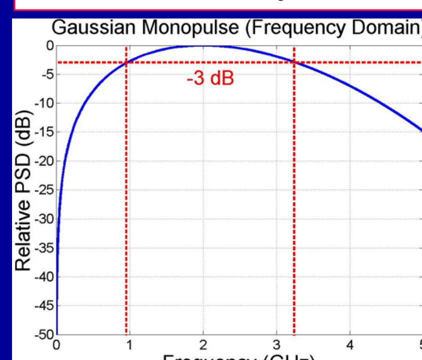
Impulse Radio

- **Dates back from first spark gap transmitter**
- **Used for military applications (LPI, LPD, radar)**
- **Time-domain “baseband” impulses are transmitted**
  - Gaussian monopulse (derivative of Gaussian pulse)

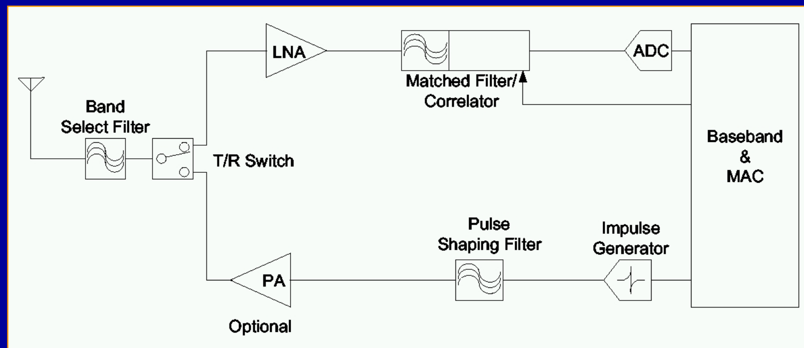
$$V(t) = 2\sqrt{e}\pi t f_c e^{-2(\pi t f_c)^2}$$

$$V(f) = \frac{1}{2}\sqrt{\frac{2e}{\pi}}\frac{f}{f_c^2}e^{-\frac{1}{2}\left(\frac{f}{f_c}\right)^2}$$





Impulse Radio



- **No frequency conversion**
  - No need for PLL or mixer
- **Modulation via pulse position (PPM), amplitude (PAM), sign**
- **Spectral control requires pulse shaping or filtering**
  - Half-power bandwidth is 116% of center frequency
- **Reception requires very precise time correlation**
  - PPM may use 200 ps variation to differentiate “0” and “1”
  - Multipath effects “smear” the arrival time of a pulse

Low-Rate WPAN

- **Requirements: low data rate, low price, very low power**
  - 200 kbps (simple data), < 10 kbps (wireless sensors, etc.)
  - Longer range: 0 – 30 m, > 100 m at very low data rate
  - Very low (or no) battery consumption
    - Several months to several years self-powered operating time
    - 100 uW is approximate limit for energy scavenging (IEEE 802.15-03/157r1)
  - Low complexity, small, form factor appropriate for sensors
  - Able to handle high noise, high multipath environments
  - Precision position determination (10 cm – 1 m accuracy)
- **WPAN unmanaged, dynamic, and unpredictable**
  - Devices may be mobile – enter and leave network randomly
  - IR-UWB well suited to intermittent or periodic data bursts
- **IR-UWB may allow for very low power consumption**
- **IR-UWB also allows for position determination**
  - Inherent feature of IR communication
  - Little additional power consumption
  - Due to precise timing required for pulse acquisition

Low-Power Impulse Radio

- **IR modifies carrier-based low power RF rules**
- **TX efficiency can be very good**
  - Pulse transmission may not require linear PA
  - Discarding LNA and maximizing TX power may be net win
- **Usual suspect circuits not needed**
  - No PLL or upconversion/downconversion mixer
  - PA may not need to be linear
- **Major decrease in power consumed by decreased duty cycle**
  - TX is on only when transmitting a pulse
  - RX is on only when expecting a pulse
- **Redundancy decreases required SNR but increases duty cycle**
  - Too much redundancy may be a net loss
- **Very accurate timing required**
  - Pulses are short: timing error causes missed pulse
  - RX duty cycling depends on knowing when pulse is coming
  - Position determination accuracy set by timing accuracy

Low-Power IR-UWB for Low-Rate WPAN

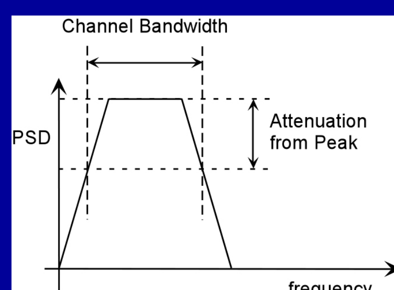
- **Emission limit: -41.3 dBm / MHz, 500 MHz minimum BW**
  - -14.3 dBm maximum output power at minimum BW
  - 38 μW transmitted power
  - TX power consumption = TX power * efficiency * duty cycle
  - IR-UWB efficiency can be very high, duty cycle very low
- **"Crystal Radio" detection (rectifier, LPF)**
  - Filtering is required at RF (or at IF if downconverted)
  - Extremely short baseband RX pulses
    - High rate ADC or analog signal processing
    - Proper timing critical to minimize RX on time
- **Noise figure can trade-off with range, data rate**
  - 15 dB NF + loss not unreasonable (for 75 m indoor system)
    - Detailed power/noise budget in IEEE 802.15-03/157r1

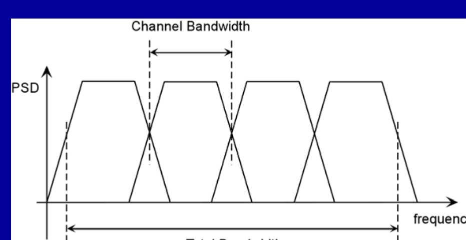
Outline

- **Acknowledgements: work of my graduate students**
  - UWB introduction & power considerations: Jackson Harvey
  - Data converters: Shubha Bommalingaiahna-pallya
- **Introduction to UWB**
- **High-rate WPAN**
  - OFDM & MBOA proposal
  - Frequency hopping
  - DSSS XSI/Motorola proposal
  - Circuits for carrier based UWB
- **Low-rate WPAN**
  - Impulse radio based UWB
- **Broadband circuits**

Bandwidth

- **Amount of spectrum occupied by signal**
  - Attenuation (absolute or relative to carrier) must be specified
  - For UWB, 10 dB BW > 20% or > 500 MHz
- **"Instantaneous" bandwidth**
  - BW over short period
  - Minimum BW in signal path
- **Total bandwidth**
  - N times instantaneous BW for N channels
  - Sets signal path BW if no channel-dependent tuning is performed





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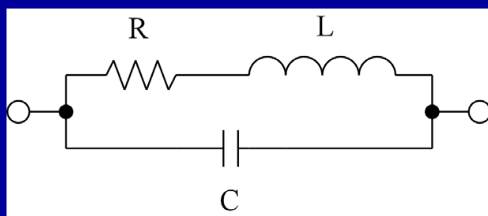
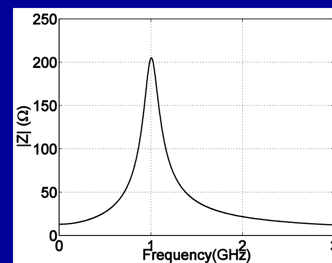
Parallel Resonant Loads

- **Parallel resonant loads used in narrowband RF systems**
  - Capacitance inevitable, but impedance required
  - Impedance of capacitor inversely proportional to frequency
  - Inductor resonated with capacitor to increase impedance
  - Inductor has parasitic resistance



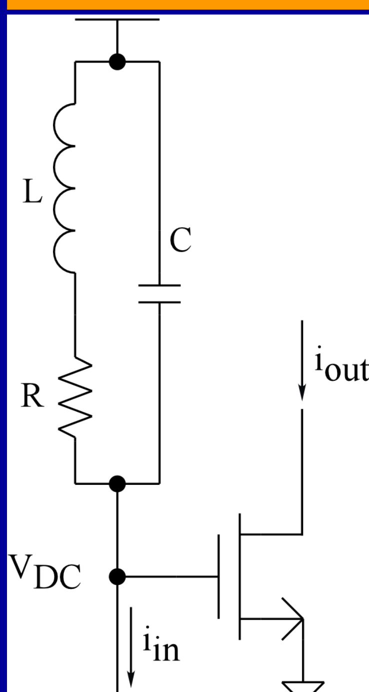


  - Parallel tank impedance varies with frequency
    - Inherently limited bandwidth
    - Impedance inversely proportional to bandwidth

$$Q = \frac{\sqrt{L/C}}{R} = \frac{Z_0}{R} \approx \frac{Z_{f_0}}{Z_0} \approx \frac{f_0}{BW_{3dB}}$$

$$f_0 \approx \frac{1}{2\pi\sqrt{LC}}$$

Current Gain Cell



- **Representative of RF gain circuits**
- **Tank impedance converts I to V**
- **MOS gm converts V to I**
- **C is assumed to be MOS C_{GS}**
  - Ignores C_{GD} and parasitic C of L

$$Z = \frac{Q}{\omega_0 C} \quad g_m = \omega_t C \quad \left|\frac{i_{out}}{i_{in}}\right| = Q\frac{\omega_t}{\omega_0}$$

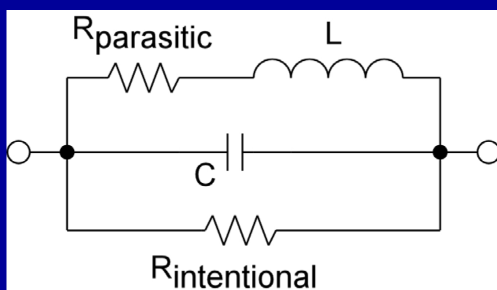
- **Gain is directly proportional to Q, f_t**
- **Gain is inversely proportional to f_0**

$$\left|\frac{i_{out}}{i_{in}}\right| = \frac{f_t}{BW}$$

Gain inversely proportional to bandwidth!

Broadbanding: de-Qing

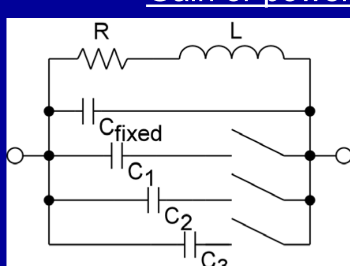
- **Defining attribute of UWB: wide (fractional) bandwidth**
- **Parallel or series resonant tanks inherently bandlimited**
  - Maximum Q desired for gain vs. power consumption
  - Maximum Q leads to minimum bandwidth
  - Q for bandwidth at frequency
- **Conclusion: maximum Q tank has too little bandwidth**
- **Simple solution: reduce Q**
  - Add intentional parallel resistance
  - Problem: reduces gain per power, increases noise



**Side benefit:
Gain variation with
process and temperature
can be reduced.**

Broadbanding: C-tuning

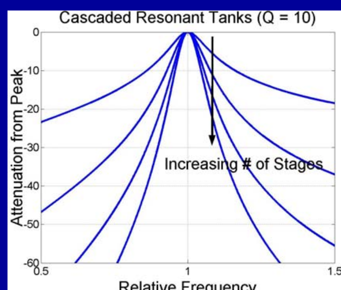
- **Only channel bandwidth needed at any time**
  - Solution: tune signal path tank frequencies
  - L, C, or both must be varied with signal frequency
  - Integrated variable L or switched L difficult
    - Series switch significantly degrades Q and linearity
  - Variable capacitor can tune frequency
    - Varactor introduces signal and control nonlinearity
    - Switched C useful, especially for grounded capacitor
    - Problem: impedance varies widely with frequency
      - Gain or power consumption vary widely with f

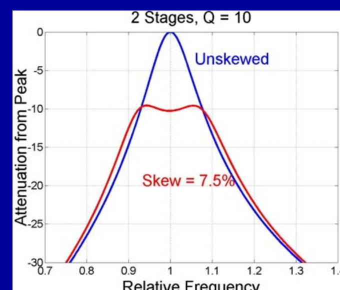


$$\left|\frac{Z_{\max}}{Z_{\min}}\right| = \left(\frac{\omega_{0,\max}}{\omega_{0,\min}}\right)^2$$

Broadbanding: Multistage

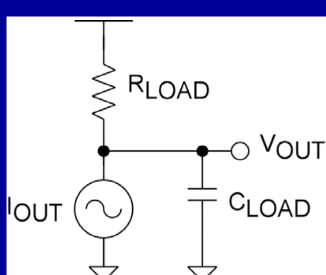
- **Bandwidth is reduced by each narrowband stage**
  - 3 dB BW reduced by ~ $\sqrt{2}$ by each added stage
- **Solution: "skew" resonant frequency of stages**
  - Bandwidth at any given attenuation increased
    - Gain is made more constant over frequency
  - Problem: peak gain is reduced
    - Lower gain or higher power consumption
  - Problem: gain of each stage not stabilized over frequency
    - Noise and linearity become function of frequency



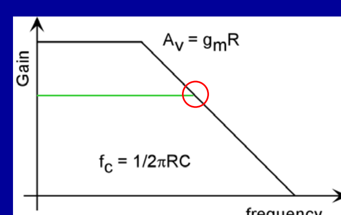


Lowpass (RC) Load

- **Physical resistor is ideally broadband load**
- **Parasitic and load capacitance causes undesired pole**



$$|Z| = \frac{R}{\sqrt{1+\omega^2 C^2 R^2}}$$



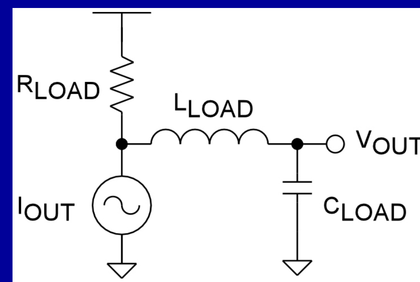
- **To increase pole, R must be decreased (for fixed C)**
  - Constant gain-bandwidth product (g_m / C)
- **Parasitic C of resistor: distributed RC**
- **Resistor contributes noise and DC voltage drop**

Broadbanding: Series Peaking

- **Load C is isolated from R by L**

$$v_{OUT} = i_{OUT} \frac{R}{1-\omega^2 LC + j\omega CR}$$

Complex Pole Pair



- **BW increased up to 1.41 X**

$$L = \frac{R^2 C}{2}$$

- **Phase/Amplitude distortion**
  - Maximum BW case is also maximally flat amplitude
  - Maximally flat group delay case gives 1.36 X BW

$$L = \frac{R^2 C}{3}$$

- **High Q inductor not required (parasitic absorbed into load R)**

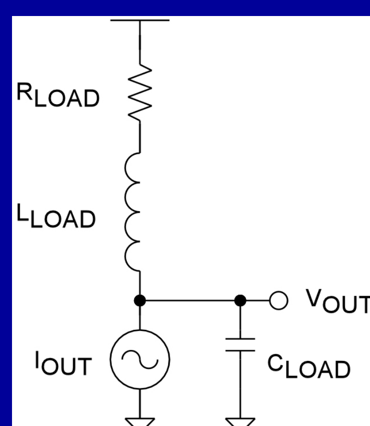
Broadbanding: Shunt Peaking

- **Load C again isolated from R by L**
  - Z of L increases as Z of C decreases
  - BW extended up to 1.85 X

Zero

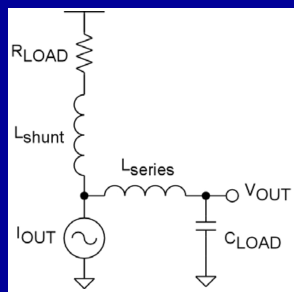
$$v_{OUT} = i_{OUT} \frac{R + j\omega L}{1-\omega^2 LC + j\omega CR}$$

Complex Pole Pair

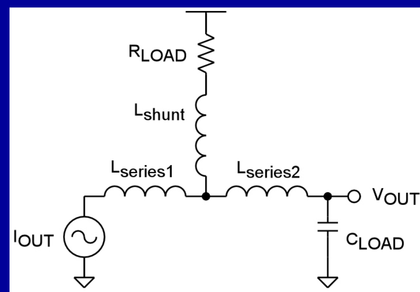


- **High-Q inductor not required**
  - Parasitic R absorbed into R_{LOAD}
- **Phase/amplitude distortion**
  - 20 % amplitude peaking at max BW
  - Maximally flat amplitude at 1.7 X BW
  - Maximally flat delay at 1.6 X BW

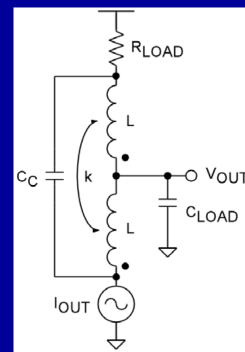
Broadbanding: Advanced Structures



Shunt-Series Peaking



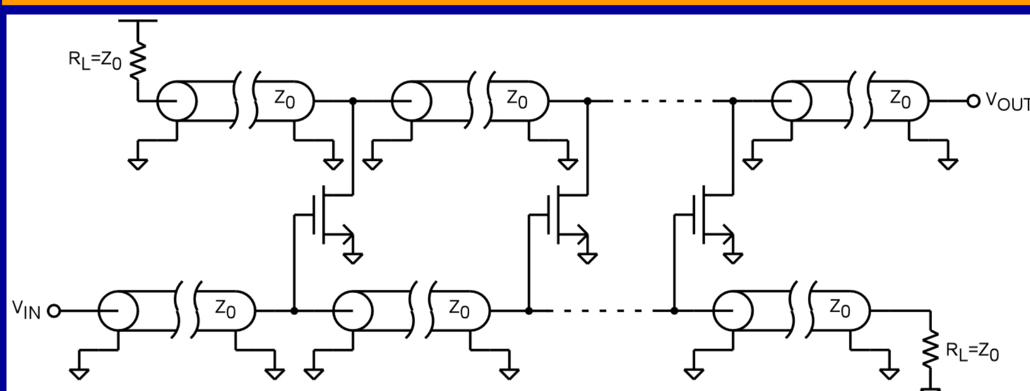
Shunt-Double Series Peaking



T-Coil Peaking

- **Combinations of shunt peaking and series peaking**
  - Progressively improved bandwidth
- **T-coil can be laid out as overlapping planar spiral inductors**
  - C_C may be realized directly by overlap capacitance
- **T-coil peaking allows bandwidth extension by 2.83 X**
  - Additional compensation for output C can be added in series

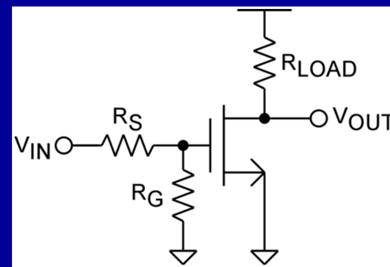
Broadbanding: Distributed Amplifier



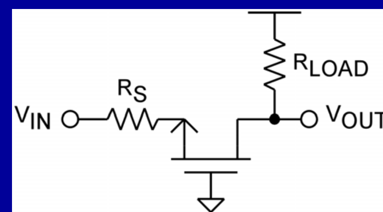
- **Lumped amplifiers charge all capacitors in parallel**
  - Trade off bandwidth for gain (G*BW product ~ constant)
- **Distributed amplifier charges capacitances in series**
  - Trades off delay (instead of BW) for gain
- **Uses parallel combination of amplifiers rather than cascade**
- **Gain depends linearly on number of stages**

Broadband LNA for UWB

- **R matched common source LNA**
  - Broadband input match
  - Poor noise figure
    - 3 dB attenuation (adds to NF)
    - Thermal noise of matching resistor
    - Minimum NF = 3 (4.6) dB
  - Voltage gain $A_v = g_m R_{LOAD}/2$
  - BW limited by RC at input, RC at output



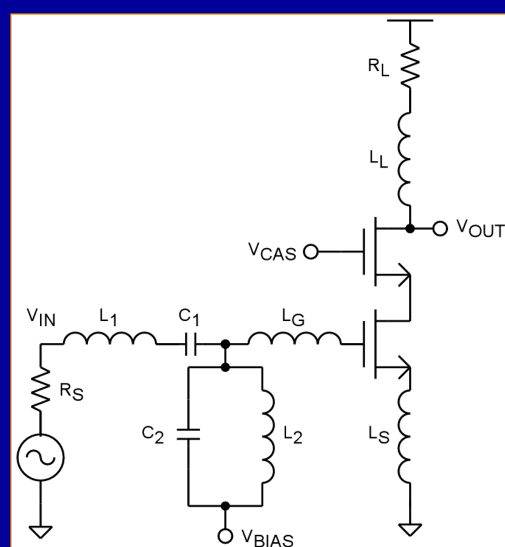
- **Common gate LNA**
  - Broadband input match ($1/g_m$)
  - Minimum NF ~ 2.2 dB (long channel)
  - Voltage gain $A_v = g_m R_{LOAD}/2$
  - BW limited by RC at input, RC at output



- **No need for inductors**
  - Area efficient, easy to model

Broadband Tuned LNA

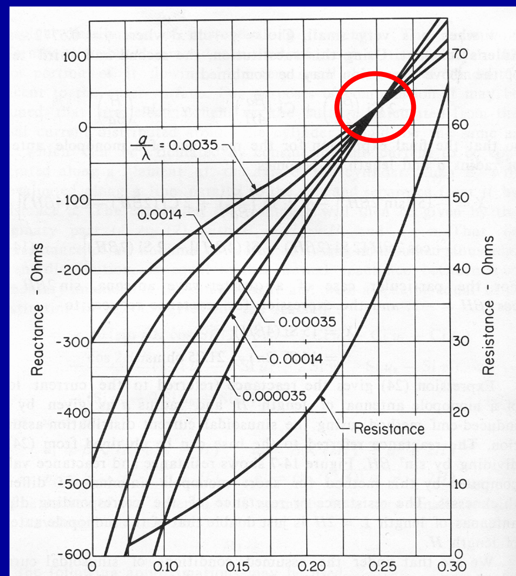
- **Common-source LNA**
- **Pseudo-ladder filter input**
  - Input match 3 – 10 GHz
- **Shunt peaked output**
  - BW > 10 GHz
- **Power similar to standard narrowband LNA (9 mW)**
- **10 dB power gain**
- **Average 5 dB NF over band**
- **Problem: many inductors**
  - Large area
- **Similar to Ismail and Abidi, ISSCC 2004, pp. 384 – 385 & Won Namgoong, PC**



After Bevilacqua and Niknejad, ISSCC 2004, pp. 382 - 383

Antennas for UWB

- **Most antennas, bandwidth (impedance and/or pattern) often too narrow to support wideband UWB signals**
- **Traditional "frequency independent" antennas**
  - E.g., log periodic dipole arrays
  - Radiation occurs at different positions along the antenna as the frequency varies causing signal dispersion
- **Antenna impedance frequency dependent**
  - E.g. short dipole antenna



Dipole length is wavelength
(α = dipole wire radius   from Jordan & Balmain)

Antennas for UWB: What to do?

- **Use inherently broadband antennas with constant phase center**
  - E.g., biconical dipoles and TEM horns
- **Resistively loaded traveling wave-like structure**
  - Useful for creating short UWB antennas but sacrifices efficiency
- **Co-design antenna and electronics**
  - Predistort UWB pulse so radiated field has desired pulse shape
  - Linearize the antenna's phase response using FIR filters
    - Especially useful for frequency independents spirals, etc
    - Requires high sampling rate
  - Alternately, do a broadband impedance match with the antenna
    - UC Berkeley (Broderson et. al.)

Outline

- **Acknowledgements: work of my graduate students**
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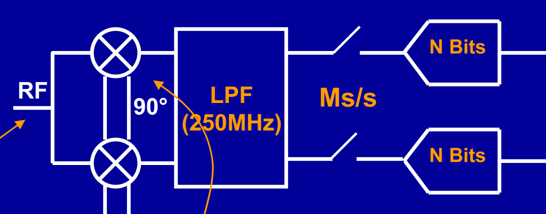
  - OFDM & MBOA proposal
  - Frequency hopping
  - DSSS XSI/Motorola proposal
  - Circuits for carrier based UWB
- **Low-rate WPAN**
  - Impulse radio based UWB
- **Broadband circuits**
- **Data converters for UWB**

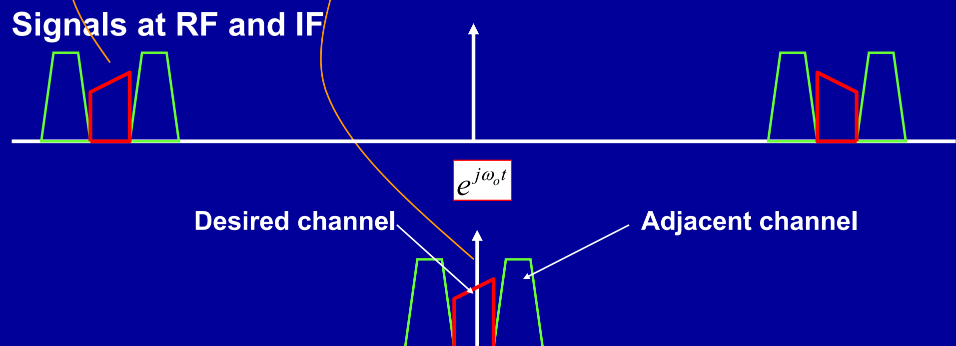
Analog Design Group, University of Minnesota (harjani@ece.umn.edu)

Data Converter & Anti-alias Filter

- **Direct conversion RF architecture for MBOA proposal**



- **Signals at RF and IF**



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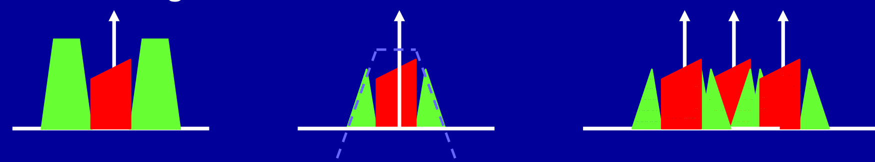
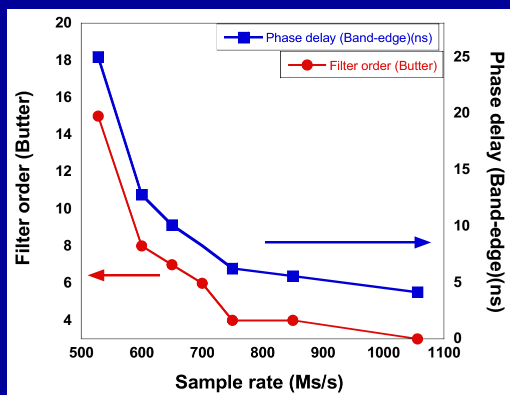
Data Converter Overview

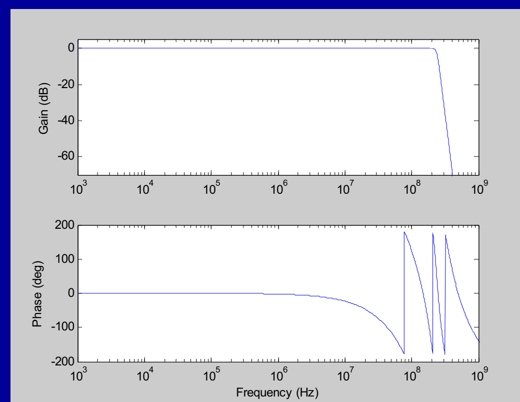
- **Baseband signals**



After Mixer **After LPF** **After Sampling**

- **Anti-alias filter & sampling rate (ACPR=+16dB, SNR=12dB)**





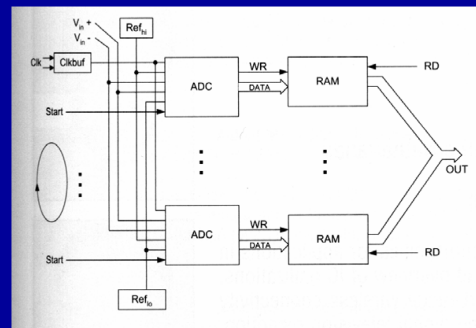
Butterworth Filter **Butterworth Filter**

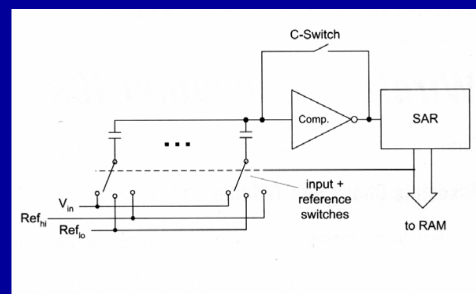
Data Converters for UWB

- **We only focus on ADCs (DACs are a similar but easier)**
- **ADC requirements (<< 200mW)**
  - MBOA
    - Speed – 528MHz
    - Resolution – 4 bits [2]
  - DSSS [3]
    - Speed – 57MHz/1.368GHz/20GHz depending on architecture
    - Resolution – 4 bits
- **ADC architectures**
  - 1-bit/clock converters
    - Flash ADC
    - Folding ADC
    - Pipeline ADC
  - Interleaved & parallel converters
    - Parallel ΣΔ ADC
    - Interleaved SAR ADC
  - Frequency channelized converters

Interleaved SAR ADC

- **Time inteleaving can be used to increase speed**
- **Charge redistribution successive approximation ADCs are known for low power**
- **8 identical stages are interleaved**
- **Mismatch between stages can be digitally calibrated out**
  - Simple digital calibration.
  - Gain of each stage identified individually
- **Power consumption**
  - 6 b, 600Ms/s converter
  - Lowest FOM 0.4pJ/Conver

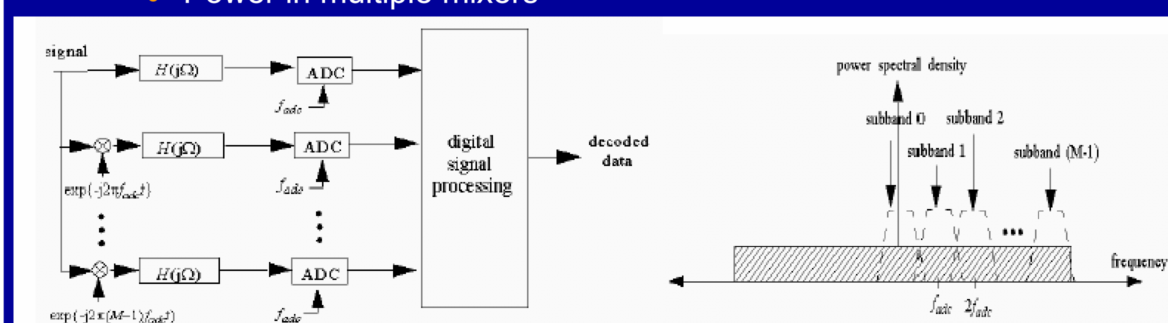




Draxelmayr, ISSCC 2004

Frequency Channelized ADC

- **UWB large bandwidth**
  - High sampling (multiple Gs/s for DSSS)
- **Narrowband in-band interferers because large bandwidth**
  - Large dynamic range
- **Solution**
  - Breakup frequency band into multiple subbands
  - Need to compensate for analog mismatch between paths
  - Power in multiple mixers



Ref: Won Namgoong, USC

Summary and Conclusions

- **Wide, unlicensed band available for civilian use**
  - Wide bandwidth may allow low power, high rate multimedia
- **Large fractional bandwidth required**
  - Requires modifications to narrowband design methodology
  - Broadbanding required to achieve total bandwidth
  - Frequency hopping allows wide total bandwidth
    - Fast hopping is difficult to achieve with low phase noise
  - Impulse radio UWB
    - Simple, but poor spectral control
    - Time domain nature makes antenna design difficult
- **System decisions greatly impact circuit design**
  - Systems requiring low EVM require high dynamic range
  - Fast hopping requires careful synthesizer design
  - OFDM amplitude distribution makes Class B unsuitable
  - Antenna & electronics need to be designed together
  - Large bandwidth makes data converter design more challenging

Summary and Conclusions

- **Two proposals under consideration for IEEE 802.15.3a**
  - MBOA: FHSS QPSK OFDM
    - Good spectral control, multiple bands ease regulatory problems
    - Fast hopping difficult: high power and phase noise
    - FCC compliance issue is not settled
    - Many difficulties of OFDM reduced by QPSK constellation
    - Guard tones allow for proprietary features
  - Motorola/XSI: DSSS
    - Spectral control more difficult, only two bands
    - No frequency hopping – frequency synthesis simplified
    - Near/far problem only partially mitigated by two bands
      - TDMA required to solve near/far problem
    - Complexity very implementation dependent
      - Can trade off complexity for performance

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University of Minnesota

Twin Cities Campus

Multirate and Subband Signal Processing in Ultrawideband Communications

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Electrical and Computer Engineering Department
University of Minnesota

Overview

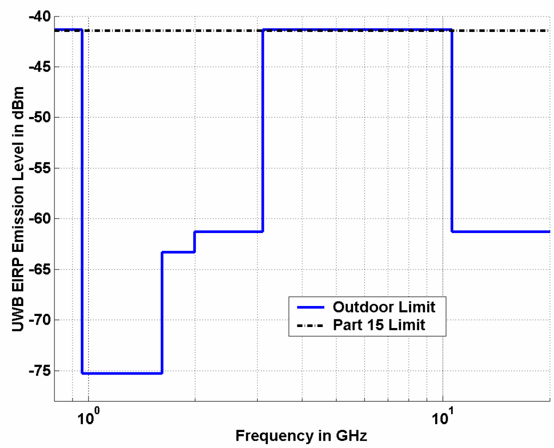
- Introduction
- Multirate techniques in UWB system design
- Subband techniques in UWB ranging
- Subband approaches in ADC
- Conclusion

Overview

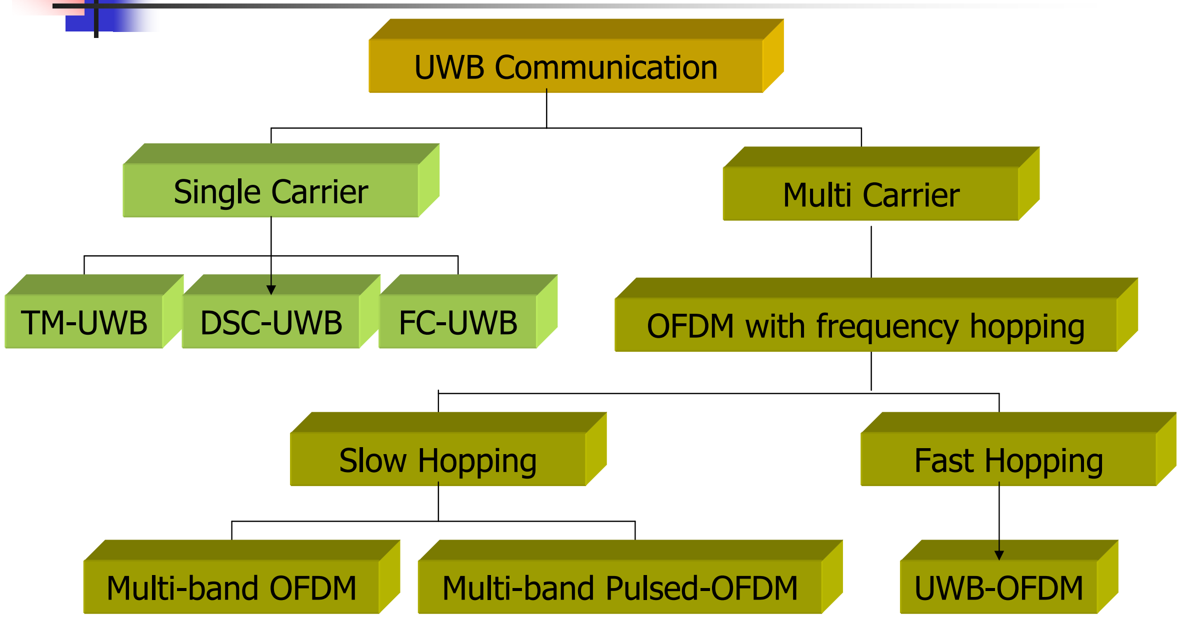
- Introduction
  - Unified view of UWB systems

UWB Communications

- Ultra-wideband communications
  - Fractional bandwidth (BW/fc) > 25%
  - BW > 1.5 GHz
- New FCC regulations
  - 3.1 GHz – 10.6 GHz band
  - Part 15 applies
  - Contiguous BW > 500 MHz



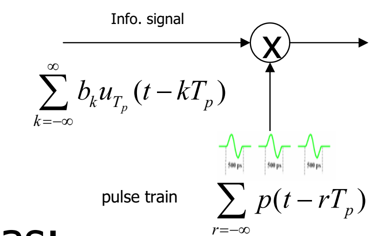
UWB Systems



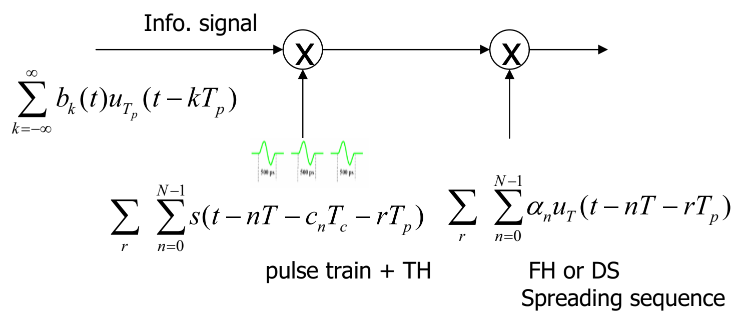
Unified View of UWB systems

- General form:

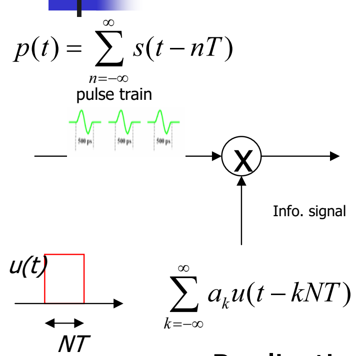
$$x(t) = \sum_{r} \sum_{k=1}^{N} b_k^r p(t - rT_p) e^{-j2\pi k f_0 t}.$$

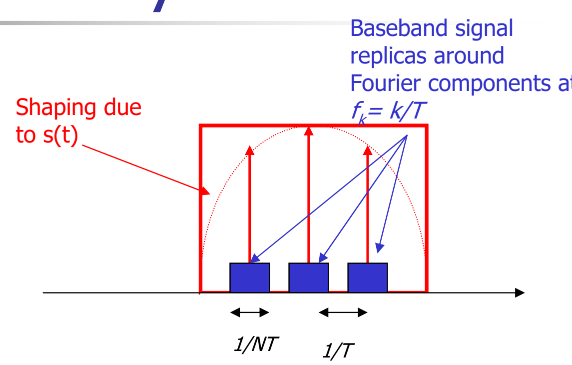


- Advantageous to view p(t) as:
  p(t)= [pulse train]x[spreading sequence]



Spectral Efficiency





- Replication in time and frequency domains needed for reliable communications
- Poor spectral use
  - Spectral gaps
  - Spectral shaping due to *S(f)*
- Coupling between time resolution, *s(t)* and duty cycle

Spectrum Spreading in UWB

- Different Types of UWB according to frequency Spreading :
  - TM-UWB: (Spreading by Time Hopping)

    $$p(t)=\sum_{n=0}^{N-1} s(t-nT-c_nT_c)$$

  - DS-UWB: (Spreading by Direct Sequence)

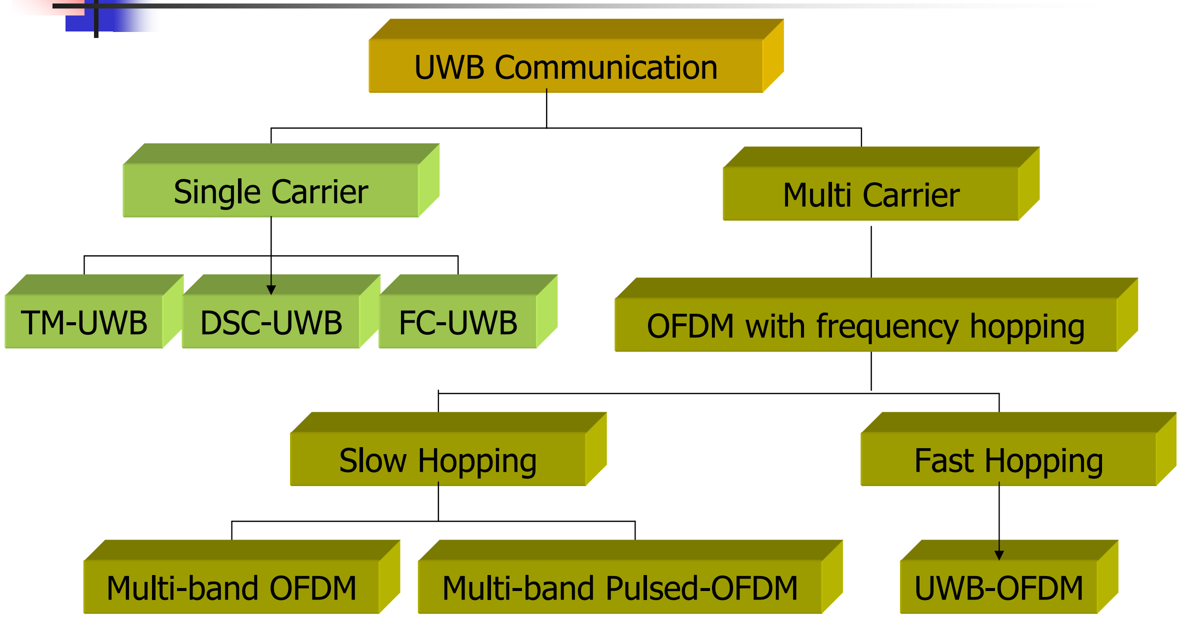
    $$p(t)=\sum_{n=0}^{N-1} c_n s(t-nT)$$

  - FH-UWB: (Spreading by Frequency Hopping)

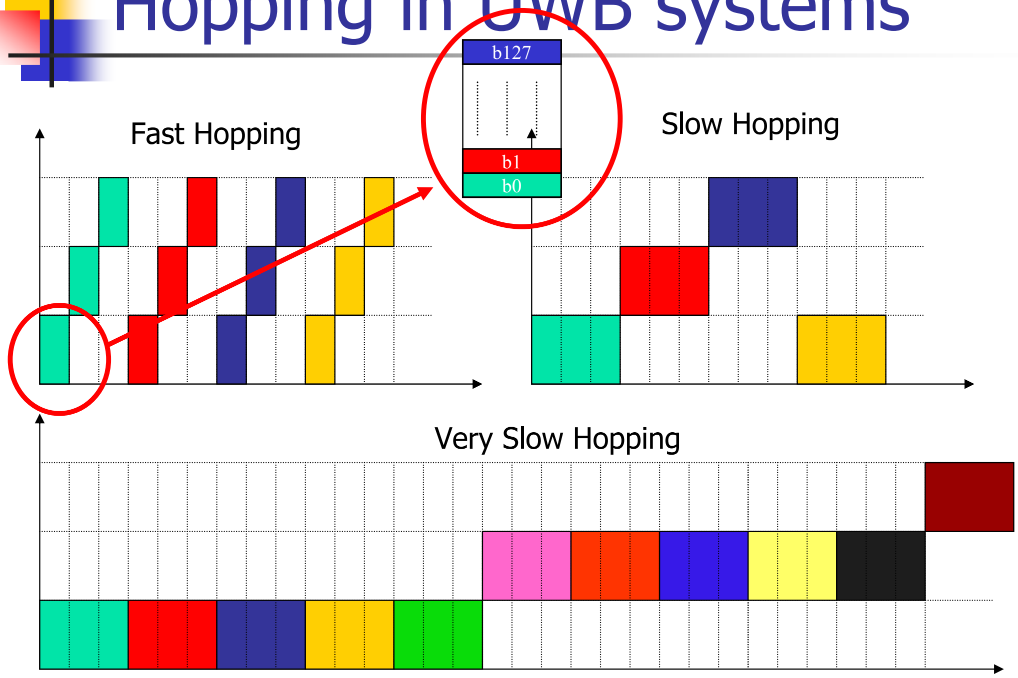
    $$p(t)=\sum_{n=0}^{N-1} s(t-nT)e^{-j\frac{2\pi c_n t}{T_c}}$$

- Compound Systems

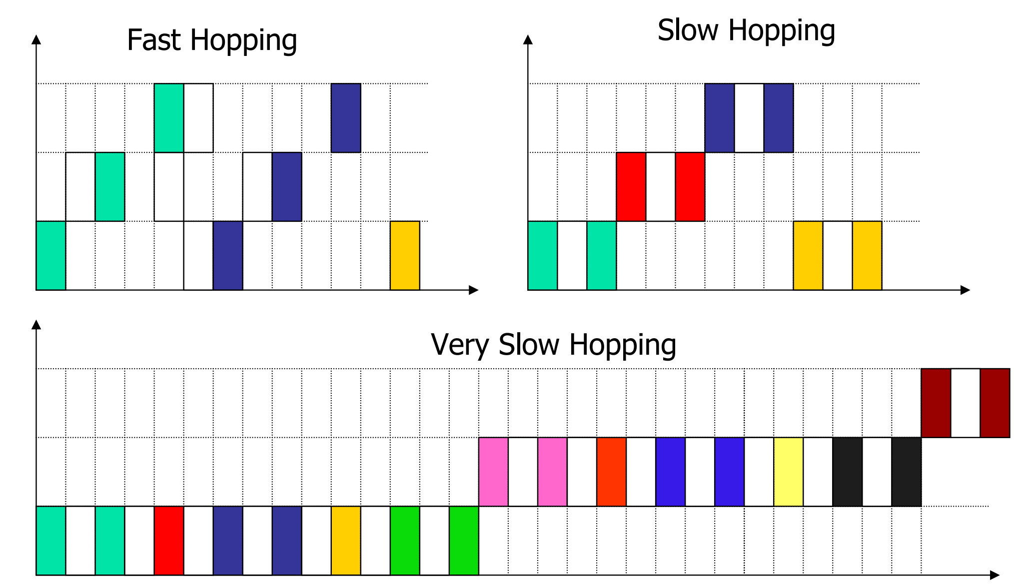
UWB Systems



Hopping in UWB systems



Duty Cycle in UWB systems



MC-UWB Systems

Multi Carrier UWB / OFDM with frequency hopping

- **Slow Hopping**
  - **Multi-band OFDM**
  - **Multi-band Pulsed-OFDM**
- **Fast Hopping**
  - **UWB-OFDM**

Multi-band OFDM

- Poor time resolution
- No Multipath diversity
- Simple FFT receiver
- Strong FEC/interleaving
- Moderate multipiconet performance

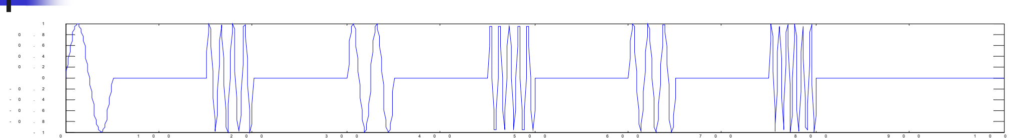
Multi-band Pulsed-OFDM

- Moderate time resolution
- Some multipath diversity
- Simple FFT receiver
- low complexity coding
- Better multipiconet performance

UWB-OFDM

- Fine time resolution
- full multipath diversity
- Rake receiver needed?
- low complexity coding
- Best multipiconet performance

UWB-OFDM



T_s

T

$$p(t) = \sum_{n=0}^{N-1} s(t - nT) e^{-j\frac{2\pi c(n) t}{T_c}}$$

- for $f_0 = 1/NT$ $\{p_k(t) = p(t) e^{j2\pi k f_0 t}\}$ are orthogonal for $k=0,\ldots,N-1$.

$$x(t) = \sum_r \sum_{k=0}^{N-1} b_k^r \, p(t - rT_p) e^{j2\pi k f_0 (t - rT_p)}$$

- Paths with delay difference of multiple of T_c/N are resolvable. (resolution ~ 100-500 psec)

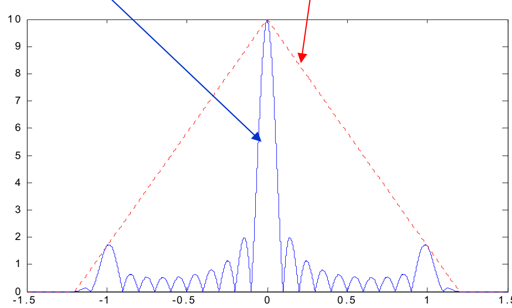
Multipath Resolution

- Multipath Interference determined by time resolution T_c/N:

$$X_p^{(1)}(\tau_1-\tau_2,0)=\frac{\sin(N\pi(\tau_1-\tau_2)/T_c)}{\sin(\pi(\tau_1-\tau_2)/T_c)}\times X_s(\tau_1-\tau_2,0)$$

- Paths with delay difference of multiple of T_c/N are resolvable:

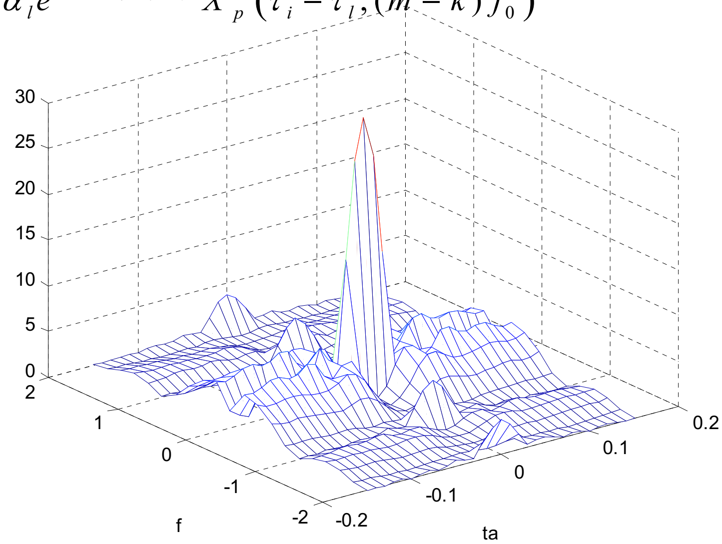
$$X_p^{(1)}(\tau_1-\tau_2,0)=N\delta_{\tau_1-\tau_2}$$



Inter Channel Interference

$$ICI=2\sqrt{\frac{E_b}{N}}\sum_{\substack{k=0\\k\neq m}}^{N-1}\sum_{l=0}^{L-1}b_k\alpha_l e^{j2\pi mf_0(\tau_i-\tau_l)}X_p\left(\tau_i-\tau_l,(m-k)f_0\right)$$

- For same delay the sub-carriers are orthogonal
- In different delays the sub-carriers are not exactly orthogonal **unless** no frequency hopping is used $\Rightarrow$ ICI
- Costas hopping sequence minimizes ICI



Single and Multi-Channel Receiver

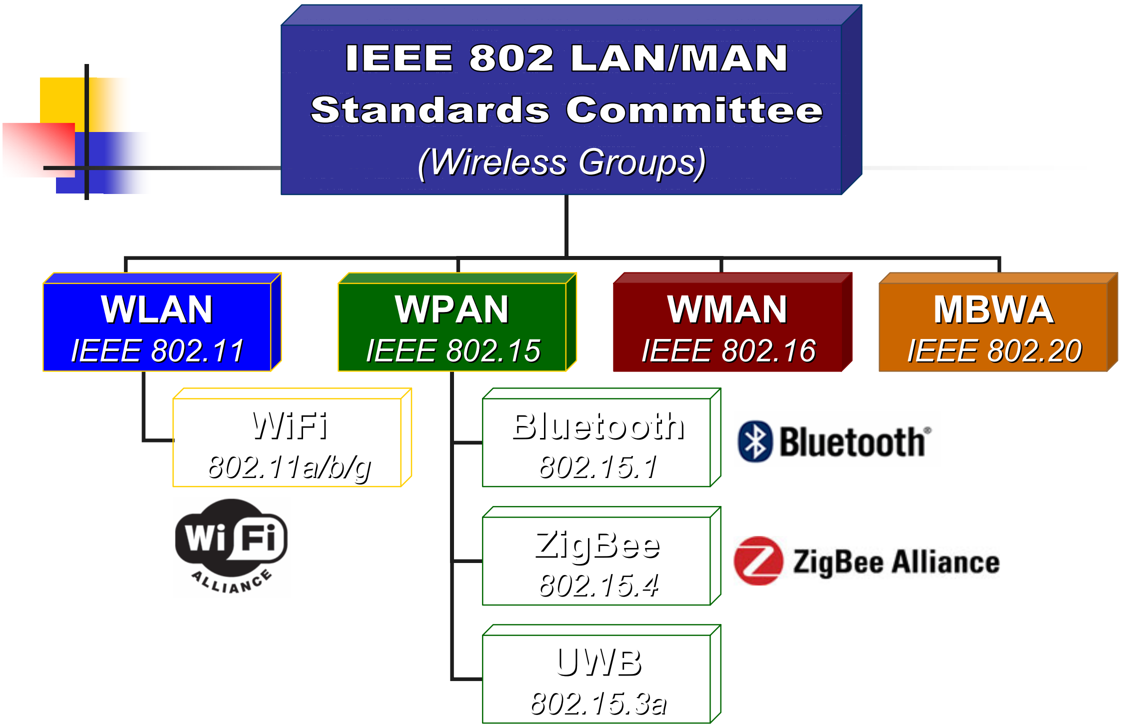
- If N is Large (N>100) then Signal to Interference ratio is large (S/I>10db) or no frequency hopping is used ⇒ Single Channel Detectors or Pulsed OFDM

- If N is small (N<100) then Signal to Interference ratio is low (S/I<10db) ⇒ Multi Channel Detectors

Overview

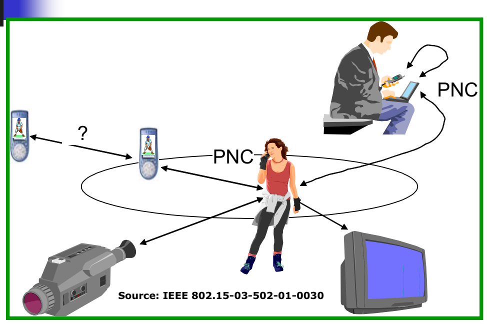
- Introduction

- Multirate techniques in UWB system design
  - WPANs
  - Multiband OFDM
  - Pulsed Multiband OFDM
  - Outage Capacity
  - Performance, Complexity and Power Consumption Comparison



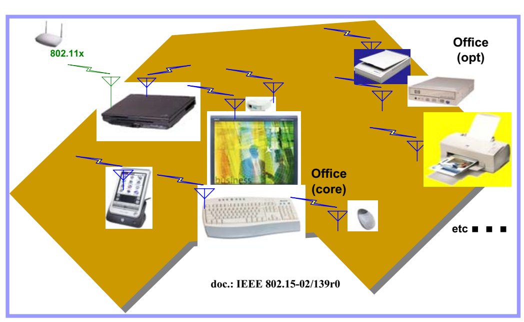
Source: Chew et al, UC Berkeley

High Speed Wireless Connectivity



Nokia's perspective

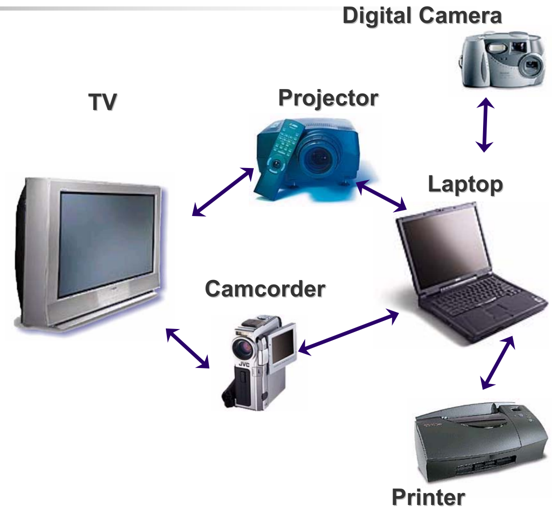
Sony's perspective



Intel's perspective

IEEE 802.15.3a Technical Requirements

- 110 Mbps @ 10 meters, 200 Mbps @ 4 meters
  - 8% PER for 1024 octet frames
- 4 piconet co-operation in close proximity
  - Minor degradation allowed
- Coexistence and Interference Rejection
  - Both required for usual list of IEEE802 PHYs
- Power Consumption
  - 100 mW at 110 Mbps
  - 250 mW at 200 Mbps
  - Power Save
- Emphasis on QoS - Corrected error rate of 10^{-9}
- Cost and complexity are concern



after: Time Domain

Overview

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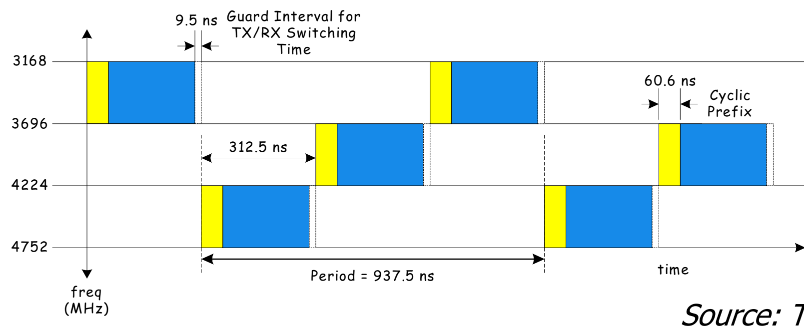
Multi-band OFDM system

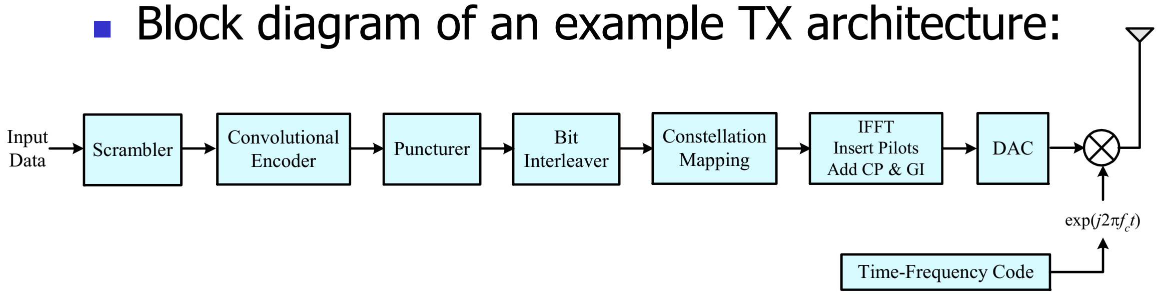
- 100 bits of coded data per symbol
- frequency spreading of factor 2 by symmetric conjugate
- Convolutional code of rate 11/32 and 11/16 for rates 110 and 220 Mb/s



Source: TI

Multi-band OFDM: TX Architecture

- Block diagram of an example TX architecture:



- Architecture similar to *conventional* OFDM system.
- For a given superframe, the time-frequency code is specified in the beacon by the PNC.

Source: TI

MB-OFDM vs "Other" UWB systems

MB-OFDM	"Other" Common UWB Systems
▪ Fills spectrum with larger number of carriers and short pulses	▪ Spread spectrum using DSS, TH or FH, possibly in addition to pulsation
▪ Exploits diversity mainly via heavy coding, interleaving and band hopping, no Rake receiver	▪ Exploit diversity mainly via Rake reception

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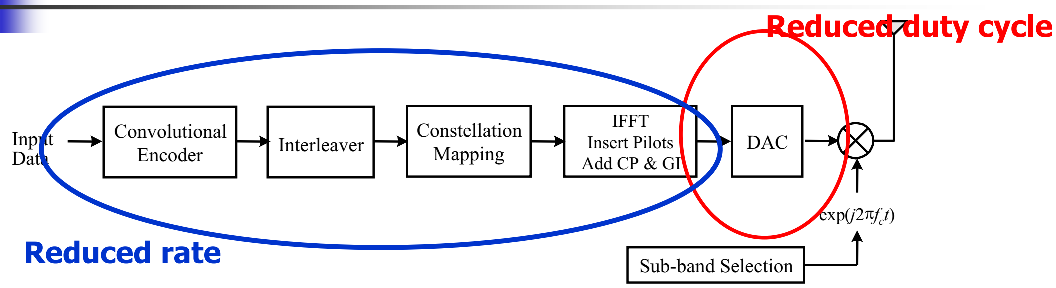
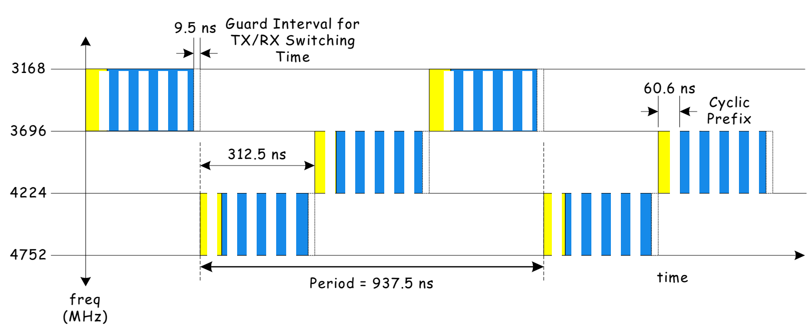
Multi-band Pulsed-OFDM



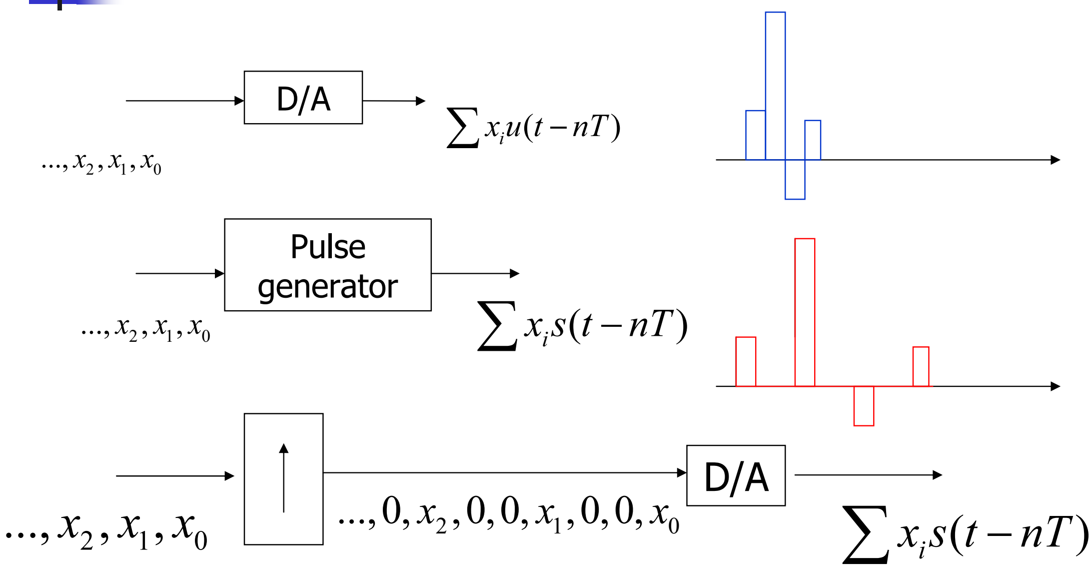
- Pulsed OFDM can be generated by:
  - Reducing rate of baseband section and,
  - either replacing DAC with pulse train generator
  - Or upsampling signal after IFFT and using normal DAC

Multi-band Pulsed-OFDM system

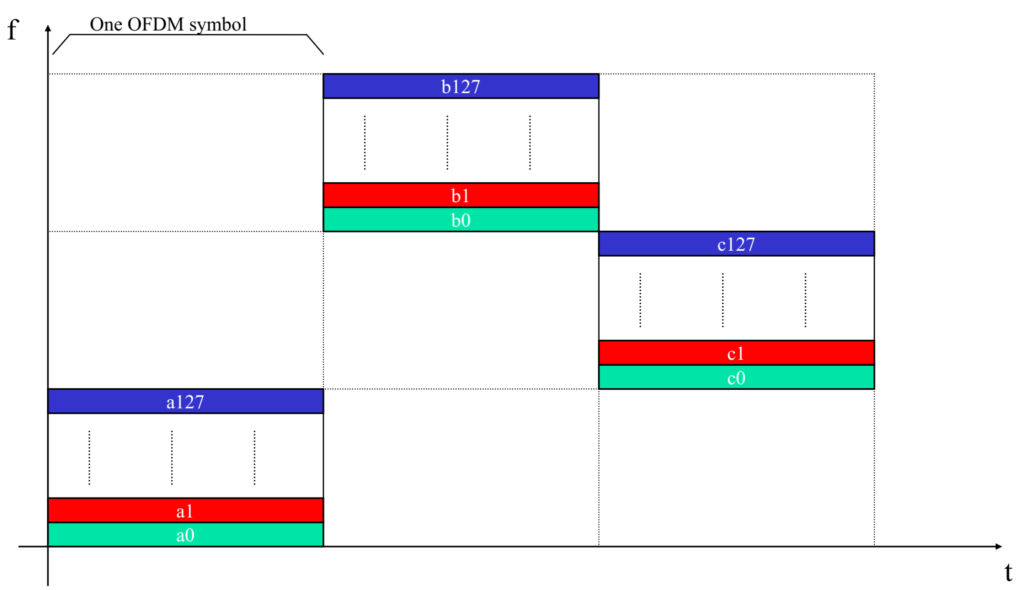
- Transmit Pulsed-OFDM modulated signals in each sub-band
- Number of Carriers = 32
- Multipath fading eliminated by:
  - Inherited diversity gain by pulsating
  - Light coding and interleaving: Convolutional code of rate 2/3



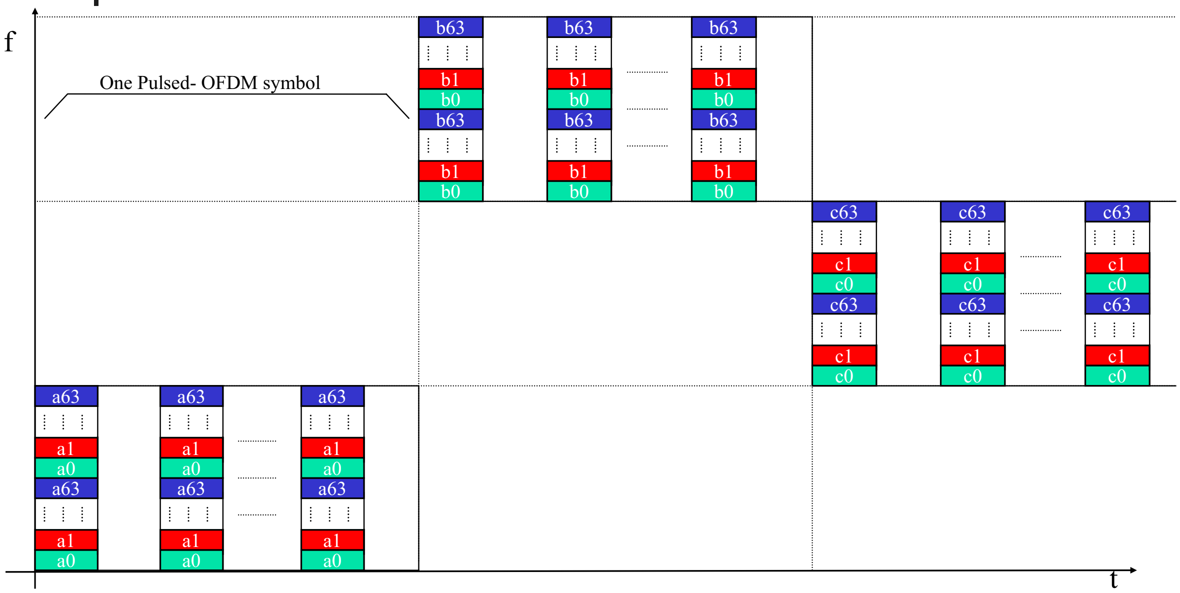
Pulsed OFDM D/A structure



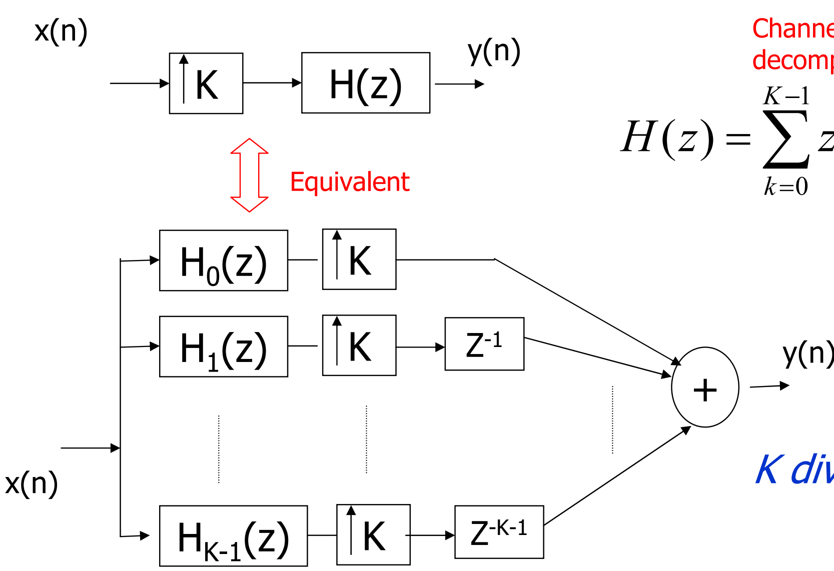
Pulsed-OFDM Spectrum



Pulsed-OFDM Spectrum



Pulsed-OFDM Analysis with digital model

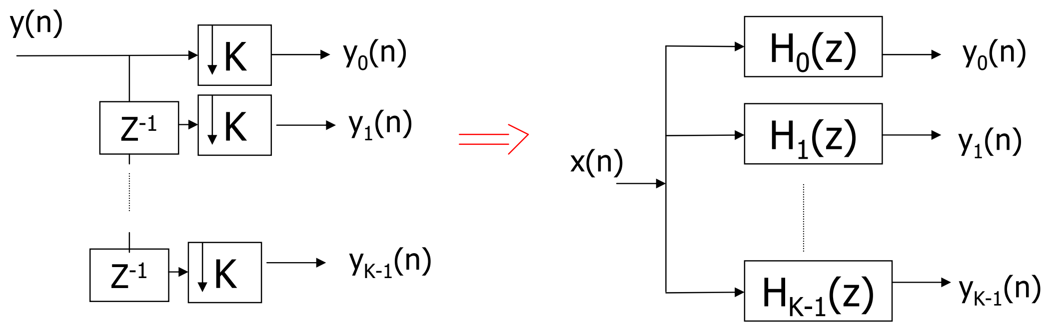


Channel poly-phase decomposition

$$H(z) = \sum_{k=0}^{K-1} z^{-k} H_k(z^K)$$

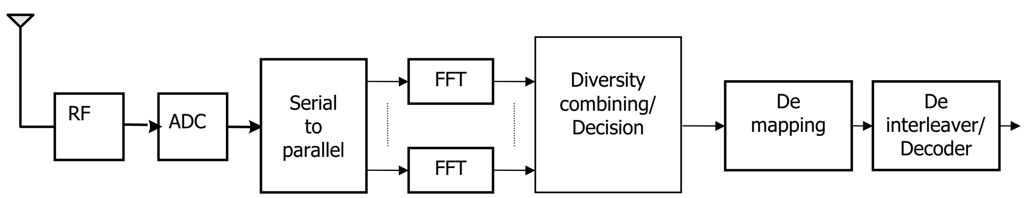
K diversity branch

Discrete Time Model: K diversity Channel



K diversity branch

Pulsed-OFDM Receiver



- K FFT to demodulate each branch
- Diversity combining with MRC, equal gain or selective combining
- No rake receiver!

Exploiting Diversity in Pulsed OFDM

- Diversity combining
  - MRC, equal gain, selective or generalized selective
  - MRC and equal gain require sampling rate equal to symbol bandwidth
  - Selective combining uses a sampling rate = symbol bandwidth/K
    - Complexity and power savings not obvious since it requires more stringent timing synchronization and drift correction

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Optimum upsampling rate

- Optimum upsampling rate K depends on:
  - Channel characteristics
  - Coding and interleaving scheme

- To have an algorithm regardless of coding and modulation:
  - Define K_{opt} as the one that maximize Capacity
  - For a fading channel we use capacity versus outage probability

Optimum upsampling rate

- Capacity of AWGN channel:

$$C = w \ln(1+\gamma)$$

- In fading channel capacity is a random variable:

$$p_{\gamma}(\gamma) = \frac{1}{\bar{\gamma}} \exp\left(-\frac{\gamma}{\bar{\gamma}}\right)$$

- Outage probability is the probability that instantaneous capacity is less than a rate R:

$$P_{out} = \Pr\left(C(\gamma) < R\right).$$

Outage Capacity

- q outage capacity C_q of a fading channel is equal to the maximum rate R, such that the outage probability is less than q.
  - Example: $C_{1\%}$ is the rate corresponding to an outage probability of less than 1%

- q can be interpret as a measure of the complexity needed for a system to reach the outage capacity
  - *Example: The rate of $C_{1\%}$ can be achieved with less complexity than $C_{5\%}$*

Outage Capacity of pulsed-OFDM system in Rayleigh Fading

- The Pulsed OFDM divides the whole bandwidth w to K parallel channels, then:

instantaneous capacity ← $$C(\gamma) = \frac{w}{K}\ln(1+\gamma^{(K)}).$$ → SNR of K-folded diversity

- For Rayleigh channels with MRC combining:

$$p_{\gamma}^{(K)}(\gamma) = \frac{1}{\bar{\gamma}(K-1)!}\left(\frac{\gamma}{\bar{\gamma}}\right)^{K-1}\exp\left(-\frac{\gamma}{\bar{\gamma}}\right).$$

- Outage probability

$$P_{out} = \Pr\left(C(\gamma) < R\right) = \Pr\left(\frac{w}{K}\ln(1+\gamma^{(K)}) < R\right) = \Pr\left(\gamma^{(K)} < \left(e^{K\frac{R}{w}} - 1\right)\right)$$

Optimum upsampling rate

- Maximum upsampling rate
  - the diversity branches should be uncorrelated then:

$$K_{\max} = \lfloor w / B_c \rfloor = \lfloor w T_{spread} \rfloor$$

Coherence Bandwidth of channel (B_c)   Maximum Delay spread of channel (T_{spread})

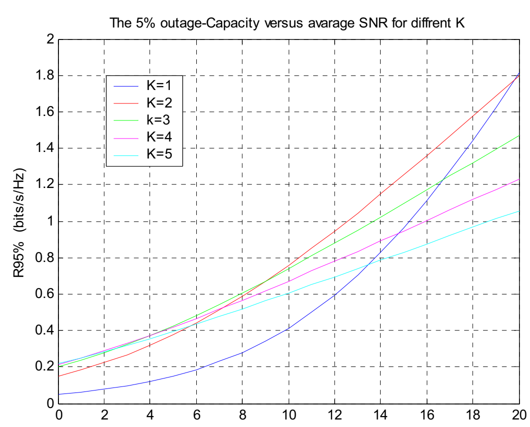
- K_{opt} defines as the one that maximize outage Capacity for a given outage probability

Algorithm

- Determine the maximum possible upsampling rate:

$$K_{\max} = \lfloor w / B_c \rfloor = \lfloor w T_{spread} \rfloor$$

- Choose an outage probability q as optimality criterion according for a target complexity.
- plot the capacity versus SNR curves for $K=1,\dots K_{max}$.
- For a given SNR, or SNR range, choose the K that provides maximum outage capacity.



Capacity with $q=5\%$ outage probability versus SNR for pulsed-OFDM systems with different upsampling rates

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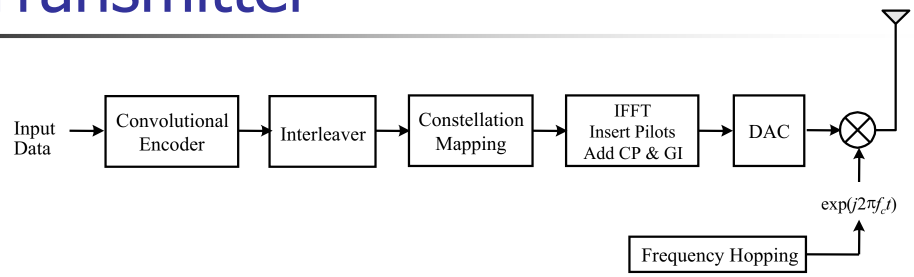
Pulsed OFDM

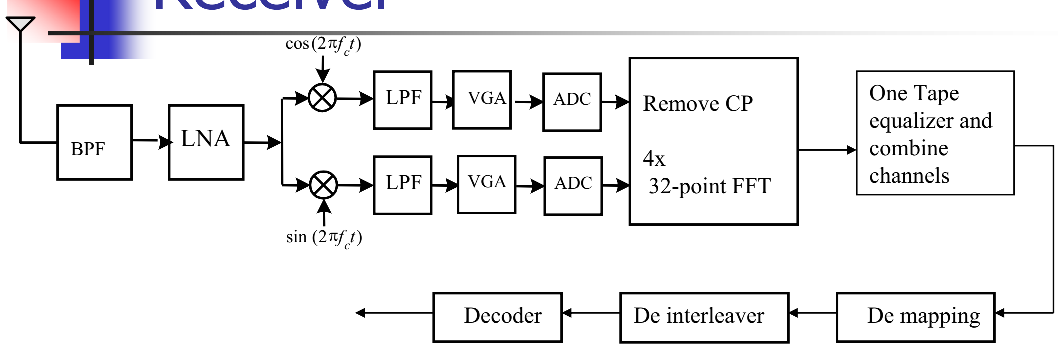
- Exploit added diversity to reduce system complexity
- Setting for IEEE 802.15.3a
  - W=528 MHZ (same band plan as MB-OFDM)
  - Number of sub-carriers=32
  - Different duty cycle is used different rates:
    - 1/4 for 110Mbits/s (K=4)
    - 1/3 for 165 Mbits/s (K=3)
    - ½ for 220 Mbits/s (K=2)
    - 1 for 440 Mbits/s (K=1)
  - Convolutional Coding rate 2/3

Complexity Comparison: Transmitter



	Coder	IFFT	DAC	RF
MB-OFDM	Rate 11/32 Punctured from 1/3	128-point	normal	
MB-POFDM	Rate 2/3 Punctured from 1/2	32-point	Pulse generator	
Complexity	same	Pulsed is simpler	same	???

Complexity Comparison: Receiver



	RF	FFT	Equalizer	ADC
MB-OFDM		128-point	128 * 1-tap	
MB-POFDM		4 * 32-point	Diversity Combiner	
Complexity	???	Pulsed is simpler	same	same

Power Consumption Comparison:

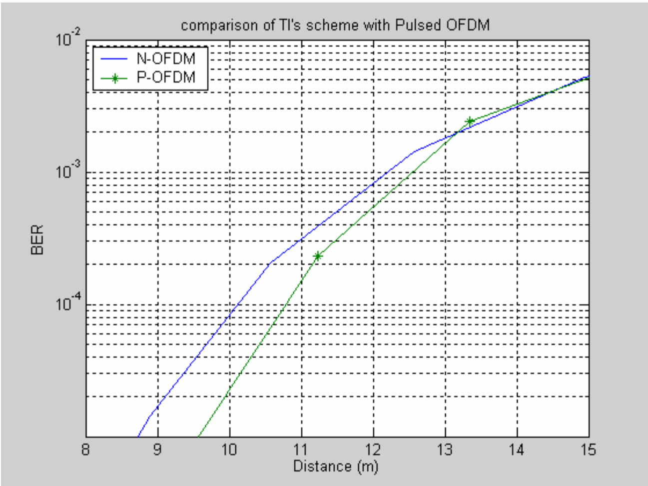
Power Consumption ~ Processing clock rate

	Input data	After Coding with Puncturing	After Puncturing	After constellation mapping	Output of IFFT	Input to FFT	Input to Decoder
Non-pulse	110 MHz	330MHz	320 MHz	160 MHz	320MHz	320MHz	320MHz
Pulsed	110 MHz	220MHz	160 MHz	80 MHz	80MHz	320MHz	160MHz

Clock rate in different parts of Transceiver

Performance Comparison

- BER versus distance for CM4 channel

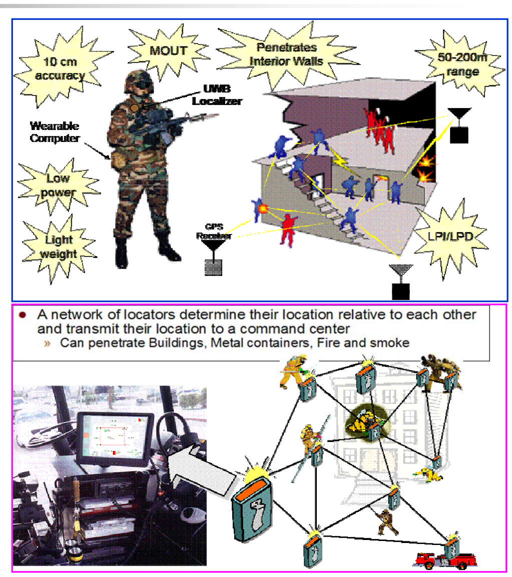


Overview

- Introduction
- Multirate techniques in UWB system design
- Subband techniques in UWB ranging
  - Ranging techniques
  - FFT range resolution enhancement
  - Range resolution enhancement with multirate virtual signal synthesis

Applications of Ranging Ability in Wireless personal Area networks

- Finding People
  - Situational Awareness for Soldiers
  - Firefighter Rescue
- Finding Assets
  - Autonomous Manifesting
  - ISO Container Security
- Machine-to-Machine (M2M)
  - Wireless Sensor Networks
  - Home/Office Automation
  - Robotics



*Patrick Houghton, Aetherwire & Location

Time estimation accuracy

- The variance of estimation error in AWGN*:

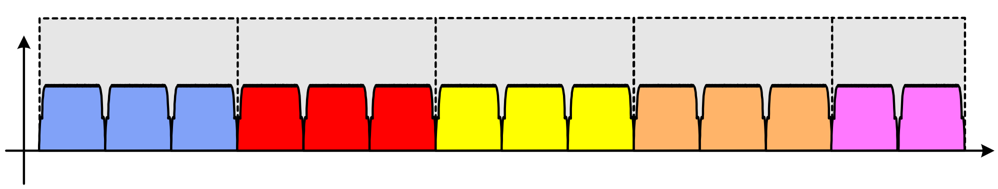
$$\mathrm{var}(\hat{\tau}) \geq 1/\left[(E_s/2N_0).w^2\right]$$

  - Es : The signal energy
  - N0/2: The AWGN density
  - *w* : The mean square bandwidth of signal

- Time resolution ~ *1/bandwidth*

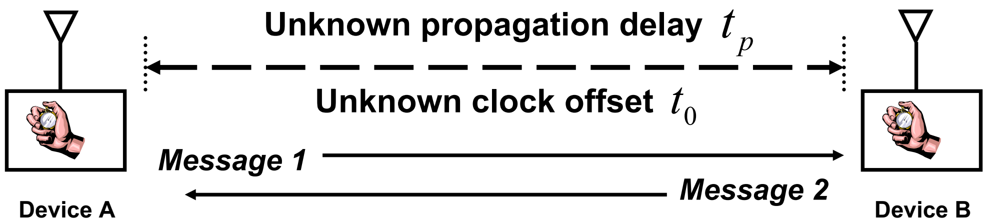
*S. M. Kay, *Fundamentals of Statistical Signal Processing, volume I: Estimation Theory*, Prentice Hall PTR, 1st edition, March 26, 1993

Multi-band OFDM system



- UWB OFDM system for the IEEE 802.15.3a wireless personal area networks
- Multi-band system divides whole UWB bandwidth into 14 sub-bands
- At a given time only a single sub-band is used to transmit data

Ranging in Multi-band OFDM system: **Two-Way Time Transfer method***



$$T_{2AR} = T_{2BT} - t_o + t_p \qquad T_{1BR} = T_{1AT} + t_o + t_p$$

Two equations in two unknowns yield:

$$t_p = \tfrac{1}{2}\left[\left(T_{2AR} - T_{1AT}\right) - \left(T_{2BT} - T_{1BR}\right)\right]$$

$$t_o = \tfrac{1}{2}\left[\left(T_{2BT} + T_{1BR}\right) - \left(T_{2AR} + T_{1AT}\right)\right]$$

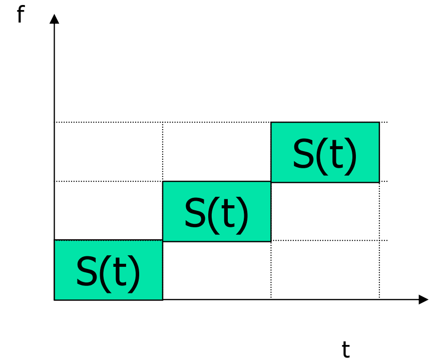
*** US Naval Observatory, *Telstar* Satellite, circa 1962**
http://www.boulder.nist.gov/timefreq/time/twoway.htm
Unmatched detect-delays in the two devices may require one-time offset calibration.

Overview

- Introduction
- Multirate techniques in UWB system design
- Subband techniques in UWB ranging
  - Ranging techniques
  - FFT range resolution enhancement
  - Range resolution enhancement with multirate virtual signal synthesis

Improved Time Resolution Through Multiple Reception

- Assume a multi-band system with N sub-band each with bandwidth *w* :
  - Transmit identical high time resolution sequence on N bands
  - A coarse resolution of *1/W* is achieved in each sub-band by processing returns through matched filters



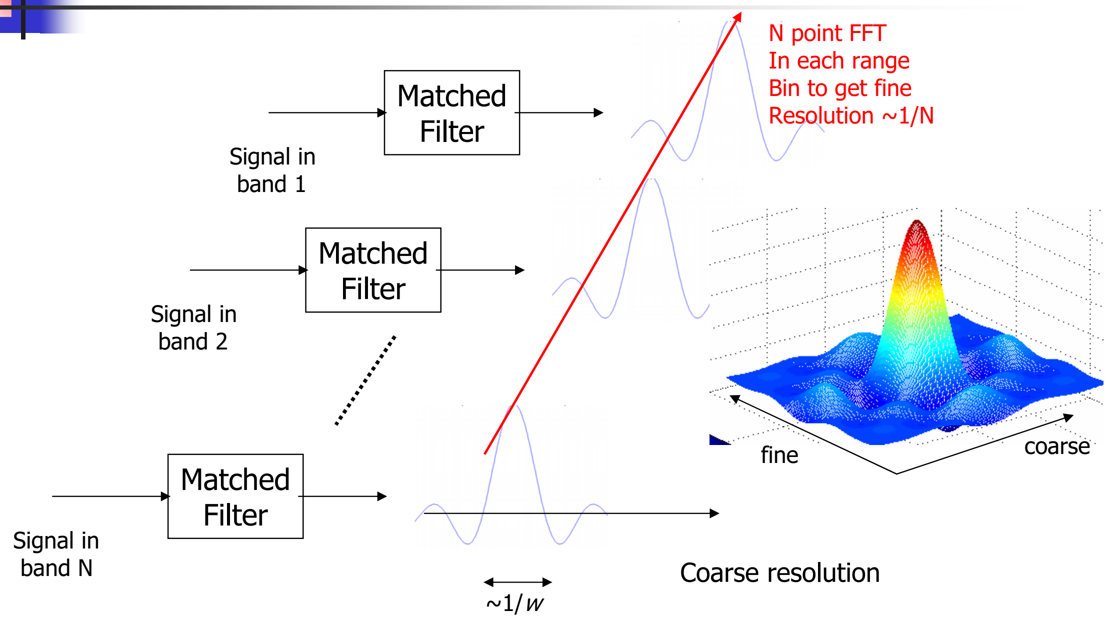
- Enhanced Resolution:
  - Traditional Scheme: Average estimates from different bands to get resolution equal to $(1/\sqrt{N}\ w)$
  - Run N point FFT at each range bin across returns from different bands to get fine resolution equal to (1/(N*w*) = 1/Total BW)

FFT method: Theory

- Transmitted signal in n^{th} band : $s(t)\, e^{j\omega_0 nt}$
- Received signal in n^{th} band: $s(t-\tau_0)\, e^{j\omega_0 n(t-\tau_0)}$
- Output of baseband matched filter (after demodulation): $e^{-j\omega_0 n\tau_0} R_s(\tau - \tau_0)$
  $R_s(t)$ = discrete time autocorrelation of $s(t)$
- Absolute value of FFT-range map:

$$\underbrace{\frac{|\sin(\omega_0(\tau-\tau_0)N/2)|}{|\sin(\omega_0(\tau-\tau_0)/2)|}}_{\substack{fine\quad resolution\\ along\quad FFT\quad axis 2}} \underbrace{R_s(\tau-\tau_0)}_{\substack{coarse\quad resolution\\ along\quad axis 1}}$$

FFT method: Possible Implementation



FFT method: Possible Implementation

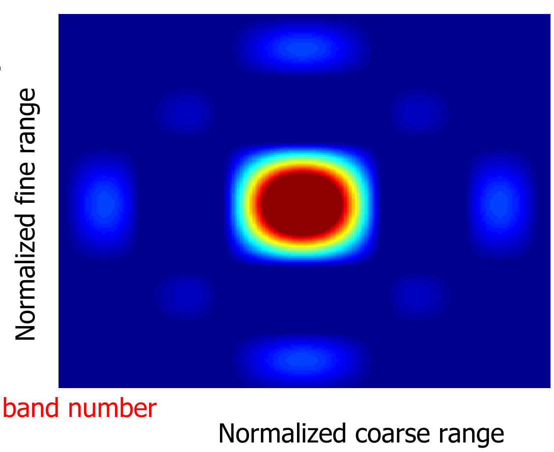
- FFT computed with respect to band number with $\Delta\tau = 1/(Nw)$
  - Each bin is multiplied by

k: normalized fine resolution $\tau = k\,\Delta\tau$

$$e^{\frac{j2\pi kn}{N}}$$

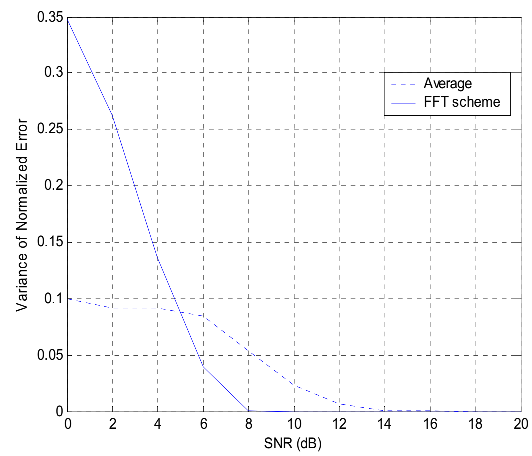
n: band number

  - 2D plot: N point FFT in each coarse range bin: column = FFT, row = bin



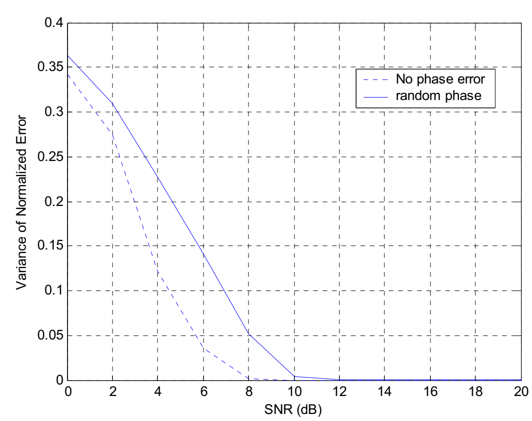
Performance

- Variance of normalized error versus SNR for both averaging and FFT schemes
- Number of sub-bands N=4
- Ranging signal: PN sequence in Preamble of Multi-band OFDM system



Phase error effects

- Variance of normalized error versus SNR for FFT scheme with and without phase mismatch between sub-bands
- Number of sub-bands N=4
- Ranging signal: PN sequence in Preamble of Multi-band OFDM system

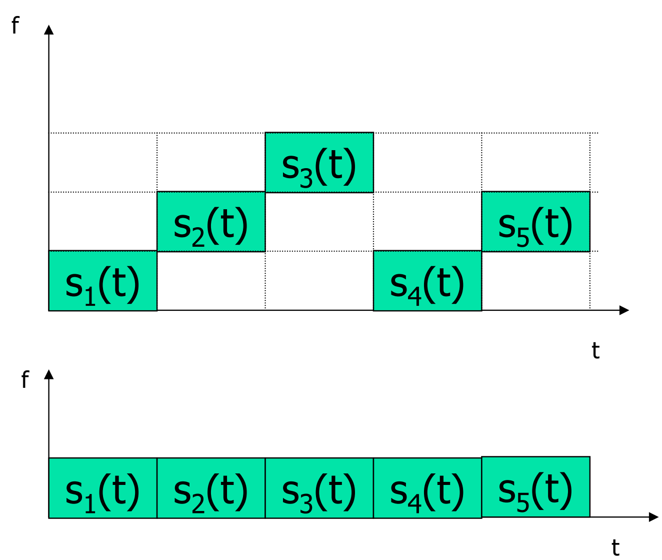


Overview

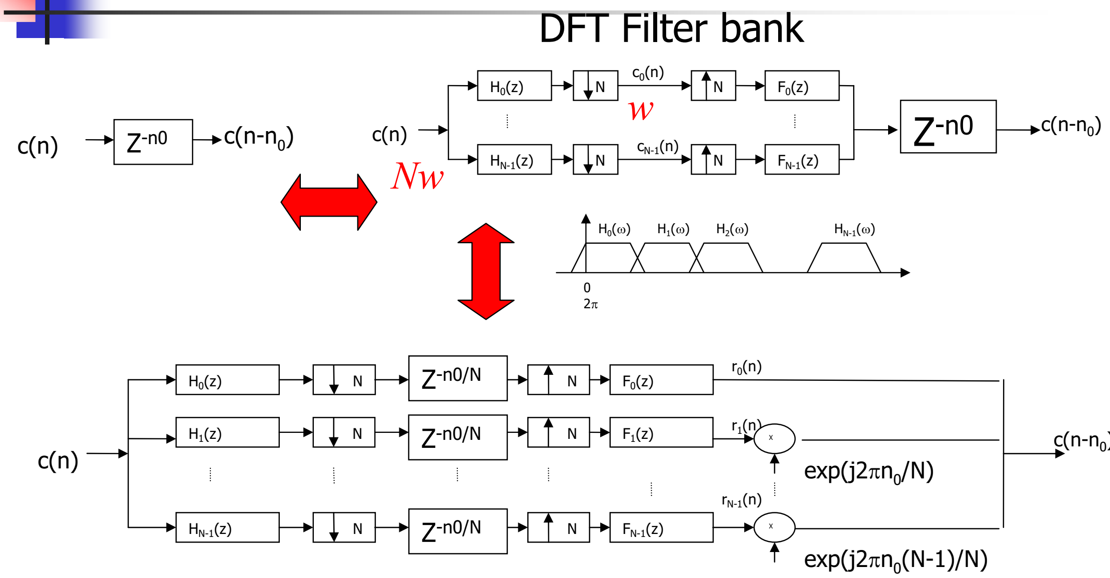
- Introduction
- Multirate techniques in UWB system design
- Subband techniques in UWB ranging
  - Ranging techniques
  - FFT range resolution enhancement
  - Range resolution enhancement with multirate virtual signal synthesis

Subband ranging

- Take a PN sequence of length (N*M) and make a wavelet decomposition to get N sub-sequences of length M
- Send each sub-sequence in one sub-band and combine the received signals using a complete reconstruction filter bank
- Correlate the output of filter bank with original signal



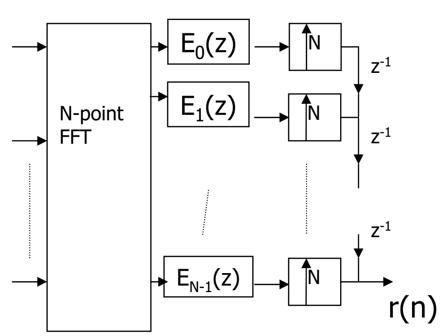
Subband ranging with DFT Filterbanks



Implementation

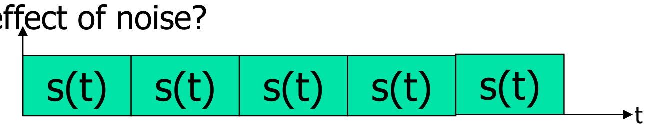
$$F_0(z) = \sum_{k=0}^{N-1} E_k(z^N) z^{-(N-1-k)}$$

$$F_k(z) = F_0\left(\left(ze^{-j2\pi k/N}\right)\right) \quad k = 1, \ldots, N-1.$$

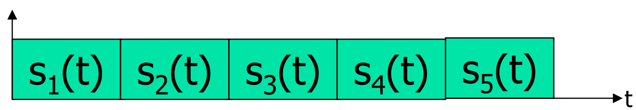


Noise effect and resource allocation

- With limited number of time-frequency slots available, should we
  - Use the same signal and average over the estimations to reduce the effect of noise?



  - Use wavelet methods to increase the overall bandwidth and resolution?



Noise effect and resource allocation

- The variance of estimation error in AWGN with density $N_0/2$ is equal to:

$$\operatorname{var}(\hat{\tau}) \geq 1/\left[(E_s / 2N_0) . w^2 \right]$$

The energy of the shaping pulse — The mean square bandwidth of signal

- with signal of bandwidth *w* and averaging N times:

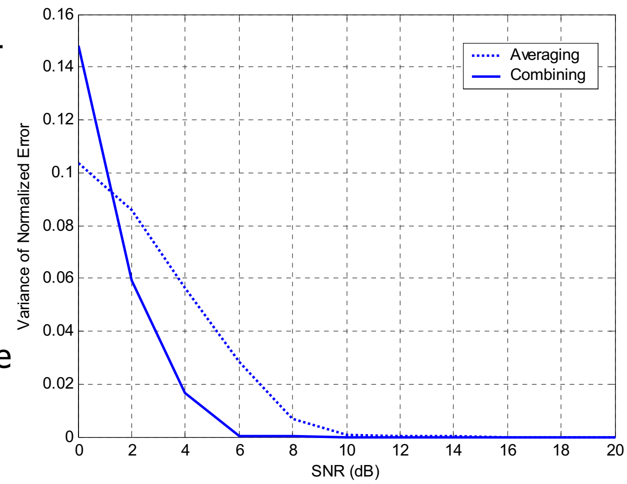
$$\operatorname{var}(\hat{\tau}_{ave}) = \operatorname{var}(\hat{\tau}_w) / N$$

- with signal of overall bandwidth N*w*:

$$\operatorname{var}(\hat{\tau}_{Nw}) = \operatorname{var}(\hat{\tau}_w) / N^2$$

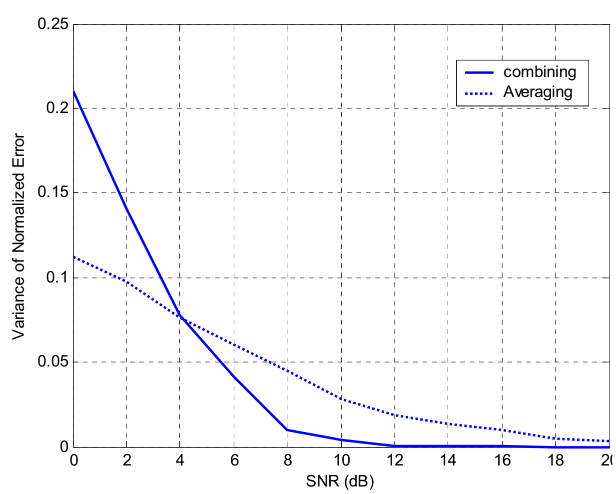
Performance

- Variance of normalized error versus SNR for both averaging and subband schemes
- Number of sub-bands N=3
- Ranging signal: PN sequence in Preamble of Multi-band OFDM system



Fading effects

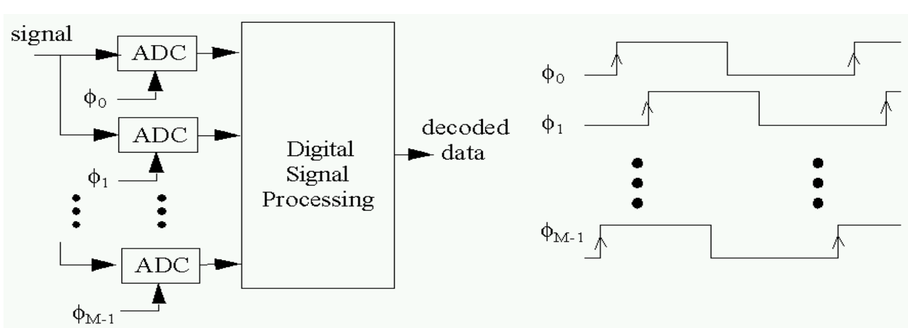
- Variance of normalized error versus SNR for subband scheme in fading channels
- Number of sub-bands N=3
- Ranging signal: PN sequence in Preamble of Multi-band OFDM system



Overview

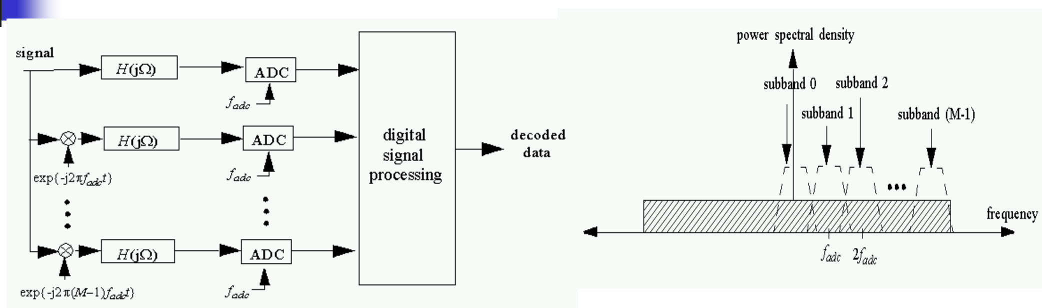
- Introduction
- Multirate techniques in UWB system design
- Subband techniques in UWB ranging
- Subband approaches in ADC

Time-Interleaved ADC



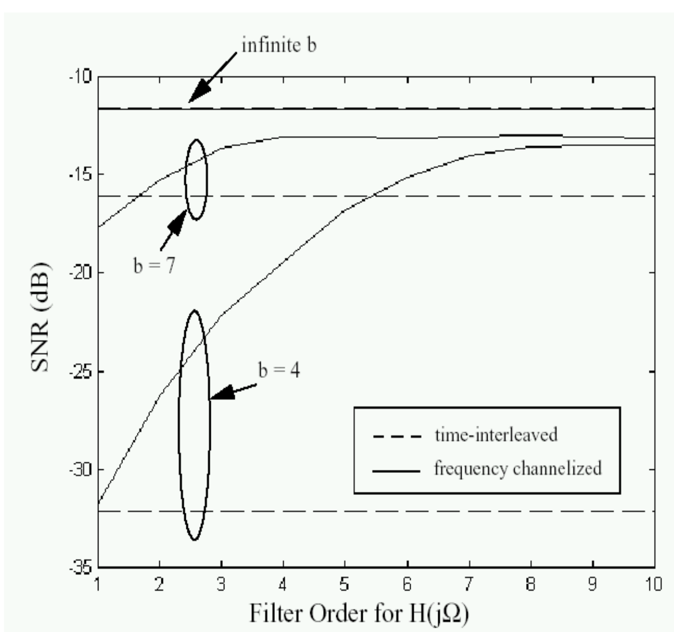
- ADC sees the full bandwidth of the input signal.
  - Sample/hold circuitry becomes difficult to design.
  - Sensitive to sampling jitter.
- Large dynamic range required in the presence of narrowband interferers.

Frequency Channelized ADC Using Lowpass Filters



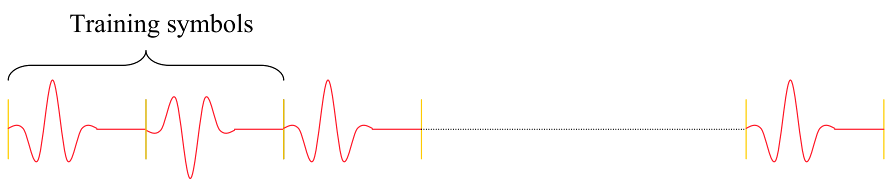
- Same number of ADCs (critically sampled).
- ADC input bandwidth reduced.
  - Sample/hold circuitry relaxed.
  - More robust to sampling jitter.
- Reduced dynamic range requirement.
- Sampling jitter and mixer phase noise present.

Effect of Filter Order with Narrowband Interferer Present



Oversampled Channelized Receiver in Transmitted Reference System

- Transmit a block of data modulated pulses.
  - First N pulses are used for training.

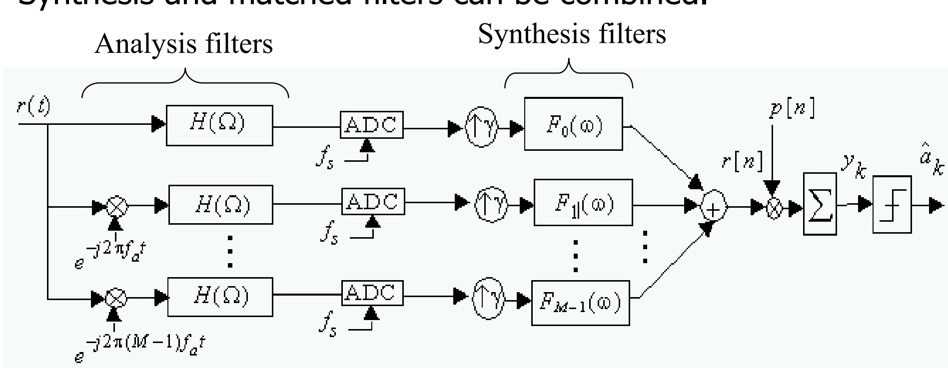


- Estimate matched filter response by averaging first N training pulses.
- Use this estimate to correlate and detect transmitted data.
- Use oversampled channelized receiver.
  - ADC samples at a slightly higher rate (~30%) than the minimum necessary.

Oversampled Channelized Receiver I

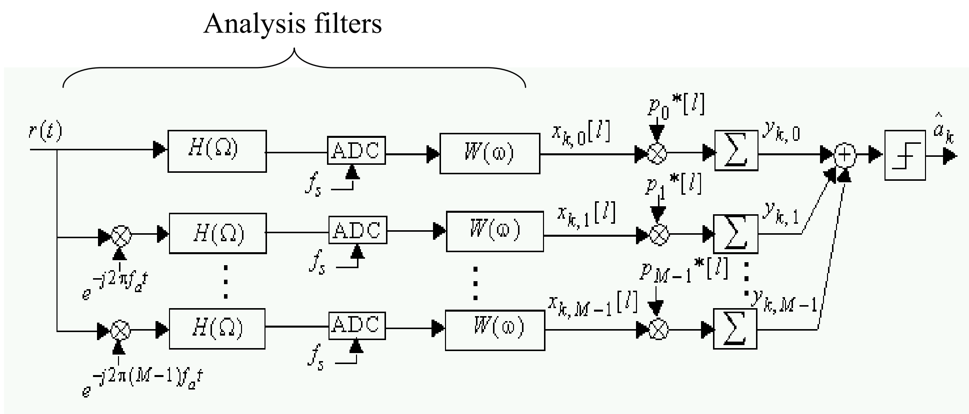
- For perfect reconstruction (PR) filter bank, matched filter is time-reversed complex conjugate of propagation channel pulse response.
- For power complementary analysis filters (ie, $\sum |H_m(\omega)|^2 = c$), PR synthesis filter is time-reversed complex conjugate of analysis filter.

→ Synthesis and matched filters can be combined.



Oversampled Channelized Receiver II

- Power complementary analysis filters realized digitally after ADC.
- Optimal detection obtained by correlating each subband independently.
- Convergence speed slightly faster than full band receiver.



Conclusion

- Multirate UWB system design techniques offer and advantageous trade-off between complexity and performance
- Subband approaches lead to efficient ranging procedures with an accuracy equal to that of systems working with a much larger bandwidth
- Novel subband A/D designs potentially attractive in UWB systems

Selected References

- Unified UWB and multirate approaches in system design
  - "An interference suppressing OFDM system for ultra wideband width radio channels," D. Gerakoulis and P. Salmi,*IEEE Conference on Ultra Wideband Systems and Technologies (UWBST'02*), May 2002.
  - "Synchronous UWB-OFDM**,"** Ebrahim Saberinia and A. H. Tewfik, *IEEE International Symposium on Advances in Wireless Communications*, Victoria, BC, Canada, September 2002.
  - "High Bit Rate Ultrawideband OFDM," E. Saberinia and Ahmed H. Tewfik, *Proc. of the 2002 IEEE Global Telecommunications Conf. (Globecom),* Taipei, Taiwan, November 2002.
  - "Multi-band OFDM: merged proposal #1," Merged proposal for the IEEE 802.15.3a standard, Anuj Batra at al,*IEEE 802.15 work group official web site*, http://grouper.ieee.org/groups/802/15/pub/2003/ Jul03/, San Francisco, CA,USA, July 2003.
  - ``Multi-carrier ultra-wideband multiple-access with good resilience against multiuser interference,'' Z. Wang.in *Proc. of 37th Conf. on Info. Sciences and Systems*, Johns Hopkins University, March 2003."

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- Unified UWB and multirate approaches in system design
  - "Single and Multi-carrier UWB Communications," E. Saberinia and Ahmed H. Tewfik, *Proc. of the Seventh International Symposium on Signal Processing and Its Applications*, Paris, France, July 2003.
  - "Analog To Digital Converter Resolution Of Multi-Band OFDM And Pulsed-OFDM Ultra Wideband Systems," E. Saberinia, A. Tewfik, K.-C. Chang and G. Sobelman, *First IEEE-EURASIP International Symposium on Control, Communications and Signal Processing*, Hammamet, Tunisia, March 2004.
  - "Pulsed OFDM modulation for Ultra wideband Communications," E. Saberinia, A. Tewfik, J. Tang and K. Parhi, *2004 IEEE Int. Symp. On Circuits and Systems (ISCAS'04),* Vancouver, B.C., Canada, May 2004.
  - "Outage Capacity of Pulsed-OFDM Ultra wideband Communications," E. Saberinia, A. Tewfik, J. Tang and K. Parhi, *2004 Joint UWBST & IWUWBS,* Kyoto, Japan, May 2004.
  - "Design and Implementation of Multi-band Pulsed-OFDM System for Wireless Personal Area Networks," E. Saberinia and A. Tewfik, *2004 IEEE Int. Conf. on Comm. (ICC'04),* Paris, France, June 2004.

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- Subband techniques in UWB ranging
  - "Ranging in Multi-band Communication Systems," E. Saberinia and Ahmed H. Tewfik, *Proc. of the IEEE 2004 Spring Vehicular Technology Conference,* Milan, Italy, May 2004.
  - "Enhanced Time Resolution In Band Limitted Communication Systems," E. Saberinia and Ahmed H. Tewfik, *XII European Signal Proc. Conf. (EUSIPCO2004),* Vienna, Austria, September 2004. (updated pre-print also available)

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- Unified UWB and multirate approaches in system design
- Subband approach to UWB ADC
  - W. Namgoong, "A Channelized Digital Ultra-Wideband Receiver", *IEEE Transactions on Wireless Communication,* vol. 2, May 2003, pp. 502-510.
  - L. Feng, W. Namgoong, "An Oversampled Channelized Ultra-Wideband Receiver", *IEEE Ultra Wideband Systems and Technologies, May 2004, Kyoto, Japan.*

Multi-Band OFDM UWB RF System Issues

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Outline

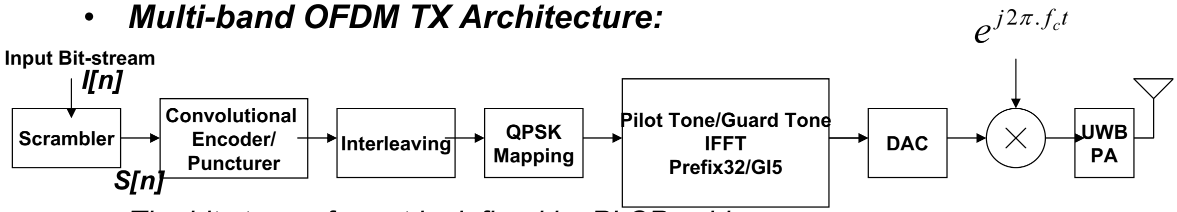
- ***Introduction to UWB***
- ***UWB Transmitter Design***
  - ***I/Q mismatch in UWB transmitter***
  - ***LO impurity in UWB transmitter***
  - ***LO Leakage in UWB transmitter***
- ***UWB Receiver Design***
  - ***System Specs.***
  - ***LNA Design***
  - ***Mixer Design***
- ***Future Work***

Introduction to UWB

- ***UWB uses unlicensed 3.1 –10.6GHz band***
- ***Provides a wireless PAN with data payload communication capabilities of 55, 80, 110, 160, 200, 320, and 480 Mb/s.***
- ***We follow the TI and Intel proposal Multi-band OFDM System proposal***
- ***OFDM advantages:***
  - ***OFDM has been adopted for several technologies***
  - ***OFDM is spectrally efficient.***
  - ***Good performance in narrowband interference.***
  - ***Robustness in multi-path environments.***

Introduction to UWB

- ***Multi-band OFDM TX Architecture:***

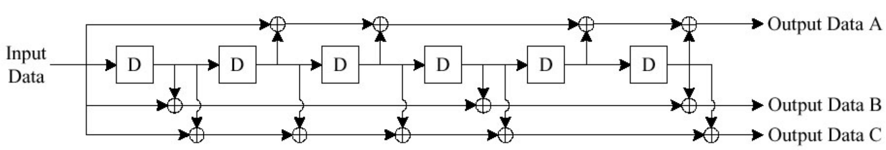


- *The bit stream format is defined by PLCP sublayer*
- *Scrambler uses Pseudo random binary sequence generator* $g(D)=1+D^{14}+D^{15}$

$$S_n = I_n \oplus x_n$$
$$x_n = x_{n-14} \oplus x_{n-15}$$

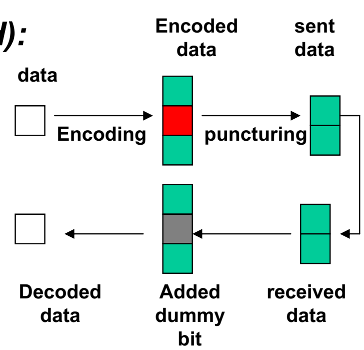
Where S_n, I_n ***are the output & input of the scrambler,*** x_n ***is the random binary sequence***

- *Convolutional Encoder provides Forward Error Correction (FEC)*

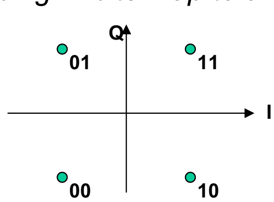


Introduction to UWB

- ***Multi-band OFDM TX Architecture (continued):***
  - *Puncturer:*
    - *A procedure of omitting some of the encoded bits*
    - *Reduce total number of bits transmitted*
    - *Increase the coding rate (from 1/3) to 11/32, ½, 5/8, ¾, etc*
  - *Interleaving: An efficient method against burst errors*
    - *Symbol interleaving: Permutes the bits across OFDM symbols for frequency diversity*
    - *Tone interleaving: Bits across tones in one symbol for robustness against narrow-band interference*



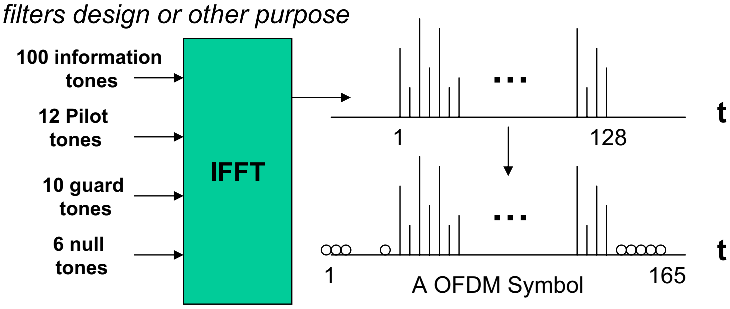
  - *QPSK mapping: 2 bits map to a complex number , a tone of OFDM symbol*



Input bits (b0 b1)	*I*	*Q*
00	*-1*	*-1*
01	*-1*	*1*
10	*1*	*-1*
11	*1*	*1*

Introduction to UWB

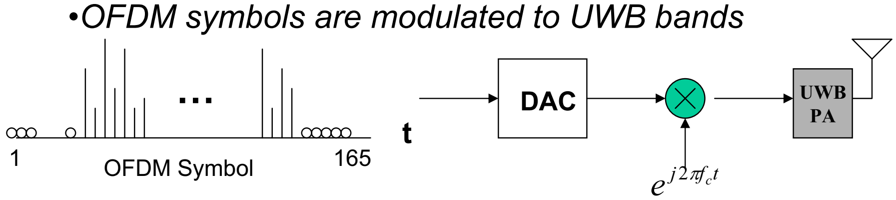
- ***Multi-band OFDM TX Architecture (continued):***
  - *•128 tones per OFDM symbol*
    - *•100 Information tones (or 50 independent tones use 100 position for freq. Spreading)*
    - *•12 Pilot Tones for coherent detection against freq. offset and phase noise*
    - *•10 Guard tones, relax filters design or other purpose*
    - *•6 null tones,*



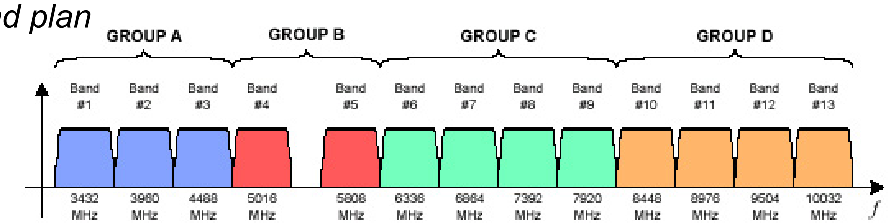
  - *•IFFT: Convert 128 tones to 128 time-domain samples*
  - *•Add zero-pad prefix (60.6ns=32 sample time) to remove PSD ripple*
  - *•and 5 sample time guard intervals for switch between bands*

Introduction to UWB

- ***Multi-band OFDM TX Architecture (continued):***
  - *•OFDM symbols are modulated to UWB bands*



  - *•Band plan*



    - *•Mode 1 device use Group A*
    - *•Mode 2 device uses Group A and Group C*
    - *•Group B and D are reserved for future*

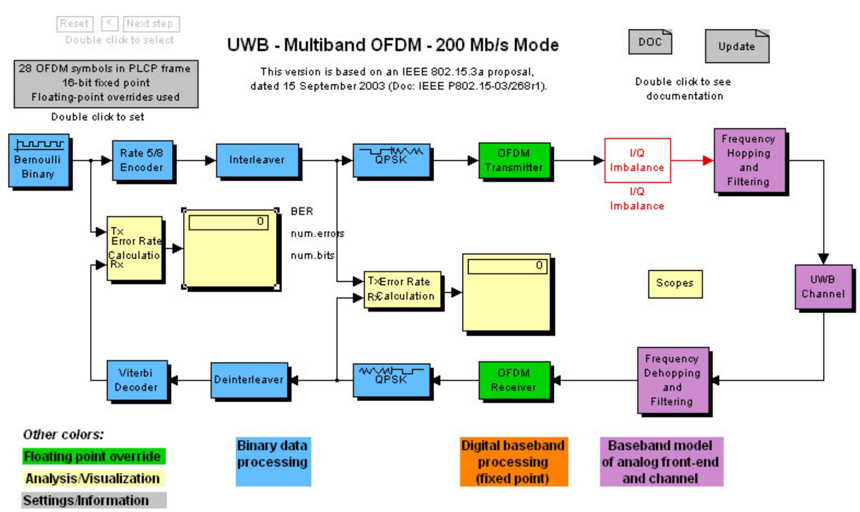
Multi-Band OFDM System Parameters*

Info. Data Rate	110 Mbps	200 Mbps	480 Mbps
Modulation/Constellation	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK
FFT Size	128	128	128
Coding Rate (K=7)	R = 11/32	R = 5/8	R = 3/4
Spreading Rate	2	2	1
Information Tones	50	50	100
Data Tones	100	100	100
Info. Length	242.4 ns	242.4 ns	242.4 ns
Cyclic Prefix	60.6 ns	60.6 ns	60.6 ns
Guard Interval	9.5 ns	9.5 ns	9.5 ns
Symbol Length	312.5 ns	312.5 ns	312.5 ns
Channel Bit Rate	640 Mbps	640 Mbps	640 Mbps
Frequency Band	3168 – 4752 MHz	3168 – 4752 MHz	3168 – 4752 MHz
Multi-path Tolerance	60.6 ns	60.6 ns	60.6 ns

** From TI proposal*

UWB Transmitter Simulation

A snapshot:

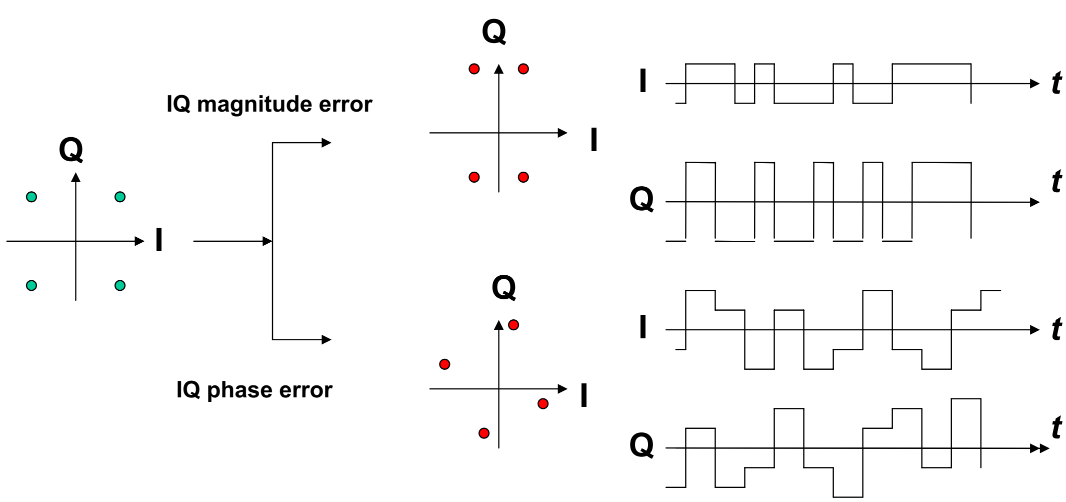


UWB System Simulation

- ***Goal: Make the simulation as realistic as possible***
- ***Current Model Assumptions***
  - *Random data transmission (no data scrambling used)*
  - *Fixed (selectable) number of data symbols per packet Continuous frame-to-frame operation (no coder state resetting via tail bits)*
  - *Fixed transmit power level; link-SNR specified, No PA*
  - *Assume perfect receiver, Idealized timing/frequency acquisition*
  - *Only simulate the highest mandatory rate 200Mbps*
- ***The following non-idealities are introduced to the simulation***
  - ***I/Q mismatch***
  - ***LO impurity***
    - ***Spurs***
    - ***Phase noise***
  - ***LO leakage***

IQ imbalance in UWB transmitter

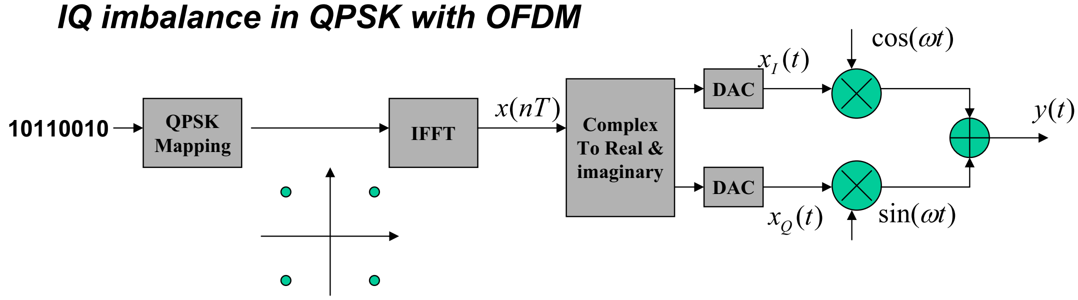
IQ imbalance in QPSK system (no OFDM)



- **Cause EVM (Error Vector Magnitude)**
- **Degrade Signal-to-noise ratio**

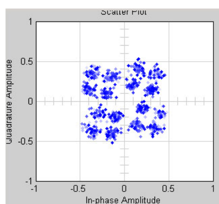
IQ imbalance in UWB transmitter

IQ imbalance in QPSK with OFDM



Ideal complex modulation carrier waveform:

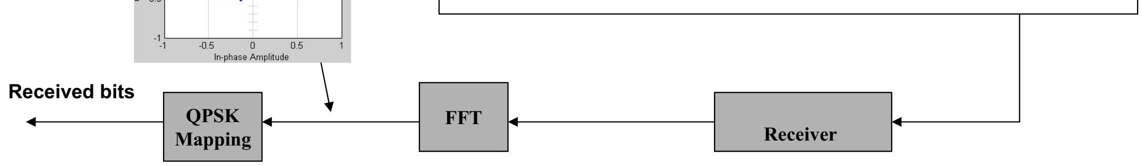
$$y(t) = x_I(t) * \cos(\omega t) + x_Q(t)\sin(\omega t)$$



IQ imbalanced modulated waveform:

$$y(t) = x_I(t) * \cos(\omega t) + \lambda x_Q(t)\sin(\omega t + \theta)$$

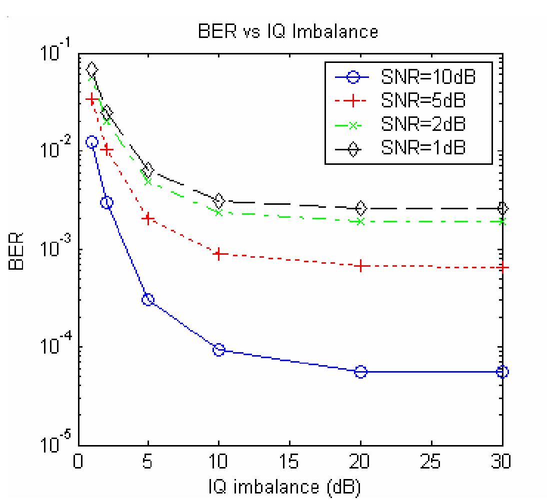
$$= (x_I(t) + \lambda x_Q(t)\sin\theta)\cos(\omega t) + (\lambda x_Q(t)\cos\theta)\sin(\omega t + \theta)$$



IQ imbalance in UWB transmitter

IQ magnitude imbalance test results for UWB:

Channel mode: CM2, non-line of sight, distance 0-4m
Channel index: 50
*I/Q imbalance is defined as 20*log10(I/(I-Q))*

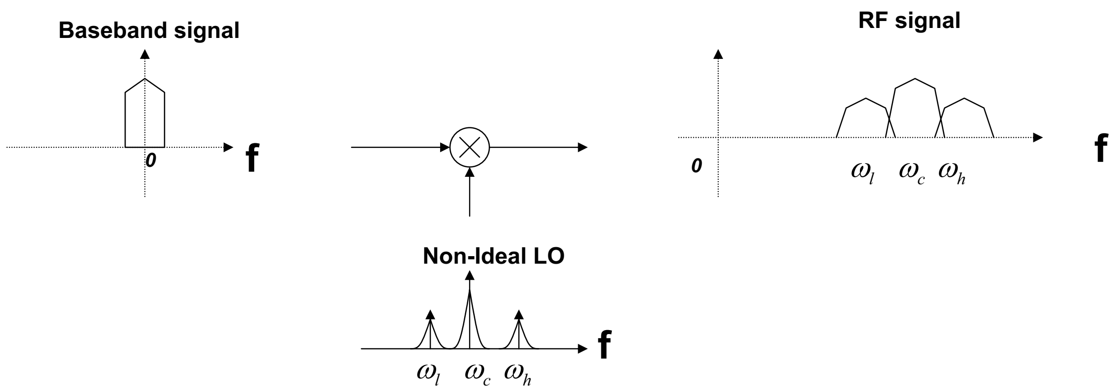


- **BER is determined by channel SNR when IQ imbalance is above 20dB**
- **IQ imbalance starts to affect BER when less than 20dB**

LO impurity in UWB Transmitter

LO from frequency synthesizer comes with Spurs and phase noise

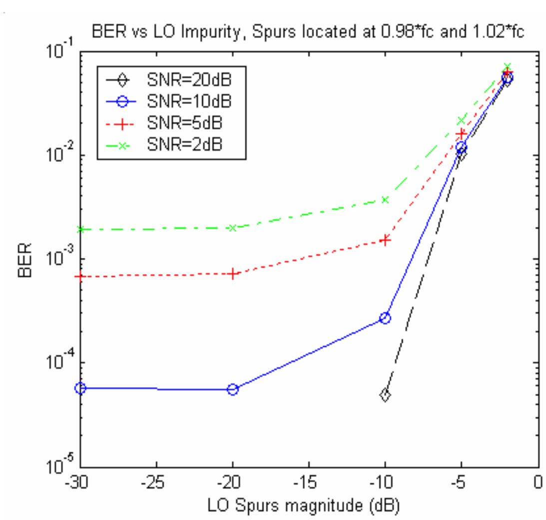
Non-ideal LO effect in the Mixer:

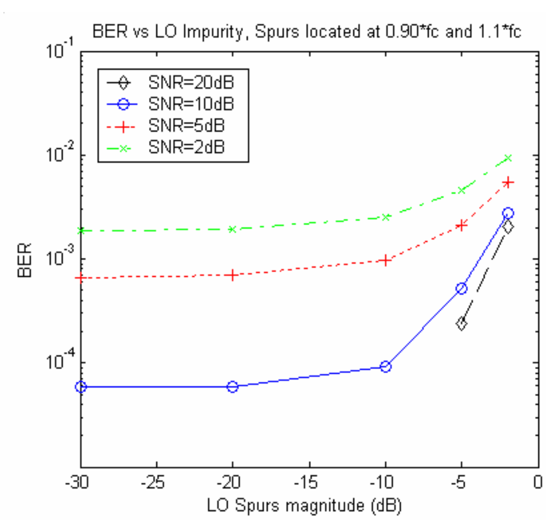


LO impurity in UWB Transmitter

Simulation of LO impurity impact on UWB transmitter

- ***Two cases:*** ***A: Spurs at 0.98*fc & 1.02*fc B: Spurs at 0.9*fc & 1.1*fc***
- ***Channel mode: non-line-of-sight, distance 0-4m, Channel index: 50***
- ***LO Spurs has little impact on BER when less than –20dB***
- ***The closer the spurs to LO, the more impact it has***

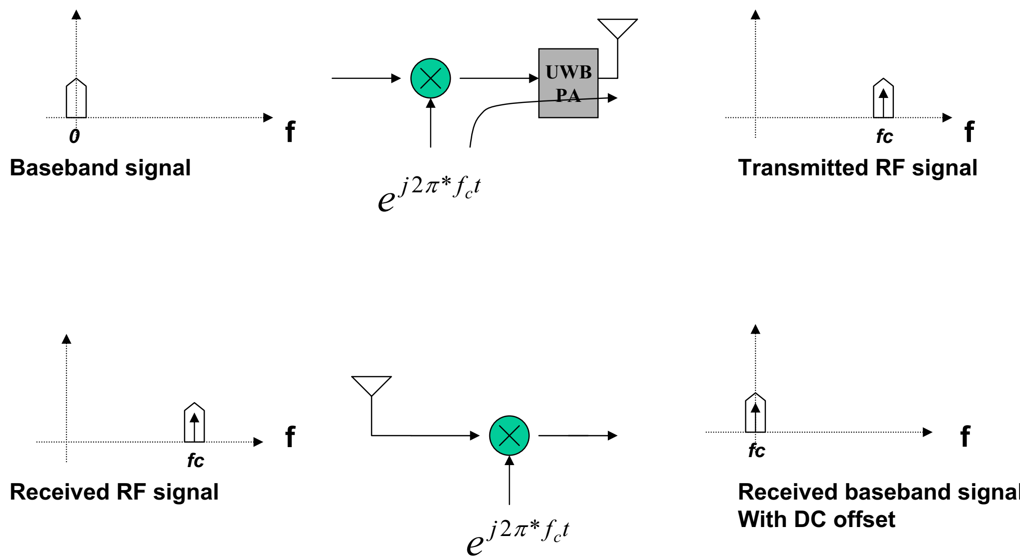




LO Leakage in UWB Transmitter

LO leakage causes:

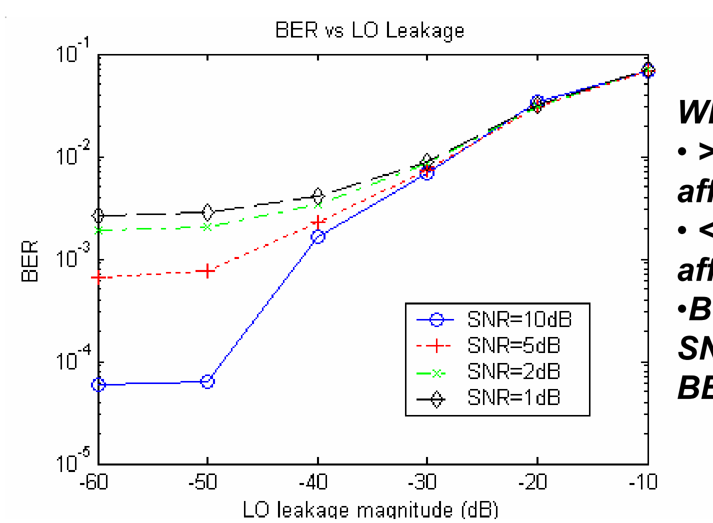
- ***DC offset at receiver***
- ***Interference to other receivers using the same band***



LO Leakage in UWB Transmitter

Simulation of LO Leakage on UWB transmitter

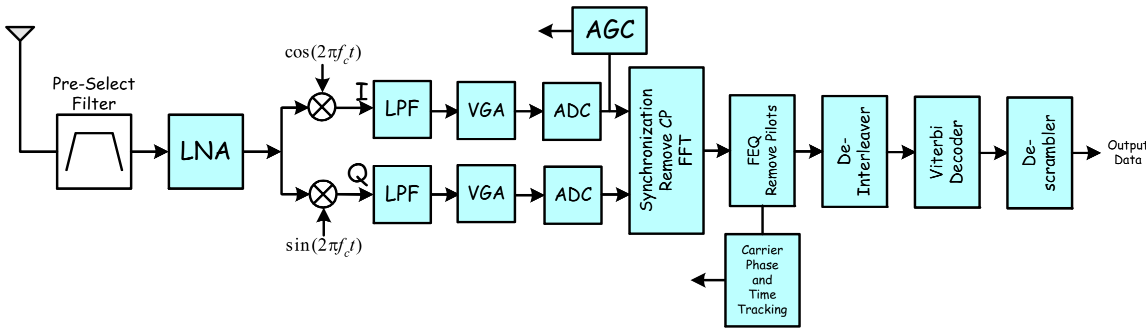
- ***LO Leakage magnitude is specified in dB w.r.t. LO magnitude***
- ***Channel mode: non-line-of-sight, distance 0-4m,***
- ***Channel index:50***



When LO leakage
- ***>-30dB, BER is mainly affected by LO leakage***
- ***<-50dB, BER is mainly affected by SNR***
- ***Between –30 and –50dB, both SNR and LO leakage affect BER***

Multi-Band OFDM Receiver Architecture*

- *Block diagram of an example RX architecture:*



** From TI Proposal*

Link Budget and Receiver Sensitivity*

- *Assumption: AWGN and 0 dBi gain at TX and RX antennas.*

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
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	3.0 dB	3.0 dB	3.0 dB
Link Margin	5.5 dB	10.2 dB	12.2 dB
RX Sensitivity Level	-80.0 dBm	-76.7 dBm	-72.7 dB

** From TI Proposal*

Key Block Specifications

	NF (dB)	*Gain (dB)*	*IIP3 (dBm)*
LNA	*4*	*10*	*-2*
Mixer	*10*	*6*	*10*
Filter	*10*	*0*	*18*

Assumptions:

- **Min distance of operation = 0.1m**
- **Maximum of three UWB systems operating concurrently**
- **External Notch filter filters out non-Multi-Band OFDM jammers (802.11a/b/g, Bluetooth, PCS etc)**

Other Considerations

- ***DC Offset: Important for direct conversion systems:*** ***Multi-Band OFDM system rejects the sub-carrier at DC.***
- ***1/f noise:*** ***Sub-carrier at DC is rejected, subcarrier spacing = 4.125 MHz which is far away from the 1/f noise corner frequency. Impact of 1/f noise is low.***
- ***IIP2:*** ***Completely differential design to increase IIP2***
- ***LO Re-radiation:*** ***Use cascode LNA to improve isolation and reduce carrier leakage***

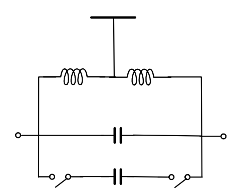
Paths to Broadband LNA

- ***Resistive Load, Resistive Input Match***
    - Good Broadband Gain and Input Match
    - High Noise Figure
    - Headroom
- ***LC Match***
    - Broadband match possible using multiple LC sections
    - Good noise performance
    - Requires on-chip inductors for tuning: High cost

Design Methodology

- Load Tuning
    - LC Tune LNA load for 6GHz-8GHz band using package bondwire inductance and on-chip capacitors
    - Switch in extra capacitance to tune to 3GHz-4.5GHz band

Allows for a broad-band load without the use of resistors or on-chip inductors. Fixed LC tuning would require multiple LC sections and therefore on-chip inductors



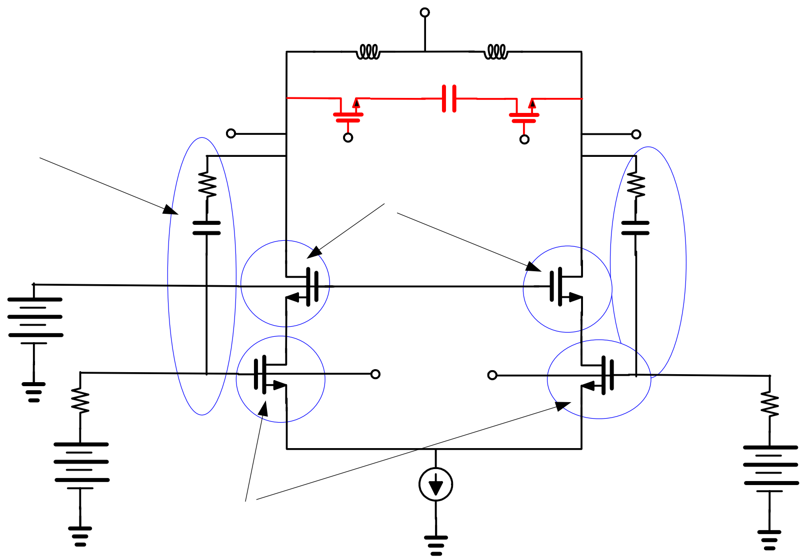
$$\omega_{high} = \frac{1}{\sqrt{L_{bond} . C_{dev}}}$$

$$\omega_{low} = \frac{1}{\sqrt{L_{bond} \cdot (C_{dev} + Cl)}}$$

- Input match
    - Use package bondwires to match input
    - Add RC feedback
    - Size devices for best input match (as opposed to sizing for best NF): Increases NF, but allows for input matching without on-chip inductors

Load tuning also provides extra filtering and eases IP2 spec on mixer

LNA Design



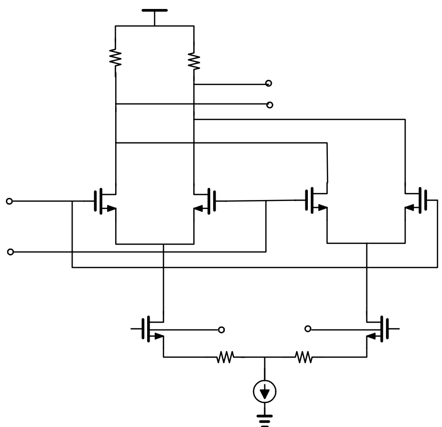
Simulation Results - I

Freq	Gain	NF	Return Loss
MHz	dB	dB	dB
3432	11	3.25	-4.6
3960	11.8	3.3	-4.9
4488	14	3.4	-5.2
6336	18.53	3.4	-5.9
6864	21	3.5	-6.1
7392	21.9	3.65	-5.9
7920	20.8	3.8	-5.4

10 dB gain step between bands.
VGA will need to compensate.

Noise Figure	*3.8dB (worst case)*
Input IP3	*-3 dBm*
Input IP2	*+40 dBm with 5% device mismatch* *+30 dBm with 5% device mismatch AND 10% bondwire mismatch*
Current Consumption	*8mA (from a 2.7V supply)*
Frequency band switching time	*3nS*

Mixer



Simulation Results

- ***Noise Figure = 7dB***
- ***Gain = 6dB***
- ***Current Consumption = 4mA (from a 2.7V supply)***

Gilbert cell mixer with resistive loads and degeneration

V_{DD}

+

Mixer Spur Performance

- ***IIP2 quantifies "wide-band" distortion".***

  Ex.: Fspur=4.1GHz, Finterest=8.2GHz, Flo=8GHz
  then Finterest_OUT=200MHz
  2XFspur - Flo=200MHz !!

LNA is frequency selective (Gain at 4.1GHz is different from gain at 8.2GHz). IIP2 for mixer not a true figure of merit for the system as it assumes the gain for 4.1GHz is the same as that for 8.2GHz.

Mixer Spur Simulation Strategy

- ***Simulate Mixer+LNA***
- ***Inject Minimum Detectable Signal at input of LNA at freq of interest***
- ***Inject spur(s) which would create a signal close to frequency of interest***
- ***Make sure the spur output is at least 10dB below signal of interest***

LNA+Mixer Spur Results

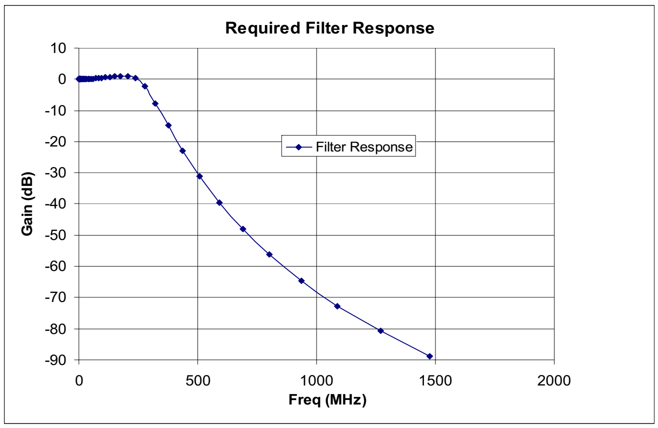
RF signal power = -73dBm, Spur power = -30dBm

5% device mismatch, 10% bondwire mismatch

Signal of interest	*Spur*	*LO*	*Mixing Product*	*Fout Spur*	*Fout interest*	*Spur Rejection (dBc)*	*Spur Rej LNA with Resistive Loads*
8.1G	*4.1G*	*8G*	*2.Fspur-Flo*	*200M*	*100M*	*17.2*	*10.1*
4.1G	*8.2G*	*4G*	*Fspur-2.Flo*	*200M*	*100M*	*4*	*0*
7.1G	*4.1G, 3.1G*	*7G*	*Fspur1+Fspur 2-Flo*	*200M*	*100M*	*14.5*	*8.6*

Filter Specification

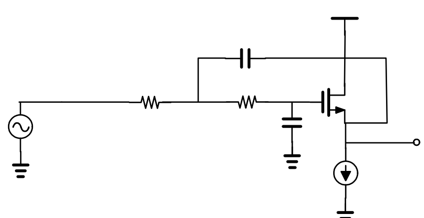
- **Need a low pass filter to filter out adjacent channels from other UWB systems**
- **Required adjacent channel suppression > 30dB (500MHz from center frequency) => at least 4th order LPF**
- **Minimum noise contribution**
- **No inductors**



Filter Topologies

Currently investigating different filter topologies

- ***Sallen-Key filter with unity gain buffer***



- ***Gm-C filter***

Sallen-Key Filter

- **Low current**
- **No inductors**
- **Good noise performance**
- **Low complexity**

- **Finite Zout of source follower introduces a zero which limits rejection (particularly problematic for MOS due to low Gm)**

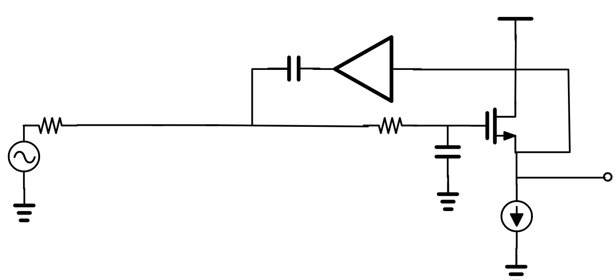
$$H(s)=\frac{K}{s^2C_1C_2R_1R_2+s[C_1(R_1+R_2)+C_2R_1(1-K)]+1}$$

Zero output impedance

$$H(s)=\frac{s^2C_1C_2R_2r_o+sC_2r_o+K}{s^2[C_1C_2R_1R_2+C_1C_2r_o(R_1+R_2)]+s[C_1(R_1+R_2)+C_2(r_o+(1-K)R_1)]+1}$$

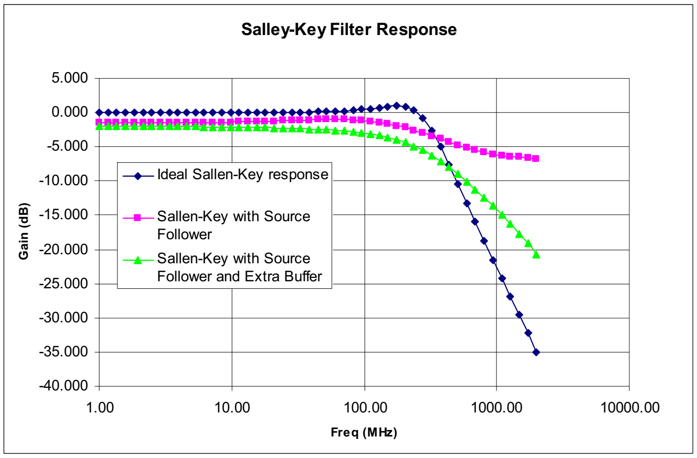
Finite output impedance

Techniques for Enhancing Rejection of Sallen-Key



- Extra buffer "isolates" source follower Zout and pushes the zero to a higher frequency
- Band-width could be reduced due to limited band-width of extra buffer

2 Pole Sallen-Key Filter Response: Preliminary Simulation Results



- **~17dB improvement in rejection at 2GHz by using extra buffer**
- **~10 dB rejection of adjacent band with extra buffer**
- **Bandwidth reduced due to finite bandwidth of buffer**

Still To Evaluate

- **Noise Performance**
- **Input IP3**
- **Group Delay**

Conclusions

- ***UWB Multi-Band OFDM offers significant data rate enhancements over existing 802.11 systems.***
  - ***What is the performance?***
  - ***What is the cost?***
  - ***What are the markets?***
- ***TBD!!!***