High Performance CMOS Radio Design for Multi Band OFDM UWB

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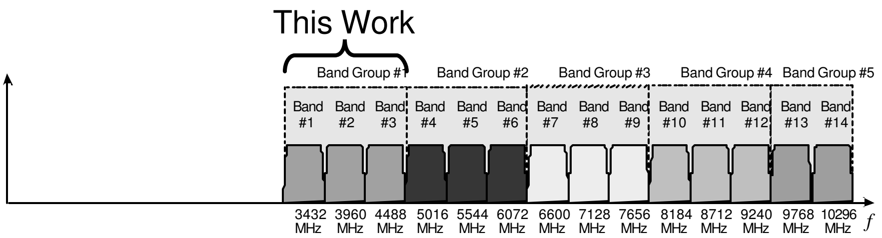
Scope of Presentation

- A Brief Overview of UWB
- Multi-band OFDM System Characteristics
  - Non-Linearity
  - Band Width
  - Noise
- Architectures for VCO, Synthesizer, RX & TX
  - Frequency Generation Solutions, VCO & PLL
    - Spurs & Multi Pico Nets
  - Base Band Filters
  - Receive RF, Analog & ADC
  - Transmit RF, Analog & DAC
- RF Digital Isolation for SOC Implementation
  - Cross Talk

MBOA UWB Band Plan



"Lowest 3 Band" Solutions

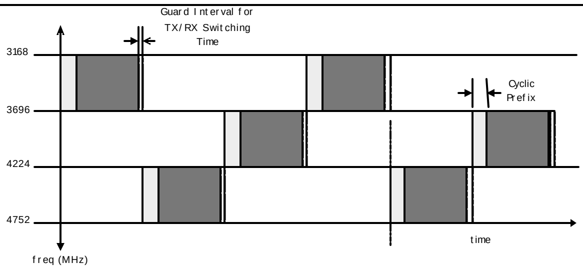
•Best Channel Characteristics

•Simplest Off-Chip Filtering Requirements

➔Earliest Introduction to Market

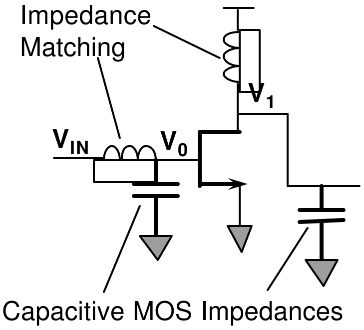
Overview of Multi-band OFDM

- Basic idea: divide the spectrum into channels that are 528 MHz wide.
- Transmitter and Receiver Process Smaller Bandwidth Signals (528 MHz).
- Insert a 2nS Guard Interval Between OFDM Symbols to Allow Sufficient Time to Switch RFIC Between Channels.
- Each Channel has 128 Sub Carriers 4.25MHz Apart
- 3X Power 1/3 of the Time



Low Power & Low Noise RF CMOS

4GHz: $NF_{min} < 1dB$ @ 16dB Gain



RF CMOS Higher Reactive Impedances

➔Narrower Band Widths Improve RF

- **$V_0 \sim V_{IN} X Q_{IN}$**
- **$V_1 \sim I_{SIG} X Q_L$**
- **Input S/N ~ V_0 ~ Q**
- **Gain ~ V_1 ~ Q**
- **$I_{Bias} \sim 1/Q$**

➔Inductors (Q = 2) Can Improve Noise and Lower Power

Inductively Biased Nodes Allow Voltage Swings Outside the Supply Rails

➔Higher Dynamic Range

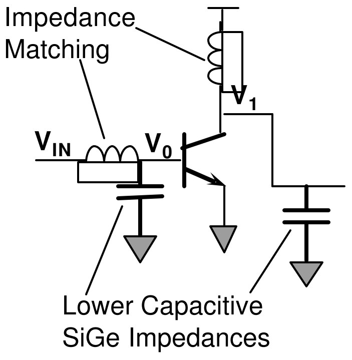
Base Band Op Amps Use Feed Back To Improve Performance

➔Narrower Band Widths

Easy Migration to System on a Chip

Low Power & Low Noise RF SiGe

4GHz: NF_{min} < 1dB @ >16dB Gain



RF SiGe: Lower-Q, Smaller RF Impedances ➔High Performance RF Well Suited for Broad Band

- **$V_0 \sim V_{IN} X Q_{IN}$**
- **$V_1 \sim I_{SIG} X Q_L$**
- **Input S/N ~ V_0 ~ Q**
- **Gain ~ V_1 ~ Q**
- **I_{Bias} ~ 1/Q**

➔Inductors (Q = 2) Can Still Improve Noise and Lower Power

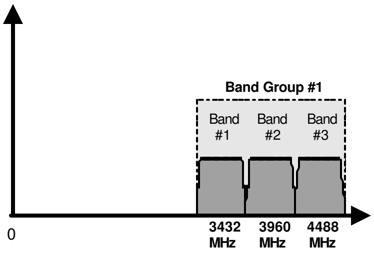
Inductively Biased Nodes Support Voltage Swings Outside the Supply Rails

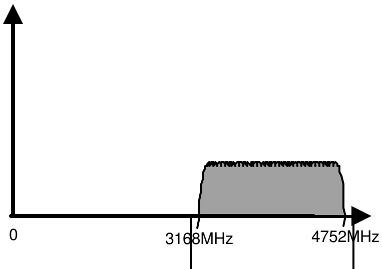
➔Higher Dynamic Range

Very Good Base Band Amps with Low Gains & Broad Band Widths

➔Lower Amounts of Feed Back

UWB Solutions: 3168MHz to 4752GHz





- Narrow Instantaneous RF Band Widths
- Lower Converter Sampling Rates
- Base Band Filters/VGA's
  - Lower-Q
  - Smaller Band Width

4.25 MHz Carrier Spacing/No Zero Tone
  - No 1/f Noise

➔CMOS Friendly System Requirements

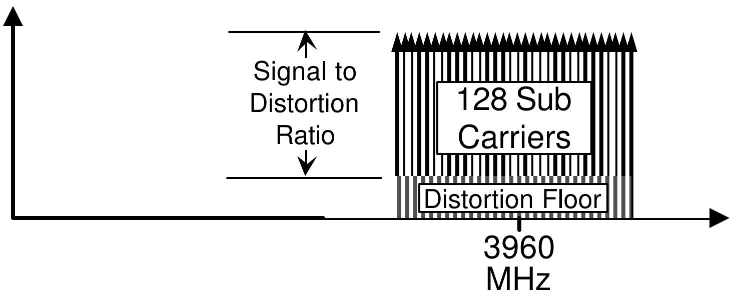
Broad RF Band Widths
Broad Base-Band Band-Widths
Higher-Q Base-Band Filters
High Converter Sampling Rates
➔SiGe Friendly System Requirements

MBOA UWB: Distortion Floor for TX/RX

2nd and 3rd Order “Beats” Set Inter-Modulation Distortion Floor in MBOA UWB

$V_{in} = V_A\mathrm{Cos}(a) + V_B\mathrm{Cos}(b) + V_C\mathrm{Cos}(c)$

$V_{out} = \underbrace{k_1V_{in}}_{\boxed{\text{Signal}}} + \underbrace{k_2V_{in}^2 + k_3V_{in}^3}_{\boxed{\text{Distortion}}}$

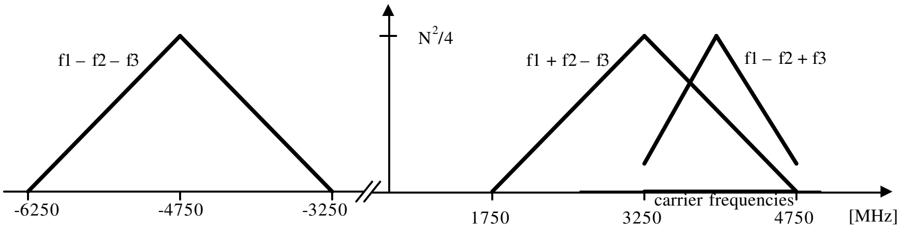


3rd Order Inter Modulation Floor: 128 Sub Carriers

$V_{IN} = A\cos(a) + B\cos(b) + C\cos(c)$

$V_{OUT} = k_1V_{IN} + k_2V_{IN}^2 + \boxed{k_3V_{IN}^3}$

$$k_3V_{IN}^3 = k_3\,[\tfrac14 A^3\cos(3a) + \tfrac14 B^3\cos(3b) + \tfrac14 C^3\cos(3c) + \tfrac34 A^2B\cos(2a +/- b) + \tfrac34 A^2C\cos(2a +/- c) + \tfrac34 B^2A\cos(2b +/- a) + \tfrac34 B^2C\cos(2b +/- c) + \tfrac34 C^2A\cos(2c +/- a) + \tfrac34 C^2B\cos(2c +/- b) + {}^3/_2 ABC\cos(a +/- b +/- c)]$$



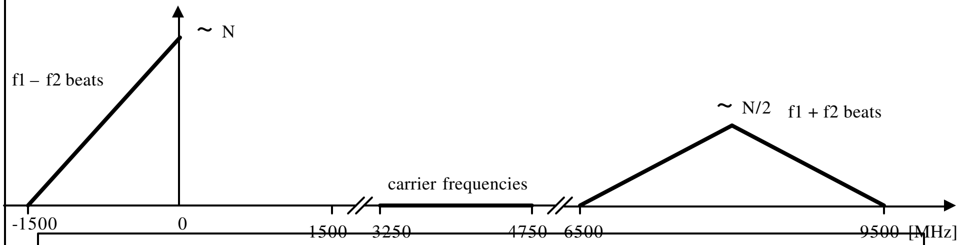
- Triple beats are 6dB higher than two-tone IM3 products
- Many more triple beats than IM3 products
- ~ $3N^2/8$ beats near middle of band
- ~ $N^2/4$ product terms near edge of band
- CTB(dBc) = IM3(dBc) + 6 + 10 log($3N^2/8$)

UWB Second Order Inter Modulation Floor

$V_{IN} = A\,\mathrm{Cos}(a) + B\,\mathrm{Cos}(b) + C\,\mathrm{Cos}(c)$

$V_{OUT} = k_1 V_{IN} + \boxed{k_2 V_{IN}^2} + k_3 V_{IN}^3$

$$k_2 V_{IN}^2 = \tfrac{1}{2} k_2 A^2 + \tfrac{1}{2} k_2 B^2 + \tfrac{1}{2} k_3 B^2 + k_2 AB\cos(a \pm b) + k_2 AC\cos(a \pm c) + k_2 BC\cos(b \pm c) + \tfrac{1}{2} k_2 A^2\cos(2a) + \tfrac{1}{2} k_2 B^2\cos(2b) + \tfrac{1}{2} k_2 C^2\cos(2c)$$



- CSO products are out of band in RF path
- Generate Signal dependent DC offsets at LNA output
- Reduced By Low-Q L-C Filtering Before Down Conversion

Multi-Band OFDM System Parameters

Info. Data Rate	110 Mbps	200 Mbps	480 Mbps	
Modulation/Constellation	OFDM/QPSK	OFDM/QPSK	OFDM/QPSK	1
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	2
Symbol Length	312.5 ns	312.5 ns	312.5 ns	3
Channel Bit Rate	640 Mbps	640 Mbps	640 Mbps	
Frequency Band	3168 – 4752 MHz	3168 – 4752 MHz	3168 – 4752 MHz	4
Multi-path Tolerance	60.6 ns	60.6 ns	60.6 ns	

1) Tolerant of Inter-Mods, Image, and Synthesizer Noise
2) Fast Synthesizer 9.5nS for System ➔ ~ 2nS for RFIC
3) Short “In-Channel” Settling Times for RFIC
4) Frequencies Readily Obtained on CMOS RFIC

Link Budget and Receiver Sensitivity

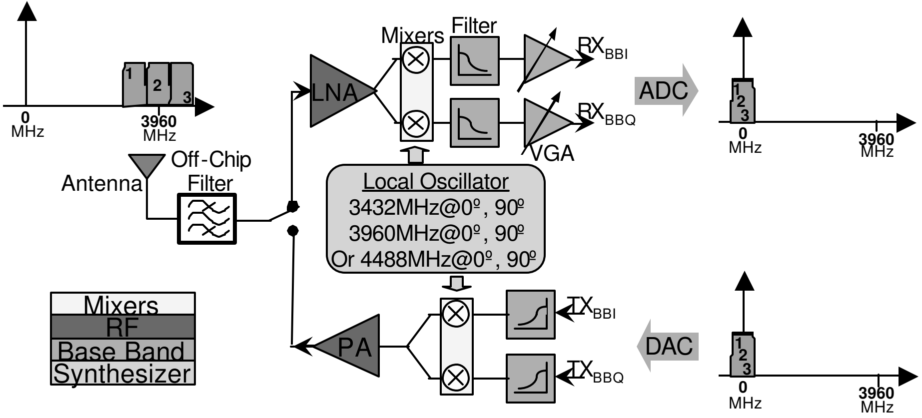
Assumption: AWGN and 0 dBi gain at TX/RX antenna

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	1
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	2
Total Noise Power	-87.0 dBm	-84.4 dBm	-80.6 dBm	
Required Eb/N0	4.0 dB	4.7 dB	4.9 dB	3
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	

1) Very Low TX Power ➔ Fully Integrated PA
2) 6.5dB for switch + filter + receiver ➔ ~ 4.5dB for RFIC
3) Tolerant of Inter-Mods, Image, and Synthesizer Noise

Direct Conversion UWB Transceiver

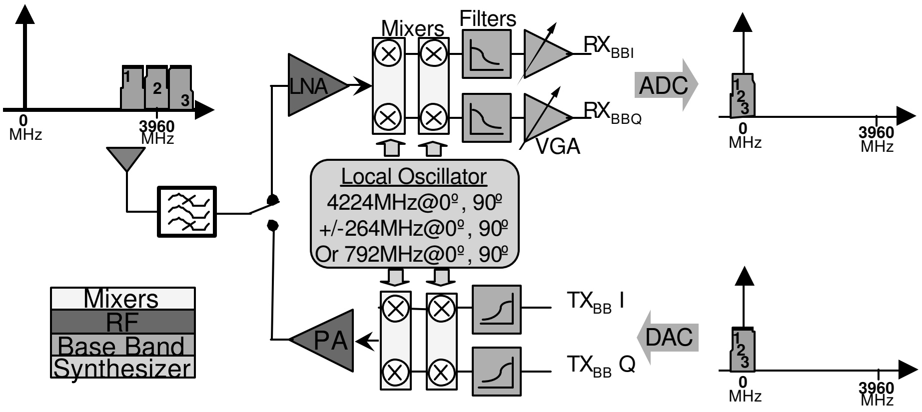
Low Power, Low Noise ~ 4dB, Low Cost, 480MBPS



Channel Switching Time ~ 2nS (~10,000 Times Faster Than 802.11)
➔Complex Frequency Synthesis & Frequency Conversion
Low TX Power ~ -10dBm RMS
➔Fully Integrated PA
➔Very Low Noise RFIC Required NF ~ 4dB

Direct Conversion UWB Transceiver

Low Power, Low Noise ~ 4dB, Low Cost, 480MBPS



Channel Switching Time ~ 2nS, Two RF LO Frequencies Needed

➔Unique Frequency Synthesis & Frequency Conversion

Low TX Power ~ -10dBm RMS

➔Fully Integrated PA

More Complex Dual Stage RX/TX ➔ Simpler Frequency Synthesis

MBOA UWB: Frequency Synthesis

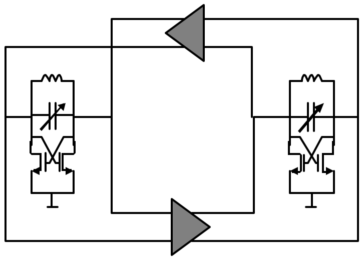
- Fast Frequency Hopping
  - Necessary condition for multi-band proposals
  - Frequency switching time < 2ns
- Standard Closed Loop PLL Design is Far Too Slow
- Frequency Synthesis Using Single-Sideband Generation
- All Frequencies Derived From Multiples of 16MHz
  - All IC cells fully synchronous
    - ADC outputs, mixer LOs, RX & TX digital base band, …

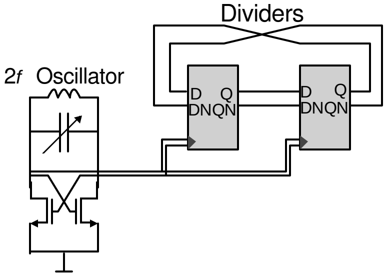
Frequency Synthesis

(Generating 3 Frequencies from 1)

- VCO center frequency = 4224MHz = 264 x 16MHz
  - 4224 MHz ÷ 4 output = 1056MHz, ÷ 16 output = 264MHz
- Single sideband generation principle: $?_2$=Sine Wave
  - $\mathrm{Cos}(\omega_1 t)\times\mathrm{Cos}(\omega_2 t)-\mathrm{Sin}(\omega_1 t)\times\mathrm{Sin}(\omega_2 t) = \mathrm{Cos}[(\omega_1+\omega_2)t]$
  - $\mathrm{Cos}(\omega_1 t)\times\mathrm{Sin}(\omega_2 t)+\mathrm{Sin}(\omega_1 t)\times\mathrm{Cos}(\omega_2 t) = \mathrm{Sin}[(\omega_1+\omega_2)t]$
  - $\mathrm{Cos}(\omega_1 t)\times\mathrm{Cos}(\omega_2 t)+\mathrm{Sin}(\omega_1 t)\times\mathrm{Sin}(\omega_2 t) = \mathrm{Cos}[(\omega_1-\omega_2)t]$
  - $\mathrm{Cos}(\omega_1 t)\times\mathrm{Sin}(\omega_2 t)-\mathrm{Sin}(\omega_1 t)\times\mathrm{Cos}(\omega_2 t) = \mathrm{Sin}[(\omega_1-\omega_2)t]$
  - Unwanted Frequency Rejected ~ 30dB
- All three frequencies can be generated rapidly
  - 792MHz = 1056MHz – 264MHz
  - Channel 1: 4224 - 792 = 3432MHz
  - Channel 2: 4224 - 264 = 3960MHz
  - Channel 3: 4224 + 264 = 4488MHz

Quadrature Voltage Controlled Oscillators





Ring Oscillator

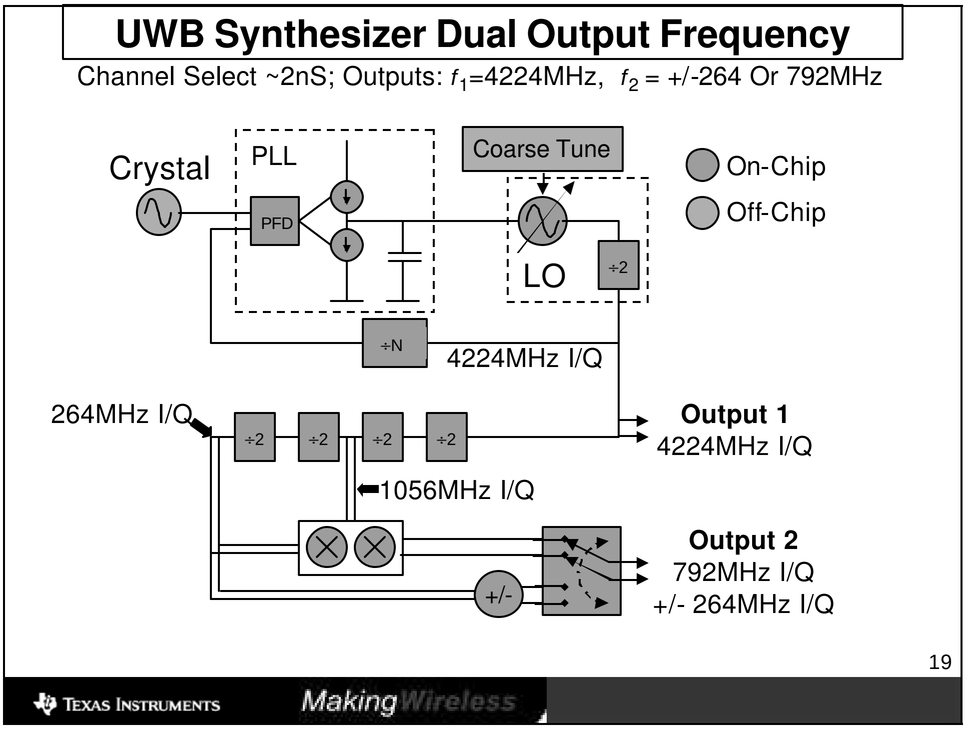
- Quadrature Output VCO
  - No Separate Phase Splitter
- Lower Operating Frequency
  - Better Yield?
- Variable MOS capacitors set frequency to 4224MHz

2*f* Oscillator (8448MHz)

- Reduced 1*f* Radiation
- Reduced VCO Pulling
- Smaller Implementation
- Higher Inductor Q's

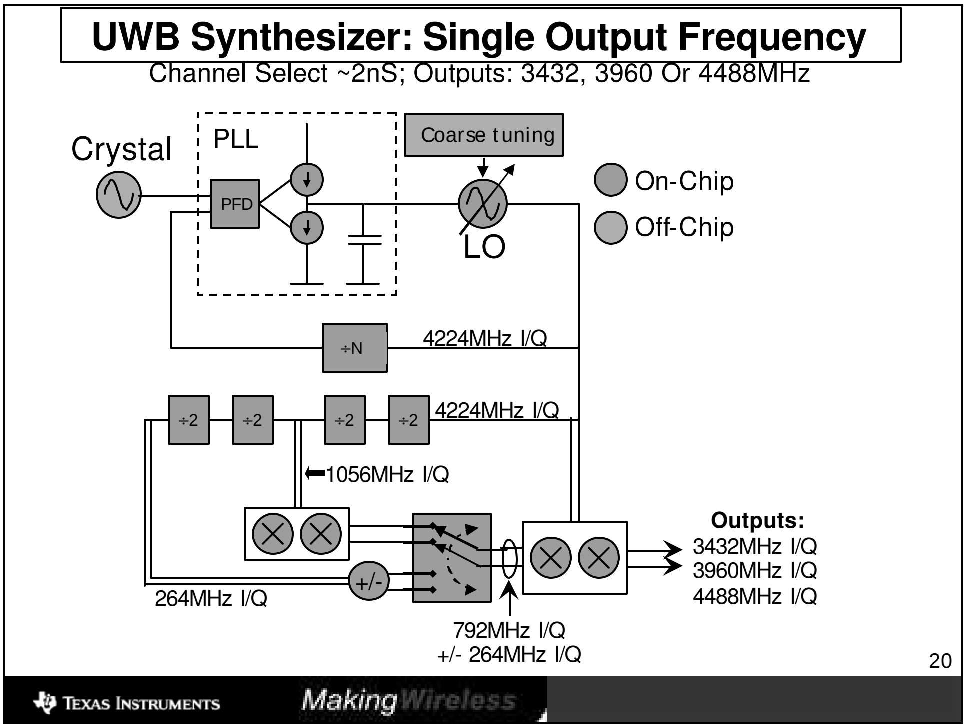
Two-Stage $D_{\text{Flip-Flop}}$ Dividers

- Divided Clocks in Quadruture



UWB Synthesizer Dual Output Frequency

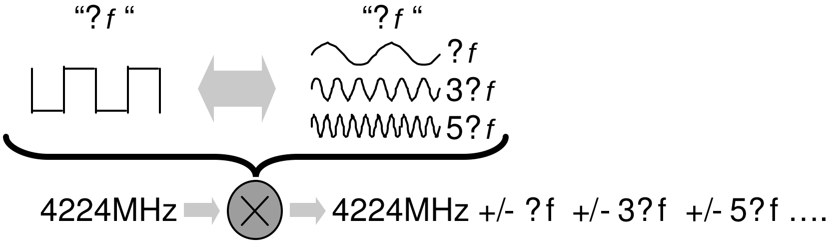
Channel Select ~2nS; Outputs: f_1=4224MHz, f_2 = +/-264 Or 792MHz



UWB Synthesizer: Single Output Frequency

Channel Select ~2nS; Outputs: 3432, 3960 Or 4488MHz

“Non-Linear” Frequency Conversion: Spurs!



“?*f* “ “?*f* “

?*f*

3?*f*

5?*f*

4224MHz → 4224MHz +/- ?f +/- 3?f +/- 5?f ….

Single sideband generation principle: $\underline{?f = ?_2/2\pi = \text{Square wave}}$

$\{\text{Cos}(\omega_1 t)\times\text{Cos}(\omega_2 t)-\text{Sin}(\omega_1 t)\times\text{Sin}(\omega_2 t) = \underline{\text{Cos}[(\omega_1+\omega_2)t]}\}$

$+\{\text{Cos}(\omega_1 t)\times\text{Cos}(3\omega_2 t)+\text{Sin}(\omega_1 t)\times\text{Sin}(3\omega_2 t) = \underline{\text{Cos}[(\omega_1-3\omega_2)t]}\}/3$

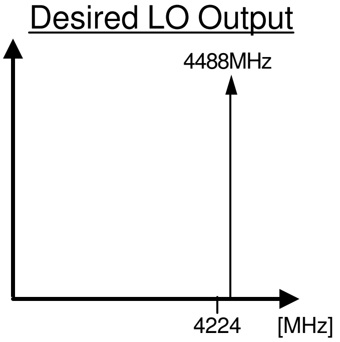
$+\{\text{Cos}(\omega_1 t)\times\text{Cos}(5\omega_2 t)+\text{Sin}(\omega_1 t)\times\text{Sin}(5\omega_2 t) = \underline{\text{Cos}[(\omega_1+5\omega_2)t]}\}/5 + \ldots$

➔ $?f_{264}$ = 264MHz & -792MHz & 1320MHz & …

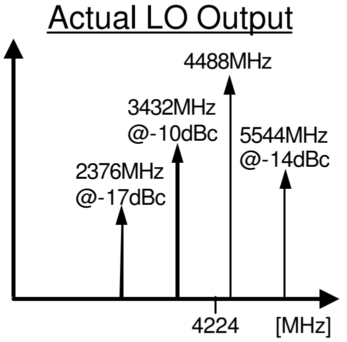
➔ $?f_{792}$ = 792MHz & -2376MHz & …

- Channel 1 Output = 3432MHz, 6600MHz, 264MHz,…
- Channel 2 Output = 3960MHz, 5016MHz, 2904MHz,…
- Channel 3 Output = 2376MHz, 3432MHz, 4488MHz,…

LO Spurious & Multiple Pico Nets



Desired LO Output



Actual LO Output

LO Spurious

- Mix Channel 1 on Top of Channel 3
- Transmit on Channel 1 When Channel 3 is Selected

➔ Prevent Coexistence of Multiple Pico-Nets

- Mix Undesired Wireless Standards Into UWB Receive Bands
- Transmits UWB Data Into Spectrum Allocated to Other Standards

➔ Hampers Coexistence with Other Wireless Standards

Base Band Filters

RX Channel Select Filter (528MSPS ADC)

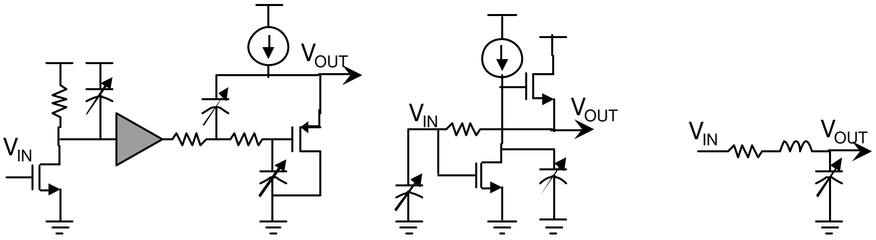
- 3rd Order All Pole Response
- F_c ~ 250MHz
- On-Chip Auto Tuning of Filter Corner
- Filter can be integrated into the VGA
  - Real pole at Output of Mixer
  - Complex pole can be combined with VGA Op-Amp

TX Image Reject Filter (1056MSPS DAC)

- Second Order Response
- +0 to +1dB @ 250MHz
- Auto Tuning of Filter Corner

MBOA UWB Base Band Filters

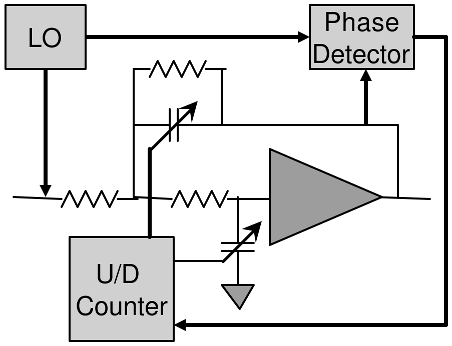
(One-Half of Differential Section Shown)



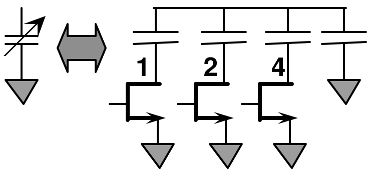
Sallen & Key	Op-Amp Based	L-C
Low-Q	Higher-Q	Moderate-Q
Stable	Stability Issues	Most Stable
Moderate power	Moderate Power	Zero power
Requires Buffer	Low-Z Drive	Requires Buffer
No Voltage Gain	Has Gain	No Gain

Base Band Self-Calibration: Example

Base Band Filter



Tuned Capacitor

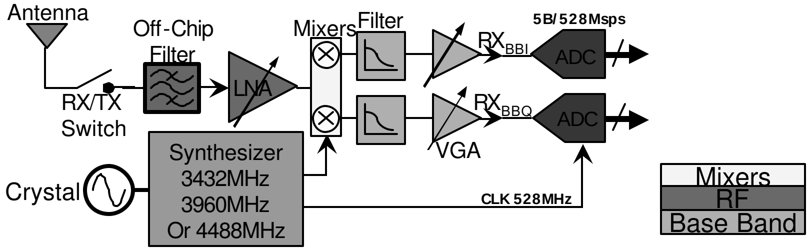


Fine Line CMOS➔Negligible Switching Parasitic for Filters, Matching Networks and VCO’s Below ~ 10GHz

Filter Self-Calibration

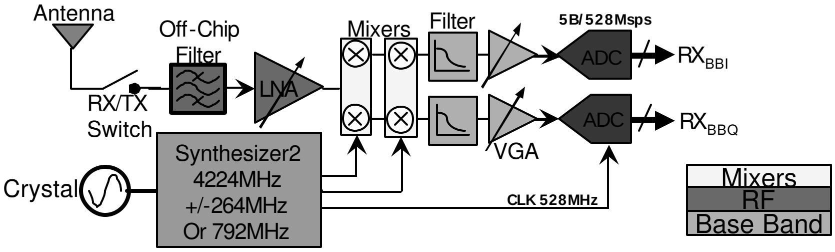
- Higher Yield & Lower Costs
- Higher Realized Performance
- RF/Analog Self Testing at DC Probe

ADC Spec/Issues for UWB Receiver



- ADC:
  - ***5bits/528MHz***
  - Power Hungry Component in UWB
- VGA & Base Band Filters
  - Large Gain Range
  - Flat Response to ~ 240MHz
  - Can Combine Base Band Filters With Gain Blocks
  - May Need 50O Drive
- More Complex Synthesizer ➔LO Spurs
- Standard Receive Mixers
- Gain Step in LNA

ADC Spec/Issues for UWB Receiver



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  - Can Combine Base Band Filters With Gain Blocks
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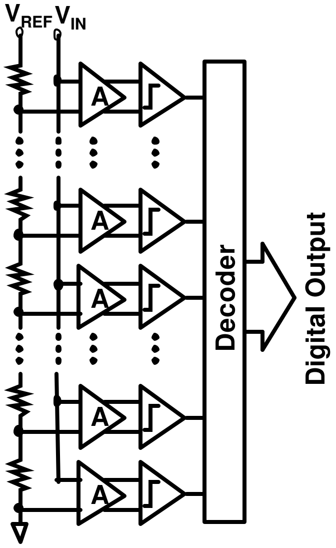
- Less Complex Synthesizer
- Dual Stage Receive Mixers ➔ LO Spurs
- Gain Step in LNA

Basic Flash ADC

Continuous time signal with infinite resolution → Discrete time signal with finite resolution



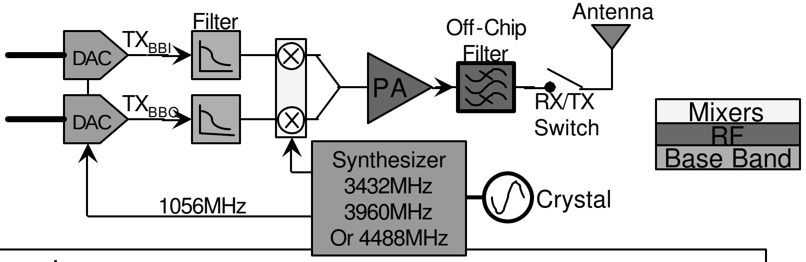
Structure

- Input Capacitance ~ $2^{\text{\# of Bits}}$
- Pre-Amps & Comparators ~ $2^{\text{\# of Bits}}$
  - ➔ Area & Power ~ $2^{\text{\# of Bits}}$
- Sample & Hold Not Required

Performance Issues

- Input Feed-Through to Reference
- Comparator Kickback
- Clock Jitter

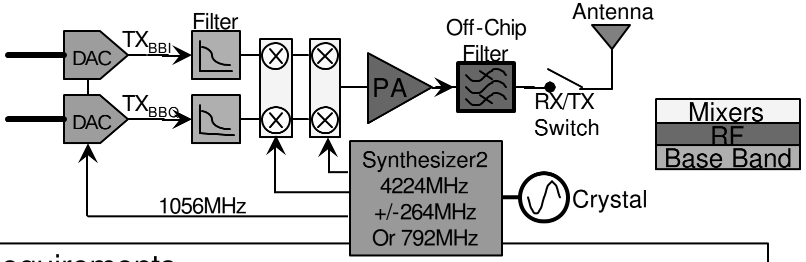
Transmitter 1 for MBOA UWB



Requirements

- DAC: 5bits @ 1.056GHz Sampling Rate
- Low pass Filter
  - Flat To ~ 240MHz
  - Suppresses (1056 – 264)MHz and Beyond
- Simple Up-Conversion Mixers
- A Single RF Output Synthesizer
  - Shared with DAC & Receiver
  - Higher Complexity LO Generation ➔LO Spurs

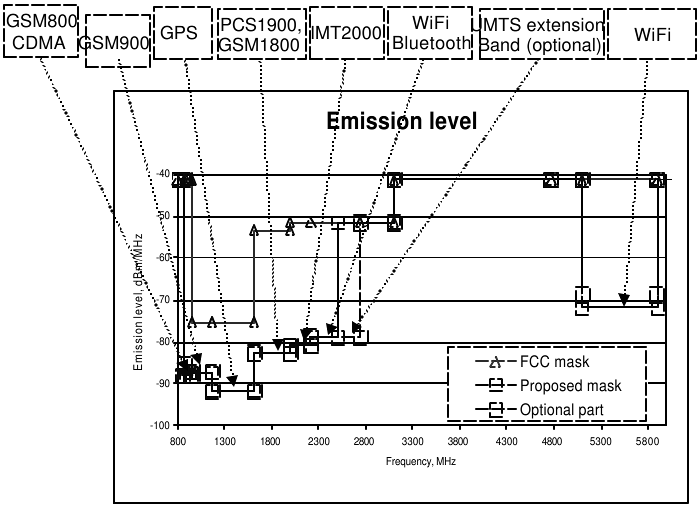
Transmitter 2 for MBOA UWB



Requirements

- DAC: 5bits @ 1.056GHz Sampling Rate
- Low pass Filter
  - Flat To ~ 240MHz
  - Suppresses (1056 – 264)MHz and Beyond
- Two Stage Up-Conversion Mixers
  - Spurious Issues
- Simpler Dual RF Output Synthesizer
  - Shared with DAC & Receiver
  - Switching Time < 2ns

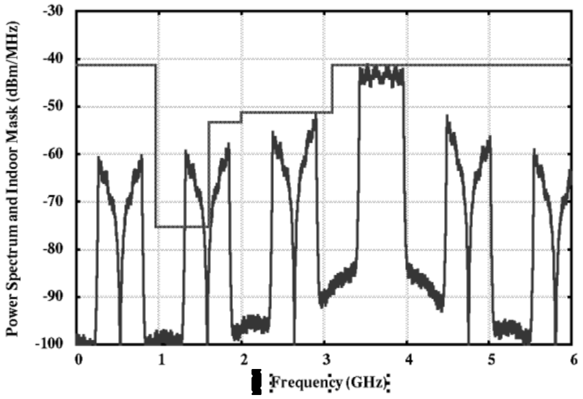
Band Set #1 Emission Mask Proposal



GSM800 CDMA
GSM900
GPS
PCS1900, GSM1800
IMT2000
WiFi Bluetooth
UMTS extension Band (optional)
WiFi

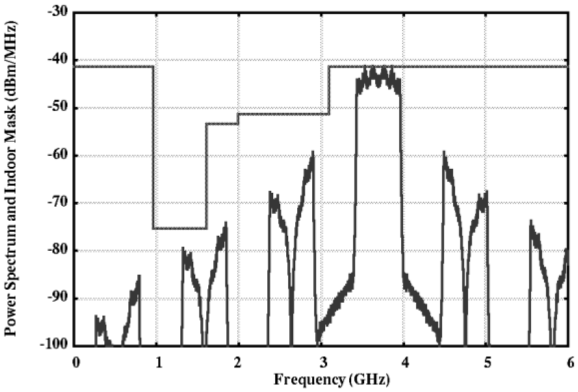
TX Base Band Output Spectrum: No Filter

- High level simulation (DAC and mixer)
- 2nd left sided image in GPS band Violates TX Mask

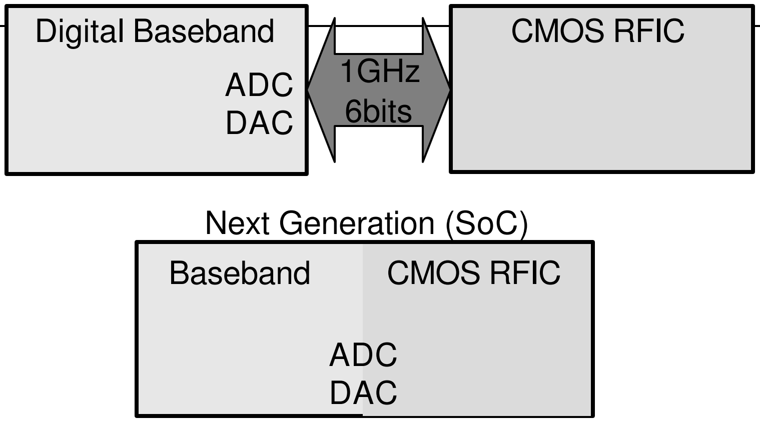


Base Band Output Spectrum with Filtering

- Simple Low-pass filter ➔5dB Margin
- Additional RF Filtering Improves Margin



UWB Transceiver Design Approach



Multi-Chip to Full System on a Chip

- Self Calibration: RF/VCO/Analog Base Band
- Cross Talk Suppression: System & Design Level

System on a Chip

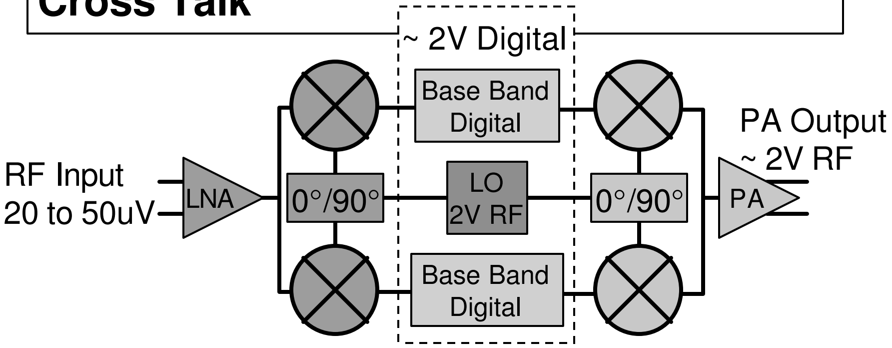
Advantages

- Reduced Implementation Cost
- Improved Vender Acceptance

Challenges

- Cost of Lower Yield
- Device Modeling
- Cross Talk

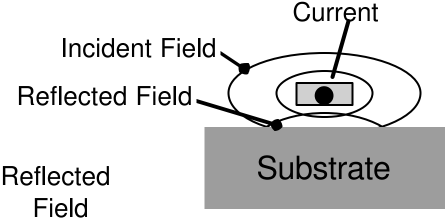
Cross Talk



On-Chip Coupling

- TX Output/Harmonics Pull VCO
- Strong RF Input/Harmonics Pull VCO
- Digital Contaminates Base Band or RF
- Digital Over-Drives RF or Base Band Input
- TX Output Over-Drives RX Input (UMTS)
- TX/RX Mode Changes “Kick” VCO
- VCO Feed Though Violates FCC Max Power

Inductive Cross Talk



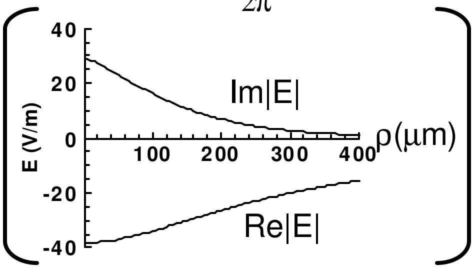
Inductive Vector Potential:

Incident Field

Reflected Field

$$E(f,\rho,z)\propto I\int_0^\infty \frac{dk_\rho k_\rho}{k_z} J_0(k_\rho \rho)\left[e^{ik|z-z'|}+Ae^{-ik_z z}\right],\quad f=\frac{c}{2\pi}\sqrt{k_\rho^2+k_z^2}$$

$$E(2GHz,\rho,z)\Rightarrow \frac{6\cdot 10^3 V}{\rho(\mu m)}+$$

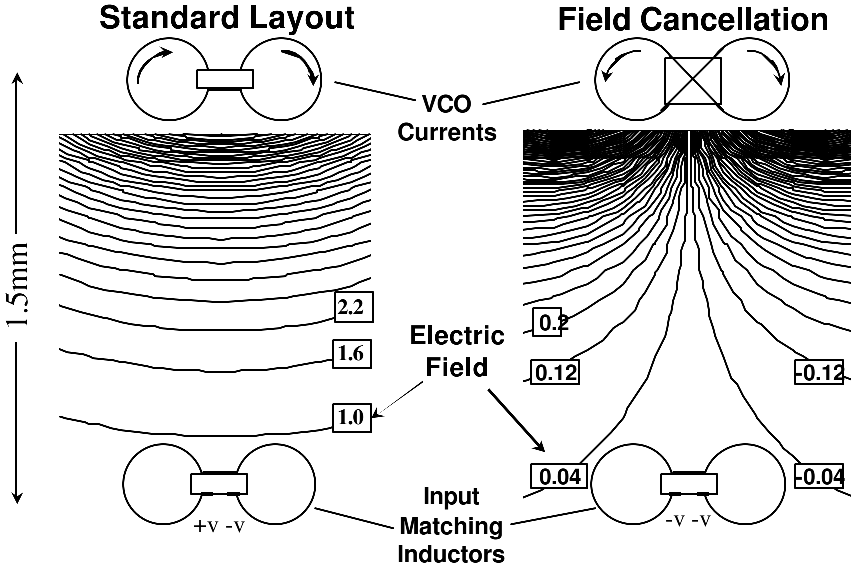


Static Component

Dynamic Component: Weakly Spatially Dependent

Magneto Static Cross Talk

(No Simple Board Level Solution)



Standard Layout

Field Cancellation

VCO Currents

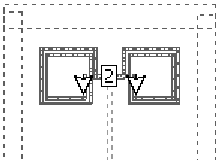
Electric Field

Input Matching Inductors

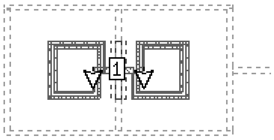
Cross Talk Suppression

Electro Magnetic Isolation

Standard Layout



Anti-Symmetric Layout



Anti-Symmetric Layout: ~ 20dB More Isolation

System Level & On-Chip Cross Talk Suppression

- Digital Spectral Content Far From RF
- VCO Electromagnetically Isolated and Resistant to LF Pulling
- LNA Input Narrow Band and Electromagnetically Isolated
- Layout/Floor Plan Optimized with Electromagnetic Solver

Electrostatic Cross Talk

Shielded Scalar Potential:

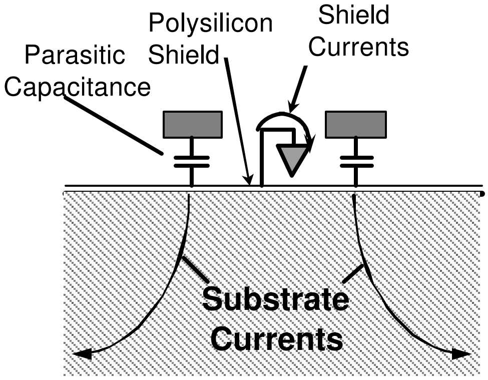
$$\phi_i \sim q\int \frac{1}{\left|\bar{r}_i - \bar{r}_j\right|} - \frac{1}{\left|\bar{r}_i - \bar{r}_j - 2z\hat{z}\right|} dl_j$$

- Frequency Independent
- Decreases Rapidly for $\left|r_i - r_j\right| > 2z \sim 10\mu m$

Shielding Requirements:

$R_{Shield} << R_{Substrate}$ with
$C_{parasitic} \times [R_{Shield} || R_{Substrate}] << (2\pi f)^{-1}$

$$R_{Substrate} \sim \frac{\rho_{Substrate}}{4\pi} \int_{\sqrt{A/4\pi}}^{\infty} \frac{1}{r^2} dr$$



Parasitic Currents are Shunted to Ground Through Low Loss Substrate Shielding
➲Improves Q
➲Greatly Reduces Cross Talk

Conclusion

- MBOA UWB Was Developed for a High Performance CMOS Implementation.
- VCO Core Requirements & Many RX/TX Requirements are More Relaxed Than Other Wireless Standards.
- LO Spurious Requirements for MBOA UWB and Base Band Bandwidth are the Primary Design Challenges
- MBOA UWB Was Developed for a Direct Migration to Full, Low-Cost System on a Chip