CMOS for Ultra Wideband and 60 GHz Communications

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The lower UWB bands have use restrictions, but FCC requirements will allow a wide variety of new applications.

The 57-64 GHz band can transmit up to .5 Watt with little else constrained – it could be used for a “high power” UWB.
Let's Start with UWB – A different regime...

Usual goal

Energy Limited

Bandwidth Limited

Low signal to noise ratio
Bandwidth inefficient

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Signaling Approaches

Sinusoidal, Narrowband

Impulse, Ultra-Wideband
FCC Emissions Limit for Indoor Systems

Allowed emissions from a PC

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Two Standards (Application Areas)
Evolving – First one is 802.15.3a

High Speed, Inexpensive Short Range Communications (3.1-10.6 GHz)

» FCC limit of -41dBm/Mhz at 10 feet severely limits range
   – Even using all 7.5 GHz of bandwidth the maximum power that can be transmitted is equivalent to having -2dBm (.6 mW) from an isotropic radiator (EIRP)
   – For short range communications this may be OK – e.g. line of sight from 10 feet for connecting a camcorder to a set-top box, “wireless Firewire”

» Advantage is that it should be less expensive and lower power than a WLAN solution (since 802.11a > 100 Mbits/sec for short range) – goal is to be the same as Bluetooth
High rate - 802.15.3a (proposals)

- Bit rate should be at least
  - 110 Mb/s at 10 meters
  - 200 Mb/s at 4 meters
  - >480 Mb/s at ?

- Power consumption
  - <110 mW for 110 Mb/s
  - < 250 mW for 200 Mb/s
Two Approaches

- Using conventional frequency domain techniques in 500 MHz sub-bands – which are further subdivided using OFDM

- Impulse Radios – a “time domain” approach
Frequency domain approach: OFDM with Freq hopping (TI, Intel)

- OFDM with Viterbi – basically a wideband 802.11a
  - 25 times more bandwidth than 802.11a
  - QPSK sub-channel modulation (3-4 bit A/D’s at > 1 GHz)

- Fast frequency hopping for multi-access and interference avoidance
  - In the OFDM guard interval over 1.5 GHz (TI proposal)
  - More than 100 times faster hopping than Bluetooth
  - Over 20 times more bandwidth than Bluetooth
  - Too fast for digital synthesis so needs to be an analog implementation
Time Domain Approach: Impulse Radio

(From Bob Scholtz – USC Ultralab)
Impulse Based Signaling

Biphase signalling

- Basically pulsed rate data transmission – sort of optical fiber without the fiber…
- Key design problem, as in wireline transmission, is time synchronization
- New problem is very large ISI from multipath and low signal to noise ratios

Totally new kind of radio – unknown implementation requirements

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Observation

Most probable strategy for UWB to make an impact in high rate at much lower power and cost than existing techniques is to use a pulse based approach.

Hard to understand that by scaling up conventional techniques by an order of magnitude that power and cost will reduce by an order of magnitude???
Second Application Area – 802.15.4a

Low Data Rate, Short Range Communications with Locationing (< 960 MHz)

» Round trip time for pulse provides range information – multiple range estimates provides location

» Used for asset tracking – a sophisticated RFID tag that provides location

» Can be used to track people (children, firemen in buildings)

» Sensor networks
Locationing and Imaging Applications

- Used for asset tracking – a sophisticated RFID tag that provides location
- Can be used to track people (children, firemen in buildings)
- Sensor networks (HVAC)
- Imaging behind walls
- Motion tracking
Location and Imaging (< 1 GHz)

- Transmit short discrete pulses instead of modulating code onto carrier signal
  - Pulses last ~1-2 ns
  - Resolution of inches

- UWB provides
  - Indoor locationing measurements
  - Relative location
  - Insensitivity to multipath
  - Material penetration (0-1 GHz band)
Locationing and Imaging (< 1GHz)

- **Advantages**
  - Unique capability of UWB
  - Mostly digital implementation with low performance analog
  - Standards not as critical

- **Disadvantages**
  - Markets not defined (but Microsoft has defined a standard and 802.15.4a is starting up)
  - Unknown architectures
For UWB to be Disruptive

Exploit locationing and imaging capability

Or

High rate communications using a digital pulse based system
What about the IEEE/industry standards process?

- It is moving very fast to come up with a standard that is probably unimplementable (at least at low cost and power)
- Their history has been less than stellar
  - Zigbee (a very primitive approach, but early)
  - Home RF (hear about that any more?)
  - Bluetooth (way too complicated)

*Will UWB be next on this list?*
Example design: UWB CMOS Transceiver Chip

A single chip CMOS UWB transceiver at power levels on the order of a few milliwatts for locationing and tracking applications

» Flexible design for a wide range of data rates to investigate UWB transmission characteristics

» For low rate applications, reception at below thermal noise levels

» Develop limits of locationing accuracy

Being Implemented by PhD students Ian O’Donnell, Mike Chen, Stanley Wang
### UWB Integrated Transceiver Project

**Targeting Sensor Network Application**

**Specifications:**
- 100kbps over 10m with $10^{-3}$ BER
- 1mW total (TX+RX) power consumption
- 0-1GHz bandwidth

**All-CMOS Integrated UWB Transceiver**

**Aggressive Low-Power Design**
- “Mostly-Digital” approach, simplify analog front-end
- Provide Flexible Platform for Further Research

http://bwrc.eecs.berkeley.edu/Research/UWB
CMOS Analog Frontend
Transceiver Analog Front-End

Focus:
- Low voltage, low power CMOS circuit design with minimum external components
- Accurate, flexible, controllable pulse reception window
- Antenna/circuit co-design

Status:
Design Nearly Complete
Some Layout Done
UWB Antenna

- UWB antenna for indoor wireless applications
  - Broadband
  - Omni-directional
  - Small size
- Small size -- Narrowband
  - Antenna Q \( \sim \frac{\lambda^3}{\text{antenna size}} \)
  - Almost impossible to have 50 ohm radiation resistance over the whole bandwidth
- Small size -- Omni-directional
  - Phase difference on the antenna is small
Need co-design of Antenna and LNA/pulser

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Small Antenna Modeling

Take small Loop Antenna as an example

- E-fields in all directions are with almost the same waveform
- Only one resistor in our model
- By superposition, waveform across Rrad is equal to the far-zone E-fields
- Can estimate radiated E-field in SPICE
Parallel Sampling of Window of Time

Three Clocking Timescales:

- $T_{\text{SAMPLE}}$ (<ns)
- $T_{\text{WINDOW}}$ (~10’s ns)
- $T_{\text{PULSE\_REP}}$ (~100’s ns)
UWB Sampling and A/D

Input signal from amplifier

Buffers & Comparators

Samplers

1 1 0 1 0

Buffers & Comparators

Samplers

Transient start signal at \( T_0 \)

\( T_0 + T_{\text{sample}} \)

\( T_0 + 2T_{\text{sample}} \)

\( T_0 + 3T_{\text{sample}} \)

\( T_{\text{symbol}} \)

\( T_{\text{chip}} \)

\( T_{\text{chip}} \)}
Oscillator Accuracy (Matching)

Drift < 25ps Over Symbol

Crystal

Precision Component

TCXO

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The received signal is dominated by interference (wide open front-end from .1-1GHz)

Interferers:
- TV: 174-216MHz, 470-806MHz
- ISM: 902-928MHz, 2.4-2.4835GHz, 5.725-5.850GHz
- Cell phone: 824-849MHz, 870-893MHz
- Pager: 929-930MHz
- PCS: 1.85-1.99GHz
- Microwave Oven: 2.45GHz
Interference model determines A/D bitwidth

1-bit A/D Is Adequate
Interference Dominates
(Noise Figure Not Critical)
UWB Receive Baseband
Specs for Baseband

- Pulse Repetition Rate: 100kHz to 100 MHz
- Receive pulse match filter length \((N_{\text{ripple}} = N_{\text{pulse}} + N_{\text{spread}})\): < 64ns (128 samples)
- Sampling rate: 2 GHz
- PN length ranges from 1 to 1024 chips which correlates the output of the match filter
Processing gain – How much is needed?

Let's take as an input Echip/No of -11dB.
(1) Acquisition mode, ~400 chips is enough for suppressing the acquisition error below 1e-3.

<table>
<thead>
<tr>
<th>Chips</th>
<th>Prob. of Miss lock</th>
<th>Prob. of False alarm</th>
<th>Eb/No @ output</th>
</tr>
</thead>
<tbody>
<tr>
<td>300</td>
<td>0.0037</td>
<td>0.0041</td>
<td>14.4245 dB</td>
</tr>
<tr>
<td>400</td>
<td>0.86e-3</td>
<td>1.3e-3</td>
<td>15.6643 dB</td>
</tr>
</tbody>
</table>

(2) Data recovery mode, ~100 chips could achieve an uncoded bit error rate of 1e-3.

<table>
<thead>
<tr>
<th>Chips</th>
<th>BER</th>
<th>BER</th>
<th>BER</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>0.1663</td>
<td>100</td>
<td>200</td>
</tr>
<tr>
<td>100</td>
<td>1.1e-3</td>
<td></td>
<td></td>
</tr>
<tr>
<td>200</td>
<td>2e-5</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
RX: Digital Backend

- Acquisition: 128-Tap Matched Filter x 128 x 11 PN Phases
- Synchronization: Early/On-Time/Late PN Phases
Chip design

Process: 0.13um (ST Microelectronics)
Size: 3.3mm x 3.3mm; 245,000 Standard Cells
Status: In Place-and-Route Stage
## Area and power estimation

<table>
<thead>
<tr>
<th>Block</th>
<th>Area (mm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pulse Matched Filter (256 inputs, 128 outputs)</td>
<td>4.951512</td>
</tr>
<tr>
<td>PN Generator (max 1024 chips)</td>
<td>0.232100</td>
</tr>
<tr>
<td>Peak detector Block (128 inputs)</td>
<td>2.880800</td>
</tr>
<tr>
<td>Data Recovery (Track 3 samples)</td>
<td>0.068600</td>
</tr>
<tr>
<td>Control Logic (state flow)</td>
<td>&lt;0.001</td>
</tr>
<tr>
<td>PN correlators (contain 128 correlators)</td>
<td>2.469600</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>10.614000</strong></td>
</tr>
</tbody>
</table>
Pulse Transmitter

- Major advantage of impulse radios is the simplicity of the transmit chain – almost completely digital except for the final antenna driver...
- No need for linearity, just fast transitions
UWB Pulser/Antenna Co-design

- Large Current Radiator (LCR) as the UWB antenna
- Notch filter for FCC radiation mask

- H-bridge pulser to drive inductive load
- Flexible driving force by parallel structure
H-bridge Simulation Results

• Doublet is generated
• Pulse-width ~ 1nS
• Smoothed after low-pass filtering at the receiver

• Meet FCC’s rule
• EIRP will increase when PRF(Pulse Repetition Freq) increases

<table>
<thead>
<tr>
<th>EIRP (dBm/MHz)</th>
<th>Frequency (GHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>VRrad</td>
<td>Vfiltered</td>
</tr>
</tbody>
</table>

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Driver Circuit Layout

- STMicroelectronics 0.13um CMOS process
- Chip area: 0.49mm²
- 1.2V Vdd
- 2 drivers with enables -- Can either drive a monopole or dipole
- Each driver with 16 levels of driving capabilities
Status

- Chip tape out by summer in .13 micron technology
- Stay tuned at http://bwrc.eecs.berkeley.edu/Research/UWB/
19 GHz of Unlicensed Bandwidth!

- The 57-64 GHz band can transmit up to .5 Watt with little else constrained.
- How can we use these new resources?

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60 GHz Research Team

Gary Baldwin, Bob Brodersen, Ali Niknejad

CMOS:
- Chinh Doan: LNA/PA, T-Lines
- Brian Limketkai: VCO, Phase Noise
- Sohrab Emami: Actives, Mixer
- Hanching Fuh: PA
- Eddie Ng: Freq. Dividers
- Sayf Alalusi: Antenna Array/FE Filters

SiGe:
- Eddie Ng: LNA, Freq Dividers
- Mounir Bohsali: Mixers
- Patrick McElwee: PA
60 GHz Unlicensed Allocation (1998)

- **Japan**:
  - Oxygen absorption band
  - Wireless LAN
  - Test
  - Radar
  - Unlicensed Pt-to-Pt
  - Mobile ICBN
  - Road Info.

- **Europe**:
  - Wireless LAN

- **U.S.**:
  - Unlicensed
  - ISM

*Frequency GHz*

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Why Isn’t 60 GHz in Widespread Use?

- Oxygen absorbs RF energy at 60 GHz
- The technology to process signals at 60 GHz is very expensive
- The signal radiated is attenuated by the small antenna size – i.e. the power received at 60 Ghz from a half wave dipole is 20 dB less than at 5GHz.
Oxygen attenuation

The oxygen attenuation is about 15 dB/km, so for most of the applications this is not a significant component of loss.

For long range outdoor links, worst case rain conditions are actually a bigger issue.
The technology to process signals at 60 GHz is very expensive.

Yes, it has been expensive, but can we do it in standard CMOS?
Importance of Modeling at 60 GHz

- Transistors
  - Compact model not verified near $f_{\text{max}}/f_t$
  - Table-based model lacks flexibility
  - All parasitics are more critical
  - Highly layout dependent

- Passives
  - Need accurate reactances
  - Loss not negligible
  - Scalable models desired
  - Substrate effects must be carefully modeled
60 GHz Test Chips

- **December 2001 CMOS**
  - SOLT De-embedding
  - NMOS transistors
  - 0.15µm/0.13µm to 5.0µm/5.0µm
  - Long high-speed multi-finger NMOS devices
  - Diodes
  - Inductors

- **February 2002 CMOS**
  - SOLT De-embedding
  - High-speed PMOS devices
  - DC measurement structures for NMOS/PMOS
  - Coplanar transmission lines
  - T-line impedance matching networks
  - Low-noise amplifier
  - Oscillator

- **July 2002 SiGe**
  - 30 GHz to 5 GHz Mixer
  - 55 GHz Oscillator
  - 28 GHz LNA
  - 60 GHz 50Ω Output Buffer
  - Flip-flop divider, Injection-Locked Divider
  - Caps, Inds, BJTs, T-lines

- **September 2002 CMOS**
  - TRL de-embedding
  - Transformers, Inductors
  - Power transistors
  - Finger capacitors
  - Optimized NMOS transistors
  - Coplanar and Microstrip Lines

- **December 2002 CMOS**
  - Coplanar and Microstrip Lines
  - Bypass and coupling caps
  - Distributed Filter
  - Amplifiers
  - Oscillators

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Active CMOS Device CMOS Modeling

The real $f_{max}$ is the important number to look at.

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130 nm CMOS device

6-8 dB gain at 60 GHz!

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Modern CMOS Process - Modeling Challenges

- Lossy substrate (~10 Ω-cm)
- 6–8 metal levels (copper)
- Chemical mechanical planarization (20-80% metal density)
  - Slots required in metal lines
  - Fill metal in empty areas
- Multiple dielectric layers

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CMOS Model at Microwave Frequencies

\[ f_t \approx \frac{g_m}{2\pi C_{gg}} \]

\[ f_{\text{max}} \approx \frac{f_t}{2 \sqrt{R_g (g_mC_{gd}/C_{gg}) + (R_g + r_{ch} + R_s) g_{ds}}} \]
Key design parameter is gate width...

- If the device is designed correctly and enough current is used, with .13 micron $f_{\text{max}}$ can easily surpass 100 GHz
- Phillips reported 150 GHz $f_{\text{max}}$ in .18 micron technology

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Example Issue: CPW vs. Microstrip

- Small coupling to substrate
- High-$Z_0$ lines
- $Q$ of inductive line $\sim 20$
- $Q$ of capacitive line $\sim 15$
- Metal underpass to suppress odd-mode propagation

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- Negligible coupling to substrate
- Low-$Z_0$ lines
- $Q$ of inductive line $\sim 12$
- $Q$ of capacitive line $\sim 25$
CPW Filters

- Generate electrical models
- Optimize over line lengths in ADS
- Layout, import, and simulate in HFSS
Now that we know CMOS can do it: The open question is…

- What is the best way to use 5 GHz of bandwidth to implement a high datarate link?
  - Extremely inefficient modulation but at a very high rate? (say 2 GHz of bandwidth for 1 Gigabit/sec) – requires analog processing
  - Or use an efficient modulation, so lower bandwidth. e.g. OFDM – but needs digital processing and a fast A/D
Use 5 GHz as an IF frequency
60 GHz Antenna Array Receiver

- Antenna elements are small enough to allow direct integration into package or large numbers in an array
- Spatial diversity offers resilience to multi-path fading
- Beam forming provides high antenna gain
- Higher the frequency the better!
Conclusions

- UWB radios provide a new way to utilize the spectrum and there is a wide variety of unique applications of this technology. However, it takes a completely new kind of radio design…

- At the present state of technology CMOS is able to exploit the unlicensed 60 GHz band. However, what kinds of systems should be built with all this bandwidth?

There is 19 GHz of bandwidth ready to be used for those willing to try something new!