INTRODUCTION TO RF CMOS IC DESIGN FOR WIRELESS APPLICATIONS

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Outline

• Introduction
• Wireless Standards and migration to 3G
• CMOS technology for RF
• CMOS radio Challenges
• Bluetooth as an example for a wireless system
• Radio Architectures
• CMOS Circuit Design
• Conclusions
An electronic postcard and a video conference display are just two of the multimedia possibilities illustrated by a pair of computer-generated concept cell phones.

A triple-band GSM phone capable of working in the 900-, 1800-, and 1900-MHz bands. It is Bluetooth enabled, which means among other things that it can connect to the headset without needing wires.
Tremendous growth in Wireless Applications
Demands expertise from different areas (more integration of people)
- Many Wireless Applications and Gadgets (Multi-dimensional)
- More Functional Integration in 3G
**Wireless Standards and Migration**

1G                               2G                         3G

<table>
<thead>
<tr>
<th>Europe</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>NMTS</td>
<td>Standardize</td>
<td>GSM</td>
<td>Higher Data rates</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>TACS</td>
<td>&quot;Roaming&quot;</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>German System C</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

| N. America |               |               |               |               |               |               |
| AMPS       | Capacity      | IS-54, IS-136 | Higher Data rates |               |               |               |
|            | "lack of spectrum" | IS-95 |               |               |               |               |
|            |               | PCS1900       |               |               |               |               |

| Japan |               |               |               | PDC           | Capacity      | Higher Data rates |
|       | Capacity      |               |               |               | "lack of spectrum" |               |

- **Push to 3G caused by:**
  1- Demand for Higher Data Rates
  2- Capacity
  3- Global Roaming
3G Cellular Standards and Harmonization

- 3GPP for the similar ETSI and ARIB WCDMA proposals (TDD)
- 3GPP2 for CDMA2000 and similar WCDMA proposals (FDD)
Third Generation Cell Phones

3G demands

- More Capacity
- Higher data rates
- More Functions

- Backward Compatibility
- Global Roaming

- Lower Cost
- Small Size
- Long Battery lifetime

WCDMA (5MHz)

Multi-Standard (Programmable)

Low Power CMOS solution

Programmable CMOS Integrated Wireless Transceivers

- Multi-dimensional applications and Multi-standard support
## Summary of Cellular Phone, Cordless Phone, LAN and PCS Standards

<table>
<thead>
<tr>
<th>Wireless Standard</th>
<th>Access Scheme</th>
<th>Frequency Spectrum (MHz)</th>
<th>Channel Spacing</th>
<th>Frequency Accuracy</th>
<th>Modulation Technique</th>
<th>Data Rate</th>
<th>Peak Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>AMPS</td>
<td>FDD</td>
<td>824–849(Tx) 869–894(Rx)</td>
<td>30kHz</td>
<td>2.5ppm</td>
<td>FM</td>
<td>N/A</td>
<td>3W</td>
</tr>
<tr>
<td>DCS-1800</td>
<td>TDMA</td>
<td>1710–1785(Tx) 1805–1850(Rx)</td>
<td>200kHz</td>
<td>90Hz</td>
<td>GMSK</td>
<td>270.8kbs</td>
<td>0.8, 5.8W</td>
</tr>
<tr>
<td>GSM</td>
<td>TDMA/FDMA/FDD</td>
<td>890–915(Tx) 935–960(Rx) 890–915(Tx) 935–960(Rx)</td>
<td>200kHz</td>
<td>90Hz</td>
<td>GMSK</td>
<td>270.8kbs</td>
<td>0.8, 5.8W</td>
</tr>
<tr>
<td>EGSM</td>
<td>TDMA</td>
<td>880–915(Tx) 925–960(Rx) 880–915(Tx) 925–960(Rx)</td>
<td>200kHz</td>
<td>90Hz</td>
<td>GMSK</td>
<td>270.8kbs</td>
<td>0.8, 5.8W</td>
</tr>
<tr>
<td>PCS-1900</td>
<td>TDMA</td>
<td>1880–1910(Tx) 1930–1930(Rx)</td>
<td>200kHz</td>
<td>90Hz</td>
<td>GMSK</td>
<td>270.8kbs</td>
<td>0.8, 5.8W</td>
</tr>
<tr>
<td>IS-54 (IS-136) (D-AMPS)</td>
<td>TDMA/FDD</td>
<td>824–849(Tx) 869–894(Rx) 824–849(Tx) 869–894(Rx)</td>
<td>30kHz</td>
<td>200Hz</td>
<td>π/4–QPSK</td>
<td>48kbs</td>
<td>0.8, 2.3W</td>
</tr>
<tr>
<td>DECT</td>
<td>TDMA/TDD</td>
<td>1881–1897</td>
<td>1.728MHz</td>
<td>50kHz</td>
<td>GFSK</td>
<td>1.152Mbs</td>
<td>250mW</td>
</tr>
<tr>
<td>802.11 (DSSS)</td>
<td>CDMA</td>
<td>2400–2483</td>
<td>N/A</td>
<td>25ppm</td>
<td>QPSK</td>
<td>1.211Mbs</td>
<td>1W</td>
</tr>
<tr>
<td>WCDMA (UMTS)</td>
<td>CDMA</td>
<td>1920–1980(Tx) 2110–2170(Rx)</td>
<td>5MHz</td>
<td>+/- 0.1ppm</td>
<td>QPSK</td>
<td>3.84Mbs</td>
<td>0.125, 0.25, 0.5, 2W</td>
</tr>
<tr>
<td>IS-95</td>
<td>CDMA</td>
<td>824-849(Tx) 869-894(Rx) 824-849(Tx) 869-894(Rx)</td>
<td>1.25MHz</td>
<td>N/A</td>
<td>OQPSK</td>
<td>1.2288Mbs</td>
<td>N/A</td>
</tr>
<tr>
<td>Bluetooth (802.11FH)</td>
<td>CDMA/FH</td>
<td>2400-2483</td>
<td>1MHz</td>
<td>20ppm</td>
<td>GFSK</td>
<td>1Mbs</td>
<td>0-20dBm</td>
</tr>
</tbody>
</table>
A single handset to support all wireless environments
Frequencies: A limited natural resource

Companies pay billions for licenses to use these bands!
## Short-Range Wireless Standards

<table>
<thead>
<tr>
<th>Standards</th>
<th>Frequency Range</th>
<th>Multiple Access</th>
<th>Modulation</th>
<th>Data Rate</th>
</tr>
</thead>
<tbody>
<tr>
<td>IEEE 802.11 WLAN Standards</td>
<td>2.4GHz DSSS</td>
<td>2.4GHz</td>
<td>DSSS</td>
<td>1Mbps 2Mbps</td>
</tr>
<tr>
<td></td>
<td>2.4GHz FHSS</td>
<td>2.4GHz</td>
<td>FHSS</td>
<td>1Mbps 2Mbps</td>
</tr>
<tr>
<td></td>
<td>2.4GHz DSSS</td>
<td>2.4GHz</td>
<td>DSSS</td>
<td>5.5Mbps 11Mbps</td>
</tr>
<tr>
<td>High Data Rate</td>
<td>2.4GHz FHSS</td>
<td>2.4GHz</td>
<td>CCK</td>
<td>1Mbps 2Mbps</td>
</tr>
<tr>
<td>5GHz OFDM</td>
<td>5.250GHz</td>
<td>5.775GHz</td>
<td>OFDM</td>
<td>6,9,12,18</td>
</tr>
<tr>
<td></td>
<td>5.250GHz</td>
<td>5.600GHz</td>
<td>OFDM</td>
<td>24,36,48,54</td>
</tr>
<tr>
<td>HIPERLAN/2</td>
<td>5.250GHz</td>
<td>5.600GHz</td>
<td>OFDM</td>
<td>6,9,12,18</td>
</tr>
<tr>
<td></td>
<td>16/64 QAM</td>
<td>BPSK/QPSK</td>
<td></td>
<td>27,36,54Mbps</td>
</tr>
<tr>
<td>Bluetooth™ Spec. 2.0 (5MHz)</td>
<td>2.4GHz</td>
<td>2.4GHz</td>
<td>2GFSK</td>
<td>1Mbps 2Mbps</td>
</tr>
<tr>
<td></td>
<td>2.4GHz</td>
<td>2.4GHz</td>
<td>2GFSK</td>
<td>5Mbps 10Mbps</td>
</tr>
</tbody>
</table>
# 2.4GHz Standards

<table>
<thead>
<tr>
<th>IEEE 802.11 DSSS</th>
<th>IEEE 802.11 FHSS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• CDMA, 1-2Mbps</td>
<td>• CDMA, 1-2Mbps</td>
</tr>
<tr>
<td>• DBPSK, DQPSK</td>
<td>• 2GFSK, 4GFSK</td>
</tr>
<tr>
<td>• -80dBm sensitivity</td>
<td>• -80dBm/-75dBm sensitivity</td>
</tr>
<tr>
<td>• 11bit Barker Code</td>
<td>• Simple demodulator</td>
</tr>
<tr>
<td>• Date rate can be increased.(HR/DSSS)</td>
<td>• good immunity</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>IEEE 802.11 FHSS</th>
<th>Spec 1.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>• 1-2Mbps, 2-4GFSK</td>
<td>• 1-2Mbps, 2-4GFSK</td>
</tr>
<tr>
<td>• 1MHz BW</td>
<td>• 1MHz BW</td>
</tr>
<tr>
<td>• -80/-75dBm sensitivity</td>
<td>• -80/-70dBm sensitivity</td>
</tr>
<tr>
<td>• hopping rate by the regulatory authorities</td>
<td>• 50hops/s</td>
</tr>
<tr>
<td>• 1Mbps, 2GFSK</td>
<td>• Mainly for home networking</td>
</tr>
<tr>
<td>• 1MHz BW</td>
<td></td>
</tr>
<tr>
<td>• -70dBm sensitivity</td>
<td></td>
</tr>
<tr>
<td>• 1600hops/s</td>
<td></td>
</tr>
<tr>
<td>• smaller size, lower cost</td>
<td></td>
</tr>
</tbody>
</table>
Multistandard operation

- WLAN 5G (IEEE802.11a, HIPERLAN2), WLAN 2.4G (IEEE802.11b, IEEE802.11g), WCDMA
- Reconfigurable hardware to choose from above
- Separate Bluetooth transceiver
- Coordination required if Bluetooth and 2.4G band operate simultaneously
Multistandard operation

- WLAN 5G (IEEE802.11a, HIPERLAN2)
- WLAN 2.4G (IEEE802.11b, IEEE802.11g)
- WCDMA
- Separate Bluetooth transceiver
- Reconfigurable radio to choose one of the standards
Integration in Wireless Systems

**Objective:**
- Low Cost/Low Power/High volume implementation of radio functions that are formally implemented using bulky, expensive and power hungry hybrid components.
- Multi-mode/Multi-band operation
- Service Integration

**Optimum Technology Choice**
CMOS technology for RF
CMOS Technology RF Capabilities

<table>
<thead>
<tr>
<th>Year Technology node</th>
<th>1999 180nm</th>
<th>2000</th>
<th>2001</th>
<th>2002 130nm</th>
<th>2003</th>
<th>2004</th>
<th>2005 100nm</th>
<th>2008 70nm</th>
<th>2011 50nm</th>
<th>2014 35nm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Min. Digital Supply (V)</td>
<td>1.8-1.5</td>
<td>1.5-1.2</td>
<td>1.2-0.9</td>
<td>0.9-0.6</td>
<td>0.6-0.5</td>
<td>0.5-0.3</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Min. Analog Supply (V)</td>
<td>3.3-2.5</td>
<td>2.5-1.8</td>
<td>1.8-1.5</td>
<td>1.5</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>RF Frequency (GHz)</td>
<td>0.9-2.5</td>
<td>0.9-10</td>
<td>0.9-100</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>f max (GHz)</td>
<td>25</td>
<td>28</td>
<td>32</td>
<td>35</td>
<td>40</td>
<td>45</td>
<td>50</td>
<td>60</td>
<td>150</td>
<td>175</td>
</tr>
<tr>
<td>f t (GHz)</td>
<td>20</td>
<td>20</td>
<td>25</td>
<td>30</td>
<td>30</td>
<td>35</td>
<td>40</td>
<td>50</td>
<td>120</td>
<td>140</td>
</tr>
<tr>
<td>Noise Figure (dB)</td>
<td>1.5</td>
<td>1.2</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td>&lt;1</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

*CMOS is a good candidate for RF Circuits.*

*Integration, and packaging rather than the technology are the limiting factors*

*International Technology Roadmap for semiconductor, 1999 edition*
Smaller transistors and faster CMOS

\[ F_T \approx \frac{1}{L_G} \]

\[ F_T = \frac{g_m}{2\pi C_{IN}} \]

\[ V_{DD(max)} \propto T_{ox} \propto L_G \]

\[ F_T \approx \frac{1}{L_G^2} \]

Ft is no problem in CMOS
# CMOS Vs Bipolar

<table>
<thead>
<tr>
<th>CMOS</th>
<th>Bipolar</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Symmetric behaviour</td>
<td>• Higher $gm$ for same bias</td>
</tr>
<tr>
<td>• Better Linearity (higher signal swing)</td>
<td>• High $f_t$</td>
</tr>
<tr>
<td>• Higher $f_t$ at submicron feature size</td>
<td>• Low thermal and 1/f noise, but produces input current noise</td>
</tr>
<tr>
<td>• Better scaling properties</td>
<td>• Lower DC offset</td>
</tr>
<tr>
<td>• Low static power (no DC gate current)</td>
<td>• No body effect</td>
</tr>
<tr>
<td></td>
<td>• Lower overdrive ($V_{CE sat}$)</td>
</tr>
</tbody>
</table>
CMOS Interconnect Reverse Scaling

- Top metal layers – larger pitches – thicker lines: for power handling and reduce losses
- Interconnect dielectric thickness is twice the metal thickness: minimize interlevel shorts and minimize capacitance
- Hence top metal layers are far from the silicon substrate thus minimizing substrate losses
CMOS Interconnect Reverse Scaling

- Distance between top metal layer and silicon substrate currently about 1.5µm per metal layer
- 10 metal layer technology by the end of the decade

* “Exploiting CMOS reverse interconnect scaling in multigigahertz amplifier and oscillator design”, B.Kleveland, C.H.Diaz et al., JSSC, Oct 2001
CMOS Interconnect Reverse Scaling

- This feature allows use of
  - Coplanar transmission lines using top metals
  - Distributed amplifier design
  - Distributed Oscillator design
  - can use CMOS for > 10GHz operation !!!
Passives

• Inductors
  technology advances result in top metal layers that thicker (low resistance) and further away from the silicon substrate (lower substrate losses)

• Capacitors
  metal-metal capacitors have better performance than poly-poly capacitors and have less parasitic capacitance to substrate

• Varactors
  Capacitance between the gate and the bulk can be made used of to achieve tunable capacitance
Inductors

• Top metal layers provide low loss
• moderate Q values can be achieved
• provides gain while consuming minimum voltage headroom
Inductors

- Large inductor values possible with multi-layer inductors in modern processes due to mutual coupling
- Interlayer capacitance reduced by using alternate metal layers
- Advanced CMOS processes using Cu technology can achieve Q values up to 20
- Same concept can be used to build on-chip transformers
Inductor model
Capacitors

- Capacitance between two metal layers
- Low resistance metal layers – reduced loss
RF capacitor model
Varactors

- Variable capacitance between gate and bulk connection
- Typically used to achieve wide tuning range in VCO’s
RF Layout Techniques

- RF and analog layout completely different from digital layout.
- Digital layouts focus on minimizing area. They use standard cells with emphasis on minimizing the interconnect area.
- RF and analog layouts concerned with matching accuracy and noise immunity rather than minimizing area.
- Layout involves optimizing individual transistor layouts.
- Techniques such as interdigitized layouts and common centroid layouts adopted to improve matching.
- Substrate taps and wells are used to improve noise immunity.
- Symmetry critical for differential paths.
Transistor Layout

• Multiple finger layout to minimize gate resistance
• Poly contacted at both ends to reduce gate resistance
• Dummy gates at the ends – to minimize effects of boundary dependent etching
• Interdigitized layouts where matching is critical
• Common centroid layout where matching is critical
• Guard bands surrounding the layout to reduce noise
• Transistors to be matched should have same orientation
Transistor Layout

Poor Layout  Equivalent circuit  Proper Layout
Transistor Layout

Higher gate resistance

Reduced gate resistance

Gate folds used with relatively wide devices
Resistor Layout

\[ R = 2R_{\text{contact}} + (W/L)R_{\text{sh}} \]
\[ R_{\text{sh}} \text{ – sheet resistance of poly} \]

- Contact resistance should be taken into account
- Dummy resistors at the ends – to minimize effects of boundary dependent etching
- Interdigitized layouts where resister matching is critical
- Guard bands surrounding the resistor layout to reduce noise
- Noise isolation by placing resistors over a well
- Matched resistors should have same orientation
Resistor Layout

Guard band

dummy
Capacitor Layout

\[ C_{\text{eff}} = A_{\text{eff}} \left( \varepsilon_0 \varepsilon_r / t_{\text{ox}} \right) \]

\[ A_{\text{eff}} = (W-2x)(L-2x) \approx WL - 2(W+L)x \]

- Effective area smaller than designed due to etching effects
- Since \( A_{\text{eff}} \) proportional to perimeter, keep area-perimeter ratio constant for better matching
- Dummy capacitors at the ends – to minimize effects of boundary dependent etching
- Common centroid layouts where matching is critical
- Guard bands surrounding the layout to reduce noise
- Noise isolation by placing capacitors over a well
Capacitor Layout

Guard band
Matching Issues

- Second order size effects minimized by constructing large devices based on unit cells
- Boundary conditions for all devices should be matched

Interdigitized

Common centroid
CMOS Circuit Techniques

Advanced considerably over the last decade

- Offset Cancellation (chopping), self calibration and trimming
- Low voltage switched capacitor, Sample-and-Hold
- Noise shaping ($\Sigma$-$\Delta$ technique)
- Class AB biasing and adaptive biasing
- Low voltage CMOS bandgaps
- Gain boosting
- Current division
- Statistical modeling and yield enhancement
Recent Examples of CMOS Transceivers

<table>
<thead>
<tr>
<th>Author</th>
<th>Architecture</th>
<th>Operating Band</th>
<th>Techn,</th>
<th>Power consumption</th>
</tr>
</thead>
<tbody>
<tr>
<td>J. Rudell et al. (ISSCC’97)</td>
<td>Wideband IF</td>
<td>DECT</td>
<td>0.6µm</td>
<td>198mW</td>
</tr>
<tr>
<td>Abidi et al. (ISSCC’97)</td>
<td>Zero_IF</td>
<td>ISM (800-900MHz)</td>
<td>1.0µm</td>
<td>177mW</td>
</tr>
<tr>
<td>M. Steyaert et al. (ISSCC’98)</td>
<td>Low-IF</td>
<td>DCS 1800</td>
<td>0.35µm</td>
<td>190mW</td>
</tr>
<tr>
<td>D. Schaeffer at al. (ISSCC’98)</td>
<td>Low-IF / Weaver</td>
<td>GPS</td>
<td>0.5µm</td>
<td>115mW</td>
</tr>
<tr>
<td>S. Wu at al. (ISSCC’98)</td>
<td>Weaver</td>
<td>GSM/DCS1800</td>
<td>0.6µm</td>
<td>72mW-75mW</td>
</tr>
<tr>
<td>D. McNalley (ISSCC99)</td>
<td>Zero-IF</td>
<td>ISM</td>
<td>0.6µm</td>
<td>450mW</td>
</tr>
<tr>
<td>Rasavi (JSSC, March 99)</td>
<td>Zero-IF</td>
<td>IEEE802.11 WLAN</td>
<td>0.6µm</td>
<td>80mW</td>
</tr>
<tr>
<td>HUT (ISSCC99)</td>
<td>Zero-IF</td>
<td>WCDMA @2GHz</td>
<td>0.35Bi0MOS</td>
<td>128mW</td>
</tr>
<tr>
<td>T. Melly et al. (CICC’00)</td>
<td>Zero_IF</td>
<td>WISNET @433MHz</td>
<td>0.5µm</td>
<td>100mW</td>
</tr>
</tbody>
</table>

Power amplifier is included.
CMOS Radio Challenges
CMOS radio challenges: circuits

- Good RF characterization and modeling is needed scalable models, passives, varactors
- Process technology with better substrate isolation
- Good modeling of substrate coupling effects, fully incorporated in the design process
- Better design kits for RF design
CMOS radio challenges: System

- Adopt system partitioning and mixed-signal strategy that lend themselves naturally to deep-submicron CMOS
- Maximize digital content
  
  requires high speed ADCs/DACs with good DR
- Incorporate antenna and front-end passives (RF filters, Balun, switches) very early in the design process
- Adopt pragmatic SOC and SOP (System On Package) strategies
CMOS radio challenges: System

- Good package models, fully incorporated in the design process
- Mapping strategy for system to block specifications that is amenable to CMOS design capability
- Complete understanding of the wireless system standards to optimize the system and avoid unnecessary over design
- Test verification, qualification and certification
Bluetooth™ Technology - Creating a world without wires

The BLUETOOTH trademarks are owned by Ericsson.
The Bluetooth SIG

- Bluetooth was introduced in 1998 by Ericsson, IBM, Intel, Nokia and Toshiba.
- Currently, more than 2000 adopters
- Bluetooth enabled devices have started to appear on the market (2001)
- Visit www.bluetooth.com

Visit www.bluetooth.com
Bluetooth chipsets in m units

Source: Cahner in stat
Bluetooth Technology

- Radio interface, operating in the 2.45 GHz "free" ISM band.
- Transmitting power less than 1 mW, typical operating range up to 10 meters (30 ft)
- Up to 730 kbit/s user data rates, both circuit and packet switched connection
- Very cost effective design! Integration into computer and phone chipsets is foreseen

NOKIA  ERICSSON  intel  IBM  TOSHIBA

- The initial creator group consists of these companies
Bluetooth Is . . .

- Major joint computing and telecomm industry initiative
- Revolutionary radio technology solution
  - Cable replacement, no line of sight restrictions
  - Open specification
- Perfect for mobile devices
  - Small, low power, and low cost
The technology

- Short range wireless technology
- Range up to 100 meters
- Operate at the unlicensed 2.4 ISM band
- Form small ad hoc networks called piconets
  - One master and 7 active slaves
- 1 Mb/s rate
- Robust and reliable transmission using frequency hop spectrum
- Support link level security including authentication and encryption
- Plug-and-play service discovery
- Supports legacy applications
- Enable cheap single chip implementation at low power
Bluetooth usage scenarios 1(3)

- Cable replacement
Bluetooth usage scenarios 2(3)

- Access point to networks
Bluetooth usage scenarios 3(3)

- Personal Area Networking building small local IP subnets
Protocol architecture

- Bluetooth core consists of Link Manager, Baseband and RF
- L2CAP, SDP, RFCOMM, BNE constitute the host stack
Bluetooth radio

- frequency hopping spread spectrum
  - $2.402 \text{ GHz} + k \text{ MHz}, \ k=0, \ldots, 78$
  - 1,600 hops per second
- GFSK modulation
  - 1 Mb/s symbol rate
- transmit power
  - 0 dbm (up to 20dbm with power control)
Baseband

- Form Piconets and Scatternets
- Use paging and inquiry procedures to synchronize transmission hop frequency and clock of the devices
- Implement channel access control based on Time Division Duplex (TDD)
- Support data and voice links
- Provide flow and error control
- Voice coding including the error resistant voice coding scheme CVSD (Continuous Variable Slope Delta)
Link Manager

- Establish links between devices
- Piconet management
- Security support including authentication, encryption and key management
- Link commands configuration and information
L2CAP

- Link Layer and Connection Adaptation Protocol (L2CAP)
- Adapt upper layers protocols over the Baseband
- Set up both connectionless and connection-oriented logical channels
- Provide quality of service as well as packet segmentation and reassembly
Other protocols

- **RFCOMM**
  - Emulate serial lines used by many legacy applications (e.g. dial-up networking, LAN access)
  - Provide reliable and in sequence delivery of byte stream
  - Support multiple concurrent connections to one or more BT devices

- **SDP (Service Discovery Protocol)**
  - Searches for services by service attributes
  - Supports service browsing

- **Bluetooth Network Encapsulation (BNE)**
  - Encapsulate Ethernet over the transport of IP
Profiles

- Main tool for interoperability between BT devices for a specific usage model (application and devices)
- Define the set of procedures (from different protocols) and the messages required
- Specify the order in which the procedures are combined
- Define the roles of involved devices
- Four general profiles have been specified
  - Generic Access profile
  - Serial Port Profile
  - Service Discovery Application Profile
  - Generic Object Exchange Profile
- A number of application profiles has been specified e.g. LAN Access, Dial-up Networking, File Transfer, Headset.
The profile tree

- Telephony Profiles
  - Cordless Telephony
  - Intercom

- Dial-up networking
- Headset
- Fax

- Networking Profiles
  - LAN Access
  - Synchronization
  - Object Push

- Object Exchange Profiles
  - File Transfer

- Generic Bluetooth Access Profiles
  - Generic Object Exchange
  - Service discovery application

- Transport Profiles
  - Serial Port

- Generic access
Embedded Bluetooth solutions

Courtesy of Spirea AB, Stockholm
The flexible solution strategy

Spirea Flexible Bluetooth Solutions

Radio HW
Vendor 3
Vendor 2
Vendor 1

SPIREA BlueTraC™

SPIREA BlueInt™

Baseband HW
Vendor 6
Vendor 5
Vendor 4

SPIREA BlueBase™

SPIREA BlueSoC™
(bb+radio)

SPIREA BlueAmp™
(100m range)

Courtesy of Spirea AB, Stockholm
Bluetooth HW

<table>
<thead>
<tr>
<th>Multiple chip alternatives</th>
<th>First generation</th>
<th>Second generation</th>
<th>Third generation</th>
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</thead>
<tbody>
<tr>
<td>Baseband 0.25 µm</td>
<td>FLASH</td>
<td>Baseband 0.25 µm</td>
<td>Baseband + ROM 0.15 µm</td>
</tr>
<tr>
<td>RF module RF 0.5 µm</td>
<td></td>
<td>RF module RF 0.25 µm</td>
<td>RF module RF 0.15 µm</td>
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</table>

<table>
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<tr>
<th>Single-chip alternatives</th>
<th></th>
<th></th>
<th>Single-chip module</th>
</tr>
</thead>
<tbody>
<tr>
<td>FLASH</td>
<td>RF + BB module RF+BB 0.25 µm</td>
<td>RF-BB 0.15 µm</td>
<td></td>
</tr>
</tbody>
</table>
Bluetooth radio

Ericsson Bipolar radio
- One fully tested unit - easy to use
- Radio IC, filters and baluns are matched together
- Ideal for embedded applications and applications requiring a flexible form factor

Smallest size
- RF IC flipchip mounted - No package
- Filter, impedance matched baluns and switch integrated into LTCC substrate

Lowest height
- Self shielding design!

Output power/receiver sensitivity
- Class 2 ("10m"), -70dBm at BER 0.1%
Modules

Ericsson Bluetooth™ Module

- Radio, Baseband and Flash memory
- Firmware: Supports all Bluetooth protocol layers up to HCI
- UART and USB interfaces for high speed data transfer rates
- PCM and USB interfaces for voice
- Low energy consumption
- Point to multi-point operation
- Built-in shield
- FCC and ETSI type approved
Bluetooth radio and baseband architectures

The Bluetooth transmitter upconverts the baseband information to the frequency-modulated carrier. Frequency hopping and bursting are performed at this level. Conversely, the Bluetooth receiver downconverts and demodulates the RF signal. The Bluetooth channels are each 1 MHz wide. Frequency hopping occurs over 79 channels.
Radio Architectures
Super Heterodyne Receivers

- Discrete IR and IF filters not amenable for Integration
- Channel selection done at IF
- Low dynamic range baseband circuits
- Multi-Standard programmability in IF stage is difficult to achieve
Integrated Receivers

- Eliminates the need for discrete IR and IF filters
- Signal + Blockers are translated to baseband
- Channel selection done at baseband
- High dynamic range baseband circuits required
- Multi-standard programmability in baseband circuits
Direct Conversion Receiver

- Digital servo loop implementation using DSP (for offset cancellation)
- Baseband Filter programmability for multi-standard support
- Digitally programmable variable gain amplifiers
WCDMA/GSM/DECT Multi-standard Receiver

- Zero-IF receiver architecture
- Multiple narrow-band LNAs are used to get the high gain and low noise figure with low power.
- I/Q Mixers, low-pass analog filters, analog-to-digital converters are shared for all the standards
- Advanced Offset cancellation algorithm is needed to solve the DC offset problem
WCDMA/GSM/DECT Multi-standard Receiver

- Single-pole-four-throw switch controlled by Standard-switching Signal. (MURATA Filter and Switch)
- Only one LNA of the three works to save power controlled by the Standard-switching signal
- Two I/Q mixers are shared by all.
FSK low-IF Receiver

- Bluetooth, HomeRF, IEEE 802.11b(FHSS)
- Image Rejection by Hartley Method
- Quadrature Detector for Demodulator
RF CMOS Circuit Design
LNA

- First stage in the receiver chain
  - sensitivity of the system
  - determines the overall NF of the system
- Input matching
- Provide enough gain to overcome the noise of subsequent stages (Sensitivity)
- Add as little noise as possible
- Accomodate a large dynamic range without distortion
LNA

Typical single ended CMOS LNA
LNA Design

Common Source

• Amplifying device must be large and biased at high current to reduce noise

• Large input device => large input capacitance thereby attenuating the input signal thus magnifying ‘noise’.

• Hence NF is minimized by proper choice of transistor size and bias current at the operating frequency of interest.

• Min. NF is achieved varies with bias current and device size

\[ NF_{\text{min}} \approx 1 + 2.3 \left( \frac{\omega}{\omega_T} \right) \]

optimum device width \( W_{\text{opt}} \approx \frac{1}{3 \omega L_s C_{\text{ox}} R_s} \)
LNA Design

- \( Z_{in} = \frac{gm \cdot C_{gs}}{L_s} + s(L_g + L_s) + \frac{1}{s \cdot C_{gs}} \)

  Input matched with proper choice of \( gm, C_{gs}, L_s \) and \( L_g \)

  Power constraints and minimum noise figure determine the transistor size and hence \( gm \) and \( C_{gs} \).

  Choose \( L_s \) to achieve 50 Ohm match

  Design \( L_g \) to tune out the additional capacitance at the operating frequency

- Gain depends on the parasitics of Q1 and load.

- Cascode device improves reverse isolation.

- Additional stage may be needed to drive a 50 Ohm load (heterodyne architectures).
LNA

Common Gate

- Input matching is simpler

\[ Z_{\text{in}} = \frac{1}{(g_{\text{m}} + sC_{\text{gs}})} \]

- Higher linearity.
- Better reverse isolation.
- However, higher NF due to limitations on the choice of \( g_{\text{m}} \).
Mixer

- Frequency translation by multiplying two signals

\[ \cos(\omega_c t) \cdot \cos(\omega_s t) = \cos(\omega_c + \omega_s)t + \cos(\omega_c - \omega_s)t \]

upconversion                     downconversion

- Is NOT Linear Time Invariant (LTI)
- LTI systems cannot produce spectral components that are not in the input
- To 'MIX', system has to be Non-Linear or Time Variant
- Important properties
  - Conversion Gain
  - Noise Figure – SSB vs DSB
  - Linearity
  - Port Isolation
Mixer

- 'Nonlinearity’ based Mixers provide frequency translation through indirect multiplication.

- Assuming the nonlinearity is characterized by,
  \[ V_{out} = \sum A_n (Vin)^n \]

If \( V_{in} = V_c \cos(\omega_c t) + V_s \cos(\omega_s t) \)

Second order nonlinearity would result in a cross modulation component,

\[ V_{out(\text{cross})} = A_2 V_c V_s [\cos(\omega_c - \omega_s)t + \cos(\omega_c + \omega_s)t ] \]
Mixer

- Gilbert multiplier based mixers
- Switching transistors => multiply by square wave
Basic Oscillator Theory

(a) feedback model    (b) negative resistance model
Oscillator Circuits

- **RC Oscillators**
  - easy to realise
  - low, medium frequency
  - poor phase noise performance

- **LC Oscillators**
  - high frequency
  - good phase noise performance
  - suited for RF wireless applications
Voltage Controlled Oscillators (VCO)

- Wireless applications require that oscillators be tunable by a control signal
- Control signal is usually in the form of a voltage
VCO Design Parameters

Voltage controlled oscillators design parameters

- Tuning Range
- Tuning linearity
- Output amplitude
- Output spectral purity (Phase Noise)
- Power Consumption
LC VCO Design

Basic LC VCO topology in CMOS technology

\[ f = \frac{1}{2\pi\sqrt{LC_L}} \]
Multi Band VCO

- Multi-band operation is accomplished by tuning LC VCO with two control lines, one for continuous tuning and the other for digital band selection. The continuous tuning is used for PLL control and channel select. The digital tuning is used for RF band selection using MOSFET varactors.

Examples:
1. A synthesizer for 900MHz/1800MHz GSM transceiver using wide-band IF double conversion architecture with a fixed IF of 300MHz. A multi-band VCO can be designed to operate in the bands of 1200MHz and 1500MHz. Fig. (a)
2. The VCO can be shared between 1800MHz frequency band (GSM, PCS, WCDMA) and the GPS band 1600MHz. Fig. (b)
A Dual-Mode Frequency Synthesizer for 3G

A fully integrated dual mode frequency synthesizer for GSM and WCDMA with maximum hardware sharing:

![Diagram of a Dual-Mode Frequency Synthesizer]
**A Dual-Mode Frequency Synthesizer for 3G (cont’)**

<table>
<thead>
<tr>
<th></th>
<th>Shared components</th>
<th>Non-shared components</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>VCO</td>
<td>Integer frequency divider</td>
</tr>
<tr>
<td><strong>GSM</strong></td>
<td>1580-1630MHz</td>
<td>Divided by 246-254</td>
</tr>
<tr>
<td></td>
<td></td>
<td>/2 output divider, /32 input divider, 2nd $\Delta\Sigma$ modulator</td>
</tr>
<tr>
<td><strong>WCDMA</strong></td>
<td>1785-1845MHz</td>
<td>Divided by 357-369</td>
</tr>
</tbody>
</table>

Frequency divider:
- Integer frequency divider for GSM
- Fractional frequency divider for WCDMA

Dual band VCO:
- NMOS accumulation mode varactor for band-to-band switching
- PN junction varactor for in-band tuning

Shared components:
- PFD, CP, integer frequency divider, loop filter, VCO, reference signal, 70% of total die area
Performance Specifications of Frequency synthesizers

- Frequency range
- Frequency resolution
- Lock time
- Spectral purity
  - phase noise
  - harmonics
  - spur
Power Amplifiers

Challenging because

- Most power hungry block in the transceiver
- discrete or hybrid implementation is favoured
- Large current in output device and matching network – packaging problem
- Parasitic effects introduce instability – Layout considerations
Power Amplifiers - classification

Classified according to
- biasing (A, B, AB, C)
- circuit topology (D, E, F, G, H, S)

Class A $\eta = 50\%$

Class B $\eta = 78.6\%$
Power Amplifiers – classification

Class E
- Switching power amplifier
- Can achieve $\eta=100\%$ (theoretical)
- Efficiency and output power can be optimized simultaneously
- The transistor operates as a switch
- It requires a transistor with large breakdown voltage

Class F
- Nonlinear amplifier + harmonic distortion
- The main idea is to use different termination impedance for different harmonics to make the drain voltage approach a square wave
- Efficiency between 85% to 88%
Power Amplifiers – Linearization

Mainly used in basestations

- Spectrally efficient modulation schemes to minimize spectral regrowth
- In multi-carrier systems, amplifiers should be linear to avoid cross-modulation
- Having both linear+efficient PA requires use of non-linear PA (high efficiency) and the application of linearization techniques
- Linearization techniques such as
  - Feedforward
  - Feedback
  - Envelope elimination and restoration
  - predistortion
RF Measurement Techniques
Example - Phase noise measurements

• Measurement at primary frequency of source is not possible (dynamic ranges of 160dB and 1Hz bandwidths in the GHz region would be required for the spectrum analyzer!)

• Alternate methods
  • Direct RF spectrum measurement after downconversion
  • Frequency discrimination
  • Quadrature phase detection
Direct RF Spectrum Measurement

- The signal is downconverted to the range of a spectrum analyzer with desired IF bandwidth
- Noise floor of spectrum analyzer is better at lower frequencies
- Good approximation when sidebands are symmetrical (AM noise not present)
- Phase noise sidebands from reference frequency at the mixer are also translated down so reference source must have much better phase noise performance than oscillator under test
Frequency discrimination

- If the noise level is beyond the dynamic range of the spectrum analyzer, the carrier needs to be eliminated.
- This is the case for measurements at high offset frequencies.
- High linearity is required by the discriminating device.

\[ S_v(f) = \frac{1}{K_f^2} S_v(f) \]

Where \( K_f \) = discriminator sensitivity (volt/Hz).
Quadrature phase detection

- Use a double balanced mixer with the unknown source and reference source set in phase quadrature (90°) at the input (this eliminates the carrier).
- For phase fluctuations $\phi \ll 1$ radian the voltage fluctuations at the mixer output are $v=K\phi$ where $K$ is the calibration factor.
- If the phase noise of reference is > 10dB below the noise of the oscillator then the measured noise would be that of the oscillator.
Analog Baseband Chains
Goals/Motivation

- **Develop baseband chains for 3G Integrated Wireless receivers**
  - Tailored for Integrated Cellular, cordless and Indoor applications
  - Based on regular modules for short design time
- **Investigate and propose new CMOS circuits and techniques suitable for integrated receivers**
  - Low Power Consumption
  - Digitally Programmable
  - Simple and Robust Filter/VGA/OTA circuit structures
WCDMA/GSM/DECT Multi-standard Receiver

- Two exactly same branches are needed for I/Q channels
- Filtering specifications are set as a WCDMA channel filter
- Automatic gain control range is set for all the three standards
- Anti-aliasing filter is used to filter out the noise and blockers outside of the sampling frequency of the analog-to-digital converter.
- Proper interleaving order of amplifying and filtering should be optimized to satisfy both the noise performance and the nonlinearity performance
Example
Digitally programmable baseband chain for a GSM/DECT multistandard receiver

- Enables cell phones to be used as a cordless phone by supporting both GSM/DECT modes of operation
- Utilizes wide band double conversion technique to allow integration
- Focus set to develop the baseband section of the receiver chain
GSM/DECT multi-standard receiver

- **DC offset cancellation in DSP**
  - DC offset fed back to baseband section to be subtracted from signal
  - VGA with digital offset correction capability is preferred

- **Channel selection to be performed using DSP**
  - Relaxes filtering requirements (only AAF is necessary)
  - Software programmable FIR filters for multistandard operation
  - Requires the use of high dynamic range sigma delta converter
  - Baseband VGA to reduce the ADC dynamic range
Programmable AAF Filter

- Capacitor array for digitally programmable bandwidth

- Based on Sallen Key topology
  - Few Active elements (better Linearity + Less Noise! + Simple to design)
  - Based on unity gain buffer (Simple + High frequency)
  - Low power Class AB CMOS buffer necessary for low power consumption
The digitally controlled VGA section

- Two stage VGA sections to achieve wide gain control with fine gain steps
- Digital offset trimming using current division network (6 bit)
The digitally controlled VGA section

Digitally controlled Norton VGA die photo
The digitally controlled baseband chain

- Programmable bandwidth that covers 100KHz GSM band, 700KHz DECT and Support for 2.1MHz WCDMA also tested
- 30dB gain control range with 1dB gain step and gain error < 0.4dB
The digitally controlled baseband chain for receiver

<table>
<thead>
<tr>
<th>Block</th>
<th>parameter</th>
<th>measurement</th>
</tr>
</thead>
<tbody>
<tr>
<td>Filter</td>
<td>IIP3 (In Band)</td>
<td>29dBm</td>
</tr>
<tr>
<td></td>
<td>IIP3 (Out of Band)</td>
<td>41dBm</td>
</tr>
<tr>
<td></td>
<td>Input referred Noise</td>
<td>26nV/sqrt(Hz)</td>
</tr>
<tr>
<td></td>
<td>In band ripple</td>
<td>0.1dB</td>
</tr>
<tr>
<td></td>
<td>Stop band attenuation</td>
<td>70dB</td>
</tr>
<tr>
<td></td>
<td>Current consumption</td>
<td>0.58mA</td>
</tr>
<tr>
<td>VGA</td>
<td>Max.Gain</td>
<td>24dB</td>
</tr>
<tr>
<td></td>
<td>Min Gain</td>
<td>-6dB</td>
</tr>
<tr>
<td></td>
<td>Gain step</td>
<td>1dB</td>
</tr>
<tr>
<td></td>
<td>Gain error</td>
<td>0.4dB</td>
</tr>
<tr>
<td></td>
<td>IIP3</td>
<td>27dB</td>
</tr>
<tr>
<td></td>
<td>Input referred noise</td>
<td>16.5nV/sqrt(Hz)</td>
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<td></td>
<td>Bandwidth (Cl=20pF)</td>
<td>4.1MHz</td>
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<tr>
<td></td>
<td>Current Consumption</td>
<td>0.82mA</td>
</tr>
</tbody>
</table>
Digitally Programmable CMOS Filter/VGA for wireless base stations

Specifications

- Signal of Interest: 12MHz - 23MHz
- Pass Band of Filter: 12MHz - 23MHz (-0.5dB corner points)
- Pass Band Ripple: < 0.5dB
- Stop Band: 0MHz - 5MHz and after 40MHz
- Stop Band Attenuation: > 25dB
- Programmable Gain: -10 dB to 30 dB in steps of 1 dB
- Linearity (IMD): > 53 dBc
- Signal to Noise Ratio: > 57 dB (noise integrated over 5MHz Bandwidth)
Proposed Filter/VGA Chain

- 6 dB gain buffers in 5 filter stages provide fixed 30 dB gain.
- Use filter stages with voltage gain to eliminate the need for VGA stages.
- 5 digitally programmable attenuators attenuate 30 dB gain in 1 dB steps of gain
Use the buffer circuit to implement fully differential Sallen-Key filter sections.

Filter tuning is achieved by 4 bit binary weighted capacitor array.

Use resistive chain to attenuate the gain in 1/3/6 dB steps.

Programmable gain variation: -10 – 30 dB
5 bit digital control
The frequency response of VGA/Filter chain
Conclusion

• Design Techniques achieving maximum hardware share at minimum power consumption (configurable radio, programmable analog baseband)

• Improvement in technology, characterization, packaging techniques are needed

• Migration to future wireless standards for higher data rates and multimedia applications

• Eventual convergence of LAN, WAN, PAN infrastructures for seamless wireless communication

• Need for higher levels of integration, available only in CMOS technologies

• Technology scaling favors multi GHz RFCMOS

• New challenges, careful system partitioning, good mixed signal strategy, maximize digital content
No one likes to be wired!