RF CMOS Products for Cellular Phone Applications: Challenges and Architectures

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Workshop GAAS01

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outline

- Overview of cellular RF markets and requirements
  - technology comparison of BiCMOS and CMOS RF
- GSM CMOS RF transceiver
  - GSM CMOS RF transmitter
  - GSM CMOS RF receiver
- Future trends
Technology progress in transit frequency $f_t$ and maximum frequency $f_{\text{max}}$ as driver for RF-ICs for consumer applications on the mass market

- **Bipolar:** $f_t$ & $f_{\text{max}}$ doubling within 18 months = Moore’s Law
- **CMOS:** $f_t$ & $f_{\text{max}}$ fast increase since 1980 now stagnation of $f_{\text{max}}$

Graph showing:
- Bipolar: ft & fmax doubling within 18 month = Moore’s Law
- CMOS: ft & fmax fast increase since 1980 now stagnation of fmax
- TV-VHF Tuner / GSM900
- TV-VHF/UHF Tuner / GSM1900
- WCDMA, WLAN
- Auto radar
- MW/SW & TV-IF


Graph axes:
- Y-axis: ft & fmax (GHz)
- X-axis: Year

Legend:
- Bip (ft)
- Bip (fmax)
- CMOS (ft)
- CMOS (fmax)
Infineon 120nm CMOS Technology

- 120 nm RF Transistor with $f_T > 100$ GHz ($V_{DD}=1.5V$)
- Oxide thickness 2.8 nm
- 400 nm analogue I/O Transistor ($V_{DD}=2.5V$)
- 6 copper layers up to 550 nm thick
- MIM CAP (2 fF/um²)
- Diffusion and Polysilicon Resistors
GSM RF Transmitter Architectures

Quadrature modulators
- IF modulation / upconversion
- Direct modulation
  - Offset LO
  - LO frequency division
- Cartesian loop transmitter

Sigma-Delta modulators
- Sigma-Delta modulation PLL with PM modulator

Polar modulators
- Sigma-Delta modulation PLL with AM modulator
- Sigma-Delta modulation PLL with PA modulation

Polar transmitters
- Polar loop modulator
- Polar loop transmitter

EER techniques

Polar modulation techniques
Linear Modulation Architectures

High data rates require linear modulation techniques using e.g. 8PSK, QAM 64, OFD (opposed to GMSK):

Problems of Linear Transmit Architectures

• PA Feedback to VCO: Leakage of modulated TX signal back into VCO creates sidebands
• Stringent requirements for GSM / EDGE Transmit Noise in Receive Bands:
  – GMSK: -162 dBc/Hz (20 MHz Offset)
  – 8PSK: -157dBc/Hz (20 MHz Offset)
• Each signal processing step after transmit signal generation (VCO) is extremely critical concerning noise and consumes a lot of current
Direct modulation architecture (LO frequency division)

Direct modulation with LO division (usually by 2 or 4) is very suitable for highly integrated low cost solution:

- Provides very wide band, well defined 0/90 degree relation
- Only one synthesizer needed
- But: This concept is sensitive to PA feedback (harmonics)
Direct modulation architecture (LO frequency division)

- Spectral regrowth due to H3 conversion
Polar transmitter

- Not seen in mass production of cellular phones so far
- Huge dynamic range for PA control (power level + modulation range)
- Matching of amplitude / phase path is essential
- AM/PM and AM/AM modelling needed over temperature / productio
## Comparison of modulation techniques

<table>
<thead>
<tr>
<th></th>
<th>Quadrature</th>
<th>Sigma Delta Modulation</th>
<th>Polar Modulation</th>
<th>Polar Transmitter</th>
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<td>System BOM</td>
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High Performance RX Front Ends for RF in CMOS

- Direct conversion receiver is preferred architecture for both BiCMOS and CMOS GSM systems (low BOM / no SAW filters)
- Critical performance parameters for RX front ends in CMOS are
  - flicker noise
  - matching
  - low break through voltages
  - low $g_m/I$ ratio / low driving capability
  - complicated ESD and latch up security
  - substrate crosstalk when bulk CMOS is used

- CMOS front-ends are complicated to do, but with a good system approach, design and layout very good results are achievable
Challenges for CMOS Receivers

• Improvements of RF Receivers in CMOS processes
  – potential implementation of self alignment procedures to overcome process variation issues
  – due to high speed digital, signal processing can be done closer to the antenna, thus shrinking of RX is enabled
  – availability of very fast CMOS devices: 0.13µm $f_t=100$GHz

• But: remaining RF building blocks are even more challenging:
  – LNA: power gain, cross talk sensitivity and matching to 50Ohms
  – Mixer: dynamic range, driving level for switching transistors for optimum noise,
  – flicker noise optimization
Design Issues for CMOS RF Receivers

- Even in a highly digitized radio two complicated building blocks remain in the receiver

  - **LNA**
    - power gain
    - noise figure
    - matching to 50 Ohms
    - ESD

  - **Mixer**
    - flicker noise performance
    - IP2
    - headroom with low supply voltage
High Performance RF CMOS Receivers

- Potential solutions for LNA:
  - Trans-impedance amplifiers
    - good noise performance
    - good crosstalk performance
    - higher current consumption
    - limited headroom
    - low area consumption
  - Coil LNA’s
    - good noise performance
    - limited crosstalk performance due to inductive coupling
    - lower power consumption
    - improved linearity
    - larger die area
  - Only coil LNA achieves sufficient performance
Results CMOS Sigma Delta GSM Transceiver

Features:

• Direct Conversion RX and TX
• Supported Bands 850/900/1800/1900 MHz
• Internal RX and TX VCO
• $\Sigma\Delta$-Modulation Loop for GMSK
• Constant gain receiver for 14 bit ADC
• Part of complete GSM/GPRS Platform
• 48-pin VQFN Plastic Package
Sigma-Delta Transceiver block diagram
Delta-Sigma Frac.-N PLL Modulation Loop

\[ \text{f}_{\text{ref}} = 26 \text{ MHz} \]

20 bit accuwidth in MASH
Concept of Predistortion Filter

\[
\frac{\Phi_{out}(s)}{\Phi_{ref}(s)} = N \cdot \frac{1}{1 + \frac{N}{s} \cdot \frac{1}{KPK_{VCO}Z(s)}} = N \cdot G(s)
\]

\[
f_{out}(s) = N_{mod}(s) \cdot f_{ref} \cdot G(s) \cdot G(s)^{-1} = N_{mod}(s) \cdot f_{ref}
\]
Voltage Controlled Oscillator Core

- Differential Cross Coupled
- MOS Tuning Element
- VCO gain 60 MHz +/-10%
- 1300 MHz frequency range
VCO Frequency Band Select

10 Bit VCO: Frequenz vs. Binärwort

Frequency Accuracy: 2 MHz per bit
Loop Dynamic Requirements

rious power spectral density
frequency offset

400 kHz

-90 ... -95 dBc/Hz
app. -111 dBc/Hz

⇒ high loopfilter suppression needed at 400 kHz, but the modulation needs to have a wide bandwidth!
Driver Amplifier

- **Differential Output**
  - 1.5 V Supply Voltage
  - Drives 50 Ohm Load
  - Broadband (flat over band)
  - Low Noise

- **Separate 900/1800 MHz Outputs**
  - 8.5 dBm @ 900 MHz
  - 8 dBm @ 1800 MHz
High margin to GSM Specification due to low phase noise
PLL Settling Time

analog PLL settling time < 80 µs
Chip Photograph

TX

RX-Filter

LNA

VCO
# Performance Summary

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<thead>
<tr>
<th></th>
<th>GSM850/GSM900</th>
<th>GSM1800/1900</th>
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</thead>
<tbody>
<tr>
<td><strong>Gain</strong></td>
<td>57 dB</td>
<td>57 dB</td>
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<tr>
<td><strong>Noise Figure</strong></td>
<td>2.6 dB</td>
<td>3 dB</td>
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<tr>
<td><strong>1 dB Compression</strong></td>
<td>-22 dBm</td>
<td>-22 dBm</td>
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<tr>
<td><strong>IIP2</strong></td>
<td>50 dBm</td>
<td>50 dBm</td>
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<tr>
<td><strong>RX Phase Noise</strong></td>
<td>&lt;-129 dBc/Hz</td>
<td>&lt;-123 dBc/Hz</td>
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<tr>
<td>@ 600 kHz</td>
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<tr>
<td><strong>TX Phase Noise</strong></td>
<td>-96 dBc/Hz</td>
<td>-100 dBc/Hz</td>
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<tr>
<td>@ 40 kHz</td>
<td>&lt;-162 dBc/Hz</td>
<td>&lt;-157 dBc/Hz</td>
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<tr>
<td>@ 20 MHz</td>
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<tr>
<td><strong>Phase error</strong></td>
<td>1.4 °</td>
<td>1.6 °</td>
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<tr>
<td><strong>TX Output Power</strong></td>
<td>8.5 dBm</td>
<td>8 dBm</td>
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<tr>
<td><strong>Power consumption</strong></td>
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<tr>
<td>TX</td>
<td>210 mW</td>
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<tr>
<td>RX</td>
<td>250 mW</td>
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Future trends

- Reconfigurability for Multi Mode / Multi Function Terminals

- Talk/Voice Centric
- Browse
- Computer
- Audio
- TV
- Games
- Video
Single chip CMOS Multiband/Multimode Transceiver

Transmit/Receive Bands:
- RX: 800 - 2200 MHz
- TX1: 776 - 958 MHz
- TX2: 1710 - 1990 MHz

Standards:
- GSM/EDGE
- UMTS
- CDMA2000/IS95