High Performance RF in Wireless Infrastructures

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Content

• Wireless infrastructures
  – State-of-the-art
  – Need for (further) integration
• (Re) Quest for High Performance RF
  – Technology
  – Design
• Concluding remarks
Wireless communication

- Cellular base station
- Cellular handheld
- Ka/Ku band satellite
Trend in cellular mobile handset

1995

2000

2007

2009

GSM900

GSM900/1800/1900

Quad EDGE

Triple WCDMA

3.9G
Thanks to impressive integration.

ISSCC1999

ISSCC2009

GSM900 TRx
0.25μm CMOS

WCDMA/HSDPA/HSUPA/EGPRS TRx
0.13μm CMOS
State-of-the-art cellular handheld

• Typical consumer market product
  – Cost is key

  – Integration of functionality in Si-based technology

  – CMOS scaling lead to RF capability of devices

  – SoC solutions became possible
Let’s look at cellular base station

- Tower + cabinets
- A single cabinet
- A single rack
State-of-the-art BS Transceiver
And a single RF IP block: LNA

Rx LNA at 900MHz:
22 SMD components around a single pHEMT GaAs device!
Cellular base station

• Observation 1: Discrete components
  – Expensive
  – Compound semiconductor technology
  – …

• Observation 2: Duplication
  – Expensive

Why if we can reach impressive integration levels in the handheld?
Satellite infrastructure: Ku band

Low Noise Block (LNB) down converter
State-of-the-art Ku LNB

discrete implementation using mainly Compound Semiconductor Technologies (pHMET GaAs)
Satellite infrastructure

• Observation: Discrete components
  – Expensive
  – Compound semiconductor technology
  – Manual trimming
  – …
Wireless infrastructure

it's performance!!

Cost is not an issue
Size is not really an issue
Power dissipation is not an issue
## A few examples: base station LNA

<table>
<thead>
<tr>
<th>900MHz</th>
<th>Spec HH</th>
<th>Spec BS</th>
<th>avago</th>
<th>Asia-Pacific Microwave Conf. 2000</th>
<th>JSSC 2007</th>
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</thead>
<tbody>
<tr>
<td><strong>NF [dB]</strong></td>
<td>&lt; 2</td>
<td>&lt; 0.6</td>
<td>0.53</td>
<td>1.35</td>
<td>0.2 non-50Ω</td>
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<tr>
<td><strong>1-dB OCP [dBm]</strong></td>
<td>&gt; -5</td>
<td>&gt; +15</td>
<td>+18</td>
<td>+8</td>
<td>+1</td>
</tr>
<tr>
<td><strong>OIP3 [dBm]</strong></td>
<td>&gt; 8</td>
<td>&gt; +30</td>
<td>+33</td>
<td>+22</td>
<td>+12</td>
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<tr>
<td><strong>Gain [dB]</strong></td>
<td>&gt; 15</td>
<td>&gt; 15</td>
<td>18</td>
<td>13</td>
<td>17</td>
</tr>
<tr>
<td><strong>S11 [dB]</strong></td>
<td>&lt; -10</td>
<td>&lt; -20</td>
<td>&lt; -20</td>
<td>&lt; -10</td>
<td>&lt; -11</td>
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<tr>
<td><strong>Pdiss [mW]</strong></td>
<td>low</td>
<td></td>
<td>216</td>
<td>38</td>
<td>43</td>
</tr>
<tr>
<td><strong>technology</strong></td>
<td></td>
<td></td>
<td>0.5µm GaAs</td>
<td>0.25µm BiCMOS</td>
<td>90nm CMOS</td>
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</table>
A few examples: satellite LNA

<table>
<thead>
<tr>
<th>Frequency Range</th>
<th>Spec</th>
<th>NEC</th>
<th>Ellinger 2004</th>
<th>Aspemyr 2006</th>
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<tbody>
<tr>
<td><strong>10-12GHz</strong></td>
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<tr>
<td>NF [dB]</td>
<td>&lt; 0.6</td>
<td>0.35</td>
<td>3</td>
<td>2.1</td>
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<tr>
<td>Gain [dB]</td>
<td>&gt; 10</td>
<td>&gt; 13</td>
<td>14</td>
<td>12.3</td>
</tr>
<tr>
<td>Pdiss [mW]</td>
<td>20</td>
<td></td>
<td>2.3</td>
<td>11.2</td>
</tr>
<tr>
<td>technology</td>
<td></td>
<td></td>
<td>0.25(\mu)m GaAs</td>
<td>0.25(\mu)m BiCMOS</td>
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<tr>
<td><strong>18-22GHz</strong></td>
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<td></td>
<td></td>
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</tr>
<tr>
<td>NF [dB]</td>
<td>&lt; 1</td>
<td>0.7</td>
<td>5.5</td>
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<tr>
<td>Gain [dB]</td>
<td>&gt; 10</td>
<td>&gt; 13</td>
<td>10</td>
<td></td>
</tr>
<tr>
<td>Pdiss [mW]</td>
<td>20</td>
<td></td>
<td>24</td>
<td></td>
</tr>
<tr>
<td>technology</td>
<td></td>
<td></td>
<td>0.25(\mu)m GaAs</td>
<td>0.13(\mu)m CMOS</td>
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</tbody>
</table>
A few examples: satellite VCO

<table>
<thead>
<tr>
<th>15GHz</th>
<th>Hittite</th>
<th>Asia-Pacific Microwave Conf. 2009</th>
<th>BCTM 2007</th>
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<tbody>
<tr>
<td>Frequency</td>
<td>15GHz</td>
<td>13.5GHz</td>
<td>15GHz</td>
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<tr>
<td>PN @ 100kHz [dBm/Hz]</td>
<td>-105</td>
<td>-84.4</td>
<td>-82</td>
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<tr>
<td>Po [dBm]</td>
<td>+7</td>
<td>-4</td>
<td>+2</td>
</tr>
<tr>
<td>Pdiss [mW]</td>
<td>4.5</td>
<td>18</td>
<td></td>
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<tr>
<td>technology</td>
<td>GaAs - InGaP</td>
<td>0.18μm CMOS</td>
<td>0.18μm SiGe:C</td>
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</tbody>
</table>
Content

• Wireless infrastructures
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• Concluding remarks
The need for integration is coming

- In cellular base stations
  - Increased density of base stations to cope with data traffic (Shanghai: every 500m!)
  - More standards / bands / phased arrays
  - Power reduction: the ‘green’ label
  - Tower mounted units instead of ‘base’ station
  - Robustness, yield, …
The need for integration is coming

• In satellite communication
  – Next Ka-satellite market India and South Americas: but then price of LNB must reduce
  – LNB/BUC is powered by Set Top Box (STB)
    • Ultimate goal is the universal QUAD LNB/BUC supplying 4 STBs minimum, but powered by still 1 STB worse case (backward compatible)
      – Ku-band & Ka-band & both polarizations
The need for integration is coming

- **Wireless infrastructure will benefit from integration**
  - More functionality
  - Improved yield and thus lower cost
  - Improved reliability (ESD, automatic calibration, BIST, adaptive matching, …)
  - Less PCB issues at customer site
  - Paves the path towards spatial selectivity to mitigate interference, support tracking, boost TX power, etc.

- **But this all requires Si-based RF solutions**
  - GaAs-like technology lack dense integration
Wireless infrastructure

Two-step approach:

Improve Si-technology
Different architecture/circuit design
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Improve Si-technology

Base station

LDMOS
GaN
X-band Radar

LDMOS
GaN
X-band Radar

GSM,3G
BS:ss
WiMAX
802.11a/n
802.11b/g
UWB

GaAs
Sat Ku
Sat Ka
Sat return
PtP
Car Radar

BiCMOS
SiGe

BiCMOS replacement

CMOS

Performance/output power

freq [GHz]

low
medium
high
very high

2 5 10 30

CMOS

BiCMOS replacement

BiCMOS
SiGe

DECT
BT

802.11b/g

GSM,3G

802.11a/n
UWB

802.11a/n
UWB

BiCMOS
replacement
Improve Si-technology

Performance/output power

- BiCMOS
  - SiGe
  - GSM, 3G
  - WiMAX
  - 802.11a/n
  - 802.11b/g
  - DECT
  - BT

- RF-CMOS
  - 65/45/32 nm

- GaAs
- LDMOS
- GaN
- X-band Radar

Base station
- BS:ss
- Car Radar
- PtP
- SoC driven
- Sat Ka
- Sat Ku
- Sat return
- WiMAX
- 802.11b/g
- 802.11a/n
- UWB
- DECT
- BT
- GSM, 3G

freq [GHz]

low

medium

high

very high

SoC driven
Improve Si-technology

- Performance/output power
- LDMOS
- GaN
- X-band Radar
- Base station
- BiCMOS
- SiGe
- GSM,3G
- BS:ss
- RF-CMOS 65/45/32 nm
- SoC driven
- 802.11a/n
- UWB
- 802.11b/g
- DECT
- BT
- WiMAX
- PtP
- Car Radar
- Sat Ku
- Sat Ka
- Sat return
- WiMAX
- 802.11a/n
- UWB
- 802.11b/g
- DECT
- BT
- WiMAX
- PtP
- Car Radar
- Sat Ku
- Sat Ka
- Sat return
- SiGe:C BiCMOS
- GaAs
- GaAs replacement
- LDMOS
- GaN
- BiCMOS
- SoC driven

- Frequency [GHz]
- Low: 2, Medium: 5, High: 10, Very High: 30
**Technology: SiGe:C front-end**

**SiGe:C NXP technology**
**TSMC 65nm CMOS**

65nm NMOS $\rightarrow$ capacitive nature
SiGe:C $\rightarrow$ real part (base resistance)

**Impedance match**

$$Z_s = Z_i^* \implies P_{s,\text{av}} = P_{i,\text{del}}$$

**Noise match**

$$Z_s = Z_{\text{opt}}$$
SiGe:C NXP technology
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High performance RF design

Use the density of Si-based technology

- Use advanced architectures
- Use digital!
  - Adaptivity
  - Calibration
  - Signal processing power
  - ...

and a mix of disciplinary fundamental research (IC design, EM, SP, ...)
An example: BST LNA

Package: HLQFN16R
Die photo’s
Why a Module?

![Diagram of a module with a 1st gain stage consisting of a switch followed by a variable attenuator, and a 2nd gain stage consisting of a switch and a variable attenuator. The input is RFin, and the output is RFout.]

- 0.25μm SiGe:C BiCMOS
  - $ft = 216\text{GHz}$, $BV_{ceo} = 1.45V$
  - $NF_{min} (@2GHz) \approx 0.4dB$

- 0.25μm SiGe:C BiCMOS
  - $ft = 130\text{GHz}$, $BV_{ceo} = 3V$
  - $NF_{min} (@2GHz) \approx 0.7dB$
Design: 1st gain stage
1\textsuperscript{st} gain stage: gain mode

input matching

interstage matching: low impedance
1st gain stage: bypass mode

Exploit high-ohmic substrate to eliminate non-linear capacitances

Note: 2nd die will influence the input matching!!
**Measurement 1st gain stage**

![Graph showing NF vs frequency](image)

<table>
<thead>
<tr>
<th>Performance</th>
<th>Active mode</th>
<th>Bypass mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pdiss [mW]</td>
<td>350</td>
<td>0</td>
</tr>
<tr>
<td>Gain [dB]</td>
<td>19</td>
<td>-1.1</td>
</tr>
<tr>
<td>Input IP3 [dBm]</td>
<td>+14</td>
<td>+41</td>
</tr>
<tr>
<td>Output IP3 [dBm]</td>
<td>+33</td>
<td>+40</td>
</tr>
<tr>
<td>Output CP1dB [dBm]</td>
<td>+15</td>
<td>&gt; +15</td>
</tr>
</tbody>
</table>
Design: 2\textsuperscript{nd} gain stage

- **RFin**
- **GND**
- **VCC**
- **RFout**

**Input matching**

**Variable attenuator**

**Output stage**

- 0 – 30 dB
- High OIP3
Design: variable attenuator

Translinear section instead of MOS switches

- better linearity
- very good reverse isolation
- slightly higher NF
- gain
Design: variable attenuator

<table>
<thead>
<tr>
<th></th>
<th>JSSC 2008</th>
<th>JSSC 2011</th>
<th>This work</th>
</tr>
</thead>
<tbody>
<tr>
<td>NF</td>
<td>3.5</td>
<td>1.5</td>
<td>6</td>
</tr>
<tr>
<td>IIP3</td>
<td>22</td>
<td>17</td>
<td>32</td>
</tr>
</tbody>
</table>
Design: output stage

output matching

OCP1dB = +20dBm
→ 3Vpeak @ 50Ω
→ HV devices

80mA

Two in parallel to handle the current
Design: 2 dies
Measurements: NF vs. Gain

Measurements performed at 65°C
Measurements: IIP3 vs. Gain

Measurements performed at 65°C

17dB by 1st gain stage

OIP3 = 37dBm
Measurements: S11 vs. Gain

Accuracy!!

-16
-18
-20
-22
-24
-26

S11 (dB)

freq (Hz)
Some examples: Ka VCO

Transformer-based Colpitts VCO

increase $L \rightarrow$ increase in $Q \rightarrow$ improves PN
increase $L \rightarrow$ increase tank impedance $\rightarrow$ degrades PN

Use transformer:

$L_{\text{transformer}} > L_{\text{tank}}$

Primary: M6
Secondary: M5+M3

$Q=35 \ @ \ 17\text{GHz}$ for $L=400\mu\text{H}$
Some examples: Ka VCO
Some examples: BS PA

- BB + DPD
- RF DSP + Modulator
- CMOS
- HV analog Driver
- Class-E PA
- GaN
- Power Module
- Power Supply
- Pout
- Power control
- out phasing architecture
Some examples: BS PA

1.2V ‘digital’

65nm CMOS

5V pulsed signal

Power Module

CMOS

HV analog Driver

Class-E PA

GaN

Pout

2 Watt

20 Watt

65nm CMOS

2 Watt

5V pulsed signal

1.2V ‘digital’
Class-E Out-phasing PA

65nm CMOS Driver

Wideband Chireix Combiner

GaN

S1

S2

V_{GP1} V_{GN1} V_{DD,CMOS} V_{DD,CMOS} V_{GG} V_{GG}

V_{GP2} V_{GN2} V_{DD,CMOS} V_{DD,CMOS} V_{DD,CMOS} V_{GG}

2\theta

LC-match

Z_0

L_m

C_m

Z_0, Z_{0e}

I_1

I_2

V_{DD}

V_{DD}

V_{DD}

V_{DD}

V_{DD}

CMOS

Driver

Wideband

Chireix

Combiner

GaN

65nm CMOS
Some examples: BS PA

20W Out-phasing PA Line-up (CMOS + GaN)

PA line up + matching: 5 cm²
Some examples: BS PA

- **Supply Decoupling Cap**
- **CMOS Driver**
- **RFin**
- **RFout**
- **Vdd**

**Simplified schematic**

- **Vg_{pmos}**
- **Vdd**
- **RFout**

**directly 50\Omega**

**ED-NMOS**
Temperature gradients

CMOS2 (top left)

GaN2 (top right)
Some examples: BS PA

$V_{DD,GaN} = 28V; V_{DD,CMOS} = 4.5V$

DE >50% and BW >8% @ 10dB
DE >60% and BW >10% @ 6dB
Some examples: BS PA

DE >60% over 10dB
EFF >50% over 8dB
Record for out-phasing PA
Concluding remarks

• Wireless infrastructure IP dominated by compound technology, and for a reason!
• Modern Si-based technologies offer good RF performances, but still less than pHEMT technology
• Combination of improved architectures / circuits and Si-technology might lead to pHEMT replacement in wireless infrastructure

Quest for High Performance RF
Acknowledgement

• Team members RF ADT @ NXP
• N. Pulsford, N. Kramer, M. Geurts (NXP)