22.2
An Octave-Range Watt-Level Fully Integrated CMOS Switching Power Mixer Array for Linearization and Back-Off Efficiency Improvement

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Outline

• Background
• Power mixer array
• Power mixer details
• Block diagram and operation modes
• Measurement results
• Conclusion
Primary Constraints in Wireless Communication

- **Cost**
  - CMOS
  - Die Area
  - Fully-Integrated

- **(Battery) Size**
  - Power Efficiency

- **BW Limitation**
  - Spectral Efficiency
Pros and Cons of Conventional Approaches

- **Class-AB**
  - Poor efficiency
- **Doherty & Out-phasing**
  - Phase shifter
- **Supply modulation**
  - DC-DC converter
- **Digital PA**
  - Aliasing & output noise
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Power Mixer Array Transmitter Subsystem

- Power generation is done by several identical mixers
- Power mixer array subsumes some of the functionality of a conventional transmitter
Segmented Power Generation

- When a symbol does not require full output power some power generation blocks are turned off
Back-Off Efficiency Improvement

- Power efficient and compatible with CMOS processes
- CMOS is good at switching on and off

\[ \sum \]

\[ \text{Power Consumption} \]

\[ \text{Output Power} \]
Linearity Improvement
Linearity Improvement

\[ V_i \rightarrow PG_1 \rightarrow PG_2 \rightarrow PG_3 \rightarrow \ldots \rightarrow PG_n \rightarrow \Sigma \rightarrow V_o \]

\[ \sum V_{i_k} \rightarrow V_o \]
Linearity Improvement

• Linearity improves as the output increases
BB Input Signal Generation

- Input signals are pulse shaped to avoid spurious and alias problems
BB Circuit Sharing

- BB circuits such as DAC and LPF can be shared by using switch
Output Network and Signal Combination

- Transformer is suitable for a large impedance transformation ratio
- Output current of the power mixers can be linearly combined at the output network

\[ Z_0 >> Z_L \]
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Power Mixer

• Current commuting mixer

• Boost the voltage swing & output impedance

• Amplitude modulation
  – “Linear” Amplitude modulation
  – Large bandwidth

• Switching operation
  – High Efficiency
  – Low Noise
Translucent Waveform of Power Mixer

- Peak efficiency = 60%, Peak power = 33dBm @ 1.8 GHz
Gain and Non-Linearity of Power Mixer

- The transconductance and the current gain is non-linear to the differential mode of the input voltage ($V_{DIFF}$)
1. Class-AB Operation

- These non-linearities can cancel each other
- Improved back-off efficiency
2. Baseband Replica Linearizer

- Dynamically match the power mixer core and BB replica amplifier using feedback
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Block Diagram of the Implemented System

- Analog BB Replica Linearizer Array
- Analog BB Distributor
- Digital Controller
- Digital LO Distributor
- On-Chip

- Envelope (BB)
- Phase (LO)
- RF Output

- LBB+
- LBB-
- CM
- I_{out}+
- I_{out}-
- C_{11}
- V_{DD}
- C_{2}
- PAD
- R_{Load}

- PM0
- PM13
- PM14
- PM15
1. Baseline Analog (BA) Mode

- Class-AB operation for linearity and efficiency improvement
- Equivalent to one large power mixer
2. Linearized Analog (LA) Mode

- One large power mixer with feedback linearizer
3. Efficient Segmented (ES) Mode

- Segmented power generation for linearity and efficiency improvement

![Diagram of Power Mixer Array Current](image)
Die Photo

- Fully-integrated in a 130nm CMOS Technology
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Frequency Response

- PAE is larger than 40% from 1.5 to 2 GHz
- Output power is larger than 1W from 1.2 to 2.4 GHz

LO input power = +3 dBm
BB input (0-p, single) = 450mV
Gain and PAE for Different Operation Mode

- BA and LA mode have very high linearity
- ES mode and BA mode show improved efficiency

Frequency = 1.8 GHz, CW
Linearity Robustness

- LA and ES modes are robust to power mixer linearity

<table>
<thead>
<tr>
<th>Linearity Robustness</th>
<th>Gain (Normalized) [dB]</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>BA Mode</strong></td>
<td></td>
</tr>
<tr>
<td><strong>LA Mode</strong></td>
<td></td>
</tr>
<tr>
<td><strong>ES Mode</strong></td>
<td></td>
</tr>
</tbody>
</table>

- Frequency = 1.8 GHz, CW

\( V_{CM} = 0.4V \)
\( V_{CM} = 0.45V \)
\( V_{CM} = 0.5V \)
EVM & PAE for 16QAM Modulation

Frequency = 1.8 GHz
Symbol Rate = 50 kSym/s

<table>
<thead>
<tr>
<th></th>
<th>BA Mode</th>
<th>LA Mode</th>
<th>ES Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pout [dBm]</td>
<td>+27.1</td>
<td>+27.6</td>
<td>+26.4</td>
</tr>
<tr>
<td>PAE</td>
<td>25%</td>
<td>18%</td>
<td>26%</td>
</tr>
<tr>
<td>EVM</td>
<td>4.3%</td>
<td>5.0%</td>
<td>4.5%</td>
</tr>
</tbody>
</table>
LO Leakage and Output Power Range

- More than 100dB output power range is achieved

Frequency = 1.8 GHz
# of the Power Mixer = 1
\( V_{CM} = 0.2V \)

- BA Mode, w/ DC Offset Adj.
- BA Mode
- LA Mode
- ES Mode

103dB

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WCDMA (PAPR = 3.5 dB, 3.84 Mcps)

<table>
<thead>
<tr>
<th></th>
<th>Band I</th>
<th>Band II</th>
<th>Band III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency [GHz]</td>
<td>1.95</td>
<td>1.83</td>
<td>1.75</td>
</tr>
<tr>
<td>Power [dBm]</td>
<td>+28.4</td>
<td>+28.3</td>
<td>+28.3</td>
</tr>
<tr>
<td>PAE</td>
<td>28%</td>
<td>28%</td>
<td>30%</td>
</tr>
<tr>
<td>EVM</td>
<td>3.7%</td>
<td>3.5%</td>
<td>2.9%</td>
</tr>
</tbody>
</table>

- Output power > +28dBm
- PAE ~ 30%
- EVM, spectrum mask, and ACLR specifications are satisfied
WCDMA (PAPR = 5.2 dB, 3.84Mcps)

<table>
<thead>
<tr>
<th>Frequency [GHz]</th>
<th>Band I</th>
<th>Band II</th>
<th>Band III</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power [dBm]</td>
<td>+25.1</td>
<td>+25.3</td>
<td>+25.5</td>
</tr>
<tr>
<td>PAE</td>
<td>19%</td>
<td>20%</td>
<td>21%</td>
</tr>
<tr>
<td>EVM</td>
<td>3.4%</td>
<td>3.0%</td>
<td>3.1%</td>
</tr>
</tbody>
</table>

- Output power > +25dBm
- PAE ~ 20%
- EVM, spectrum mask, and ACLR specifications are satisfied
WiMAX (5MHz & 10MHz BW)

BA Mode, Frequency = 1.75GHz, BW = 5MHz, 99.9% PAPR = 8.5dB

POUT = +25.0 dBm

EVM = 4.9%

<table>
<thead>
<tr>
<th>Bandwidth [MHz]</th>
<th>5</th>
<th>10</th>
</tr>
</thead>
<tbody>
<tr>
<td>Output Power [dBm]</td>
<td>+25.0</td>
<td>+25.0</td>
</tr>
<tr>
<td>PAE</td>
<td>20%</td>
<td>20%</td>
</tr>
<tr>
<td>EVM</td>
<td>4.9%</td>
<td>4.8%</td>
</tr>
</tbody>
</table>
**Performance Summary**

### Modulation performance

<table>
<thead>
<tr>
<th>Modulation</th>
<th>Frequency</th>
<th>PAPR</th>
<th>Modulation BW</th>
<th>Mode</th>
<th>Pout</th>
<th>PAE</th>
<th>EVM</th>
</tr>
</thead>
<tbody>
<tr>
<td>16QAM</td>
<td>1.8 GHz</td>
<td>5.9 dB</td>
<td>50 kHz</td>
<td>BA</td>
<td>+27.1 dBm</td>
<td>25%</td>
<td>4.3%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>LA</td>
<td>+27.6 dBm</td>
<td>18%</td>
<td>5.0%</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td>ES</td>
<td>+26.5 dBm</td>
<td>26%</td>
<td>4.5%</td>
</tr>
<tr>
<td>WCDMA</td>
<td>1.75 - 1.95 GHz</td>
<td>3.5 dB</td>
<td>3.84 MHz</td>
<td>BA</td>
<td>+28.0 dBm</td>
<td>30%</td>
<td>2.9%</td>
</tr>
<tr>
<td></td>
<td></td>
<td>5.2 dB</td>
<td></td>
<td>BA</td>
<td>+25.5 dBm</td>
<td>21%</td>
<td>3.1%</td>
</tr>
<tr>
<td>WiMax</td>
<td>1.75 GHz</td>
<td>8.5 dB (99%)</td>
<td>5, 10 MHz</td>
<td>BA</td>
<td>+25.0 dBm</td>
<td>20%</td>
<td>4.9%</td>
</tr>
</tbody>
</table>

### Basic performance

- Frequency: 1.8 GHz
- Maximum Output Power: +31.3 dBm
- Peak PAE: 42%
- LO Input Power: 3 dBm
- Die Area: 2.56 mm²
- Max. LO to RF Power Gain: 28.3 dB
- BB to RF Voltage Conversion Gain: Max. 20.2 dB, Min. -18.6 dB
- Output Power Range: 103 dB
- OP1dB: BA-mode +30.2 dBm, LA-mode +31.3 dBm, ES-mode +28.5 dBm

### Power consumption

<table>
<thead>
<tr>
<th>Supply</th>
<th>Power</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power Mixer Array</td>
<td>3 V</td>
</tr>
<tr>
<td>Digital LO Distributor</td>
<td>1.2 V</td>
</tr>
<tr>
<td>Analog BB Replica Linearizer</td>
<td>3 V</td>
</tr>
<tr>
<td>Analog BB Distributor</td>
<td>3 V</td>
</tr>
<tr>
<td>Digital Controller</td>
<td>1.2 V</td>
</tr>
</tbody>
</table>
Conclusion

- Fully-integrated power mixer array transmitter subsystem occupies 2.6mm$^2$ in a 130nm CMOS technology.

- Output power is larger than 1W with a PAE of 40%, from 1.5 to 2 GHz.

- Three operation modes of BA, LA, and ES are demonstrated with high linearity and improved efficiency.

- Output power range of greater than 100dB is achieved without any RF gain control circuit.

- WCDMA and WiMax modulated output signals are successfully measured with a linear output power of +28.2dBm and with a PAE of 30% for WCDMA.
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For additional multimedia material: See http://www.isscc.org