Switched-Capacitor Power Amplifiers for NB-IoT

Salvatore Levantino
Outline

- Internet-of-Things communications
- Digital RF power amplifiers
- High-efficiency digital PAs
- Switched-capacitor class-D PAs
What is Internet of Things?

>5B IoT connections by 2025¹

- Smart cities: Lighting, traffic sensors, smart parking, etc.
- Mobile health: Wearables, gateways, remote patient, etc.
- Smart utilities: Smart grid, gas/water/electric meters
- Environmental monitoring: Agriculture, forecast fire/air pollution sensors, etc.
- Connected building: Security, video surveillance, smoke detectors, etc.
- Connected industrial: Process/equipment monitoring, HVAC, etc.
- Connected retail: Vending machines, ATM, digital ads, etc.
- Asset tracking: Fleet management, pet/kid trackers, shipping, etc.

¹ www.qualcomm.com
Evolution of LTE for Internet-of-Things

Scaling up in performance and mobility

LTE-A

LTE

LTE-M

NB-IoT

Today

3GPP Release 13+

Applications

Mobile

Connected cars

Smartwatch

Smart cities

Smart metering

www.qualcomm.com
LTE technologies for IoT devices
3GPP Release 13+

LTE Cat-M1 (eMTC)
- Brodest range of IoT capabilities with support for future advanced features, e.g. voice support

LTE Cat-NB1 (NB-IoT)
- Scalable to lowest cost/power for delay-tolerant, low-throughput IoT use cases, e.g. remote sensors

--www.qualcomm.com--
Reduced LTE complexity to enable low-cost modules

<table>
<thead>
<tr>
<th></th>
<th>LTE Cat-1</th>
<th>LTE Cat-M1</th>
<th>LTE Cat-NB1</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Peak data rate</strong></td>
<td>DL: 10 Mbps</td>
<td>DL: 1 Mbps</td>
<td>DL: 20 kbps</td>
</tr>
<tr>
<td></td>
<td>UL: 5 Mbps</td>
<td>UL: 1 Mbps</td>
<td>UL: 60 kbps</td>
</tr>
<tr>
<td><strong>Bandwidth</strong></td>
<td>20 MHz</td>
<td>1.4 MHz</td>
<td>200 kHz</td>
</tr>
<tr>
<td><strong>RX antenna</strong></td>
<td>MIMO</td>
<td>Single RX</td>
<td>Single RX</td>
</tr>
<tr>
<td><strong>Duplex mode</strong></td>
<td>Full duplex FDD/TDD</td>
<td>Full/Half duplex FDD/TDD</td>
<td>Half duplex FDD</td>
</tr>
<tr>
<td><strong>Transmit power</strong></td>
<td>23 dBm</td>
<td>23 or 20 dBm*</td>
<td>23 or 20 dBm*</td>
</tr>
</tbody>
</table>

www.qualcomm.com

Higher throughput, lower latency, higher mobility

Reduced baseband complexity and memory size

*Integrated PA is possible
IoT applications require **low cost** radios. Many use cases require **km range** and **multi-year battery life**.

Evolution of cellular communications for IoT leverage existing **infrastructure** and spectrum.

The standards are defined to reduce complexity and enable **efficient radio transceivers** with DSP and power amplifier integrated in a **single chip in silicon**.
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Why RF power amplifiers are important?

- RF power amplifiers (PAs) are responsible for large part of mobile devices power consumption.

- Increase in **PA efficiency** would mean longer usage time, smaller battery, lower cost.
What is a *digital* power amplifier or a *digital* RF transmitter?

**Diagram:**
- Local Oscillator
- Digital Phase Modulator
- Digital Signal Processor
- Digital Power Amplifier
- Antenna

N digital bits → Digital Phase Modulator

M digital bits → Digital Power Amplifier

Full integration in CMOS is possible
Why digitize an RF transmitter?

- To achieve high **power efficiency** at **linear** output power
- **Small die area**, CMOS scaling friendly
- Digital control: easy to reconfigure, **flexible**

Enable low cost IoT radios
Peak-to-average power ratio

- More data throughput (Mb/s) into a finite spectrum resource (MHz) (Higher spectral efficiency)

- Typically, the higher the spectral efficiency the larger the peak-to-average ratio (PAPR) of the transmitted signal
- **Power efficiency** degrades with **back-off** from peak amplitude
- Average signal amplitude is much lower than the peak
- **Average efficiency:**
  \[ \int \text{PDF}(A) \cdot \text{Efficiency}(A) \cdot dA \]
- Average efficiency is lower than peak efficiency
PA experiences **compression** prior achieving peak output power.

Compression causes signal **distortion, quality degradation** and **spectral regrowth**.

**Additional signal back-off** needs to be applied to meet the required signal quality.
Impact of PA compression
LTE Cat-M1 signal with 16-QAM modulation and SC-FDMA

Spectral regrowth in adjacent channels
Constellation errors

6 dB
2.5 dB

Keysight SystemVue and VSA
Drivers and Technical Challenges and Tradeoffs

Drivers
- Km range
- Long battery life

RF PA tradeoffs
- CMOS integration
- Power efficiency
- Linearity

Drivers
- Low-cost pervasive nodes
- High data rate
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Efficiency of digital PAs

- Achieve high-efficiency at back-off output power:
  - Switching operation

- Minimize **transistor power dissipation**:
  \[
  \frac{1}{T} \int V_{DS}(t) \cdot I_D(t) \cdot dt
  \]
DPA efficiency: switching operation

- Input voltage is a **square-wave** rather than a sinusoid
- Amplitude is modulated controlling the number of active units
- Lower power dissipation ($V_{DS}I_D$)
- **Class D⁻¹** operation

D. Chowdhury, JSSC, May 2012
Digital RF transmitters

- Digital PAs allow direct digital control of PA amplitude and phase
- Enable **high-efficiency** nonlinear PA topologies
- **Leveraging DSP** to correct for PA distortion, mismatch, spectral regrowth, etc.
- Possible in modern **CMOS processes** where DSP cost is much lower
Area efficiency

Digital Signal Processor:
- Signal conditioning
- Distortion correction

Conventional TX

Digital TX

Digital inverter chain

Digital PA

Area saving

Same area
In recent years, a new design paradigm has emerged which is based on digital PAs and digital RF transmitters. It allows the adoption of high-efficiency PAs, leveraging the low cost of DSP to correct for PA nonlinearity.
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A CMOS inverter driven by a square-wave produces an inverted square-wave $V_{DS}$.
Class-D power amplifier

- A CMOS inverter driven by a square-wave produces an inverted square-wave $V_{DS}$
- The series LC tank filters out odd harmonic current
- Output voltage across the load resistance $R$ is a sine-wave
- Theoretical 100% efficiency, as $V_{DS}I_D$ is always zero
How to \textit{digitally} control the amplitude of the sinusoid:

- Replicate device $N$ times
- Activate only $n < N$ device
- Selection of active cell done through \textit{gating} of the phase signal
Switched-Capacitor PA (or SCPA)

- Series cap is also split into the $N$ unit cells.

$N$ unit cells

$V_{dd}$

$C_i$

$R$

$C_i$

$L$

$EN$

$n$ active cells

$(N-n)$ inactive cells
Class-D DPA vs. SCPA

Class-D DPA

- **Dissipation** in the resistive divider

$n$ active cells

$R_{\text{mos}}$

Resistive divider

SCPA

- **No dissipation** in the capacitive divider

$n$ active cells

$(N-n)C_i$

Capacitive divider
- **Class-D DPA** efficiency degrades quickly at lower output power.
- **SCPA** maintains high efficiency across the output power range.

![Graph showing power efficiency comparison between Class-D DPA and SCPA](image-url)
Digital PAs vs. discrete PAs

- **DPAs** can beat performance of most discrete PAs
- DPAs can be integrated into CMOS SoC with much lower added cost
- **Discrete HBT PAs** still has performance advantage at much higher cost
Impact of CMOS scaling on SCPA

- Peak efficiency increases
- SCPA power density slightly degrades

Drain efficiency [%]

Transistor area [µm²]

SCPA area [µm²]

A. Truppi, to be presented at IEEE ISCAS Conf., 2018
Conclusions

- Many IoT use cases require **low cost** devices with **km range** and **multi-year battery life**
- The **new LTE standards for IoT** exploit cellular infrastructure to increase coverage and penetration
- NB-LTE-radio transceivers can be integrated in a small-footprint single-chip integrated in CMOS, but require **transmitters capable of delivering 20-to-23-dBm linear output power**
A new design paradigm has emerged in recent years, which is based on the adoption of high-efficient digital PAs, which leverage the low cost of DSP to correct for PA nonlinearity.

SCPAs in CMOS allow power efficiency and area suitable for LTE IoT applications.

CMOS scaling has a positive impact on SCPA power efficiency, though it slightly degrades power density.