A 350μW CMOS MSK Transmitter and 400μW OOK Super-Regenerative Receiver for Medical Implant Communications

Jose L. Bohorquez,
Joel L. Dawson,
Anantha P. Chandrakasan

Microsystems Technology Laboratories, Massachusetts Institute of Technology
Outline

- Motivation: MICS band
- Transmitter architecture
- Super-Regenerative Theory
- Receiver architecture
- Measurement results
Wireless Communications with Medical Implants
MICS band

- Medical Implant Communications Service
- Commissioned by FCC in 1999
- 402-405 MHz band
- 10 channels, 300 kHz bandwidth each
- Maximum EIRP = 25μW (-16dBm)

Observation:
Maximum output power: 25\(\mu\)W EIRP
MSK: Minimum Shift Keying

Direct Modulation Transmitter

- 0’s represented by $f_{LO} = f_0 - \Delta F$
- 1’s represented by $f_{HI} = f_0 + \Delta F$

![Diagram showing Direct Modulation Transmitter](image)

- Output Power (dBm)
  - Bit Rate = 200kB/s
  - MICS Mask Spec
  - 20dB
Oscillator Using Loop Antenna

\[ Z_{in} = jX_L + R_{loss} + R_{rad} \]

\[ Q = \frac{\omega_0 L}{R_{loss} + R_{rad}} \]

\[ \eta = \frac{R_{rad}}{R_{loss} + R_{rad}} \]

radiation efficiency
Digitally Controlled Oscillator

MICS requirements
Frequency range: 402-405MHz
Frequency stability: +/- 100ppm = +/- 40kHz

Design goal:
Frequency range: 392—415MHz
Frequency steps : < 2kHz
Digitally Controlled Oscillator

\[ L = 20\text{nH} \]

\[ f_{\text{max}} = 415\text{MHz} \quad \Rightarrow \quad C_{\text{min}} = 7.35\text{pF} \]

\[ f_{\text{min}} = 392\text{MHz} \quad \Rightarrow \quad C_{\text{max}} = 8.24\text{pF} \]

\[ \Delta f < 2\text{kHz} \quad \Rightarrow \quad \Delta C_{\text{min}} = 71\text{aF} \]

\[ \frac{C_{\text{max}} - C_{\text{min}}}{dC} \approx 12.5\times10^3 \]

14 bits of resolution
\[ f_0 \text{ is a nonlinear function of:} \]

\[ C_C, C_M, C_F, \text{ and } C_{\Delta F} \]
Capacitor Array Predistortion

![Graph showing the relationship between $C_F$ and $N_F$ with three lines: Linear, Predistorted, and PWL.](image)
Capacitor Array Predistortion

Predistortion and thermometer coding.

32 Columns

8 Rows

$C_F$

$N_F$

Linear
Predistorted
PWL
Capacitor Array Predistortion

DCO Frequency (MHz)

- Linear
- Predistorted
- PWL

\[ N_F \]
Capacitor Array Predistortion

![Graph showing freq step (Hz) vs. N_F with three lines: Linear, Predistorted, and PWL.]

- Linear
- Predistorted
- PWL
DCO Architecture
DCO Architecture

DCO Architecture

Direct Modulation Transmitter

 SPI

\( N_C^{<4:0>}, N_M^{<4:0>}, N_F^{<7:0>} \)

set \( f_{DCO} \)

\( N_{AF}^{<7:0>} \)

Data In, \( m(t) \)

<7:0>

DCO

PCB Antenna
Receiver Topology

Classical Homodyne Receiver

Direct Modulation Transmitter
Super Regeneration Theory

DCO

PCB Antenna

$I_{BIAS}$

$f_{BB}$

\[ G_m \cdot v_o(t) \]

\[ v_o(t) \]

\[ C \]

\[ L \]

\[ R \]
Super Regeneration Theory

\[ \mathcal{G}(t) \cdot v_o(t) \]

\[ i_a(t) \]

\[ v_o(t) \]

\[ f_{BB} \]

\[ f_{BB} \]

\[ I_{BIAS} \]

\[ DCO \]

\[ PCB \]

\[ Antenna \]

\[ L \]

\[ R \]

\[ C \]

\[ G_m(t) = K_G t \]
Root Locus for Time Varying $G_m$

$$G_m(t) = K_G t$$
Root Locus for Dynamic Damping Function
SRR Response to Sinusoidal Input

Sinusoidal Input Current

\[ i_a(t) = I_a \sin(\omega_a t + \phi_a) \]

\[ v_o(t) \propto I_a \cdot Z_0 \left( \sqrt{\frac{\pi}{2}} \frac{\omega_a}{\omega_s} \right) \left( e^{-\frac{\left(\frac{\omega_a - \omega_0}{2\omega_s}\right)^2}{2\tau_s^2}} \right) \sin(\omega_0 t + \phi_a) \]

Static Gain
Filtering
Time-dependent Gain
Oscillation
SRR Response to Sinusoidal Input

Sinusoidal Input Current
\[ i_a(t) = I_a \sin(\omega_a t + \phi_a) \]

\[ v_o(t) \propto I_a \cdot Z_0 \left( \sqrt{\frac{\pi}{2}} \frac{\omega_a}{\omega_s} \right) \left( e^{\frac{(\omega_a - \omega_0)^2}{2\omega_s^2}} \right) \left( e^{\frac{t^2}{2\tau_s^2}} \right) \sin(\omega_0 t + \phi_a) \]

Static Gain  Filtering  Time-dependent Gain  Oscillation

Time-dependent Gain
\[ t = 5\tau_s \]
\[ G_{dB} = 70\text{dB} \]

Sinusoidal Input Current
\[ i_a(t) = I_a \sin(\omega_a t + \phi_a) \]
Receiver Topology
Receiver Topology

![Diagram of Receiver Topology]

- $G_m(t)$
- $V_{EP}(t)$
- $V_{EM}(t)$

26
Receiver Topology

![Diagram of Receiver Topology]

- $V_{EP}(t)$
- $V_{EM}(t)$
- $V_{OS}$
- $V_{COMP}$

27
Receiver Topology

$V_{COMP}$

$NT$

$N_{COUNT}$

} Data = 1
Receiver Topology
Receiver Topology

\[ G_0 \quad G_m(t) \]

\[ t_a \quad t_b \]

\[ i_a(t) \]

\[ v_o(t) \]

short: 1  long: 0  short: 1
Receiver Topology
Receiver Topology
Receiver Topology
Die Photo

Fabricated in IBM 90nm CMOS

Active Area

1.0mm

0.5mm

1.0mm

2.0mm
Measured DCO Tuning Curves

\[ \Delta f_{DCO} / \Delta NC \approx 344 \text{kHz/step} \]

(NM=32, NF=128)

\[ \Delta f_{DCO} / \Delta NM \approx 47 \text{kHz/step} \]

(NC=32, NF=128)

\[ \Delta f_{DCO} / \Delta NF \approx 590 \text{Hz/step} \]

(NC=32, NM=32)

\( f_{DCO} \) at 37°C

\( f_{DCO} \) at 25°C

\( f_{DCO} \) at 45°C
Measured Spectral Mask

Bit Rate = 200kbps

Bit Rate = 120kbps

ΔMkr2 -175.50 kHz
-25.247 dB
Measured Receiver Time Signals

RF Signal at Antenna
DCO Output
Env. Det. Output
Comparator Output
Counter
Data Out (N_T=250)

<table>
<thead>
<tr>
<th>count</th>
<th>count</th>
<th>count</th>
<th>count</th>
<th>count</th>
</tr>
</thead>
<tbody>
<tr>
<td>173</td>
<td>335</td>
<td>327</td>
<td>177</td>
<td>342</td>
</tr>
<tr>
<td>Data Out = 1</td>
<td>Data Out = 0</td>
<td>Data Out = 0</td>
<td>Data Out = 1</td>
<td>Data Out = 0</td>
</tr>
</tbody>
</table>
$f_o = 403.65 \text{ MHz}$

Bit Rate=30kbps

$P_{DC} = 373\mu W$

$P_{RF} = -91\text{dBm}$

BER = 0

$P_{RF} = -98\text{dBm}$

BER = 0.13e-3

$P_{RF} = -101\text{dBm}$

BER = 10.3e-3
Conclusions

- Ultra-low power transceiver for medical implant communications
  
  **Transmitter**
  - consumes less than 350\(\mu\)W
  - uses direct MSK modulation
  - meets MICS spectral mask specifications

  **Receiver**
  - consumes less than 400\(\mu\)W
  - uses super-regeneration to demodulate OOK signals
  - -99dBm sensitivity at 30kbps (BER=10\(^{-3}\))
  - -93dBm at 120kbps (BER=10\(^{-3}\))

- Capacitor predistortion

- A PCB loop antenna as part of the DCO resonator
The authors acknowledge the support of the Focus Center for Circuit & System Solutions (C2S2), one of five research centers funded under the Focus Center Research Program, a Semiconductor Research Corporation Program.

IBM and TAPO for chip fabrication.