Wireless Integrated Circuits and Systems for Advanced Implantable/Wearable Medical Devices

Mehdi Kiani, Ph.D.
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Integrated Circuits and Systems Lab (ICSL)
Electrical Engineering Department, Pennsylvania State University
Advanced Implantable Medical Devices: Brain Computer Interface and Bioelectronics Medicine

Electroceuticals
Integrated Circuits and Systems Lab (ICSL) Research Projects

- Distributed Millimeter-Sized Brain Implants
- High-Resolution Implantable Gastric Interfacing
- Ultrasonic Wireless Power Transfer (WPT)
- Energy Harvesting
- Eyelid Drive System
Conventional Inductive Power Transmission Links

Key Parameters:

1. Power Efficiency \( (\eta = \eta_{PA} \times \eta_{Ind} \times \eta_{PM}) \) for large \( V_R \)

2. Voltage-Conversion Efficiency (VCE) = \( V_L/V_{R,peak} \) for small \( V_R \)
Current-Mode Resonant Power Delivery (CRPD)

- \( t_0 < t < t_1 \): SW is ON: Energy storage in the receiver inductor (\( L_2 \))
- \( t_1 < t < t_2 \): SW is OFF: Power delivery to \( C_L || R_L \)
  \( V_R \) jumps to \( V_D + V_L \)!
- \( t_2 < t < t_3 \): SW is OFF
## Conventional Voltage- and Current-Mode Integrated Power Managements

<table>
<thead>
<tr>
<th>Structures/Conditions</th>
<th>Load ((R_L))</th>
<th>Receiver-Coil Voltage ((V_R))</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Small</td>
<td>Large</td>
</tr>
<tr>
<td>Voltage-Mode (VM)</td>
<td>😊</td>
<td>😞</td>
</tr>
<tr>
<td>Current-Mode (CM)</td>
<td>😞</td>
<td>😊</td>
</tr>
</tbody>
</table>

Neither VM- nor CM structures can achieve the highest performance!
Proposed Voltage/Current-Mode Integrated Power Management (VCIPM) Concept

Sadeghi and Kiani, ISSCC17, JSSC17
Adaptive Reconfigurable VCIPM Chip with Self-Regulation

Sadeghi and Kiani, ISSCC17, JSSC17
Self-Regulation in Voltage Mode with Reverse Current

Conventional

Proposed

$\Delta V_{L,\text{dec}}$

$\Delta V_{L,\text{inc}}$

Sadeghi and Kiani, ISSCC17, JSSC17
Over-Voltage Protection in Voltage Mode with Reverse Current

**Conventional**

**Proposed**

[iLCM]
Measurement Setup and VCIPM Die

**Inductive Link Specification**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Inductance</td>
<td>250μH</td>
<td>Inductance</td>
<td>4.4μH</td>
</tr>
<tr>
<td># of Turns</td>
<td>35</td>
<td># of Turns</td>
<td>14</td>
</tr>
<tr>
<td>Diameter</td>
<td>17cm</td>
<td>Diameter</td>
<td>3cm</td>
</tr>
<tr>
<td>Quality factor</td>
<td>62</td>
<td>Quality factor</td>
<td>29</td>
</tr>
</tbody>
</table>

- 0.35-μm CMOS
- Freq. = 1 MHz
- $V_L = V_{DD} = 3.2$ V

Sadeghi and Kiani, ISSCC17, JSSC17
Measurements: Input Power Variation in Voltage Mode (VM)

$R_L = 100 \text{ k}\Omega$

Sadeghi and Kiani, ISSCC17, JSSC17
Measurements: VCIPM Mode Change

\[ R_L = 100 \text{ k}\Omega \]

Current Mode (CM):
- \( V_S \) was changed
- \( 4 \text{ V} \)

Voltage Mode (VM):
- \( 10 \text{ V} \)
- \( 50 \mu s \)

\( V_L \)

\( V_R \)

\( 3.2 \text{ V} \)

\( 1.2 \text{ V} \)

\( 5 \text{ V} \)

\( 3.3 \text{ V} \)
Measurements: Input Power Variation in Current Mode (CM)

$R_L = 100 \text{ k}\Omega$

Sadeghi and Kiani, ISSCC17, JSSC17
Measurements: Maximum VCE in CM

Max VCE = 3.5 V/V at $R_L = 100 \text{ k}\Omega$, $f_{sw} = 166.6 \text{ kHz}$
Measurements: Range Extension

VCIPM chip extended the range for 125%

$R_L = 100 \, k\Omega$
## VCIPM Chip Benchmarking

<table>
<thead>
<tr>
<th>Publication</th>
<th>ISSCC 2012</th>
<th>CICC 2015</th>
<th>ISSCC 2016</th>
<th>ISSCC 2015</th>
<th>ISSCC 2016</th>
<th>This Work</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMOS Tech (µm)</td>
<td>0.5</td>
<td>0.18</td>
<td>0.35</td>
<td>0.35</td>
<td>0.18</td>
<td>0.35</td>
</tr>
<tr>
<td>Application</td>
<td>WPT</td>
<td>WPT</td>
<td>WPT</td>
<td>WPT</td>
<td>Battery Charger</td>
<td>WPT</td>
</tr>
<tr>
<td>Rx Structure</td>
<td>VM</td>
<td>VM</td>
<td>VM</td>
<td>CM</td>
<td>CM</td>
<td>VM-CM</td>
</tr>
<tr>
<td>Freq (MHz)</td>
<td>13.56</td>
<td>15</td>
<td>6.78</td>
<td>2</td>
<td>0.05</td>
<td>1</td>
</tr>
<tr>
<td>Max VCE (V/V) @ R_L (kΩ)</td>
<td>0.84/1.4 @0.5</td>
<td>1.67 @0.77</td>
<td>~0.9 @0.0042</td>
<td>0.83 @0.1</td>
<td>-</td>
<td>3.55 @100</td>
</tr>
<tr>
<td>Max PCE (%) @ P_L (mW)</td>
<td>77 @19</td>
<td>87.7 @33</td>
<td>92.2 @6000</td>
<td>87.1 @220</td>
<td>61.2 @0.0028</td>
<td>77 @10</td>
</tr>
<tr>
<td>Self-Startup</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Self-Regulation</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Range Extension (%)</td>
<td>33</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>125</td>
</tr>
<tr>
<td>Line Regulation (%)</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>VM: 0.8 CM: 2.5</td>
</tr>
<tr>
<td>Load Regulation (%)</td>
<td>-</td>
<td>&lt;2.5</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>VM: 0.75 CM: 2.2</td>
</tr>
<tr>
<td>Active Area (mm²)</td>
<td>0.585</td>
<td>0.112</td>
<td>~4.77</td>
<td>~4.8</td>
<td>0.54</td>
<td>0.52</td>
</tr>
<tr>
<td>Over-Voltage Protection (OVP)</td>
<td>No</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Off-Chip Capacitors</td>
<td>4</td>
<td>3</td>
<td>3</td>
<td>4</td>
<td>-</td>
<td>2</td>
</tr>
</tbody>
</table>

Sadeghi and Kiani, ISSCC17, JSSC17
ASSIST Project: Efficient and Reconfigurable Circuit Interface for Multi-Modal Mechanical and Directed-Magnetic Energy Harvesting

Wrist-worn Harvester

Challenges:

- Decaying sinusoidal with small varying envelope
- Variable frequency
- Multi beams with unknown phases
- Modularity
- Dual modality

Prof. Susan Trolier-McKinstry
Prof. Shad Roundy
Reconfigurable Dual-Modal Shared-Intermediate-Inductor Harvesting Circuit
Acknowledgements

• Graduate Students
  ▪ Ahmed Ibrahim, Ph.D.
  ▪ Miao Meng, Ph.D.
  ▪ Hesam Sadeghi, Ph.D.
  ▪ Philip Graybill, Ph.D.
  ▪ Enhao Zhang, M.Sc.

• Funding Agencies
  ▪ National Science Foundation (NSF)
  ▪ National Institutes of Health (NIH)
Wearable Electronics with Conductive Textiles

Jan 18th, 2018
ASSIST Industry-Day Meet,
North Carolina State University

Our Team at FIU:
Prof. Shubhendu Bhardwaj
Prof. John Volakis
Mr. Dieff Vital (Grad Student)
Dr. Jingni Zhong (Post-Doc)
Electrical and Computer Engineering,
Florida International University, Miami, Florida

Active RF modules

Coupled RF systems

Passive antenna interfaces and power collectors
Potential Markets for Textile Electronics

- Concussion-detecting helmets
- Performance metrics (heart rate, oxygen levels, etc.)
- Sleep monitoring
- Location tracking
- Performance matrix tracking
- Integrated sensors in curtains, seats, carpets
- Security / Emergency
- Integrated communication interfaces and sensing tactical gears
- Sensors/ Antennas integrated in Car-seats/belts
- Enhanced WiFi/GSM connection
- Sensor-enabled Space Suits
Prior Technologies for Wearable

- Existing Sensors and wearables are rigid, breakable, bulky and obtrusive.

- Idea would be develop simple, integrative solutions on textile.

- Future of wearables will rely of less (not more) complexity.

Textile electronics suddenly provides whole lot of area to work with...

... and in the form of clothes, its always in our vicinity.
Textile Technology at FIU

- Assistant Yarn
- Color option
- Can be Aesthetically worn

Conductive thread
Cu core and Silver Coating

CAD Embroidery Machine

Antennas (Low loss antennas)

RF to DC converters (efficiency more than 70%)

- Communication interfaces and Power Harvesting systems using
  - RF Modules
  - Antennas
Ambient RF-Power Collection Use-cases

- Wifi routers and Laptops typically emit 0.1 W power
- Cell phones emit anywhere between 0.5 W to 3 W of power
- Effective paradigm would require ‘creative’ and ‘effective’ scavenging strategies.

Power Availability

- In home environment, under close proximity with laptops, wifi routers
  - Smart TVs, (with continuous video stream traffic)
  - Further optimization via strategic location of routers in frequently used areas – Kitchen, bedroom etc.

- Urban Outside environment
  - Urban areas with large number of ambient radiators in close vicinity.

- Desk areas with larger wifi traffic
A Simple Test to RF Measure Power

TEXTILE Spiral antenna (2.4dB gain) used in these test. Cell phone placed about 20cm from the spiral at broadside.

**Ambient RF Power**
- GSM: -40dBm
- Wifi: -30dBm

**During Phone Calls**
- GSM: -10dBm
- Wifi: -30dBm

**During Video Streaming**
- GSM: -40dBm
- Wifi: -15dBm

Higher power/distances would be realizable with higher gain + larger areas/gain+ polarization diversity + multiband antennas/harvesters.
Power expectations of upto mWatts range under:

- Urban outside areas
- Busy internet usable Home-/hospital environments

Integration with other modalities of harvesting:
- Breath harvester system (Dr. Chris Rahn’s)
- Wearable communication interfaces cec aSOC (Prof. Doug Werner and Prof. Ben Calhoun)
Integrating ground planes via use of Multiplayer structures

Passive antenna interfaces and power collectors
Measured Antennas (Patch)

- Extending the fabrication to multilayer structures.
- Patch antenna implemented on Fabric.
- ≈ 5 dBi gain / -30 dB Matching on textile (numbers close to PCB)

Measurements (FIU-Star Lab Chamber): high efficiency, agreement with simulation model
Losses: PCB v/s Embroidered

- New design paradigm and manufacturing rules are to be uncovered.
- Our study concluded that losses in embroidered circuits is a function of ‘direction of threads’.
- Loss minimization with ‘smart’ and ‘strategic’ embroidery steps is desired.
- Loss levels ultimately can be brought down to PCB regimes.
- Single layer, but broadband spiral design for RF communication interfaces.

On-textile Spiral Antenna, Fabricated: Oct/Nov 2017

Measurements (FIU-Star Lab Chamber): high efficiency, agreement with simulation model
Developments at FIU: Harvesters

**First Iteration** of Circuits with peak efficiency up to 40%

**Second Iteration** Harvester Circuits with Efficiency > 80%

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**Mechanical/Textile Process**

![Mechanical/Textile Process Diagram]

First Iteration:
- Circuit diagram with C1, R, C2, and a diode.
- Efficiency: 40%
- Image: Nov, 2017

Second Iteration:
- Circuit diagram with C1, R, C2, and a diode.
- Efficiency: > 80%
- Image: Jan, 2018

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**Graphs**

- RF-DC conversion efficiency vs. input power (P_in) in [dBm].
- Measured Textile Harvester vs. Simulations.

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**Summary**

- Progress in wearable textile electronics at FIU.
- Development of harvesting circuits.
- Improved efficiency from the second iteration.
On Going Work and Imminent Developments

Efforts:

- Array integration for large area harvester applications.
- Antenna miniaturization for enhanced packing density
- Power combining methods with other modalities
- Integration with Testbeds / wound healing.
More work to be done...

Conclusion:
- Conductive textiles have demonstrated, near PCB performance for small circuits and antenna interfaces.
- Efficient antenna / Harvesters already demonstrated.
- Expectation of 0.5 mW of power from array is realizable based on current data.

Barriers/ Next Endeavors:
- Integration with test beds.
- Demonstrate real power generation and establishing effective use cases.

Newly Established RFCOM-LAB at FIU engineering center