Resonant Inductive Coupling
Wireless Power Transfer

Elisenda Bou Balust
Outline

- Introduction
  - Energy Challenges in Nanotechnology
  - Resonant Inductive Coupling
  - RIC Scalability
- WPT-Based Active Energy Harvesting
- New Nano-Applications
  - Wireless Nano Sensor Networks
  - Claytronics
  - Nano-materials

All nodes need to be individually powered

Ambient Energy is not enough

ACTIVE energy harvesting

Resonant Inductive Coupling

Graphene Inductors
Introduction – Overview

Resonant Inductive Coupling is a type of Electromagnetic WPT

• Very promising efficiencies → Above 80% PTEff.
• Relative large distances → 3 times the tx/rx diameters.

Potential applications

• Electric vehicle charging
• Sensor networks
• Biomedical Implants
• Commercial electronic devices

• RIC is a very novel technology (< 4y)
**Introduction – Radiative & Non-Radiative behaviors**

- Electromagnetic WPT is the **transmission of EM fields**

- **Dual composition** of EM fields → a WPT system can **behave differently depending on the separation** between Tx and Rx
  - **Non-Radiative** (Near Field Region) → changes in current/charge distrib.
  - **Radiative** (Far Field Region) → changes in Magnetic/Electric fields.

- Where is the limit? Maxwell's equations for an **Infinitesimal Dipole**

\[
E_{e,\theta} = \frac{j\sigma_0 I_e dl \pi}{\lambda^2} \sin \theta \left[ - \left( \frac{\lambda}{2\pi r} \right)^3 - j \left( \frac{\lambda}{2\pi r} \right)^2 + \left( \frac{\lambda}{2\pi r} \right) \right] e^{-j\frac{2\pi r}{\lambda}} \\
E_{e,r} = \frac{2\pi \sigma_0 I_e dl}{\lambda^2} \cos \theta \left[ - j \left( \frac{\lambda}{2\pi r} \right)^3 + \left( \frac{\lambda}{2\pi r} \right)^2 \right] e^{-j\frac{2\pi r}{\lambda}} \\
E_{e,\phi} = 0
\]
Introduction – Radiative & Non-Radiative behaviors

- The region where all the contributions are equal is the boundary region between near and far-field.
- Separation not sharp → mid-range zone where radiative and non-radiative fields coexist.

- If $r << \lambda/2\pi$ Electrostatic & induction terms → non-radiative (reactive) near-field zone
- If $\lambda/2\pi < r < \lambda$ Induction & Radiation terms → mid-range
- If $r >> \lambda/2\pi$ Radiation term dominates → far-field zone
Introduction – EM. Inductive WPT

- First demonstrated in the *early 20th century* by Nikola Tesla, but thought impractical due to the undesirably large electric fields.

- In 1960 WPT EMI was reintroduced for biomedical applications (artificial hearts).

  - Since then, commonly used in *implantable devices*.
  - These inductors, such as typical transformers, required a *very short distance* between transmitter and receiver (*centimeters range*).
Introduction – Radiative & Non-Radiative behaviors

- **Later systems** implemented resonant transmitter coils
  - Each coil capacitively loaded forming a tuned LC resonating circuit at a common frequency.
  - Inductive links used in medical and consumer applications, but limited to the near-range (less than the dimensions of the coils).

**Resonant**

**Non-Resonant**
Introduction – Radiative & Non-Radiative behaviors

- In 2007, EMI links extended to larger ranges (several times the diameter of the antennas) stretching RIC in strong-coupling regime.
  - Demonstrated lighting a bulb at 2m with 40% Efficiency

- Strong coupled RIC attracted lot of attention
  - Harmless to humans (non-radiative).
  - No direct line-of-sight needed
  - Good efficiencies at several meters.

- RIC is foreseen as a key enabling technology for wireless power transfer in the following years.
Introduction – Radiative & Non-Radiative behaviors
Exploring RIC Scalability

- There are scattered examples of RIC for different frequencies/sizes of the coils

<table>
<thead>
<tr>
<th>Coil Diam. [cm]</th>
<th>f [MHz]</th>
<th>Turns</th>
<th>d/r_m</th>
<th>Eff [%]</th>
<th>P_{out} [W]</th>
<th>Ref</th>
<th>Year</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>(2.56,2.56)</td>
<td>10.38</td>
<td>20</td>
<td>2.34</td>
<td>60</td>
<td>1.21</td>
<td>[51]</td>
<td>2009</td>
<td>4 Coils</td>
</tr>
<tr>
<td>(2.56,2.56)</td>
<td>10.38</td>
<td>20</td>
<td>4.37</td>
<td>15</td>
<td>0.20</td>
<td>[51]</td>
<td>2009</td>
<td>4 Coils</td>
</tr>
<tr>
<td>(32,32)</td>
<td>10</td>
<td>5</td>
<td>25</td>
<td>1.3</td>
<td>-</td>
<td>[52]</td>
<td>2008</td>
<td>2 Coils</td>
</tr>
<tr>
<td>(4.6,4.6)</td>
<td>3.7</td>
<td>1</td>
<td>1.3</td>
<td>95</td>
<td>3000</td>
<td>[53]</td>
<td>2011</td>
<td></td>
</tr>
<tr>
<td>(3.0,3.0)</td>
<td>19.22</td>
<td>4</td>
<td>0.33</td>
<td>90</td>
<td>-</td>
<td>[54]</td>
<td>2010</td>
<td>Optimum Load</td>
</tr>
<tr>
<td>(6.4,2.2)</td>
<td>0.7</td>
<td>40</td>
<td>1.07</td>
<td>82</td>
<td>0.1</td>
<td>[31]</td>
<td>2011</td>
<td>AWG44 Litz Wire</td>
</tr>
<tr>
<td>(6.4,2.2)</td>
<td>0.7</td>
<td>40</td>
<td>1.73</td>
<td>72</td>
<td>0.08</td>
<td>[31]</td>
<td>2011</td>
<td>AWG44 Litz Wire</td>
</tr>
<tr>
<td>(100,100)</td>
<td>0.2</td>
<td>1</td>
<td>200</td>
<td>50</td>
<td>80</td>
<td>[44]</td>
<td>2010</td>
<td>Superconducting</td>
</tr>
<tr>
<td>(6,6)</td>
<td>10</td>
<td>1</td>
<td>2.5</td>
<td>85.7</td>
<td>200</td>
<td>[55]</td>
<td>2010</td>
<td>Optimum Load</td>
</tr>
<tr>
<td>(6,6)</td>
<td>10</td>
<td>1</td>
<td>5</td>
<td>42.3</td>
<td>70</td>
<td>[55]</td>
<td>2010</td>
<td>Optimum Load</td>
</tr>
<tr>
<td>(6,2)</td>
<td>0.7</td>
<td>-</td>
<td>1.73</td>
<td>36</td>
<td>0.05</td>
<td>[56]</td>
<td>2004</td>
<td>Non Resonant</td>
</tr>
<tr>
<td>(2.4,2)</td>
<td>2</td>
<td>32</td>
<td>1</td>
<td>40</td>
<td>-</td>
<td>[57]</td>
<td>2010</td>
<td></td>
</tr>
</tbody>
</table>
Exploring RIC Scalability

RIC efficiency as a function up to 10 times the radii of the antennas.
WPT-Based Active Energy Harvesting

- EH would allow successful deployment of battery-less self-powered Wireless sensor networks (WSN) nodes, biomedical implants and body area networks.

- Despite EH is already successful in niche applications, the most ubiquitous source of energy, EM harvesting, is still not feasible.

- To circumvent the current short and mid-terms limits of EH technologies, artificially increase ambient energy, active radiation of a single energy source (energy broadcast).

- The high-efficiency WPT RIC systems become of strong interest as an enabler of active electromagnetic WPT based energy harvesting.
Nano-Materials: Graphene-Based coils

- How to increase the range of the system?
  - Decrease losses (improve Q)
- To reduce losses, several technologies have been proposed:
  - Superconducting dielectric-less coils
    - ohmic losses negligible
    - More complexity
  - Litz-Wire Coils
    - minimize skin & proximity effects
    - Low frequencies 1-2MHz.

- Because high frequency/low loss coils are necessary in Wireless Power and Data Systems, we propose to use new materials such as **graphene-based nano-coils** for the design and implementation of active energy harvesting systems.
Nano-Materials: Graphene-Based coils

“High-Frequency Behavior of Graphene-Based Interconnects—Part II: Impedance Analysis and Implications for Inductor Design” Deblina Sarkar, Student Member, IEEE, Chuan Xu, Student Member, IEEE, Hong Li, Student Member, IEEE, and Kaustav Banerjee, Senior Member, IEEE

Diameter = 200 μm, N=4, Wire width= 8 μm, Wire thickness $H = 2 \, \mu m$
Nano-Materials: Graphene-Based coils

Same graphene-doped coils simulated with Finite Element Field-Solver FEKO

Differences with previous results due to the non-ideal dielectric substrate used.
Wireless Nano-Sensor Networks

. One of the potential applications of RIC systems is **WPT networks**.

. Due to the behavior of RIC systems, this WPT method is very suitable for broadcast applications where coils could be active (resonant) or inactive (non-resonating) without inquiring in significant losses to the transmitter's power.

. Because in RIC systems, antennas act as transmitter and receiver at the same time, WPT meshed networks could be implemented and miniaturized.
Wireless Nano-Sensor Networks

- RIC inductors can operate as transmitter and receiver at the same time
- Increase in distance range by using the different nodes as repeaters.
Claytronics – Intelligent Matter

- RIC can be used as a potential means for providing power to catoms without using electrical connections.

- WPT to multiple small receivers has been demonstrated by Prof. Goldstein.

*Magnetic Resonant Coupling As a Potential Means for Wireless Power Transfer to Multiple Small Receivers*  Benjamin L. Cannon, James F. Hoburg, Daniel D. Stancil and Seth Copen Goldstein
Conclusions

- In WNSN and claytronics, every node needs to be **powered individually**.
- The challenge to power this nodes using energy harvesting is still unsolved.
- We propose to use **Active Energy Harvesting** to circumvent the energy requirements.
- Because of its scalability in frequency and size, **Resonant Inductive Coupling** is proposed as a method to perform Active Energy Harvesting in the nano-scale.
- **Graphene based inductor antennas** have been simulated to act as the transmitters and receivers of such a RIC system.