Dual-Band Multi-Receiver Wireless Power Transfer: Architecture, Topology, and Control

Ming Liu, Minjie Chen
Princeton University
Dual-Band Wireless Power Transfer Applications

**LF(kHz):** High power, High efficiency;  **HF(MHz):** High spatial freedom, Compact size;

One transmitter can support LF/HF receivers

One receiver can pick up power from LF/HF transmitters
Challenges for Dual-Band Wireless Power Transfer

- Co-location of receivers induces large impedance variation
- HF inverters, e.g., Class-E, are usually sensitive to load impedance variation

Existing compensation: switched capacitor tunable matching network
Steering more power towards capacitive branch with inductive load.

Steering more power towards inductive branch with capacitive load.

Maintain pure resistive load for both inverters with wide reactance variation range.
Amplitude and Phase Modulation

Amplitude Ratio $K_{LC}$

$$K_{LC} = \left| \frac{V_L}{V_C} \right| = \left| \frac{X_O + X_{tx}}{X_{tx} \cos (\Delta_{LC}) + R_{tx} \sin (\Delta_{LC})} \right|.$$ 

Phase Difference $\Delta_{LC}$

$$\Delta_{LC} = \Phi_L - \Phi_C = \arcsin \sqrt{\frac{X^2_O}{X^2_{tx} + R^2_{tx}}}.$$ 

- Both inverters always see pure resistive load and adaptively split the power.
Schematic of the Dual-Band Transmitter

• LF and HF systems share the switches Q1, Q2, Q3, Q4.
Dual-Band Reconfigurable Receiver with Low Switch Count

- Share the switches Qr1 and Qr2 at LF and HF, less switch count.
Performance Analysis of the Dual-Band Rectifier

- Lower voltage stress
- Lower THD
A Dual-Band Multi-Receiver WPT Prototype

Dual Band Operation: 100 kHz and 13.56 MHz
Power Rating of TX: 65 W at both frequencies
Input/Output Voltage: 50V/20 V at both frequencies
Spacing: 2.8 cm distance, up to 5 cm misalignments
Experimental Waveforms of the Inverters

\[ Z_{tx} = 14 - 26j \, \Omega \]

VDS of Class E Inverters with RSN

VDS of Class E Inverters without RSN
Experimental Waveforms of the Rectifier

$V_{DS}$ at 13.56MHz

$V_{DS}$ at 100kHz

20V/div, 40ns/div

10V/div, 2µs/div
Decoupled Power Modulation of LF and HF Operation

- In the power modulation, the reactance compensation is achieved at the same time.
Efficiencies with LF and HF Systems Working Together

- Efficiency can be further improved by improving the quality factor of the coupling coils.

### Efficiency vs. LF power modulation

<table>
<thead>
<tr>
<th>Phase of two LF inverters (degree)</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>60%</td>
</tr>
<tr>
<td>72</td>
<td>65%</td>
</tr>
<tr>
<td>144</td>
<td>70%</td>
</tr>
<tr>
<td>216</td>
<td>75%</td>
</tr>
<tr>
<td>288</td>
<td>80%</td>
</tr>
<tr>
<td>360</td>
<td>75%</td>
</tr>
</tbody>
</table>

### Efficiency vs. HF power modulation

<table>
<thead>
<tr>
<th>Duty cycle of two dc-dc converters</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.2</td>
<td>70%</td>
</tr>
<tr>
<td>0.4</td>
<td>65%</td>
</tr>
<tr>
<td>0.6</td>
<td>60%</td>
</tr>
<tr>
<td>0.8</td>
<td>75%</td>
</tr>
</tbody>
</table>

- Efficiency can be further improved by improving the quality factor of the coupling coils.
Impedance and Efficiency vs. Misalignment at MHz

- Up to 13% of efficiency improvements with the high misalignment, (e.g., 5cm).
Measured Waveforms vs. Misalignment

V<sub>DS</sub> of Class E Inverters without RSN control

V<sub>DS</sub> of Class E Inverters with RSN control

- In the close-loop control: K<sub>LC</sub> and Δ<sub>LC</sub>, are automatically selected from a look-up table according to the measured dc power ratio P<sub>L</sub>/P<sub>C</sub> of the HF inverters.
Conclusion

• A dual-band high performance transmitter with a reactance steering network which can maintain ZVS operation for the HF inverters across a wide load variation range;

• A dual-band reconfigurable receiver which functions as a half bridge rectifier at LF and functions as a Class-E rectifier at HF; This dual-band receiver has low component count and can achieve high power density;

• An online load impedance estimation algorithm and a look-up table based close loop control to maintain ZVS operation of the HF inverters;

• A complete demonstration of the dual-band WPT system with lower component count, higher efficiency, and higher power-density.
Thank you!