Hardware Design
of Wireless Power Products

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Outline

• General System Design
• Designing for High Efficiency
• Wireless Fast Charge Solution
• Safety Consideration
• Merging Applications
Wireless Power System Overview

72% → 80%

Base Station
- Input Power
- DC/DC Converter
- Controller & Protection
- Power Inverter
- Communication
- Transmitter

Power

Messages

Mobile Device
- Synchronous Rectifier
- DC/DC Regulator
- Communication
- Controller & Protection
- Receiver

90% 90% 90%
Transmitter Design Requirements

- **Limited power transmitter types approved by WPC**
  - LP Type A Design: A1 ~ A34
  - LP Type B Design: B1 ~ B7
  - Medium Power Design: MPA1 ~ MPA5

- **Power control methods**
- **Operating frequency (100kHz~205kHz)**
- **Communication protocol**

Reference: WPC PC0 specification V1.2.2
Coil & Positioning

A10 19V Tx

A6 12V Tx

B1 20V Tx
**LP Type-A Transmitter Design (A1-A34)**

<table>
<thead>
<tr>
<th>Type</th>
<th>Vin (V)</th>
<th>Freq (kHz)</th>
<th>Lp (uH)</th>
<th>Cp (nF)</th>
<th>Vcp (Vpp)</th>
<th>Positioning</th>
<th>Inverter</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>19</td>
<td>110-205</td>
<td>24</td>
<td>100</td>
<td>200</td>
<td>Guided</td>
<td>Half-Bridge</td>
</tr>
<tr>
<td>A2</td>
<td>3-12</td>
<td>140</td>
<td>24</td>
<td>200</td>
<td>50</td>
<td>Free</td>
<td>Full-Bridge</td>
</tr>
<tr>
<td>A3</td>
<td>3-12</td>
<td>105-140</td>
<td>16.5</td>
<td>180</td>
<td>100</td>
<td>Free</td>
<td>Full-Bridge</td>
</tr>
<tr>
<td>A4</td>
<td>5-11</td>
<td>110-180</td>
<td>24</td>
<td>100</td>
<td>40</td>
<td>Free</td>
<td>Full-Bridge</td>
</tr>
<tr>
<td>A5</td>
<td>5</td>
<td>110-205</td>
<td>6.3</td>
<td>400</td>
<td>100</td>
<td>Guided</td>
<td>Full-Bridge</td>
</tr>
<tr>
<td>A6</td>
<td>12</td>
<td>115-205</td>
<td>11.5</td>
<td>147</td>
<td>100</td>
<td>Free</td>
<td>Half-Bridge</td>
</tr>
<tr>
<td>A7</td>
<td>3-12</td>
<td>105-140</td>
<td>13.6</td>
<td>180</td>
<td>100</td>
<td>Free</td>
<td>Full-Bridge</td>
</tr>
<tr>
<td>A8</td>
<td>5-11</td>
<td>110-180</td>
<td>24</td>
<td>100</td>
<td>100</td>
<td>Free</td>
<td>Full-Bridge</td>
</tr>
<tr>
<td>A9</td>
<td>2-15</td>
<td>105-115</td>
<td>24</td>
<td>100</td>
<td>100</td>
<td>Guided</td>
<td>Full-Bridge</td>
</tr>
<tr>
<td>A10</td>
<td>19</td>
<td>110-205</td>
<td>24</td>
<td>100</td>
<td>200</td>
<td>Guided</td>
<td>Half-Bridge</td>
</tr>
<tr>
<td>A11</td>
<td>5</td>
<td>110-205</td>
<td>6.3</td>
<td>400</td>
<td>100</td>
<td>Guided</td>
<td>Full-Bridge</td>
</tr>
</tbody>
</table>

Note: Type A1, A5 and A9 have been deprecated.
# LP Type-B Transmitter Design (B1-B7)

<table>
<thead>
<tr>
<th>Type</th>
<th>Vin (V)</th>
<th>Freq (kHz)</th>
<th>Lp (μH)</th>
<th>Cm (nF)</th>
<th>Vcm (Vpp)</th>
<th>Positioning</th>
<th>Inverter</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>0-20</td>
<td>105-113</td>
<td>8.1-9.6</td>
<td>300/200</td>
<td>36</td>
<td>Free</td>
<td>Half-Bridge</td>
</tr>
<tr>
<td>B2</td>
<td>0-20</td>
<td>105-113</td>
<td>11.7-12.3</td>
<td>256/147</td>
<td>36</td>
<td>Free</td>
<td>Half-Bridge</td>
</tr>
<tr>
<td>B3</td>
<td>12</td>
<td>105-113</td>
<td>11.6-13.5</td>
<td>222/133</td>
<td>36</td>
<td>Free</td>
<td>Full-Bridge (Phase)</td>
</tr>
<tr>
<td>B4</td>
<td>12</td>
<td>105-113</td>
<td>8.8-9.5</td>
<td>300</td>
<td>36</td>
<td>Free</td>
<td>Full-Bridge (Phase)</td>
</tr>
<tr>
<td>B5</td>
<td>12</td>
<td>96</td>
<td>8.8-9.5</td>
<td>356/82</td>
<td>36</td>
<td>Free</td>
<td>Full-Bridge (Phase)</td>
</tr>
<tr>
<td>B6</td>
<td>5</td>
<td>125-135</td>
<td>5.8-6.2</td>
<td>1000</td>
<td>25</td>
<td>Free</td>
<td>Full-Bridge (Phase)</td>
</tr>
<tr>
<td>B7</td>
<td>15</td>
<td>115</td>
<td>6.1</td>
<td>300/100</td>
<td>40</td>
<td>Free</td>
<td>Full-Bridge (Phase)</td>
</tr>
</tbody>
</table>
Examples of Wireless Power Transmitters

- Single Coil 5V Tx (au)
- Single Coil 12V Tx (CP)
- A11 Coil 5V Tx (Samsung)
- 3-Coils 12V Tx (Nokia DT-900)
- Type-B Array Coil 12V Tx (Sanwa)
- Moving Coil 12V Tx (Panasonic)
Receiver Design Requirements

- More freedoms on Receiver design
- Dual resonant circuit
- Output Power level, Received Power
- Load disconnection (OVP, UVP, OCP, OTP)
- Communication protocol

\[ f_s = \frac{1}{2\pi \sqrt{L_s \cdot C_s}} = 100^{\pm x} \text{ kHz} \]

\[ f_d = \frac{1}{2\pi \sqrt{L_s \cdot \left(\frac{1}{C_s} + \frac{1}{C_d}\right)^{-1}}} = 1000^{\pm 10\%} \text{ kHz} \]
In-band Communication

- FSK modulation from TX to RX
  - Option for MP
  - Bi-direction communication
- ASK modulation from RX to TX
  - Capacitive load modulation
  - Resistive load modulation
Examples of Wireless Power Receivers

- WPT Receiver EVB
- WPT Receiver on board
- iPhone 4 sleeve
- iPhone 6 sleeve
- WPT Receiver inside
Outline

- General System Design
- Designing for High Efficiency
- Wireless Fast Charge Solution
- Safety Consideration
- Merging Applications
Equivalent Circuit of Coupled Coils

\[
V_p = j\omega(L_p - M) \cdot I_p + j\omega M \cdot (I_p - I_s)
\]

\[
j\omega M \cdot (I_p - I_s) = j\omega(L_s - M) \cdot I_s + Z_L \cdot I_s
\]

\[
j\omega M \cdot I_p = (R_s + j\omega L_s + Z_L) \times I_s
\]

\[
V_P = (R_p + j\omega L_p) \cdot I_p + Zeq \cdot I_p
\]

\[
Zeq = \frac{(\omega M)^2}{Z_L + (R_s + j\omega L_s)}
\]
Coil Link Efficiency

Coil Link Efficiency:

\[
\text{Eff}_{\text{LINK}} = \frac{\text{Re}\{\text{Ze}_q\}}{R_p + \text{Re}\{\text{Ze}_q\}} \times \frac{\text{Re}\{Z_L\}}{R_s + \text{Re}\{Z_L\}}
\]

- **Rp** = 24\(\mu\)H
- **Rs** = 0.23\(\Omega\)
- **Lp** = 24\(\mu\)H
- **Ls** = 13\(\mu\)H
- **M** = 7.2\(\mu\)H
- **f** = 120kHz

Efficiency vs. RL (Ohm) graph

RL (Ohm):

0% 10% 20% 30% 40% 50% 60% 70% 80% 90% 100%

Efficiency:

1 10 100 1000
Maximum Coil Link Efficiency

**Optimal Output Impedance**

\[ Z_{L\_OPT} = R_s \cdot \sqrt{1 + k^2 Q_1 Q_2} - j \omega L_s \]

**Maximal Link Efficiency:**

\[ \text{Eff}_{\text{LINK}\_MAX} = \frac{k^2 Q_1 Q_2}{\left( 1 + \sqrt{1 + k^2 Q_1 Q_2} \right)^2} \]

Coil Link Efficiency Estimation

<table>
<thead>
<tr>
<th>Rx coil</th>
<th>k</th>
<th>Q1</th>
<th>Q2</th>
<th>Eff_max</th>
<th>R_L_opt (Ohm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Coil-A</td>
<td>0.551</td>
<td>82.8</td>
<td>45.4</td>
<td>94.2%</td>
<td>5.8</td>
</tr>
<tr>
<td>Coil-B</td>
<td>0.609</td>
<td>60.0</td>
<td>31.6</td>
<td>92.7%</td>
<td>6.6</td>
</tr>
<tr>
<td>Coil-C</td>
<td>0.557</td>
<td>79.2</td>
<td>22.6</td>
<td>91.9%</td>
<td>9.4</td>
</tr>
<tr>
<td>Coil-D</td>
<td>0.621</td>
<td>59.6</td>
<td>32.0</td>
<td>92.9%</td>
<td>8.2</td>
</tr>
</tbody>
</table>
Receiver Power Stage

- Thermal is the key factor
- Higher voltage level for higher power
- Single stage switching charger
High Efficiency Design Considerations

- Lower $R_{DS\_ON}$ for lower $P_{CON\_LOSS}$
- Low Qg to reduce Driving Loss
- Good ZCD & Mode control is required
- Low ESR (NP0/C0G)
- Low Rs_ac
- High Q-factor Coil
- LDO has higher Eff. than Buck converter
- Current Sense Resistor
- Low $I_Q$ & Capacitive modulation

Integrated Receiver
Integrated Receiver in One Chip

Protection

Power Stage

MCU Controller

(Refer to RT1650 datasheet)
Integrated Receiver

WL-CSP-48B
3 mm x 3.4 mm

Coil

RT1650

Load

WL-CSP-48B 3 mm x 3.4 mm

your power partner.

RICHTEK
Programmable Synchronous Rectifier

- Asynchronous Mode
- Half-Synchronous Mode
- Full-Synchronous Mode

- $V_{AC1} - V_{AC2}$ (2V/div)
- $V_{RECT}$ (2V/div)
- $I_{AC1}$ (1A/div)

Rectifier Efficiency

- Efficiency (%) vs Output Current (A)
- 5W
- 7.5W
Receiver Efficiency Measurement

Receiver Efficiency: from Rx AC in to Rx DC out

\[ P_{IN} \rightarrow P_{OUT} \]

\( V_{OUT} \) = 5V

Receiver Efficiency with WPC A1 Tx

Efficiency (%) vs. Output Power (W)

- RT1650
- CMPETR
Measured Thermal Performance

>10 °C reduction on receiver IC at 5W output power compared to competitor IC
# HB/FB Inverter Comparison

<table>
<thead>
<tr>
<th></th>
<th>Half-Bridge</th>
<th>Full-Bridge</th>
</tr>
</thead>
<tbody>
<tr>
<td>Resonator Voltage</td>
<td>1/2</td>
<td>1</td>
</tr>
<tr>
<td>Resonator Current</td>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>SW Conduction Loss</td>
<td>2 (-) (-)</td>
<td>1 (+) (+)</td>
</tr>
<tr>
<td>SW Driving Loss</td>
<td>1 (+)</td>
<td>2 (-)</td>
</tr>
</tbody>
</table>
High Efficiency Design Considerations

• Half-Bridge Inverter

- Buck Converter for power control
- Low ESR Cap (NP0/C0G)
- Low Rs_ac High Q-factor Coil
- Buck has better Eff. for high Vin
- Lower $R_{DS\_ON}$ for lower $P_{CON\_LOSS}$
- Low Qg to reduce Driving Loss
- Lower $I_Q$
Integrated Solution for A10 & A11

A10 Design

- MCU
- Controller
- Power Inverter Driver
- Buck Converter
- Current Sense

A11 Design

- MCU
- Controller
- Power Inverter
- DC-DC Regulator
- Current Sense

(Refer to RT3181 datasheet)
Measured System Efficiency

System Efficiency

<table>
<thead>
<tr>
<th>Type</th>
<th>Inverter</th>
<th>Vin</th>
<th>Eff. at 5W</th>
</tr>
</thead>
<tbody>
<tr>
<td>A10</td>
<td>HB</td>
<td>19V</td>
<td>81%</td>
</tr>
<tr>
<td>A1</td>
<td>HB</td>
<td>19V</td>
<td>80%</td>
</tr>
<tr>
<td>A6</td>
<td>HB</td>
<td>12V</td>
<td>76%</td>
</tr>
<tr>
<td>A11</td>
<td>FB</td>
<td>5V</td>
<td>79%</td>
</tr>
</tbody>
</table>

System Efficiency: from Tx DC in to Rx DC out

\[ V_{OUT} = 5V \]
Outline

• General System Design
• Designing for High Efficiency
• Wireless Fast Charge Solution
• Safety Consideration
• Merging Applications
## Fast Charging Specification

<table>
<thead>
<tr>
<th>Mode</th>
<th>Qualcomm QC2.0</th>
<th>Mediatek PE</th>
<th>Mediatek PE+</th>
<th>Mediatek PE+2.0</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Output Voltage</strong></td>
<td>5V/9V/12V (Class A)</td>
<td>3.6V~5V</td>
<td>5V/7V/9V/12V</td>
<td>5V~20V (500mV/step)</td>
</tr>
<tr>
<td><strong>Communication Interface</strong></td>
<td>USB D+ &amp; D-</td>
<td>USB $V_{BUS}$</td>
<td>USB $V_{BUS}$</td>
<td>USB $V_{BUS}$</td>
</tr>
<tr>
<td><strong>Protocol</strong></td>
<td>Voltage Level</td>
<td>Current modulation</td>
<td>Current modulation</td>
<td>Current modulation</td>
</tr>
<tr>
<td><strong>Requirement with RT3180 receiver</strong></td>
<td>Decoder IC (integration of H/W &amp; S/W)</td>
<td>No (software improvement)</td>
<td>No (software improvement)</td>
<td>No (software improvement)</td>
</tr>
<tr>
<td><strong>Remark</strong></td>
<td>Low cost Easy implement</td>
<td>Low cost Easy implement (+)</td>
<td>Low cost Easy implement (+)</td>
<td>Low cost Easy implement (+)</td>
</tr>
</tbody>
</table>
PE+ Wireless Fast Charging Solution

Wireless Medium Power TX

Rectifier
DC-DC Converter
Controller & Protection
Charger

Adjust output voltage depends on current pattern at \( V_{BUS} \)

Current pattern for increasing output voltage

(Refer to RT3180/RT3181 datasheet)
PE+2.0 Wireless Fast Charging Solution

Adjust output voltage depends on current pattern at $V_{BUS}$

Wireless Medium Power TX

RT3180

- Rectifier
- DC-DC Converter
- Controller & Protection

Charger

$V_{BUS}$

GND

5.5V - 6V - 6.5V

5V

WDT time out

20V - 19.5V - 19V

12.5V

WDT time out

*0 Watch Dog Timer

Change voltage one step sequentially by current pattern.

Change voltage directly by current pattern.

Returned when WDT expired.

(Refer to RT3180/RT3181 datasheet)
QC2.0 Wireless Fast Charging Solution

Adjust output voltage depends on D+ & D- signal

Protocol Decoder for D+, D-

<table>
<thead>
<tr>
<th>Vout</th>
<th>5V</th>
<th>9V</th>
<th>12V</th>
</tr>
</thead>
<tbody>
<tr>
<td>D+</td>
<td>0.6V</td>
<td>3.3V</td>
<td>0.6V</td>
</tr>
<tr>
<td>D-</td>
<td>GND</td>
<td>0.6V</td>
<td>0.6V</td>
</tr>
<tr>
<td>V1</td>
<td>1</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>V2</td>
<td>1</td>
<td>1</td>
<td>0</td>
</tr>
</tbody>
</table>

(Refer to RT3180/RT3181 datasheet)
Receiver Efficiency and Power Loss

- Higher $V_{OUT}$ brings higher efficiency and lower power loss
- Higher $V_{OUT}$ could support higher output power level

![Graph showing efficiency and power loss vs output power for different $V_{OUT}$ values]
Outline

• General System Design
• Designing for High Efficiency
• Wireless Fast Charge Solution
• Safety Consideration
• Merging Applications
Safety Design Considerations

- Foreign Object Detection
- EMI/RFI Management
- Complete Protection functions
  - OVP
  - UVLO
  - OCP
  - OTP
  - In-band communication
  - Sleep mode operation

(Measured on v1.0 transmitter)
Foreign Object Detection

• Power Loss Method

\[
P_{\text{Loss}} = P_{\text{PT}} - P_{\text{PR}}
\]

<table>
<thead>
<tr>
<th>Maximum Power [W]*</th>
<th>Maximum $P_{\Delta}$ [mW]</th>
</tr>
</thead>
<tbody>
<tr>
<td>0...5</td>
<td>350</td>
</tr>
<tr>
<td>5...10</td>
<td>500</td>
</tr>
<tr>
<td>10...15</td>
<td>750</td>
</tr>
</tbody>
</table>

* The lower limit is not included in the range.

• AVID FOD transmitter with 20mW accuracy
Foreign Object Detection

- **Q-Factor Method**
  - The change of Primary coil Q-factor
  - Detect Q-factor before Power Transfer Phase
  - Receiver send FOD Status Packet in Negotiation phase
FCC Requirements

- FCC Part 18 (Consumer devices)
  - In-band communication for power management
- FCC Part 15 (Intentional radiator)
  - Class A (industrial, commercial and engineering devices)
  - Class B (consumer devices)
  - Second frequency used for communication

<table>
<thead>
<tr>
<th>Conducted Emissions</th>
<th>Frequency (MHz)</th>
<th>Quasi-Peak Limit (dBuV)</th>
<th>Average Limit (dBuV)</th>
</tr>
</thead>
<tbody>
<tr>
<td>FCC Part 15 (Class A)</td>
<td>0.15 – 0.5 0.5 – 30</td>
<td>79 73</td>
<td>66 60</td>
</tr>
<tr>
<td>FCC Part 15 (Class B)</td>
<td>0.15 – 0.5 0.5 – 5 5- 30</td>
<td>66 to 56* 56 60</td>
<td>56 to 46* 46 50</td>
</tr>
<tr>
<td>FCC Part 18</td>
<td>0.15 – 0.5 0.5 – 5 5- 30</td>
<td>66 to 56* 56 60</td>
<td>56 to 46* 46 50</td>
</tr>
</tbody>
</table>

* Decreases with the logarithm of the frequency.
European Union Requirements

- **EN55011 (ISM Charging device)**
- **ETSI Test Standard EN 300 330-1**
  - If data communication function included at the same frequency
  - EMI design becomes challenge for frequency >148.5kHz

Table 6: H-field limits at 10 m

<table>
<thead>
<tr>
<th>Frequency range (MHz)</th>
<th>H-field strength limit ($H_f$) dBA/m at 10 m (note 8)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.009 ≤ f &lt; 0.090</td>
<td>72 descending 3 dB/oct above 0.03 MHz or according to note 1 (see note 5)</td>
</tr>
<tr>
<td>0.09 ≤ f &lt; 0.119</td>
<td>42</td>
</tr>
<tr>
<td>0.119 ≤ f &lt; 0.135</td>
<td>66 descending 3 dB/oct above 0.119 MHz or according to note 1 (see notes 3 and 5)</td>
</tr>
<tr>
<td>0.135 ≤ f &lt; 0.140</td>
<td>42</td>
</tr>
<tr>
<td>0.140 ≤ f &lt; 0.1485</td>
<td>37.7</td>
</tr>
<tr>
<td>0.1485 ≤ f &lt; 30</td>
<td>-5 (see note 4)</td>
</tr>
<tr>
<td>0.315 ≤ f &lt; 0.600</td>
<td>-5</td>
</tr>
<tr>
<td>3.155 ≤ f &lt; 3.400</td>
<td>13.5</td>
</tr>
</tbody>
</table>
EMI Design Considerations

- High Frequency Model

\[ \frac{dv}{dt} \frac{di}{dt} \]

Ringing at switching node

Trace inductance

ESL

C_{GD}

C_{GS}

C_{OSS}
Solutions for Reducing Switching Noise

Input filter & common choke could be option

Smart Driver with programmable capability

Input capacitor placement

Integrated MOSFET has lower ESL

Keep small loop for the resonator

Good PCB layout & ground plane are helpful
EMI Measurement of WPT Product

• Combination of Transmitter and Receiver
• Worst case charging setup
• Measurement results relating to corresponding limit
Outline

• General System Design
• Designing for High Efficiency
• Wireless Fast Charge Solution
• Safety Consideration
• Merging Applications
Emerging Applications

- Smart cup
- Wireless Robotic Fish Aquarium
- Wireless fish finder

Emerging Applications

• Wireless charging
• Sensors
• Wireless connection
• Recording
• Training

Reference: www.adidas.com, http://www.94fifty.com,

94Fifty Smart Sensor Basketball

Adidas miCoach Smart Ball
Emerging Applications

• Innovation from BB-8
• Added value to toys
• Wireless powered toys will be more

Reference: www.luxatic.com
Emerging Applications

• Wireless charging stations for mini-UAVs
• Reduce weight
• Extending service area

If Mini-UAVs standby on wireless charging stations, then ...

Summary

- WPC provides a good platform for designers & users
- Higher efficiency is achievable for WPT
  - End-to-end system efficiency > 80%
- Wireless power is able to support Fast-Charge
  - Adjustable $V_{OUT}$, $P_{O\_MAX}=15W$
- To meet safety design requirement is Must
- Wireless power will bring more applications
RICHTEK your power partner.

thank you.