WIRELESS POWER
CONSORTIUM

Qi Specification

Power Delivery

Version 1.3

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RELEASE HISTORY

Specification Version	Release Date	Description
1.3	January 2021	Initial release of this document.

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1 General

The Wireless Power Consortium (WPC) is a worldwide organization that aims to develop and promote global standards for wireless power transfer in various application areas. A first application area comprises flat-surface devices such as mobile phones and chargers in the Baseline Power Profile (up to 5 W) and Extended Power Profile (above 5 W).

1.1 Structure of the Qi Specification

General documents

- Introduction
- Glossary, Acronyms, and Symbols

System description documents

- Mechanical, Thermal, and User Interface
- Power Delivery
- Communications Physical Layer
- Communications Protocol
- Foreign Object Detection
- NFC/RFID Card Protection
- Authentication Protocol

Reference design documents

- Power Transmitter Reference Designs
- Power Receiver Design Examples

Compliance testing documents

- Power Transmitter Test Tools
- Power Receiver Test Tools
- Power Transmitter Compliance Tests
- Power Receiver Compliance Tests

NOTE: The compliance testing documents are restricted and require signing in to the WPC members' website. All other specification documents are available for download on both the WPC public website and the WPC website for members.

1.2 Scope

The *Qi Specification, Power Delivery* (this document) comprises guidelines and requirements for Power Receiver design, including circuitry, power consumption, operating power levels, power transfer efficiency, and standby power.

1.3 Compliance

All provisions in the *Qi Specification* are mandatory, unless specifically indicated as recommended, optional, note, example, or informative. Verbal expression of provisions in this Specification follow the rules provided in ISO/IEC Directives, Part 2.

Table 1: Verbal forms for expressions of provisions

Provision	Verbal form
requirement	“shall” or “shall not”
recommendation	“should” or “should not”
permission	“may” or “may not”
capability	“can” or “cannot”

1.4 References

For undated references, the most recently published document applies. The most recent WPC publications can be downloaded from http://www.wirelesspowerconsortium.com. In addition, the *Qi Specification* references documents listed below. Documents marked here with an asterisk (*) are restricted and require signing in to the WPC website for members.

- Product Registration Procedure Web page*
- Qi Product Registration Manual, Logo Licensee/Manufacturer*
- Qi Product Registration Manual, Authorized Test Lab*
- Power Receiver Manufacturer Codes,* Wireless Power Consortium
- The International System of Units (SI), Bureau International des Poids et Mesures
- Verbal forms for expressions of provisions, International Electotechnical Commission

For regulatory information about product safety, emissions, energy efficiency, and use of the frequency spectrum, visit the regulatory environment page of the WPC members’ website.

1.5 Conventions

1.5.1 Notation of numbers

- Real numbers use the digits 0 to 9, a decimal point, and optionally an exponential part.
- Integer numbers in decimal notation use the digits 0 to 9.
- Integer numbers in hexadecimal notation use the hexadecimal digits 0 to 9 and A to F, and are prefixed by "0x" unless explicitly indicated otherwise.
- Single bit values use the words ZERO and ONE.

1.5.2 Tolerances

Unless indicated otherwise, all numeric values in the *Qi Specification* are exactly as specified and do not have any implied tolerance.

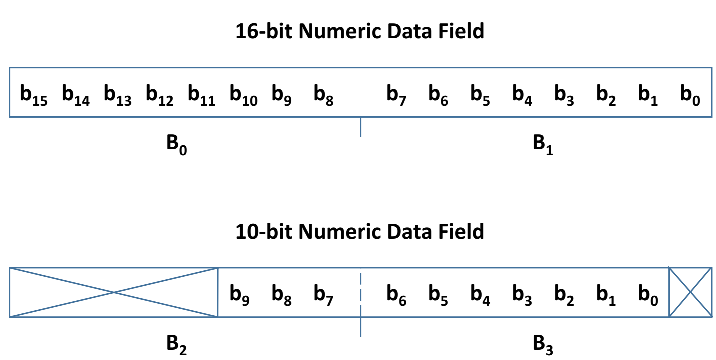
1.5.3 Fields in a data packet

A numeric value stored in a field of a data packet uses a big-endian format. Bits that are more significant are stored at a lower byte offset than bits that are less significant. Table 2 and Figure 1 provide examples of the interpretation of such fields.

Table 2: Example of fields in a data packet

<table>
<tr><th></th><th>b_7</th><th>b_6</th><th>b_5</th><th>b_4</th><th>b_3</th><th>b_2</th><th>b_1</th><th>b_0</th></tr>
<tr><td>B_0</td><td colspan="8" rowspan="2">(msb)
16-bit Numeric Data Field
(lsb)</td></tr>
<tr><td>B_1</td></tr>
<tr><td>B_2</td><td colspan="5">Other Field</td><td colspan="3">(msb)</td></tr>
<tr><td>B_3</td><td colspan="7">10-bit Numeric Data Field (lsb)</td><td>Field</td></tr>
</table>

Figure 1. Examples of fields in a data packet



1.5.4 Notation of text strings

Text strings consist of a sequence of printable ASCII characters (i.e. in the range of 0x20 to 0x7E) enclosed in double quotes ("). Text strings are stored in fields of data structures with the first character of the string at the lowest byte offset, and are padded with ASCII NUL (0x00) characters to the end of the field where necessary.

EXAMPLE: The text string “WPC” is stored in a six-byte fields as the sequence of characters 'W', 'P', 'C', NUL, NUL, and NUL. The text string “M:4D3A” is stored in a six-byte field as the sequence 'M', ':', '4', 'D', '3', and 'A'.

1.5.5 Short-hand notation for data packets

In many instances, the *Qi Specification* refers to a data packet using the following shorthand notation:

<MNEMONIC>/<modifier>

In this notation, <MNEMONIC> refers to the data packet's mnemonic defined in the *Qi Specification, Communications Protocol*, and <modifier> refers to a particular value in a field of the data packet. The definitions of the data packets in the *Qi Specification, Communications Protocol*, list the meanings of the modifiers.

For example, EPT/cc refers to an End Power Transfer data packet having its End Power Transfer code field set to 0x01.

1.6 Power Profiles

A Power Profile determines the level of compatibility between a Power Transmitter and a Power Receiver. Table 3 defines the available Power Profiles.

- *BPP PTx*: A Baseline Power Profile Power Transmitter.
- *EPP5 PTx*: An Extended Power Profile Power Transmitter having a restricted power transfer capability, i.e. $P_{\mathrm{L}}^{(\mathrm{pot})}$ = 5 W.
- *EPP PTx*: An Extended Power Profile Power Transmitter.
- *BPP PRx*: A Baseline Power Profile Power Receiver.
- *EPP PRx*: An Extended Power Profile Power Receiver.

Table 3: Capabilities included in a Power Profile

Feature	BPP PTx	EPP5 PTx	EPP PTx	BPP PRx	EPP PRx
A*x* or B*x* design	Yes	Yes	No	N/A	N/A
MP-A*x* or MP-B*x* design	No	No	Yes	N/A	N/A
Baseline Protocol	Yes	Yes	Yes	Yes	Yes
Extended Protocol	No	Yes	Yes	No	Yes
Authentication	N/A	Optional	Yes	N/A	Optional

2 Introduction

Figure 2 provides a simplified model of a wireless power system, consisting of six blocks. The three blocks to the left of the power transfer interface represent a Power Transmitter and its supply. The three to the right represent a Power Receiver and its Load. Typically, these blocks comprise the following elements.

Supply; in many cases a separate adapter such as a USB PD brick.

Inverter; a half-bridge or full-bridge for DC/AC conversion.

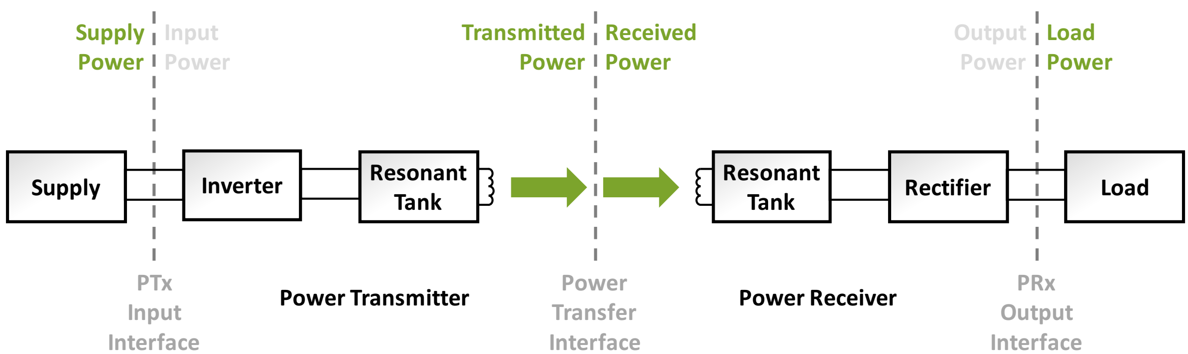
Resonant Tank; a coil and series capacitor boosting the power transfer capability.

Resonant Tank; a coil and series capacitor enhancing the power transfer efficiency.

Rectifier; either a diode bridge or an active (synchronous) bridge for AC/DC conversion.

Load; a battery with associated control circuitry.

Figure 2. Simplified model of a wireless power transfer system



With reference to Figure 2, the following definitions are central to the understanding of a wireless power system.

Power Signal: An alternating magnetic field.

Supply Power: The power dissipated from the supply.

Power Transmitter: A subsystem that can generate a Power Signal.

Power Transmitter Product:
A device containing one or more Power Transmitters.

Transmitted Power: The power from the Power Signal dissipated by any object that is not an integral part of the Power Transmitter Product.

Power Receiver: A subsystem that can extract electric power from a Power Signal.

Power Receiver Product:
A device containing a Power Receiver.

Received Power: The power from the Power Signal dissipated by any component that is an integral part of the Power Receiver Product.

Test Power Transmitter:
A Power Transmitter Product designed to analyze and check the operation of a Power Receiver Product's wireless power functionality.

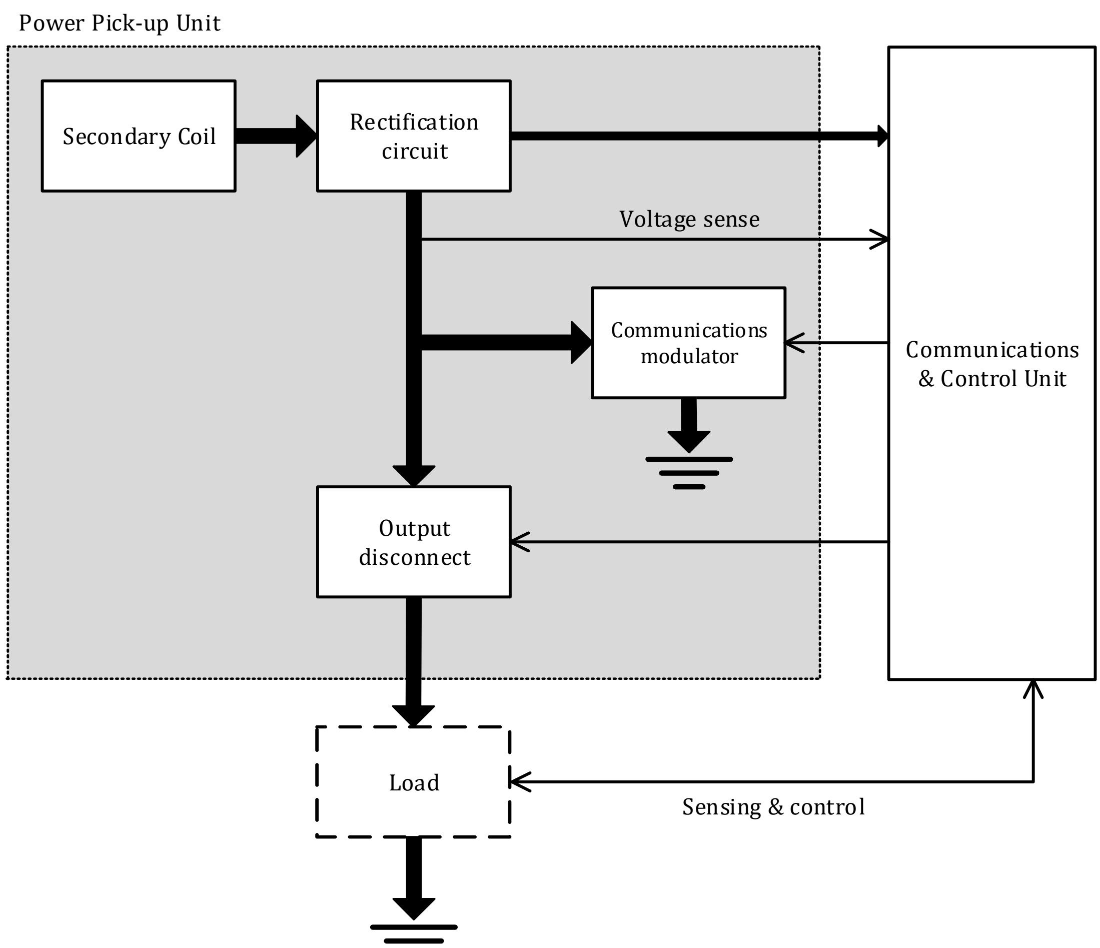
Test Power Receiver: A Power Receiver Product designed to analyze and check the operation of a Power Transmitter Product's wireless power functionality.

Load Power: The power dissipated in the Load.

3 Power Receiver construction

Figure 3 illustrates an example of a functional block diagram for a Baseline Power Profile Power Receiver.

Figure 3. Functional block diagram for a Baseline Power Profile Power Receiver



In this example, the Power Receiver consists of a Power Pick-up Unit and a Communications and Control Unit. The Power Pick-up Unit on the left-hand side of Figure 3 comprises the analog components of the Power Receiver:

- A dual resonant circuit consisting of a Secondary Coil plus series and parallel capacitances to enhance the power transfer efficiency and enable a resonant detection method (see Section 3.1, *Dual resonant circuit*).
- A rectification circuit that provides full-wave rectification of the AC waveform using, for example, four diodes in a full-bridge configuration or a suitable configuration of active components (see Section 3.2, *Rectification circuit*). The rectification circuit may perform output smoothing as well. In this example, the rectification circuit provides power to both the Communications and Control Unit of the Power Receiver and the output of the Power Receiver.

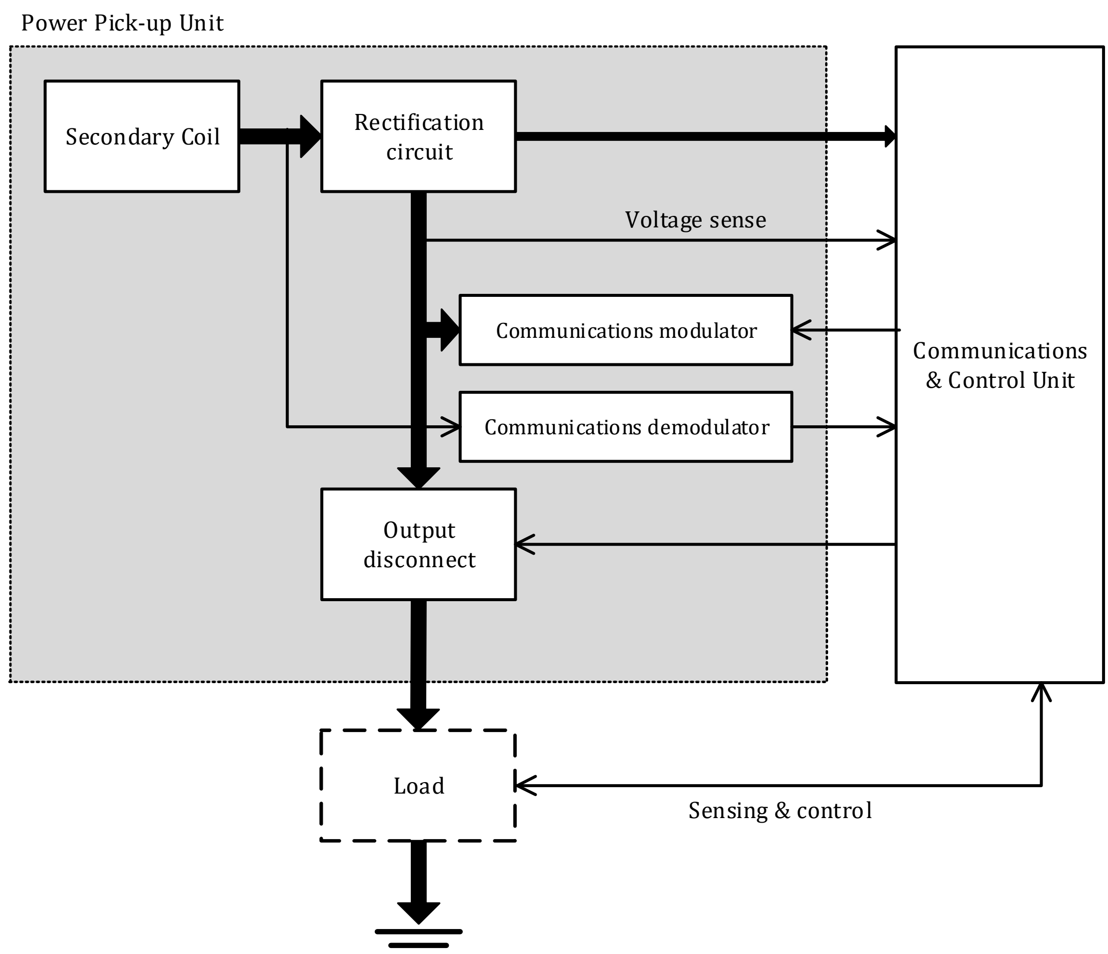
- A communications modulator (see Section 3.4, *Communications modulator*). On the DC side of the Power Receiver, the communications modulator typically consists of a resistor in series with a switch. On the AC side of the Power Receiver, the communications modulator typically consists of a capacitor in series with a switch (not shown in Figure 3).
- An output disconnect switch, which prevents current from flowing to the output when the Power Receiver does not provide power at its output. In addition, the output disconnect switch prevents current back flow into the Power Receiver when the Power Receiver does not provide power at its output. Moreover, the output disconnect switch minimizes the power that the Power Receiver draws from the Power Transmitter when a Power Signal is first applied to the Secondary Coil.
- A rectified voltage sense.

The Communications and Control Unit on the right-hand side of Figure 3 comprises the digital logic part of the Power Receiver. This unit executes the relevant power control algorithms and protocols, drives the communications modulator, controls the output disconnect switch, and monitors several sensing circuits in both the Power Pick-up Unit and the load. (A good example of a sensing circuit in the load is a circuit that measures the temperature of a rechargeable battery.)

NOTE: This version of the Specification minimizes the set of Power Receiver design requirements defined in this section. Accordingly, compliant Power Receiver designs that differ from the sample functional block diagram shown in Figure 3 are possible. For example, an alternative design includes post-regulation of the output of the rectification circuit (e.g., by using a buck converter, battery charging circuit, power management unit, etc.). In yet another design, the Communications and Control Unit interfaces with other subsystems of the Power Receiver Product, e.g. for user interface purposes.

Figure 4 illustrates an example of a functional block diagram for an Extended Power Profile Power Receiver. The communications demodulator enables the communication of data from the Power Transmitter to an Extended Power Profile Power Receiver. The presence of a communications demodulator is the only difference with the functional block diagram of a Baseline Power Profile Power Receiver.

Figure 4. Functional block diagram for an Extended Power Profile Power Receiver



Power Pick-up Unit components are described in the subsections below.

A Power Receiver design shall include a dual resonant circuit as defined in Section 3.1, *Dual resonant circuit*, a rectification circuit as defined in Section 3.2, *Rectification circuit*, sensing circuits as defined in Section 3.3, *Sensing circuits*, a communications modulator as defined in Section 3.4, *Communications modulator*, and an output disconnect switch as defined in Section 3.6, *Output disconnect*.

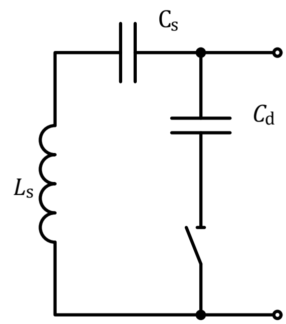
A Power Receiver design for the Extended Power Profile shall also include a communications demodulator as defined in Section 3.5, *Communications demodulator*, and shall be able to function meaningfully if the Power Transmitter restrictions limit the output of power from the Power Receiver to 5 W; see Section 3.7, *Shielding*.

3.1 Dual resonant circuit

The dual resonant circuit of the Power Receiver comprises the Secondary Coil and two resonant capacitances. The purpose of the first resonant capacitance C_s is to enhance the power transfer efficiency. The purpose of the second resonant capacitance C_d is to enable a resonant detection of the receiver position on some Power Transmitter designs.

Figure 5 illustrates the dual resonant circuit. The switch in the dual resonant circuit is optional. If the switch is not present, the capacitance C_d shall have a fixed connection to the Secondary Coil L_s. If the switch is present, it shall remain closed[1] until the Power Receiver transmits its first Packet (see the *Qi Specification*, *Communications Protocol*).

Figure 5. Dual resonant circuit of a Power Receiver



The dual resonant circuit shall have the following resonant frequencies:

$$f_s = \frac{1}{2\pi \cdot \sqrt{L_s' \cdot C_s}} = 100^{+x}_{-y} \text{ kHz},$$

$$f_d = \frac{1}{2\pi \cdot \sqrt{L_s \cdot \left(\frac{1}{C_s} + \frac{1}{C_d}\right)^{-1}}} = (1000 \pm 10\%) \text{ kHz}.$$

In these equations, L_s' is the self-inductance of the Secondary Coil when placed on the Interface Surface of a Power Transmitter and—if necessary—aligned to the Primary Cell; and L_s is the self-inductance of the Secondary Coil without magnetically active material that is not part of the Power Receiver design close to the Secondary Coil (e.g. away from the Interface Surface of a Power Transmitter). Moreover, the tolerances x and y on the resonant frequency f_s are $x = y = 5\%$ for Power Receivers that specify a Maximum Power value in the Configuration Packet of 3 W and above, and $x = 5\%$ and $y = 10\%$ for all other Power Receivers.

NOTE: When determining the capacitance value C_d, make sure to account for any parasitic capacitances between the terminals of the dual resonant circuit that may affect the resonance frequency value f_d.

1 The switch shall remain closed even if no power is available from the Secondary Coil.

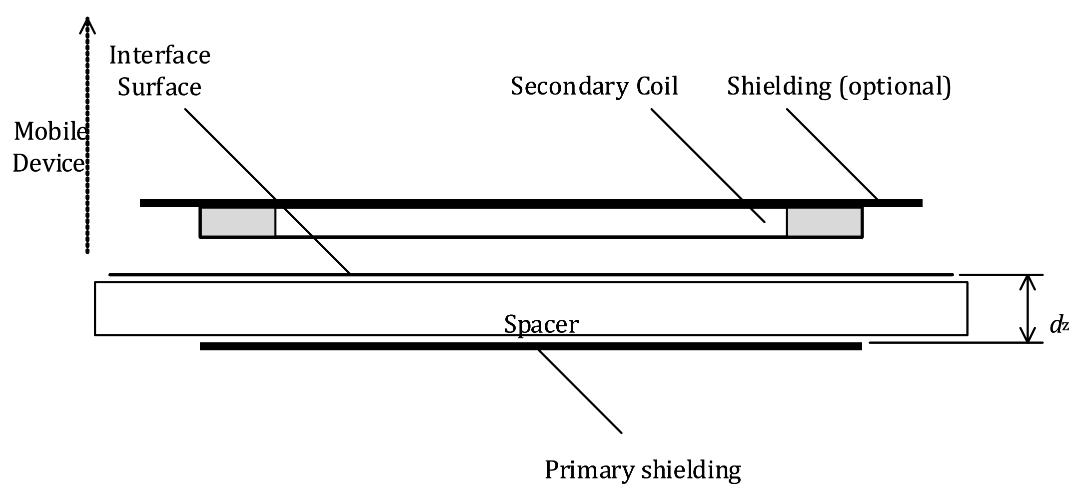
The quality factor Q of the loop consisting of the Secondary Coil, switch (if present), resonant capacitance C_s and resonant capacitance C_d, shall exceed the value 77. Here the quality factor Q is defined as:

$$Q = \frac{2\pi \cdot f_d \cdot L_s}{R}$$

where R is the DC resistance of the loop with the capacitances C_s and C_d short-circuited.

Figure 6 shows the environment that is used to determine the self-inductance L'_s of the Secondary Coil. The primary Shielding shown in Figure 6 consists of material PC44 from TDK Corp. The primary Shielding has a square shape with a side of 50 mm and a thickness of 1 mm. The center of the Secondary Coil and the center of the primary Shielding shall be aligned. The distance from the Receiver Interface Surface to the primary Shielding is d_z = 3.4 mm. Shielding on top of the Secondary Coil is present only if the Receiver design includes such Shielding. Other Power Receiver Product components that influence the inductance of the Secondary Coil shall be present as well when determining the resonant frequencies. The excitation signal that is used to determine L_s and L'_s shall have an amplitude of 1 V RMS and a frequency of 100 kHz.

Figure 6. Characterization of resonant frequencies



3.2 Rectification circuit

The rectification circuit shall use full-wave rectification to convert the AC waveform to a DC power level.

3.3 Sensing circuits

The Power Receiver shall monitor the DC voltage V_r directly at the output of the rectification circuit.

3.4 Communications modulator

The Power Receiver shall have the means to modulate the Primary Cell current and Primary Cell voltage as defined in *Qi Specification*, *Communications Physical Layer*.[2] This version of the Specification leaves the specific loading method as a design choice to the Power Receiver. Typical methods include modulation of a resistive load on the DC side of the Power Receiver and modulation of a capacitive load on the AC side of the Power Receiver.

3.5 Communications demodulator

For the Extended Power Profile, the Power Receiver shall have the means to demodulate frequency-shift keying (FSK) data from the Power Signal frequency as defined in *Qi Specification*, *Communications Physical Layer*. This Specification leaves the specific method up to the designer of the Power Receiver.

3.6 Output disconnect

The Power Receiver shall have the means to disconnect its output from the subsystems connected thereto. If the Power Receiver has disconnected its output, it shall ensure that it still draws a sufficient amount of power from the Power Transmitter, such that Power Receiver to Power Transmitter communications remain possible (see *Qi Specification*, *Communications Physical Layer*).

The Power Receiver shall keep its output disconnected until it reaches the *power transfer* phase for the first time after a Digital Ping (see the *Qi Specification*, *Communications Protocol*). Subsequently, the Power Receiver may operate the output disconnect switch any time while the Power Transmitter applies a Power Signal.

NOTE: The Power Receiver may experience a voltage peak when operating the output disconnect switch (and changing between maximum and near-zero power dissipation).

[2] Note that the dual resonant circuit as depicted in Figure 5 (in Section 3.1) does not prohibit implementation of the communications modulator directly at the Secondary Coil.

3.7 Shielding

An important consideration for a Power Receiver designer is the impact of the Power Transmitter's magnetic field on the Power Receiver Product. Stray magnetic fields could interact with the Power Receiver Product and potentially cause its intended functionality to deteriorate or cause its temperature to increase due to the power dissipation of generated eddy currents.

It is recommended to limit the impact of magnetic fields by means of Shielding on the top face of the Secondary Coil (see the *Qi Specification, Mechanical, Thermal, and User Interface* for a diagram of the secondary coil assembly). This Shielding should consist of material that has parameters similar to the materials listed in the *Qi Specification, Power Receiver Design Examples*. The Shielding should cover the Secondary Coil completely. Additional Shielding beyond the outer diameter of the Secondary Coil might be necessary depending upon the impact of stray magnetic fields.

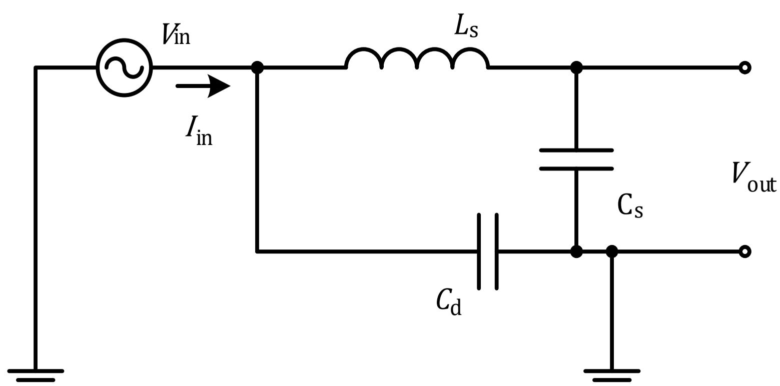
4 Power Receiver design guidelines (informative)

4.1 Large-signal resonance check

In the course of designing a Power Receiver, it should be verified that the resonance frequency f_s of the dual resonant circuit remains within the tolerance range defined in Section 3.1, *Dual resonant circuit*, under large-signal conditions. The test defined in this section serves this purpose.

Step 1. Connect an RF power source to the assembly of Secondary Coil, Shielding and other components that influence the inductance of the Secondary Coil and series resonant capacitance C_s; see Figure 7. The presence of the parallel capacitance C_p is optional.

Figure 7. Large signal secondary resonance test



Step 2. Position the assembly and an appropriate spacer on primary Shielding material, as shown in Figure 5 (in Section 3.1).

Step 3. Measure the input voltage V_{in} as a function of the frequency of the RF power source in the range of 90…110 kHz, while maintaining the input current I_{in} at a constant level, preferably at about twice the maximum value intended in the final product.

Step 4. Verify that the frequency at which the measured V_{in} is at a minimum, occurs within the specified tolerance range of the resonance frequency f_s.

4.2 Power Receiver coil design

The mutual inductance M of a Secondary Coil, in combination with optional Shielding and other Power Receiver Product components, and the Primary Coil of a Power Transmitter design A10 should satisfy the following relations:

- $\frac{V_0}{\omega M} < 0.8$ A, if the Primary Coil and Secondary Coil centers are aligned; and
- $\frac{V_0}{\omega M} < 1.0$ A, if the Primary Coil and Secondary Coil centers have a lateral offset of $5\sqrt{2}$ mm.

Here V_0 is the maximum output voltage expected from the Secondary Coil—or any other voltage that the Power Receiver designer considers relevant—and $\omega = 2\pi f$, with f = 100 kHz, the frequency at which the mutual inductance (in units of 1 henry) is measured.

5 Power Transmitter construction

5.1 Power Transmitter reference designs

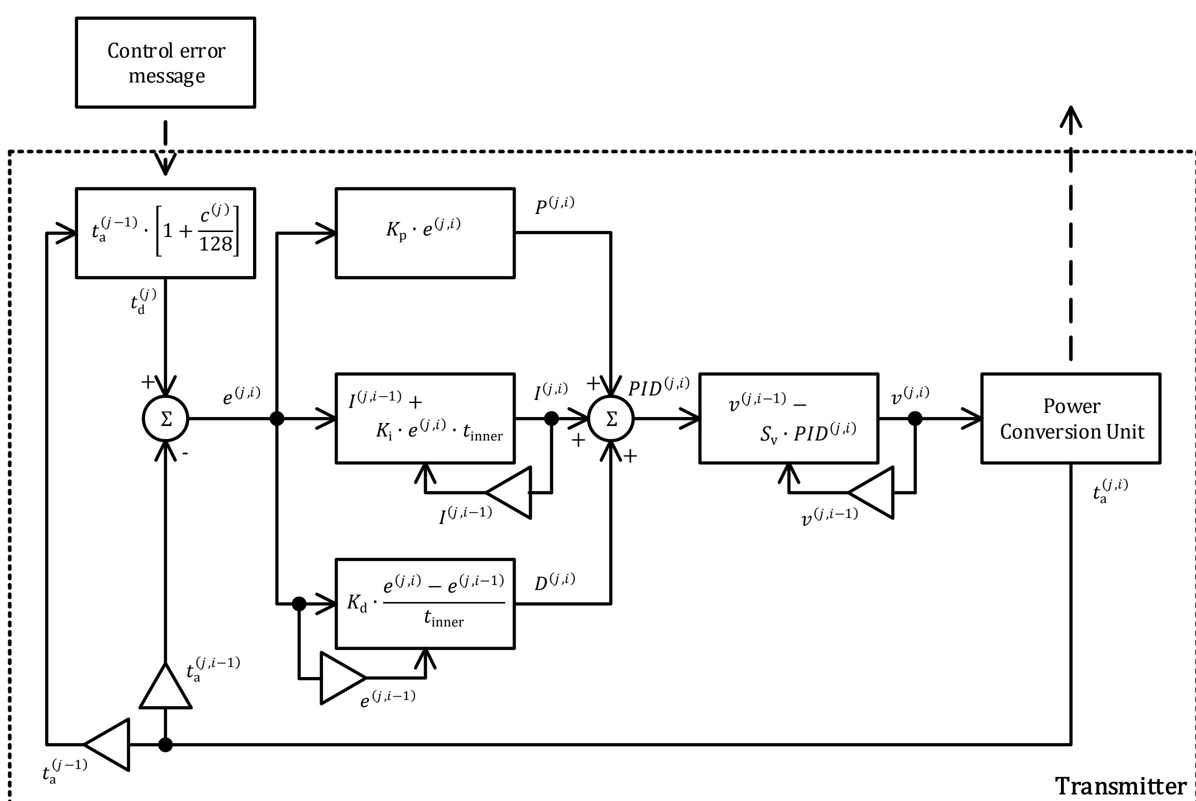
The *Qi Specification* includes a set of Power Transmitter reference designs that were developed, tested, and certified by member companies of the Wireless Power Consortium. Many of the reference designs have been consolidated into the *Qi Specification, Power Transmitter Reference Designs* book, and more recent designs are in the form of individual documents. All approved reference designs are available for download from the *Qi Specifications* download page of the WPC members' website (login required):

https://members.wirelesspowerconsortium.com/members/members-info/swg/specifications.html.

5.2 Power transfer control

This version of the Specification, defines a specific method, which the Power Transmitter shall use to control its Primary Cell current towards the new Primary Cell current (see *Qi Specification, Communications Protocol* for a description of the power transfer phases). This method is based on a discrete proportional-integral-differential (PID) algorithm as illustrated in Figure 8.

Figure 8. PID control algorithm



To execute this algorithm, the Power Transmitter shall execute the steps listed below, in the order of appearance. In the definitions of these steps, the index j = 1, 2, 3, ... labels the sequence of Control Error Packets, which the Power Transmitter receives.

- Upon receipt of the j^{th} Control Error Packet, the Power Transmitter shall calculate the new Primary Cell current $t_{\text{d}}^{(j)}$ as

$$t_{\text{d}}^{(j)} = t_{\text{a}}^{(j-1)} \cdot \left[1 + \frac{c^{(j)}}{128}\right]$$

where $t_{\text{a}}^{(j-1)}$ represents the actual Primary Cell current—reached in response to the previous Control Error Packet—and $c^{(j)}$ represents the Control Error Value contained in the j^{th} Control Error Packet. Note that $t_{\text{a}}^{(0)}$ represents the Primary Cell current at the start of the *power transfer* phase.

- If the Control Error Value $c^{(j)}$ is non-zero, the Power Transmitter shall adjust its Primary Cell current during a time window t_{active}. For this purpose, the Power Transmitter shall execute a loop comprising of the steps listed below. The index i = 1, 2, 3, ... i_{max} labels the iterations of this loop.
    - The Power Transmitter shall calculate the difference between the new Primary Cell and the actual Primary Cell current as the error

    $$e^{(j,i)} = t_{\text{d}}^{(j)} - t_{\text{a}}^{(j,i-1)}$$

    where $t_{\text{a}}^{(j,i-1)}$ represents the Primary Cell current determined in iteration $i - 1$ of the loop. Note that $t_{\text{a}}^{(j,0)}$ represents the actual Primary Cell current at the start of the loop.
    - The Transmitter shall calculate the proportional, integral, and derivative terms (in any order):

    $$P^{(j,i)} = K_{\text{p}} \cdot e^{(j,i)}$$

    $$I^{(j,i)} = I^{(j,i-1)} + K_{\text{i}} \cdot e^{(j,i)} \cdot t_{\text{inner}}$$

    $$D^{(j,i)} = K_{\text{d}} \cdot \frac{e^{(j,i)} - e^{(j,i-1)}}{t_{\text{inner}}}$$

    where K_{p} is the proportional gain, K_{i} is the integral gain, K_{d} is the derivative gain, and t_{inner} is the time required to execute a single iteration of the loop. In addition, the integral term $I^{(j,0)} = 0$, and the error $e^{(j,0)} = 0$. The Power Transmitter shall limit the integral term $I^{(j,i)}$ such that it remains within the range $-M_{\text{I}}$ ... + M_{I}—if necessary, the Power Transmitter shall replace the calculated integral term $I^{(j,i)}$ with the appropriate boundary value.

- The Power Transmitter shall calculate the sum of the proportional, integral, and derivative terms:

  $$PID^{(j,i)} = P^{(j,i)} + I^{(j,i)} + D^{(j,i)}.$$

  In this calculation, the Power Transmitter shall limit the sum $PID^{(j,i)}$ such that it remains within the range $-M_{\text{PID}} \ldots +M_{\text{PID}}$.

- The Power Transmitter shall calculate the new value of the controlled variable

  $$v^{(j,i)} = v^{(j,i-1)} - S_{\text{v}} \cdot PID^{(j,i)},$$

  where S_{v} is a scaling factor that depends on the controlled variable. In addition, the controlled variable $v^{(j,0)} = v^{(j-1,i_{\max})}$, with $v^{(0,0)}$ representing the actual value of the controlled variable at the start of the *power transfer* phase, is either the Operating Frequency, the duty cycle of the inverter, or the voltage input to the inverter. If the calculated $v^{(j,i)}$ exceeds the specified range (see the definition of the individual Power Transmitter designs in *Qi Specification, Power Transmitter Reference Designs* or in the applicable Power Transmitter design document), the Power Transmitter shall replace the calculated $v^{(j,i)}$ with the appropriate limiting value.

- The Power Transmitter shall apply the new value of the controlled variable $v^{(j,i)}$ to its Power Conversion Unit.

- The Power Transmitter shall determine the actual Primary Cell current $t_{\text{a}}^{(j,i)}$.

The maximum number of iterations of the loop $i_{\max}$, and the time t_{inner} required to execute a single iteration of the loop shall satisfy the following relation:

$$i_{\max} \cdot t_{\text{inner}} = t_{\text{active}}, \text{ with } 1\text{ ms} \le t_{\text{inner}} \le 5\text{ ms}$$

- The Power Transmitter shall determine the Primary Cell current $t_{\text{a}}^{(j)}$ exactly at $t_{\text{delay}} + t_{\text{active}} + t_{\text{settle}}$ after the end of the j^{th} Control Error Packet.

See the definition of the individual Power Transmitter designs in *Qi Specification, Power Transmitter Reference Designs* or in the applicable Power Transmitter design document for the values of K_{p}, K_{i}, K_{d}, M_{I}, and M_{PID}.

6 Power consumption

In consideration of compliance testing (see the *Qi Specification, Power Receiver Compliance Tests*), a Power Receiver shall not drive the Transmitted Power of Test Power Transmitter #2 above 7500 mW with the Power Receiver being positioned on TPT#2 such that power transfer can be sustained without interruption.

7 Meaningful functionality

(Extended Power Profile) If the Power Receiver is not able to negotiate its intended Guaranteed Load Power level with the Power Transmitter, it shall negotiate a lower Guaranteed Load Power level, and function meaningfully at that power level. Meaningful functionality includes charging a connected battery at a rate lower than intended.

NOTE: The following examples list cases in which the Power Receiver may not be able to negotiate its target operating power.

- The Power Receiver is positioned on a BPP Power Transmitter.
- The Potential Power provided in the Power Transmitter Capability Packet is lower than the Power Receiver's target operating power.
- The Power Transmitter is powered by an external power supply that is designed to provide no more than 5 W of power.

8 Unintentional Magnetic Field Susceptibility (Informative)

8.1 Limits

It should also be noted that a Power Receiver can be exposed to higher than expected fields during otherwise normal operation. For example, if the Power Receiver is suddenly moved such that its coupling with the Power Transmitter changes significantly, the communications channel can become unusable and the voltage generated across the Secondary Coil can increase unexpectedly.

8.2 Protection

In the case that the output disconnect switch is open, it is recommended that a Power Receiver can withstand a voltage generated across its Secondary Coil of at least U_{ovp}. Here, U_{ovp} is the larger of

- 1.6 times the maximum target rectified voltage as defined in Table 4, or
- the voltage that results if coupled with a type MP-A1 Power Transmitter that is operating at its minimum Operating Frequency and maximum phase difference between the legs of its full-bridge inverter.

Table 4: Examples of the recommended U_{ovp}

Maximum Target Rectified Voltage [V]	Recommended U_{ovp} [V]
12	20
20	32
30	48

8.3 Power Transmitter detection

To detect whether the Power Signal originates from a Power Transmitter, as described in the *Qi Specification, Communications Physical Layer*, the Power Receiver should also take into account the Power Transmitter designs defined in the *Qi Specification, Power Transmitter Reference Designs* or in the applicable Power Transmitter design document.

9 Load Steps

A Power Receiver Product may perform load steps and dumps that are beyond the control of its Power Receiver. A load step or dump causes an immediate impedance change, which is reflected from the Secondary Coil to the Primary Coil and results in a change of the rectified voltage. Due to the latency of the control loop (which is mainly due to the time that is required to communicate Control Error Packets), it takes a while before the rectified voltage is readjusted to a (new) desired value. The Power Transmitter should ensure that the established Power Transfer Contract is not terminated during such an event. Therefore, an implementation of a Power Transmitter—following one of the designs defined in the *Qi Specification, Power Transmitter Reference Designs* or in the applicable Power Transmitter design document—should meet load steps from 10% to 100% of the Maximum Power (as communicated by the Power Receiver in the Configuration Packet) and load dumps from 100% to 10%.

9.1 Load step test procedure

9.1.1 Baseline Power Profile load step test

The following procedure is recommended to verify that the Power Transmitter is able to handle load steps and dumps:

1. Position Test Power Receiver #1 in configuration B on the Interface Surface of the Power Transmitter Product with an initial load of 32 Ω, a Power Control Hold-off Time of t_{delay} = 100 ms, and an interval time between consecutive Control Error Packets of t_{interval} = 250 ms.
2. Establish communication and regulate the rectified voltage to V_{r} = (7 ± 2%) V.
3. Change the load from its initial value to 127 Ω and regulate the rectified voltage to V_{r} = (7 ± 2%) V.
4. Change the load from 127 Ω to 10 Ω, Δt_1 = 50 ms before a sending a Control Error Packet.
5. Verify that the Test Power Receiver continues to regulate and that the Power Transmitter Product responds to the Control Error Packets by adjusting V_{r}.
6. Measure the rectified voltage (V_0, V_1, and V_{min}) with timings as shown in Figure 9, where Δt_2 = 1800 ms.
7. Verify that the measured values comply with the limits provided in Table 5.

Figure 9. Load step test diagram

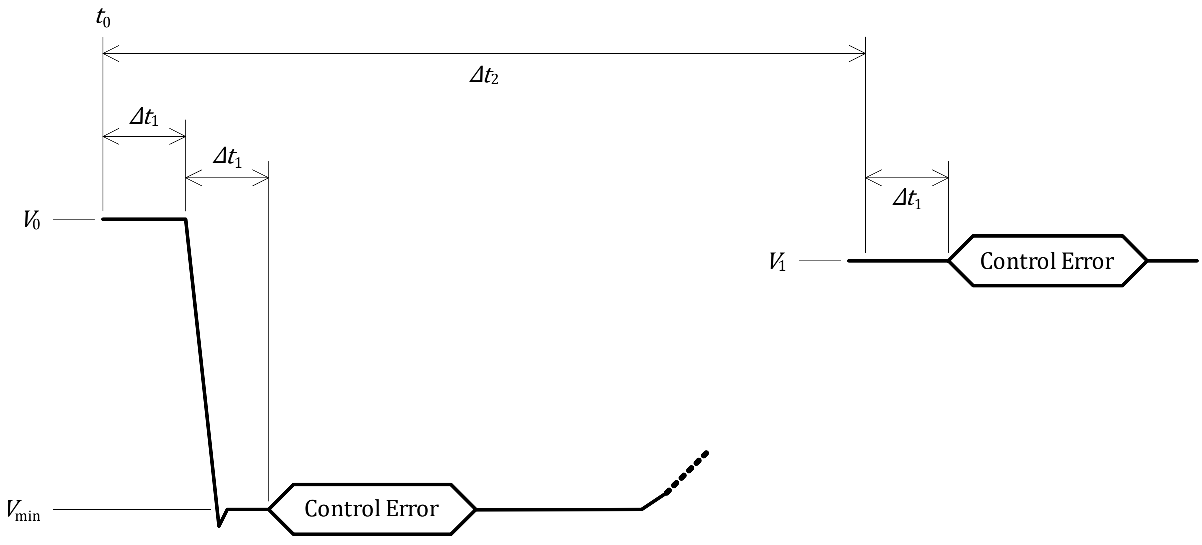


Table 5: Load step limits

Voltage	Minimum	Target	Maximum	Unit
V_0	6.9	7.0	7.1	V
V_{min}	4.0	7.0	7.1	V
V_1	6.0	V_0	7.1	V

9.1.2 Extended Power Profile load step test

1. Position the Test Power Receiver on the Interface Surface of the Power Transmitter Product, with an initial load of R_{init}, a Power Control Hold-off Time of t_{delay} = 100 ms, and an interval time between consecutive Control Error Packets of $t_{interval}$ = 250 ms. See Table 6 for relevant parameters.
2. Establish communications and regulate the rectified voltage to V_r.
3. Change the load from its initial value to R_{light} and regulate the rectified voltage V_r.
4. Change the load from R_{light} to R_{heavy} at Δt_1 = 50 ms before a sending a Control Error Packet.
5. Verify that the Test Power Receiver continues to regulate and that the Power Transmitter Product responds to the Control Error Packets by adjusting V_r.
6. Measure the rectified voltages (V_0, V_1, and V_{min}) with timings as shown in Figure 9 above, where Δt_2 = 1800 ms.
7. Verify the measured values with the limits provided in Table 5.

Table 6: Load step definitions

Test Power Receiver	Initial Load R_{init}	Light Load R_{light}	Heavy Load R_{heavy}	Rectified Voltage V_r
TPR#1B	32 Ω	127 Ω	10 Ω	(7 ± 2%) V
TPR#MP1B	72 Ω	96 Ω	10 Ω	(12 ± 2%) V

Table 7: Load step limits

Test Power Receiver	Voltage	Minimum [V]	Target [V]	Maximum [V]
TPR#1B	V_0	6.9	7.0	7.1
	V_{min}	4.0	7.0	7.1
	V_1	6.0	V_0	7.1
TPR#MP1B	V_0	11.8	12.0	12.2
	V_{min}	6.9	12.0	12.2
	V_1	10.3	V_0	12.2

9.2 Load dump test procedure

9.2.1 Baseline Power Profile load dump test

1. Position Test Power Receiver #1 in configuration B on the Interface Surface of the Power Transmitter Product, with an initial load of 32 Ω, a Power Control Hold-off Time t_{delay} = 100 ms, and an interval time between consecutive Control Error Packets t_{interval} = 250 ms.
2. Establish communication and regulate the rectified voltage to V_{r} = (7 ± 2%) V.
3. Change the load from its initial value to 10 Ω and regulate the rectified voltage to V_{r} = (7 ± 2%) V.
4. Change the load from 10 Ω to 127 Ω, Δt_1 = 50 ms before a sending a Control Error Packet.
5. Verify that the Test Power Receiver continues to regulate and that the Power Transmitter Product responds to the Control Error Packets by adjusting V_{r}.
6. Measure the rectified voltage (V_0, V_1, and V_{min}) with timings as shown in Figure 10, where Δt_2 = 1800 ms.
7. Verify that the measured values comply with the limits provided in Table 8.

Figure 10. Load dump test diagram

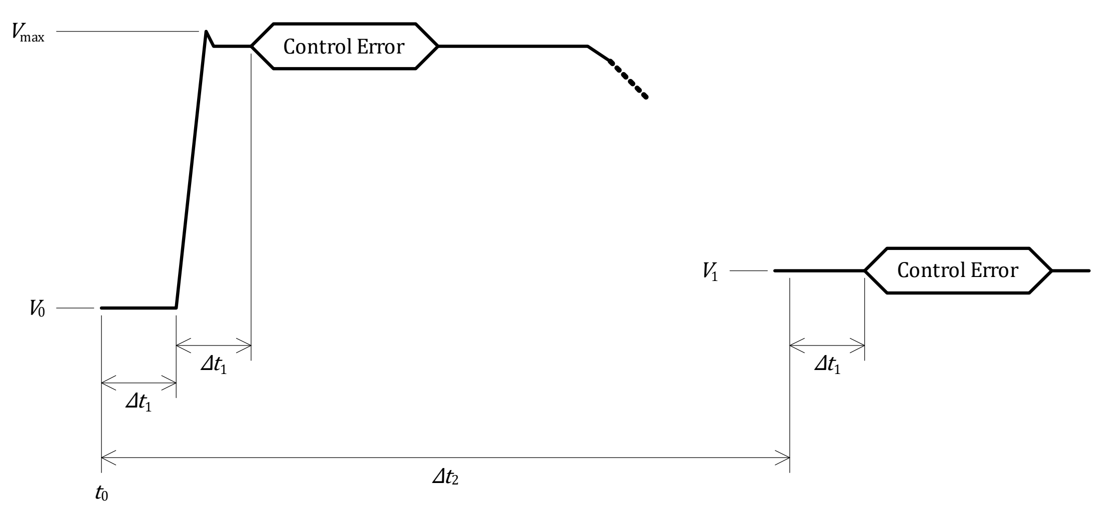


Table 8: Load dump limits (Baseline Power Profile)

Voltage	Minimum	Target	Maximum	Unit
V_0	6.9	7.0	7.1	V
V_{min}	6.9	7.0	12.0	V
V_1	6.9	V_0	8.0	V

9.2.2 Extended Power Profile load dump test

- Position the Test Power Receiver on the Interface Surface of the Power Transmitter Product, with an initial load of R_{init}, a Power Control Hold-off Time of t_{delay} = 100 ms, and an interval time between consecutive Control Error Packets of t_{interval} = 250 ms. See Table 9 for the relevant parameters.
- Establish communications and regulate the rectified voltage to V_{r}.
- Change the load from its initial value to R_{heavy} and regulate the rectified voltage V_{r}.
- Change the load from R_{heavy} to R_{light} at Δt_1 = 50 ms before a sending a Control Error Packet.
- Verify that the Test Power Receiver continues to regulate and that the Power Transmitter Product responds to the Control Error Packets by adjusting V_{r}.
- Measure the rectified voltages (V_0, V_1, and V_{min}) with timings as shown in Figure 10 above, where Δt_2 = 1800 ms.
- Verify the measured values with the limits provided in Table 9.

Table 9: Load dump definitions (Extended Power Profile)

Test Power Receiver	Initial Load R_{init}	Light Load R_{light}	Heavy Load R_{heavy}	Rectified Voltage V_{r}
TPR#1B	32 Ω	127 Ω	10 Ω	(7 ± 2%) V
TPR#MP1B	72 Ω	96 Ω	10 Ω	(12 ± 2%) V

Table 10: Load dump limits

Test Power Receiver	Voltage	Minimum [V]	Target [V]	Maximum [V]
TPR#1B	V_0	6.9	7.0	7.1
	V_{min}	6.9	7.0	12.0
	V_1	6.9	V_0	8.0
TPR#MP1B	V_0	11.8	12.0	12.2
	V_{min}	11.8	12.0	20.5
	V_1	11.8	V_0	13.7

10 Over-voltage protection

A Power Transmitter shall limit the amplitude of its Power Signal (or magnetic field strength) such that it does not generate a rectified voltage higher than 20 V at the output of a properly designed Power Receiver.

NOTE: Examples of properly designed Power Receivers are provided in the *Qi Specification, Power Receiver Design Examples*. In addition, the set of Test Power Receivers defined in the *Qi Specification, Power Transmitter Test Tools*, are also examples of properly designed Power Receivers.

The Power Signal depends on the amount of current that runs through the Primary Coil. This amount is primarily determined by the Power Transmitter's Operating Point, the Power Receiver's load impedance, and the coupling between the Primary Coil and Secondary Coil. Whereas the Power Receiver can—to a certain extent—control its load impedance and the Power Transmitter's Operating Point by transmitting appropriate Control Error Packets, it has little control over the coupling. As a consequence, scenarios exist in which a higher-than-expected voltage can result at the Power Receiver's output.

In one scenario, the user initially places the Power Receiver at a position where the coupling is poor and subsequently moves it to a position where the coupling is strong. In practice this can happen when the user keeps the Power Receiver hovering at a small distance above the Interface Surface before setting it down, or when the user places the Power Receiver with a large misalignment between the Primary Coil and Secondary Coil and subsequently slides it into better alignment.

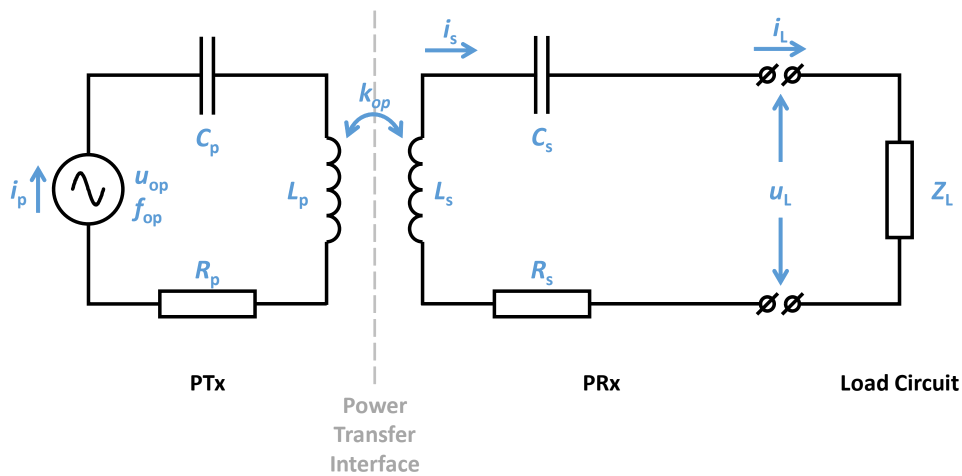
In either case, the Power Transmitter can detect the Power Receiver and establish communications before the coils are properly aligned. The Power Receiver can then start to control its output voltage to a higher level, such as 12 V, in order to prepare for connecting its load. If the coupling is poor, the Power Receiver typically can reach its target voltage only by driving the power Transmitter to use a high Primary Coil current (and therefore a strong Power Signal or high magnetic field). If the coupling suddenly improves substantially, as in the above scenarios, the Power Receiver does not have time to drive the Power Transmitter back to a lower Primary Coil current. As a result, its output voltage can substantially increase—up to tens of volts if no special precautions are taken.

Many Power Receiver implementations that are based on common IC technology cannot handle such voltages, with 20 V being a safe upper limit. Moreover, design constraints often are of such a nature that commonly used solutions for over-voltage protection cannot be applied. For example, large Zener diodes or dummy loads that can handle the excess power typically are too bulky to fit in space-limited designs. Accordingly, the Power Receiver typically has no alternative but to rely on the Power Transmitter to keep its voltage below the safe limit.

Whereas a Power Transmitter can hold its Primary Coil current to a sufficiently low level, placing a hard limit on the Primary Coil current can prevent a Power Receiver from reaching its target power level when it has connected its load. A better solution is to define more than one limit according to the amount of power that is transmitted: the Power Transmitter should use a low current limit if the Transmitted Power is low to prevent an over-voltage from occurring in the Power Receiver, and it should use a high current limit if the Transmitted Power is high to enable the Power Receiver to reach its target Operating Point without creating an over-voltage in the Power Receiver. The system model and analysis below explain this approach in more detail.

Figure 11 illustrates a simplified model of the system comprising a Power Transmitter on the left and a Power Receiver on the right. For clarity, the load circuit is drawn separately from the Power Receiver. The Power Transmitter consists of a power source (u_{op}, f_{op}), a capacitance C_p, an inductance L_p, and a resistance R_p. The power source supplies a sinusoidal voltage u_{op} at a frequency f_{op}. The Power Receiver consists of a capacitance C_s, an inductance L_s, and a resistance R_s. A load having an impedance Z_L is connected to the output terminals of the Power Receiver. The symbols u_L, i_L, i_p, and k_{op} represent the load voltage, load current, Primary Coil current, and coupling factor.

Figure 11. Simplified system model



For simplicity, the Power Receiver in the model includes neither a rectifier nor a resonance at a frequency f_d as defined in Section 3.1, *Dual resonant circuit* and Section 3.2, *Rectification circuit*. The absence of the additional resonance does not significantly affect the results discussed below. The effect of the rectifier is described at the end of this section.

Table 11 lists the parameters associated with the system model in Figure 11. Instead of the resonant capacitances C_p and C_s, and the resistances R_p and R_s, the resonant frequencies f_p and f_s, and quality factors Q_p and Q_s are provided. The relations between these parameters are as follows:

$$f_p = \frac{1}{2\pi\sqrt{L_p C_p}}, \qquad f_s = \frac{1}{2\pi\sqrt{L_s C_s}}, \qquad Q_p = \frac{2\pi f_p L_p}{R_p}, \qquad Q_s = \frac{2\pi f_s L_s}{R_s}$$

The Power Transmitter controls the amount of power it transfers by adjusting the amplitude of its voltage and frequency in the ranges given in Table 11. At start-up, it uses the ping voltage u_{ping} and ping frequency f_{ping}. To control the power up, it decreases its frequency while keeping its voltage constant at the maximum value. To control the power down, it increases the frequency at constant voltage, and after reaching the maximum frequency value decreases the voltage while keeping the frequency constant at that maximum.

At start-up, the Power Receiver uses a load impedance Z_{ping}, which represents the load of its control electronics such as a microprocessor. After start-up, the Power Receiver can adjust its load impedance to reach its target Operating Point as given by the target voltage u_{L} and target current i_{L}.

Table 11: Parameters of the simplified model

Power Transmitter				**Power Receiver**		
L_{p}	25	µH		L_{s}	35	µH
f_{p}	100	kHz		f_{s}	100	kHz
Q_{p}	100			Q_{s}	40	
u_{op}	2…24	V (pk)		u_{L}	12	V (rms)
f_{op}	100…200	kHz		i_{L}	1.5	A (rms)
u_{ping}	24	V (pk)		Z_{L}	0.1…1000	Ω
f_{ping}	175	kHz		Z_{ping}	800	Ω

Power Transmitter operation is subject to these constraints:

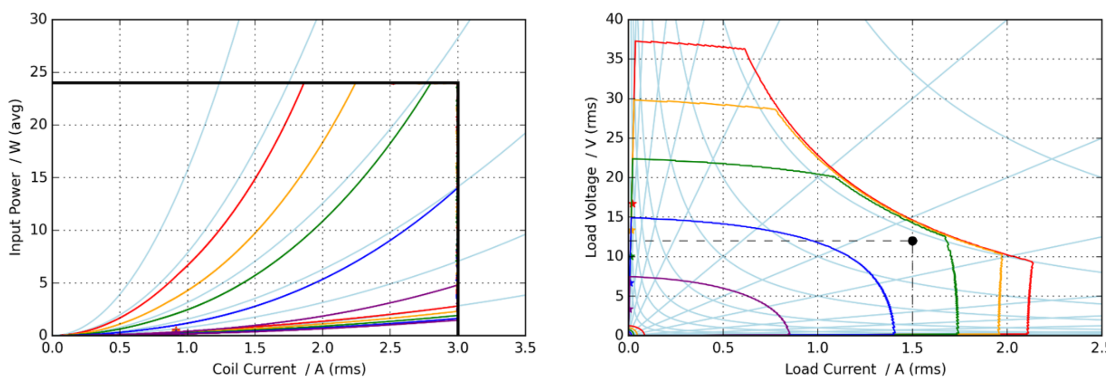
- The Power Transmitter only uses the part of its Operating Frequency range where the Primary Coil current decreases while the Operating Frequency increases. This constraint ensures that the Control Error Packets from the Power Receiver have a consistent effect: a positive Control Error Value causes the Primary Coil current to increase, and a negative Control Error Value causes the Primary Coil current to decrease.

NOTE: A positive Control Error Value directs the Power Transmitter to increase its voltage, or to decrease its Operating Frequency if the voltage has reached its maximum value. A negative Control Error Value directs the Power transmitter to increase its Operating Frequency, or to decrease its voltage if the Operating Frequency has reached its maximum value. This method of power control is used by many of the Power Transmitter designs provided in the *Qi Specification, Power Transmitter Reference Designs* or in the applicable Power Transmitter design document.

- The Power Transmitter limits the amount of power that it takes from its power source. In the simplified model, the maximum average power is 24 W.
- The Power Transmitter limits the amount of Primary Coil current. Two examples are discussed below. In the first example, the Primary Coil current is limited at the fixed value of 3 A rms. In the second example, the Primary Coil current limit depends on the Transmitted Power, increasing from 0.75 A (rms) at near zero Transmitted Power up to about 2.7 A (rms) at near maximum Transmitted Power.

The diagram on the left in Figure 12 illustrates the full operating space of the Power Transmitter in terms of its Primary Coil current and the power it takes from its power source. The diagram on the right illustrates the operating space of the Power Receiver in terms of its load current and voltage. The solid black lines in the Power Transmitter's diagram indicate its power and current limits. The solid black dot in the Power Receiver's diagram indicates its target Operating Point. The colors of the different curves represent different coupling factors. The red curve corresponds to a coupling factor of 0.56 (good coupling). The yellow, green, blue, and purple curves correspond to 80%, 60%, 40%, and 20% of the "red" value. Each curve forms a closed contour limiting the operating space of the Power Transmitter and Power Receiver for the associated coupling factor (for the parts of the contour that coincide with the power limit, the current limit, or the diagram axes this may be difficult to see). The Power Transmitter and Power Receiver can reach any point within a contour given appropriate values of the Power Transmitter's Operating Frequency and voltage. Finally, the stars indicate the ping Operating Points of the Power Transmitter and Power Receiver.

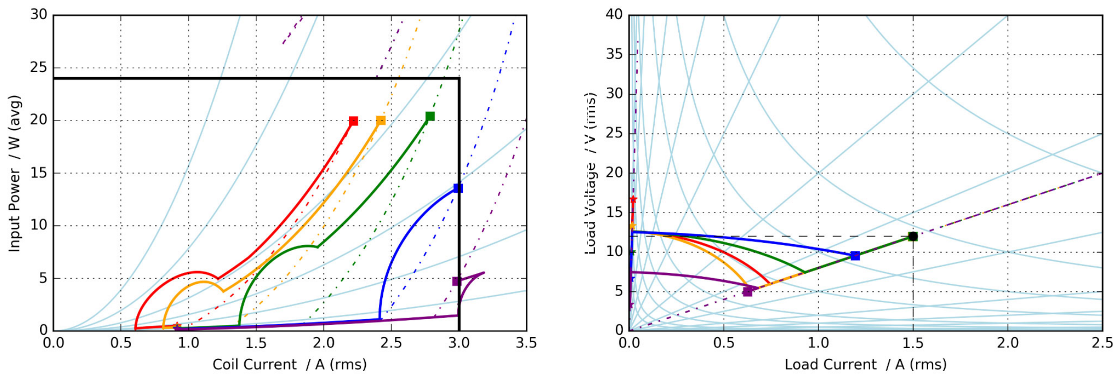
Figure 12. Operating space with a fixed-maximum Primary Coil current



The diagram on the right shows that the Power Receiver can reach its target Operating Point for a coupling factor greater than about 0.3, because that Operating Point lies well within the green contour (a coupling factor of 60% · 0.56). The diagram also makes clear that the load voltage can potentially reach levels well above 20 V (rms) for coupling factors greater than 0.3. For example, the top left corner of the yellow curve, representing a coupling factor of 80% · 0.56 and a load impedance of 1 kΩ, reaches a load voltage of 30 V (rms).

The solid curves in Figure 13 illustrate the "trajectories" that the Power Transmitter and Power Receiver follow through their operating space when controlling from the ping Operating Point to the target Operating Point at different coupling factors. Each trajectory starts from the ping Operating Point, which is indicated by a star. The Power Receiver first controls its load voltage to a value just over 12 V (rms). In the Transmitter's diagram this is the slightly slanted line near the bottom (less than 1 W of input power). In the Power Receiver it is the steep line close to the vertical axis. Next the Power Receiver changes its load from the ping load impedance to the target load impedance (12 V / 1.5 A = 8 Ω). This load step increases the Power Transmitter's power and Primary Coil current, and it decreases the load voltage. For the lowest coupling (purple curve) the Primary coil current even exceeds the limit. In this example, the Power Transmitter does not enforce its current limit instantly, but instead controls its Operating Point back to the limit after completion of the load step. Finally, the Power Receiver controls its voltage to the target value, which is possible for the highest coupling factors only (red, yellow, and green curves). At the lower coupling factors (blue and purple curves), the Power Transmitter hits is current limit. The solid squares indicate the final Operating Point for each coupling factor.

Figure 13. System control with a fixed-maximum Primary Coil current (1)



As a clear illustration of the scenarios described earlier in this section, the dashed and dotted curves in Figure 13 show the trajectories that the Power Transmitter and Power Receiver follow if the coupling factor changes between zero and 0.56. The load impedance and the Power Transmitter's Operating Point are fixed on these trajectories (i.e. the Power Transmitter does not enforce its limits during the coupling step). As shown in the diagram on the right, the load voltage can reach values up to about 20 V (rms) at the target load impedance of 8 Ω. To reach this voltage, the input power and Primary Coil current exceed their limits substantially (see the left diagram). The behavior is radically different at the ping impedance of 800 Ω, where the load voltage can reach values well over 20 V (rms). Corresponding trajectories are not visible in the diagram on the left because the coupling step causes hardly any change in the Primary Coil current and input power. Even if the Power Transmitter would instantly enforce its limits, the load voltage would reach these high levels. This is clearly visible in Figure 14, where the maximum load voltage is much reduced at the target load impedance but not at the ping impedance. In fact, the maximum reachable load voltages can be read directly from the red contour in Figure 12 (diagram on the right).

Figure 14. System control with a fixed-maximum Primary Coil current (2)

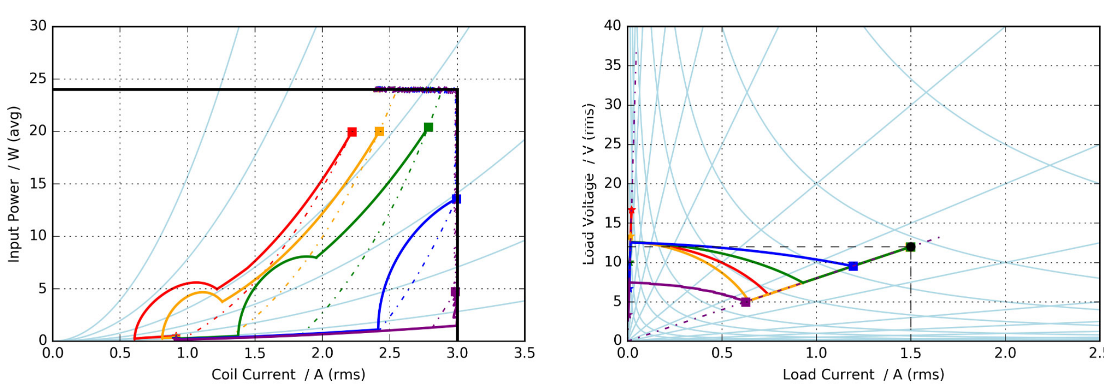
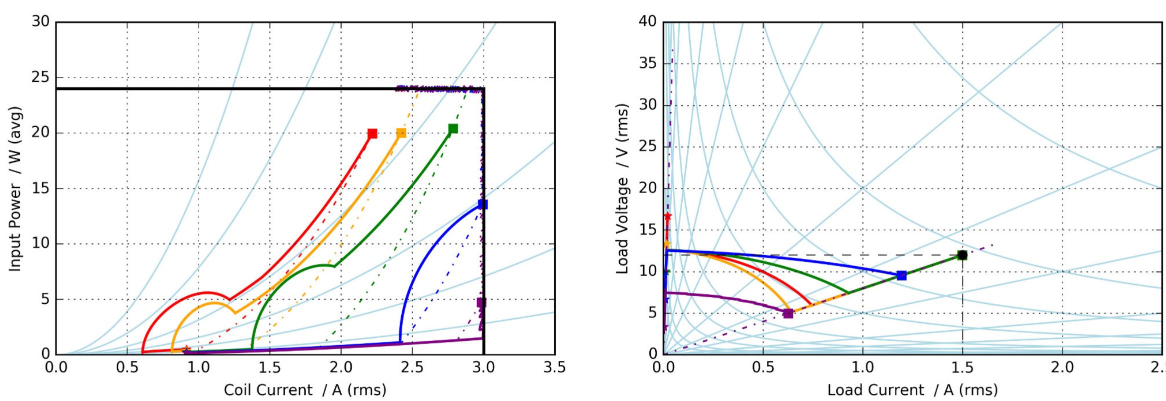


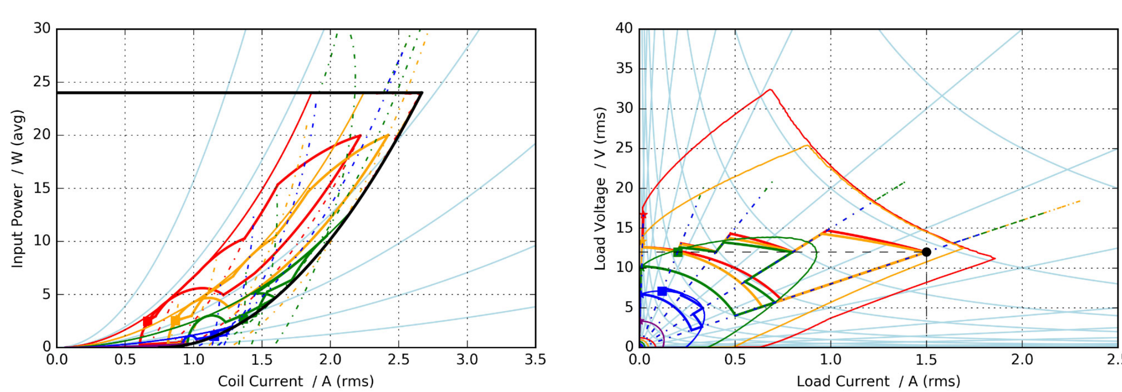
Figure 15 illustrates that a Primary Coil current limit that depends on the Transmitted Power (or on the input power) is a means to mitigate high load voltages in the Power Receiver. Clearly, the highest load voltages reached using this limit stay well below 20 V (rms). This example also illustrates that the cost of this approach is a reduced coupling range over which the Power Receiver can reach its target Operating Point (the green curve representing a coupling factor of 60% · 0.56 no longer reaches the target Operating Point). This means that proper alignment of the Power Transmitter and Power Receiver becomes important. Different shapes of the current limit yield a different trade-off between maximum load voltage and the coupling range.

Figure 15. System control at power-dependent maximum Primary Coil current (1)



As a final example, Figure 16 illustrates the full operating space that results from the power-dependent current limit; the trajectories that result if the Power Receiver scales its power back from its target to load powers of 10 W, 5 W, and 3 W; and the maximum voltages that result from coupling steps at these additional Operating Points. In most cases, the maximum voltage does not exceed 20 V (rms), and where it does exceed 20 V (rms) it is not by much.

Figure 16. System control at power dependent maximum Primary Coil current (2)



All practical Power Receiver implementations use a rectifier as part of the load circuit shown in Figure 11 (see also Section 3.2, *Rectification circuit*). Moreover, most Power Receiver implementations include a capacitor directly after this rectifier to smoothen the ripple on the rectified voltage. In combination with a high load impedance (low load current), this smoothing capacitor typically charges to a level approaching the peak voltage that is present at the input to the rectifier. When determining the appropriate (power-dependent) current limit this effect should be taken into account. Special care should be taken in designing Power Transmitters that use duty-cycle control (instead of frequency or voltage control), because the peak voltage in those designs can be substantially higher than the rms voltage that is used in the above examples. (The voltage waveform at the input to the rectifier resembles the waveform generated by the Power Transmitter's power source.)

11 External Power Input (Informative)

11.1 Available power—Extended Power Profile only

To meet the recommended minimum system efficiency (see Section 13.2, *Power Transmitter efficiency*), the power supply of a Power Transmitter should be able to provide at least 20 W.

Once the Power Transmitter has completed the *negotiation* phase, and therefore has established a Power Transfer Contract, its power supply should not reduce the power below the level that is necessary to fulfill the Guaranteed Load Power in the Power Transfer Contract. Note that this provision typically is relevant only if multiple Power Transmitters share a single power supply. For example, if two Power Transmitters share a single 30 W power supply, only one of the two at a time can negotiate a Guaranteed Load Power of 15 W—which translates to an input power of 20 W or more. The other one then has to stick to a Guaranteed Load Power of 5 W—which translates to an input power of 7.5 W or more. In order to make this work reliably, some communication should be provided between the Power Transmitters and the power supply.

12 Power Levels (Extended Power Profile only)

12.1 Potential Load Power

The Power Transmitter designs using the Extended Power Profile and defined in the *Qi Specification, Power Transmitter Reference Designs* can support a Potential Load Power of up to 15 W. A Power Transmitter that is constructed according to one of these Power Transmitter designs can provide the amount of power that Test Power Receiver #MP1 needs to function at its intended Control Point. In particular, this means that if Test Power Receiver #MP1 is positioned appropriately relative to the Power Transmitter, it can provide

- 8 W of power at its output in configuration A if the Potential Load Power is ≥ 8 W;
- 15 W of power at its output in configuration B if the Potential Load Power is 15 W; and
- 12 W of power at its output in configuration C if the Potential Load Power is ≥ 12 W.

12.2 Light load

A Power Transmitter shall be able to continuously provide power at 5% of the Maximum Power level that is contained in the Power Transfer Contract, with a minimum of 250 mW.

NOTE: Power Receivers that operate in stand-by mode, or have a nearly full battery may present such a light load to the Power Transmitter for longer periods of time. The minimum light-load power level that a Power Transmitter is required to support corresponds to a negotiated Maximum Power level of 5 W.

13 System Efficiency (Informative)

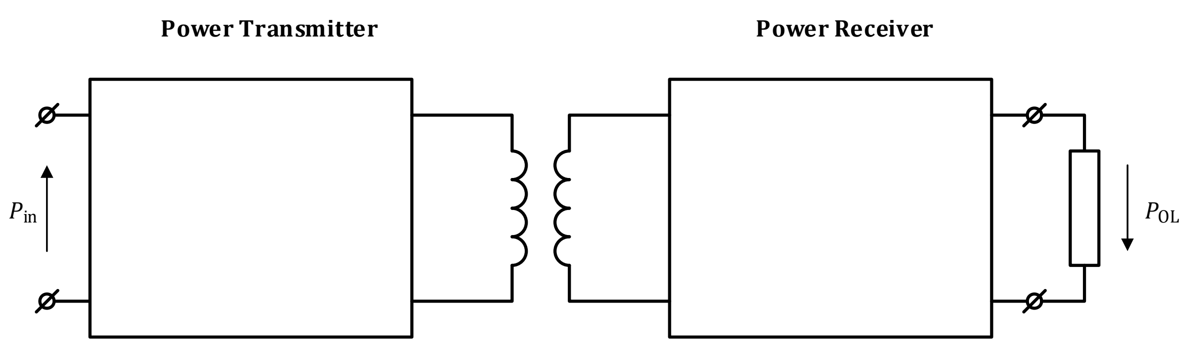
The efficiency of a wireless power transfer System depends on the combination of the specific Power Transmitter and the specific Power Receiver that are used, as well as their alignment. Since the Power Transmitter and Power Receiver are subsystems of two separate pieces of end equipment that may originate from different manufacturers, the efficiency of each can only be measured with a reference test fixture of the other subsystem. Below defines the procedure to measure the system efficiency with the help of the Test Power Transmitters and Test Power Receivers, which are defined in the *Qi Specification, Power Receiver Test Tools* and *Qi Specification, Power Transmitter Test Tools*.

13.1 Definition

Figure 17 shows a schematic diagram of a wireless power transfer System, consisting of a Power Transmitter coupled to a Power Receiver. As illustrated, P_{in} represents the DC input power to the (inverter stage of the) Power Transmitter, and P_{OL} represents the amount of DC power that is consumed in the load that is connected to the output terminals of the Power Receiver. The system efficiency is defined as:

$$\eta_{\text{system}} = \frac{P_{\text{OL}}}{P_{\text{in}}}$$

Figure 17. System efficiency



13.2 Power Transmitter efficiency

13.2.1 Baseline Power Profile

Table 12 indicates the recommended minimum system efficiency of a Power Transmitter for Baseline Power Profile devices, as measured with the set of Test Power Receivers defined in the *Qi Specification, Power Transmitter Test Tools*. It is also recommended that if the Power Transmitter Product is to be delivered with an AC adapter, the AC adapter should be Energy Star compliant.

Table 12: Recommended minimum system efficiency (Baseline Power Profile)

Test Power Receiver	Load [Ω]	Minimum System Efficiency [%]
TPR#1A	3.5	55
TPR#1B	8.7	65
TPR#1C	10	50
TPR#1D	75	25
TPR#1E	5	55

The system efficiency of the Power Transmitter Product is measured using Test Power Receiver #1, as defined in the *Qi Specification, Power Transmitter Test Tools*. Measurement of the Power Transmitter efficiency shall proceed as follows:

1. Position Test Power Receiver #1 on the Interface Surface of the Power Transmitter Product.
2. Calculate the Power Transmitter efficiency η_{system} as:

$$\eta_{\text{system}} = \frac{P_{\text{OL}}}{P_{\text{in}}}$$

3. Repeat the above 2 steps 3 times, and calculate the average Power Transmitter efficiency η_{average} as:

$$\eta_{\text{average}} = \frac{1}{3}\sum_{i=1}^{3} \eta_{\text{system}}(i)$$

13.2.2 Extended Power Profile

Table 13 provides recommendations for the minimum system efficiency for Extended Power Profile devices. Note that this table augments Table 12.

Table 13: Recommended minimum system efficiency (Extended Power Profile)

Test Power Receiver	Volume I Power Transmitter (5 W)		Volume II Power Transmitter (15 W)	
	Load [Ω]	Minimum System Efficiency [%]	Load [Ω]	Minimum System Efficiency [%]
TPR#1A	3.5	55	3.5	55
TPR#1B	8.7	65	8.7	65
TPR#1C	10	50	10	50
TPR#1D	75	25	75	25
TPR#1E	5	55	5	55
TPR#MP1A	—	—	4.2	65
TPR#MP1B	—	—	9.6	70
TPR#MP1C	—	—	12	75

13.3 Power Receiver efficiency

Measurement of the Power Receiver efficiency shall proceed as follows:

1. **Baseline Power Profile:** Position the Power Receiver Product under test on the Interface Surface of Test Power Transmitter #2 defined in the *Qi Specification, Power Receiver Test Tools*.

   Extended Power Profile: Test Power Transmitter #MP1 is used to determine the efficiency of a Power Receiver that negotiates a Guaranteed Load Power Value of 15 W in the Power Contract.

2. The power delivered to the load of the Power Receiver must be predetermined or set to a known condition P_{0L}.

3. Measure the amount of power P_{in} input of the Test Power Transmitter, at a power dissipation P_{0L} in the load of the Power Receiver under test.

4. Calculate the system efficiency for the Power Receiver η_{system} as:

$$\eta_{\text{system}} = \frac{P_{\text{OL}}}{P_{\text{in}}}$$

5. Repeat the above 3 steps 3 times, and calculate the average Power Receiver efficiency $\eta_{average}$ as:

$$\eta_{\text{average}} = \frac{1}{3}\sum_{i=1}^{3} \eta_{\text{system}}(i)$$

14 Stand-by Power (Informative)

The purpose of the stand-by mode of operation is to reduce the power consumption of a wireless power transfer system when power transfer is not required. There are two ways to enter stand-by mode. The first is when the Power Transmitter does not detect the presence of a valid Power Receiver. The second is when the Power Receiver transmits only an End Power Transfer Packet. In stand-by mode, the Power Transmitter only monitors if a Power Receiver is placed on or removed from the Interface Surface of the Power Transmitter Product.

It is recommended that the Power Transmitter Product's power consumption in stand-by mode of operation meets the Energy Star EPS Requirements for "Energy consumption for No-Load" and the European Commission, Code of Conduct of Energy Efficiency of External Power Supplies for "No-load power consumption." It is also recommended that a Power Receiver is designed in a manner that when wireless power is not required, the Power Receiver will send an End Power Transfer Packet to put the Power Transmitter Product in stand-by mode.

14.1 Transmitter Measurement Method

Measurement of the stand-by power shall proceed as follows:

1. Determine the average power consumption of the input source to the Power Transmitter Product over 1 hour in the case where there is no Power Receiver Product present on the Interface Surface of the Power Transmitter Product.

   NOTE: The input source may consist of an AC adapter in the case of a mains-operated Power Transmitter Product or a DC adapter in the case of a battery-operated Power Transmitter Product, such as in automotive applications.

2. Determine the average power consumption of the input source to the Power Transmitter Product over 1 hour in the case where Test Power Receiver #4 is present on the Interface Surface of the Power Transmitter Product. If the Power Transmitter Product can serve simultaneous Power Receiver Products, multiple Test Power Receivers should be present on the Interface Surface.

   NOTE: The Test Power Receiver always transmits an End Power Transfer Packet with payload 0x01 (Charge Complete) in response to a Digital Ping (see the *Qi Specification, Power Transmitter Test Tools*).

15 Object Detection (Informative)

A Power Transmitter may use a variety of methods to efficiently discover and locate objects on the Interface Surface. These methods, also known as "analog ping," do not involve waking up the Power Receiver and starting digital communications. Typically zero or more analog pings precede the Digital Ping, which the Power Transmitter executes in the first *power transfer* phase. This section provides some analog ping examples.

15.1 Resonance shift

This analog ping method is based on a shift of the Power Transmitter's resonance frequency, due to the presence of a (magnetically active) object on the Interface Surface.

For a type A10 Power Transmitter, this method proceeds as follows: The Power Transmitter applies a very short pulse to its Primary Coil, at an Operating Frequency f_{od}, which corresponds to the resonance frequency of the Primary Coil and series resonant capacitance (in case there is no object present on the Interface Surface). This results in a Primary Coil current I_{od}. The measured value depends on whether or not an object is present within the Active Area. It is highest if the resonance frequency has not shifted due to the presence of an object. Accordingly, if I_{od} is below a threshold value I_{odt}, the Power Transmitter can conclude that an object is present. Note that the values of f_{od} and I_{odt} are implementation dependent.

The Power Transmitter can apply the pulses at regular intervals t_{odi}, where each pulse has a duration of at most t_{odd} μs. Measurement of the Primary Coil current I_{od} should occur at most t_{odm} μs after the pulse. See also Figure 18 and Table 14.

Figure 18. Analog ping based on a resonance shift

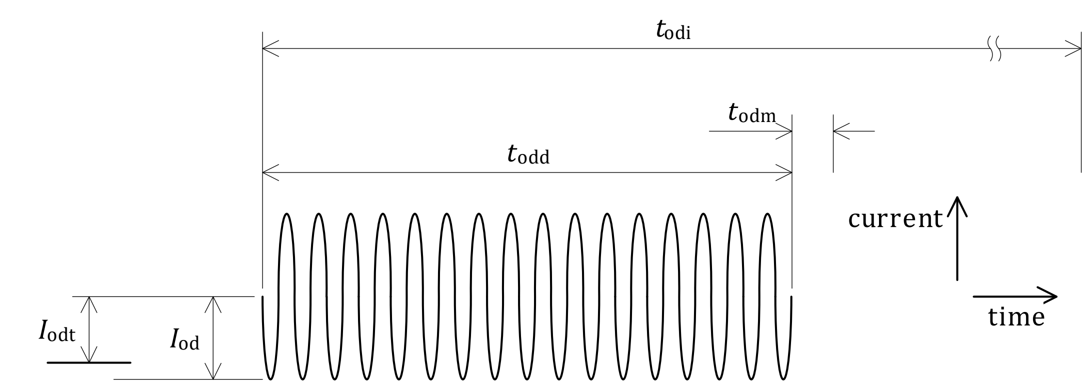


Table 14: Analog ping based on a resonance shift

Parameter	**Symbol**	**Value**	**Unit**
Object detection interval	t_{odi}	500	ms
Object detection duration	t_{odd}	70	µs
Object detection measurement	t_{odm}	19.5	µs

For type B1 and B2 Power Transmitters, this method proceeds as follows: The Power Transmitter applies a very short pulse to a set of Primary Coils, which the multiplexer has connected in parallel. Note that this set is not necessarily limited to a Primary Cell. The Operating Frequency f_{od} of the pulse corresponds to the resonance frequency of the set of Primary Coils and the capacitance of the impedance matching circuit (in case there is no object present on the Interface Surface). This results in a current I_{od} through the inductance of the impedance matching circuit. The measured value depends on whether or not an object is present within the Active Area. It is lowest if the resonance frequency has not shifted due to the presence of an object. Accordingly, if I_{od} is above a threshold value I_{odt}, the Power Transmitter can conclude that an object is present. Note that the values of f_{od} and I_{odt} are implementation dependent.

The Power Transmitter can apply the pulses at regular intervals t_{odi}, where each pulse has a duration of at most t_{odd} µs. Measurement of the current I_{od} should occur at most t_{odm} µs after the pulse. See also Figure 18 and Table 14.

15.2 Capacitance change

This analog ping method is based on a change of the capacitance of an electrode on or near the Interface Surface, due to the placement of an object on the Interface Surface.

This method is particularly suitable for Power Transmitters that use Free Positioning, because it enables implementations that have a very low stand-by power, and yet exhibit an acceptable response time to a user. The reason is that (continuously) scanning the Interface Surface for changes in the arrangement of objects and Power Receivers thereon is a relatively costly operation. In contrast, sensing changes in the capacitance of an electrode can be very cheap (in terms of power requirements).

NOTE: Capacitance sensing can proceed with substantial parts of the Power Transmitter Product powered down.

Power Transmitters designs that are based on an array of Primary Coils can use the array of Primary Coils as the electrode in question. For that purpose, the multiplexer should connect all (or a relevant subset of) Primary Coils in the array to a capacitance sensing unit—and at the same time disconnect the Primary Coils from the driving circuit. Power Transmitter designs that are based on a moving Primary Coil can use the detection coils on the Interface Surface (see Section 16.2, *Moving Primary Coil based Free Positioning*) as electrodes.

It is recommended that the capacitance sensing circuit is able to detect changes with a resolution of 100 fF or better. If the sensed capacitance change exceeds some implementation defined threshold, the Power Transmitter can conclude that an object is placed onto or removed from the Interface Surface. In that case, the Power Transmitter should proceed to localize the objects and attempt to identify the Power Receivers on the Interface Surface, e.g. as discussed in Section 16, *Power Receiver Localization (Informative)*.

16 Power Receiver Localization (Informative)

This section discusses several aspects that relate to the discovery of Power Receivers amongst the objects that the Power Transmitter has discovered on its Interface Surface.

16.1 Primary Coil array based Free Positioning

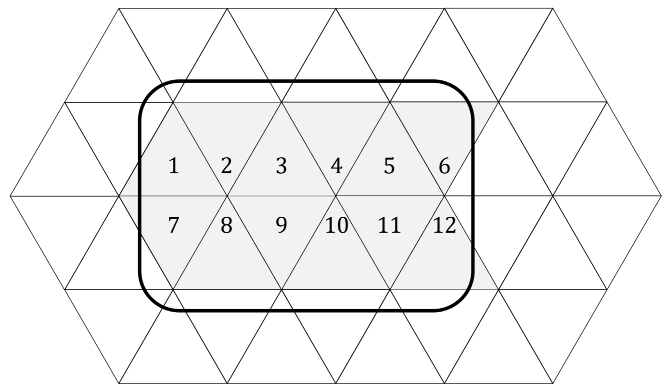
This section discusses one sample approach, which is particularly suited to a Primary Coil array-based Power Transmitter. In this approach, the Power Transmitter first discovers and locates the objects that are present on its Interface Surface (e.g. using any of the methods discussed in Section 15, *Object Detection (Informative)*). This results in a set of Primary Cells, which represents the locations of potential Power Receivers. For each of the Primary Cells in this set, the Power Transmitter executes a Digital Ping (see the *Qi Specification, Communications Protocol*), removing the Power Signal after receipt of a Signal Strength Packet (or an End Power Transfer Packet, or after a time out).[3] This yields a new set of Primary Cells, namely those that report a Signal Strength Value above a certain threshold—which the Power Transmitter chooses. Finally, the Power Transmitter executes an extended Digital Ping for each of the Primary Cells in this new set in order to identify the discovered Power Receivers (see the *Qi Specification, Communications Protocol*). The Power Transmitter should take the situations discussed in Section 16.1.1, *A single Power Receiver covering multiple Primary Cells*, Section 16.1.2, *Two Power Receivers covering two adjacent Primary Cells*, and Section 16.1.3, *Two Power Receivers covering a single Primary Cell* into account in order to select the most appropriate Primary Cells from the set for power transfer.

16.1.1 A single Power Receiver covering multiple Primary Cells

Figure 19 shows a situation in which the final set contains 12 Primary Cells. In order to select the most appropriate Primary Cell from this set, the Power Transmitter compares all Basic Device Identifiers that it has obtained. In this case, they are all identical. Accordingly, the Power Transmitter concludes that all Primary Cells in the set correspond to one and the same Power Receiver. Therefore, the Power Transmitter selects the Primary Cell that has the highest Signal Strength Value as the most appropriate Primary Cell to use for power transfer. In the specific example shown in Figure 19, this could be Primary Cell 2, 3, 4, 5, 8, 9, 10, or 11.

[3] NOTE The Power Transmitter should ensure that after terminating a Digital Ping using a particular Primary Cell, it waits sufficiently long—for example t_{reset} (see the *Qi Specification, Communications Protocol*)—prior to executing a Digital Ping to that same Primary Cell or any of its neighboring Primary Cells. This ensures that any Power Receiver that is present on the Interface Surface at the location of the Primary Cell can return to a well-defined state.

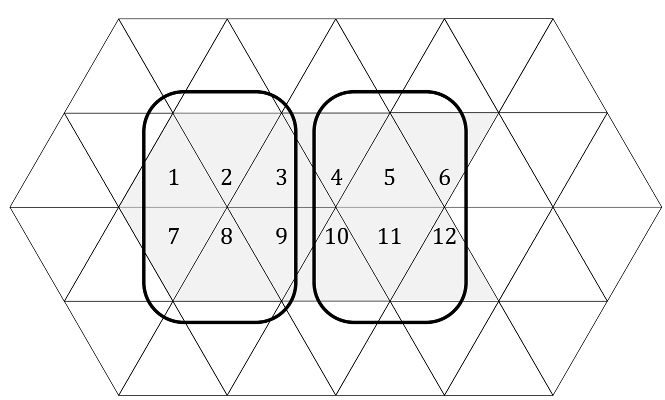
Figure 19. Single Power Receiver covering multiple Primary Cells



16.1.2 Two Power Receivers covering two adjacent Primary Cells

Figure 20 shows a situation in which the final set contains 12 Primary Cells—the same set as in the situation discussed in Section 16.1.1, *A single Power Receiver covering multiple Primary Cells*. In order to select the most appropriate Primary Cell from this set, the Power Transmitter compares all Basic Device Identifiers that is has obtained. In this case, the Power Transmitter determines that there are two subsets of identical Basic Device Identifiers. Accordingly, the Power Transmitter concludes that it is dealing with two distinct Power Receivers. Therefore, the Power Transmitter selects the most appropriate Primary Cell from each subset. In the specific example shown in Figure 20, this could be Primary Cell 2, or 8 for the left-hand Power Receiver, and Primary Cell 5, or 11 for the right-hand Power Receiver. Note that due to interference, the Power Transmitter most likely cannot communicate reliably using Primary Cells 3, 4, 9, and 10.

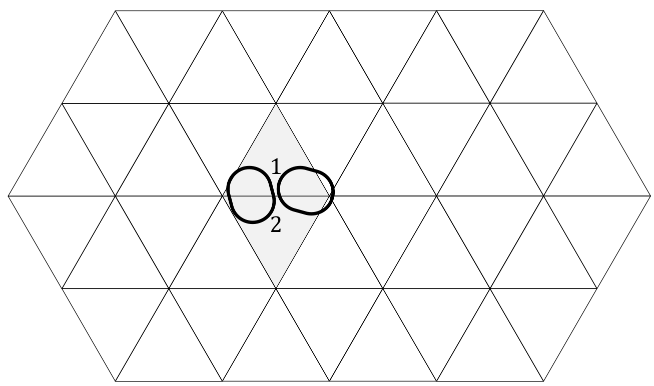
Figure 20. Two Power Receivers covering two adjacent Primary Cells



16.1.3 Two Power Receivers covering a single Primary Cell

Figure 21 shows a situation in which the final set contains 2 Primary Cells. Here, the underlying assumption is that the two Power Receivers have widely different response times (t_{wake}, see the *Qi Specification, Communications Protocol*) to a Digital Ping. For example, the left-hand Power Receiver responds very fast (close to $t_{\mathrm{wake}}^{(\mathrm{early})}$), whereas the right-hand Power Receiver responds very slow (close to $t_{\mathrm{wake}}^{(\mathrm{late})}$). This enables the Power Transmitter to receive the Signal Strength Packet from the fast Power Receiver, but not from the slow one. However, the Power Transmitter cannot reliably receive any further communications—from either Power Receiver—due to collisions between transmissions from the two Power Receivers. Accordingly, the Power Transmitter cannot select a Primary Cell for power transfer.

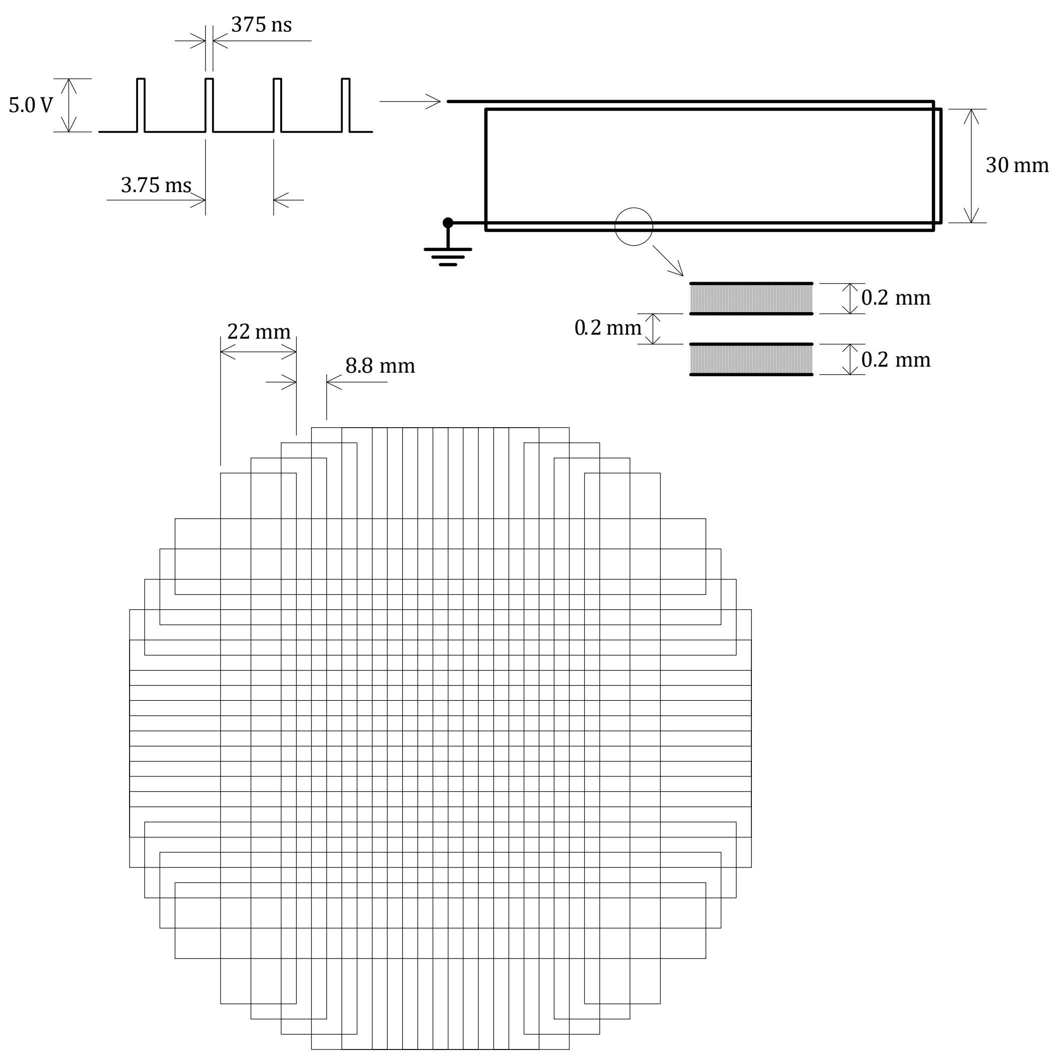
Figure 21. Two Power Receivers covering a single Primary Cell



16.2 Moving Primary Coil based Free Positioning

In the case of moving Primary Coil based Free Positioning, typically a special Detection Unit provides discovery and localization of a Power Receiver. This Section 16.2, *Moving Primary Coil based Free Positioning* discusses an example of such a Detection Unit, which makes use of the resonance in the Power Receiver at the detection frequency f_d. In this sample Detection Unit, detection coils are printed on the Interface Surface of the Power Transmitter Product. The top right-hand part of Figure 22 shows a single rectangular detection coil, which consists of two windings. The width of the detection coil is 22 mm, and its length depends on the size of the Interface Surface. As shown in the bottom part of Figure 22, a first set of these detection coils is laid out in parallel to cover the entire Interface Surface in such a way that the areas of two adjacent detection coils overlap by 60%. A second set of these detection coils is laid out similarly, but orthogonal to the detection coils in the first set.

Figure 22. Detection Coil



Detection of a Power Receiver proceeds as follows: In first instance, the Power Transmitter uses the detection coils as an electrostatic sensor to detect the placement or removal of objects on the Interface Surface (see Section 15, *Object Detection (Informative)*). Once the Power Transmitter has detected an object, it uses the detection coils to determine the position of that object on the Interface Surface. For this purpose, the Power Transmitter applies a short pulse train to each of the detection coils—one by one. This pulse train consists of 8 pulses, and is shaped to trigger the resonance in the Power Receiver at the frequency f_{d}. See the top left-hand part of Figure 22. As a result, a minute amount of energy is transferred to the resonant circuit in the Power Receiver. Immediately after the pulse train terminates, this energy is re-radiated, which the Power Transmitter can detect using the detection coils. By analyzing the Responses from each of the detection coils, the Power Transmitter can determine the location of the Power Receiver on the Interface Surface. Subsequently, the Power Transmitter can move its coil underneath the Power Receiver, and can start to transfer power as defined in the *Qi Specification, Communications Protocol*. During power transfer, the Power Transmitter can adjust the position of the Primary Coil in order to optimize its coupling to the Secondary Coil, e.g. by maximizing the system efficiency. The Power Transmitter can calculate the system efficiency from its input power and the Actual Power Value contained in the Actual Power Packets, which it receives from the Power Receiver.

An advantage of this detection method is that it is insensitive to Foreign Objects that do not exhibit a resonance near the detection frequency f_{d}. The reason is that such objects do not store and re-radiate energy picked up from the pulse train. Consequently, a Power Transmitter does not need to move the Primary Coil to attempt power transfer to such objects.

16.3 User-assisted positioning

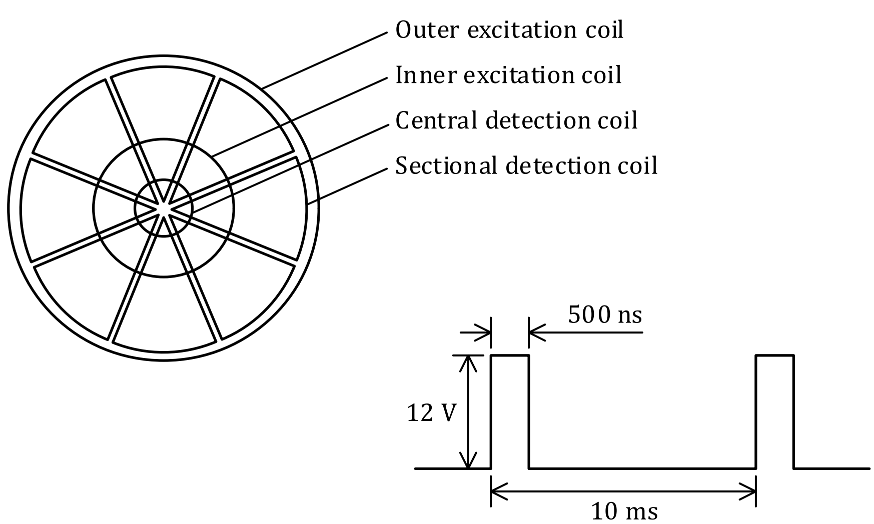
16.3.1 Example 1

In the case of user-assisted positioning, typically a special Detection Unit provides discovery and localization of a Power Receiver so as to guide the user to move the Power Receiver Product towards the center of the Primary Coil. This section discusses an example of such a Detection Unit, which makes use of the resonance in the Power Receiver at the detection frequency f_d. In this sample Detection Unit, detection coils are printed on a circuit board underneath the Interface Surface of the Power Transmitter Product.

The top left-hand part of Figure 23 shows a configuration of detection coils, which consists of a center detection coil aligned to the Primary Coil and a set of sectional detection coils surrounding the center detection coils. Typically, there are 8 sectional detection coils. The combination of all detection coils forms a circular detection area. The size of this circular detection area typically is equal to or larger than the area of the Primary Coil.

In order to excite the resonance signal from the Power Receiver, an outer excitation coil is formed close to the outer circumference of the sectional detection coils. If the detection area for user-assisted positioning is much larger than the area of Primary Coil, one or more inner excitation coils should be added.

Figure 23. Detection Unit



Basically, the Detection Unit uses the detection coils as an electromagnetic sensor array to determine the position of a Power Receiver on the Interface Surface. For this purpose, the Power Transmitter applies a short single pulse to an excitation coil, in order to trigger the resonance in the Power Receiver at the frequency f_d. See the bottom right-hand part of Figure 23. As a result, a minute amount of energy is transferred to the resonant circuit in the Power Receiver. Immediately after the pulse terminates, the energy is re-radiated and is captured by the detection coils as a Response signal. After analyzing the distribution of Responses from each of the detection coils, the Power Transmitter can determine the location of the Power Receiver on the Interface Surface.

The Power Transmitter can use this information to provide feedback to the user, such that the user can properly move the Power Receiver towards the center of the Primary Coil of the Power Transmitter. If all sectional detection coils have approximately the same resonance level, the positioning is finished and then the Power Transmitter can start to transfer power as defined in the *Qi Specification, Communications Protocol*. In addition, the circular detection coil at center is available for the detection of small Secondary Coils.

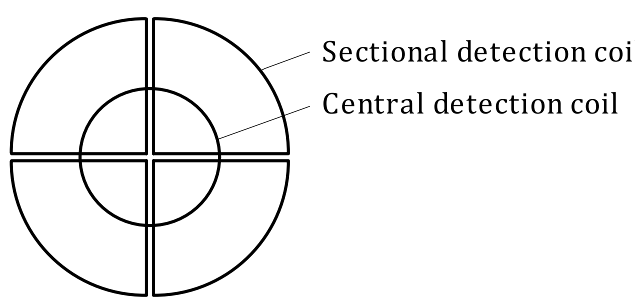
16.3.2 Example 2

In the case of user-assisted positioning, typically a special Detection Unit provides discovery and localization of a Power Receiver so as to guide the user to move the Power Receiver Product towards the center of the Primary Coil. This section discusses an example of such a Detection Unit, which makes use of the resonance in the Power Receiver at the detection frequency f_d. In this sample Detection Unit, detection coils are printed on a circuit board underneath the Interface Surface of the Power Transmitter Product.

At first, a Clapp oscillator supplies its output signal to the Primary Coil, and a frequency sensor watches the output signal. If the Power Receiver comes near to the Primary Coil, the Shielding of the Power Receiver affects to the Primary Coil, and the frequency of the output signal is changed. If the frequency sensor detects the frequency change, the Clapp oscillator is stopped, and the Power transmitter starts to supply signal to the detection coils.

Figure 24 shows a configuration of detection coils, which consists of a center detection coil aligned to the Primary Coil, and a set of sectional detection coils surrounding the center detection coils. Typically, there are 4 sectional detection coils. The combination of all detection coils forms a circular detection area.

Figure 24. Detection Coils



Basically, the Detection Unit uses the detection coils as an electromagnetic sensor array to determine the position of a Power Receiver on the Interface Surface. For this purpose, the Power Transmitter provides the signal at the frequency f_d. Each detection coil's resonance level shows the location of the Power Receiver on the Interface Surface. The Power Transmitter can use this information to provide feedback to the user, such that the user can properly move the Power Receiver towards the center of the Primary Coil of the Power Transmitter.