WIRELESS POWER
CONSORTIUM

Qi Specification

Foreign Object Detection

Version 1.3

January 2021

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RELEASE HISTORY

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

Table of Contents

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, Foreign Object Detection* (this document) defines methods for ensuring that the power transfer proceeds without heating metal objects in the magnetic field of a Power Transmitter. Although the Power Transmitter may optionally use any of these methods, some of them require assistance by the Power Receiver.

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.

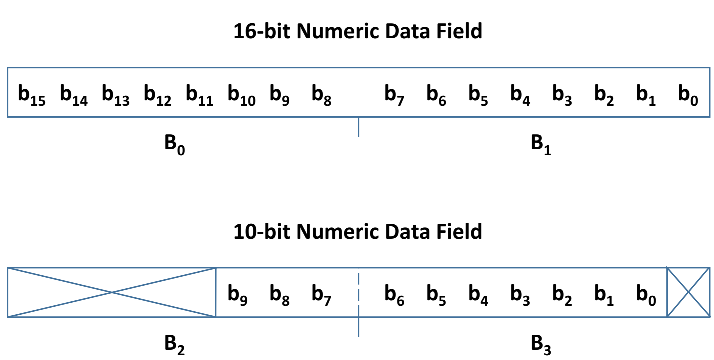
1.5.3 Fields in a data packet

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

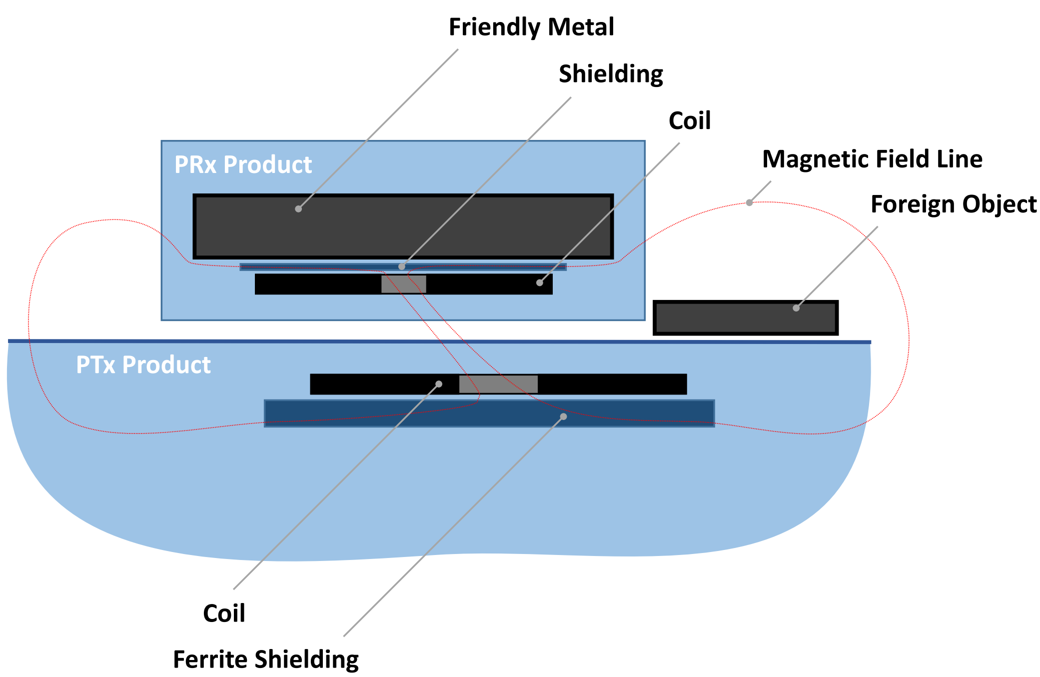
Feature	BPP PTx	EPP5 PTx	EPP PTx	BPP PRx	EPP PRx
A*x* or B*x* design	Yes	Yes	No	N/A	N/A
MP-A*x* or MP-B*x* design	No	No	Yes	N/A	N/A
Baseline Protocol	Yes	Yes	Yes	Yes	Yes
Extended Protocol	No	Yes	Yes	No	Yes
Authentication	N/A	Optional	Yes	N/A	Optional

2 Introduction

In a normal use case of a power transfer according to the *Qi Specification*, the Power Signal (magnetic field) of the Power Transmitter interacts with the Power Receiver Product only. However, sometimes a user accidentally places metallic objects such as coins, paper clips, keys, or pieces of aluminum foil next to or underneath the Power Receiver Product, either before the power transfer starts, or while it is ongoing. The *Qi Specification* refers to such objects as Foreign Objects.

A problem with Foreign Objects is that they can dissipate power from the magnetic field, and as a result heat up to unsafe temperature levels. The system should therefore not initiate the power transfer, limit the power level, or stop the power transfer when it detects that one or more Foreign Objects are present.

Figure 2. Power transfer system including a Foreign Object



A factor complicating Foreign Object Detection (FOD) is the presence of Friendly Metals in the magnetic field. A Friendly Metal is similar to a Foreign Object in the sense that it can dissipate power from the magnetic field. However, unlike a Foreign Object, it is an integral part of the Power Receiver Product or Power Transmitter Product. In many cases, it is hard for a Power Transmitter to distinguish properly between Foreign Objects and Friendly Metals. Typically, no single method is sufficient to solve the problem. Accordingly, the Power Transmitter should use multiple methods to maximize the probability of detecting Foreign Objects, while minimizing the probability of false alarms.

3 Avoidance of Foreign Object heating

As explained in Section 2, *Introduction*, the Power Signal can heat up Foreign Objects that are present in the Operating Volume. Therefore, a Power Transmitter Product shall ensure that such Foreign Objects do not reach unsafe temperature levels. This may involve limiting or terminating the power transfer.

Section 4, *Pre-power transfer FOD methods*, and section 5, In-power transfer FOD methods, provide methods the Power Transmitter can use to detect Foreign Objects. These methods involve the Power Receiver sending information about its design properties to the Power Transmitter. The Power Receiver shall provide the design information associated with all methods.

In addition, the Power Transmitter can monitor the temperature of its Interface Surface for hot spots. Moreover, it can actively cool its Interface Surface to drain heat away from the Power Receiver and Foreign Objects.

3.1 Representative Foreign Objects

Foreign Objects can have many different sizes, shapes, and material compositions. To address this diversity, the *Qi Specification, Foreign Object Detection* (this document) defines the required FOD capabilities of a Power Transmitter in terms of a set of Representative Foreign Objects. Table 4 lists these objects.

Table 4: Representative Foreign Objects

Designator	Shape	Material	Dimensions	Limit / C°
RFO#1	Disk	Steel 1.1011 DIN RFe160	ø15 mm, 1 mm thick	60
RFO#2	Ring	DIN 3.2315 EN AW-6082 ISO AlSi1MgMn	ø20 mm (inner) ø22 mm (outer) 1 mm thick	60
RFO#3	Foil	EN AW-1050 DIN 3.0255 Al99.5	ø20 mm, 0.1 mm thick	80
RFO#4	Disk	DIN 3.2315 EN AW-6082 ISO AlSi1MgMn	ø22 mm, 1 mm thick	60

When one of the Representative Foreign Objects is present in the Operating Space, the Power Transmitter shall not heat it to a temperature above the limit associated with that object.

4 Pre-power transfer FOD methods

A Power Transmitter can use several methods to detect Foreign Objects before initiating a power transfer to a Power Receiver. Some of these methods depend on the Power Receiver providing information about its design properties.

In one method, described in Section 4.1, *Resonance change*, the Power Transmitter examines the Operating Volume by applying a weak Power Signal and analyzing changes in a resonance frequency and quality factor of its tank circuit. To discriminate between Foreign Objects and Friendly Metals, it can compare the observed changes to the ones the Power Receiver produces in a reference tank circuit. To enable this comparison, the Power Receiver shall communicate a Reference Resonance Frequency and Reference Quality Factor to the Power Transmitter.

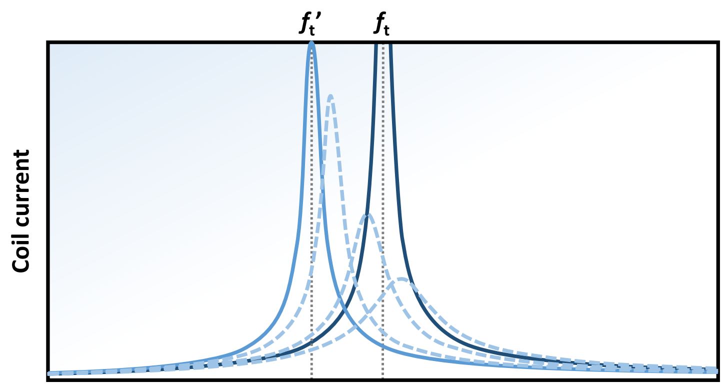
NOTE: Resonance change is the only pre-power FOD method described in this version of the *Qi Specification, Foreign Object Detection* (this document). Because this method uses properties of the Enhanced Protocol (see the *Qi Specification, Communications Protocol*, for details), it is available to EPP and EPP5 products only.

4.1 Resonance change

When a user places a Power Receiver Product in a Power Transmitter's Operating Volume, the inductance of the Power Transmitter's coil typically increases due to the proximity of the Power Receiver's Shielding. This results in a decrease of the Power Transmitter's resonance frequency. At the same time, power absorption in the Friendly Metals of the Power Receiver Product causes the quality factor of the resonance to decrease.

Figure 3 shows an example of this effect, with the curves in the diagram illustrating the behavior of the resonance under various conditions. When the Operating Volume is empty, the resonance occurs at the frequency f_{t} (dark curve). When a Power Receiver Product is present in the Operating Volume, the resonance shifts to a (typically lower) frequency f'_{t} . The magnitude of the shift depends on the design properties of the Power Transmitter and the Power Receiver Product, as well as on the position of the latter in the Operating Volume. For example, the shift is typically smaller for a phone in a protective case than for the same phone without such a case. The reason is the increased distance between the phone's Shielding and the Power Transmitter's coil.

Figure 3. Resonance shift caused by a Power Receiver Product and Foreign Objects



The dashed curves in Figure 3 show the shift of the resonance curve when a Foreign Object is present in the Operating Volume in addition to the Power Receiver Product. Typically, the Foreign Object counters the shift induced by the Power Receiver Product, and reduces the strength of the resonance (i.e. the quality factor). The reason is that the Foreign Object introduces a power loss and shields ferrites in the Power Receiver Product from the Power Transmitter's coil.

The Power Transmitter can use the change in the resonance frequency to determine whether a Foreign Object is present in the Operating Volume. However, it needs help from the Power Receiver to do so. This is because one Power Receiver Product can produce the same change as another Power Receiver Product and a Foreign Object combined. To support the resonance change FOD method, the Power Receiver shall send a Reference Resonance Frequency $f_{\mathrm{t}}'^{(\mathrm{ref})}$ and a Reference Quality Factor $Q_{\mathrm{t}}'^{(\mathrm{ref})}$ using FOD data packets in the negotiation phase of the communications protocol.

The Resonance Reference Frequency and the Reference Quality Factor are the resonance frequency and quality factor of a reference tank circuit loaded with the Power Receiver Product. See Section 4.1.2, *Obtain reference values*, for details. To ensure that contributions of Foreign Objects to the resonance change dominate over those of Friendly Metals, an EPP Power Receiver Product shall have a Reference Quality Factor of $Q_{\mathrm{t}}'^{(\mathrm{ref})} \geq 25$.

NOTE: The resonance Reference Frequency and the Reference Quality factor are not properties of the resonance in the Power Receiver's tank circuit. Instead, they reflect how Friendly Metals and ferrites in the Power Receiver Product affect the resonance in the Power Transmitter's tank circuit.

The resonance-change based FOD method therefore consists of the following steps.

1. Measure the resonance properties, i.e. f_{t}' and Q_{t}' .
2. Obtain reference values for these quantities, i.e. $f_{\mathrm{t}}'^{(\mathrm{ref})}$ and $Q_{\mathrm{t}}'^{(\mathrm{ref})}$.
3. Determine the probability that a Foreign Object is present.
4. Inform the Power Receiver if the probability exceeds a threshold.
5. Stop the power transfer if the risk of heating a Foreign Object to an unsafe temperature is too high.

The following section describe steps of the method in detail.

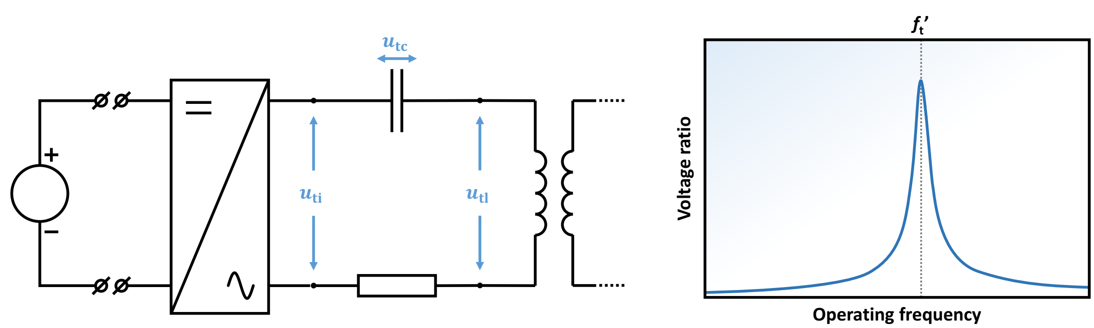
4.1.1 Measure the resonance properties

The Power Transmitter should measure its resonance properties—as affected by the presence of a Power Receiver in the Operating Volume—before executing a Digital Ping and waking up the Power Receiver. If the Power Receiver would wake up, the additional load adds to the Q factor, yielding a spurious result. Accordingly, the Power Transmitter should use as low a Power Signal as possible.

NOTE: The Power Signal is low enough if the Power Transmitter keeps the rectified voltage of TPR#MP3 below 0.85 V. See *Qi Specification, Power Transmitter Test Tools*, for details on the construction of this TPR.

The recommended method of measuring the resonance properties is to make a frequency sweep, while measuring the voltage u_{ti} applied to the tank circuit as well as the resulting voltage u_{tl} across the coil. The ratio $u_{\mathrm{tl}}/u_{\mathrm{ti}}$ of these two voltages at the highest point of the shifted resonance yields the quality factor Q'_{t} .

Figure 4. Measuring the resonance properties



4.1.2 Obtain reference values

Once the Power Transmitter has measured the properties of its resonance, it should execute a Digital Ping to wake up the Power Receiver. The latter shall send FOD/rf and FOD/qf data packets in the negotiation phase of the communications protocol to provide its Reference Resonance Frequency $f_{\mathrm{t}}'^{(\mathrm{ref})}$ and Reference Quality Factor $Q_{\mathrm{t}}'^{(\mathrm{ref})}$; see the *Qi Specification, Communications Protocol*, for details.

The Reference Resonance Frequency and Reference Quality Factor are the properties of a reference coil assembly as affected by the proximity of the Power Receiver Product. Figure 5 provides an illustration of the reference coil assembly, which consists of a ferrite, a coil, and a cover. Table 5 defines its properties, and the *Qi Specification, Power Transmitter Test Tools*, provides details for constructing and calibrating it. For details about determining $f_{\mathrm{t}}'^{(\mathrm{ref})}$ and $Q_{\mathrm{t}}'^{(\mathrm{ref})}$, see Annex A, *Determining the reference FOD values (normative)*.

NOTE: The reference coil assembly is based on the A10 and MP-A1 Power Transmitter designs; see the *Qi Specification, Power Transmitter Reference Designs*, for additional details.

Figure 5. Reference coil assembly

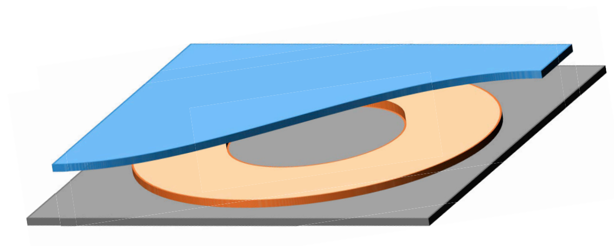


Table 5: Properties of the reference coil assembly

Dimension	Value	Unit
Ferrite: relative permeability $\mu_r = 650 + j \times 25$		
Length	53.3	mm
Width	53.3	mm
Thickness	2.54	mm
Coil; centered on the ferrite; 105 × 40 AWG type 2 litz wire		
Outer diameter	43	mm
Inner diameter	20.5	mm
Thickness	2.1	mm
Number of turns per layer	10	N/A
Number of layers	2	N/A
Cover: magnetically passive material		
Thickness	2.5	mm

At an operating frequency of 100 kHz, the inductance of the reference coil assembly is about $L_{\mathrm{t}}^{(\mathrm{ref})} = 25$ μH with a resistance of about $R_{\mathrm{t}}^{(\mathrm{ref})} = 100$ mΩ. See the *Qi Specification, Power Transmitter Test Tools*, for details.

4.1.3 Determine the presence of a Foreign Object

The Power Transmitter should use the measured resonance frequency f_{t}', the measured quality factor Q_{t}', the received Reference Resonance Frequency $f_{\mathrm{t}}'^{(\mathrm{ref})}$, and the received Reference Quality Factor $Q_{\mathrm{t}}'^{(\mathrm{ref})}$ to determine the probability that a Foreign Object is present in its Operating Volume. In the calculations involved, the Power Transmitter should account for its design differences with the reference coil assembly used to determine the reference values.

4.1.4 Inform the Power Receiver

The Power Transmitter shall inform the Power Receiver about the probability that a Foreign Object is present in the Operating Volume. If the probability is below a threshold, it shall respond to the FOD Status data packet with ACK. If the probability is above the threshold, it shall respond with NAK. See the *Qi Specification, Communications Protocol*, for details about aborting the power transfer when the Power Transmitter discovers a Foreign Object.

NOTE: When the Power Transmitter has not yet received both reference values, it may not be able to confidently determine the probability of a Foreign Object being present. In that case, it may respond with ACK to FOD Status data packets until it has all values it needs.

4.1.5 Stop the power transfer

Upon receiving a NAK response to an FOD data packet, a Power Receiver may switch to the power transfer phase of the Baseline Protocol (see the *Qi Specification, Communications Protocol*) limiting its Load Power level to 5 W or less. If the Power Transmitter assesses that the risk of heating a Foreign Object to unsafe temperatures is too high, it may remove the Power Signal.

5 In-power transfer FOD methods

A Power Transmitter can use several methods to detect Foreign Objects while the power transfer to a Power Receiver is in progress. Most of these methods depend on the Power Receiver providing information about the ongoing power transfer.

One method involves estimating the power loss to Foreign Objects by balancing the Transmitted Power and Received Power levels. To enable this method, the Power Receiver shall provide sufficiently accurate Received Power level data to the Power Transmitter on a regular basis. Because this FOD method involves one-way communications from the Power Receiver to the Power Transmitter only, it applies to products in all power profiles. Section 5.1, *Basic power loss accounting*, describes this method in detail.

An improvement of this basic method is calibrated power loss accounting. This more advanced method is available to EPP and EPP5 products only because it uses properties of the Enhanced Protocol (see the *Qi Specification, Communications Protocol*, for details). Moreover, it assumes that at least one pre-power transfer FOD method is available as well. Typically, the Power Transmitter and Power Receiver calibrate the estimated power loss at the start of the power transfer phase. Section 5.2, *Calibrated power loss accounting*, describes this method in detail.

5.1 Basic power loss accounting

In this FOD method, the Power Transmitter estimates the amount of power P_{F0} dissipated in Foreign Objects using the Received Power level data it receives from the Power Receiver. If the estimated power loss exceeds a threshold $\Delta P_{\mathrm{FO}}^{(\mathrm{thr})} \approx 500\ \mathrm{mW}$ for some period, there is a risk of heating Foreign Objects to unsafe temperatures. In that case, Power Transmitter may take one of the following actions.

- Request the Power Receiver to reduce its power consumption (Extended Protocol only)
- Ignore the Power Receiver's CE data packets and change its operating point to reduce the Transmitted Power level (and therefore the amount of power dissipated in the Foreign Objects)
- Abort the power transfer

NOTE: Experiments and simulations of the temperature rise in Foreign Objects of various sizes, shapes and materials compositions have shown that a power dissipation of up to about 500 mW such objects is acceptable in most cases.

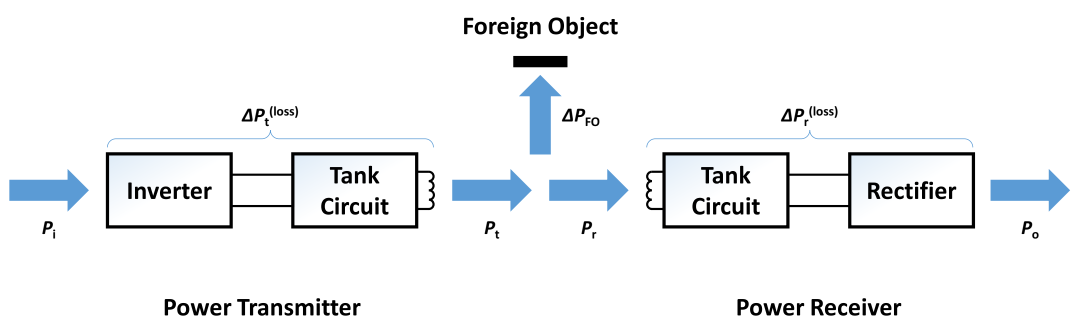
5.1.1 Method

The power P_{FO} that Foreign Objects dissipate from the Power Signal is equal to the difference of the Transmitted Power P_{t} and Received Power P_{r}, i.e.

$$\Delta P_{\mathrm{FO}} = P_{\mathrm{t}} - P_{\mathrm{r}} = \left[P_{\mathrm{i}} - P_{\mathrm{t}}^{(\mathrm{loss})}\right] - \left[P_{\mathrm{o}} - P_{\mathrm{r}}^{(\mathrm{loss})}\right]$$

In this equation, P_{i} represents the input power to the Power Transmitter; P_{o} the output power from the Power Receiver; $\Delta P_{\mathrm{t}}^{(\mathrm{loss})}$ the power loss in the Power Transmitter; and $\Delta P_{\mathrm{r}}^{(\mathrm{loss})}$ the power loss in the Power Receiver. Figure 6 illustrates the equation.

Figure 6. Power loss accounting



The power loss incurred in a Power Receiver Product typically includes the following contributions.

- The power loss in the tank circuit
- The power loss in the rectifier
- The power loss in ferrite(s) that serve to constrain the magnetic field
- The power loss in metal parts of the Power Receiver Product that are exposed to the magnetic field

By measuring its operating current, the Power Receiver can determine its tank circuit and rectifier losses with relatively good accuracy. However, it is more difficult for the Power Receiver to measure its ferrite and Friendly Metal losses. Moreover, the latter can depend strongly on the position of the Power Receiver Product in the Operating Volume. As a result, the Power Receiver can typically determine its ferrite and Friendly Metal losses with much less accuracy than its circuit losses.

The power loss incurred in a Power Transmitter Product typically includes a similar set of contributions.

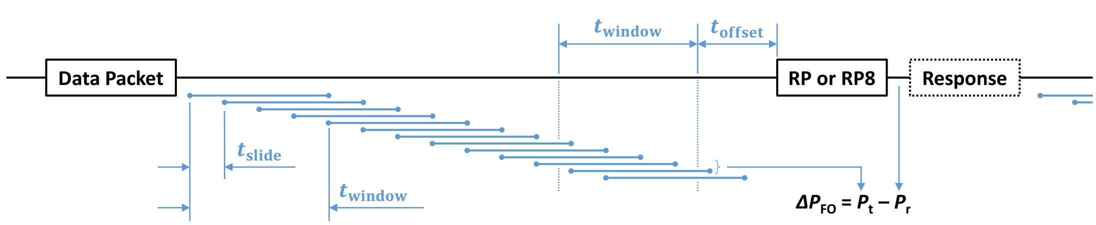
- The power loss in the inverter
- The power loss in the tank circuit
- The power loss in ferrite(s) that serve to constrain the magnetic field
- The power loss in metal parts of the Power Transmitter Product that are exposed to the magnetic field

Like a Power Receiver, a Power Transmitter can determine its inverter and tank circuit losses with relatively good accuracy, and its ferrite and Friendly Metal losses with more difficulty. However, since the latter typically depend only weakly on the position of the Power Receiver Product in the Operating Volume, the Power Transmitter can determine them with relatively good accuracy as well—and in most cases with much better accuracy than a Power Receiver can determine its ferrite and Friendly Metal losses.

In the power loss accounting method, the Power Transmitter monitors the Foreign Object loss ΔP_{FO} while the power transfer is ongoing. Hereto, the Power Receiver shall determine its Received Power level and regularly send this information to the Power Transmitter. The reported Received Power level is the average over a time window preceding the data packets used to communicate it. The offset and size of this window are elements of the Power Transfer Contract. For details, see the *Qi Specification, Communications Protocol*. To estimate the Foreign Object loss P_{FO} as accurately as possible, the Power Transmitter should determine its Transmitted Power level in a time window that matches the Power Receiver's time window as closely as possible. Because the Power Transmitter does not know when the Power Receiver will report its Received Power level next, it should determine its Transmitted Power level in sliding windows and select the best match. See Figure 7 for an illustration.

To estimate the Foreign Object loss P_{FO} as accurately as possible, the Power Transmitter should determine its Transmitted Power level in a time window that matches the Power Receiver's time window as well as possible. Because the Power Transmitter does not know when the Power Receiver will report its Received Power level next, it should determine its Transmitted Power level in sliding windows and select the best match. See Figure 7 for an illustration.

Figure 7. Sliding windows for determining the Transmitted Power level



In this example, the Power Transmitter starts to measure its Transmitted Power level after receiving a data packet. It uses a window size equal to the one in the Power Transfer Contract, and an appropriate sliding offset t_{slide}. Smaller sliding offsets yields larger overlaps between the Power Transmitter and Power Receiver windows. For example, a sliding offset of 25% of the window size yields an overlap of 75% in the worst-case misalignment. When the Power Transmitter detects the preamble of a data packet, it stops taking measurements. If the received data packet was an RP8 or RP data packet, it takes the last measured Transmitted Power value from the appropriate sliding window and calculates the Foreign Object loss. If this loss is below the threshold, it sends an ACK response (mode 0, 1, and 2 of RP data packets only) and starts measuring its Transmitted Power level again. If the loss is above the threshold several times in a row, the Power Transmitter should conclude that a Foreign Object is present and take appropriate action to prevent heating it.

5.1.2 Received power accuracy

The effectiveness of the power loss accounting method depends on the accuracy with which the Power Transmitter and Power Receiver can determine their Transmitted Power and Received Power levels. As discussed in Section 5.1.1, *Method*, the Power Receiver typically does not determine its Received Power level by measuring it directly, but instead by calculating it from a measured output power (to the Load), an estimate of its circuit loss (tank circuit, rectifier, etc.), and an estimate of its ferrite and Friendly Metal losses.

The Power Receiver shall report an overestimated Received Power value $P_{\mathrm{r}}^{(\mathrm{est})}$ in its RP8 and RP data packets such that

$$P_{\mathrm{r}} \leq P_{\mathrm{r}}^{(\mathrm{est})} \leq P_{\mathrm{r}} + \Delta P_{\mathrm{r}}$$

where P_{r} represents the Received Power level, and $P_{\mathrm{r}}^{(\mathrm{est})}$ represents a margin as provided in Table 6.

Table 6: Estimated Received Power accuracy

Estimated Received Power	ΔP_{r}	Unit
$P_{\mathrm{r}}^{(\mathrm{est})} \leq 5$ W	350	mW
5 W < $P_{\mathrm{r}}^{(\mathrm{est})} \leq 10$ W	500	mW
10 W < $P_{\mathrm{r}}^{(\mathrm{est})}$	750	mW

NOTE: Table 6 implies that a reported amount of Received Power $P_{\mathrm{r}}^{(\mathrm{est})}$ = 5 W, implies an actual amount of Received Power P_{r} in the range of 4.65 W up to and including 5 W.

It is hard—if not impossible—for a Power Receiver to estimate the contributions of the power loss in its Friendly Metals to the Received Power level with an accuracy that is independent of its position and orientation in the Operating Volume. The estimate therefore suffers from a systematic error or bias that depends on the position and orientation. If the latter represent too large a misalignment between the Power Transmitter and Power Receiver, the Estimated Received Power accuracy may fail the above requirement.

5.1.3 FOD threshold

The diagrams in Figure 8 illustrate the impact of the estimated Received Power and Transmitted Power level accuracies on the FOD threshold. The horizontal axes represent the power level, which increases towards the right. According to the requirement given in section 5.1.2, Received Power accuracy, the actual Received Power level is somewhere in the vertically hatched area to the left of the Estimated Received Power level $P_{\mathrm{r}}^{(\mathrm{est})}$. Assuming that the Power Transmitter estimates its Transmitted Power level with an accuracy of $\pm\Delta P_{\mathrm{t}}$, the actual Transmitted Power level is somewhere in the horizontally hatched area centered on the estimated Transmitted Power level $P_{\mathrm{r}}^{(\mathrm{est})}$.

A Foreign Object that can heat up to unacceptably high temperatures is present in the Operating Volume if the actual Foreign Object loss ΔP_{FO} exceeds a threshold $\Delta P_{\mathrm{FO}}^{(\mathrm{thr})}$, i.e.

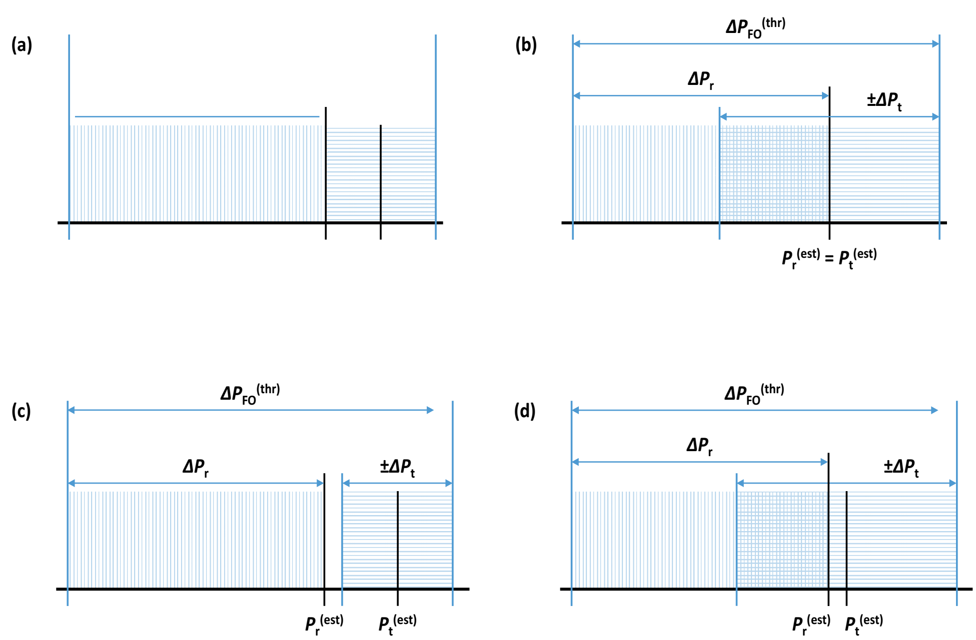
$$\Delta P_{\mathrm{FO}} = P_{\mathrm{t}} - P_{\mathrm{r}} > \Delta P_{\mathrm{FO}}^{(\mathrm{thr})}$$

Since the Power Transmitter only knows the estimated power levels, it should use the following condition

$$\Delta P_{\mathrm{FO}}^{(\mathrm{est})} = P_{\mathrm{t}}^{(\mathrm{est})} - P_{\mathrm{r}}^{(\mathrm{est})} > \Delta P_{\mathrm{FO}}^{(\mathrm{thr})} - \Delta P^{(\mathrm{margin})}$$

where term $\Delta P^{(\mathrm{margin})}$ helps the Power Transmitter to ensure that the actual Foreign Object loss ΔP_{FO} does not exceed the threshold $\Delta P_{\mathrm{FO}}^{(\mathrm{thr})}$, regardless of the uncertainty in the estimated power loss. See the example below for additional details.

Figure 8. Accuracy and FOD threshold



Assume a Power Transmitter accuracy of $\Delta P_{\mathrm{L}} = 75$ mW, and an Estimated Received Power level of at most 5 W. As shown in diagrams (a) and (c), the Power Transmitter should use $\Delta P^{(\mathrm{margin})} - (350 + 75)$ mW to ensure that the Foreign Object loss does not go above $\Delta P_{\mathrm{FO}}^{(\mathrm{thr})} = 500$ mW undetected. In this case, the accuracy ranges do not overlap. Diagrams (b) and (d) show that if the Power Transmitter has an accuracy of $\Delta P_{\mathrm{L}} = 150$ mW, it should set $\Delta P^{(\mathrm{margin})} - 350 + 150$ mW to ensure the same. However, in this case, the accuracy ranges overlap, and false-positive FOD triggers can occur as explained later in this section. To avoid the latter issues, the Power Transmitter can use $\Delta P_{\mathrm{FO}}^{(\mathrm{thr})} = 650$ mW with $\Delta P^{(\mathrm{margin})} = 500$ mW obtaining the situation of diagram (a). However, in this case Foreign Object temperatures can rise to higher levels without the Power Transmitter being able to detect such.

On closer inspection of the diagrams in Figure 8, it follows that the FOD sensitivity depends on biases in the power level estimates. These biases are typically different for different positions and orientations of the Power Receiver in the Operating Volume. For example, for positions and orientations of the Power Receiver in the Operating Volume where the actual Received Power level is close to the Estimated Received Power level, and the actual Transmitted Power level is close to the lower bound of the accuracy range, the FOD sensitivity is high. In this case, the Power Transmitter detects a Foreign Object loss close to zero. On the other hand, for positions and orientations where the actual Received Power level is close to lower bound of the tolerance range, and the Transmitted Power level is close to the upper bound, the Power Transmitter detects Foreign Object losses above ΔP_{F0} only, i.e. the FOD sensitivity is low.

As a final observation, if the Power Transmitter uses overlapping accuracy ranges to keep the uncertainty in the estimated Foreign Object loss below the threshold $\Delta P_{\mathrm{FO}}^{(\mathrm{thr})}$, as shown in diagram (b) and (d) of Table 8, there is a risk of false-positive FOD triggers. For example, in the crosshatched area of diagram (d), the actual Received Power level and the actual Transmitted power level can be equal, i.e. no Foreign Object is present, while the estimated levels indicate an overrun of the FOD threshold. As shown in diagram (c), such false positives do not occur with non-overlapping accuracy ranges, because in case of an FOD threshold overrun, the actual Transmitter Power level always exceeds the actual Received Power level.

5.2 Calibrated power loss accounting

Because it is difficult for a Power Receiver to determine its ferrite and Friendly Metal losses accurately, it is likely that its estimate of the Receiver Power level has a systematic error or bias. Moreover, this bias typically depends strongly on the position and orientation of the Power Receiver Product in the Operating Volume. A Power Transmitter can enhance its FOD sensitivity and robustness by calibrating this bias away. However, before doing so it should verify that the Operating Volume is empty of Foreign Objects. Otherwise, it risks reducing its FOD performance rather than enhancing it.

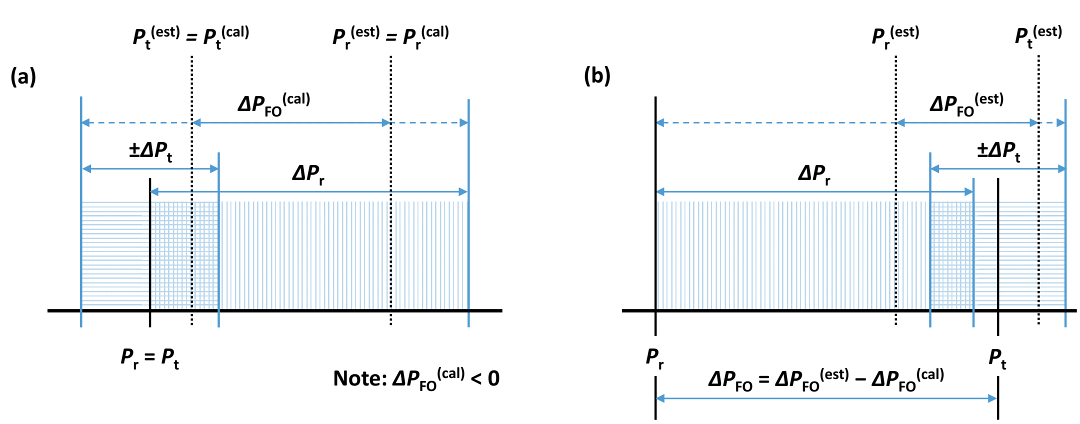
Power level calibration is available only in the Extended Protocol. In this protocol, the Power Transmitter can use the methods discussed in Section 4, *Pre-power transfer FOD methods*, to verify that it is safe to calibrate the estimated power levels.

5.2.1 Calibrated FOD threshold

When calibrating the estimated Foreign Object loss, the Power Transmitter has determined that the Operating Volume is empty of Foreign Objects, and therefore it knows that the Transmitted Power and Received Power levels are equal, i.e. $P_L = P_r$; see Figure 9(a). However, the estimated Transmitted Power and Estimated Received Power levels are typically not equal. The horizontally hatched areas in Figure 9 indicates where the estimated Transmitted Power level can be relative to the actual Transmitted Power level. The vertically hatched area indicates the same for the Estimated Received Power level. Clearly, the estimated Foreign Object loss typically has a negative value at calibration, i.e. $\Delta P_{\mathrm{FO}}^{(\mathrm{cal})} = P_{\mathrm{t}}^{(\mathrm{cal})} - P_{\mathrm{r}}^{(\mathrm{cal})} < 0$. Only when both estimated power levels are in the crosshatched area, i.e. the overlap between the horizontally and vertically hatched areas, the estimated Foreign Object loss can be positive. Accordingly, at calibration the Power Transmitter should expect the estimated Power loss to be in the range from $\Delta P_t + \Delta P_r$ to ΔP_t.

NOTE: If the Power Transmitter obtains a value outside this range when calibrating, to should conclude that something is wrong, and refrain from using the calibration data. For example, at an Estimated Received Power Level of 8 W, the associated accuracy is ΔP_r = 500 mW. Assuming the Power Transmitter's accuracy is 150 mW, the calibration data should be in the range from -650 mW up to 150 mW.

Figure 9. Calibrating the estimated Foreign Object loss



Using the calibration data, the Power Transmitter should assume that a Foreign Object is present in the Operating Volume if the estimated Foreign Object loss $\Delta P_{\mathrm{FO}}^{(\mathrm{est})}$ exceeds the effective FOD threshold $\Delta P_{\mathrm{FO}}^{(\mathrm{thr})}$ + $\Delta P_{\mathrm{FO}}^{(\mathrm{cal})}$, i.e.

$$\Delta P_{\mathrm{FO}}^{(\mathrm{est})} = P_{\mathrm{t}}^{(\mathrm{est})} - P_{\mathrm{r}}^{(\mathrm{est})} > \Delta P_{\mathrm{FO}}^{(\mathrm{thr})} + \Delta P_{\mathrm{FO}}^{(\mathrm{cal})}$$

Figure 9(b) shows how the Power Transmitter can determine the actual Foreign Object loss ΔP_{FO} quite accurately using the calibration data. In this example, the estimated Foreign Object loss $\Delta P_{\mathrm{FO}}^{(\mathrm{est})}$ is far smaller than the actual Foreign Object loss.

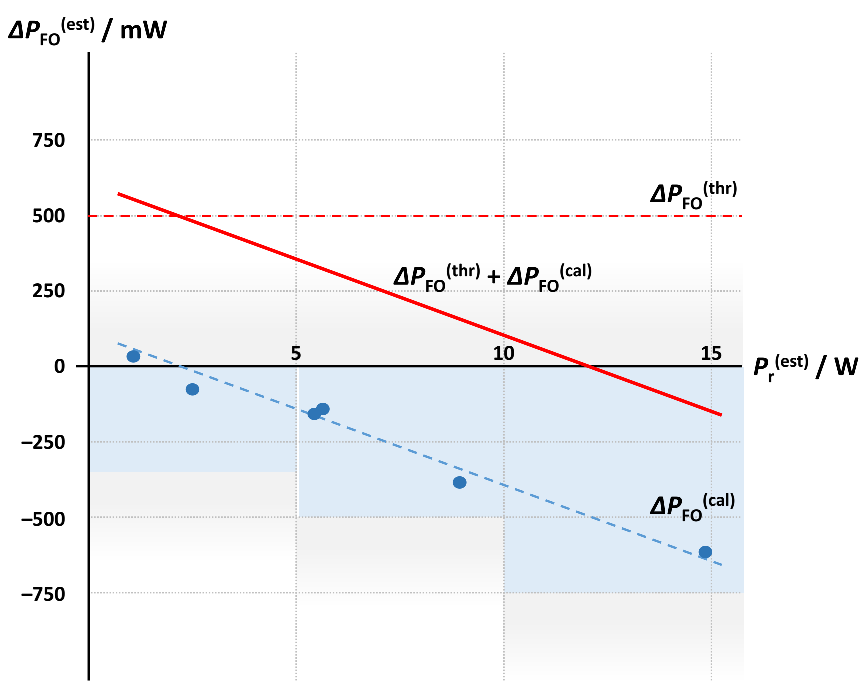
In order to enhance its FOD reliability over a wider range of power levels, the Power Transmitter should collect calibration data at multiple operating points and construct a calibration curve. The Power Receiver should enable the Power Transmitter to collect several calibration data points in the first few seconds of the power transfer phase by stepping through several power levels. See Section 5.2.2, *Calibration protocol*, for the details.

Figure 10 shows an example of a calibration curve. In this example, the Power Transmitter has collected six calibration data points (blue circles). The shaded areas of the diagram indicate the accuracy ranges of the Power Receiver (blue) and Power Transmitter (gray). All data points are in this area, as explained at the top of this section. The Power Transmitter should use a best-fit line through the data points (dashed blue line) to determine calibration values at power levels where it does not have actual measurement data. The calibrated FOD threshold (solid red line) follows from adding this line to the uncalibrated threshold $\Delta P_{\mathrm{FO}}^{(\mathrm{thr})}$ (the dashed red line).

NOTE: Instead of calibrating the estimated Foreign Object loss, the Power Transmitter may calibrate the Estimated Received Power, In that case, the above equation reads as

$\Delta P_{\mathrm{FO}}^{(\mathrm{cal})} = P_{\mathrm{t}}^{(\mathrm{est})} - \left[P_{\mathrm{r}}^{(\mathrm{est})} + \Delta P_{\mathrm{FO}}^{(\mathrm{cal})}\right] > \Delta P_{\mathrm{FO}}^{(\mathrm{thr})}$, with $\Delta P_{\mathrm{FO}}^{(\mathrm{thr})}$ the power-level independent threshold.

Figure 10. Calibration curve and effective FOD threshold

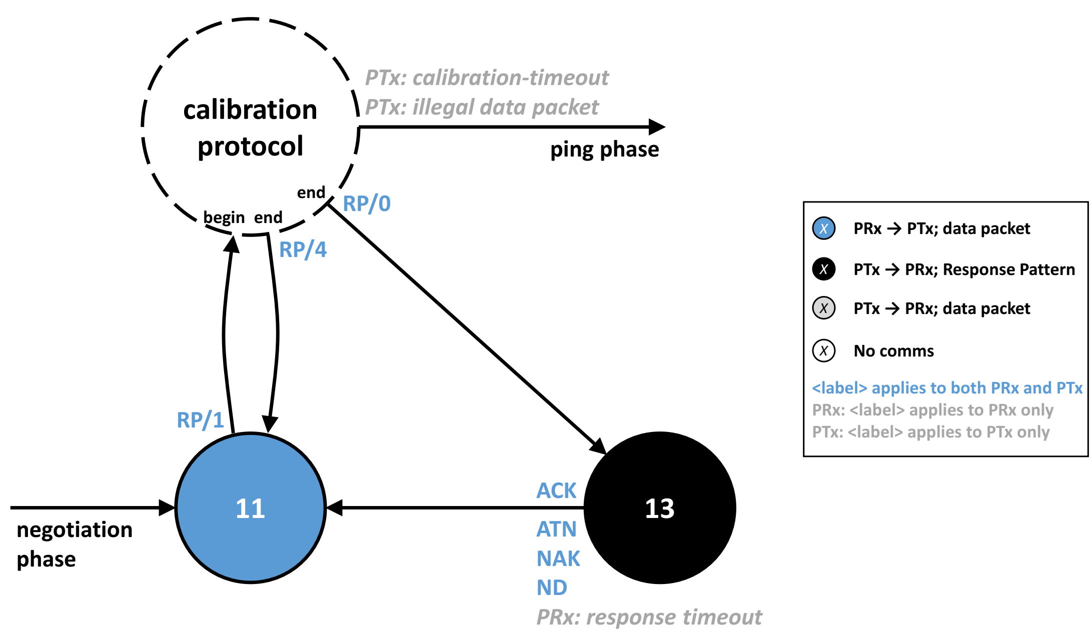


When determining the FOD threshold, the Power Transmitter should not only account for induction heating caused by the Foreign Object loss, but also for heat conduction from the Power Transmitter Product and/or Power Receiver Product to Foreign Objects. Typically, this means that the Power Transmitter should use an FOD threshold that decreases with increasing power level (because the surface temperatures of Power Transmitter Products and Power Receiver Products are generally higher at higher transferred power levels). The dashed red line in Figure 10 should therefore not be horizontal but have a negative slope.

5.2.2 Calibration protocol

As shown in Figure 11, the Power Receiver shall initiate the calibration protocol from state 11 at the start of the power transfer phase. Accordingly, the first RP data packet a Power Receiver sends shall be RP/1. If the Power Transmitter has confirmed its support for recalibration (i.e. ACK'ed an SRQ/rcs data packet), the Power Receiver may initiate the calibration protocol multiple times. Otherwise, the Power Receiver shall not initiate the calibration protocol again in the power transfer phase. See Section 5.2.3, *Calibration performance considerations*, for additional information. Figure 12 provides the details of the calibration protocol.

Figure 11. Calibration protocol



Transitions from state 11

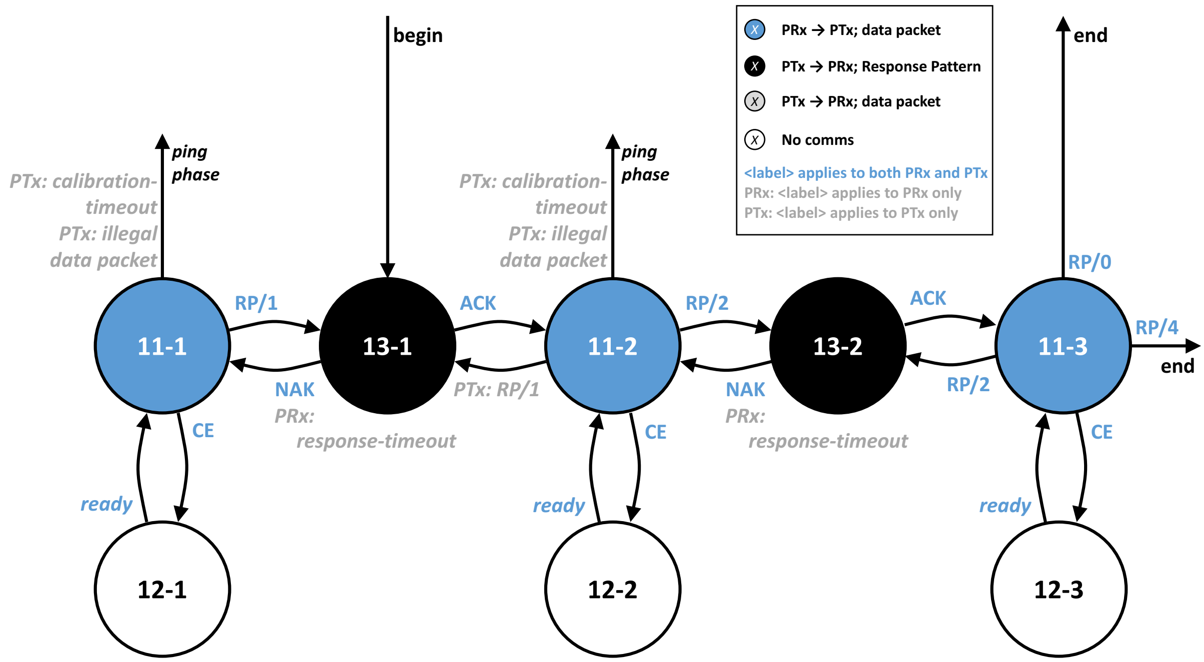
State 11 is the main state of the power transfer phase. See the *Qi Specification, Communications Protocol*, for details and additional transitions.

- *RP/1*. The Power Receiver has sent the first calibration data point, initiating the calibration protocol. The Received Power level reported in this data packet should be at most 10% of the Reference Power level contained in the Power Transfer Contract.

Transitions from state 13

See the *Qi Specification, Communications Protocol*, for details.

Figure 12. Calibration protocol details



Transitions from state 11-1

In state 11-1, the Power Receiver provides the first calibration data point. The following transitions are possible from this state.

NOTE: State 11-1 is a restricted form of state 11.

- *RP/1*. The Power Receiver has sent an RP/1 data packet. The Received Power level reported in this data packet should be at most 10% of the Reference Power level contained in the Power Transfer Contract.
- *CE*. The Power Receiver has sent a CE data packet.
- *PTx: calibration-timeout*. The Power Transmitter has not been able to construct a calibration curve before the calibration timeout $t_{calibrate}$. See below for the value of $t_{calibrate}$.
- *PTx: illegal data packet*. The Power Transmitter has received a data packet other than CE or RP/1.

Transitions from state 12-1

This state is identical to state 12 in the power transfer phase. See the *Qi Specification, Communications Protocol*, for details.

Transitions from state 13-1

In state 13-1, the Power Transmitter provides feedback about the first calibration data point. The following transitions are possible from this state.

NOTE: State 13-1 is a restricted form of state 13.

- *ACK*. The Power Transmitter has accepted the first calibration data point. It is ready for the Power Receiver to step up its power level. The Power Transmitter should wait for the power level to stabilize before using this transition. It may consider the power level to be stable when it has received two consecutive CE/0 data packets (i.e. two consecutive CE data packets containing a Control Error Value of 0).
- *NAK*. The Power Transmitter does not accept the first calibration data point yet.
- *PRx: response-timeout*. The Power Receiver has not detected a response to the RP/1 data packet before the timeout t_{response}. See the *Qi Specification, Communications Protocol*, for the timeout value.

Transitions from state 11-2

In state 11-2, the Power Receiver sends a next calibration data point. The following transitions are possible from this state.

NOTE: State 11-2 is a restricted form of state 11.

- *RP/2*. The Power Receiver has sent an RP/2 data packet. The Received Power level reported in the final RP/2 data packet should be close to the Reference Power level contained in the Power Transfer Contract.
- *CE*. The Power Receiver has sent a CE data packet.
- *PTx: calibration-timeout*. The Power Transmitter has not been able to construct a calibration curve before the calibration timeout $t_{\text{calibrate}}$. See below for the value of $t_{\text{calibrate}}$.
- *PTx: illegal data packet*. The Power Transmitter has received a data packet other than CE, RP/1 or RP/2.
- *PTx: RP/1*. The Power Transmitter has received an RP/1 data packet. This can happen if the Power Receiver has timed out on the ACK Response Pattern following the preceding RP/1 data packet.

Transitions from state 12-2

This state is identical to state 12 in the power transfer phase. See the *Qi Specification, Communications Protocol*, for details.

Transitions from state 13-2

In state 13-2, the Power Transmitter provides feedback about the next calibration data point. The following transitions are possible from this state.

NOTE: State 13-2 is equivalent to state 13.

- *ACK*. The Power Transmitter has accepted the next calibration data point. It is ready for the Power Receiver to step up its power level. The Power Transmitter should wait for the power level to stabilize before using this transition. It may consider the power level to be stable when it has received two consecutive CE/0 data packets (i.e. two consecutive CE data packets containing a Control Error Value of 0).
- *NAK*. The Power Transmitter does not accept the next calibration data point yet.
- *PRx: response-timeout*. The Power Receiver has not detected a response to the RP/2 data packet before the timeout t_{response}. See the *Qi Specification, Communications Protocol*, for the timeout value.

Transitions from state 11-3

Upon reaching state 11-3, the Power Transmitter has created a two-point calibration curve. In this state, the Power Receiver may provide additional calibration data points. The following transitions are possible from this state.

NOTE: State 11-3 is a restricted form of state 11.

- *RP/0*. The Power Receiver has sent an RP/0 data packet, terminating the calibration protocol.
- *RP/2*. The Power Receiver has sent an RP/2 data packet, continuing the calibration protocol. The Received Power level reported in the final RP/2 data packet should be close to the Reference Power level contained in the Power Transfer Contract.
- *RP/4*. The Power Receiver has sent an RP/4 data packet, terminating the calibration protocol.
- *CE*. The Power Receiver has sent a CE data packet.
- *PTx: calibration-timeout.* The Power Transmitter has not been able to construct a calibration curve before the calibration timeout $t_{\mathrm{calibrate}}$. See below for the value of $t_{\mathrm{calibrate}}$.
- *PTx: illegal data packet*. The Power Transmitter has received a data packet other than CE, RP/0, RP/2 or RP/4.

Transitions from state 12-3

This state is identical to state 12 in the power transfer phase. See the *Qi Specification, Communications Protocol*, for details.

Calibration data-packet timings

Table 7 provides an overview of the timing constraints that apply to the calibration protocol. See the Qi Specification, Communications Protocol, for the definitions of t_{received}.

Table 7: Timing constraints in the calibration protocol

Parameter	Side	Symbol	Minimum	Target	Maximum	Unit
Received Power (RP/1) interval	PRx	t_{received}	N/A	N/A	550	ms
Received Power (RP/2) interval	PRx	t_{received}	N/A	N/A	2,050	ms
Calibrated	PTx	$t_{\text{calibrated}}$	N/A	N/A	10	s
Calibration timeout	PTx	$t_{\text{calibrationtimeout}}$	N/A	N/A	15	s

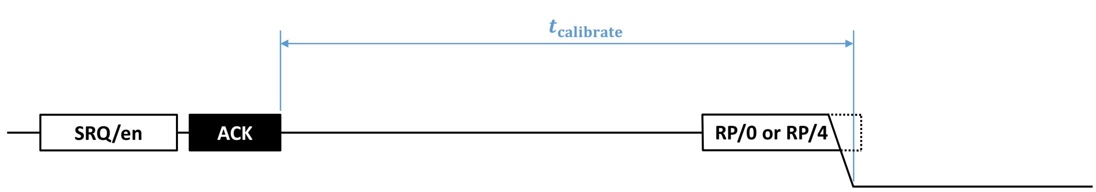
Power-loss calibration timeout

The Power Transmitter shall ACK an RP/2 data packet within a time interval $t_{\text{calibrated}}$ into the power transfer phase. If the Power Transmitter has not received an RP/0 or RP/4 data packet at the timeout $t_{\text{calibrationtimeout}}$, it shall remove the Power Signal.

NOTE: The purpose of this timeout is to enable the Power Transmitter to establish a calibration curve sufficiently fast soon after it has executed its pre-power transfer FOD method(s) to ensure that the Operating Volume is devoid of Foreign Objects.

NOTE: If the Power Transmitter does not intend to make use of the calibration data, it should send ACK Response Patterns to the RP/1 and RP/2 data packets it receives at the start of the power transfer phase.

Figure 13. Power-loss calibration



Examples

Figure 14 shows a data packet sequence providing two calibration data points. At position (a), the Power Receiver switches from the negotiation phase to the power transfer phase, connects the Load, and starts controlling the power level to the first calibration data point. After the power level has become stable (two consecutive CE/0 data packets), the Power Transmitter accepts the data point (position (b)). Subsequently, the Power Receiver starts controlling the power level to the second calibration data point. At position (d), after the power level has become stable again, the Power Transmitter accepts the data point. This concludes the two-point calibration protocol, and the Power Receiver continues with the power transfer using RP/0 data packets.

Figure 14. Example of a packet sequence for the initial two-point calibration

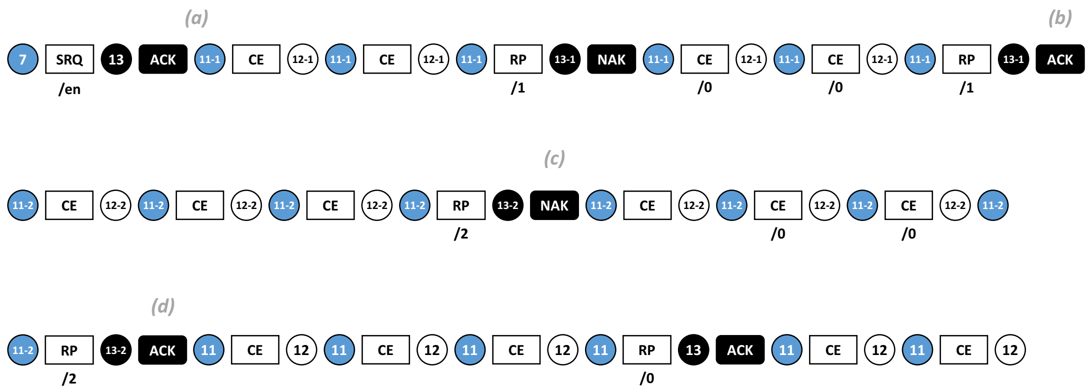
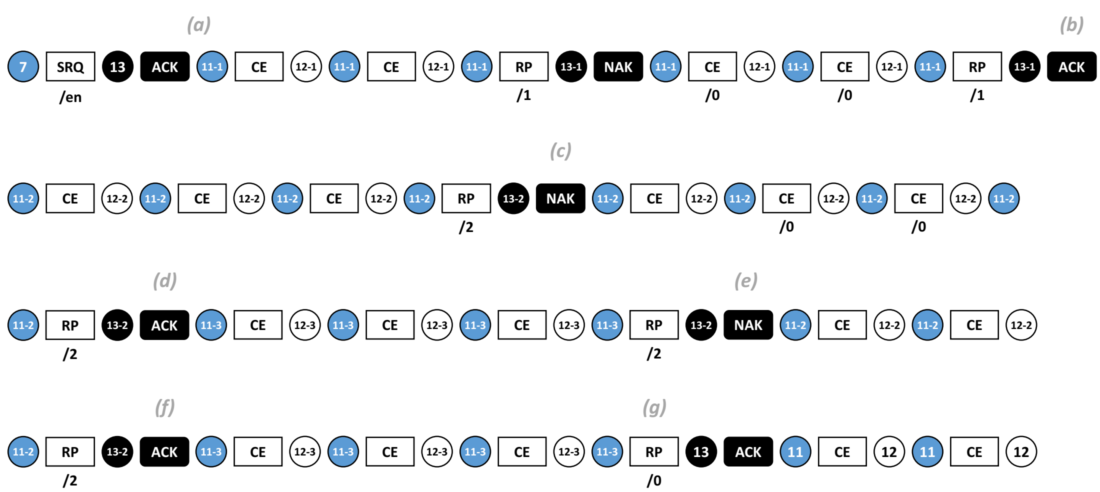


Figure 15 shows a data packet sequence providing three calibration data points. The part of the data packet sequence up to position (d) is identical to the above example. At position (e), the Power Transmitter rejects the third calibration data point, for example because the power level is not stable yet. At position (f), the Power Transmitter accepts the third calibration data point, and at position (g) it sees that the Power Receiver has concluded the calibration protocol, and presumably has reached its target operating point.

Figure 15. Example of a packet sequence for the multi-point calibration



5.2.3 Calibration performance considerations

Power-loss calibration substantially enhances the FOD sensitivity and robustness against false-positive events. However, Power Transmitters and Power Receiver should be aware of a number of issues.

Shift of the Power Receiver Product

The Power Transmitter's calibration curve is valid only as long as the Power Receiver Product's position in the Operating Volume does not change. This has the following implications.

When a user places a Power Receiver Product in the Operating Volume of a Power Transmitter Product, the latter may already start the communications protocol, proceeding to the calibration phase before the Power Receiver Product has come to rest. The Power Transmitter should therefore ensure that the Power Receiver Product has transmitted multiple consecutive CE/0 data packets before ACK'ing an RP/1 data packet. The latter is a sufficient indication that the Power Receiver Product is in a stable position in the Operating Volume. If this means that the Power Transmitter cannot ACK an RP/1 data packet within the calibration timeout defined in Section 5.2.2, *Calibration protocol*, the Power Transmitter should remove the Power Signal as defined in the latter section and initiate a new Digital Ping.

If in the power transfer phase the Power Receiver discovers that its position has changed, it should send an EPT/rst or EPT/rep data packet requesting the Power Transmitter to remove the Power Signal, initiate a new Digital Ping, and construct a new calibration curve. For example, if the Power Receiver suddenly has to send non-zero Control Error data packets to keep the power level at a stable level, it is likely that its position has changed (or that a Foreign Object has entered the Operating Volume).

NOTE: The *Qi Specification, Communications Protocol*, recommends the Power Transmitter to suppress potentially distracting user interface events when restarting the power transfer following an EPT/rep data packet. The Power Receiver should do the same, making the procedure transparent to the user.

Extrapolation of the calibration curve

Minute changes in the slope of the calibration curve $\Delta P_{\mathrm{FO}}^{(\mathrm{cal})}$ can lead to substantial changes in the effective FOD threshold at higher power levels. For example, a change in the slope of a few milliwatts per watt can result in tens of milliwatts differences in the effective FOD threshold. See Table 8 for a detailed example. It assumes that the Power Transmitter and Power Receiver create a calibration curve from data points taken at two power levels of 0.5 W and 5 W. For various reasons, the estimated power levels can differ slightly from run to run, without any change in the position of the Power Receiver. (One reason for the differences is that the Power Transmitter and Power Receiver typically do not sample the Transmitted Power and Received Power at exactly the same time, so small fluctuations in the Load will affect the calibration curve.) The example in Table 8 shows that differences only 10 mW in the estimated power levels can yield a difference of 100 mW in the effective FOD threshold extrapolated to a power level of 15 W. Accordingly, in the second run of this example, the Power Transmitter allows Foreign Objects to reach higher temperatures than in the first run.

Table 8: Example of the issue with extrapolating the power-loss calibration curve

Parameter	Run 1 Value	Run 2 Value	Unit
RP/1			
$P_{r}^{(est)}$	0.510	0.520	W
$P_{t}^{(est)}$	0.490	0.480	W
$\Delta P_{FO}^{(cal)}$	-20	-40	mW
RP/2			
$P_{r}^{(est)}$	5.34	5.33	W
$P_{t}^{(est)}$	5.02	5.03	W
$\Delta P_{FO}^{(cal)}$	-320	-300	mW
Calibration curve			
intercept	11.7	-11.9	mW
slope	-62.1	-54.1	mW/W
*Effective FOD thresholds**			
$P_{r}^{(est)}$ = 5 W	201	218	mW
$P_{r}^{(est)}$ = 15 W	-420	-323	mW
* Assuming $\Delta P_{FO}^{(thr)} = 500$ mW			

From the above example, it is clear that the system should not operate at power levels where the Power Transmitter is extrapolating its calibration curve. As a particularly common use case, a Power Receiver intending to increase the power level after successfully authenticating the Power Transmitter should therefore take appropriate action. It has two options to proceed.

1. The Power Transmitter supports recalibration. In this case, the Power Receiver may initiate the calibration protocol to provide the Power Transmitter with additional calibration data points.
   a) The Power Receiver intends to increase the power level without changing its operating mode (or operating voltage, see the next subheading). In this case, the Power Receiver should use the current power level as the RP/1 power level and the highest intended power level as the RP/2 power level.

   b) The Power Receiver intends to change its operating mode and increase the power level. In this case, the Power Receiver should change the operating mode, and subsequently use the lowest and highest intended power levels in the new operating mode as the RP/1 and RP/2 power levels.

2. The Power Transmitter does not support recalibration. In this case, the Power Receiver should restart the power transfer and make sure to include the new higher power level in the calibration protocol. (Hereto it should send an EPT/rst or EPT/rep data packet requesting the Power Transmitter to remove the Power Signal and initiate a new Digital Ping, enabling construction of a new calibration curve.)

NOTE: The above procedure of restarting the power transfer is particularly important for a Power Receiver keeping the power level at 5 W or below while authenticating the Power Transmitter. Upon restarting the power transfer, such a Power Receivers should remember that it authenticated the Power Transmitter successfully—otherwise it would not have to restart the power transfer—and make sure to switch to the higher power level during the calibration protocol.

When a Power Transmitter determines that it is extrapolating the calibration curve to determine the effective FOD threshold, it should respond with ATN to an RP/0 data packet to interrupt the Power Receiver. When the latter sends a DSR/poll data packet, it should respond with a CAP data packet, setting the Available Load Power level to a value within the calibrated range. If the Power Receiver does not negotiate a lower power level in response to the CAP data packet, the Power Transmitter should reduce its Transmitted Power level, or remove the Power Signal. See the *Qi Specification, Communications Protocol*, for details.

Operating mode change

Some Power Transmitters use the input power instead of the Transmitted Power level to construct the calibration curve. In such Power Transmitters, the calibration curve becomes invalid when the Power Receiver changes its operating mode, e.g. switching from 5 V rectified voltage to 9 V or 12 V. The reason is that in the new operating mode, the efficiencies of both the Power Transmitter and the Power Receiver are different from those in the initial operating mode. This means that although the circuit and Friendly Metal losses change. However, having used the input power level to construct the calibration curve, the Power Transmitter does not account for those. Accordingly, the effective FOD threshold will not be accurate in the new operating mode. To guard against these Power Transmitters, a Power Receiver should restart the Power Transfer when it intends to change its operating mode. (As in the other cases discussed in this section, the Power Receiver should send an EPT/rst or EPT/rep data packet, requesting the Power Transmitter to Remove the Power Signal, initiate a new Digital Ping, and construct a new calibration curve. The Power Receiver should make sure to start operating in the intended mode before sending RP/2 data packets.)

Annex A: Determining the reference FOD values (normative)

To determine the Reference Resonance Frequency $f_t'^{(\mathrm{ref})}$ and the Reference Quality Factor $Q_t'^{(\mathrm{ref})}$ of a Power Receiver Product, perform the following steps:

1. Connect an LCR meter or equipment providing similar functionality to the reference coil assembly, without positioning the Power Receiver Product on the latter.
2. Measure the inductance $L_t^{(\mathrm{ref})}$ and quality factor $Q_t^{(\mathrm{ref})} = \dfrac{2\pi f^{(\mathrm{ref})} L_t^{(\mathrm{ref})}}{R_t^{(\mathrm{ref})}}$ of the reference coil assembly at an operating frequency of $f^{(\mathrm{ref})}$ = (100 ± 0.2) kHz, with an applied voltage of at most 1 V (rms). The accuracies of $L_t^{(\mathrm{ref})}$ and $Q_t^{(\mathrm{ref})}$ shall be 4% and 6.4%, respectively.
3. Calculate $C_t^{(\mathrm{ref})} = \dfrac{1}{4\pi^2 f^{(\mathrm{ref})^2} L_t^{(\mathrm{ref})}}$.

   NOTE: Adding an ideal series capacitor with capacitance $C_t^{(\mathrm{ref})}$ to the reference coil assembly yields a tank circuit with a resonance frequency of $f^{(\mathrm{ref})}$.
4. Position the Power Receiver Product on top of the reference coil assembly.
5. Measure the inductance L_t and quality factor $Q_t' = \dfrac{2\pi f^{(\mathrm{ref})} L_t'}{R_t'}$ of the reference coil assembly at an operating frequency of $f^{(\mathrm{ref})}$ = (100 ± 0.2) kHz, with an applied voltage of at most 1 V (rms). The accuracy of L_t' shall be 4%. The accuracy of Q_t' shall be Q_t' × 0.04% with a minimum of 2%.

   EXAMPLE: The accuracy of Q_t' = 100 shall be 4%. The accuracy of Q_t' = 25 shall be 2%.
6. Calculate $f_t' = \dfrac{1}{2\pi\sqrt{L_t' C_t^{(\mathrm{ref})}}} = 100\ \mathrm{kHz} \times \sqrt{\dfrac{L_t^{(\mathrm{ref})}}{L_t'}}$.

   NOTE: f_t' represents the effective resonance frequency of the tank circuit from step 3.
7. Determine the Reference Resonance Frequency $f_t'^{(\mathrm{ref})}$ and the Reference Quality Factor $Q_t'^{(\mathrm{ref})}$ as the average of the resonance frequency f_t' and quality factor Q_t' values obtained at five positions. One of these positions centers the coils of the reference coil assembly and the Power Receiver Product. The other four positions are (5 ± 0.5) mm north, east, south, and west of this position. Do not change the orientation of the Power Receiver Product relative to the reference coil assembly when moving it from one position to the next. Figure 16. An example, the dashed line in this figure represents the outline of the Power Receiver Product in the north position.

Figure 16. Positions for measuring the Reference Resonance Frequency and Reference Quality Factor