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colour inside

Wireless power transfer – Airfuel alliance resonant baseline system specification (BSS)

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WIRELESS POWER TRANSFER – AIRFUEL ALLIANCE RESONANT BASELINE SYSTEM SPECIFICATION (BSS)

FOREWORD

International Standard IEC 63028 has been prepared by technical area 15: Wireless power transfer, of IEC technical committee 100: Audio, video and multimedia systems and equipment.

The text of this International Standard is based on the following documents:

FDIS	Report on voting
100/2901/FDIS	100/2941/RVD

Full information on the voting for the approval of this International Standard can be found in the report on voting indicated in the above table.

This document has been drafted in accordance with the ISO/IEC Directives, Part 2.

The committee has decided that the contents of this document will remain unchanged until the stability date indicated on the IEC website under "http://webstore.iec.ch" in the data related to the specific document. At this date, the document will be

- reconfirmed,
- withdrawn,
- replaced by a revised edition, or
- amended.

A bilingual version of this publication may be issued at a later date.

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INTRODUCTION

In today's world, mainstream consumer mobile devices are ubiquitously supported by wireless technologies for data communication and connectivity functions while charging function is primarily supported by wired technologies. The development of wireless power transfer technologies offers increased user convenience for charging mobile devices; technologies include inductive, resonant, uncoupled (RF, ultrasonic, laser) methods.

IEC 63028 defines a specific wireless charging approach based on resonant technology and specifies technical requirements for the AirFuel™[1] resonant wireless power transfer (WPT) systems.

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1 AirFuel™ is the trade name of a product supplied by AirFuel Alliance. This information is given for the convenience of users of this document and does not constitute an endorsement by IEC of the product named.

WIRELESS POWER TRANSFER – AIRFUEL ALLIANCE RESONANT BASELINE SYSTEM SPECIFICATION (BSS)

1 Scope

This document defines technical requirements, behaviors and interfaces used for ensuring interoperability for flexibly coupled wireless power transfer (WPT) systems for AirFuel Resonant WPT. This document is based on AirFuel Wireless Power Transfer System Baseline System Specification (BSS) v1.3.

Products implementing this document are expected to follow applicable regulations and global standards.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

AirFuel Wireless Power Transfer System Baseline System Specification (BSS) v1.3 [viewed 2017-03-13]. Available at: http://www.airfuel.org/technologies/specification-download

AirFuel Wireless Power Transfer System Baseline System Specification (BSS) v1.2.1 [viewed 2017-03-13]. Available at: http://www.airfuel.org/technologies/specification-download

Bluetooth core specification v4.0, or later versions as they are available [viewed 2017-03-13]. Available at: https://www.bluetooth.org/docman/handlers/downloaddoc.ashx?doc_id=229737

CSA4, or later versions as they are available [viewed 2017-03-13]. Available at: https://www.bluetooth.org/docman/handlers/DownloadDoc.ashx?doc_id=269452

3 Terms, definitions, symbols and abbreviated terms

3.1 Terms and definitions

For the purposes of this document, the following terms and definitions apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

- IEC Electropedia: available at http://www.electropedia.org/
- ISO Online browsing platform: available at http://www.iso.org/obp

3.1.1
advertisement
connectable, undirected advertising event where the device transmits three WPT service specific ADV_IND packets and accepts both scan requests and connect requests

Note 1 to entry: There is one ADV_IND packet transmitted on each of the advertising channels.

Note 2 to entry: Receipt of an advertisement is defined to be receipt of one of the three advertisement packets.

3.1.2
category
type of power receiving unit (PRU)

Note 1 to entry: Refer also to the definition of power receiving unit (3.1.17).

3.1.3
charge area
<PRU larger than the test area> region of maximum overlap between the PTU charge area and the PRU resonator

Note 1 to entry: The charge area is provided by the vendor, the PRU is the entire device, and the test area is the charge area in tests.

3.1.4
charge area
<PRU smaller than the test area> region of maximum overlap between the PTU charge area and the PRU

Note 1 to entry: The charge area is provided by the vendor, and the test area is the charge area in tests.

Note 2 to entry: This does not preclude the PRU resonator being larger than the PTU resonator.

Note 3 to entry: Additionally, "within the charge area" is equated to mean "within the test area".

Note 4 to entry: The charge area includes the specification of the Z heights intended for the final product, from the surface of resonator coil.

3.1.5
class
type of power transmitting unit (PTU)

Note 1 to entry: Refer also to the definition of power transmitting unit (3.1.18).

3.1.6
concurrent multiple charging
transmission of power from one transmitting resonator to multiple receiving resonators

Note 1 to entry: Magnetic resonant coupling can occur among one transmitting resonator and many receiving resonators, while tight coupling is restricted to only one transmitting coil and one receiving coil. Thus, tightly coupled technology only allows one-to-one power transmission.

3.1.7
delta R1
change in a PTU resonator's measured resistance when a PRU is placed at the center of PTU's charge area as compared to the resistance when no objects are in the charge area

Note 1 to entry: This measurement refers to the use of a PRU with an open-circuit resonator.

3.1.8
device registry
list of active PRU's maintained by the PTU

3.1.9
dominant PRU
PRU consuming the highest percentage of its rated output power (V_{RECT} x I_{RECT} / $P_{\mathrm{RECT\_MAX}}$)

3.1.10
flexibly coupled wireless power transfer
power transfer system that provides power through magnetic induction between a transmitter coil and a receiver coil, where the coupling factor (k) between the coils can be within a range between large and very small (e.g., less than 0,025)

Note 1 to entry: Also, in a flexibly coupled system, the transmitter (i.e., the primary) coil can be of the same size, or much larger than the receiver (i.e., secondary) coil. The allowable difference in coil size enables concurrent charging of multiple devices as well as more flexible placement of receiver coils within the charge area.

3.1.11
high voltage region
PRU region in which V_{RECT} levels result in high power dissipation without damaging the PRU

3.1.12
keep-out volume
volume outside of the charge area in which no testing is performed

Note 1 to entry: This parameter is defined by the PTU vendor.

3.1.13
low voltage region
V_{RECT} voltages below the operational range

3.1.14
normal operation
range of all specified WPT states other than PRU System Error state for over-voltage

3.1.15
over-voltage
V_{RECT} voltages greater than $V_{\text{RECT\_MAX}}$

Note 1 to entry: Over-voltage can permanently damage PRU components if the PRU does not correct the condition (see 8.3.6).

3.1.16
OVP switch
switch in the PRU that opens or closes to protect the PRU

3.1.17
power receiving unit
unit receiving electrical power wirelessly from a power transmitting unit

3.1.18
power transmitting unit
unit transferring electrical power wirelessly to each power receiving unit

3.1.19
rectifier efficiency
ratio of rectified power to PRU received power (P_{RECT} / $P_{\text{RX\_OUT}}$)

3.1.20
resonance
condition of a body or system when it is subjected to a periodic disturbance of the same frequency as the natural frequency of the body or system

Note 1 to entry: At this frequency, the system displays an enhanced oscillation or vibration.

3.1.21
resonator
magnetic field generator that satisfies the resonance condition for efficiently transferring electrical power from a PTU to a PRU

Note 1 to entry: Both a coil and an electrical conducting wire are examples of a resonator.

3.1.22
wireless power transfer
processes and methods that take place in any system where electrical power is transmitted from a power source to an electrical load without interconnecting wires

3.2 Symbols and abbreviated terms

3.2.1 Symbols

For the purposes of this document, the following symbols for variable parameters apply.

3.2.1.1
η_{RECT}
rectifier efficiency (P_{RECT} / P_{RX_OUT})

3.2.1.2
I_{RECT}
DC current out of the PRU's rectifier

3.2.1.3
I_{RECT_REPORT}
I_{RECT} value reported by a PRU to a PTU

3.2.1.4
I_{RX_IN}
RMS current out of the resonator/into the rectifier, while in the PRU on state

3.2.1.5
I_{TX}
RMS current into the PTU resonator coil

3.2.1.6
$I_{TX\_LONG\_BEACON}$
RMS current into the PTU resonator during the long beacon period in the PTU power save state

Note 1 to entry: This current is used to provide minimum power for waking up a PRU signaling module and MCU, and to initiate communication.

3.2.1.7
$I_{TX\_SHORT\_BEACON}$
RMS current into the PTU resonator while in the PTU power save state

Note 1 to entry: This current is used to detect the PTU impedance change caused by the placement of an object in the charge area.

3.2.1.8
I_{TX_START}
RMS current into the PTU resonator that provides minimum power for waking up a PRU signaling module and MCU

Note 1 to entry: This current is also used to initiate communication and registration.

3.2.1.9
P_{IN}
DC power into the PTU

3.2.1.10
P_{TX_IN}
input power to the PTU resonator

3.2.1.11
$P_{TX\_IN\_MAX}$
maximum input power to the PTU resonator

3.2.1.12
P_{RECT}
average power out of the PRU's rectifier AVG (V_{RECT} x I_{RECT})

3.2.1.13
P_{RECT_BOOT}
maximum average power out of the PRU's rectifier as declared by the vendor

Note 1 to entry: The rectifier power is measured over a 1 ms interval.

3.2.1.14
P_{RECT_IN}
average power into the PRU rectifier

3.2.1.15
$P_{RX\_REPORTED}$
product of reported rectified voltage and current (V_{RECT_REPORT} x I_{RECT_REPORT})

3.2.1.16
P_{RX_OUT}
power out of the PRU resonator

3.2.1.17
R_{RECT}
effective load resistance at the output of the PRU's rectifier

3.2.1.18
R_{RECT_MP}
maximum power point resistance

3.2.1.19
R_{RX_IN}
parasitic resistance of the PRU resonator

3.2.1.20
V_{PAa}
DC input voltage to the PTU's power amplifier

3.2.1.21
V_{RECT}
DC voltage at the output of a PRU's rectifier

3.2.1.22
V_{RECT_REPORT}
V_{RECT} value which a PRU reports to a PTU

3.2.1.23
Z_{RX_IN}
input impedance of the PRU resonator and matching network

For the purposes of this document, the following symbols for PTU/PRU design dependent variable parameters apply.

3.2.1.24
ADV_PWR_MIN
minimum BLE advertisement power as seen at the PTU BLE antenna

3.2.1.25
$I_{TX\_ABS\_MAX}$
absolute maximum PTU current

3.2.1.26
$I_{TX\_LONG\_BEACON\_MIN}$
minimum allowed current during PTU long beacon

3.2.1.27
$I_{TX\_SHORT\_BEACON\_MIN}$
minimum allowed current during PTU short beacon

3.2.1.28
I_{TX_MAX}
operational maximum PTU current

3.2.1.29
I_{TX_MIN}
operational minimum PTU current

3.2.1.30
$I_{TX\_NOMINAL}$
nominal PTU resonator current driving all PRUs to operate in the optimum voltage region

3.2.1.31
P_{RECT_MAX}
PRU's maximum rated P_{RECT} power

3.2.1.32
P_{RECT_MIN}
PRU's minimum rated P_{RECT} power

3.2.1.33
$P_{RX\_OUT\_MAX}$
maximum output power of the PRU resonator

3.2.1.34
R_{RX_MIN}
minimum resistance presented to the PRU resonator terminals during normal operation

3.2.1.35
R_{RECT_MP}
R_{RECT} resistance that achieves maximum P_{RECT} power

3.2.1.36
R_{TX_IN}
real part of Z_{TX_IN}

3.2.1.37
V_{RECT_BOOT}
boot V_{RECT} voltage

Note 1 to entry: Below this level, the PRU cannot enter the PRU boot state.

3.2.1.38

V_{RECT_HIGH}

maximum operational V_{RECT} voltage

3.2.1.39

V_{RECT_MAX}

PRU's maximum allowable V_{RECT} voltage

3.2.1.40

V_{RECT_MIN}

minimum operational V_{RECT} voltage

Note 1 to entry: Below this voltage, PRUs might not deliver full power.

3.2.1.41

V_{RECT_SET}

PRU's preferred V_{RECT} voltage

3.2.1.42

V_{RECT_UVLO}

under voltage lock out V_{RECT} voltage

Note 1 to entry: Below this level, the PRU might not enable MCU and communication module.

3.2.1.43

X_{TX_IN}

imaginary part of Z_{TX_IN}

3.2.1.44

$|Z_{PA\_SOURCE}|$

magnitude of the output impedance of the matching network and connected power amplifier of the PTU

3.2.1.45

$|Z_{PA\_SOURCE\_MIN}|$

magnitude of the minimum allowable source impedance of the amplifier or supply that provides current to the PTU resonator

3.2.1.46

$Z_{TX\_IN\_LOAD\_CHANGE}$

minimum load change in Z_{TX_IN} created by a PRU when placed in the charge area of a PTU

Note 1 to entry: The load change is measured when an I_{TX} current greater than or equal to $I_{TX\_SHORT\_BEACON\_MIN}$ is applied.

Note 2 to entry: This value is specific to a PTU resonator design.

3.2.1.47

$Z_{TX\_IN\_LOAD\_DETECT}$

magnitude of the minimum real and imaginary change in Z_{TX_IN} that the PTU resonator circuitry can be able to detect

3.2.1.48

Z_{TX_IN}

input impedance of PTU resonator

3.2.2 Abbreviated terms

BLE bluetooth low energy

BSS baseline system specification

GAP generic access profile

GATT generic attribute profile

MCU microcontroller

NFC near field communication

LE low energy

OCP over-current protection

OEM original equipment manufacturer

OTP over-temperature protection

OVP over-voltage protection

PA power amplifier

PRU power receiving unit

PTU power transmitting unit

RCE resonator coupling efficiency

RFU reserved for future use

UUID universally unique identifier

WPT wireless power transfer

4 System description

The AirFuel Alliance WPT system transfers power from a single power transmitter unit (PTU) to one or more power receiver units (PRUs.) The power transmission frequency is 6,78 MHz, and up to eight devices can be powered from a single PTU depending on transmitter and receiver geometry and power levels. The bluetooth low energy (BLE) link in the AirFuel Resonant system is intended for control of power levels, identification of valid loads and protection of non-compliant devices.

Figure 1 illustrates the basic WPT system configuration between a PTU and a PRU. The PTU can be expanded to serve multiple independent PRUs. The PTU comprises three main functional units which are a resonator and matching unit, a power conversion unit, and a signaling and control unit. The PRU also comprises three main functional units like the PTU.

The control and communication protocol for the WPT network is designed as the bidirectional and half duplex architecture and is used to signal PRU characteristics to the PTU as well as to provide feedback to enable efficiency optimization, over-voltage protection, under-voltage avoidance, and rogue object detection.

The WPT network is a star topology with the PTU as the master and PRUs as slaves. The PTU and the PRU perform the bidirectional communication to each other to identify the device compliance and to exchange the power negotiation information.

In this document, Clause 5 provides high level requirements and Clause 6 identifies device classifications. Clause 7 provides power transfer requirements (including a fixed 6,78 MHz operating frequency, resonator requirements and load parameters) while Clause 8 provides PTU and PRU power control requirements. Clause 9 provides signaling requirements, Clause 10 identifies approved PTU resonator designs, and Annex A (informative) includes reference PRUs for PTU acceptance testing. Annex B is an informative annex for PTU lost power. Annex C is a normative annex for user experience requirements. Annex D is an informative annex for addressing resonator coupling efficiency (RCE) measurements.

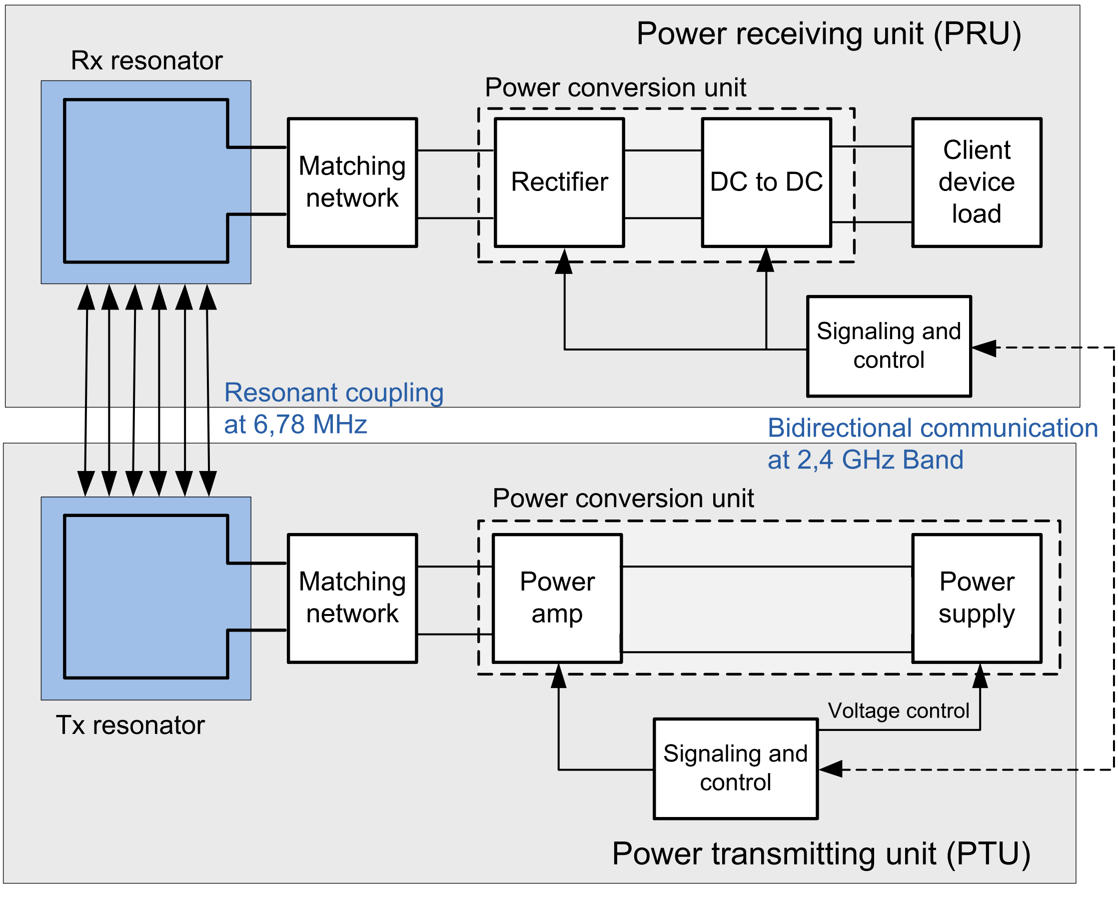


Figure 1 – Wireless power transfer system

5 Conformance and backwards compatibility

PRU and PTU devices shall comply with the AirFuel Wireless Power Transfer System Baseline System Specification (BSS) v1.3, the AirFuel Wireless Power Transfer System Baseline System Specification (BSS) v1.2.1, and the Bluetooth core specification v4.0 with CSA4.

Devices compliant with this document shall be backwards compatible with devices which are in compliance with the AirFuel Wireless Power Transfer System Baseline System Specification (BSS) v1.3, and the AirFuel Wireless Power Transfer System Baseline System Specification (BSS) v1.2.1 published by the AirFuel Alliance. To be backwards compatible, devices shall adhere to the following behavior.

Upon completion of device registration, if the device, based on the exchanged information, determines that it is connected to a prior version AirFuel resonant device or to an AirFuel resonant device with unsupported optional features, then the device shall not perform any procedure related to the unsupported features of the connected AirFuel resonant device. Further, if a device receives any unknown or unsupported information from the connected AirFuel resonant device, such information in any form or manner shall be ignored.

For AirFuel resonant devices, the following applies.

a) The PRU shall be interoperable with all previous BSS version PTUs and shall support all mandatory features for the version to which the previous version PTU complies. The PRU may support the optional features that the PTU supports in the previous version for which the PTU complies. The PRU shall not request or initiate any feature (mandatory or optional) that is not supported by the previous version PTU.

b) The PTU shall be interoperable with all previous BSS version PRUs and shall support all mandatory features for the version to which the previous version PRU complies. The PTU may support the optional features that the PRU supports in the previous version for which the PRU complies. The PTU shall not request or initiate any feature (mandatory or optional) that is not supported by the previous version PRU.

6 Device types

6.1 PTU classification

AirFuel resonant PTU classes are defined by the following.

a) A PTU class is determined by the highest category PRU supported by that PTU as determined in Table 1. For example, a PTU that supports category 4 and below PRUs is considered a class 3 PTU. The maximum output power capability of a PTU of class n shall be larger than or equal to the value of $P_{\mathrm{TX\_IN\_MAX'}}$ of its class as denoted in Table 1. The output power of a PTU is denoted by P_{TX} in Figure 2, where P_{TX} is the real power, Avg ($V(t)$ x $I(t)$). See Clause 7 for power transfer requirements.

b) The minimum PRU support requirements are specified in Table 1. The minimum support requirement specifies the number of highest category PRUs that the PTU shall support at the least. The PTU shall support power allocation for PRUs of all categories lower than the highest supported category specified in Table 1, at least up to the max number of devices specified in the table, per the limitation of available power. PTU vendors may specify a different charge area for the Category 1 PRUs from other PRU categories.

NOTE The minimum category support requirement specified in Table 1 does not limit PTUs from supporting PRUs of higher category, if the PTU is capable of supporting higher category devices.

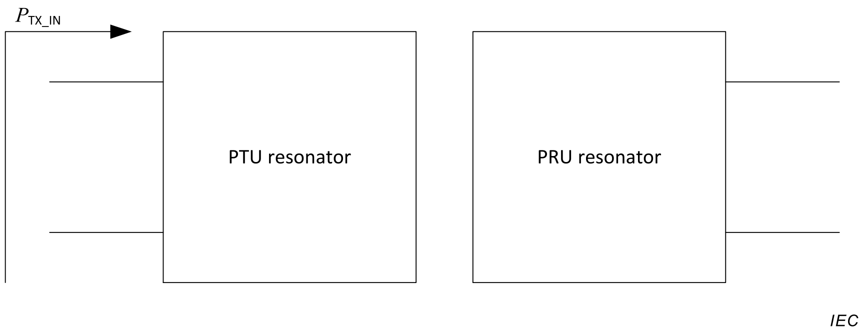


Figure 2 – PTU-PRU resonator $P_{\mathrm{TX\_IN}}$

Table 1 – PTU classification

	$P_{\mathrm{TX\_IN\_MAX'}}$ watts	**Minimum category support requirements**	**Minimum value for max number of devices supported**
Class 1	2	1 x Category 1	1 x Category 1
Class 2	10	1 x Category 3	2x Category 2
Class 3	16	1 x Category 4	2x Category 3
Class 4	33	1 x Category 5	3x Category 3
Class 5	50	1 x Category 6	4x Category 3
Class 6	70	1 x Category 7	5x Category 3

The minimum number of maximum category devices is provided as a guideline for calculating $P_{\mathrm{TX\_IN\_MAX'}}$, and is not meant to restrict the size of a corresponding class.

6.2 PRU category

Illustrated in Figure 3, the PRU resonator output power denoted by P_{RX_OUT} is the real power Avg V(t) x I(t). Table 2 lists the PRU resonator output power ($P_{RX\_OUT\_MAX'}$) for PRU categories. See Clause 7 for power transfer requirements.

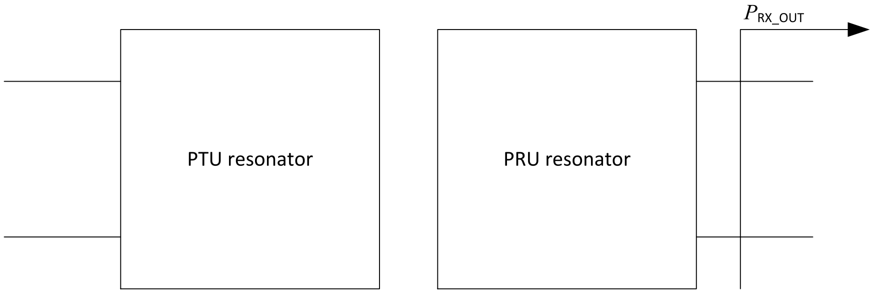


Figure 3 – PTU-PRU resonator P_{RX_OUT}

The PRU shall not draw more power than specified for its category. See Table 2.

Table 2 – PRU category

PRU	$P_{RX\_OUT\_MAX'}$ Watts	Example applications
Category 1	For further study	BT Headset
Category 2	3,5	Feature Phone
Category 3	6,5	Smart Phone
Category 4	13	Tablet, Phablet
Category 5	25	Small Form Factor Laptop
Category 6	37,5	Regular Laptop
Category 7	50	

NOTE 1 For P_{RX_OUT}, the PRU power is the output power of the PRU resonator.

NOTE 2 6,5 W is intended to allow 5 W at the charge port if the implementation has an efficiency greater than 80 %.

7 Power transfer specifications

7.1 System equivalent circuit and reference parameters

The equivalent circuit of the PTU resonator shall be series-tuned, or series-shunt-tuned. The equivalent circuit of the PRU resonator shall be series-tuned, shunt tuned, or series-shunt tuned. Figure 4 shows the interface point where the reference parameters are measured.

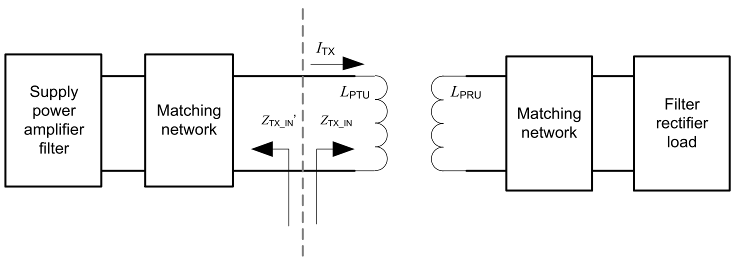


Figure 4 – Equivalent circuit and system parameters

7.2 General system requirements

7.2.1 Operating frequency

The resonator system shall operate at 6,78 MHz ± 15 kHz.

7.2.2 Z_{TX_IN} relationship to R_{RECT}

The real part of Z_{TX_IN} shall be inversely related to the load resistance of the rectifier. An increase in R_{RECT} shall cause a decrease in Z_{TX_IN}. A decrease in R_{RECT} shall cause an increase in Z_{TX_IN}.

7.2.3 Power stability

Under all operational conditions (transient/steady state) involving two or more PRUs, the change in rectified-output power of a first PRU should be no more than 10 % in the following two conditions.

a) A second PRU is physically added or removed from the charge area in a location that does not overlap with the first PRU.

b) A second PRU which is already in the charge area makes step response from 0 % load to 100 % load in less than 1 ms.

7.2.4 PTU co-location protection

A PTU shall protect itself when collocated with a PTU resonator of Clause 10, which is conducting up to $I_{TX\_ABS\_MAX}$. This includes all areas outside of the keep-out volume, in addition to the charge area.

7.2.5 PRU self-protection (informative)

PRUs can experience high field strengths as a result of $I_{TX\_ABS\_MAX}$ (from any class PTU) and are expected to protect themselves accordingly, including the situation of a link loss and failed to reconnect to PTU. This includes all areas outside of the keep-out volume, in addition to the charge Area.

7.3 Resonator requirements

7.3.1 Resonator coupling efficiency (RCE)

7.3.1.1 General

Resonator coupling efficiency (RCE) is defined as the maximum of the ratio of the power delivered by the PRU coil to a load, divided by the power delivered to the PTU coil, at 6,78 MHz. RCE is also equal to the maximum value of $|S_{21}|^2$ between one PTU and one PRU, occurring with perfectly-matched port impedance conditions, meaning S_{11} and S_{22} are zero, when the reference port impedances are as specified in 7.3.1.2 and 7.3.1.3. See informative Annex D, for RCE calculations.

The calculated value of RCE shall be equal to or higher than the minimum values given in Table 3, when the PRU is within the charge area specified in Clause 10.

NOTE 1 The actual measurements of S_{11}, S_{22}, S_{21}, and S_{12} can be made with nominal 50 Ω reference port conditions and the results converted to meet this RCE definition as well as finding the matching source and load, defined in 7.3.1.2 and 7.3.1.3. A step-by-step procedure to determine the maximum RCE and matching impedances is included in Annex D.

NOTE 2 Assessment for a new PRU is performed on all approved PTUs before that PRU is determined to be compliant with the specification.

Table 3 – Minimum RCE (percent and dB) between PRU and PTU

	Category 1	Category 2	Category 3	Category 4	Category 5	Category 6	Category 7
Class 1	N/A	N/A	N/A	N/A	N/A	N/A	N/A
Class 2	N/A	74 (-1,3)	74 (-1,3)	N/A	N/A	N/A	N/A
Class 3	N/A	74 (-1,3)	74 (-1,3)	76 (-1,2)	N/A	N/A	N/A
Class 4	N/A	50 (-3)	65 (-1,9)	73 (-1,4)	76 (-1,2)	N/A	N/A
Class 5	N/A	40 (-4)	60 (-2,2)	63 (-2)	73 (-1,4)	76 (-1,2)	N/A
Class 6	N/A	30 (-5,2)	50 (-3)	54 (-2,7)	63 (-2)	73 (-1,4)	76 (-1,2)
NOTE The RCE is stated as "% (db)".							

NOTE 3 When multiple PRUs are used, the coupling efficiency will increase.

7.3.1.2 Reference port impedance of PTU resonator

The reference port impedance of the PTU resonator to measure S_{21} is defined as Z_{TX_IN}, and is PTU and PRU resonator design dependent.

7.3.1.3 Reference port impedance of PRU resonator

The reference port impedance of the PRU resonator to measure S_{21} is defined as Z_{RX_IN}, and is PTU and PRU resonator design dependent.

7.3.2 PTU resonator requirements

7.3.2.1 Approved PTU resonator designs

A PTU being tested for compliance to the specification shall use an accepted PTU resonator from the AirFuel resonant accepted PTU resonator list, prior to the completion of compliance testing.

7.3.2.2 Resonator current

7.3.2.2.1 Threshold values

The following are PTU resonator current threshold value requirements.

a) The PTU resonator coil current shall not exceed I_{TX_MAX} during either the long beacon-on period or the short beacon-on period.

b) The PTU shall conduct a current greater than $I_{TX\_SHORT\_BEACON\_MIN}$ through the PTU resonator coil during the short beacon-on period.

c) The PTU shall conduct a current greater than $I_{TX\_LONG\_BEACON\_MIN}$ through the PTU resonator coil during the long beacon-on period.

d) The PTU shall conduct a current greater than or equal to I_{TX_MIN} through the PTU resonator coil during the PTU Power Transfer state, unless any PRU is reporting a V_{RECT} over V_{RECT_HIGH}

e) The PTU shall be capable of conducting a current $I_{TX\_NOMINAL}$ through the PTU resonator coil during the PTU Power Transfer state. The tolerance of $I_{TX\_NOMINAL}$ shall be no greater than 5 % excluding measurement error. $I_{TX\_NOMINAL}$ shall be derated at high values of R_{TX_IN} based on the value of $P_{TX\_IN\_MAX}$, which is defined according to the PTU class[2]. The equation for the derated current is:

2) Note that in implementation, the provision of $I_{TX\_NOMINAL}$ to all loads is not intended to cause a rise in the charging area temperature.

$$I_{TX\_NOMINAL\_DERATED} = \text{MIN}\ (I_{TX\_NOMINAL}, \text{SQRT}\ (P_{TX\_IN\_MAX}/R_{IN\_TX}))$$

f) The PTU shall be capable of conducting a current I_{TX_MAX} through the PTU resonator coil. I_{TX_MAX} shall be derated at high values of R_{TX_IN} based on the value of $P_{TX\_IN\_MAX}$, which is defined according to the PTU Class. The equation for the derated current is:

$$I_{TX\_MAX\_DERATED} = \text{MIN}\ (I_{TX\_MAX}, \text{SQRT}\ (P_{TX\_IN\_MAX}/R_{IN\_TX}))$$

g) The PTU resonator coil shall not conduct more than $I_{TX\_ABS\_MAX}$ in any transient or steady state condition.

A PTU may operate between I_{TX_MIN} and $I_{TX\_ABS\_MAX}$. A PTU shall operate between $I_{TX\_NOMINAL}$ and I_{TX_MAX}

7.3.2.2.2 Transitions

The PTU resonator coil shall not exceed its PTU resonator design maximum slew rate.

7.3.2.3 Resonator power supply characteristics

The PTU resonator shall be driven by a supply that has a source impedance that is greater than $|Z_{PA\_SOURCE\_MIN}|$ of the accepted PTU resonator used in the PTU (per its AirFuel resonant PTU resonator class n design template). A resonator's $|Z_{PA\_SOURCE\_MIN}|$ shall be selected such that PRUs do not experience an increased R_{RECT_MP} when operating on the PTU resonator.

NOTE 1 $|Z_{PA\_SOURCE\_MIN}|$ is specified because it affects the source impedance of PRUs.

NOTE 2 $|Z_{PA\_SOURCE\_MIN}|$ is specified to approximate a current source behavior at the PTU resonator interface.

NOTE 3 The test is performed with all resonator interface test (RIT) devices that are applicable to the PTU class.

7.3.2.4 Charge and test area

The boundaries of the PTU charge area and the PRU resonator area should be identified by the PTU and PRU vendors, respectively. Vendor charge area indication shall be equal or smaller than test charge area (charge area in tests). The keep-out volume shall be a bounded volume, and the PTU resonator designer shall provide a PTU mechanical housing design to indicate how the mechanical housing should prevent the PRU from being placed inside this keep-out volume.

7.3.2.5 Resonator power supply impedance range

The PTU shall be capable of conducting current levels through the PTU resonator coil that satisfy the resonator current threshold values across its specified range of Z_{TX_IN} (see Figure 5).

$$R_{TX\_IN\_MIN} \le \text{Re}\{Z_{TX\_IN}\} \le R_{TX\_IN\_MAX}$$

$$X_{TX\_IN\_MIN} \le \text{Im}\{Z_{TX\_IN}\} \le X_{TX\_IN\_MAX}$$

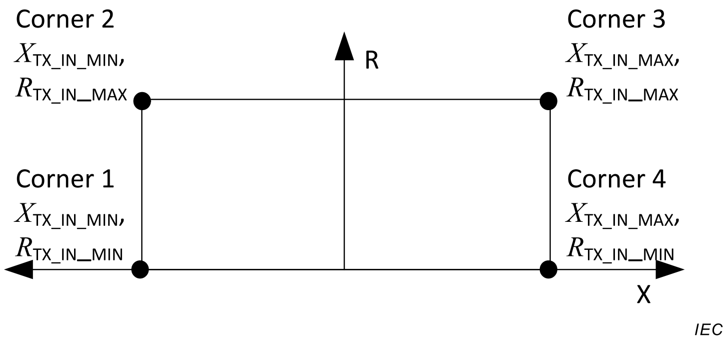


Figure 5 – PTU resonator-load considerations

For a specific PTU resonator, the allowed induced impedance for each PRU category shall be selected appropriately to account for the number of PRUs supported in that category.

7.3.2.6 Resonator geometry

The PTU resonator geometry shall be built to the requirements of Clause 10.

NOTE The above PTU resonator requirements are resonator design specific, and numbers for the above parameters are specified in Clause 10.

7.3.2.7 Resonator impedance sensitivity

The PTU resonator control circuitry shall be capable of detecting a load change of $Z_{TX\_IN\_LOAD\_DETECT}$ in the value of Z_{TX_IN}.

$Z_{TX\_IN\_LOAD\_DETECT}$ shall be at least 30 % less than both the real (R) and imaginary (X) components of the $Z_{TX\_IN\_LOAD\_CHANGE}$ specified for the PTU resonator used in the PTU resonator and resonator interface acceptance test.

7.3.3 PRU resonator requirements

7.3.3.1 PRU operating points

7.3.3.1.1 General

V_{RECT} can be derived as a function of the Z matrix between the PTU and PRU coils (see Annex D), I_{TX}, rectifier characteristics and load. The relationship between all of the parameters is dependent on PRU implementation. It is the responsibility of the original equipment manufacturer (OEM) to produce a design that allows for conformance.

NOTE The requirements in 7.3.3.1 apply under all valid load conditions (i.e., P_{RECT_MIN} to P_{RECT_MAX}) within the charge area (including minimum and maximum coupling), unless otherwise noted.

7.3.3.1.2 PRU Low Voltage sub-state threshold

A PRU's V_{RECT} shall exceed its V_{RECT_BOOT} while consuming P_{RECT_BOOT}, when I_{TX} is greater than $I_{TX\_LONG\_BEACON\_MIN}$ or I_{TX_MIN} (whichever threshold is lower) on presently approved PTU resonators (see Clause 10).

This requirement is for start-up conditions, and a PRU load is not required (see 8.3.4.1).

7.3.3.1.3 PRU Optimum Voltage sub-state threshold

With a PTU resonator that supports charging only a single device of the PRU's category, the following applies.

a) The PRU's V_{RECT} shall exceed its V_{RECT_MIN} if I_{TX} is greater than or equal to I_{TX_MAX}.

a) The PRU's V_{RECT} shall not exceed its $V_{\text{RECT\_HIGH}}$ if I_{TX} is less than or equal to $I_{\text{TX\_NOMINAL}}$.

For a PTU resonator that supports charging multiple devices of the PRU's category, a PRU shall be in the PRU Optimum Voltage sub-state when I_{TX} is equal to $I_{\text{TX\_NOMINAL}}$ on presently approved PTU resonators (see 10.3).

7.3.3.1.4 PRU set-point limit

A PRU shall not require I_{TX} to exceed $I_{\text{TX\_MAX}}$ to reach $V_{\text{RECT\_SET}}$ on presently approved PTU resonators (see 10.3).

7.3.3.1.5 PRU over-voltage threshold

A PRU in normal operation shall not enter the PRU System Error state if I_{TX} is less than or equal to $I_{\text{TX\_MAX}}$ on presently approved PTU resonators (see 10.3).

7.3.3.1.6 PRU over-voltage protection

A PRU shall not be damaged if I_{TX} is less than or equal to $I_{\text{TX\_ABS\_MAX}}$ on presently approved PTU resonators (see 10.3) for any period of time. This includes all areas outside of the keep-out volume, in addition to the charge area.

7.3.3.1.7 Margin between $V_{\text{RECT\_HIGH}}$ and $V_{\text{RECT\_MAX}}$

$V_{\text{RECT\_MAX}}$ shall be greater than 1,1 x $V_{\text{RECT\_HIGH}}$.

7.3.3.2 PRU-induced reactance change

A PRU shall present $X_{\text{TX\_IN}}$ which is within the $X_{\text{TX\_IN}}$ range defined in Clause 10.

7.3.3.3 PRU-induced resistance change

A PRU shall present $R_{\text{TX\_IN}}$ which is within the $R_{\text{TX\_IN}}$ range defined in Clause 10.

7.3.3.4 Short beacon PRU-induced impedance

On or before March 1, 2015, a PRU of Category 2 or greater should create a change in reactance and/or resistance of at least $Z_{\text{TX\_IN\_LOAD\_CHANGE}}$ when placed in charge area of all currently approved PTU resonators.

After March 1, 2015, a PRU of Category 2 or greater shall create a change in reactance and/or resistance of at least $Z_{\text{TX\_IN\_LOAD\_CHANGE}}$ when placed in charge area of all currently approved PTU resonators.

If a Category 1 PRU does not create an impedance change of at least $Z_{\text{TX\_IN\_LOAD\_CHANGE}}$ when placed in charge area of all currently approved PTU resonators, then it shall advertise that it does not create an impedance shift in the PRU advertising payload (see 9.5.2).

7.4 Load parameters

7.4.1 Load parameters introduction

PRUs with non-integrated loads (e.g., backpack phone chargers that plug into a mobile phone) shall comply with the requirements in 7.4.2 to 7.4.4 for any devices with which they might be connected. This can require the PRU to include mechanisms to ensure that they are compliant when connected to their intended load devices.

7.4.2 Minimum load resistance

The minimum value of R_{RECT} shall be greater than the maximum power point resistance (R_{RECT_MP}). The maximum power point resistance, R_{RECT_MP}, is defined as the load resistance measured after the rectifier at which maximum power delivery is achieved.

NOTE R_{RECT_MP} is a function of $|Z_{PA\_SOURCE}|$ PTU resonator design, and PRU resonator design.

7.4.3 Maximum allowable dynamic load

The load, measured at the output of the rectifier, shall not change by more than 650 mW/µs or X/µs, whichever is greater. X shall be calculated as 2 % times the maximum output power of the PRU resonator in mW.

7.4.4 Maximum load capacitance

The effective load capacitance connected after the rectifier shall be no greater than the maximum effective capacitance shown in Table 4.

Table 4 – Maximum load capacitance

Category	Maximum effective capacitance µF
Category 1	For further study
Category 2	100
Category 3	100
Category 4	100
Category 5	100
Category 6	130
Category 7	130

8 Power control specifications

8.1 Control objectives

The control specifications are designed to

a) protect PRU's V_{RECT} from over-voltage (i.e., $V_{RECT} > V_{RECT\_MAX}$),

b) reduce PRU's V_{RECT} such that $V_{RECT} \leq V_{RECT\_HIGH}$ within 5 s after a PRU reports its $V_{RECT} > V_{RECT\_HIGH}$,

c) ensure that all PRUs are provided a V_{RECT} voltage greater than V_{RECT_MIN} and less than V_{RECT_HIGH}, if objectives a) and b) are satisfied, and

d) control I_{TX}, if objectives a), b) and c) are satisfied, to:

   1) optimize the V_{RECT} of the PRU with the highest percentage utilization of P_{RECT} power, or

   2) maximize the total system efficiency.

8.2 PTU specifications

8.2.1 PTU state

The PTU shall have the following states: PTU Configuration, PTU Power Save, PTU Low Power, PTU Power Transfer, PTU Local Fault, and PTU Latching Fault. See Figure 6.

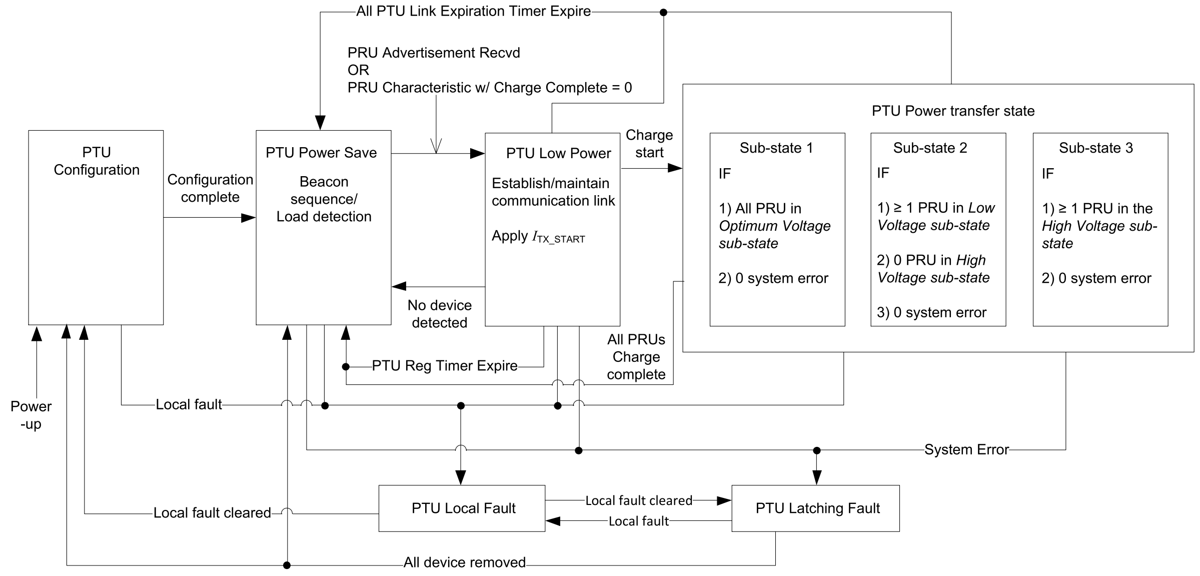


Figure 6 – PTU state model

8.2.2 General state requirements

8.2.2.1 General state introduction

8.2.2 defines requirements that are not specific to one PTU state.

8.2.2.2 New device registration

The PTU shall allow for registration of new devices after receiving valid PRU advertisements (see 9.6.3) in the PTU Power Save, PTU Low Power and PTU Power Transfer states.

8.2.2.3 PTU link supervision timer

The PTU shall maintain a separate link supervision timer for each PRU connection. The link supervision timer shall be started at zero seconds when a connection is established. The link supervision timer shall reset immediately after any BLE message is received from the PRU. The link supervision timer shall expire in one second.

If a PTU link supervision timer expires with less than 2 W of P_{TX_IN} variation before the timer expires, the PTU shall attempt the link loss reconnection procedure. See 9.4.5.3.3. If the reconnection procedure is not successful within 1,1 s after the PTU link expiration, the PRU shall be removed from the system registry. The PTU may consider that a PRU malfunction has occurred and enter the PTU Latching Fault state.

If the PTU link supervision timer expires with greater than or equal to 2 W of P_{TX_IN} variation before the timer expires, then the PTU shall remove the PRU from the system registry. If afterwards, the system registry is empty, the PTU shall enter the PTU Power Save state.

8.2.2.4 Messaging latency

Latency introduced by packet error rate is not considered as part of this document.

8.2.2.5 PTU response time for PRU detection

The PTU shall be capable of detecting a PRU placed in the charge area and enter PTU Power Transfer state or inform the PRU of power denial within the time as specified in Table 5.

NOTE 1 The PTU informs the PRU of power denial through writing in the permission field of the PRU control characteristic as described in Table 20.

Table 5 – Time requirement to enter PTU Power Transfer state

Condition	Maximum time for initiating charge of PRU s
Category 1 PRU	3,5
Until March 01, 2015: PRU creates less than $Z_{TX\_IN\_LOAD\_CHANGE}$	7
PRU creates $Z_{TX\_IN\_LOAD\_CHANGE}$ or greater and no extended long beacon request from PRU	1
PTU extends long beacon	3,5

See 7.3.3.4, for short beacon PRU-induced impedance, $Z_{TX\_IN\_LOAD\_CHANGE}$.

NOTE 2 For category 2-5 PRUs, the maximum time for initiating charge of a PRU is based on short beacon operation (see 8.2.3.3) as well as the PTU-PRU ability to establish a BLE connection and complete WPT registration (see 8.2.4.2).

8.2.2.6 PTU Registration Timer

The PTU shall start a registration timer when a valid advertisement (see 9.6.3) is received. The timer shall be stopped when the PTU writes the control characteristic to the PRU. The registration timer shall expire in 500 ms. If the registration timer expires, the PTU may provide an indication to the user that a PRU connection attempt has failed.

If the PTU Registration Timer expires, the PTU shall terminate the connection with the PRU which failed to register, if the BLE connection was already established prior to registration timeout.

8.2.3 PTU power save state

8.2.3.1 State entry procedure

8.2.3.1.1 Beacon sequence start

The PTU shall start the beacon sequence within 50 ms of entering the PTU Power Save state.

8.2.3.1.2 Device registry

The PTU's device registry shall be cleared, except for the registry information of PRUs in charge complete connected mode.

8.2.3.2 Beacon sequence

During the PTU Power Save State, the PTU shall

a) periodically apply current to the PTU resonator to detect changes of impedance of the PTU resonator, and
b) periodically apply current to the PTU resonator to allow communication between PTU and PRU.

The beacon sequence is comprised of long beacons and short beacons as shown in Figure 7.

NOTE 1 Short beacon purpose is to detect changes in PTU impedance caused by the placement of an object in charge area. The use of short beacon reduces standby power.

NOTE 2 Long beacon purpose is to guarantee that PRUs have sufficient power to boot and respond.

See 9.6.3 for additional requirements.

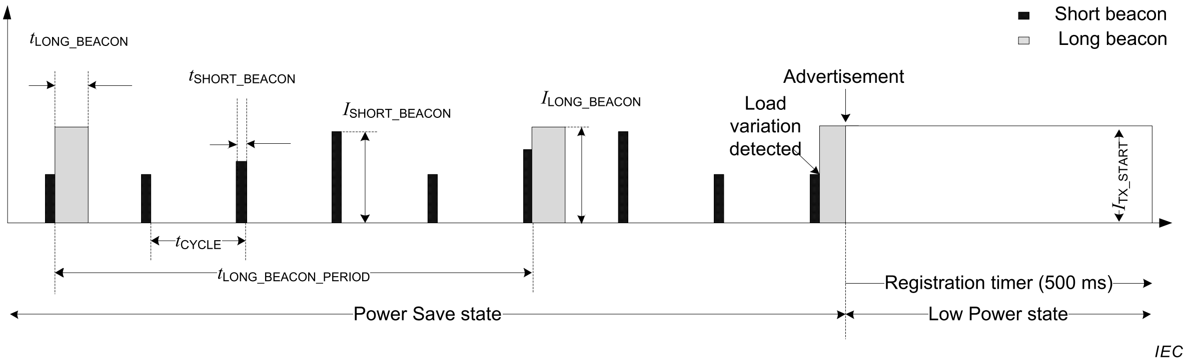


Figure 7 – Beacon sequences

8.2.3.3 Short beacon

8.2.3.3.1 Short beacon timing

The PTU shall periodically apply a short beacon to the PTU resonator to detect changes in impedance. The period, t_{CYCLE}, shall be 250 ms ± 5 ms. The short beacon-on-period (t_{SHORT_BEACON}) shall be between 10 ms and 30 ms.

8.2.3.3.2 Short beacon current

$I_{TX\_SHORT\_BEACON\_MIN}$ is defined to be a measureable current greater than $I_{TX\_SHORT\_BEACON\_MIN}$ and sufficient to enable detection of Category 2 and larger PRUs. See also 7.3.2.2.1 for short beacon current requirements.

8.2.3.3.3 Load variation detection

With the short beacon, the PTU shall be capable of sensing the reactance and resistance change of $Z_{TX\_IN\_LOAD\_DETECT}$. $Z_{TX\_IN\_LOAD\_DETECT}$ is called out in 10.3. See Figure 8. See also 7.3.3.4 for short beacon PRU-induced impedance.

The PTU shall initiate long beacon immediately when it detects a load variation during short beacon.

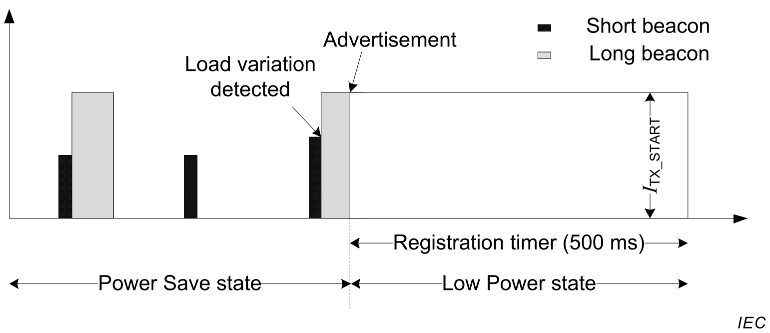


Figure 8 – Load variation detection

8.2.3.4 Long beacon

8.2.3.4.1 Long beacon timing

The PTU shall periodically apply current, $I_{TX\_LONG\_BEACON}$, to the PTU resonator. The PTU shall apply current $I_{TX\_LONG\_BEACON}$, as defined in 8.2.3.4.2, within 10 ms of the short beacon ending. The beacon-on-period (t_{LONG_BEACON}) shall be 105 ms ± 5 ms, unless exiting PTU Power Save state, in which case it may be shorter. The beacon period

($t_{LONG\_BEACON\_PERIOD}$) shall be longer than 850 ms and shall not exceed 3 000 ms. The long beacon shall be concatenated with a short beacon.

If the PRU requires long beacon extension, it shall generate a 100 Hz ± 20 Hz load variation with a 45 % – 55 % duty cycle for at least 22 ms during the long beacon period. The PRU load variation shall be between 0,5 W and 1,1 W at the rectifier during the positive edge of the clock signal.

The PTU shall extend the long beacon to 3 000 ms when it detects at least two load variations at (100 ± 20) Hz during the long beacon.

NOTE 1 The purpose of the long beacon is to induce sufficient voltage in a PRU to elicit a response.

NOTE 2 The beacon-on-period is defined as the period of time during which the I_{TX} is greater than $I_{TX\_LONG\_BEACON\_MIN}$. Rise and fall times are not included.

8.2.3.4.2 Long beacon current

See 7.3.2.2.1 for long beacon current requirements.

8.2.3.4.3 Device discovery

The PTU shall scan for WPT service related BLE advertisements during the long beacon-on period. See Figure 9 and 9.4.5.

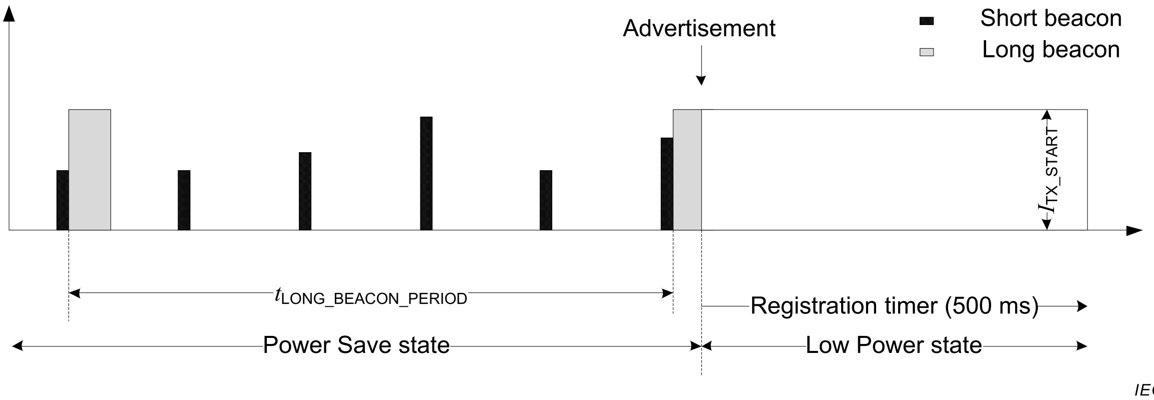


Figure 9 – Discovery

8.2.4 PTU Low Power state

8.2.4.1 State entry procedure

8.2.4.1.1 I_{TX} adjustment

The PTU shall apply a current ranging from 0,8 x I_{TX_START} to I_{TX_START} within 100 ms of entering the PTU Low Power state. I_{TX} shall change monotonically between its previous state and a level between 0,8 x I_{TX_START} and I_{TX_START}. The PTU shall then maintain the current between 0,8 x I_{TX_START} to I_{TX_START} until exiting the PTU Low Power state.

NOTE I_{TX_START} is sufficient to wake up the communication circuit of the PRU.

8.2.4.1.2 Other state entry procedures

None.

8.2.4.2 WPT device registration

In the PTU Low Power state, the PTU shall establish a BLE connection with the PRU and complete registration according to the requirements in 9.4.5 and 9.3.7

8.2.5 PTU Power Transfer state

8.2.5.1 State entry procedure

8.2.5.1.1 I_{TX} adjustment

The PTU shall apply a current ranging from 0,8 x $I_{TX\_NOMINAL}$ to $I_{TX\_NOMINAL}$ within 500 ms of entering the PTU Power Transfer state.

8.2.5.1.2 Other state entry procedures

None.

8.2.5.2 General requirements

8.2.5.2.1 PTU Power Transfer state I_{TX}

The PTU shall continuously apply I_{TX}. The PTU shall adjust its I_{TX} as per the algorithms specified in 8.2.5.5.1.

8.2.5.2.2 I_{TX} adjustment timing

The PTU shall adjust I_{TX} at least once every 250 ms if an adjustment is required, and if I_{TX} has settled (see 8.2.5.2.4) from its previous adjustment, and if all connected PRUs' Dynamic Parameter Characteristics (see 9.5.7) are received within that interval. Prior to writing a PRU Control Characteristic with Enable PRU output = "1" (see 9.5.4), the PTU may apply $I_{TX\_NOMINAL}$ with 10 % tolerance for expecting a V_{RECT} drop on the PRU due to additional loading. However, if any of these three conditions are not met, then I_{TX} shall not be adjusted.

8.2.5.2.3 PTU I_{TX} transition response

When increasing or decreasing I_{TX}, the transition shall not be under-damped. See Figure 10.

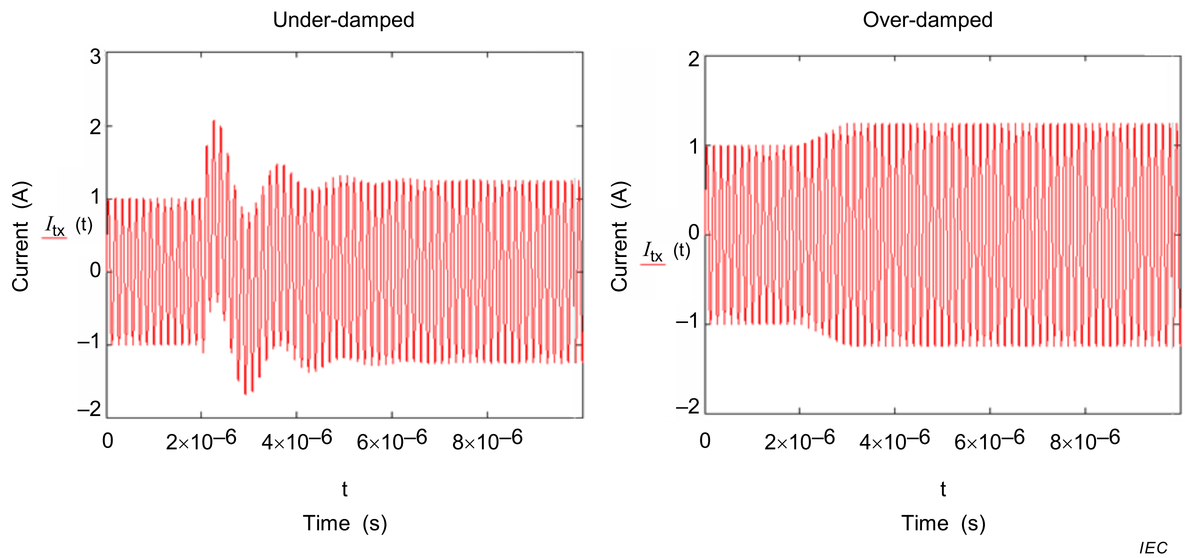


Figure 10 – PTU I_{TX} transition responses

8.2.5.2.4 PTU Power Transfer state I_{TX} settling time

I_{TX} shall reach steady state (90 % of the delta between the start and end current values) within 250 ms of any transition.

8.2.5.3 Sub-state definitions and transitions

The PTU Power Transfer state shall have three sub-states with the conditions for entering the sub-state shown in Table 6.

Table 6 – Sub-state of PTU Power Transfer

Sub-state	Condition for entering sub-state
1	All PRUs are in Optimum Voltage sub-state 0 system error
2	One or more PRUs are in Low Voltage sub-state 0 device are in High Voltage sub-state 0 system error
3	One or more PRUs are in High Voltage sub-state 0 system error

8.2.5.4 PRU reported values

The sub-state of a PRU is determined by examining the V_{RECT} reported by the PRU in relation to the $V_{RECT\_MIN\_STATIC}$ and $V_{RECT\_HIGH\_STATIC}$ parameters reported in the PRU Static Parameter Characteristic (see 9.5.6.3). If the PRU reports $V_{RECT\_MIN\_DYN}$ and $V_{RECT\_HIGH\_DYN}$ parameters in the PRU Dynamic Parameter Characteristic (see 9.5.7), the PTU shall use the most recently reported values in place of the values reported in the PRU Static Parameter Characteristic.

8.2.5.5 PTU Power Transfer sub-state 1

8.2.5.5.1 PTU Power Transfer sub-state 1 algorithm selection

The PTU shall use either the $V_{RECT\_MIN\_ERROR}$ or η_{MAX} algorithm. The PTU may switch between algorithms. However, the PTU shall not make an adjustment to I_{TX} that will cause any PRU operation to move outside of the optimum voltage region.

It is recommended that the PTU select the preferred algorithm of the dominant PRU.

NOTE For V_{RECT} X I_{RECT}/P_{RECT_MAX}, P_{RECT_MAX} is reported in the PRU Static Parameter Characteristic value.

8.2.5.5.2 PTU Power Transfer sub-state 1 *V*RECT_MIN_ERROR algorithm

If the PTU is paired with one PRU, the PTU shall minimize the value of $E_{VRECT} = |V_{RECT} - V_{RECT\_SET}|$.

If the PTU is paired with more than one PRU, the PTU shall adjust I_{TX} to minimize the E_{VRECT} for the PRU with the highest percentage utilization of its rated output.

The percentage of the rated output shall be calculated as P_{RECT} / P_{RECT_MAX}. P_{RECT_MAX} is the maximum output power of a PRU design.

NOTE $P_{RECT} = I_{RECT}$ x V_{RECT}.

8.2.5.5.3 PTU Power Transfer sub-state 1 *η*MAX algorithm

The PTU shall adjust I_{TX} to maximize the total system efficiency. η_{MAX} is calculated as $\Sigma(P_{RX\_REPORTED})/P_{IN}$.

8.2.5.5.4 PTU Power Transfer sub-state 1 I_{TX} adjustment step size

I_{TX} adjustments shall have a step size no greater than 5 % of I_{TX_MAX} and no smaller than 1 % of I_{TX_MAX} with the following exceptions.

a) If any PRU's V_{RECT} is greater than V_{RECT_HIGH} x 0,95, the positive I_{TX} step size may be reduced.
b) If any PRU's V_{RECT} is less than V_{RECT_MIN} x 1,05, the negative I_{TX} step size may be reduced.
c) If the dominant PRU's V_{RECT} is between V_{RECT_SET}/1,05 and V_{RECT_SET}/0,95, the positive and negative I_{TX} step size may be reduced.
d) If I_{TX} is above I_{TX_MAX}, the positive I_{TX} step size may be reduced to avoid exceeding $I_{TX\_ABS\_MAX}$.

While using the $V_{RECT\_MIN\_ERROR}$ algorithm, the PTU shall be able to drive I_{TX} to get V_{RECT} of a PRU within 5 % of V_{RECT_SET}, unless doing so requires the I_{TX} to exceed I_{TX_MAX} or to fall below $I_{TX\_NOMINAL}$. See 7.3.2.2.1 for operational limits on I_{TX}.

If only Category 4 and above PRUs are present, adjustments may be made at up to a step size of 10 %.

8.2.5.6 PTU Power Transfer sub-state 2

8.2.5.6.1 PTU Power Transfer sub-state 2 algorithm

The PTU shall increase I_{TX} until all PRUs have $V_{RECT(N)} \geq V_{RECT\_MIN(N)}$, however the PTU should not make an adjustment to I_{TX} that causes any PRU to move into the High Voltage sub-state or the PRU System Error state for an over-voltage.

8.2.5.6.2 PTU Power Transfer sub-state 2 I_{TX} adjustment step size

I_{TX} adjustments shall have a step size no greater than 5 % of I_{TX_MAX} and no smaller than 1 % of I_{TX_MAX}.

8.2.5.7 PTU Power Transfer sub-state 3

8.2.5.7.1 PTU Power Transfer sub-state 3 algorithm

The PTU shall decrease I_{TX} until all PRUs report $V_{RECT(N)} \leq V_{RECT\_HIGH(N)}$.

8.2.5.7.2 PTU Power Transfer sub-state 3 I_{TX} adjustment step size

I_{TX} adjustments shall have a step size no greater than 5 % of I_{TX_MAX} and no smaller than 1 % of I_{TX_MAX}.

8.2.6 PTU Configuration state

8.2.6.1 State entry procedure

8.2.6.1.1 I_{TX} adjustment

If I_{TX} > 50 mA_{rms} at the state entry, the PTU shall decrease I_{TX} to below 50 mA_{rms} within 500 ms of entering the PTU Configuration state.

8.2.6.1.2 PTU Configuration state time limit

The PTU shall exit the PTU Configuration state within 4 s of entering the state.

8.2.6.1.3 Device registry

The device registry shall be cleared.

8.2.6.2 PTU Configuration state functions

The PTU may perform self and system checks during the PTU Configuration state.

8.2.6.3 PTU Configuration state I_{TX}

I_{TX} shall remain below 50 mA_{rms}.

8.2.7 PTU Local Fault state

8.2.7.1 General

The PTU may exit any state and enter the PTU Local Fault state if the PTU experiences any local fault condition that requires power to be shut down. This may include, but is not limited to, PTU local over-temperature, local over-current, local over-voltage or any local PTU failure.

Before reaching a PTU over-temperature condition, the PTU shall attempt to limit the power allocated (i.e., drawn) by the PRUs being charged. For example, the PTU may send an Adjust power command to all PRUs receiving power that support the command, to reduce to a lower percentage of P_{RECT_MAX} (e.g., 66 %). Other implementations may include sending Disable PRU output, switching PTU power transfer sub-state algorithms, switching dominant PRU, or any other power limiting implementation.

8.2.7.2 State entry procedure

8.2.7.2.1 I_{TX} adjustment

If I_{TX} > 50 mA_{rms} at the state entry, the PTU shall decrease I_{TX} to below 50 mA_{rms} within 500 ms of entering the Fault state.

8.2.7.2.2 Device registry

The device registry shall be cleared.

8.2.7.3 PTU Local Fault state I_{TX}

I_{TX} shall remain below 50 mA_{rms}.

8.2.8 PTU latching fault state

8.2.8.1 General

A PTU enters the PTU Latching Fault state in response to at least one of the triggers listed in Table 7.

8.2.8.2 State entry procedure

8.2.8.2.1 I_{TX} adjustment

If I_{TX} > 50 mA_{rms} at the state entry, the PTU shall decrease I_{TX} to below 50 mA_{rms} within 500 ms of entering the PTU Latching Fault state.

8.2.8.2.2 Device registry

The device registry shall be cleared.

8.2.8.3 Clearing PTU latching fault

Unless the PTU is in the PTU Local Fault state, the PTU shall first attempt to clear the latching fault. If the PTU is unable to clear the latching fault, the PTU remains in the latching fault persistently which requires user interaction for clearing. The PTU shall attempt up to three times to clear the latching fault. Each PTU attempt for clearing the latching fault shall take between 1,1 s and 30 s from the start of the latching fault. The PTU shall clear the latching fault up to three times in succession by transitioning back to the PTU Power Save state, thus causing a system restart. If there are more than three successive latching faults, the PTU shall stay in the PTU Latching Fault state persistently and provide an indication to the user to clear the latching fault. The user clears persistent latching faults by removing all devices from the PTU (see 8.2.8.4).

The count of successive latching faults, for the purposes of remaining in the PTU Latching Fault state, shall be cleared after five minutes of continuous operation with no system errors. The count shall also be cleared when the user clears a persistent latching fault condition.

8.2.8.4 Load variation detection

After 1 s ± 0,1 s from entering the PTU Latching Fault state, the PTU shall perform the short beacon sequence with constant I_{TX} described in 8.2.3.3. The PTU shall transition to PTU Power Save or PTU Configuration state if the short beacons detect a load variation indicating the removal of device or devices from the charge area (except for PTU Local Fault conditions).

8.2.9 PTU state transitions

8.2.9.1 PTU state transitions introduction

The PTU shall not make any state transitions unless they are defined in 8.2.9 as required or optional.

The PTU shall make all transitions designated as required.

8.2.9.2 PTU Power-up

PTU is powered up.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
Null	PTU Configuration	Required	None	None

8.2.9.3 PTU configuration complete

The PTU completes a self-test.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PTU Configuration	PTU Power Save	Required	None	At least one PTU Local Fault

8.2.9.4 Device detected and charge start from PTU Power Save

The PTU shall begin device registration when one of the following occurs.

- The PTU receives a valid advertisement (see 9.6.3) from a non-connected PRU.
- The PTU reads a dynamic parameter or receives an alert from a connected PRU that indicates charge required (Charge complete = 0).

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PTU Power Save	PTU Low Power	Required	0 system errors or PTU receives: – Advertisement or – Characteristic with Charge complete = 0	None

8.2.9.5 PTU link supervision timer expired

The PTU link supervision timer expires for one or more PRUs.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PTU Power Transfer PTU Low Power	PTU Power Save	Required	0 system errors All connections lost	At least one PTU Local Fault
PTU Power Transfer PTU Low Power	PTU Latching Fault	Optional	0 system errors Any connection lost without power variation and unsuccessful reconnection	None

8.2.9.6 PTU-PRU registration complete

The PTU has completed the registration process and sent a PRU Control Characteristic to the PRU.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PTU Low Power	PTU Power Transfer	Required	0 system errors and bit field for permission equal to "0000 0000"	None
PTU Low Power	PTU Power Save or PTU Local Fault or PTU Power Transfer	Optional	0 system errors and bit field for permission not equal to"0000 0000"	None

8.2.9.7 Charge complete

This state transition indicates that a PTU has received a charge complete notification from all PRU units.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PTU Power Transfer	PTU Power Save	Required	0 system errors All PRU units indicate charge complete	At least one PTU Local Fault

8.2.9.8 PTU local fault

The PTU experiences a local fault condition.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PTU Power Save	PTU Local Fault	Optional	None	The local fault does not cause a state transition itself
PTU Low Power				
PTU Power Transfer				
PTU Configuration				
PTU Latching Fault				

8.2.9.9 PTU local fault cleared

The PTU determines that the PTU Local fault has been cleared.

NOTE The PTU Local fault is cleared when the conditions that caused the local fault are resolved.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PTU Local Fault	PTU Configuration	Optional	None	State preceding the PTU Local Fault was a PTU Latching Fault.
PTU Local Fault	PTU Latching Fault	Optional	State preceding the PTU Local Fault was a PTU Latching Fault	None

8.2.9.10 PTU Registration Timer expired

The PTU Registration Timer has expired.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PTU Low Power	PTU Power Save	Required	None	Entering PTU Latching Fault

8.2.9.11 PTU latching fault

The PTU latching faults are defined in Table 7.

Table 7 – PTU latching faults

PTU latching faults	Latching fault description
1	Rogue object detected
2	System error – PRU over-voltage, over-current, over temperature
3 to 16	Reserved

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PTU Power Save	PTU Latching Fault	Required	None	None
PTU Low Power				
PTU Power Transfer				

8.2.9.12 User clears PTU latching fault

All latching faults are cleared by the user intervention.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PTU Latching Fault	PTU Power Save or PTU Configuration	Required	User intervention occurs	At least one PTU Local Fault

8.2.10 PTU Test Mode

PTU Test Mode is intended to operate with one PRU tester, the one that is requesting the initiation of testing, connected to the PTU. For a list of Tester Commands, see 9.5.7.14.

While in PTU Test Mode, the PTU behavior shall adhere to the protocol revision to which it complies, except as specified below.

a) The PTU shall enter PTU Test Mode after reading a PRU Static Parameter Characteristic flag in the PRU Information octet during the PRU's device registration. See 9.5.6.7 for details of the PRU Static Parameter Characteristic Information Bit Field.

b) The PTU shall enter Test Mode only if the PRU Static Characteristic Parameter message with the Test Mode bit set is received in less than 15 s after power is applied to the PTU.

c) The PTU shall remain in test mode until the PRU simulator that initiated test mode is disconnected, or PTU shut down (power cycle).

d) If a second PRU connects with the PTU in Test Mode, the PTU shall transition to a non-operational condition, similar to a hard reset, that is recoverable only by power cycle.

   NOTE For the purposes of this requirement, connection with a second PRU is defined as the PTU having received the PRU's Static Characteristic message.

e) I_{TX} in Test Mode shall be adjustable incrementally up or down as commanded by a field in the PRU Dynamic Parameter Characteristic value sent from the PRU that initiated test mode. See 9.5.7.14 for details of the PRU Dynamic Parameter Characteristic Tester Command. Commands to increase or decrease I_{TX} shall result in PTU I_{TX} increasing or decreasing in increments of greater than or equal to 5 % $I_{\mathrm{TX\_MAX}}$.

f) When in Test Mode, current shall not be controlled by the external (BLE) feedback. Internal feedback, including tuning adjustment, if part of PA internal control, is acceptable.

g) After adjusting I_{TX} by PRU simulator command or after adjusting load impedance, I_{TX} shall settle to steady state within 250 ms, after which no further changes in I_{TX} should be made until the next adjustment.

h) The PTU in Test Mode shall have the ability to drive I_{TX} to $I_{\mathrm{TX\_MAX}}$ ± 5 %. The PTU in Test Mode shall be able to reach within 5 % of $I_{\mathrm{TX\_MIN}}$ or to derated current at max R load, whichever is lower.

i) I_{TX} shall not exceed $I_{\mathrm{TX\_ABS\_MAX}}$ in Test Mode.

8.3 PRU specifications

8.3.1 PRU general requirements

8.3.1.1 Local protections

8.3.1.1.1 Over-temperature

The PRU shall implement local over-temperature protection[3] such that when the PRU is operating in the Optimum Voltage sub-state and the ambient temperature is within the range

3 Local over-temperature protection can be in the form of the PRU having a heat dissipating structure.

of 0 °C to 30 °C, then the PRU shall not reach OTP limit. If the OTP limit is reached, the PRU shall report the over-temperature condition.

8.3.1.1.2 Over-current

The PRU shall implement local over-current protection and this protection shall occur at a current below the OCP alert limit. If the OCP limit is reached, the PRU shall report the over-current condition.

8.3.1.1.3 Over-voltage

The PRU shall implement local over-voltage protection. The PRU may regulate its voltage by periodically closing and opening the OVP switch so that V_{RECT} stays within a region that allows communications with the PTU, and ensures that power dissipation and voltage levels are within acceptable levels. The PRU may report the over-voltage condition (see 8.3.6) only after $V_{\mathrm{RECT}} \geq V_{\mathrm{RECT\_MAX}}$. If the OVP switch is located prior to the rectifier output, the PRU shall report the over-voltage condition after $V_{\mathrm{RECT}} \geq V_{\mathrm{RECT\_MAX}}$, and close the OVP switch within 250 ms of triggering the OVP switch.

8.3.1.2 PRU signaling

The PRU shall be able to communicate in all V_{RECT} operating regions (see Figure 11) except the Under Voltage region.

8.3.1.3 PRU link establishment

The PRU shall not attempt to join a PTU network unless it is receiving power from a PTU.

8.3.1.4 PRU link supervision timer

The PRU shall maintain a separate link supervision timer for connection with the PTU. The link supervision timer shall start when a connection is established. The link supervision timer shall reset immediately after an expected BLE message is received. The link supervision timer shall expire in one second.

If a PRU link supervision timer expires, the PRU shall attempt the link loss reconnection procedure. The PRU shall maintain use of the same device address used prior to link expiration during the reconnection procedure. See 9.4.5.2.3. If the link loss reconnection procedure fails, then the PRU shall disable its charge output.

8.3.1.5 PRU link termination

When a PRU capable of providing its own power has an established link to a PTU and V_{RECT} drops below $V_{\mathrm{RECT\_UVLO}}$, the PRU shall initiate the GAP Terminate Connection procedure within 500 ms as described in 9.4.5.2.4, Idle connection.

8.3.1.6 PRU V_{RECT} set value

$V_{\mathrm{RECT\_SET}}$ shall always be greater than or equal to $V_{\mathrm{RECT\_MIN\_STATIC}}$, and less than or equal to $V_{\mathrm{RECT\_HIGH\_STATIC}}$ as reported in the PRU Static Parameter Characteristic (see 9.5.6.3). Likewise, if the PRU reports updated values in the PRU Dynamic Parameter message (see 9.5.7), $V_{\mathrm{RECT\_SET\_DYN}}$ shall be greater than or equal to the most recently reported $V_{\mathrm{RECT\_MIN\_DYN}}$, and less than or equal to $V_{\mathrm{RECT\_HIGH\_DYN}}$. If no $V_{\mathrm{RECT\_SET\_DYN}}$ is reported, $V_{\mathrm{RECT\_MIN\_DYN}}$ shall never be greater than $V_{\mathrm{RECT\_SET}}$, and $V_{\mathrm{RECT\_HIGH\_DYN}}$ shall never be less than $V_{\mathrm{RECT\_SET}}$. If no $V_{\mathrm{RECT\_\_MIN\_DYN}}$ or $V_{\mathrm{RECT\_\_HIGH\_DYN}}$ are reported, then $V_{\mathrm{RECT\_SET\_DYN}}$ shall be greater than $V_{\mathrm{RECT\_MIN\_STATIC}}$ and less than $V_{\mathrm{RECT\_HIGH\_STATIC}}$.

8.3.1.7 PRU reported parameters

8.3.1.7.1 General

The PRU shall report V_{RECT}, I_{RECT} and PRU alert, and may report V_{OUT}, I_{OUT}, $V_{RECT\_HIGH\_DYN}$, $V_{RECT\_MIN\_DYN}$, $V_{RECT\_SET\_DYN}$ and temperature in the PRU On and PRU Boot states.

8.3.1.7.2 PRU reporting data age

At a given reporting instance, the value of each parameter shall be measured at least once since the last report. I_{RECT} and V_{RECT} values given in any report should be made within 1 ms of each other.

NOTE The 1 ms timing requirement between I_{RECT} and V_{RECT} measurements is highly desired and not intended to preclude implementations.

8.3.1.7.3 Accuracy of reported voltage

The value of V_{RECT_REPORT} shall be reported with an accuracy better than ± 3 %, unless the PRU is in the PRU System Error state.

The voltage accuracy requirement is necessary for system control. The system is specified such that multi-device PTUs can keep all combinations of PRUs in the optimum voltage region. If there is error in the reported value of V_{RECT}, the system might be unable to keep all PRUs in the optimum voltage region.

8.3.1.7.4 Accuracy of reported current

The value of I_{RECT_REPORT} shall be reported with accuracy better than 8 % of P_{RECT_MAX} divided by V_{RECT_MIN}. P_{RECT_MAX} and V_{RECT_MIN} are those reported within the PRU Static Parameters. See also Table 8.

$$\text{ABS}\ (I_{RECT} - I_{RECT\_REPORT}) \leq (8\ \%)\ (P_{RECT\_MAX} / V_{RECT\_MIN})$$

Table 8 – Example of accuracy of reported current

Allowable I_{RECT} report delta for 8 % error milliamps							
	Pwr	**Current**	**Cat 1**	**Cat 2**	**Cat 3**	**Cat 4**	**Cat 5**
Max W				3,5	5		
V_{RECT_MIN}				8	8		
	0	0,000		35,00	50,00		
	0,5	63		35,00	50,00		
	1	125		35,00	50,00		
	1,5	188		35,00	50,00		
	2	250		35,00	50,00		
	2,5	313		35,00	50,00		
	3	375		35,00	50,00		
	3,5	438		35,00	50,00		
	4	500			50,00		
	4,5	563			50,00		
	5	625			50,00		
	5,5	688			50,00		
	6	750			50,00		
	6,5	813			50,00		
	7	875					
	7,5	938					
	8	1 000					
	8,5	1 063					
	9	1 125					

8.3.2 PRU state model

The PRU can be in one of five states identified in Figure 11 and five operating regions at any given time. The operating region shall be determined by the value of V_{RECT} (as identified in Figure 12).

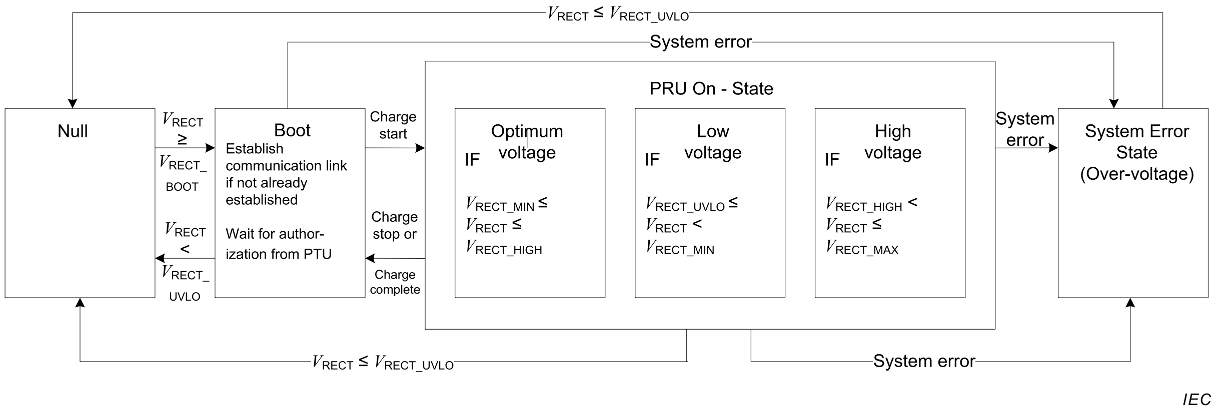


Figure 11 – PRU state model

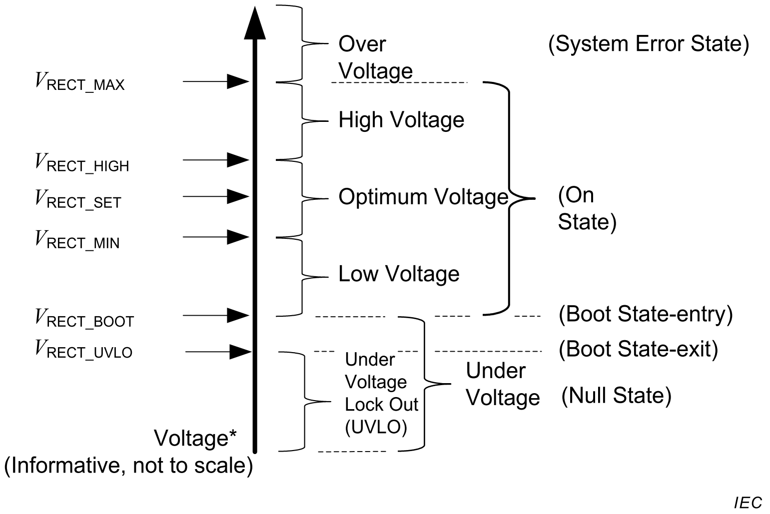


Figure 12 – V_{RECT} operating regions

8.3.3 Null state

At start-up, a PRU shall be considered to be in the Null state when $V_{RECT} < V_{RECT\_BOOT}$. After exiting the Null state, a PRU shall be considered to re-enter the Null state when V_{RECT} falls below V_{RECT_UVLO}.

8.3.4 PRU boot

8.3.4.1 State procedure

The PRU shall disable its output at start-up.

If the PRU is not in a connection with the PTU, the following applies.

- If Charge Complete = 0, and if the PRU does not generate a long beacon extension request signal, the PRU shall send an advertisement within 100 ms of I_{TX} exceeding $I_{TX\_LONG\_BEACON\_MIN}$ or I_{TX_MIN} (whichever threshold is lower).
- If Charge Complete = 0, and if the PRU generates a long beacon extension request signal, then the PRU shall send an advertisement within 3 s of I_{TX} exceeding $I_{TX\_LONG\_BEACON\_MIN}$ or I_{TX_MIN} (whichever threshold is lower).
- Otherwise, if I_{TX} continuously exceeds $I_{TX\_LONG\_BEACON\_MIN}$ or I_{TX_MIN} (whichever threshold is lower) for a period of 600 ms, the PRU shall send an advertisement within 800 ms of I_{TX} exceeding that lower threshold.
- The PRU shall not consume more than P_{RECT_BOOT} during the PRU Boot state. P_{RECT_BOOT} shall be less than 1,1 W.

8.3.4.2 Other state entry procedures

None.

8.3.5 PRU On state

8.3.5.1 PRU On state general requirements

8.3.5.1.1 Output enable/disable

The PRU shall draw less than 1,1 W (calculated at the output of the rectifier) unless allowed by the PTU. The PRU shall reduce its output to less than 1,1 W, within 1,1 s if Enable PRU output is set to "0" by the PTU (see 9.5.4).

8.3.5.1.2 Other On state requirements

None.

8.3.5.2 Optimum Voltage sub-state

A PRU is in the Optimum Voltage sub-state when $V_{RECT\_MIN} < V_{RECT} < V_{RECT\_HIGH}$.

8.3.5.3 Low Voltage sub-state

A PRU is in the Low Voltage sub-state when $V_{RECT\_BOOT} \le V_{RECT} < V_{RECT\_MIN}$.

8.3.5.4 High Voltage sub-state

A PRU is in the High Voltage sub-state when $V_{RECT\_HIGH} < V_{RECT} \le V_{RECT\_MAX}$.

NOTE In the High Voltage sub-state, the PRU might not be capable of continuous operation.

8.3.5.4.1 High voltage operation time

A PRU shall not disconnect its output if $V_{RECT\_HIGH} < V_{RECT} \le V_{RECT\_MAX}$ for a period of less than five seconds. This time shall be measured starting from the moment that the PRU communicates information indicating that it is within the High Voltage sub-state. A PRU may disconnect the output after five seconds.

8.3.5.4.2 High voltage sustain time

The PRU shall not be damaged in the High Voltage sub-state.

8.3.5.5 PRU Local Fault

PRU Local Fault is any error condition that is not required to be reported to the PTU (i.e., any non-system error). For system errors, see 8.3.6. PRU Local Faults then by their nature do not require the PTU to transition to the PTU Latching Fault state and therefore do not need to be specifically identified in this document. While experiencing a PRU Local Fault, the PRU shall continue communicating with the PTU, and shall not indicate a system error if there is not a system error (see 8.3.6). However, the PRU may adjust or disconnect its output.

8.3.6 PRU System Error state

8.3.6.1 General

A PRU shall be considered to be in the PRU System Error state when

a) over-voltage alert is active ($V_{RECT} > V_{RECT\_MAX}$), or
b) over-current alert is active, or
c) over-temperature alert is active.

8.3.6.2 Charge output

The PRU shall shut down output charging power in the PRU System Error state until the error condition is removed, except for PRU System Error state caused by PRU over-voltage.

8.3.6.3 PRU alert

The PRU shall send one or more alerts to the PTU when it is in the PRU System Error state within 250 ms of entering the PRU System Error state. See 9.5.8 and 9.5.7.

8.3.6.4 PRU alert messaging

The PRU shall be capable of sending notifications to the PTU as long as it is in the PRU System Error state and the PRU is receiving power from the PTU.

8.3.7 PRU state transitions

8.3.7.1 General

The PRU shall not make any state transitions unless they are defined in 8.3.7 as required or optional.

The PTU shall make all transitions designated as required.

8.3.7.2 Power applied

Power is applied. The PRU is in the charge area and $V_{\mathrm{RECT}} \geq V_{\mathrm{RECT\_BOOT}}$.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PRU Null	PRU Boot	Required	None	None

8.3.7.3 PRU on state

The PRU enters the PRU On state when the PRU Control is written during device registration by the PTU.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PRU Boot	PRU On	Required	None	None

8.3.7.4 Charge complete

The PRU is disconnected or the PRU sets its Charge Complete bit to "1".

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PRU On	PRU Boot	Required	None	None

8.3.7.5 Power removed

Power is removed from the PRU. This can be related to PTU shutdown ($V_{\mathrm{RECT}} < V_{\mathrm{RECT\_UVLO}}$) or the PRU has been removed from the charge area.

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PRU Boot	Null State	Required	None	None
PRU On				
PRU System Error				

8.3.7.6 PRU system error

The PRU shall transition to the PRU System Error state only if the PRU is unable to handle the condition locally without shutting down PTU power (i.e., moving to PTU Latching Fault). See 8.3.1.1. The PRU system errors are defined in Table 9.

Table 9 – PRU system errors

System error	System error description
1	PRU over-voltage
2	PRU over temperature
3	PRU over-current
4	A PRU determines it is receiving power from a first PTU, but is connected to the network of a second PTU.
5 to 16	Reserved

Origin state	Destination state	Required or optional	Additional required conditions	Exceptions
PRU Boot PRU On	PRU System Error	Required	None	None

9 Signaling specifications

9.1 Architecture and state diagrams

9.1.1 Architecture

The WPT network is a star topology (see Figure 13). The PTU exchanges information with the PRUs, and make operating point decisions, and resource allocations, if applicable. Each PRU transmits its information and receives network management information from the PTU operating as a network coordinator.

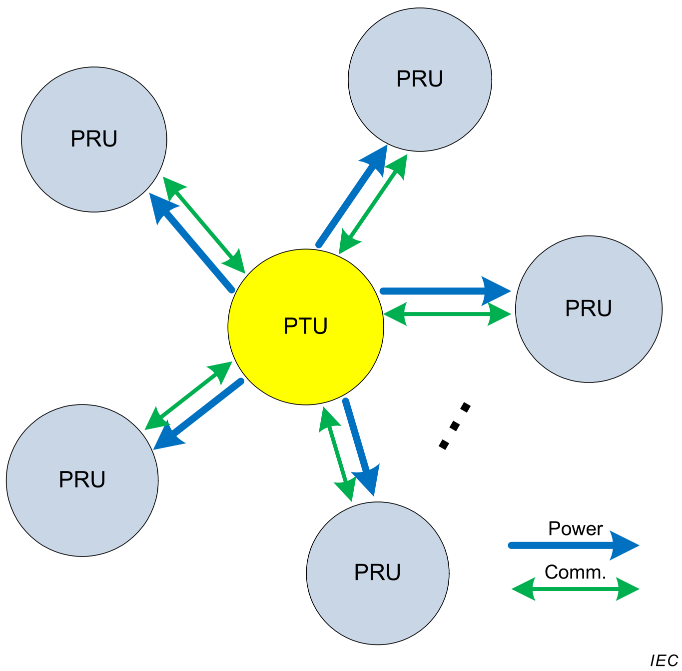


Figure 13 – Basic architecture of WPT system

The PTU shall create and maintain the WPT network.

In PTU Power Transfer state, the PTU configures timing and sequence of PRUs.

The PTU shall manage and update the device control table (which has a role of managing and checking status of PRUs in its own network) and maintain its network with its time sync clock. It manages the timing and sequence of PRU communication.

9.1.2 Overall charge process

The wireless power transfer process begins with the PTU in the PTU Power Save state applying short and long beacons to the PTU resonator as required for load variation detection and eliciting a PRU response (see 8.2). Upon device detection, the PTU transitions to PTU Low Power state, establishes a communication link with the PRU, and exchanges information necessary for wireless power transfer. See also Figure 14.

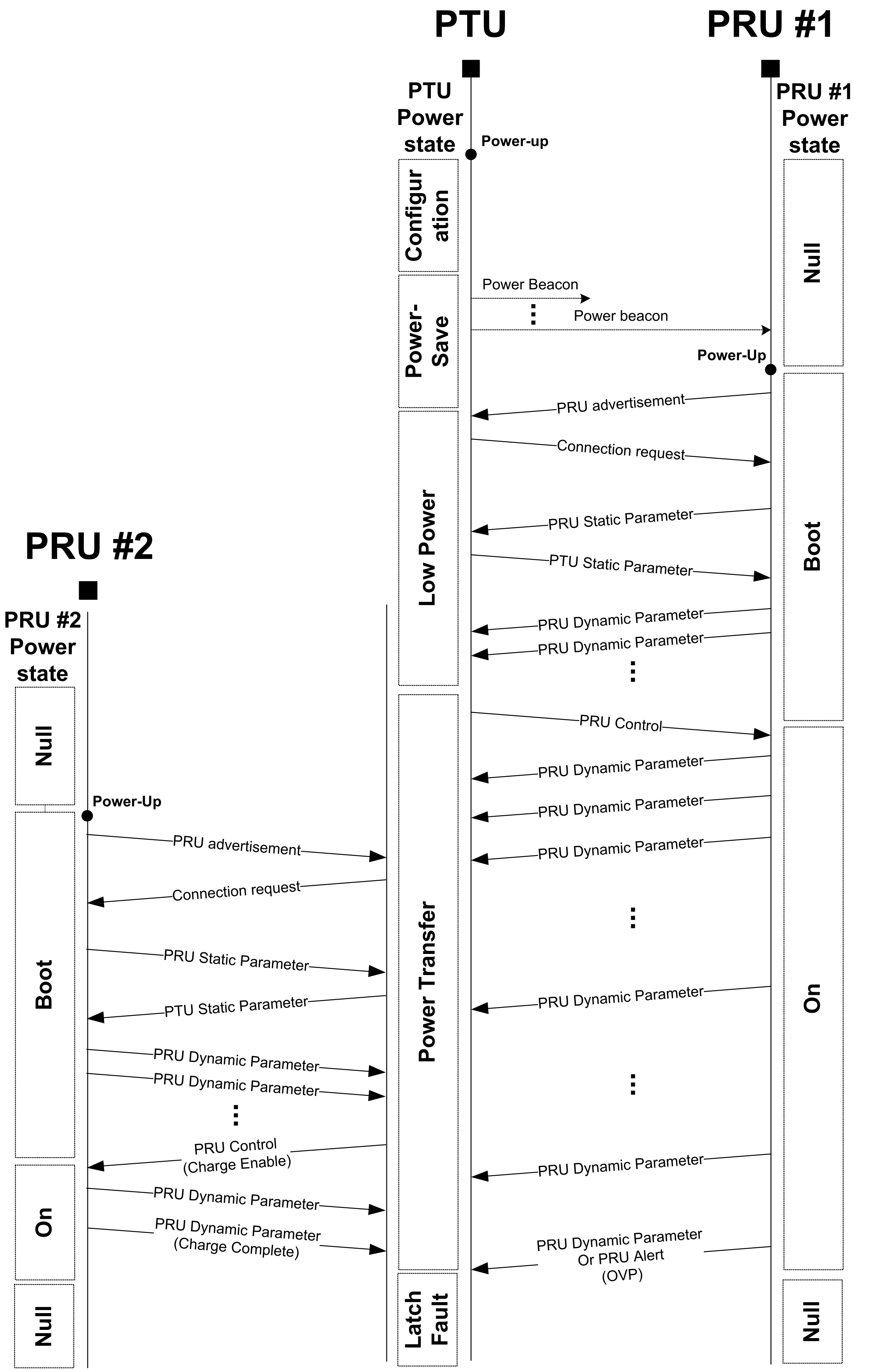


Figure 14 – Basic state procedure (informative)

No PTU power transmission except beacon power takes place until the PTU receives a PRU advertisement. The PRU repeatedly sends advertisements until it receives a PTU Connection Request (see 9.3.7).

Upon receiving the PRU advertisement, the PTU enters PTU Low Power state if it is in PTU Power Save state. The PRU stops sending advertisements after it has received a Connection Request from the PTU. The PRU and the PTU form a connection.

The PTU first reads the value of the PRU Static Parameter that describes the status of the PRU. The PTU then writes a value to the PTU Static Parameter that describes the capabilities of the PTU.

Once the devices have exchanged static information, the PTU reads the PRU Dynamic Parameter that provides measured parameters from the PRU. The PTU then writes a value to the PRU Control including the information such as enable/disable charge and permission. The PTU may write to the PRU Control as needed and the PTU periodically reads the PRU Dynamic Parameter that contains values such as voltage, current, PRU status, and/or temperature.

Charging is initiated when the PTU writes a value to the PRU Control of the PRU that enables charging and it is delivered when the PTU has enough power to charge the PRU. In this state (PRU On), the PRU Dynamic Parameter is read by the PTU at least every 250 ms.

Based on the power information in the PRU Dynamic Parameter, the PTU updates the device control table in the registry corresponding to each PRU status.

If the PRU detects a system error or completes charging, the PRU sends one or more PRU alert notifications to the PTU. The PRU Dynamic Parameter is updated to include data describing the reason for the alert before sending to the PTU (e.g., over-current, over-voltage, over-temperature and self-protection notifications).

9.2 Charge procedure and requirements

9.2.1 Removing PRU from WPT network

A PRU shall be removed from the network when the conditions described in 8.2.2.3 and 8.2.9.5 are met.

9.2.2 Power Sharing mode

Power Sharing mode allows for power allocation across multiple devices when the PTU does not have enough power to supply full $P_{\mathrm{RECT\_MAX}}$ to all devices requesting power. The PTU shall support Power Sharing mode.

See 7.3.2.2.1, 7.3.3.1.2 and 7.3.3.1.3 for the PRU V_{RECT} conditions.

When a new PRU (i.e., a PRU that makes a new connection to initiate power transfer), completes device registration, the PTU before sending a PRU Control characteristic to enable charging shall determine if the PRUs currently receiving power from the PTU need to adjust their power draw to a lower value to allow the new PRU to draw power. If power adjustments are necessary, the PTU shall first send a PRU Control Characteristic to the new PRU with Permission set to "0000 0001" (see Table 22), determine the necessary adjustment needed from all the PRUs currently receiving power and then send PRU Control characteristics with adjust power commands to the PRUs that support the command (see Table 33, bit 4 "Adjust power capability").

If the PTU determines that it needs to adjust power draw from the PRUs currently receiving power to provide power to the new PRU, the PTU shall wait for a response from all the PRUs that support the adjust power command, before:

a) deciding whether or not it can provide power to the new PRU,

b) enabling the new PRU's charge port output by writing the PRU Control Characteristic with the bit field of Permission set to "0000 0000", if the PTU decides to provide power to the new PRU.

If the PTU cannot support the new device's full $P_{\text{RECT\_MAX}}$ requirement, but the new PRU supports power adjustment, and an adjust power command would reduce P_{RECT} to a range that the PTU can support, then the PTU shall send an appropriate adjust power command. The PTU shall wait for the "Adjust power response" (see 9.5.7.13) in the PRU Dynamic Parameter from the new PRU. The new PRU shall adjust power as requested by the PTU and set the "Adjust power response" bit to "1". If the PTU reads "Adjust power response", the PTU shall write the PRU Control Characteristic with bit field of Permission set to "0000 0000", on the new PRU and initiate charge.

9.3 Bluetooth low energy requirements

9.3.1 Bluetooth low energy requirements introduction

9.3 provides baseline requirements for the Bluetooth Low Energy profile to control a WPT system which operates with resonant coupling between two or more devices.

9.3.2 Bluetooth low energy objectives

The BLE radio system is intended to provide communication between one PTU and the PRU"s being charged by that PTU.

9.3.3 PTU hardware requirement

A PTU Wireless Power Transfer service and profile shall be implemented using a Listed Bluetooth Qualified Design (QDL) with an LE Core Configuration or Basic Rate and Low Energy Combined Core Configuration as defined in the Bluetooth core specification v4.0, Volume 0, Part B, Section 3.1..

9.3.4 PRU hardware requirement

A PRU shall incorporate a compliant and qualified Bluetooth End Product with an LE Core Configuration or Basic Rate and Low Energy Combined Core Configuration as defined in the Bluetooth core specification v4.0, Volume 0, Part B, Section 3.1..

9.3.5 Basic network structure

The BLE network structure shall consist of one central device in the PTU and up to eight PRU peripherals.

9.3.6 RF requirements

9.3.6.1 PTU BLE transmit power

The PTU BLE radio shall transmit between –6 dBm and +8,5 dBm measured at the antenna connector.

9.3.6.2 PTU BLE sensitivity

The PTU BLE radio shall have sensitivity of better than –77 dBm at the antenna connector.

9.3.6.3 PTU BLE saturation

The PTU BLE radio shall support a maximum usable input level of –1 dBm at the antenna connector.

9.3.6.4 PRU BLE transmit power

The PRU BLE radio shall transmit between –6 dBm and +8,5 dBm measured at the antenna connector.

9.3.6.5 PRU BLE sensitivity

The PRU BLE radio shall have sensitivity of better than –77 dBm at the antenna connector.

9.3.6.6 PRU BLE saturation

The PRU BLE radio shall not saturate below –1 dBm at the antenna connector.

9.3.6.7 Interference (informative)

The system should accept up to 36 dB of desense from other nearby 2,4 GHz radios.

The system should accept up to 35 dB of path loss due to variable placements on the pad.

9.3.6.8 Link budget (informative)

Link budget data is provided in Table 10.

Table 10 – RF budget (informative)

Stage	Worst case loss
PTU	0 dBm
Filter	–3 dB
Antenna	–5 dB
Path loss	–35 dB
Desense	–36 dB
Antenna	–5 dB
Filter	–3 dB
Resulting signal at PRU	–87 dBm

9.3.7 Timing and sequencing requirements

If a BLE connection did not already exist, the following applies.

a) The PRU shall present an advertisement to the PTU within the time allowed by the Power Transfer and Control requirements (see 8.3.4.1). The PRU shall use an advertising interval that is no greater than 20 ms.

b) The PTU shall issue a connection request within 50 ms of the received advertisement only if the conditions in 9.6.3 are met. If the PTU does not receive response from the PRU after sending a connection request, the PTU shall restart the registration timer and retry the WPT device registration process once before declaring registration timeout.

The exact steps for the PTU's access of the PRU's WPT Service during the registration period shall be the following:

1) Read PRU Static Parameter Characteristic;
2) Write PTU Static Parameter Characteristic;
3) Read PRU Dynamic Parameter Characteristic, one or more times; and
4) Write PRU Control Characteristic (always mandatory).

Steps 1) to 3) are optional if transitioning from Charge Complete, Connected Mode and mandatory, otherwise.

During the registration period,

- the PRU shall respond, with a Read Response, to a Read Request within 50 ms, and
- the PTU shall only use the GATT Write Without Response procedure for writing characteristics on the PRU.

The BLE connection interval during the registration period ($t_{CI\_REGISTRATION}$) shall be less than or equal to 50 ms. Once the PRU Control Characteristic has been written, the BLE connection interval (t_{CI}) shall be less than or equal to 250 ms.

The PRU Dynamic Parameter Characteristic shall be read by the PTU at least every 250 ms.

The PTU shall not write a PRU Control Characteristic to a PRU, to enable charge port output, until it has read at least one PRU Dynamic Parameter Characteristic from that PRU.

If the PRU is allowed to be charged, a PRU Control characteristic containing the Enable PRU output command (see 9.5.4.3) shall be written by the PTU within 500 ms of the received advertisement.

The registration timing and sequencing described in 9.3.7 is illustrated in Figure 15 and timing constraints are identified in Table 11.

Upon completing the device registration, the PTU shall use the GATT Write Request to write the Client Configuration Characteristic Descriptor of the PRU Alert.

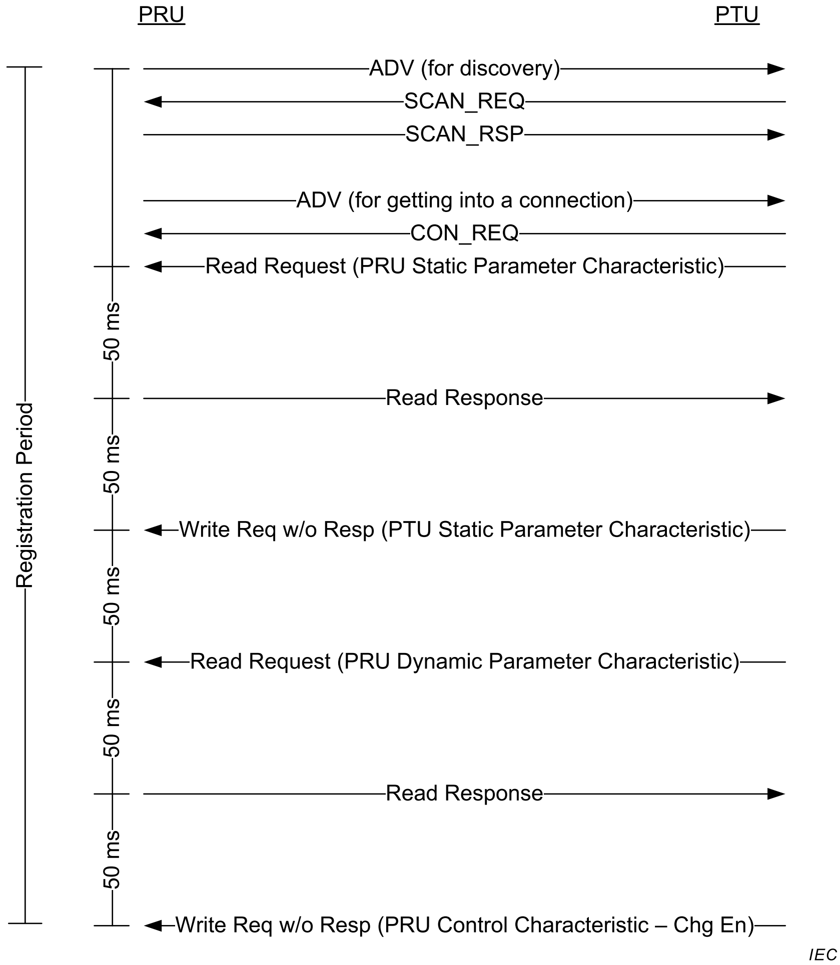


Figure 15 – Registration period timeline example (informative)

Table 11 – Timing constraints

Time constraint	Value milliseconds	Description	Reference clause
t_{SHORT_BEACON}	< 30	The short beacon-on-period	8.2.3.3.1
t_{LONG_BEACON}	105 ± 5	The long beacon-on-period	8.2.3.4.1
t_{CYCLE}	250 ± 5	The short beacon period	8.2.3.3.1
$t_{LONG\_BEACON\_PERIOD}$	> 850 ≤ 3 000	The long beacon period	8.2.3.4.1
$t_{ADVERTISEMENT}$	< 100	The PRU sends an advertisement within 100 ms of V_{RECT} exceeding V_{RECT_BOOT} on state entry	8.3.4.1
$t_{CONNECTION\_REQUEST}$	< 50	The PTU issues a connection request within 50 ms of discovery of the PRU	9.3.7
$t_{REGISTRATION}$	< 500	The PTU writes a PRU Control Characteristic containing the PRU enable command within 500 ms of the received advertisement.	9.3.7
$t_{DYNAMIC}$	≤ 250	The period in which PRU Dynamic Parameter Characteristic is read by the PTU	9.1.2 9.3.7
$t_{CI\_REGISTRATION}$	< 50	The BLE connection interval during $t_{REGISTRATION}$	9.3.7
t_{CI}	< 250	The BLE connection interval	9.3.7

9.3.8 Profile structure

The BLE client and server shall support the characteristics identified in Table 12.

Table 12 – BLE profile characteristics

Characteristic	Data direction	Properties	Description
PRU Control	PTU → PRU	Write and Read	PRU ON/OFF control. PTU initiates write when command needs to be sent
PTU Static Parameter	PTU → PRU	Write and Read	Contains static characteristics of the PTU. PTU initiates write when new device connects.
PRU Alert	PTU ← PRU	Notifications (Indications conditional upon support for the Mode Transition Procedure in 9.7)	Notifies the PTU of overvoltage, over-current, over-temperature and self-protection conditions of the PRU.
PRU Static Parameter	PTU ← PRU	Read	Contains static characteristics of the PRU. PTU initiates read when device connects (can be more)
PRU Dynamic Parameter	PTU ← PRU	Read	Contains dynamic characteristics of the PRU. PTU initiates read from each device.

9.4 BLE profile definition

9.4.1 GATT sub-procedure

9.4.1.1 GATT sub-procedure introduction

9.4 contains specific information needed to implement the BLE profile. It is intended to allow programmers to implement the BLE profile within the GATT framework.

9.4.1.2 GATT sub-procedure requirements

Additional GATT sub-procedures requirements beyond those required by all GATT clients are indicated in Table 13.

Table 13 – GATT sub-procedure

GATT sub-procedure	Requirement
Discover All Characteristic Descriptors	M
Read Characteristics Value	M
Write With Response	M
Write Without Response	M
Notifications	M

9.4.2 Configuration

9.4.2.1 Roles

The PRU shall be a GATT Server for the Wireless Power Transfer (WPT) Service.

The PTU shall be a GATT Client for the WPT Service. See Figure 16.

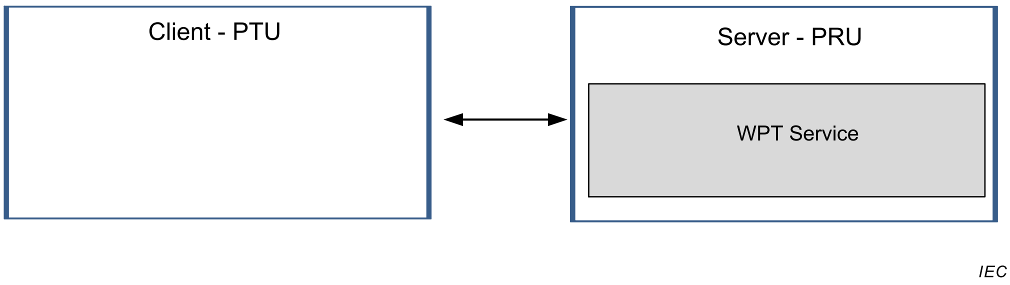


Figure 16 – PTU/PRU services/characteristics communication

NOTE Standard and WPT services and associated characteristics are defined in Table 17.

9.4.2.2 Concurrency limitations and restrictions

There are no concurrency limitations or restrictions for the PRU and the PTU roles imposed by this profile.

9.4.2.3 Topology limitations and restrictions

The PRU shall implement the GAP Peripheral role.

The PTU shall implement the GAP Central.

9.4.2.4 Transport dependencies

This profile shall operate over a Bluetooth Low Energy transport only.

9.4.2.5 Error codes

This service does not define any Attribute Protocol Application Error Codes.

9.4.2.6 Byte transmission order

All multi-byte data fields used with this service shall be sent with the least significant octet first (i.e., Little Endian). Multi-character string values shall be sent as individual byte fields. Structures such as GATT Characteristics included in this document are transmitted in the order shown where they occur from top to bottom and left to right.

9.4.3 PRU requirements

9.4.3.1 PRU requirements introduction

The PRU shall instantiate one and only one WPT Service.

The WPT Service shall be instantiated as a Primary Service.

The Bluetooth Device Information Service does not pertain to this profile. Information that is specific to the WPT capability of the PRU device, including the PRU Static Parameter Characteristic defined in 9.5.6.3, is independent of any implementation of the Bluetooth Device Information Service.

9.4.3.2 Writeable GAP device name characteristic

The PRU may support the write property for the Device Name characteristic to allow the PTU to write a Device Name to the PRU.

9.4.4 PTU requirements

9.4.4.1 PTU requirements introduction

The PTU shall discover and use the PRU's WPT Service. The Bluetooth Device Information Service does not pertain to this profile. Information that is specific to the WPT capability of the PTU device, including hardware and firmware versions, are contained in the PTU Static Parameter Characteristic defined in 9.5.5.3 and are independent of any implementation of the Bluetooth Device Information Service.

9.4.4.2 Discovery of services and characteristics

The PTU discovers the PRU's WPT service and characteristics using the WPT Service Data within the PRU advertisement payload which contains the GATT Primary Service Handle. The advertisement payload is defined in 9.5.2. The GATT Primary Service Handle, together with the handle offsets defined in 9.5.3.3 is used to discover all characteristics and descriptors in the service.

The PTU may perform service discovery using the GATT *Discover All Primary Services* sub-procedure or the GATT *Discover Primary Services by Service UUID* sub-procedure and characteristic discovery using the GATT *Discover Characteristics by UUID* sub-procedure or the *Discover All Characteristics of a Service* sub-procedure. These procedures may be used at any time except during registration. The procedures may be used in response to Service Changed indication or to discover services other than the WPT service supported by the PRU.

9.4.5 Connection establishment

9.4.5.1 Connection establishment introduction

9.4.5 describes the PRU discovery, connection establishment and connection termination procedures used by a PRU and PTU.

9.4.5.2 PRU connection establishment

9.4.5.2.1 Connection procedure for unbonded devices

This procedure is used for connection establishment when the PTU connects to a PRU which it is not bonded. This procedure is automatic and not initiated by user interaction.

The PRU shall enter the *GAP Limited Discoverable Mode* using Undirected Advertising (ADV_IND) packets for discovery and connection. PRU Discovery is used to identify a PRU device to the PTU and for receiving WPT Service specific Advertising data.

PRU Advertising Data shall contain an advertising payload as defined in 9.5.2.

The PRU shall use Security Mode 1 level 1 when connecting to an unbonded device. If a connection is not established within a time limit defined by the PRU, the PRU may exit the GAP connectable mode and wait for the next beacon signal.

9.4.5.2.2 PRU connection procedure for bonded devices

This procedure is applicable after the PRU has bonded with the PTU using the connection procedure defined in 9.3.7.

The PRU should use the recommended advertising interval value shown in 9.3.7.

Once connected, the PRU may request to change to the preferred connection parameters that best suits its use case.

If the PTU indicates during pairing that only security level 2 can be achieved, the PRU shall not request any security level higher than level 2 in responding to PTU's service request.

If a connection is not established within a time limit defined by the PRU, the PRU may exit the GAP connectable mode and wait for the next beacon signal.

9.4.5.2.3 Link loss reconnection procedure

When a connection is terminated, a PRU, if powered by the PTU, shall attempt to reconnect to the PTU by entering a GAP connectable mode using the recommended advertising interval value shown in 9.3.7. Note that if the PRU does not reconnect, it can appear to the PTU as a rogue object.

9.4.5.2.4 Idle connection

The PRU shall perform the *GAP Terminate Connection* procedure if power is removed from the PRU. The PRU shall not initiate a terminate connection to a BLE host at any time if the PRU is powered from a PTU.

9.4.5.3 PTU connection establishment

9.4.5.3.1 Connection procedure for unbonded devices

This procedure is used for connection establishment when the PTU connects to a PRU to which it is not bonded. This procedure may be initiated either through user interaction or autonomously when a PTU requires data from a PRU.

The PTU shall scan using the *GAP Limited Discovery* procedure and perform active scanning.

A PTU shall use the *GAP General Connection Establishment* procedure. The PTU may use this procedure when it requires data from one or more PRU(s). This procedure allows a PTU to connect to a PRU discovered during a scan without using the White List.

If a connection is not established within a time limit defined by the Power Control requirements (see Clause 8), the PTU may transition state and cease scanning for new devices.

9.4.5.3.2 PTU connection procedure for bonded devices

This procedure is applicable after the PTU has bonded with the PRU using the autonomous connection procedure in 9.4.5.3.1.

A PTU may use one of the following GAP connection procedures based on its connectivity requirements.

a) General Connection Establishment Procedure. The PTU may use this procedure when it requires dynamic parameters or notifications from one or more PRUs. This procedure allows a PTU to connect to a PRU discovered during a scan without using the White List.
b) Selective Connection Establishment Procedure. The PTU may use this procedure when it requires dynamic parameters or notifications from one or more PRUs. This procedure allows a PTU to connect to a PRU discovered during a scan while using the White List.
c) Direct Connection Establishment Procedure. The PTU may use this procedure when it requires data from a single (or specific) PRU. The PTU may also use this procedure for link loss reconnection described in 9.4.5.3.3.
d) Auto Connection Establishment Procedure. The PTU may use this procedure when it requires dynamic parameters or notifications from one or more PRUs. This procedure will automatically initiate connection to a PRU in the White List.

When initiating a connection while in PTU Low Power state, the PTU should use the continuous scan window/scan interval pair to attempt fast connection. When initiating a connection while in PTU Power Transfer state, the PTU should use an implementation specific scan window/scan interval to attempt a fast connection.

Notwithstanding the above, the PTU should use a scan window and scan interval suitable to its power and connection time requirements. Increasing the scan window increases the power consumption, but decreases the connection time.

The PTU should write the address of the target PRU in its White List and set its controller advertising filter policy to "process scan and connection requests only from devices in the White List".

The PTU shall support LE security mode 1, level 1 and level 2 as specified in the Bluetooth core specification v4.0.

9.4.5.3.3 Link loss reconnection procedure

When a connection is terminated due to link loss, a PTU shall attempt to reconnect to the PRU by making a connection request after detecting a PRU advertisement shown in 9.4.5.2.1.

9.4.5.3.4 Idle connection

If a connection is idle, the PTU may perform the *GAP Terminate Connection* procedure. An Idle Connection shall be determined if the PRU does not respond to Read Requests from the PTU and the PRU does not send alerts for greater than one second.

9.4.5.3.5 Fast connection interval

The PTU shall implement a connection interval that supports rapid service discovery, rapid encryption setup and the ability to receive a PRU Dynamic Parameter Characteristic from all PRUs within 250 ms.

9.4.6 Security considerations

9.4.6.1 Security considerations introduction

9.4.6 describes the security procedures used by a PRU and PTU.

9.4.6.2 PRU security considerations

All supported characteristics specified by the WPT Service shall be set to Security Mode 1 and should be set to Security Level 1 (No Security) or 2 (Unauthenticated pairing with encryption).

The PRU shall use the *SM Slave Security Request* procedure to inform the PTU of its security requirements.

9.4.6.3 PTU security considerations

The PTU may bond with the PRU.

The PTU shall accept any request by the PRU for LE Security Mode 1 and Security Level 1 or 2.

9.4.7 Charge completion

PTU support of the Charge Complete, Disconnected Mode is mandatory. Likewise, PRU support of the Charge Complete, Disconnected Mode is mandatory. A PTU may support

Charge Complete, Connected Mode. A PRU may also indicate support for the Charge Complete, Connected Mode in the PRU Static Parameter Characteristic.

PRUs shall indicate Charge Complete = 1 if they do not require charging from the PTU. When all PRUs on a PTU indicate Charge Complete = 1, the PTU shall transition to the PTU Power Save state according to 8.2.9.7.

Prior to transitioning to PTU Power Save state,

- the PTU shall instruct the PRU to disable its charge output by setting the Enable PRU output bit in the Enables field to 0 in the PRU Control,
- the PTU shall perform the GAP Terminate Connection procedure with all PRUs that do not support Charge Complete, Connected Mode, and
- the PTU may maintain a BLE connection with PRUs supporting Charge Complete, Connected Mode. Once in the PTU Power Save state, the PTU may increase the connection interval to further conserve power.

After indicating Charge Complete = 1, the PRU shall transition to PRU Boot state as described in 8.3.7.4.

9.5 WPT service characteristics

9.5.1 WPT service characteristics introduction

The PRU shall support the writing of the PRU Control and PTU Static Parameter characteristics by the PTU and the configuration of the PTU Alert characteristic by the PTU for notifications and optionally indications (conditional upon support for Mode Transition).

The PTU shall support reading the PRU Static Parameter and PRU Dynamic Parameter characteristics and shall also support the configuration of the PRU Alert characteristic for notifications and optionally indications (conditional upon support for Mode Transition).

As described elsewhere in this document, the PRU and PTU are required to determine the contents of the characteristics based on the contents of the Optional Fields Validity fields in most characteristics.

All characteristic Reserved for Further Use (RFU) bits and fields shall be set to zero by the sending entity and ignored by the receiving entity. If the PTU or PRU receives a characteristic that includes additional octets that are not recognized by the implementation, the receiving entity shall ignore those bits and continue to process the characteristic normally.

9.5.2 PRU advertising payload

9.5.2.1 PRU advertising payload introduction

For the purpose of communicating with a PTU, the PRU shall use the advertising packet payload format defined in Table 14.

Table 14 – PRU advertising payload

Flags AD Type	Service Data AD Type			
Flags	WPT Service 16-bit UUID	GATT Primary Service Handle	PRU RSSI Parameters	ADV Flags

The Flags field shall use the Bluetooth Generic Access Profile, Flags Advertising Data type format and indicate:

- LE Limited Discoverable Mode

The Service Data AD Type is used to indicate specific WPT Service information and shall use the Bluetooth Generic Access Profile, Service Data AD type format. The first 16-bits (after the AD type length field) shall hold the 16-bit Bluetooth SIG assigned Service UUID value as shown in Table 16.

The GATT Primary Service Handle field is included in the Bluetooth Generic Access Profile, Service Data Advertising Data type after the 16-bit Service UUID field and shall contain the PRU's attribute handle for the WPT Primary Service as defined in Table 17. All local characteristic handle values for this service shall be ordered sequentially starting from the (GATT Primary Service Handle + 1) in the order of the listed characteristics as represented in Table 17.

The PRU RSSI Parameters field is included in the Bluetooth Generic Access Profile, Service Data Advertising Data type after the GATT Primary Service Handle field and shall contain a PRU output power (PRU_Pwr) in bits 7 to 3 and PRU antenna gain (PRU_Gain) in bits 2 to 0, if known by the PRU application. If unknown by the PRU, the PRU application shall ensure that all bits in the unknown value fields are set to "1".

7:3	2:0
PRU_Pwr	PRU_Gain

PRU output power shall be encoded as follows:

- PRU_Pwr – 20 dBm = PRU output power in dBm, or
- PRU_Pwr = 11111b if output power unknown by PRU

3 bit PRU antenna gain shall be encoded as follows:

- PRU_Gain – 5 dB = PRU antenna gain in dBi, or
- PRU_Gain = 111b if antenna gain unknown by PRU

The ADV Flags field is included in the Bluetooth Generic Access Profile, Service Data Advertising Data type after the PRU RSSI Parameters field and shall contain AirFuel Resonant specific information and shall use the following bit format:

7	**6**	**5**	**4**	**3**	**2**	**1**	**0**
Impedance Shift Bit 2	Impedance Shift Bit 1	Impedance Shift Bit 0	Reboot Bit	OVP Status (optional)	Time Set Support	RFU	RFU

- Bits 5 to 7 – Impedance Shift Bits
- Bit 4 – Reboot Bit ("0" = recent reset, "1" = connection drop with no reset)
- Bit 3 – OVP Status (optional) – set to "0" if not used ("0" = no OVP, "1" = OVP)
- Bit 2 – Time Set Support ("0" = no support, "1" = support)

The Impedance Shift bit field shall be as defined in Table 15 (see 7.3.3.4 for Short Beacon PRU-induced Impedance).

Table 15 – Impedance shift bit

Impedance shift bits	Definition
000	Can never create an impedance shift
001	Cat 1 PRU
010	Cat 2 PRU
011	Cat 3 PRU
100	Cat 4 PRU
101	Cat 5 PRU
110	Reserved
111	Reserved

9.5.2.2 Sample data

The following shows sample data for PRU Advertising payload contents reflecting the following settings.

Flags AD Type:

- Limited Discoverable Mode is set;
- all other bits set to zero.

Service Data AD Type:

- 16-bit UUID is set to 0xFFFE;
- GATT Primary Service Handle is set to 0x0101;
- PRU RSSI Parameters is set to 0xFF;
- ADV Flags are set to:
  - CAT3 PRU;
  - Reboot bit is set to zero;
  - OVP indicator is set to zero.

Sample Data: 0000: 0201010716FEFF0101FF60

9.5.3 WPT service

9.5.3.1 WPT service introduction

The WPT Service exposes related control and status data for proper coordination between a PRU and a PTU.

9.5.3.2 WPT service UUID

Table 16 shows the mandatory UUID definitions for the WPT Service.

Table 16 – WPT service UUID

UUID	Value	Definition
WPT_CHARACTERISTIC_ BASE_UUID	0x6455e670-a146-11e2-9e96-0800200c9a67	128-bit AirFuel Resonant WPT Characteristic Base UUID.
WPT_SERVICE_UUID	0xFFFE	16-bit Bluetooth SIG assigned WPT Service UUID.

9.5.3.3 WPT service definition

The mandatory service definition for the WPT Service is shown in Table 17.

Table 17 – WPT service

Type (16 bit)	Default value	Attribute permissions	Notes	Mandatory handle value
0x2800 GATT_PRIMARY_SERVICE_UUID	WPT_SERVICE_UUID (16-bit)	GATT_PERMIT_READ	Start of WPT Service	(GATT Primary Service Handle)
0x2803 GATT_CHARACTERISTIC_UUID	Properties = read/write UUID = WPT_CHARACTERISTIC_BASE_UUID	GATT_PERMIT_READ	PRU Control Characteristic declaration	GATT Primary Service Handle) + 1
WPT_CHARGING_PRU_CONTROL_UUID	00000 (5 Octets)	GATT_PERMIT_READ | GATT_PERMIT_WRITE	PRU Control Characteristic value	GATT Primary Service Handle) + 2
0x2803 GATT_CHARACTERISTIC_UUID	Properties = read/write UUID = WPT_ CHARACTERISTIC_BASE _UUID+1	GATT_PERMIT_READ	PTU Static Parameter Characteristic declaration	GATT Primary Service Handle) + 3
WPT_CHARGING_PTU_STATIC_UUID	00000000000000000 (17 Octets)	GATT_PERMIT_READ | GATT_PERMIT_WRITE	PTU Static Parameter Characteristic value	GATT Primary Service Handle) + 4
0x2803 GATT_CHARACTERISTIC_UUID	Properties = read/notify UUID = WPT_ CHARACTERISTIC_BASE _UUID+2	GATT_PERMIT_READ	PRU Alert Parameter Characteristic declaration	GATT Primary Service Handle) + 5
WPT_CHARGING_PRU_ALERT_UUID	0 (1 Octet)	GATT_PERMIT_READ | GATT PERMIT_NOTIFY	PRU Alert Parameter Characteristic value	GATT Primary Service Handle) + 6
0x2902 CLIENT_CHARACTERISTIC_CONFIGUARATION_UUID	0 (1 Octet)	GATT_PERMIT_READ | GATT_PERMIT_WRITE	Client Characteristic Configuration UUID for PRU Alert	GATT Primary Service Handle) + 7
0x2803 GATT_CHARACTERISTIC_UUID	Properties = read UUID = WPT_ CHARACTERISTIC_BASE _UUID+3	GATT_PERMIT_READ	PRU Static Parameter Characteristic declaration	GATT Primary Service Handle) + 8
WPT_CHARGING_PRU_STATIC_UUID	0000000000000000000 (20 Octets)	GATT_PERMIT_READ	PRU Static Parameter Characteristic value	GATT Primary Service Handle) + 9
0x2803 GATT_CHARACTERISTIC_UUID	Properties = read UUID = WPT_ CHARACTERISTIC_BASE _UUID+4	GATT_PERMIT_READ	PRU Dynamic Parameter Characteristic declaration	GATT Primary Service Handle) + 10
WPT_CHARGING_PRU_DYNAMIC_UUID	00000000000000000000 (20 Octets)	GATT_PERMIT_READ	PRU Dynamic Parameter Characteristic value	GATT Primary Service Handle) + 11

The definition for the mandatory GAP Service is shown in Table 18.

Table 18 – GAP service

Type (16 bit)	Default value	Attribute permissions	Notes
0x2800 GATT_PRIMARY_SERVICE_UUID	0x1800 (GAP_SERVICE_UUID)	GATT_PERMIT_READ	Start of GAP Service
0x2803 GATT_CHARACTERISTIC_UUID	02 (properties: read only) 00 2A (UUID: 0x2A00)	GATT_PERMIT_READ	Device Name characteristic declaration
0x2A00 GAP_DEVICE_NAME_UUID	"WPT PRU"	GATT_PERMIT_READ	Device Name characteristic value
0x2803 GATT_CHARACTERISTIC_UUID	02 (properties: read only) 01 2A (UUID: 0x2A01)	GATT_PERMIT_READ	Appearance characteristic declaration
0x2A01 GAP_APPEARANCE_UUID	0x0000 (unknown)	GATT_PERMIT_READ	Appearance characteristic value
0x2803 GATT_CHARACTERISTIC_UUID	02 (properties: read only) 04 2A (UUID: 0x2A04)	GATT_PERMIT_READ	Peripheral Preferred Connection Parameters characteristic declaration
0x2A04 GAP_PERI_CONN_PARAM_UUID	50 00 (50 ms preferred min connection interval) A0 00 (250 ms preferred max connection interval) 00 00 (0 preferred slave latency) E8 03 (1 000 ms preferred supervision timeout)	GATT_PERMIT_READ	Peripheral Preferred Connection Parameters characteristic value

The definition for the GATT Service, shown in Table 19, is mandatory if service definitions on the PRU can be added, changed, or removed, optional otherwise.

Table 19 – GATT service

Type (16 bit)	Default value	Attribute permissions	Notes
0x2800 GATT_PRIMARY_SERVICE_UUID	0x1801 (GATT_SERVICE_UUID)	GATT_PERMIT_READ	Start of GATT Service
0x2803 GATT_CHARACTERISTIC_UUID	20 (properties: indicate only) 05 2A (UUID: 0x2A05)	GATT_PERMIT_READ	Service Changed characteristic declaration
0x2A05 GATT_SERVICE_CHANGED_UUID	(null value)	(none)	Service Changed characteristic value

9.5.4 PRU control

9.5.4.1 PRU control introduction

When written, this characteristic initiates PTU commands (e.g., start charge) at the PRU. The PTU shall write a PRU Control Characteristic whenever it requires a status change in the PRU. The designated PRU shall change configuration according to the PRU Control Characteristic.

9.5.4.2 PRU Control Characteristic behavior

The PRU Control Characteristic is written using the GATT Write procedure. The PTU writes this characteristic to send commands to the PRU.

9.5.4.3 PRU Control Characteristic value

The PRU Control Characteristic value fields are described in Table 20. The length of the characteristic value is 5 octets.

Table 20 – PRU Control Characteristic

Field	Octet	Description	Use	Units
Enables	1	PTU turn on, PTU on indication etc.	Mandatory	N/A
Permission	1	PRU is permitted in PTU.	Mandatory	N/A
Time Set	1	PTU sets up time.	Mandatory	ms
RFU	2	Undefined	N/A	N/A

9.5.4.4 Enables

The Enables field provides PTU instruction for power control.

Table 21 – Detail: bit field for enables

7	6	5	4	3	2	1	0
Enable PRU output	Enable PRU charge indicator	Adjust power command		RFU	RFU	RFU	RFU
1 = Enable 0 = Disable	1 = Enable 0 = Disable	00 = Maximum power 01 = 66 % x P_{RECT_MAX} 10 = 33 % x P_{RECT_MAX} 11 = 2,5 W		RFU	RFU	RFU	RFU

Enable PRU output allows the PRU to provide power to the load. See 8.3.5.1.1 for PRU power draw (PRECT) requirements in the PRU On state based on the Enable PRU output bit.

Enable PRU charge indicator, when set to "1" allows the PRU to indicate that charging may occur. Otherwise this bit is set to "0".

If the adjust power command is supported by the PRU, the PRU shall either adjust its power draw to less than or equal to the percent of P_{RECT_MAX}, specified in the bits 4 and 5, in Table 21, or not change its power draw from the current limits, due to the inability of the PRU to adjust power to a lower value, at the time of receiving the adjust power command.

If the PRU adjusts its power draw, it shall provide a response to the PTU via the Adjust Power Response PRU alert bit field specified in Table 36. PTUs shall not send this command to PRUs that do not support the adjust power command. A PTU shall not send more than one adjust power command to a PRU in a two second period.

9.5.4.5 Permission

The Permission field provides power availability (permitted/denied) reason codes.

Table 22 – Detail: bit field for permission

Value (Bit)	Description
0000 0000	Permitted without reason
0000 0001	Permitted with waiting time due to limited available power
1000 0000	Denied due to cross connection.
1000 0001	Denied due to limited available power
1000 0010	Denied due to limited PTU Number of Devices
1000 0011	Denied due to limited PTU Class support
1000 0100	Denied due to high temperature at PTU
All other values	RFU

If a PTU writes "Permitted with waiting time due to limited available power", once the PTU has power available, it shall update the value of the Permission field to "Permitted without reason" to allow the PRU to begin charging.

9.5.4.6 Time set

The Time Set field provides the time in which the PRU is to create a valid load variation.

Table 23 – Detail: bit field for time set

Value (Bit)	PTU setting time milliseconds
0000 0000	Do not perform Time Set (see 9.6.6)
0000 0001	10
0000 0010	20
0000 0011	30
0000 0100	40
0000 0101	50
0000 0110	60
0000 0111	70
0000 1000	80
All other values	RFU

NOTE This field is used for cross connection check (see 9.6.6).

9.5.5 PTU static parameter

9.5.5.1 PTU static parameter introduction

The PTU Static Parameter characteristic contains data with constant values on the PTU.

9.5.5.2 PTU static parameter characteristic behavior

The PTU Static Parameter characteristic is written using the GATT Write procedure.

This Characteristic is intended to provide static PTU parameters to a PRU.

9.5.5.3 PTU static parameter characteristic value

The PTU Static Parameter characteristic value fields are described in Table 24. The length of the characteristic value is 17 octets.

PTU static parameter characteristic shall have the following fields.

Table 24 – PTU reporting static values to PRU

Field	Octets	Description	Use	Units
Optional fields validity	1	Defines which fields are valid	Mandatory	
PTU Power	1	Power of PTU	Mandatory	
PTU Max Source Impedance	1	Maximum source impedance of the PTU	Optional	
PTU Max Load Resistance	1	Maximum load resistance of the PTU	Optional	
RFU	2	Undefined	N/A	
PTU class	1	PTU class	Mandatory	Class 1 – 5
Hardware rev	1	Revision of the PTU HW	Mandatory	
Firmware rev	1	Revision of the PTU SW	Mandatory	
Protocol Revision	1	AirFuel Resonant Supported Revision	Mandatory	
PTU Number of Devices Supported	1	Max Number of Devices	Mandatory	
RFU	6	Undefined	N/A	

9.5.5.4 Optional fields validity

The Optional Fields Validity field (see Table 25) shall identify which optional fields have valid values. All optional fields not identified as valid shall be set to zero.

Table 25 – Detail: bit field for optional fields validity

7	6	5	4	3	2	1	0
Max Impedance	Max Resistance	RFU	RFU	RFU	RFU	RFU	RFU

9.5.5.5 PTU power

The PTU Power field shall be set equal to the value shown in Table 1 according to the PTU class. The eight bits of the PTU Power field are populated per the State Definition Bit field (shown in decimal). Power values called out in Table 26 are in watts.

Table 26 – PTU power

7	6	5	4	3	2	1	0
PTU Power							

State definition									
Value decimal	**Pwr** watt	**Value** decimal	**Pwr** watt	**Value** decimal	**Pwr** watt	**Value** decimal	**Pwr** watt	**Value** decimal	**Pwr** watt
0	0	32	4,4	64	13,6	96	28	128	50
1	0,1	33	4,6	65	14	97	28,5	129	51
2	0,2	34	4,8	66	14,4	98	29	130	52
3	0,3	35	5	67	14,8	99	29,5	131	53
4	0,4	36	5,2	68	15,2	100	30	132	54
5	0,5	37	5,4	69	15,6	101	30,6	133	55
6	0,6	38	5,6	70	16	102	31,2	134	56
7	0,7	39	5,8	71	16,4	103	31,8	135	57
8	0,8	40	6	72	16,8	104	32,4	136	58
9	0,9	41	6,3	73	17,2	105	33	137	59
10	1	42	6,6	74	17,6	106	33,6	138	60
11	1,1	43	6,9	75	18	107	34,2	139	61
12	1,2	44	7,2	76	18,4	108	34,8	140 to 255	RFU
13	1,3	45	7,5	77	18,8	109	35,4		
14	1,4	46	7,8	78	19,2	110	36		
15	1,5	47	8,1	79	19,6	111	36,6		
16	1,6	48	8,4	80	20	112	37,2		
17	1,7	49	8,7	81	20,5	113	37,8		
18	1,8	50	9	82	21	114	38,4		
19	1,9	51	9,3	83	21,5	115	39		
20	2	52	9,6	84	22	116	39,6		
21	2,2	53	9,9	85	22,5	117	40,2		
22	2,4	54	10,2	86	23	118	40,8		
23	2,6	55	10,5	87	23,5	119	41,4		
24	2,8	56	10,8	88	24	120	42		
25	3	57	11,1	89	24,5	121	43		
26	3,2	58	11,4	90	25	122	44		
27	3,4	59	11,7	91	25,5	123	45		
28	3,6	60	12	92	26	124	46		
29	3,8	61	12,4	93	26,5	125	47		
30	4	62	12,8	94	27	126	48		
31	4,2	63	13,2	95	27,5	127	49		

9.5.5.6 PTU max source impedance

The PTU Max Source Impedance (see Table 27), if included, shall designate the maximum output impedance of the PA / filter in the PTU.

Table 27 – Max source impedance

7	6	5	4	3	2	1	0
PTU Max Source Impedance					RFU	RFU	RFU

State definition	
Value Decimal	**PTU maximum source impedance** ohms
0	50
1	60
2	70
3	80
4	90
5	100
6	110
7	120
8	130
9	140
10	150
11	175
12	200
13	225
14	250
15	275
16	300
17	350
18	375
19 to 31	RFU

9.5.5.7 PTU max load resistance

This field, if included, defines the maximum PTU load resistance (see Table 28) as seen at the input to the PTU resonator.

Table 28 – Max load resistance

7	6	5	4	3	2	1	0
PTU Max Load Resistance					RFU	RFU	RFU

State definition	
Value Decimal	**PTU max load resistance** ohms
0	5
1	10
2	15
3	20
4	25
5	30
6	35
7	40
8	45
9	50
10	55
11 to 31	RFU

9.5.5.8 PTU class

The PTU class field shall identify the class to which the PTU is assigned (see also 6.1).

State definition
00000000 = Class 1
00000001 = Class 2
00000010 = Class 3
00000011 = Class 4
00000100 = Class 5
00000101 to 11111111 = reserved

9.5.5.9 Hardware revision

The PTU Hardware Revision is vendor proprietary.

9.5.5.10 Firmware revision

The PTU Firmware revision is vendor proprietary.

9.5.5.11 Protocol revision

The PTU Protocol Revision field shall be assigned a number that maps to the highest AirFuel Resonant specification revision to which the PTU complies, per Table 29.

Table 29 – AirFuel protocol revision field

Protocol revision	AirFuel Resonant revision description
0	BSS v1.2.1
1	BSS v1.3
2 to 255	Reserved

9.5.5.12 PTU number of devices

This field defines the number of devices that the PTU can support. See Table 30.

Table 30 – PTU number of devices

7	6	5	4	3	2	1	0
RFU	RFU	RFU	RFU	PTU Number of Devices			

State definition	
Value Decimal	**Number of devices**
0	1
1	2
2	3
3	4
4	5
5	6
6	7
7	8
8 to 255	RFU

9.5.6 PRU static parameter characteristic

9.5.6.1 PRU static parameter characteristic introduction

The PRU Static Parameter Characteristic contains data with constant values from a PRU.

9.5.6.2 PRU static parameter characteristic behavior

This characteristic is intended to enable a PTU to read the static information from the PRU.

9.5.6.3 PRU static parameter characteristic value

The Charging Parameters characteristic value fields are described in Table 31. The length of the characteristic value is 20 octets.

Table 31 – PRU reporting static values to the PTU

Field	Octets	Description	Use	Units
Optional fields validity	1	Defines which optional fields are populated	Mandatory	
Protocol Revision	1	AirFuel Resonant Supported Revision	Mandatory	
RFU	1	Undefined	N/A	
PRU Category	1	Category of PRU	Mandatory	
PRU Information	1	Capabilities of PRU (bit field)	Mandatory	
Hardware rev	1	Revision of the PRU HW	Mandatory	
Firmware rev	1	Revision of the PRU SW	Mandatory	
$P_{\mathrm{RECT\_MAX}}$	1	$P_{\mathrm{RECT\_MAX}}$ of the PRU	Mandatory	mW x 100
$V_{\mathrm{RECT\_MIN\_STATIC}}$	2	$V_{\mathrm{RECT\_MIN}}$ (static, first estimate)	Mandatory	mV
$V_{\mathrm{RECT\_HIGH\_STATIC}}$	2	$V_{\mathrm{RECT\_HIGH}}$ (static, first estimate)	Mandatory	mV
$V_{\mathrm{RECT\_SET}}$	2	$V_{\mathrm{RECT\_SET}}$	Mandatory	mV
Delta R1 value	2	Delta R1 caused by PRU	Optional	0,01 ohms
RFU	4	Undefined	N/A	

9.5.6.4 Optional fields validity

The Optional Fields Validity field (see Table 32) shall identify which optional fields have valid values. All optional fields not identified as valid shall be set to zero.

Table 32 – Detail: bit field for optional fields validity

7	6	5	4	3	2	1	0
Delta R1	RFU	RFU	RFU	RFU	RFU	RFU	RFU

9.5.6.5 Protocol revision

The PRU Protocol Revision field shall be assigned a number that maps to the highest AirFuel Resonant specification revision to which the PRU complies, per Table 29.

9.5.6.6 PRU category

The PRU Category shall be assigned a Category number.

Bit field	Version description
0	Undefined
1	Category 1
2	Category 2
3	Category 3
4	Category 4
5	Category 5
6 to 255	Undefined

9.5.6.7 PRU information

The PRU Information shall be defined by this field. This field is used to identify PRU optional operation modes or features for future expansion.

Table 33 – Detail: bit field for PRU information

7	6	5	4	3	2	1	0
NFC receiver	Separate BTLE radio in PRU	Power Control Algorithm Preference	Adjust power capability	Charge Complete Connected Mode	PTU Test Mode	RFU	RFU
0 = Not supported 1 = Supported	0 = Not supported 1 = Supported	0 = $V_{\text{RECT\_MIN\_ERROR}}$ 1 = Max System Efficiency	0 = Not supported 1 = Supported	0 = Not supported 1 = Supported	1 = Yes 0 = No		

- NFC receiver

  This bit is set to "1" if an NFC receiver is supported. Otherwise, this bit is set to "0".
- Separate BTLE radio

  This bit is set to "1" the BTLE radio is a separate entity in the PRU. Otherwise, this bit is set to "0".
- Power Control Algorithm

  This bit is set to "1" if the preference is for Max System. Otherwise, this bit is set to "0" for $V_{\text{RECT\_MIN\_ERROR}}$
- Adjust power capability

  This bit is set to "1" if the PRU supports the Adjust power capability. Otherwise, this bit is set to "0".
- Charge Complete Connected

  This bit is set to "1" if the PRU supports Charge Complete Connected Mode. Otherwise, this bit is set to "0".
- PTU Test Mode

  This bit is set to "1" if the PRU is capable of operating as a PRU simulator and is requesting that the PTU enter PTU Test Mode. Otherwise, this bit is set to "0".

9.5.6.8 PRU hardware revision

The PRU Hardware Revision is vendor proprietary.

Bit field	Hardware revision description
	Defined by OEM

9.5.6.9 PRU firmware revision

The PRU Firmware Revision is vendor proprietary.

Bit field	Firmware revision description
	Defined by OEM

9.5.6.10 P_{RECT_MAX}

The PRU shall report its maximum rated P_{RECT} power as P_{RECT_MAX}. The value is in increments of 100 mW.

Bit field	Power mW
0 to 255	0 to 25 500

9.5.6.11 $V_{RECT\_MIN\_STATIC}$ (static, first estimate)

The PRU shall report its minimum V_{RECT} voltage as $V_{RECT\_MIN\_STATIC}$. The value is in mV.

Bit field	Voltage minimum mV
0 to 65 535	0 to 65 535

9.5.6.12 $V_{RECT\_HIGH\_STATIC}$ (static, first estimate)

The PRU shall report its maximum V_{RECT} voltage as $V_{RECT\_HIGH\_STATIC}$. The value is in mV.

Bit field	Voltage maximum mV
0 to 65 535	0 to 65 535

9.5.6.13 V_{RECT_SET}

The PRU shall report its desired V_{RECT} voltage as V_{RECT_SET}. The value is in mV.

Bit field	V_{RECT_SET} mV
0 to 65 535	0 to 65 535

9.5.6.14 Delta R1 caused by PRU

The PRU may report its Delta R1, if included, in increments of 0,01 Ω.

Bit field	Delta R1 ohms
0 to 65 535	0 to 655,35

9.5.7 PRU dynamic parameter characteristic

9.5.7.1 PRU dynamic parameter introduction

The PRU Dynamic Parameter characteristic contains measurement data with values that change during the charging process on the PRU.

9.5.7.2 PRU dynamic parameter characteristic behavior

The PRU Characteristic Behavior characteristic returns its value when read using the GATT Read Characteristic Value procedure. The PTU shall read this characteristic at least every 250 ms.

When a PTU requires a connection to a PRU to read PRU Dynamic Parameter Characteristic values it shall follow the connection procedures described in 9.4.5.3.

Based on the PRU Dynamic Parameter Characteristic, the PTU shall update the device control table in the registry corresponding to each PRU status.

9.5.7.3 PRU dynamic parameter characteristic value

The PRU Dynamic Parameter characteristic value fields are described in Table 34. The length of the characteristic value is 20 octets.

When read, this characteristic returns dynamic variables from the PRU (e.g., V_{RECT}) to the PTU.

Table 34 – PRU dynamic parameter characteristic

Field	Octets	Description	Use	Units
Optional fields validity	1	Defines which optional fields are populated	Mandatory	
V_{RECT}	2	DC voltage at the output of the rectifier.	Mandatory	mV
I_{RECT}	2	DC current at the output of the rectifier.	Mandatory	mA
V_{OUT}	2	Voltage at charge/battery port	Optional	mV
I_{OUT}	2	Current at charge/battery port	Optional	mA
Temperature	1	Temperature of PRU	Optional	Degrees Celsius (from –40 °C)
$V_{\mathrm{RECT\_MIN\_DYN}}$	2	The current dynamic minimum rectifier voltage desired	Optional	mV
$V_{\mathrm{RECT\_SET\_DYN}}$	2	Desired V_{RECT} (dynamic value)	Optional	mV
$V_{\mathrm{RECT\_HIGH\_DYN}}$	2	The current dynamic maximum rectifier voltage desired	Optional	mV
PRU alert	1	Warnings	Mandatory	Bit field
Tester Command	1	PTU Test Mode Command	Optional	Bit Field
RFU	2	Undefined		

9.5.7.4 Optional fields validity

The Optional Fields Validity field (see Table 35) shall identify which optional fields have valid values. All optional fields not identified as valid shall be set to zero.

Table 35 – Detail: bit field for optional fields validity

7	6	5	4	3	2	1	0
V_{OUT}	I_{OUT}	Temperature	$V_{\mathrm{RECT\_MIN\_DYN}}$	$V_{\mathrm{RECT\_SET\_DYN}}$	$V_{\mathrm{RECT\_HIGH\_DYN}}$	RFU	RFU
1 = Yes 0 = No	1 = Yes 0 = No	1 = Yes 0 = No	1 = Yes 0 = No	1 = Yes 0 = No	1 = Yes 0 = No	RFU	RFU

9.5.7.5 V_{RECT} – voltage at diode output

The PRU shall report the voltage at its rectifier output as V_{RECT}. The value is in mV.

Bit field	V_{RECT} mV
0 to 65 535	0 to 65 535

9.5.7.6 I_{RECT} – current at diode output

The PRU shall report the current at its rectifier output as I_{RECT}. The value is in mA.

Bit field	I_{RECT_SET} mA
0 to 65 535	0 to 65 535

9.5.7.7 V_{OUT} – voltage at charge battery port

The PRU may report its charge output voltage as V_{OUT}. The value is in mV.

Bit field	Charge battery port voltage mV
0 to 65 535	0 to 65 535

9.5.7.8 I_{OUT} – current at charge battery port

The PRU may report its charge output current as I_{OUT}. The value is in mA.

Bit field	Charge battery port current mA
0 to 65 535	0 to 65 535

9.5.7.9 PRU temperature

The PRU may report its temperature in this field. The value is in degrees Celsius, with 0 corresponding to –40 °C, and 255 corresponding to +215 °C.

Bit field	Temperature °C
0 to 255	–40 to +215

9.5.7.10 $V_{RECT\_MIN\_DYN}$ (dynamic value)

The PRU may report its dynamic minimum rectifier voltage as $V_{RECT\_MIN\_DYN}$. The value is in mV.

Bit field	V_{RECT} dynamic value mV
0 to 65 535	0 to 65 535

9.5.7.11 $V_{RECT\_SET\_DYN}$ (dynamic value)

The PRU may report the desired voltage at its rectifier output as $V_{RECT\_SET\_DYN}$. The value is in mV.

Bit field	V_{RECT} dynamic value mV
0 to 65 535	0 to 65 535

9.5.7.12 $V_{RECT\_HIGH\_DYN}$ (dynamic value)

The PRU may report its dynamic maximum rectifier voltage as $V_{RECT\_HIGH\_DYN}$. The value is in mV.

Bit field	V_{RECT} dynamic value mV
0 to 65 535	0 to 65 535

9.5.7.13 PRU alert

PRU Alert is included in both the PRU Dynamic Parameter Characteristic and the PRU Alert Characteristic so as to provide for the fastest potential delivery and response.

Table 36 – Detail: bit field for PRU alert

7	6	5	4	3	2	1	0
Over-voltage	Over-current	Over-temp	PRU Self Protection	Charge Complete	Wired Charger Detect	PRU Charge Port	Adjust Power Response

See 9.5.8 for details on the following fields.

- Over-voltage
- Over-current
- Over-temp
- PRU Self Protection
- Charge Complete
- Wired Charger Detect

The PRU Charge Port bit is set to "1" to indicate that the PRU charge port output is activated. Otherwise this bit is set to "0".

The Adjust Power Response bit is used to indicate whether or not the PRU has limited its power draw in response to the Adjust Power command. If the PRU does limit its power draw according to the PTU Adjust Power command, it shall set the "Adjust Power Response" bit to "1" and adjust power draw within one second of receiving the command. The PRU shall keep the adjust power response bit set to "1" until the PRU detects that the PTU has read the update of the Dynamic Parameter Characteristic and then reset the bit to "0". If the PRU does not have the ability to detect when the PTU has read the Dynamic Parameter Characteristic, then it shall keep the power response bit set to "1" for one second and, then reset the bit to "0".

If the PTU does not read the response bit or detect the change in P_{RECT} from the PRU within two seconds of issuing the adjust power command, the PTU shall conclude that the PRU cannot adjust power and shall not wait any further for a response from the PRU.

9.5.7.14 Tester Command

The Tester Command field (see Table 37) is optional and shall only be used by the PRU simulator when the PTU was previously requested by that PRU to enter the PTU Test Mode during device registration (see 9.5.6.6). Otherwise, this field shall remain 0x00. If not in Test Mode, the PTU shall ignore this field.

The Tester Command octet is read as 8-bit binary rather than a bit-field. See Table 38.

NOTE For test operation, the PTU does not acknowledge that it is in PTU Test Mode.

Table 37 – Detail: bit field for PRU alert

7	6	5	4	3	2	1	0
Bit 7	Bit 6	Bit 5	Bit 4	Bit 3	Bit 2	Bit 1	Bit 0

Table 38 – Test mode commands

Command number	Command description
0x00	Normal operation power control
0x01	Increase I_{TX} by one step
0x02	Decrease I_{TX} by one step
0x03	I_{TX} current shall not be adjusted
0x04 – 0xFF	Reserved

9.5.8 PRU alert characteristic

9.5.8.1 PRU alert characteristic introduction

The PRU Alert characteristic enables a PTU to receive notifications or indications of the PRU Alert characteristic from a PRU supporting this feature to show alerts (e.g., OVP, OCP, OTP and PRU Self Protection).

9.5.8.2 PRU alert characteristic behavior

The PRU Alert characteristic enables a PTU to receive notifications of the OVP, OCP, OTP and PRU Self Protection, Charge Complete and Wired Charger Detect flags from a PRU supporting this feature.

The PRU Alert characteristic also enables a PRU to send indications to the PTU regarding Mode Transition as described in 9.7 via the Mode Transition Bits.

The PTU shall be able to receive multiple notifications and indications of the PRU Alert characteristic from the PRU.

9.5.8.3 PRU alert characteristic value

The PRU Alert characteristic value fields are described in Table 39 and Table 40. The length of the characteristic value is 1 or 7 octets depending on the presence of the optional Device Address.

Table 39 – PRU alert fields

Field	Octets	Description	Use	Units
PRU Alert	1	Defines the Over-voltage, Over Current, Over Temperature and Self Protection Alerts	Mandatory	
Device Address (Optional)	6	Bluetooth device address (48 bits) used in mode transition reconnect	Conditional upon support for the Mode Transition feature.	

Table 40 – Detail: bit field for PRU alert notification

7	6	5	4	3	2	1	0
PRU Over-Voltage	PRU Over-Current	PRU Over-Temperature	PRU Self Protection	Charge Complete	Wired Charger Detect	Mode Transition Bit 1	Mode Transition Bit 0

9.5.8.4 PRU over-voltage

This bit, when set to "1", indicates that V_{RECT} at the PRU has exceeded the OVP limit. See 8.2.9.11 for PTU Latching Fault requirements. Otherwise, this bit is set to "0".

9.5.8.5 PRU over-current

This bit, when set, indicates that I_{RECT} at the PRU has exceeded the PRU's current limit. See 8.2.9.11 for PTU Latching Fault requirements.

9.5.8.6 PRU over-temperature

This bit, when set, indicates that measured temperature at the PRU has exceeded the PRU's temperature limit. See 8.2.9.11 for PTU Latching Fault requirements.

9.5.8.7 PRU Self-Protection

This bit, when set, indicates that the PRU is protecting itself by reducing power to its load. The PTU does not need to change states as a result. The PTU may provide feedback to the user via its user interface that one of the PRU's might not be charging at full rate.

9.5.8.8 Charge complete

This bit, when set, indicates that the PRU does not require charging.

9.5.8.9 Wired charger detect

This bit, when set, indicates that the PRU is powered by external wired power. When set, the PTU and the PRU should process this bit the same as when the Charge Complete bit is set.

9.5.8.10 Mode transition bits

The Mode Transition bits shall be set to a non-zero value to indicate to the PTU the duration of the pending Mode Transition procedure as described in 9.7. The bits shall indicate the Mode Transition duration values as defined in Table 41.

Table 41 – Mode transition

Value (Bit)	Mode transition bit description
00	No Mode Transition
01	2 s Mode Transition time limit
10	3 s Mode Transition time limit
11	6 s Mode Transition time limit

9.5.8.11 Device address

The Device Address field shall be included as part of the PRU Alert Notification field if and only if the Mode Transition bits are set to a non-zero value. See 9.7 for the Mode Transition procedure.

9.6 Cross connection algorithm

9.6.1 Cross connection algorithm introduction

The cross connection algorithm is a set of functions designed to prevent connection between a PTU and a PRU that is not in the PTU's charge area.

9.6.2 Definitions

A distant PRU is defined as one that is not within a given PTU's charge area. A local PRU is defined as one that is within a given PTU's charge area. A distant list is a persistent list of PRU addresses that are assumed to not be within a given PTU's charge area.

9.6.3 Acceptance of advertisement

During a long beacon, the BLE client (PTU) shall issue a connection request between 0 ms and 50 ms of a received WPT Service related advertisement provided that:

a) the RSSI of the advertisement is greater than ADV_PWR_MIN as measured at the receive antenna, AND
b) the PTU observes an impedance shift close to the time of the advertisement as described in 9.6.4.

The ADV_PWR_MIN recommended value is –60 dBm, but can vary based on implementation.

If neither of these conditions are satisfied, the PTU shall ignore advertisements from that device. If one of these conditions is satisfied, then once the 11th advertisement is received, or more than 1 700 ms elapses, then the PTU shall issue a connection request.

For information on use of the Distant List, see 9.6.5.

The PTU shall ignore any advertisements if they occur when the PTU's resonator is unpowered.

The PTU conditions for acceptance of advertisement shall not apply for PRUs in mode transition (see 9.7).

9.6.4 Impedance shift sensing

Each PTU design contains a table of Short Beacon PRU-induced Impedance, $Z_{\mathrm{TX\_IN\_LOAD\_DETECT}}$ that can be detected by the PTU. See 10.2.2.

Upon receipt of an advertisement from a PRU during a long beacon, the PTU shall look up the $Z_{TX\_IN\_LOAD\_DETECT}$ from its internal table. From the time an impedance shift is detected, the PTU shall look for an advertisement during the next 110 ms. (Note that if this period extends beyond the boundaries of the long beacon, a comparison to the values measured during the previous beacon might need to be made.)

The PTU shall then compare the impedance change to the $Z_{TX\_IN\_LOAD\_DETECT}$. (If the PTU is capable of measuring only one of reactance or resistance changes, then only one comparison is made.) If either the resistance or the reactance exceeds the values from the table, then the PTU is to consider the PRU to have an associated impedance shift. If the PRU reports Impedance Shift bits set to 000 in the PRU advertising payload (see 7.3.3.4 and 9.5.2), the PTU is to consider the PRU to have an associated impedance shift no matter what the measured value.

9.6.5 Reboot bit handling

A PTU may have an algorithm that looks for advertisements during periods when the power amplifier is off. Since advertisements are not allowed when the PRU is unpowered, any advertisement that occurs during this time may be considered an advertisement from a distant PRU. The PTU may retain the address of such advertisements and place them on a "distant" list, to be ignored in the future. This prevents future cross-connections to that PRU.

If a PTU implements such a system, it shall ignore the "distant" list whenever the reboot bit in the PRU advertisement is set to "0". In addition, it shall clear that device from the "distant" list whenever the reboot bit in the PRU advertisement is set to "0". The reboot bit indicates that the PRU has recently had power removed and re-applied, as it would if the phone were moved from one pad to another; this makes any "distant" list invalid. Otherwise, the PTU may ignore this bit.

9.6.6 Time set handling

The Time Set value shall be set to zero if the PRU does not support Time Set. For the PRU that supports Time Set, the PTU shall use a non-zero value at least once before using a Time Set value of zero.

After the PRU Control Characteristic is written that includes a non-zero Time Set value and Enable PRU output set to "1", the category 2 or greater PRU shall create a valid P_{RECT} variation of at least 0,5 W maintain that load condition for the defined time in the Time Set field (Table 23), and upon completion, the PRU shall return to its original load condition and maintain it for at least 20 ms. The PRU shall enable the output after checking cross connection by the Time Set value. Category 1 PRUs are for further study.

If present, the PTU shall detect a P_{TX_IN} change of 0,5 W or more as the PRU load variation and compare the measured load variation period to the defined PTU Time Set value with a tolerance of ± 4 ms. If the PRU does not create the expected load variation for the defined Time Set value within 500 ms and the PRU supports Time Set (see 9.5.2 for Time Set Support bit), the PTU considers that the PRU might be cross-connected, and the PTU may write a PRU Control Characteristic with permission denied due to cross connection (see 9.5.4.5) and terminate the connection with the PRU.

If there are other PRUs already charging on the PTU, the PTU may first temporarily disable charging of those PRUs to perform a time set test on the new PRU.

The PTU should not adjust I_{TX} during the Time Set procedure.

9.7 Mode transition

9.7.1 Mode transition introduction

A PRU's BLE controller may re-initialize during an active charging session when the PRU is in PRU On state as described in 8.3.5 and the PTU is in the PTU Power Transfer state as described in 8.2.5. An example of when this procedure might be necessary is when a PRU initially charging from a completely dead battery condition retains enough battery charge where it is then possible to energize other subsystems comprised in the platform containing the PRU.

If the BLE controller re-initialization procedure requires the BLE link between a PRU and a PTU to terminate and then reinitialize, then the Mode Transition procedure described in 9.7.2 shall be followed.

9.7.2 Mode transition procedure

The PRU shall notify the PTU of its intent to terminate the BLE link prior to executing its re-initialization procedure (of the BLE link). This Mode Transition notification is a GATT indication to the PTU that the PRU's physical BLE link is about to drop and that the PTU and PRU will take the following actions. It is mandatory for the PTU to support the mode transition procedures defined for both zero and non-zero Device Address fields in the Mode Transition indication.

While in the PRU On state, if the PRU needs to reinitialize the BLE link with the PTU, the PRU shall notify the PTU by issuing a Mode Transition alert. A Mode Transition shall be performed by the PRU sending an Alert characteristic indication as described in 9.5.8. The PRU shall include the following information within the Mode Transition alert.

a) The Mode Transition Bits shall be set to the (non-zero) time required for mode transition to complete. The bit settings shall indicate the duration of the Mode Transition using the format described in 9.5.8.10.
b) If known, the Device Address field shall be set to the BLE device address to be used when the PRU's advertises and reconnects to the PTU after BLE device re-initialization. If this device address is unknown at the time this indication is sent, then the PRU shall set the Device Address field to all zeros. See 9.5.8.11.

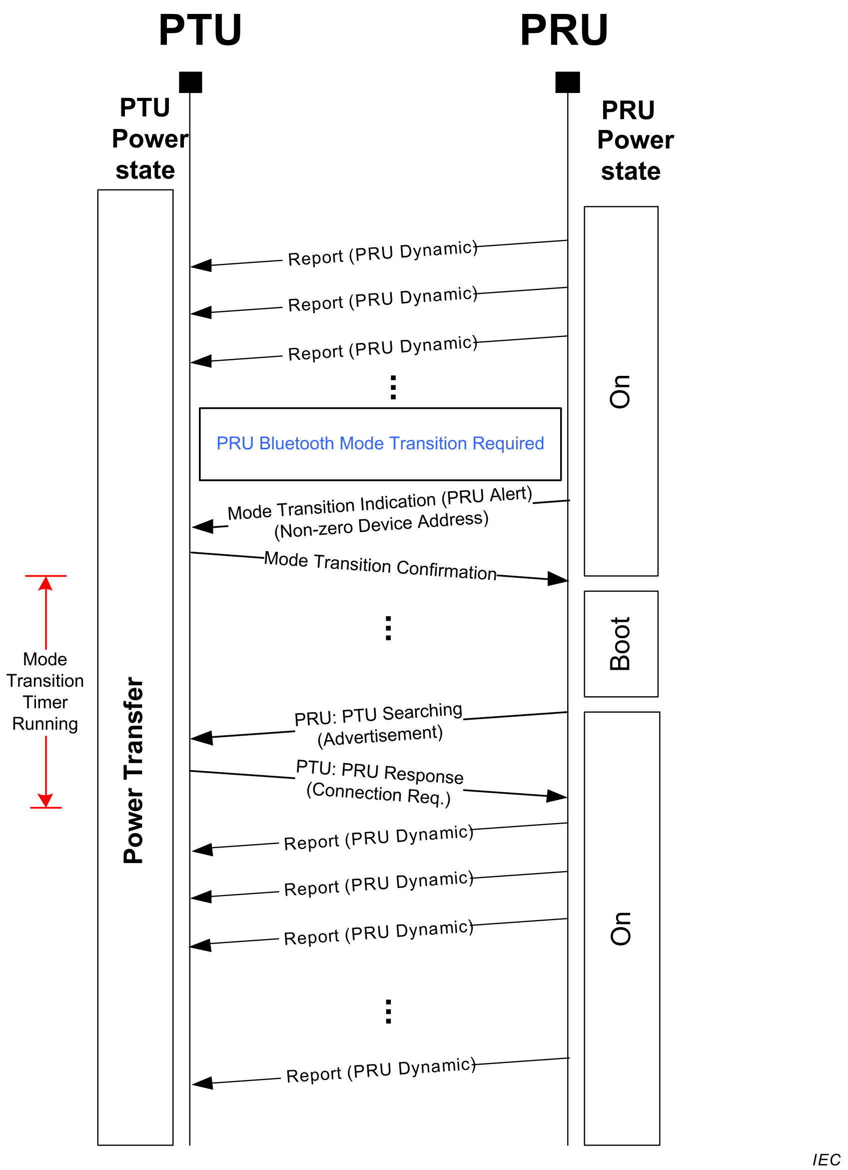
If the Mode Transition Bits indicate a period of less than or equal to three seconds, then the PTU shall maintain I_{TX} relative to the PRU for the duration of the Mode Transition period. The PTU shall exclude the PRU from being classified as a rogue object only during the Mode Transition procedure.

If the Mode Transition Bits are set to a value greater than three seconds, then prior to the beginning of the Mode Transition procedure, the PRU shall change its input impedance setting to support no more than a 1,1 W power draw and shall restrict any impedance change to this level during the entire Mode Transition procedure. The PTU shall adjust I_{TX} to this setting and shall maintain I_{TX} relative to the PRU for the duration of the Mode Transition procedure. If the Mode Transition device address is set to a non-zero value, then the Mode Transition expiration timer shall be stopped once the BLE connection is re-established. Otherwise the Mode Transition expiration timer shall be stopped once the registration procedure concludes at the issuing of the Control Characteristic containing the Enable PRU Charge command as described in 9.5.3.3.

If the PRU does not advertise and re-establish the BLE connection within the specified time frame indicated by the mode transition bit field, the PTU shall remove the PRU from the device registry, and wait for the PRU to advertise again to reconnect.

9.7.3 BLE reconnection procedure

If the Device Address field within the Mode Transition alert is set to a non-zero value, then the PRU shall use this device address as its own in advertisements issued after re-initializing. BLE device discovery shall not be executed by the PTU, and the PTU shall attempt to reconnect to the PRU on receipt of the first advertisement from the PRU as well as any subsequent advertisements due to failed connection attempts. Once reconnected, the PTU shall be able to immediately support the previous charging session parameters used prior to re-initialization, and execution of the registration procedure shall not be executed and the PRU is not subjected to the acceptance of advertisement checking specified in 9.6.3. Figure 17 contains an illustrative message sequence chart depicting this procedure. GATT responses are omitted in the chart for simplicity.



NOTE Read Requests are omitted for simplicity. Read Responses are shown as "Report (PRU Dynamic)".

Figure 17 – PRU mode transition – Device Address field set to a non-zero value

If the Device Address field within the Mode Transition alert is set to all zeros, then the PTU will not have any information regarding the address used by the PRU during BLE link reconnection. In this case, the PTU shall rediscover the PRU's BLE device address when the PRU once again begins advertising. Subsequently, the PTU shall reconnect with the PRU and execute the entire registration procedure which concludes at the issuing of the Control

Characteristic containing Enable PRU Charge command as described in 9.5.4.3. Figure 18 contains an illustrative message sequence chart depicting this procedure.

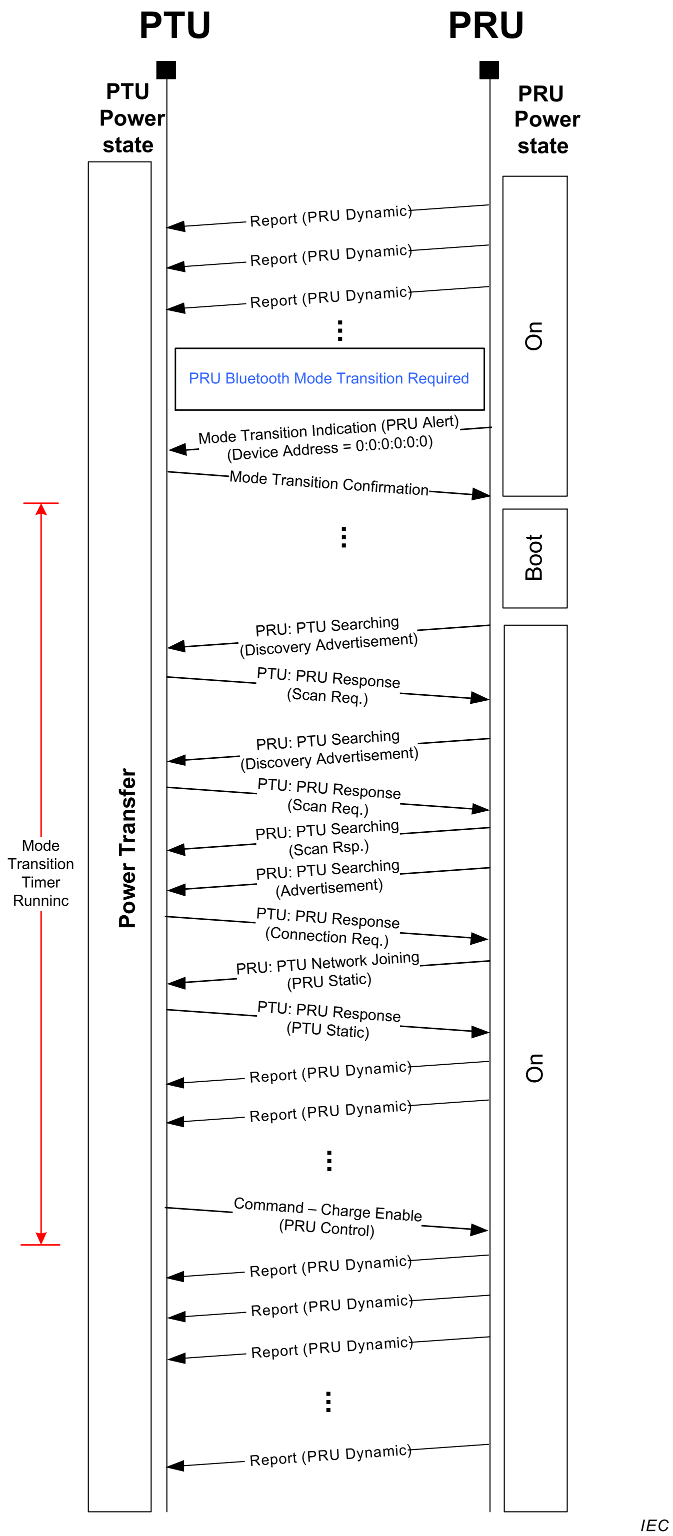


Figure 18 – PRU mode transition – Device Address field set to all zeros

10 PTU resonators

10.1 PTU resonators introduction

The purpose of Clause 10 is to define the parameters required for the specification of approved PTU resonators as well as to identify currently approved PTU resonators.

NOTE All resonator impedance ranges and interfaces are specified in a manner which excludes the influence of any adaptive matching network.

10.2 Class *n* design template

10.2.1 Class *n* design template introduction

10.2.2 and 10.2.3 are required to be completed for every class of PTU resonator design. See 6.1 for PTU classifications.

10.2.2 Table of specifications

The AirFuel Resonant accepted PTU Resonator Design Template contains PTU resonator parameters. If a parameter in the template is not applicable to the PTU resonator design (e.g., the PTU does not support a category of PRUs), that parameter is to be identified as Not Applicable (N/A). See 6.2 for PRU categories.

10.2.3 PTU resonator structure

The PTU resonator design shall include all criteria necessary to build the PTU coil to the specification. The PTU resonator structure shall be defined including, however not necessarily limited to, the following:

- resonator geometry (a dimensioned drawing of the front, side, and top views shall be included);
- required resonator clearances (e.g., to charge surface, bottom of enclosure, enclosure edges);
- tuning;
- shielding; and
- matching network (if included as a component of the design).

10.3 Approved PTU resonators

The PTU resonator designs incorporated into the Accepted PTU Resonator List comprise the set of approved PTU resonators at the time of publication of this document. Parties to agreements based on this document are also required to investigate the possibility of additional approved PTU resonators at:

https://members.airfuelalliance.org/wg/AirFuel/document/folder/122

Annex A
(informative)

Reference PRU for PTU acceptance testing

NOTE See 6.2 for PRU categories.

A.1 Category 1

For further study.

A.2 Category 2

See the RIT 3-2 design in AirFuel Resonant PTU Resonator and Resonator Interface Acceptance Test.

A.3 Category 3

A.3.1 PRU design 3-1

Table A.1 and Figure A.1 provide RIT 3-2 specific parameters and block diagram.

Table A.1 – PRU table of specifications

Parameter	Value	Units
$V_{RX\_OC\_BOOT}$	5,8	Volts
$V_{RX\_OC\_MIN}$	8,9	Volts
$V_{RX\_OC\_HIGH}$	13,7	Volts
$V_{RX\_OC\_MAX}$	18	Volts
R_{RX_MIN}	12,5	Ohms
Minimum clearance from charger area surface	0,5	millimetres

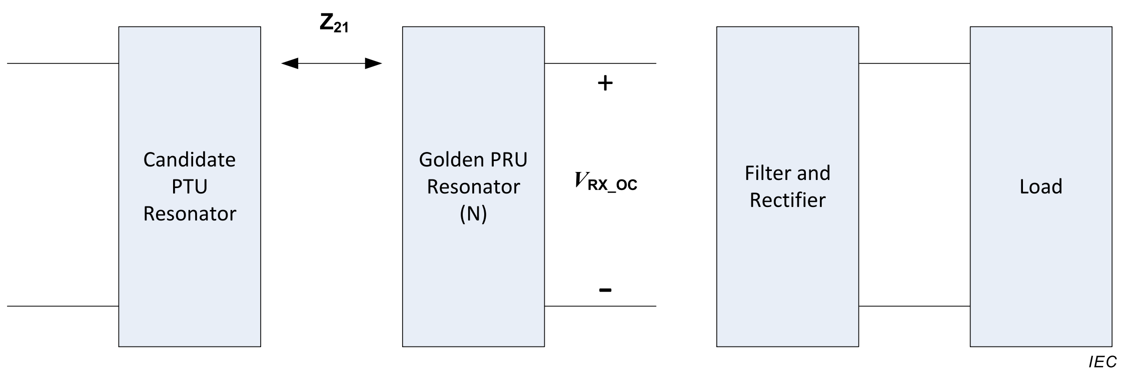


Figure A.1 – PRU design 3 block diagram

A.3.2 Geometry

Figures A.2 through A.6 provide RIT 3-2 specific geometry.

Dimensions in millimetres

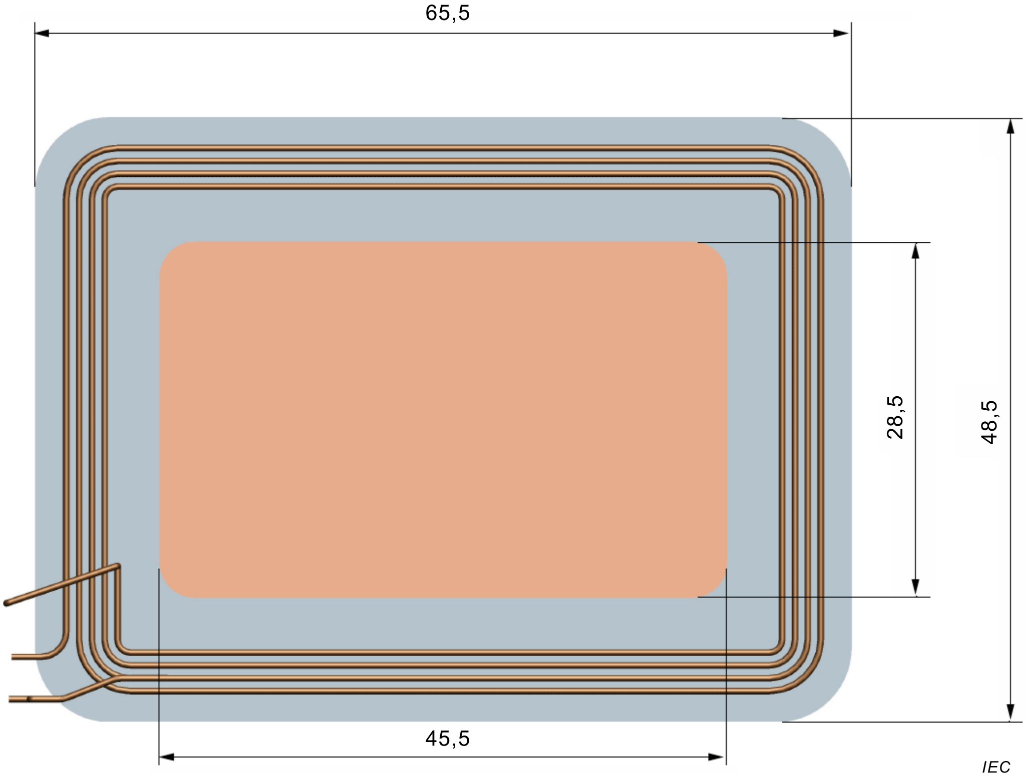


Figure A.2 – Front view

Dimensions in millimetres

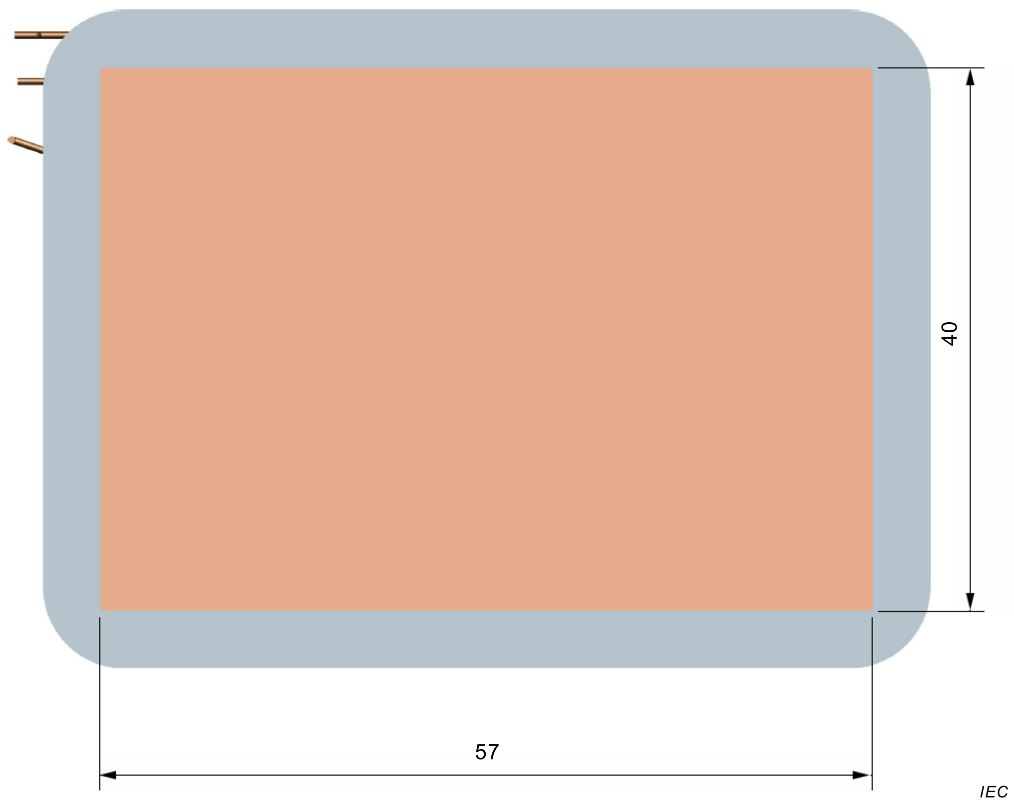


Figure A.3 – Back view

Dimensions in millimetres

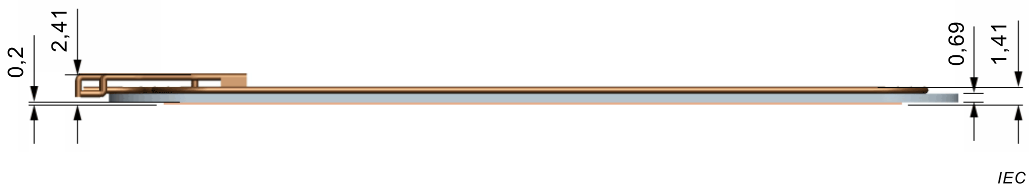
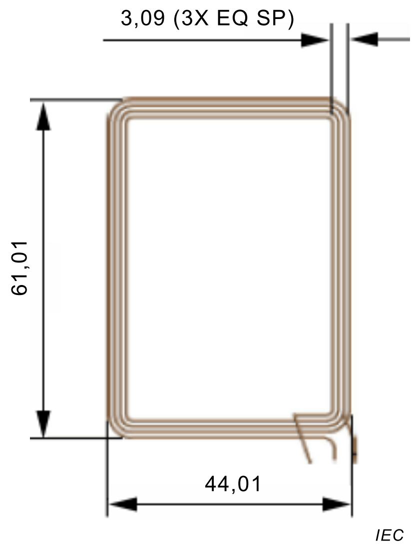


Figure A.4 – Side view

Dimensions in millimetres



NOTE "3X EQ SP" means "Three equal spaces".

Figure A.5 – Front view, coil only

Dimensions in millimetres

Figure A.6 – Side view, coil only

A.4 Category 4

For further study.

A.5 Category 5

For further study.

Annex B
(informative)

Lost power

B.1 Overview

Annex B provides considerations for the development of lost power procedures and lost power calculations.

B.2 General

Lost power is defined as the power that cannot be accounted for by the system. System power losses include:

- efficiency losses in the PTU power section;
- losses in the PTU resonator;
- radiated losses;
- losses in the PRU resonator;
- efficiency losses in the PRU power section;
- losses caused by induction heating of the body of the PRU;
- losses caused by induction heating of other objects in the vicinity.

Generally, the PTU will have the ability to measure power in and the PRU will have the ability to measure and report power out. There will always be a difference between these two caused by the losses listed above. Some of the losses (such as PTU and PRU resonator losses, and PRU induction heating losses) can be estimated and accounted for fairly accurately. Some of the losses (such as induction heating of other objects) are unknowns.

Since induction heating of other objects is undesirable, PTU designers will often wish to estimate the amount of lost power assignable to induction heating of other objects. Simulation and empirical testing demonstrates that this can be done with an accuracy of a few watts. If an unaccountable amount of lost power is detected, PTU designers might elect to shut down the PTU to prevent potential heating of other objects.

Annex B lists some of the issues surrounding lost power detection.

B.3 Cross connection issues

When a device is cross-connected, it will be reporting its power to the "wrong" PTU and will generally cause a significant amount of lost power error. This can be used to help remedy cross connection issues, since a shutdown will tend to reset all BLE links on that PTU and allow the cross-connected device to "try again".

B.4 Handoff issues

In some cases, a device might need to "hand off", i.e., to transfer control from one BLE link to another, or from one BLE radio to another. During this time, there will often be a transient in unreported power, and PTU designers need to ensure that this does not cause an undesired lost power detection shutdown.

B.5 Power noise issues

The "spectrum" of power draw of a phone in current limit (i.e., drawing maximum power during charge) is relatively quiet since most phone inputs are current-regulated. However, once fully charged or close to fully charged, the power drawn becomes very noisy and thus hard to measure accurately. System designers can overcome this by implementing filters with a time constant much longer than the 250 ms sampling interval for PRU power, but this is somewhat difficult to implement. Thus, measurement of lost power during periods other than full power might be difficult or impossible.

B.6 PTU lost power calculation

B.6.1 Lost power detection threshold

The PTU detects when $P_{\mathrm{LOST}} \geq n$ W for at least six seconds, where n is an implementation specific value.

B.6.2 Lost power detection speed

If lost power exceeds, and then stays above the implementation threshold, the PTU shall shut down within six seconds measured from the moment that the implementation threshold was first exceeded.

B.6.3 PTU lost power calculation

The PTU can implement the calculation

$$P_{\mathrm{LOST}} = P_{TX\_OUT} - P_{\mathrm{ACK}}$$

where

$P_{\mathrm{TX\_OUT}}$ is the power output of the PTU resonator;

P_{ACK} is the power consumption acknowledged by PRUs.

$$P_{\mathrm{TX\_OUT}} = P_{\mathrm{TX}} - P_{\mathrm{TX\_RESONATOR\_DISSIPATION}}$$

where

$P_{\mathrm{TX\_RESONATOR\_DISSIPATION}}$ is the power dissipated in the PTU resonator

$$P_{\mathrm{ACK}} = (P_{\mathrm{AC1}} + P_{\mathrm{RXCOIL1}} + P_{\mathrm{INDUCTION1}}) + \ldots + (P_{\mathrm{AC}\_N} + P_{\mathrm{RXCOIL}\_N} + P_{\mathrm{INDUCTION}\_N})$$

where

P_{AC1} is the power into the rectifier of PRU 1;

P_{RXCOIL1} is the power dissipated in the coil of PRU 1;

$P_{\mathrm{INDUCTION1}}$ is the power consumed by the induction heating of PRU 1.

B.6.4 PTU power transmission detection accuracy

The PTU detects the amount of power transmitted to within n W, where n is an implementation specific value.

B.6.5 PRU lost power reports

NOTE The PRU reports are used to calculate a total value of power consumption and dissipation that is acknowledged by the PRU (P_{ACK}). The parameters V_{RECT}, I_{RECT}, $R_{\mathrm{RX\_IN}}$, η_{RECT}, and Delta R1 can be used to compute the total of power delivered to the load, power consumed by any PRU circuitry, power consumed by the resonator, and power consumed by any induction heating effects.

B.6.6 Accuracy of reported power

The total error of the power acknowledged by each PRU, (P_{ACK}), is less than 0,75 W.

B.6.7 Other PRU lost power reports

None.

Annex C
(normative)

User experience requirements

C.1 General

Annex C defines the requirements that AirFuel Resonant PTUs and PRUs should meet to achieve a satisfactory overall user experience.

C.2 User indication

A user indication is a PTU and/or PRU capability to convey information to the user regarding the state of wireless power transfer. Use case and form factor may limit the capability of some devices to provide a user indication. See 9.5.4.3 for additional information on PRU charge permission.

C.2.1 PRU user indication

The PRU, if it has the capability as declared by the PRU vendor, shall provide the following user indications for wireless power transfer.

a) The PRU is charging (for initial conditions, this can also mean preparing or permitted to charge).
b) The PRU is not charging.
   1) The PRU is denied charge.
   2) The PRU is waiting to charge (i.e., there is limited charging available).
   3) An error condition is preventing the PRU from charging.

C.2.2 PTU user indication

The PTU, if it has the capability, shall provide the following user indications for wireless power transfer.

a) The PTU is charging one or more PRUs.
b) The PTU is not charging any PRUs.
   1) A PRU is denied charge.
   2) Charging is available, no PRUs are charging or present.
   3) An error condition is preventing one or more PRU from charging.

Annex D
(informative)

RCE calculations

D.1 RCE calculation (using S-parameters)

Delete this test equation:

$$\Delta = \det(S) = S_{11}S_{22} - S_{12}S_{21}$$

Optimum resonator coupling efficiency can be determined from the S-parameters. This method removes the effect of any matching network used in the measurement.

Define the following constants, which depend only on the S-parameters:

$$\begin{aligned} \Delta &= \det(S) = S_{11}S_{22} - S_{12}S_{21} \\ B_1 &= 1 + |S_{11}|^2 - |S_{22}|^2 - |\Delta|^2 \\ B_2 &= 1 + |S_{22}|^2 - |S_{11}|^2 - |\Delta|^2 \\ C_1 &= S_{11} - \Delta S_{22}^* \\ C_2 &= S_{22} - \Delta S_{11}^* \end{aligned} \tag{D.1}$$

The reflection coefficients for the generator and load at optimal efficiency are then given by:

$$\begin{aligned} \Gamma_G^{opt} &= \frac{B_1 - \operatorname{sign}(B_1)\sqrt{B_1^2 - 4|C_1|^2}}{2C_1} \\ \Gamma_L^{opt} &= \frac{B_2 - \operatorname{sign}(B_2)\sqrt{B_2^2 - 4|C_2|^2}}{2C_2}. \end{aligned} \tag{D.2}$$

The expression for the optimal efficiency in terms of the S-parameters is obtained by substituting in the values for $\Gamma_L^{opt}$and $\Gamma_{in}^{opt} = (\Gamma_G^{opt})^*$ in Equation (D.2) into:

$$RCE = \frac{1}{1 - \left|\Gamma_{in}^{opt}\right|^2} |S_{21}|^2 \frac{1 - \left|\Gamma_L^{opt}\right|^2}{\left(\left|1 - S_{22}\Gamma_L^{opt}\right|\right)^2} \tag{D.3}$$

The optimal loads can be found using the following expressions, where Z_0 = 50 Ω is the port impedance used in the S-parameter measurement:

$$\begin{aligned} Z_G &= Z_0 \frac{1 + \Gamma_G}{1 - \Gamma_G} \\ Z_L &= Z_0 \frac{1 + \Gamma_L}{1 - \Gamma_L}. \end{aligned} \tag{D.4}$$

D.2 RCE calculation (using Z-parameters)

Optimum resonator coupling efficiency can also be determined from the Z parameters.

General case: Given the 2 x 2 matrix of Z-parameters, we can determine the impedances seen at the input and output ports of the 2-port network with load impedance Z_L and generator impedance Z_G:

$$Z_{IN} = Z_{11} - \frac{Z_{12}Z_{21}}{Z_{22} + Z_L} \tag{D.5}$$

$$Z_{OUT} = Z_{22} - \frac{Z_{12}Z_{21}}{Z_{11} + Z_G} \tag{D.6}$$

For perfect conjugate matching, we want $Z_{IN} = Z_G^*$ and $Z_{OUT} = Z_L^*$. Solving these two equations for the optimum $Z_L$and Z_G we find:

$$\begin{aligned} Z_{L,opt} &= -jX_{22} + j\frac{IM[Z_{12}Z_{21}]}{2R_{11}} + R_{22}\sqrt{\left(1 + j\frac{IM[Z_{12}Z_{21}]}{2R_{11}R_{22}}\right)^2 - \frac{Z_{12}Z_{21}}{R_{11}R_{22}}} \\ &= -jX_{22} + j\frac{IM[Z_{12}Z_{21}]}{2R_{11}} + R_{22}\sqrt{1 - \left(\frac{IM[Z_{12}Z_{21}]}{2R_{11}R_{22}}\right)^2 - \frac{RE[Z_{12}Z_{21}]}{R_{11}R_{22}}} \end{aligned} \tag{D.7}$$

)

$$\begin{aligned} Z_{G,opt} &= -jX_{11} + j\frac{IM[Z_{12}Z_{21}]}{2R_{22}} + R_{11}\sqrt{\left(1 + j\frac{IM[Z_{12}Z_{21}]}{2R_{11}R_{22}}\right)^2 - \frac{Z_{12}Z_{21}}{R_{11}R_{22}}} \\ &= -jX_{11} + j\frac{IM[Z_{12}Z_{21}]}{2R_{22}} + R_{11}\sqrt{1 - \left(\frac{IM[Z_{12}Z_{21}]}{2R_{11}R_{22}}\right)^2 - \frac{RE[Z_{12}Z_{21}]}{R_{11}R_{22}}} \end{aligned} \tag{D.8}$$

where $R_{11} = RE[Z_{11}]$, $R_{22} = RE[Z_{22}]$, $X_{11} = IM[Z_{11}]$ and $X_{22} = IM[Z_{22}]$.

We can determine the optimum efficiency using

$$RCE = \frac{|Z_{21}|^2}{\left|Z_{22} + Z_{L,opt}\right|^2} \; R_{L,opt}/R_{IN} \tag{D.9}$$

where $R_{L,opt} = RE[Z_{L,opt}]$ and $R_{IN} = RE[Z_{IN}]$ evaluated with $Z_L = Z_{L,opt}$. Under optimum loading conditions,

$$\frac{R_{L,opt}}{R_{IN}} = \frac{RE\left[Z_{L,opt}\right]}{RE\left[Z_{G,opt}\right]} = \frac{R_{22}}{R_{11}} \tag{D.10}$$

and RCE can be expressed as

$$RCE = \frac{\frac{|Z_{21}|^2}{R_{11}R_{22}}}{\left(1 + \sqrt{1 - \left(\frac{IM[Z_{12}Z_{21}]}{2R_{11}R_{22}}\right)^2 - \frac{RE[Z_{12}Z_{21}]}{R_{11}R_{22}}}\right)^2 + \left(\frac{IM[Z_{12}Z_{21}]}{2R_{11}R_{22}}\right)^2} \tag{D.11}$$

D.2.1 Series tuned case

In the special case of coils with only series matching elements, $Z_{21} = Z_{12} = j\omega M$ and then

$$Z_{L,opt} = -jX_{22} + R_{22}\sqrt{1 + \frac{\omega^2 M^2}{R_{11}R_{22}}} \tag{D.12}$$

and

$$Z_{G,opt} = -jX_{11} + R_{11}\sqrt{1 + \frac{\omega^2 M^2}{R_{11}R_{22}}} \tag{D.13}$$

RCE simplifies to:

$$RCE = \frac{Q_M^2}{\left(1 + \sqrt{1 + Q_M^2}\right)^2} \tag{D.14}$$

where

$$Q_M = \frac{\omega M}{\sqrt{R_{11}R_{22}}} \tag{D.15}$$

Note that in this case $R_{11} = R_1$ and $R_{22} = R_2$, where R_1 and R_2 are the resistances of coils 1 and 2 plus series matching capacitors, respectively.

D.2.2 Other RCE calculations

None.

D.3 Conversion between S-parameters and Z-parameters

S-parameters can be converted to Z-parameters and vice-versa.

$Z_0 = 50$

S to Z Parameters	Z to S Parameters
$Z_{11}=\frac{\left((1+S_{11})(1-S_{22})+S_{12}S_{21}\right)}{\Delta_s}Z_0$ $Z_{12}=\frac{2S_{12}}{\Delta_s}Z_0$ $Z_{21}=\frac{2S_{21}}{\Delta_s}Z_0$ $Z_{22}=\frac{\left((1-S_{11})(1+S_{22})+S_{12}S_{21}\right)}{\Delta s}Z_0$	$S_{11}=\frac{(Z_{11}-Z_0)(Z_{22}+Z_0)-Z_{12}Z_{21}}{\Delta_Z}$ $S_{12}=\frac{2Z_{12}Z_0}{\Delta_Z}$ $S_{21}=\frac{2Z_{21}Z_0}{\Delta_Z}$ $S_{22}=\frac{(Z_{11}+Z_0)(Z_{22}-Z_0)-Z_{12}Z_{21}}{\Delta_Z}$
$\Delta_s=\left((1-S_{11})(1-S_{22})-S_{12}S_{21}\right)$	$\Delta_Z=(Z_{11}+Z_0)(Z_{22}+Z_0)-Z_{12}Z_{21}$

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