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Wireless power transfer – AirFuel Alliance resonant baseline system specification (BSS)

Transfert d'énergie sans fil – Spécification du système de référence (BSS) pour le système résonant d'AirFuel Alliance



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CONTENTS

FOREWORD.....	7
INTRODUCTION.....	9
1 Scope.....	10
2 Normative references	10
3 Terms, definitions, symbols and abbreviated terms.....	10
3.1 Terms and definitions.....	10
3.2 Symbols and abbreviated terms	13
3.2.1 Symbols	13
3.2.2 Abbreviated terms	17
4 System description	17
5 Conformance and backwards compatibility	18
6 Device types.....	19
6.1 PTU classification	19
6.2 PRU category	20
7 Power transfer specifications	21
7.1 System equivalent circuit and reference parameters	21
7.2 General system requirements	21
7.2.1 Operating frequency	21
7.2.2 Z_{TX_IN} relationship to R_{RECT}	21
7.2.3 Power stability	21
7.2.4 PTU co-location protection.....	21
7.2.5 PRU self-protection (informative).....	21
7.3 Resonator requirements.....	22
7.3.1 Resonator coupling efficiency (RCE)	22
7.3.2 PTU resonator requirements.....	22
7.3.3 PRU resonator requirements	24
7.4 Load parameters.....	26
7.4.1 Load parameters introduction	26
7.4.2 Minimum load resistance	26
7.4.3 Maximum allowable dynamic load.....	26
7.4.4 Maximum load capacitance.....	26
8 Power control specifications	27
8.1 Control objectives	27
8.2 PTU specifications	27
8.2.1 PTU state	27
8.2.2 General state requirements	27
8.2.3 PTU power save state.....	29
8.2.4 PTU Low Power state	31
8.2.5 PTU Power Transfer state	31
8.2.6 PTU Configuration state	34
8.2.7 PTU Local Fault state	35
8.2.8 PTU latching fault state	35
8.2.9 PTU state transitions	36
8.2.10 PTU Test Mode.....	39
8.3 PRU specifications.....	39
8.3.1 PRU general requirements.....	39

8.3.2	PRU state model	42
8.3.3	Null state	43
8.3.4	PRU boot.....	43
8.3.5	PRU On state	44
8.3.6	PRU System Error state.....	44
8.3.7	PRU state transitions	45
9	Signaling specifications	46
9.1	Architecture and state diagrams.....	46
9.1.1	Architecture	46
9.1.2	Overall charge process	47
9.2	Charge procedure and requirements	49
9.2.1	Removing PRU from WPT network	49
9.2.2	Power Sharing mode	49
9.3	Bluetooth low energy requirements	50
9.3.1	Bluetooth low energy requirements introduction	50
9.3.2	Bluetooth low energy objectives.....	50
9.3.3	PTU hardware requirement	50
9.3.4	PRU hardware requirement.....	50
9.3.5	Basic network structure	50
9.3.6	RF requirements.....	50
9.3.7	Timing and sequencing requirements.....	51
9.3.8	Profile structure	54
9.4	BLE profile definition.....	54
9.4.1	GATT sub-procedure	54
9.4.2	Configuration	54
9.4.3	PRU requirements	55
9.4.4	PTU requirements.....	56
9.4.5	Connection establishment.....	56
9.4.6	Security considerations.....	58
9.4.7	Charge completion.....	58
9.5	WPT service characteristics	59
9.5.1	WPT service characteristics introduction.....	59
9.5.2	PRU advertising payload	59
9.5.3	WPT service	61
9.5.4	PRU control.....	63
9.5.5	PTU static parameter	65
9.5.6	PRU static parameter characteristic.....	70
9.5.7	PRU dynamic parameter characteristic	73
9.5.8	PRU alert characteristic.....	77
9.6	Cross connection algorithm.....	79
9.6.1	Cross connection algorithm introduction	79
9.6.2	Definitions	79
9.6.3	Acceptance of advertisement.....	79
9.6.4	Impedance shift sensing	79
9.6.5	Reboot bit handling.....	80
9.6.6	Time set handling	80
9.7	Mode transition	81
9.7.1	Mode transition introduction.....	81
9.7.2	Mode transition procedure	81

9.7.3	BLE reconnection procedure.....	81
10	PTU resonators	84
10.1	PTU resonators introduction.....	84
10.2	Class n design template	84
10.2.1	Class n design template introduction.....	84
10.2.2	Table of specifications	84
10.2.3	PTU resonator structure	84
10.3	Approved PTU resonators	84
Annex A	(informative) Reference PRU for PTU acceptance testing	85
A.1	Category 1	85
A.2	Category 2	85
A.3	Category 3	85
A.3.1	PRU design 3-1	85
A.3.2	Geometry.....	85
A.4	Category 4	88
A.5	Category 5	88
Annex B	(informative) Lost power	89
B.1	Overview.....	89
B.2	General.....	89
B.3	Cross connection issues	89
B.4	Handoff issues	89
B.5	Power noise issues	90
B.6	PTU lost power calculation.....	90
B.6.1	Lost power detection threshold	90
B.6.2	Lost power detection speed	90
B.6.3	PTU lost power calculation	90
B.6.4	PTU power transmission detection accuracy.....	90
B.6.5	PRU lost power reports.....	91
B.6.6	Accuracy of reported power	91
B.6.7	Other PRU lost power reports	91
Annex C	(normative) User experience requirements	92
C.1	General.....	92
C.2	User indication.....	92
C.2.1	PRU user indication	92
C.2.2	PTU user indication	92
Annex D	(informative) RCE calculations.....	93
D.1	RCE calculation (using S-parameters)	93
D.2	RCE calculation (using Z-parameters).....	94
D.2.1	Series tuned case.....	95
D.2.2	Other RCE calculations.....	95
D.3	Conversion between S-parameters and Z-parameters	95
Figure 1	– Wireless power transfer system.....	18
Figure 2	– PTU-PRU resonator P_{TX_IN}	19
Figure 3	– PTU-PRU resonator P_{RX_OUT}	20
Figure 4	– Equivalent circuit and system parameters	21
Figure 5	– PTU resonator-load considerations	24

Figure 6 – PTU state model	27
Figure 7 – Beacon sequences	29
Figure 8 – Load variation detection	30
Figure 9 – Discovery	31
Figure 10 – PTU I_{TX} transition responses.....	32
Figure 11 – PRU state model	42
Figure 12 – V_{RECT} operating regions	43
Figure 13 – Basic architecture of WPT system	47
Figure 14 – Basic state procedure (informative)	48
Figure 15 – Registration period timeline example (informative)	53
Figure 16 – PTU/PRU services/characteristics communication.....	55
Figure 17 – PRU mode transition – Device Address field set to a non-zero value	82
Figure 18 – PRU mode transition – Device Address field set to all zeros.....	83
Figure A.1 – PRU design 3 block diagram	85
Figure A.2 – Front view	86
Figure A.3 – Back view	86
Figure A.4 – Side view	87
Figure A.5 – Front view, coil only	87
Figure A.6 – Side view, coil only	87
Table 1 – PTU classification.....	20
Table 2 – PRU category	20
Table 3 – Minimum RCE (percent and dB) between PRU and PTU.....	22
Table 4 – Maximum load capacitance	26
Table 5 – Time requirement to enter PTU Power Transfer state	28
Table 6 – Sub-state of PTU Power Transfer	32
Table 7 – PTU latching faults	38
Table 8 – Example of accuracy of reported current	42
Table 9 – PRU system errors	46
Table 10 – RF budget (informative).....	51
Table 11 – Timing constraints	53
Table 12 – BLE profile characteristics	54
Table 13 – GATT sub-procedure	54
Table 14 – PRU advertising payload	59
Table 15 – Impedance shift bit	61
Table 16 – WPT service UUID	61
Table 17 – WPT service	62
Table 18 – GAP service	63
Table 19 – GATT service	63
Table 20 – PRU Control Characteristic.....	64
Table 21 – Detail: bit field for enables	64
Table 22 – Detail: bit field for permission	65
Table 23 – Detail: bit field for time set.....	65

Table 24 – PTU reporting static values to PRU	66
Table 25 – Detail: bit field for optional fields validity.....	66
Table 26 – PTU power	67
Table 27 – Max source impedance.....	68
Table 28 – Max load resistance	69
Table 29 – AirFuel protocol revision field	70
Table 30 – PTU number of devices	70
Table 31 – PRU reporting static values to the PTU	71
Table 32 – Detail: bit field for optional fields validity.....	71
Table 33 – Detail: bit field for PRU information	72
Table 34 – PRU dynamic parameter characteristic.....	74
Table 35 – Detail: bit field for optional fields validity.....	74
Table 36 – Detail: bit field for PRU alert.....	76
Table 37 – Detail: bit field for PRU alert.....	77
Table 38 – Test mode commands	77
Table 39 – PRU alert fields	78
Table 40 – Detail: bit field for PRU alert notification	78
Table 41 – Mode transition.....	79
Table A.1 – PRU table of specifications	85

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

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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.

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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 AirFuelTM¹ resonant wireless power transfer (WPT) systems.

¹ AirFuelTM 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 or service.

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 ($V_{RECT} \times I_{RECT} / P_{RECT_MAX}$)

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_{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_{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 ($P_{\text{RECT}} / P_{\text{RX_OUT}}$)

3.2.1.2 I_{RECT}

DC current out of the PRU's rectifier

3.2.1.3 $I_{\text{RECT_REPORT}}$

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

3.2.1.4 $I_{\text{RX_IN}}$

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 $I_{\text{TX_LONG_BEACON}}$

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 $I_{\text{TX_SHORT_BEACON}}$

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 $I_{\text{TX_START}}$

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 ($V_{RECT} \times I_{RECT}$)

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 ($V_{RECT_REPORT} \times I_{RECT_REPORT}$)

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

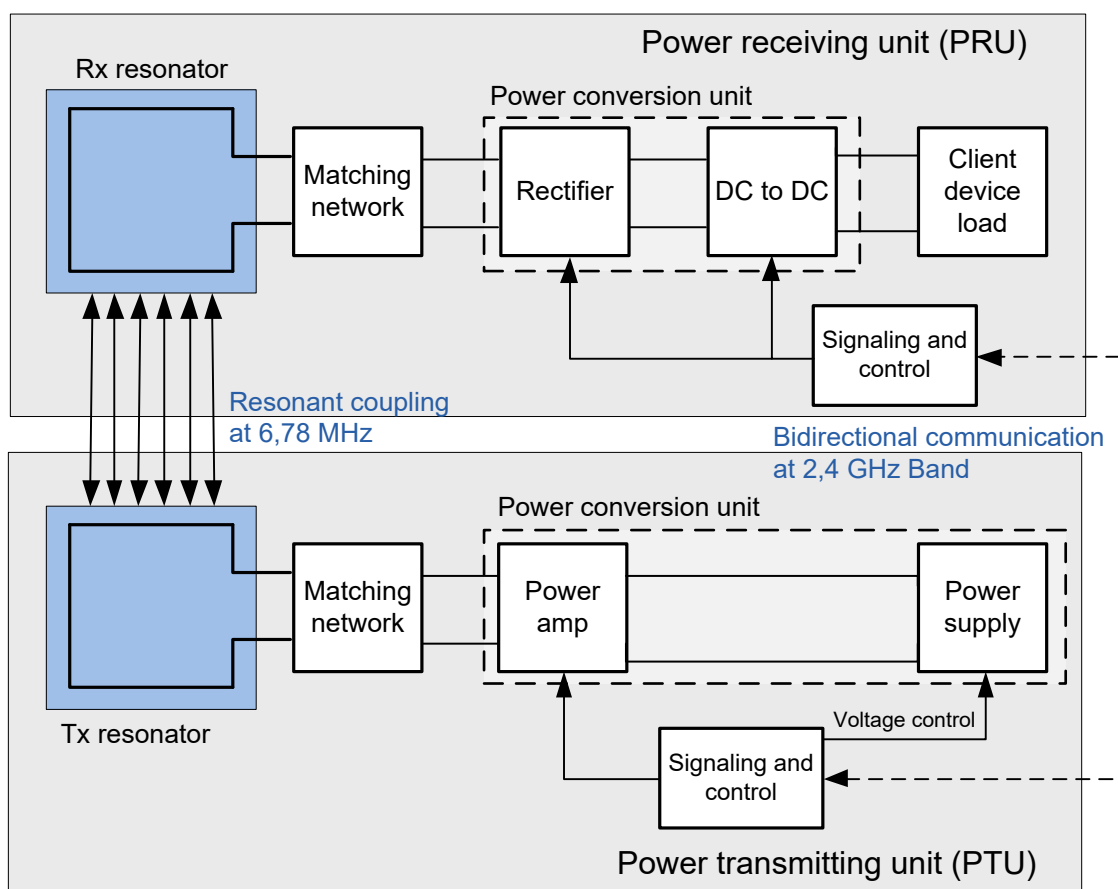
The AirFuel Alliance WPT system transfers power from a single power transmitter unit (PTU) to one or more power receiver units (PRUs.) The power transmission frequency is 6,78 MHz, and up to eight devices can be powered from a single PTU depending on transmitter and receiver geometry and power levels. 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.



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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.

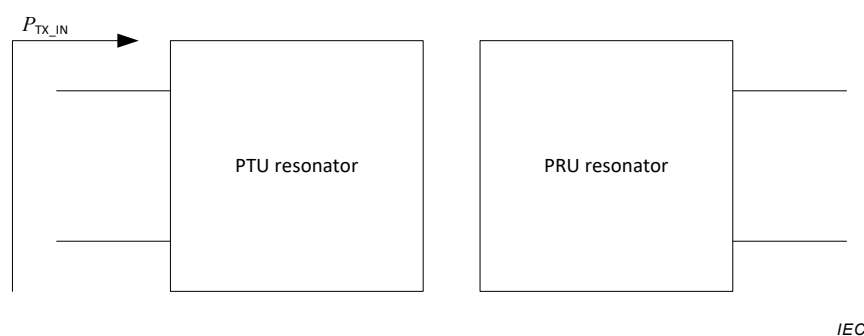
6 Device types

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 $P_{TX_IN_MAX}$ 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, $\text{Avg}(V(t) \times I(t))$. 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.



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Figure 2 – PTU-PRU resonator P_{TX_IN}

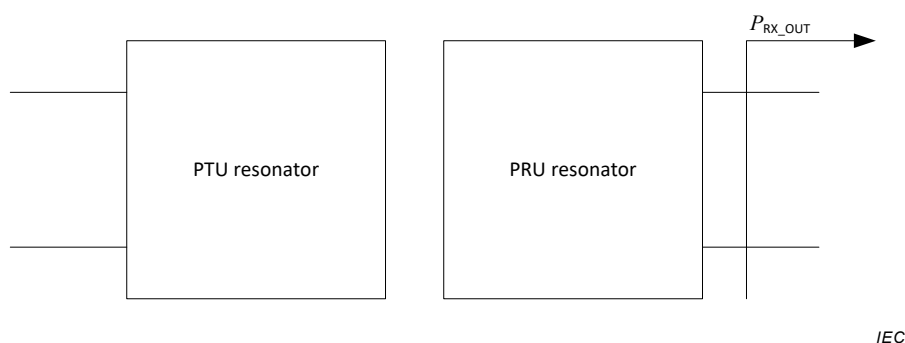
Table 1 – PTU classification

	$P_{TX_IN_MAX'}$ 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 $P_{TX_IN_MAX'}$, 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 $\text{Avg } V(t) \times I(t)$. Table 2 lists the PRU resonator output power ($P_{RX_OUT_MAX'}$) for PRU categories. See Clause 7 for power transfer requirements.



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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.

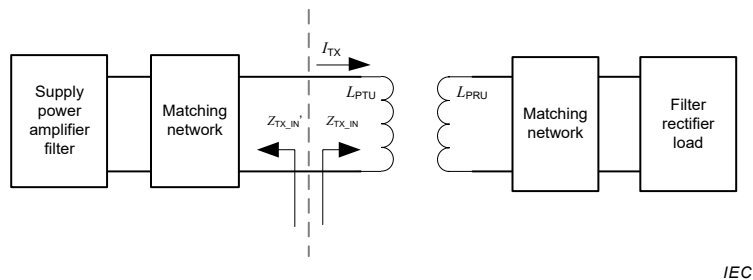


Figure 4 – Equivalent circuit and system parameters

7.2 General system requirements

7.2.1 Operating frequency

The resonator system shall operate at 6,78 MHz $\pm$ 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 second PRU is physically added or removed from the charge area in a location that does not overlap with the first PRU.
- 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.

- The PTU resonator coil current shall not exceed I_{TX_MAX} during either the long beacon-on period or the short beacon-on period.
- The PTU shall conduct a current greater than $I_{TX_SHORT_BEACON_MIN}$ through the PTU resonator coil during the short beacon-on period.
- The PTU shall conduct a current greater than $I_{TX_LONG_BEACON_MIN}$ through the PTU resonator coil during the long beacon-on period.
- 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} .
- 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 class²⁾. The equation for the derated current is:

$$I_{TX_NOMINAL_DERATED} = \text{MIN} (I_{TX_NOMINAL}, \text{SQRT} (P_{TX_IN_MAX}/R_{IN_TX}))$$

- 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:

$$I_{TX_MAX_DERATED} = \text{MIN} (I_{TX_MAX}, \text{SQRT} (P_{TX_IN_MAX}/R_{IN_TX}))$$

- 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.

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.

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).

$$R_{TX_IN_MIN} \leq \text{Re}\{Z_{TX_IN}\} \leq R_{TX_IN_MAX}$$

$$X_{TX_IN_MIN} \leq \text{Im}\{Z_{TX_IN}\} \leq X_{TX_IN_MAX}$$

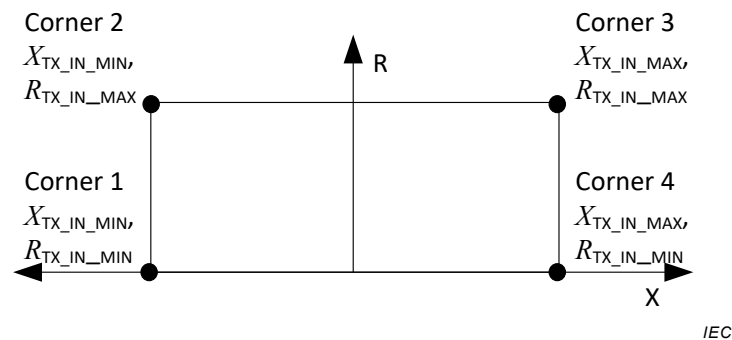


Figure 5 – PTU resonator-load considerations

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., $P_{\text{RECT_MIN}}$ to $P_{\text{RECT_MAX}}$) 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 $V_{\text{RECT_BOOT}}$ while consuming $P_{\text{RECT_BOOT}}$, when I_{TX} is greater than $I_{\text{TX_LONG_BEACON_MIN}}$ or $I_{\text{TX_MIN}}$ (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 $V_{\text{RECT_MIN}}$ if I_{TX} is greater than or equal to $I_{\text{TX_MAX}}$.
- b) 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 $1,1 \times V_{\text{RECT_HIGH}}$.

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 $Z_{TX_IN_LOAD_CHANGE}$ 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 $Z_{TX_IN_LOAD_CHANGE}$ 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 $X/\mu s$, 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

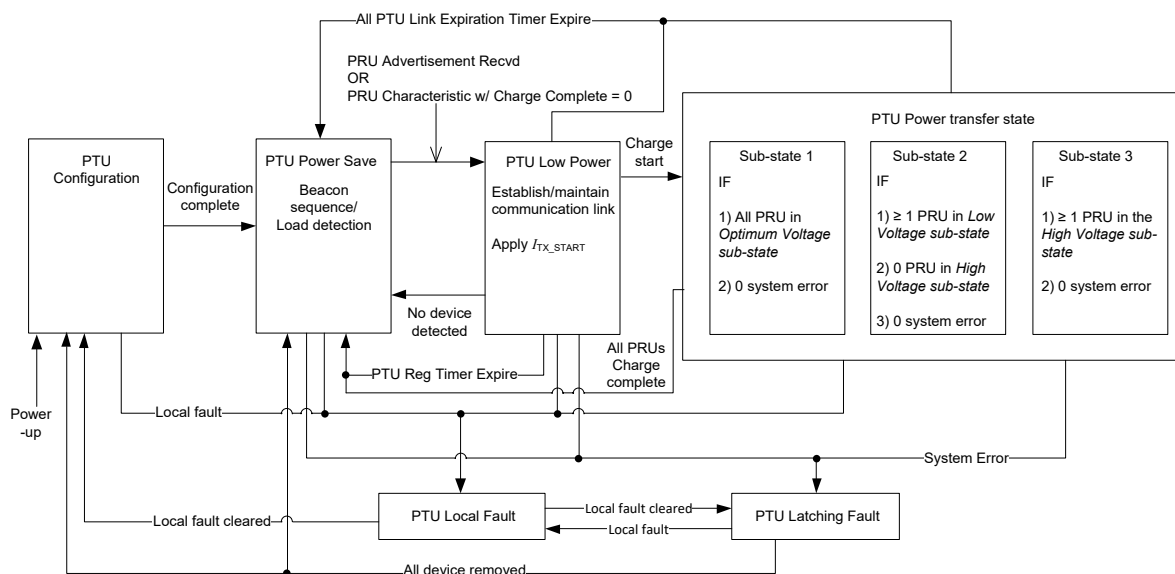
The control specifications are designed to

- a) protect PRU's V_{RECT} from over-voltage (i.e., $V_{RECT} > V_{RECT_MAX}$),
- a) reduce PRU's V_{RECT} such that $V_{RECT} \leq V_{RECT_HIGH}$ within 5 s after a PRU reports its $V_{RECT} > V_{RECT_HIGH}$,
- b) 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
- c) 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.



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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

- periodically apply current to the PTU resonator to detect changes of impedance of the PTU resonator, and
- 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.

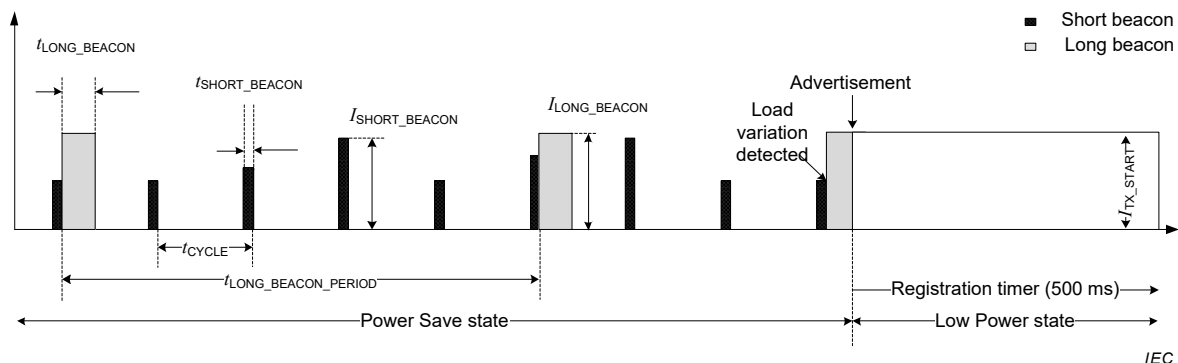


Figure 7 – Beacon sequences

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 $250 \text{ ms} \pm 5 \text{ ms}$. The short beacon-on-period ($t_{\text{SHORT_BEACON}}$) shall be between 10 ms and 30 ms.

8.2.3.3.2 Short beacon current

$I_{\text{TX_SHORT_BEACON_MIN}}$ is defined to be a measureable current greater than $I_{\text{TX_SHORT_BEACON_MIN}}$ 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.

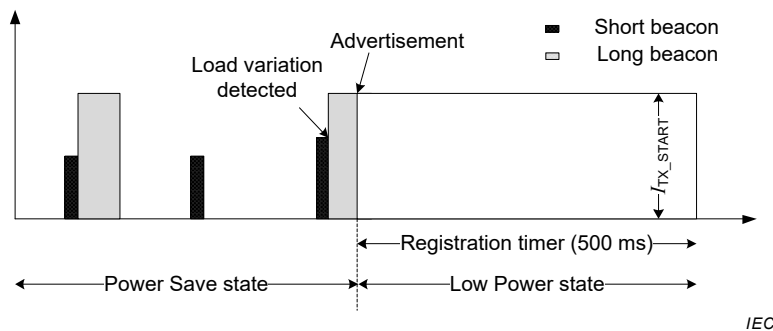


Figure 8 – Load variation detection

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 $105\text{ ms} \pm 5\text{ ms}$, 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 $100\text{ Hz} \pm 20\text{ Hz}$ 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 $(100 \pm 20)\text{ Hz}$ 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.

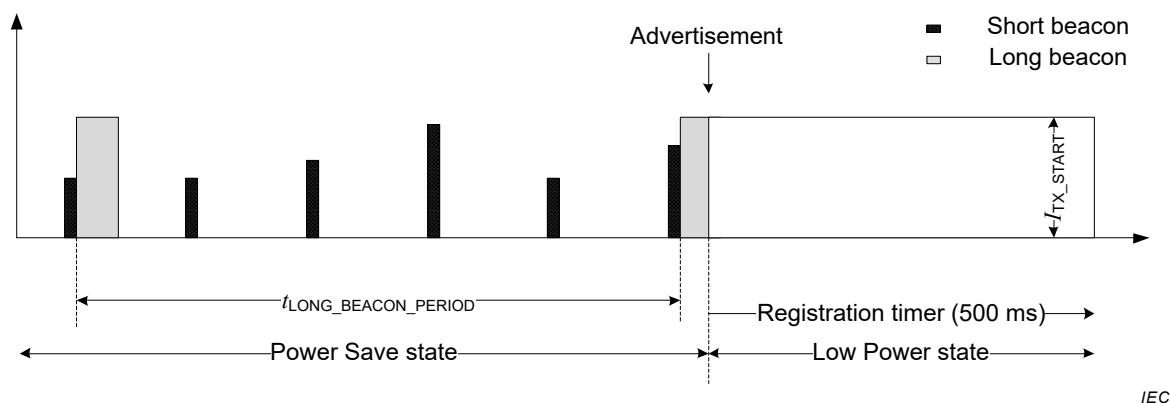


Figure 9 – Discovery

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

NOTE $I_{\text{TX_START}}$ 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 $0,8 \times I_{\text{TX_NOMINAL}}$ to $I_{\text{TX_NOMINAL}}$ 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.

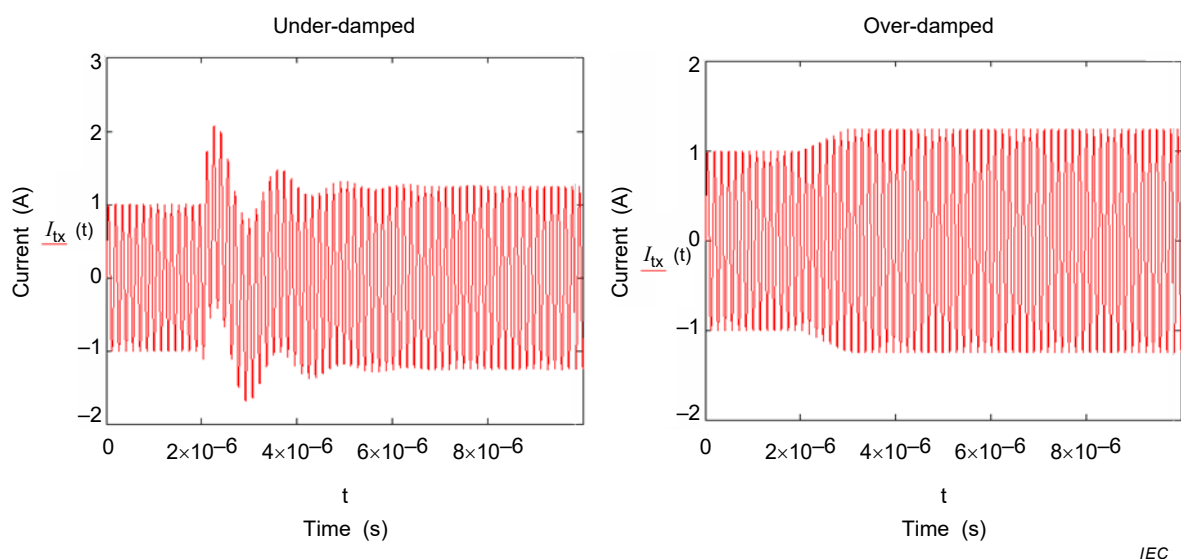


Figure 10 – PTU I_{TX} transition responses

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 $V_{\text{RECT_MIN_STATIC}}$ and $V_{\text{RECT_HIGH_STATIC}}$ parameters reported in the PRU Static Parameter Characteristic (see 9.5.6.3). If the PRU reports $V_{\text{RECT_MIN_DYN}}$ and $V_{\text{RECT_HIGH_DYN}}$ 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 $V_{\text{RECT_MIN_ERROR}}$ 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 $V_{\text{RECT}} \times I_{\text{RECT}} / P_{\text{RECT_MAX}}$, $P_{\text{RECT_MAX}}$ is reported in the PRU Static Parameter Characteristic value.

8.2.5.5.2 PTU Power Transfer sub-state 1 $V_{\text{RECT_MIN_ERROR}}$ algorithm

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

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

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

NOTE $P_{\text{RECT}} = I_{\text{RECT}} \times V_{\text{RECT}}$.

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 $\Sigma(P_{\text{RX_REPORTED}}) / P_{\text{IN}}$.

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 $I_{\text{TX_MAX}}$ and no smaller than 1 % of $I_{\text{TX_MAX}}$ with the following exceptions.

- If any PRU's V_{RECT} is greater than $V_{\text{RECT_HIGH}} \times 0,95$, the positive I_{TX} step size may be reduced.
- If any PRU's V_{RECT} is less than $V_{\text{RECT_MIN}} \times 1,05$, the negative I_{TX} step size may be reduced.
- If the dominant PRU's V_{RECT} is between $V_{\text{RECT_SET}}/1,05$ and $V_{\text{RECT_SET}}/0,95$, the positive and negative I_{TX} step size may be reduced.
- If I_{TX} is above $I_{\text{TX_MAX}}$, the positive I_{TX} step size may be reduced to avoid exceeding $I_{\text{TX_ABS_MAX}}$.

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 $I_{TX} > 50 \text{ mA}_{rms}$ 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 $I_{TX} > 50 \text{ mA}_{rms}$ 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 $I_{TX} > 50 \text{ mA}_{rms}$ 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 $1\text{ s} \pm 0,1\text{ s}$ 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 Power Save	Required	0 system errors All connections lost	At least one PTU Local Fault
PTU Low Power				
PTU Power Transfer	PTU Latching Fault	Optional	0 system errors Any connection lost without power variation and unsuccessful reconnection	None
PTU Low Power				

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_{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 $I_{TX_MAX} \pm 5\%$. The PTU in Test Mode shall be able to reach within 5 % of I_{TX_MIN} or to derated current at max R load, whichever is lower.
- i) I_{TX} shall not exceed $I_{TX_ABS_MAX}$ 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 protection³ such that when the PRU is operating in the Optimum Voltage sub-state and the ambient temperature is within the range 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.

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

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 $V_{RECT} \geq V_{RECT_MAX}$. If the OVP switch is located prior to the rectifier output, the PRU shall report the over-voltage condition after $V_{RECT} \geq V_{RECT_MAX}$, 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_{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_{RECT_SET} shall always be greater than or equal to $V_{RECT_MIN_STATIC}$, and less than or equal to $V_{RECT_HIGH_STATIC}$ 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), $V_{RECT_SET_DYN}$ shall be greater than or equal to the most recently reported $V_{RECT_MIN_DYN}$, and less than or equal to $V_{RECT_HIGH_DYN}$. If no $V_{RECT_SET_DYN}$ is reported, $V_{RECT_MIN_DYN}$ shall never be greater than V_{RECT_SET} , and $V_{RECT_HIGH_DYN}$ shall never be less than V_{RECT_SET} . If no $V_{RECT_MIN_DYN}$ or $V_{RECT_HIGH_DYN}$ are reported, then $V_{RECT_SET_DYN}$ shall be greater than $V_{RECT_MIN_STATIC}$ and less than $V_{RECT_HIGH_STATIC}$.

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 $V_{\text{RECT_REPORT}}$ shall be reported with an accuracy better than $\pm 3 \%$, 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 $I_{\text{RECT_REPORT}}$ shall be reported with accuracy better than 8 % of $P_{\text{RECT_MAX}}$ divided by $V_{\text{RECT_MIN}}$. $P_{\text{RECT_MAX}}$ and $V_{\text{RECT_MIN}}$ are those reported within the PRU Static Parameters. See also Table 8.

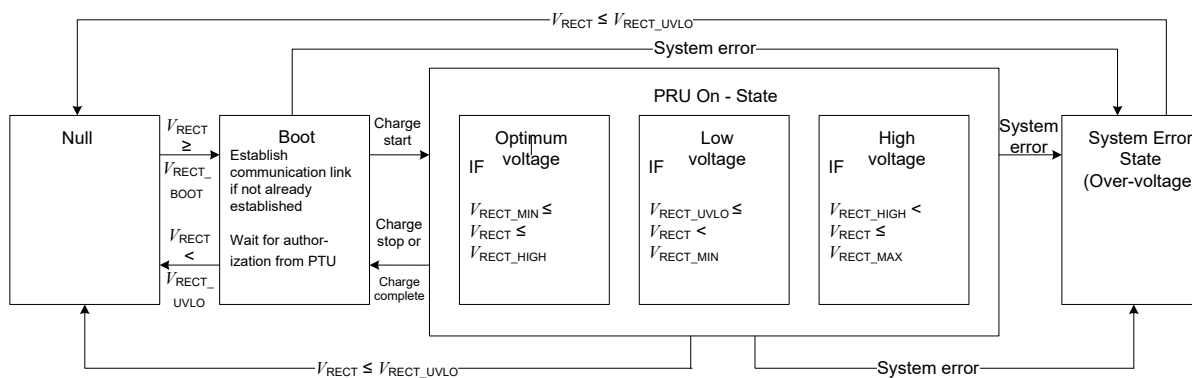
$$\text{ABS} (I_{\text{RECT}} - I_{\text{RECT_REPORT}}) \leq (8 \%) (P_{\text{RECT_MAX}} / V_{\text{RECT_MIN}})$$

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					

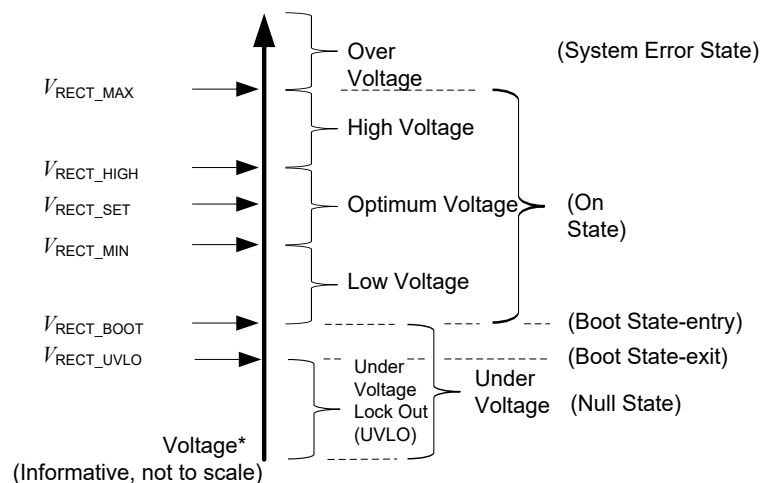
8.3.2 PRU state model

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).



IEC

Figure 11 – PRU state model



IEC

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 $V_{RECT_BOOT} \leq V_{RECT} < V_{RECT_MIN}$.

8.3.5.4 High Voltage sub-state

A PRU is in the High Voltage sub-state when $V_{RECT_HIGH} < V_{RECT} \leq V_{RECT_MAX}$.

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 $V_{RECT_HIGH} < V_{RECT} \leq V_{RECT_MAX}$ 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 $V_{RECT} \geq V_{RECT_BOOT}$.

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 ($V_{RECT} < V_{RECT_UVLO}$) 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 System Error	Required	None	None
PRU On				

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.

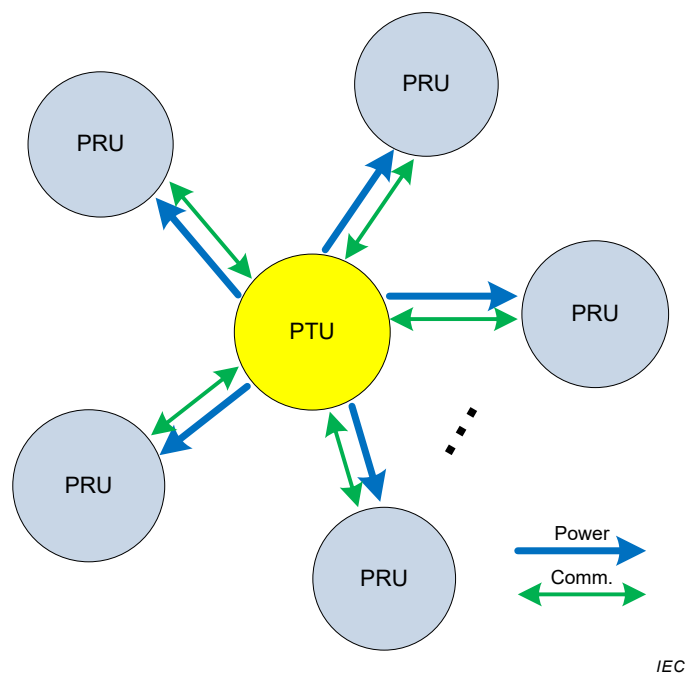


Figure 13 – Basic architecture of WPT system

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)