

The Qi Wireless Power Standard

Dries van Wageningen, Toine Staring

Philips Research Europe / Solid State Lighting, Aachen, Germany, e-mail: dries.van.wageningen@philips.com
Philips Applied Technology / Connectivity & Security, Eindhoven, Netherlands, e-mail: toine.staring@philips.com

Abstract — to enable a wide use of wireless power applications, the wireless power consortium has developed an industry standard to achieve interoperability between products that will carry the Qi logo. This paper introduces the Qi wireless power standard, explains the basic decisions that has been made in the process and provides a preview and short explanation of the system.

Keywords — interoperability, standard, power transfer, transmitter, receiver, magnetic induction, logo, system architecture, communication, control

I. INTRODUCTION

Consumers prefer solutions that are convenient and universal. Wireless solutions have been proven as convenient regarding the explosive use of mobile phones in the last decennia. Wireless power transfer is the logical step to complete the convenience by dissolving the need of connecting the phone to an adapter for battery charging. Pre-requisite for a broad market acceptance is the establishment of a standard that is widely supported by the leading industrial companies. The primary target of such standard is to establish interoperability between wireless power devices and wireless power chargers.

The wireless power consortium has been working on such standard for low power (up to 5W) devices and will continue its work for higher power levels.

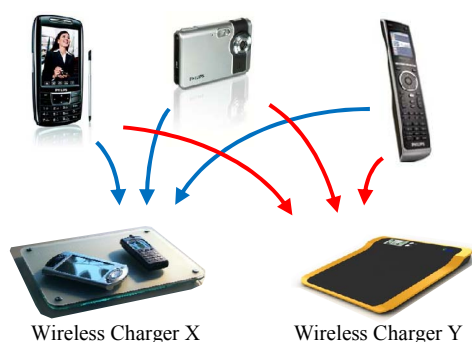


Figure 1 Interoperability between wireless power devices and wireless power chargers

II. THE CONSORTIUM AND THE LOGO

The wireless power consortium is a cooperation of companies that are representative to cover most relevant aspects for making the standard a success. Among the consortium members are leading mobile phone manufactures, battery makers, consumer electronics companies, semiconductor companies and specialists in wireless power technology.

The aim of the wireless power consortium is to enable a wide spread use of wireless power applications allowing many wireless devices to be powered by a wireless charger and inversely allowing a wireless device to be powered by different wireless chargers.

The consortium has defined a standard for providing up to 5W of power to low power mobile devices, like mobile phones, batteries and camera's. In a later state, higher power levels will be addressed as well.

The consortium has defined the logo "Qi" (pronounced as "chee", meaning "vital" energy in Asian philosophy - an intangible flow of power as a sign for compatible wireless power devices.

The Qi sign indicates that a device is compatible to the wireless consortium standard and complies with its requirements on interoperability and performance. It also means that the device needs to fulfill the international and regional regulations on safety and electromagnetic interoperability. Devices with a Qi logo can be safely powered by a charger with the Qi logo without disturbing other electronic applications.

III. BASIC DECISIONS

A. Proximity Inductive power transfer

Inductive power transfer is a well known technology, applied for a very long time in transformers where primary and secondary coil are tightly coupled, e.g. by the use of a shared magnetic permeable core. Inductive power transfer through the air with primary and secondary coil physically separated is also a known technology for more than a century. A fundamental problem in this respect is that the efficiency of the power transfer drops dramatically if the distance through the air is larger than the coil diameter.

The efficiency of the power transfer depends on the coupling (k) between the inductors and their quality (Q). The coupling depends on the distance between the inductors (z) and the relative size (D_2/D). Figure 2 shows the arrangement of the coils in this respect. The coupling is further determined by the shape of the coils and their alignment (not shown here).

The quality factor Q depends on the applied frequency, the inductance value and the resistance of the coil. Technically is difficult to obtain a quality factor above 1000. Values lower than 10 are not very useful. For mass production values around 100 can be expected.

$$Q = \frac{\omega L}{R}$$

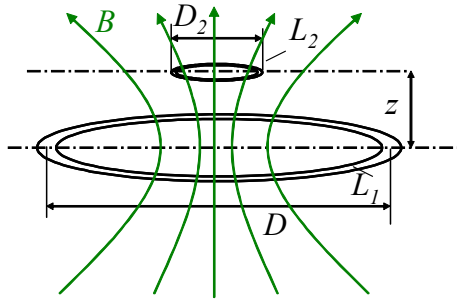


Figure 2 Arrangement of primary coil (L1) and secondary coil (L2)

Figure 3 shows the calculated optimal achievable efficiency of a system with the assumption of a quality factor of 100. All dimensions are scaled to the diameter of the larger coil D , whichever it is (transmitter or receiver coil). The values are shown as a function of the axial distance of the coils (z/D). The parameter is the diameter of the smaller coil D_2 . The figure shows that

- The efficiency drops dramatically at larger distance ($z/D > 1$) or at a large size difference of the coil ($D_2/D < 0.3$)
- A high efficiency ($>90\%$) can be achieved at close distance ($z/D < 0.1$) and for coils of similar size ($D_2/D = 0.5..1$)

So inductive power transfer between coils in proximity, e.g. when the surface of the devices are in contact with each other can be really efficient and competitive to wired solutions. These findings are published [1] and are used in this paper to explain the decision in the consortium to apply inductive proximity power.

A further advantage of the proximity is that the magnetic field will be enclosed between primary and secondary coil. This will reduce the magnetic field into the environment and will ease up to meet requirements for limiting human exposure to the field.

For these reasons, the consortium has chosen to limit the distance between primary and secondary coil to a few millimeters.

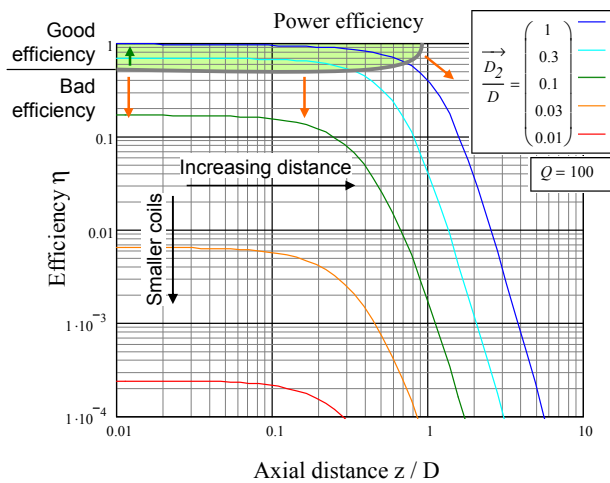


Figure 3 Power efficiency for inductive power as function of the relative distance between primary and secondary coil calculated for a quality factor of $Q = 100$

B. The dilemma between compliance and freedom of design and implementation

To achieve interoperability and a good performance, the devices have to show a standardized behavior regarding their interface. This by nature puts restrictions on the design and implementation of these devices. However in order to meet other requirements, like the support of a various applications, cost efficient implementations and product differentiation, it is necessary to keep sufficient freedom for design and implementation.

1) Magnetic field as interface

The physical interface between power transmitter and power receiver could be described in terms of the magnetic field. This might result in a minimum description of the interface and a maximum freedom for device implementation. However such interface definition would not be practical, because it is hard to define the required field distribution and to specify the actual transfer of the power in terms of the magnetic field.

2) Reference transmitters and receivers

It is more practical to describe the power transfer in terms of electrical parameters. In this context, the consortium discussed the definition of reference transmitters and reference receivers to define the interface. A transmitter should have a defined electrical result on a reference receiver and vice versa. For example a transmitter should be able to deliver 5W at the output of a reference receiver. Another example is that a receiver should be able to modulate the current, or voltage of the primary coil of a reference transmitter with sufficient depth for reliable communication.

This concept allows a high design and implementation freedom for both transmitter and receiver. A problem with this approach is that it will be very hard to prove that every transmitter, receiver combination will be interoperable. As example it is hard to guarantee that a transmitter having a larger coil size than the reference transmitter is interoperable with a receiver having a smaller coil size than the reference receiver. Although both might work well with a reference device, the coupling between such particular pair might be too low for good operation.

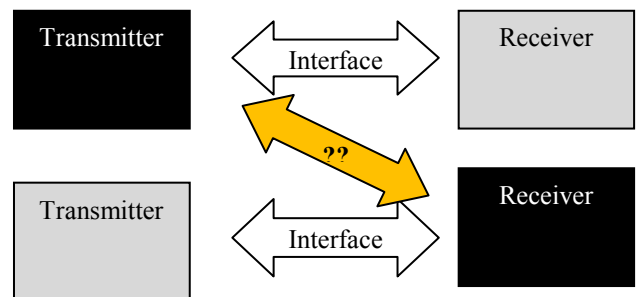


Figure 4 Interoperability between any transmitter and receiver combination is hard to guarantee if maximum design and implementation freedom is allowed to both (Black boxes indicate devices with maximum design freedom)

Since the standard is new, it is difficult to define a set of reference transmitters and receivers that will cover a wide enough spectrum to achieve sufficient certainty. More time and experience with many real products will be needed to make such approach mature (round robin tests). It is also an interesting challenge to define compliance test procedures that will meet the requirements for this approach.

3) Limitation of transmitter design freedom

To solve the above problem, the consortium intends to limit the allowed spectrum of transmitters in the first release of the specification. The specification describes a limited number of transmitter types and implementation settings that a transmitter designer has to follow in order to be compliant with the Qi standard.

The reason is obvious; this approach reduces the number of possible transmitter implementations and so also the number of possible transmitter-receiver combinations.

A small set of allowed transmitters can be regarded as stable factor in the uncertain situation of product establishment that is based on the first release of the standard. The receiver designer will have a higher confidence on the transmitter behavior by the restriction that the standard poses on the transmitter implementation. In contrary to the transmitter, the consortium preserved much design freedom for the design of the receiver to support the high number of possible applications (phones, batteries, headsets, cameras, ...) each possibly requiring a different implementation of the receiver.

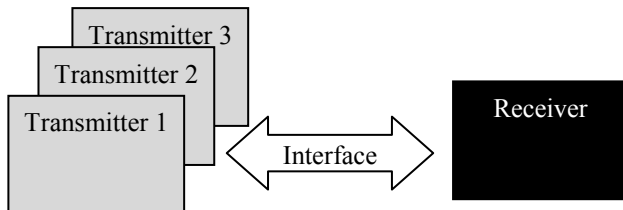


Figure 5 Small set of Transmitters (limited design freedom) to which a Receiver (high design freedom) must be interoperable

The consortium aims at more design freedom for transmitters in later stage e.g. by introducing more transmitter types and/or generalizing the transmitter descriptions.

IV. SYSTEM PREVIEW

A Qi wireless power system consists of a charging / base station and one, or more mobile devices. A base station contains one or multiple power transmitters. A mobile device contains a power receiver. The Qi interface is defined between transmitter and receiver and is divided in two basic levels:

A. Power transfer level

At this level the transmitter provides power to the receiver by means of magnetic induction.

B. Communication and control level

At this level the receiver communicates to the transmitter to control the power transfer.

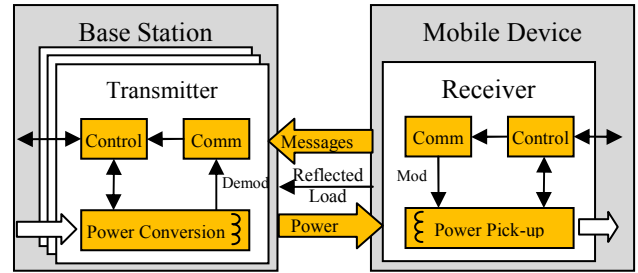


Figure 6 System Overview showing two levels: power transfer level and communication and control level.

A. Power transfer level

1) Coil alignment

To achieve a good coupling between the primary coil(s) and the secondary coil (of transmitter and receiver), the coupled coils should not only have a small distance and match in size, but they should also be aligned well in their opposite position. Optimal alignment for coils with matching size is achieved when the primary and secondary coils centers are at the same position. Figure 7 shows an example of two coils and the effect of their coupling in relation to their centered displacement. Both measured as well as calculated coupling factor are represented in this figure. Coupling factors in the range of 0.3 to 0.7 are typical. The coupling is within this range if the misalignment is limited to a few millimeters.

Note that a negative coupling factor occurs when the receiver captures the magnetic flux “from behind” when the displacement is larger than half of the diameter.

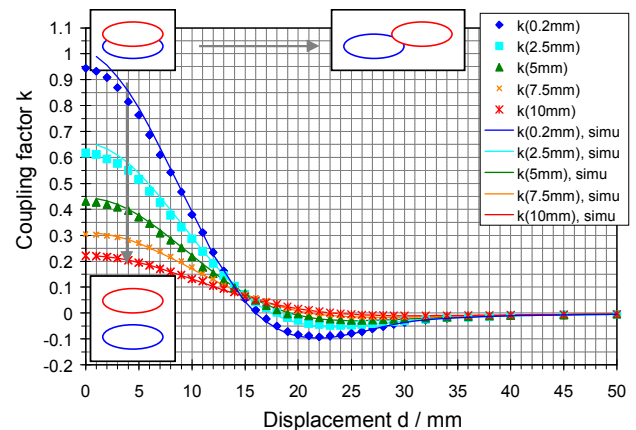


Figure 7 Example of relation between displacement and coupling factor for two coils with diameter of 30mm. Both measured (dots) as well as calculated (lines) values are shown

The Qi specification contains 3 basic transmitter types representing 3 different techniques to achieve good alignment:

- Guided positioning
- Free positioning – moving coil
- Free positioning - coil matrix

a) Guided positioning

With guided positioning, the user gets feedback for aligning the receiver to the transmitter, including in which direction to move the device as well as an acknowledgement for achieving good alignment. In principle it is left open how a receiver provides this guidance to the user. The specification however describes a transmitter that provides the means for this guidance by the use of magnetic attraction. For this transmitter, a magnet is placed at the center of the primary coil. A receiver can be equipped with a magnetic attractor at the center of the secondary coil, which could be another magnet, or any material that provides an attractive force to a magnet. The resulting attractive force between transmitter and receiver helps the user in finding alignment and by giving feedback if alignment is found. The advantage of this transmitter type is that only one primary coil is needed. The transmitter however should allow for some remaining misalignment.

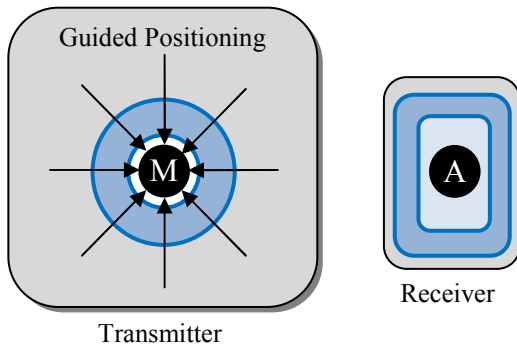


Figure 8 Transmitter with guided positioning with magnet (M) at center of the primary coil and receiver equipped with magnetic attractor (A)

b) Free positioning with moving primary coil

This transmitter supports free positioning of a receiver by locating the receiver and moving the primary coil towards the receiver's location. The transmitter contains an additional facility (not shown) to detect and locate a receiver on the transmitter. Once a receiver is detected, the transmitter moves the primary coil towards the receiver. In addition it will fine tune its position towards optimal coupling.

The advantage of this transmitter type is that free positioning is allowed and still only one primary coil is needed. Accurate alignment however requires appropriate mechanical implementation for the movement of the primary coil.

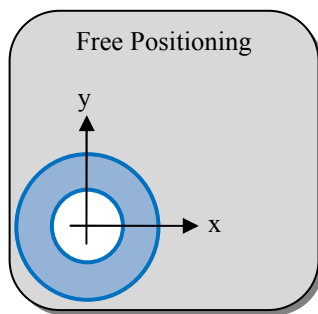


Figure 9 Transmitter with free positioning – primary coil can move to the location of the receiver coil

c) Free positioning with matrix of primary coils

This transmitter contains a matrix of primary coils distributed over the surface area via which the transmitter is able to transfer power. It supports free positioning of a receiver by activating the primary coil(s) that are at the receiver's location. To achieve homogeneous distribution of the magnetic field, the coils are positioned in three overlapping layers. The transmitter activates three overlapping primary coils that are located nearest to the receiver. These three coils generate a similar magnetic field as the single coil of the other two transmitter types. Localization of a receiver can be realized by "scanning" the primary coils on the presence of a receiver.

The advantage of this transmitter type is that free positioning is allowed. However the implementation of the array of coils, e.g. on PCB, require special attention to achieve a good quality factor (Q) and a cost efficient solution for the primary coils.

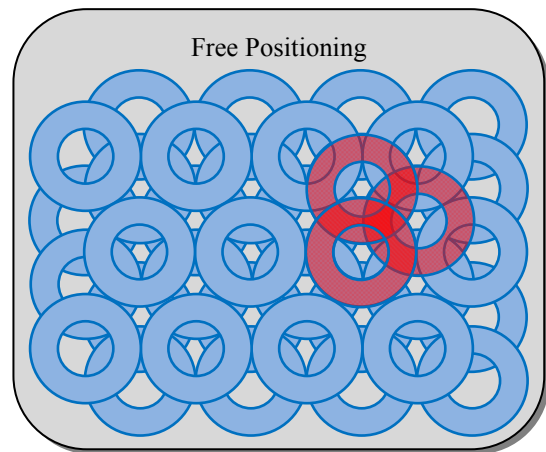


Figure 10 Transmitter with free positioning – having matrix of primary coils (Three active primary coils are indicated by a red color)

2) Power transfer facilities of transmitter

The design of each of the 3 basic transmitter designs is restricted by the specification. This is especially relevant for the primary coil, because it is the front-end of the interface to a receiver. By fixing the size and shape of the primary coil as well as the distance of the primary coil to the surface, the receiver designer can determine the expected coupling with the secondary coil. Figure 11 shows the dimensions of the primary coil for the transmitter type with guided positioning.

A further important aspect is the shielding of the primary coil. Magnetic permeable material near the primary influences the inductance value of the secondary coil when the coils are in proximity. Figure 12 shows the primary coil assembly of the guided positioning transmitter type as example.

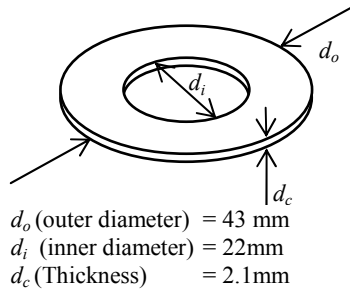


Figure 11 primary coil dimensions for transmitter with guided positioning

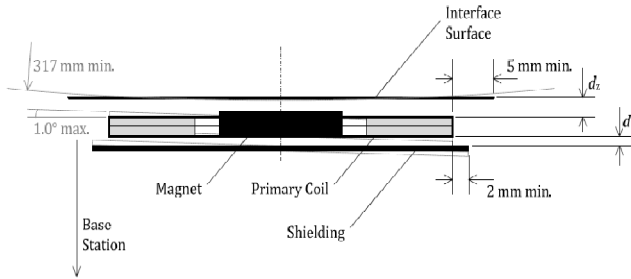


Figure 12 Primary coil assembly for transmitter with guided positioning

The electrical circuit in the transmitter that drives the current into the primary coil is restricted as well, but is subject for loosening up in the future. Figure 13, Figure 14 and Figure 15 show the electrical diagrams of the three basic transmitter designs. The inductors and resonance capacitors have fixed (but different) values for each transmitter design.

For the first design (guided positioning) the input voltage is fixed, but the frequency is variable. In the other two designs (free positioning), the frequency is fixed, but the input voltage is variable. The variable parameter is applied to control the current in the primary coil.

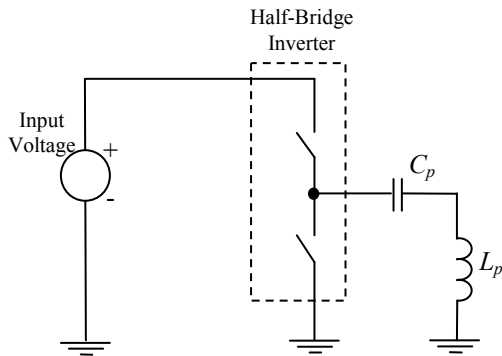


Figure 13 Electrical diagram of transmitter for guided positioning

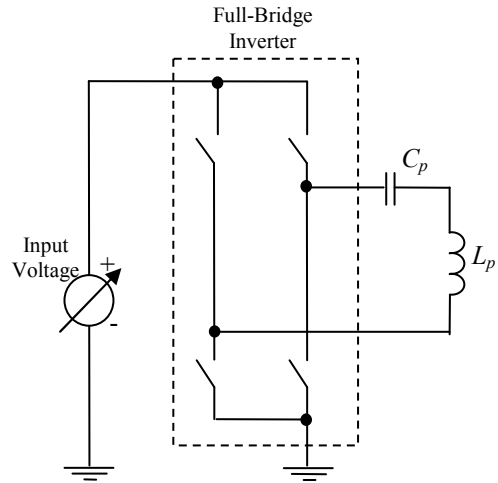


Figure 14 Electrical diagram of transmitter for free positioning with moving coil

Figure 15 shows in addition to the other figures a multiplexer with the purpose to select which primary coil(s) will be powered by the inverter. The transmitter can select e.g. three overlapping coils (as indicated in Figure 10) to provide a power signal at the location of a receiver; the inverter then provides power to these three coils in parallel. If the base station is designed for charging multiple receivers at the same time, it needs multiple inverters, one for each receiver (not shown).

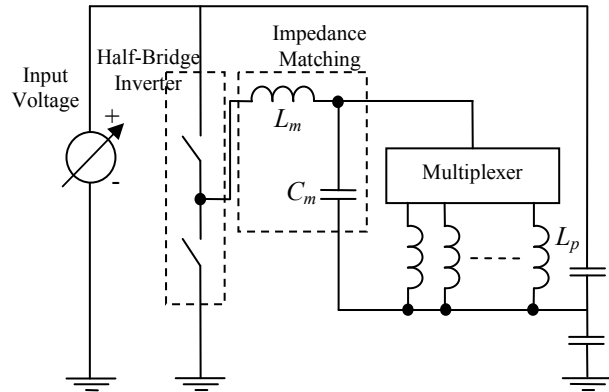


Figure 15 Electrical diagram of transmitter for free positioning with matrix of primary coils

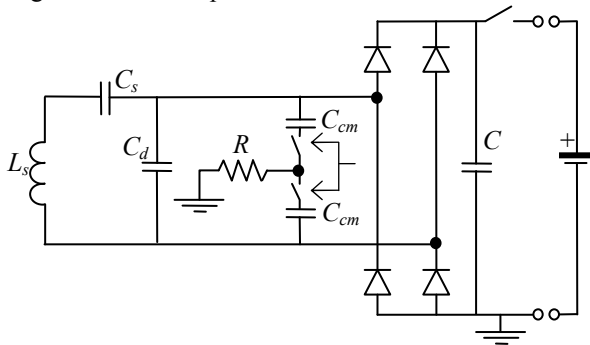
3) Power transfer facilities of receiver

The design of a receiver is largely free including the design of the secondary coil. The minor restrictions are mainly expressed as requirements, leaving significant freedom for the implementation. Most pregnant are the requirements for resonance.

Figure 16 shows a dual resonance circuit of the receiver. It contains a serial resonance capacitor (C_s) to limit the reactance of the receiver circuit. The purpose is to limit the required current in the primary coil and so to reduce the system power loss [2][3]. As a result, it reduces the heat dissipation in the transmitter and increases the power transfer efficiency.

The circuit also contains a parallel resonant capacitor (C_d). A transmitter can detect for the presence of a receiver by exiting a (small) power signal with a

The Qi specification further contains some receiver example descriptions that the designer can take as guideline for implementation. These examples are based on the experience and the validation results of the consortium and should prevent the receiver designer for making big failures. Figure 17 shows the electrical diagram of an example receiver.



V. COMMUNICATION AND CONTROL LEVEL

The consortium decided to put the receiver in control of the system. The receiver could be regarded as the client requesting a power service from the transmitter. The receiver therefore must have the ability to communicate its required power service to the transmitter. The transmitter in providing the power must have the ability to change the power signal according to the request of the receiver.

1) *Modulation / demodulation*

A receiver communicates to the transmitter by means of load modulation. To make this possible the transmitter provides a power signal to the receiver. The receiver changes its load by switching e.g. a resistor, or a capacitor (the latter only at the AC part of the receiver). The implementation of the modulator is free. As requirement it must have significant change of the current (15mA) or voltage (200mV) at the primary coil of a reference transmitter.

switching a small capacitive load between the secondary coil and (full bridge) rectifier. Experiments showed problems when switching a (resistive) load connected at the output of the rectifier due to the low internal resistance of the battery.

2) Data Formatting

Preamble	Header	Message	Checksum
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Timing diagram for a 10-bit serial transmission. The signal starts with a 'start' pulse (low), followed by 8 data bits (b0 to b7), a 'parity' pulse (low), and a 'stop' pulse (high). A time scale bar indicates 0.5ms. The data bits are: b0=1, b1=0, b2=1, b3=0, b4=1, b5=1, b6=0, b7=0.

C. System Control

1) System control phases

```

graph TD
    subgraph Transmitter
        T_Start([Start]) -- "Object Detected" --> T_Ping([Ping])
        T_Ping -- "Receiver Detected" --> T_IDC([ID&C])
        T_IDC -- "Configured" --> T_PT([PT])
        T_PT -- "Adapted" --> T_PT
        T_PT -- "Control Error" --> T_IDC
        T_PT -- "End Power" --> T_IDC
        T_PT -- "End Power / Error / Timeout" --> T_Ping
        T_PT -- "End Power / Error / Timeout" --> T_Start
    end

    subgraph Receiver
        R_Start([Start]) -- "Signal" --> R_Ping([Ping])
        R_Ping -- "Signal Strength" --> R_IDC([ID&C])
        R_IDC -- "Identification Configuration" --> R_PT([PT])
        R_PT -- "Adapted" --> R_PT
        R_PT -- "Control Error" --> R_IDC
        R_PT -- "End Power" --> R_IDC
        R_PT -- "End Power / Signal Lost" --> R_Ping
        R_PT -- "End Power / Signal Lost" --> R_Start
    end

    T_Ping -.->|Signal| R_Start
    T_IDC -.->|Signal Strength| R_Ping
    T_PT -.->|Identification Configuration| R_IDC
    T_PT -.->|Control Error| R_IDC
    T_PT -.->|End Power| R_IDC

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a) Start phase

In case a user places a receiver on a transmitter, the transmitter has to react within a considerable short time (0.5s) to indicate it has recognized a receiver. In the start phase the transmitter monitors its interface for the presence and location of any object to enable fast reaction. The specification provides some examples, but the implementation of the object monitoring is left open for the designer. The transmitter may for example shortly provide a power signal to a primary coil with a frequency that corresponds to the resonance frequency of its power conversion unit. An object near the transmitter will shift the resonance and will reduce the primary coil current. Another example is to detect a change of the capacitance of electrodes that are near the transmitter's surface. The primary coils can be applied as electrodes for that purpose. This method is of advance when the transmitter contains many primary coils in order to achieve low standby power. If a transmitter detects any change in the presence, or location of objects at its interface surface, it will enter the ping phase.

b) Ping phase

In the ping phase, the transmitter checks if a detected object is a receiver and if it has any need for power. On entering this phase, the transmitter provides a power signal on the primary coil in an attempt to establish communication with the receiver. In case no receiver reacts to this signal, the transmitter removes the power signal shortly after initiating it. If a receiver reacts on the power signal, the receiver communicates the strength of the signal it receives from the transmitter. The transmitter can apply this information to select a primary coil that provides optimal coupling in case it has multiple primary coils near the receiver. If the receiver has no need for power, it communicates this accordingly ("End Power"). In that case, the transmitter removes the power signal. If the receiver indicates any need for power, the system transits to the next phase.

c) Identification and configuration phase (ID&C)

In the identification and configuration phase, the power receiver provides information to prepare the transmitter for power transfer. The transmitter remains providing a power signal for the purpose of communication. First the receiver communicates an identifier to help the transmitter to recognize the version of the receiver, to localize the receiver unambiguously, or for any other proprietary application. In addition the receiver communicates configuration parameters to the transmitter, like the maximum required power. At the end of this phase, the transmitter decides to accept, or refuse to transfer power to the receiver. If it accepts, the system transits to the power transfer phase, otherwise it removes the power signal.

d) Power transfer phase (PT)

In the power transfer phase, the receiver controls the power transfer. The transmitter provides a power signal to the receiver e.g. to charge the battery of the mobile device, or to power any other application of the device. In addition to the other phases, where the power signal has fixed properties, the receiver can control the transmitter to change, or adapt the power signal to its desire. Figure 21 shows an overview of the power control mechanism.

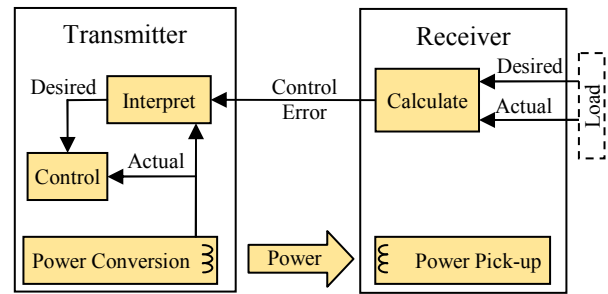


Figure 21 Power transfer control overview

To control the power transfer, the receiver communicates so called "control errors" to the transmitter. A control error indicates the difference between the desired and the actual operating point of the receiver. The receiver can apply any parameter (e.g. load voltage, or load current) as operating point for this purpose. The transmitter interprets the control error by determining a desired primary coil current relatively to the actual primary coil current. It then controls the power conversion unit to adapt the primary coil current accordingly. As a result the power transfer is controlled to the desired operation point of the receiver thereby reducing the control error towards zero.

Currently the consortium predefines the control of the primary coil current in the transmitter by the definition of a specific Proportional Integrated (PID) control loop with fixed gain parameters.

VI. CONCLUSION

The wireless power consortium provides an industry standard between power transmitters and receivers based on inductive coupling at proximity with well aligned coils. The standard provides a high design freedom for receivers and the means to control power transfer; this allows meeting the requirements of various mobile device applications both commercially as well as functionally. Confidence in achieving interoperability is achieved by limiting the design freedom for transmitters in the early phases of releasing the standard.

ACKNOWLEDGMENT

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