Design and Optimization of Simultaneous Wireless Power Transfer and Near Field Communication Systems

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Abstract

Würth Elektronik eiSos (WE) has developed a system that implements inductive wireless power transfer (WPT) along with simultaneous near field communication (NFC). The system uses a new product that combines WPT and NFC with an NFC antenna wrapped around the WPT coil to form a single efficient component. This paper describes the design goals and the optimization steps required for simultaneous operation of the WPT and NFC. This investigation is done by measurement, calculation and simulation. The developed WPT/NFC system is the first published simultaneous operating system delivering up to 190 W output power at a transfer distance of 1 cm and a data rate of 106 kbit/s with an error rate of 0 %.

1 Introduction

There are different ways to incorporate data transfer into an inductive WPT system. One route is to use in-band communication. While WPT can deliver up to some kW, the low WPT frequencies of 100-200 kHz limit the maximum data rates to some hundred bytes/s. To achieve higher data rates up to 848 kbit/s, NFC can be used for data transmission using a frequency band of 13.56 MHz. However with this wireless, standardized, near field communication technology the maximum transfer power is limited to 1 W. Unfortunately, a simultaneous operation of WPT and NFC might cause interference, because the NFC can be disturbed by the harmonics of the WPT system. Simultaneous operation means that the transfer of power and the data communication are operating at the same time. State of the art WPT and NFC systems cannot operate simultaneously. This means that the WPT has to be switched off during NFC is active. This method is called time multiplexing. To find a solution for this problem, WE investigated how to realize simultaneous working WPT/NFC systems. The first prototypes, which combine WPT and NFC in one system, are presented in previous publications of the authors [1] [2]. The advantage of these combined systems is that no custom WPT or NFC system designs are needed. Other researchers already investigated special coil designs to reduce the influence of the WPT system or build up systems, which can be used for both, WPT and NFC but not simultaneously [3] [4]. For the system developed here, only common and widely used subsystems and components are used. In this paper, the development steps of the simultaneous working prototypes are described in detail and some further design considerations and investigations are made to improve the prototypes. In addition, the influences of mismatching, caused by temperature variations and tolerances, on the WPT/NFC systems are investigated in detail.

1.1 WE WPT/NFC Combination Products

To simplify the design of a WPT/NFC system, WE developed a new product, which combines a WPT coil and an NFC antenna into one single efficient device, shown in Fig. 1.

ISBN 978-3-8007-5515-8

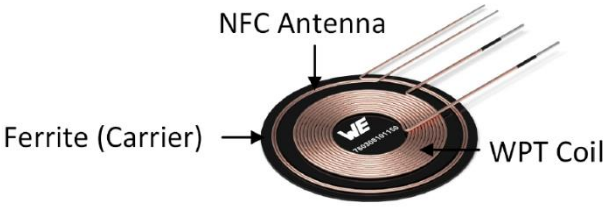

Fig. 1: WE WPT/NFC transmitter combination product (WE part number 760308101150).

The WPT coil of the part 760308101150 is the same as the MP-A11 Qi design. In addition to this transmitter, WE offers four more WPT/NFC combination products. All WE WPT/NFC products are specified in [2].

1.2 Simultaneous WPT/NFC System Setup

The simultaneous WPT/NFC system, which has been developed by WE, is described by the block diagram shown in Fig. 2.

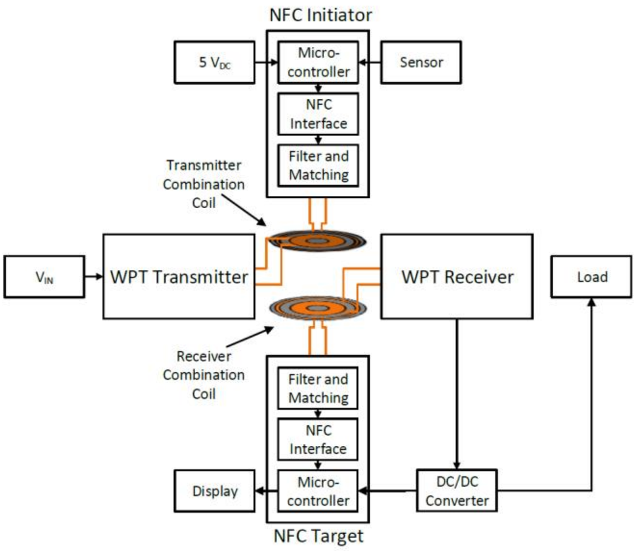

Fig. 2: Block diagram of the developed simultaneous WPT/NFC system.

Based on this setup, to achieve simultaneous operation of WPT and NFC, two different methods have been developed for the WPT transmitter and receiver parts. In the first version, the WPT transmitter and the WPT receiver parts of the WE 200 W Development Kit (WE part number 760308EMP) have been used. The WPT transmitter comprises a full bridge inverter plus peripherals, which is described in [5]. On the receiver side, a synchronous rectifier plus peripherals is used. The in-band data transmission, which is implemented in the WE 200 W Development Kit, has been deactivated, because an NFC interface is used for the communication.

In the second version, the WPT transmitter and receiver are built up using Royer converters, which are described in [6]. Compared to the first version, this is a smaller low cost solution, though the options to control the circuit are reduced significantly. At the output of the WPT receiver, an optional power management can be used. In the developed system, the WE power module reference board (WE part number 178003) has been used. The NFC initiator is based on the microcontroller board Arduino Mega 2560 with the microcontroller ATMega2560 from Atmel.

For the NFC interface, an Adafruit PN532 NFC/RFID controller shield, based on the PN532 chip set from NXP, is used. The included NFC antenna, matching and filtering circuit were removed and a self-made output NFC circuit for filtering and matching was connected on the initiator and the target side. The matching process is described mathematically, by measurement and simulation in [7]. The differential matching and filtering circuit, which is used in the system, is shown in Fig. 3.

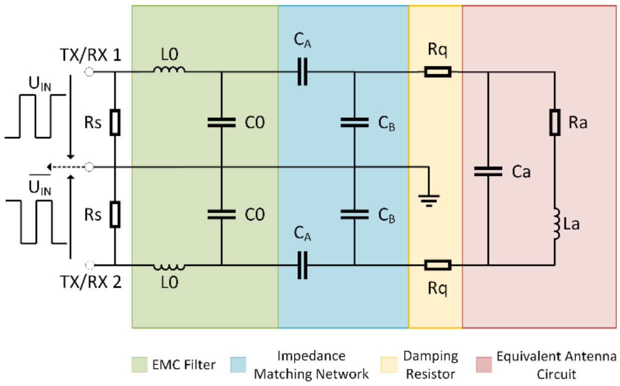

Fig. 3: Differential output NFC circuit. [7]

The single parts and the dimensioning of this differential output NFC network are described in detail in [7]. As a data source the Adafruit VL53L0X time of flight (TOF) distance sensor was implemented. The NFC target is based on an Arduino Uno Rev. 3 with the microcontroller ATmega328P from Atmel. To visualize the transmitted data the RGB LCD shield kit display from Adafruit is added. It shows the distance measured by the TOF sensor, in millimeters. The NFC standard ISO/IEC14443A is used, which has a data rate of 106 kbit/s and uses an ASK 100 % modulation and a modified Miller coding for the communication from initiator to target and a load modulation with sub carriers with Manchester coding for the communication from target to initiator.

Two different programs have been developed, one for the WPT part and one for the NFC part. The program for the WPT part deactivates the standard in-band communication of the 200 W Development Kit. The program for the NFC is based on an example delivered by Adafruit using its included reader/writer mode and card emulation mode. The receiver acts as a passive NFC target like a key card. First, the NFC initiator sends a request to write on an NFC target in fixed time intervals. If an NFC target is in range it answers the request and allows the initiator to write on it. As written data the sensor values of the TOF sensor are used. After this the receiver can send the written data to the display. [2]

2 Methods

2.1 Coupling between Tx and Rx Combination Products

To estimate the influence of the WPT system, the coupling factors between the WPT coils and NFC antennas have to be determined. First of all the effect of the distance between the combination coils to the coupling factors were simulated with Ansys Maxwell. In the second step the simulation was verified by measurement. The distance between the combination coils was varied from 1 mm to 20 mm in 1 mm steps. The distance always refers to the WPT coils, because it is the highest elevation on the combination component. For the calculation of the coupling factor L_1 and L_1' need to be measured. L_1 is the inductance of a coil in the presence of the open second coil. L_1' is the inductance of a coil in the presence of the shorted second coil. Both measurements have to be done for every distance step. The inductance was measured with a high precision LCR meter at 125 kHz. The coils were adjusted with a variable spacer. With these results and Eq. (1) the coupling factor in dependence on the distance has been determined.

$$k = \sqrt{1 - \frac{L_1'}{L_1}} \tag{1}$$

2.2 Operating Point Determination

After the coupling is known, the operating point and the waveform of the 200 W Development Kit has to be determined. The operating point is determined by the distance between the transmitter and receiver side and the necessary load at the receiver side to achieve a sinusoidal signal at the WPT coils, to reduce the harmonics of the signal. The harmonics should be avoided because they interfere with the frequency band of the NFC, which is 13.56 MHz ± 848 kHz. The load R_L, which is needed to get a sinusoidal waveform, can be calculated using Eq. (2) [8].

$$R_L = \frac{\pi^2}{8} k \omega_0 L_0 \tag{2}$$

Where R_L is the load of the WPT system, L_0 is the inductance of the receiver coil, ω_0 is the angular operating frequency and k is the coupling factor between the WPT coils.

For the operating frequency, the resonance frequency of the resonant tank is used. The formula is only an approximation, so the frequency has to be adjusted until a sinusoidal waveform is achieved. The Royer converter does not need a specific operating point, because the current waveform in the resonant tank is already sinusoidal.

2.3 Influence of the Transmitter Current on the NFC

The influence of the WPT signal waveform on the NFC frequency band has to be analyzed. This is done with the measurement of the current waveform in the WPT Tx coil creating the magnetic field and the waveform of the induced voltage in the NFC Rx antenna. The waveforms are analyzed with an oscilloscope using fast Fourier transformation (FFT). To evaluate the influence of the magnetic field, generated by the transmitter coil current, on the NFC transmission, the error rate in dependence on the transmitter current at different distances between target and initiator has been measured. The error rate is the number of incorrect values in relation to the total number of sent values.

2.4 Influence of the Temperature on the Reflection Coefficient

The operating temperature of the combination component depends on the ambient temperature and the temperature rise caused by the WPT coil, because the WPT coil and the NFC antenna share the same ferrite carrier. The temperature rise increases the series equivalent resistance R_a, which represents all ohmic losses of an NFC antenna. As a result, the load impedance and therefore the input reflection coefficient S_{11} changes, which leads to a mismatch at the NFC filter and matching circuit parts.

The temperature dependency of the resistance $R_a(T)$ can be calculated with Eq. (3).

$$R_a(\mathrm{T}) = R_{20}(1 + \alpha(T - 20°C)) \qquad (3)$$

Where R_{20} is the resistance at 20 °C and the parameter $\alpha = 4 \cdot 10^{-3}$ 1/K is the temperature coefficient.

The influence of the temperature change to the S_{11} magnitude parameter at the input of the differential output circuit of the NFC IC (see Fig. 3) has been analyzed by simulation with Keysight Advanced Design System (ADS).

2.5 Influence of the Device Tolerances on the Reflection Coefficient

The tolerances of the EMC filter inductors L_0 and capacitors C_0, the matching capacitors C_A and C_B and of the antenna inductance L_a influence the reflection coefficient S_{11} at the interface of the NFC IC and the output circuit shown in Fig. 3. These influences have been investigated by a Keysight ADS parameter sweep simulation. The nominal value, the maximum and minimum of each inductance and capacitance has been swept and the S_{11} parameter in dependence of the frequency has been simulated using a Harmonic Balance algorithm. Each inductance or capacitance has been swept while all other parameters have the nominal value. As a result, each tolerance change is determined separately for each component.

3 Results

3.1 Coupling between Tx and Rx Combination Products

The determination of the coupling factors between the WPT coils and NFC antennas by measuring and calculation using Eq. (1) and the verification by simulation with Ansys Maxwell leads to the curves shown in Fig. 4. The blue lines in Fig. 4 show the measured and simulated coupling between the WPT coils at the receiver and transmitter side and the red curves show the coupling between the WPT coil at the transmitter side and the NFC antenna at the receiver side. The product 760308101150 has been used on the transmitter and receiver sides. The deviation between simulation and measurement is lower than 0.05 for all distances.

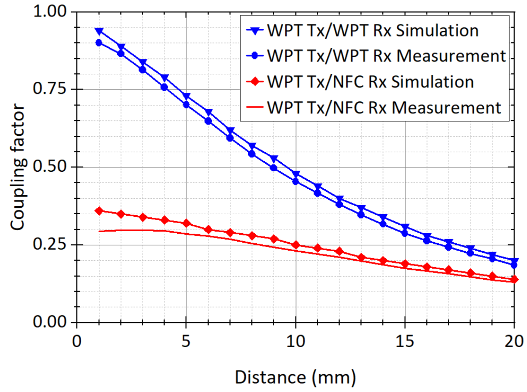

Fig. 4: Simulated and measured coupling factor of the WPT Tx coil, the Rx coil and the NFC target antenna for different distances for the product 760308101150.

The dependence of the coupling factor on the RMS current at the transmitter coil has been measured for the 200 W Development Kit by variation of the distance of the WPT coils. The input voltage at the WPT transmitter is 12 V and has not been varied for the measurement. The result is shown in Fig. 5. It can be seen, that the coupling factor between the WPT coils and the current at the transmitter side have an indirect proportional relation.

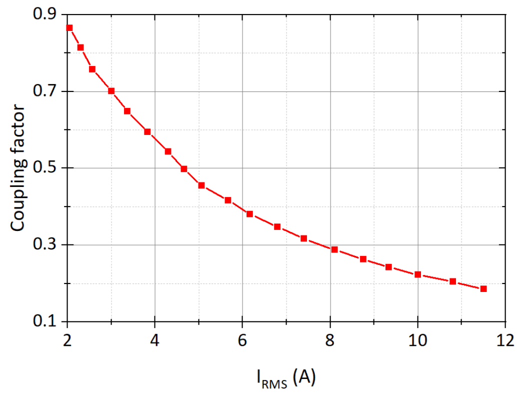

Fig. 5: Measured coupling between the WPT coils at the Tx and Rx side in dependence of the Tx RMS current with V_{in} = 12 V.

3.2 Operating Point Determination

To achieve a sinusoidal waveform at the 200 W Development Kit, the approximation Eq. (2) has been used to determine the necessary load. The inductance of the WPT coil has to be measured in the presence of the other coil for each distance. For the operating frequency, the resonance frequency of the resonant tank of the WPT system is chosen. The switching frequency of the WPT transmitter has been varied until the waveform is sinusoidal. The coupling factors for the different distances have been used from Fig. 4. Table 1 shows the operating points (load resistance R_L, resulting operating frequency f_O) of the 200 W Development Kit for distances d between 10 mm and 16 mm. In addition, the DC-to-DC efficiency η is shown for each operating point.

Tab. 1: Operating points for the 200 W Development Kit for different distances.

d (mm)	R_L (Ω)	f_O (kHz)	η (%)
10	2.12	127	72
11	1.93	123	70
12	1.74	121	70
13	1.58	119	67
14	1.43	117	64
15	1.31	115	62
16	1.20	113	60

3.3 Influence of the Transmitter Current on the NFC

To visualize the interference of the WPT system on NFC, the FFT of the ASK during data transmission of the NFC system is shown in Fig. 6.

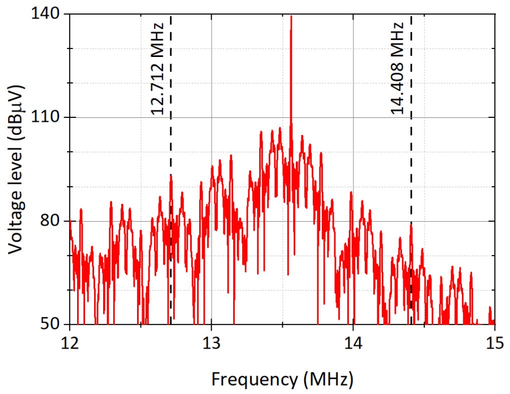

Fig. 6: FFT of the Rx NFC antenna during data transmission without an active WPT system.

The two defined subcarrier frequencies 12.702 MHz and 14.408 MHz can be seen. The analysis of the FFT of the NFC Rx antenna shows that the amplitudes of the harmonics, caused by the WPT signal, have to be lower than 90 dBµV to guarantee a working communication with an error rate less than 5 %. The maximum transferred power with the 200 W Development Kit with an error rate which does not exceed 5 % is 54 W at a distance of 10 mm (Vin = 13 V). The FFT of the Rx NFC antenna is shown in Fig. 7 at this operating point during standby with no active communication during an active WPT system.

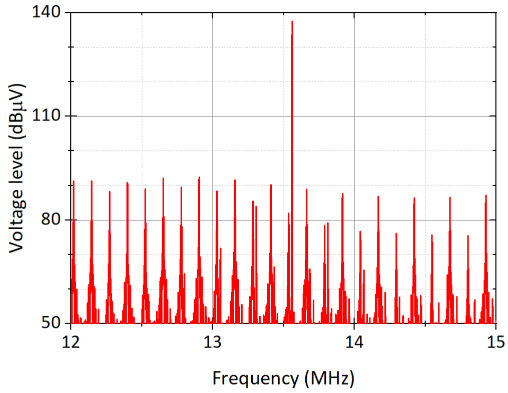

Fig. 7: FFT of the Rx NFC antenna during standby and an active WPT system.

For higher power levels the interferences superimpose the ASK signal and the error rate of the communication increases significantly, until NFC is no longer possible. This is shown in Fig. 8 where the dependency of the error rate on the WPT Tx coil current is analyzed. For a fixed distance of 10 mm the input voltage of the WPT transmitter is increased which results in a higher current. The higher current creates a stronger magnetic field interfering with the NFC. For currents higher than 5 A the rise of the error rate is very steep.

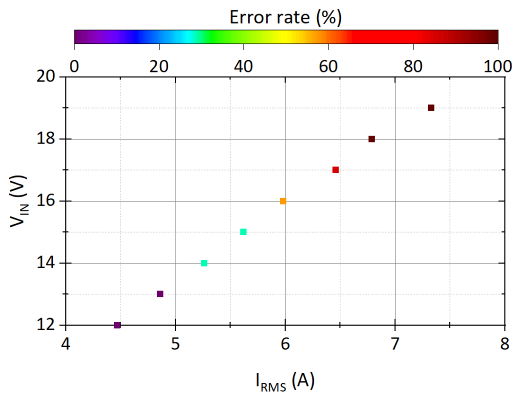

Fig. 8: NFC error rates for different RMS currents in the Tx WPT coil.

For the Royer converter no errors in the communication were measured. The WPT Tx current waveform has less harmonics interfering with the NFC frequency band. Around 160 W could be transferred with simultaneous NFC for a short time. The limiting factor in this case was the thickness of the litz wire of the WPT coils, which were heating up.

3.4 Influence of the Temperature on the Reflection Coefficient

The resistance values for R_a have been calculated for temperatures from -20 °C up to 100 °C with Eq. (3). The result is shown in Tab. 2.

Tab. 2: Resistance values of the NFC antenna for different temperatures.

T (°C)	-20	0	20	40	60	80	100
R_a (Ω)	1.0	1.1	1.2	1.3	1.4	1.5	1.6

For the different resistance values in Tab. 2, the dependence of the S_{11} parameter on the frequency has been simulated. For all other parameters of the NFC output circuit, the nominal values have been used. The result of this simulation is shown in Fig. 9.

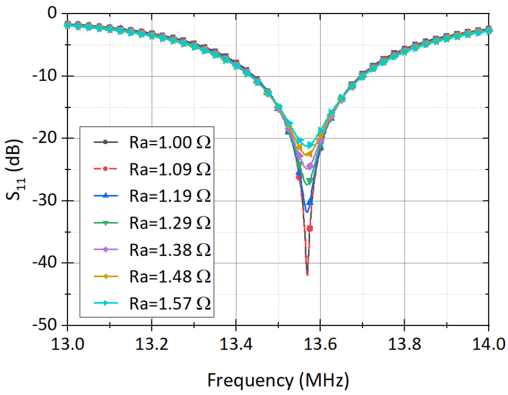

Fig. 9: S_{11} magnitude in dependence on the frequency for different NFC antenna resistances.

The S_{11} magnitude increases for resistance values, which move away from the nominal value of 1.19 Ω at room temperature. This is caused by the usage of this fixed resistance value for the impedance matching. For an operation with a fixed distance between NFC initiator and NFC target this is not a problem, because the impedance can be matched very precisely up to -40 dB or even lower. So even if the temperature range is very large the S_{11} magnitude is still small enough. If the operation distance is variable, the generally worse impedance matching for increasing or decreasing distance gets even worse through the changing wire resistance. Therefore, it is very important to verify the functionality of NFC for every operating point for the expected temperatures.

3.5 Influence of the Device Tolerances on the Reflection Coefficient

For the EMC filter, a high frequency inductor with 470 nH with 2 % tolerance and a capacitance with 247 pF with 5 % tolerance were used to achieve a corner frequency slightly above 14.408 MHz. In Fig. 10, we can see that the reflection coefficient only changes marginally within the inductor tolerance. The S_{11} magnitude and the working frequency are nearly constant. The impact of the capacitance tolerances is higher. The S_{11} magnitude can vary between -25 dB and -40 dB. In addition, the working frequency is moving further away from the NFC frequency but the working frequency is still good enough to provide a stable NFC.

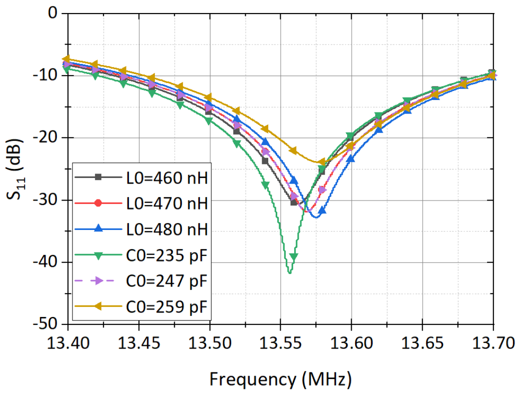

Fig. 10: Reflection coefficient vs. frequency for EMC filter components tolerances.

In the impedance matching network, two capacitances are used. C_A has a value of 32 pF and C_B a value of 182 pF. Both have a tolerance of 5 %. The tolerance of the C_A cause an increase of the S_{11} magnitude of 10 dB and changes the working frequency in the same range as C_0 does, as shown in Fig. 11. The tolerance of C_B has a much higher impact of the NFC, which could prevent a stable operation. The S_{11} magnitude increases for higher C_B values but also decreases for smaller values. The resulting frequency shift moves the working frequency nearly 300 kHz away from the NFC frequency. This results in high

S_{11} magnitudes of around -5 dB for the NFC frequency.

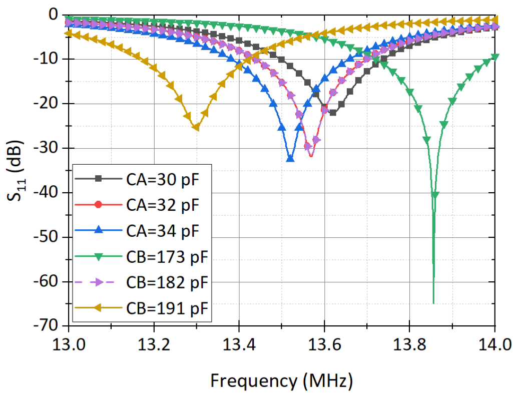

Fig. 11: S_{11} magnitude vs. frequency for impedance matching circuit components tolerances.

The NFC antenna has an inductance of 1.2 µH and a tolerance of 10 %. The high nominal tolerance can result in a failure of the NFC, as Fig. 12 shows. For the upper tolerance limits, a new impedance matching is necessary, because the frequency shift moves the working frequency several MHz away from the NFC frequency. In reality, the deviations of the inductance are much smaller than 10 %, so a new impedance matching is not required. Still, if the antennas are supplied by different manufacturers, this has to be considered.

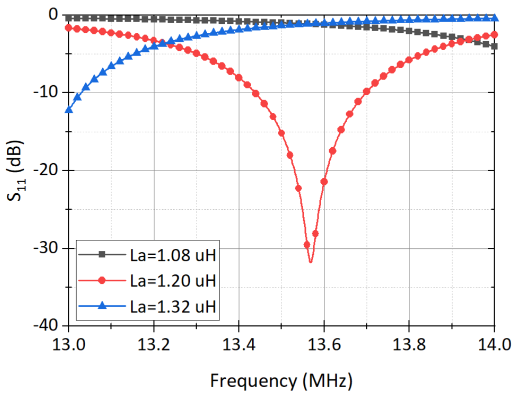

Fig. 12: Reflection coefficient magnitude vs. frequency within the NFC antenna inductance tolerance.

3.6 Summary of Necessary Design Steps for Simultaneous Operation

To achieve a simultaneous WPT/NFC operation using the 200 W Development Kit for higher powers up to 190 W, the following steps are required:

1. Definition of an operating point or operation range (e. g. 1 cm)
2. Measurement of the coupling factor between the WPT coils and the NFC antennas
3. Operating point determination, so that a sinusoidal signal is achieved for the WPT
4. Measurement of the highest possible WPT coil current without influence on the NFC frequency band
5. Approximation for the required coupling factor between the WPT coils and the NFC antennas using cross multiplication based on the indirect proportional behavior
6. Determination of the necessary WPT coil geometry, to reach a defined inductance and coupling factor

3.7 Simultaneous WPT/NFC system

The simultaneous WPT/NFC system, using the 200 W Development Kit and the Royer converters as WPT transmitter and receiver has been tested. The WPT/NFC combination component 760308101150 has been used on the Tx and Rx side.

First, a transfer distance of 1 cm has been defined (step 1).

For this distance, a coupling factor of about 0.45 can be measured between the WPT coils, which is shown in Fig. 4 (step 2).

Using Eq. (2), the operating point has been determined to R_L = 2.12 Ω and the resonance frequency has been set to f_0 = 127 kHz by tuning the switching frequency of the 200 W Development Kit WPT transmitter (step 3).

To reach a low NFC error rate, the input voltage at the WPT transmitter has been set to 12 V (see Fig. 8), which leads to a RMS current through the transmitter WPT coil of about 5 A (step 4).

Because of the indirect proportional relation of the coupling factor and the current of the WPT Tx coil (see Fig. 5), a cross multiplication can be used to determine the coupling factor, which is allowed for error free communication at higher currents. For example, a desired current of 10 A (RMS) leads to a coupling factor of k = 0.23 (step 5).

To find out, how much the distance between the NFC antennas and the WPT coils have to be varied to reach the desired coupling value, an

Ansys Maxwell parameter sweep simulation can be used (step 6).

One possible high power coil design is shown in [2]. Table 3 shows the DC-to-DC efficiencies and transferred powers at the receiver side for both WPT systems and different coils. The results have been reached for an error rate of 0 %, a distance of 1 cm, a NFC data rate of 106 kbit/s and a reflection coefficient of -35 dB at the initiator and target side.

Tab. 3: Transfer powers and efficiencies of different WPT systems and different coils.

WPT type	Used combination product	Efficiency (%)	Power (W)
200 W Kit	760308101150	72	54
	High Power Coil	80	190 W
Royer converter	760308101150	75	160 W

For the WPT system, which is set up with the Royer converters, the same operating point as for the 200 W Development Kit is used for comparison. The Royer converter WPT system provides a higher power transfer compared to the 200 W Development Kit with the product 760308101150 because the sinusoidal waveform of the Royer converter has lower harmonics at the NFC frequency band.

4 Discussion

In this paper, two simultaneous WPT/NFC systems have been designed and the design goals and optimization steps to provide a simultaneous operation of the WPT and NFC are shown. In addition, the influence of the device tolerances and the temperature on the reflection at the input port of the NFC output circuit has been examined. The main findings of this paper are the importance to ensure a sinusoidal waveform for the power transmission, so that the harmonics at the NFC frequency band are minimized and that there is an indirect proportional relation between the coupling factor and the WPT Tx current. Consequently, for a certain current at the Tx coil a maximum allowed coupling for error free communication can be determined by cross multiplication. The coupling factor between the WPT coils and NFC antennas has been adapted by the variation of the distance between the WPT coils and the NFC antennas. Another possibility to reduce the coupling would be to separate the WPT coils and NFC antennas with ferrite materials. One possible application for such a system is a wirelessly powered sensor system, which has to communicate with a high data rate without interruption. The next development goals are the increase of the NFC data rate up to 848 kbit/s without errors at a higher distance and a higher transferred power and an increased DC-to-DC efficiency.

The system developed here is the first simultaneous operating WPT/NFC setup delivering transfer powers up to 190 W at 1 cm distance, which has been published by now.

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