4^{th} *URSI AT-RASC, Gran Canaria, 19 – 24 May 2024*

Development of Adaptable Feedback Channel for Wireless Power Transmission Systems

Henrique Figueiredo Chaves[(1)(2)] and Nuno Borges Carvalho[(1)(2)]
(1) Universidade de Aveiro, Campus Universitário de Santiago, Aveiro, Portugal
(2) Instituto de Telecomunicações, Campus Universitário de Santiago, Aveiro, Portugal

Abstract

This paper introduces the development of a Feedback Channel for WPT (Wireless Power Transmission) systems to loop a complete WPT system in which the Feedback Channel is responsible for communicating to the transmitter controller the harvested power, in order to allow the optimization of the beam adjustment for the highest efficiency. Although this approach was implemented in a specific system, it is inherently designed for adaptability. This offers a versatile framework that can be integrated across WPT systems with different characteristics.

1 Introduction

The energy problems in the world are still an issue to think about, which motivated this work to be part of the area of Wireless Power Transmission (WPT) for mobile devices. Regarding this technology, there are also some challenges to be overcome, but rapid advancements in electronics have significantly propelled the growth of wireless solutions. This document is focused on far-field radiative WPT, and there is huge interest in its potential applications such as: ground-to-ground WPT to provide electricity in difficult areas to reach, ground-to-air for providing energy to aerial vehicles for communication and monitoring [1], or even space applications, such as the solar power generation in deep space and consequently its transmission to the surface of celestial bodies via microwaves [2].

Japan first suggested using microwaves to charge electric automobiles in 2004, while Hawaii recorded the world's longest wireless energy transmission in 2008 at a distance of over 148 kilometers. The quantity of scientific articles has grown in the twenty-first century, and recent years have seen some significant global research programs under progress [3].

To enhance WPT efficiency, it is essential to minimize wave spillover losses by aligning the antennas accurately. A robust WPT system requires a communication link between TX and RX for real-time monitoring of power reception during transmission. Evaluating efficiency in WPT projects is critical, and this requires accurate measurement of the power received and harvested. The communication module, assigned for measuring harvested power and relaying this information to the TX, was designated the Feedback Channel. This channel is integral not only for assessing overall efficiency but also for adjusting the beam direction to optimize power reception.

Regarding the functionalities of the proposed module, several works are reported with the implementation of backscatter mechanisms, that are passive solutions. This technology allows reflecting and modulating incident radio waves back in the transmission direction, and was used in the IoT field for other applications besides informing about the harvested power by varying its signal frequency [4].

In this paper, the novelty lies in the research and implementation of a low-complexity and low-power module. This adaptable module is capable of tracking both received and harvested power and can be integrated into WPT systems with different characteristics. So, after this introductory section, the main objectives of the work are outlined, section 3 describes the design and implementation, section 4 discusses the experimental results and in section 5 the main conclusions are presented.

2 Objectives

Taking into account that the remaining WPT system was already implemented, the following objectives were defined: design and implement an electronic mechanism responsible for measuring the power harvested in the WPT RX side; develop the wireless communication of this value to the WPT TX side and build a receiver system for this communication, resorting to a device capable of getting the harvested power value, estimate the receiver power and integrate this module with the WPT system main controller.

3 System design and implementation

The design approach of this study acknowledges the presence of a battery in the receiver, eliminating the need to develop a passive system. Nevertheless, we have focused on minimizing power consumption for this application. The overview diagram of the proposed solution including the Feedback Channel is illustrated in Figure 1. The architecture is designed to maximize scalability across various WPT systems.

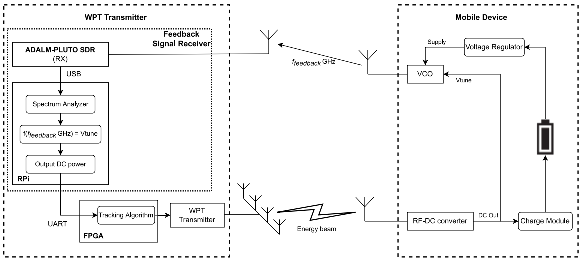

Figure 1. Feedback Channel overview diagram.

In this work, the WPT transmission operates at 5.8 GHz and although the main objective is the power measurement, this module is based on an indirect solution. The approach consists of using a component that varies the frequency of its output signal according to the DC Out voltage measured and allows it to convert that frequency back into voltage through a polynomial regression. Then, in the WPT TX (Feedback Channel RX) is implemented the correlation regression to convert the frequency of the received signal into voltage and calculate the output DC power on the RF-DC.

3.1 Voltage-frequency conversion

As shown in the diagram overview, a low-power Voltage Controlled Oscillator (VCO) is used to provide a baseband RF signal, whose frequency changes according to the DC power in the output of the RF-DC. The selected VCO was the HMC385LP4E from Analog Devices which has an output power of 4.5 dBm. Its datasheet specifies that the tuning voltage pin allows 0 to 10 V and the output frequency varies from 2.25 to 2.5 GHz. In this section it was developed a PCB for all the necessary components, the behavior of the feedback signal was studied, and a polynomial function to convert between output frequency and input voltage was determined.

In this way, not only to validate the developed board but also to determine the antenna bandwidth, a setup measurement was performed by varying the voltage in the tuning voltage pin of the VCO and measuring the frequency of the baseband RF signal on the VCO output. The laboratory setup is depicted in Figure 2 and the results obtained in Figure 3.

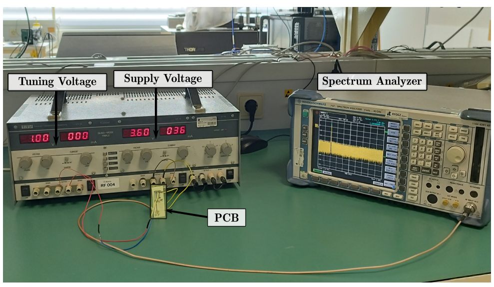

Figure 2. Setup measurement of the VCO in a laboratory environment.

From the experimental setup it is possible to verify that the

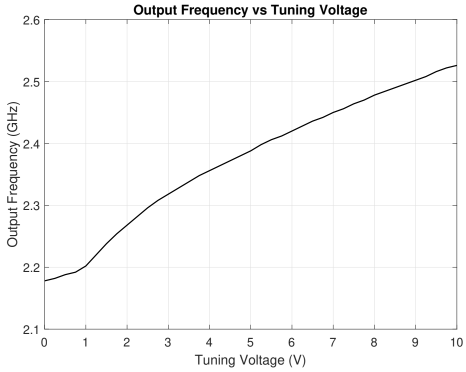

Figure 3. Laboratory measured VCO relation between output frequency and tuning voltage.

VCO power consumption is around 150 mW. When comparing the whole range of the graphic obtained with the one available in the component's datasheet, the frequency evolution has a similar behavior, thus thresholds were defined with a margin to minimize the probability of failure, so the antennas were projected to operate in a bandwidth from 2.1 to 2.6 GHz.

The measurement outcomes for the VCO enable the derivation of a straightforward polynomial function, which is instrumental in estimating the voltage value from the baseband frequency received. By applying a comparable measurement methodology to the RF-DC converters utilized in our projects, we are able to get the RF power received in the WPT RX. Consequently, these polynomial functions are incorporated into the Feedback Signal Receiver, enabling us to meet the project's objectives.

3.2 Wideband antenna

As it is necessary to consider the output frequency interval from 2.1 to 2.6 GHz, this corresponds to a fractional bandwidth of 21 % at a center frequency of 2.35 GHz. According to the literature [5], this value specifies the antenna as Ultra-wideband (UWB) antenna. When considering a 500 MHz bandwidth at a frequency close to 2.4 GHz it was proposed to design a Microstrip Patch Antenna (MPA) in the Astra MT77 substrate with permittivity (Dk) of 3, loss tangent (Df) of 0.0017 and thickness (Ts) equal to 0.762 mm.

Coaxial feed and linear polarization were chosen, but a well-known disadvantage of MPAs is their narrow bandwidth and low gain [6]. Due to the bandwidth restrictions, a simple MPA cannot achieve the desired results, so a careful study was necessary to increase the antenna bandwidth.

One possible solution to overcome this problem is to add an air layer between the radiating element and the ground plane to reduce the effective permittivity and increase the total thickness of the MPA, both of which are important factors in increasing bandwidth [7]. Besides the additional air layer, a small feed capacitive patch is also placed close to the actual radiating patch [8]. Both radiating and feed patches are etched on the same dielectric substrate and a long SMA pin is used to connect the feed patch down to the copper plane at the bottom of the antenna (ground plane). The only copper areas are the ground plane present in the bottom layer, and the feed and radiating patches in the top layer, these last two are not connected.

This approach was used to manufacture the two antennas, M3 plastic screws secured the antenna layers, with inter-layer spacing adjusted based on S_{11} measurements in the laboratory. The antennas' reflection coefficients were measured using a Keysight PNA-X (N5242A) Vector Network Analyzer.

Although simulations suggested an optimal air gap of 13.83 mm, practical adjustments led to final heights of 14.9 mm for the TX antenna and 15.1 mm for the RX antenna. The S_{11} parameter graph in Figure 4 compares the simulated and actual antennas, confirming the achievement of the targeted bandwidth. A photograph of the antenna, particularly the RX configuration, is shown in the subsequent sections.

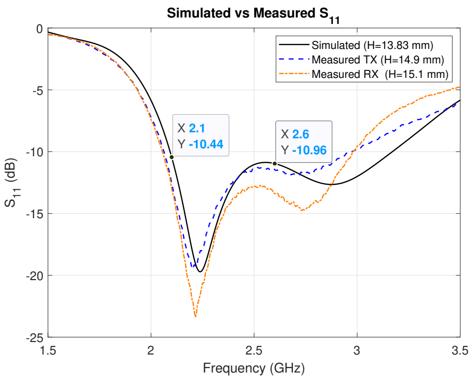

Figure 4. Comparison of the reflection coefficient between simulated, TX and RX manufactured antennas.

3.3 Feedback Signal Receiver

The Feedback Signal Receiver is a crucial sub-model designed to detect the frequency of the Feedback Channel ($f_{feedback}$ GHz). This sub-model integrates a PlutoSDR and a Raspberry Pi (RPi), harnessing their capabilities to fulfill its required functions. The harvested power is determined according to the detected frequency in the implemented spectrum analyzer and this information is relayed to the system's main controller.

As previously shown, the beam steering in the WPT TX is controlled by the FPGA, so in order to build a wireless loop where the beam control is performed according to the available DC power in the WPT RX (mobile device), it is necessary to get this value on the WPT TX side and communicate the data to the FPGA.

As the feedback frequency vary almost 500 MHz, it is required to acquire data with the PlutoSDR changing the center frequency at least 9 times to span the whole range (considering a hacked PlutoSDR with 56 MHz bandwidth). To configure and obtain the data received by the PlutoSDR, a python environment resorting to Pluto's Python API (***pyadi-iio*** [9]) was implemented in the RPi. In each iteration, the received IQ samples are processed into the frequency domain in the RPi using the FFT method and stored in an array. After the 9 iterations, is computed the PSD with all values in the array, so the frequency of the maximum peak power detected corresponds to the $f_{feedback}$ GHz in each cycle detection.

4 Experimental results

The receiver of the WPT system and the Feedback Channel TX were embedded into a 3D structure to be provided as a single product. Thus, Figure 5 presents a photo of the components integrated into the structure.

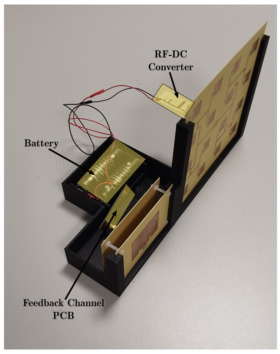

Figure 5. WPT RX and Feedback Channel TX components integration in the 3D structure. The left antenna featuring an air gap is the Feedback Channel TX, while the array of 16 elements on the right represents the WPT RX antenna.

The initial validation involved conducting a frequency detection using the PlutoSDR within the required frequency range. The setup consists of connecting the RF signal generator directly to the PlutoSDR and evaluating the developed methodology. Additionally, transmission from the Feedback Channel using known DC values was carried out to validate the Feedback Signal Receiver for subsequent integration. The modules developed for integration into a complete WPT system were tested in an anechoic chamber, as shown in Figure 6.

The objective was to measure the power in the RF-DC output when the transmitter changed the beam in different directions. The Feedback Channel RX antenna is placed below the WPT TX structure, and the UART cables (communication between FPGA and RPi) are shown below. In order to confirm the Feedback Channel power measurement, the value was also measured with a digital voltmeter. The values measured with both devices present a maximum error of 16 mW.

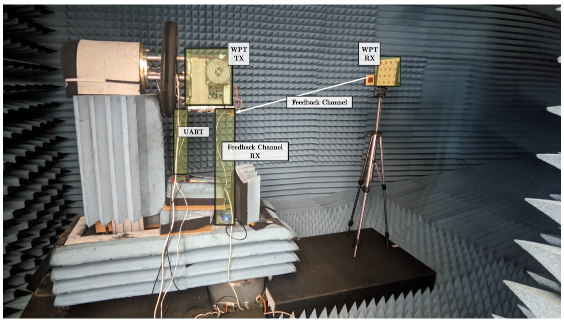

Figure 6. Complete WPT system integration with the developed Feedback Channel in the anechoic chamber.

During the anechoic chamber tests, with TX and RX of the WPT system aligned and phase settings varied between -30 to 30 degrees via FPGA, peak efficiency was identified at 0 degrees. In response, the Feedback Channel alerted the main controller to realign to this setting. The Feedback Channel adeptly detected the optimal angle for maximum power reception when the RX location was varied, always aligning with the highest power configuration. Additionally, it signaled when no energy was being received by displaying a message on the terminal, emphasizing its crucial role in ensuring safety against the potential hazards of transmitted power.

Usually, energy is not necessary to operate the backscatter on the WPT RX side, but it requires a total of three antennas including the passive tag which changes the frequency according to DC Out value. The implementation of the tag electronic circuit needs research for each specific solution and is more complex than mainly a battery and a VCO. Thus, the simplicity of implementation and robustness of the module is considered an advantage of the Feedback Channel proposed in this work.

As described, the approach for this Feedback Channel used a set of concepts and components that makes its degree of complexity quite low. The features obtained with this Feedback Channel implementation enable the possibility to be integrated into WPT systems up to 3 meters and 60º of solid angle. Regarding the process duration, the frequency sweep performed by the Feedback Signal Receiver takes about 200 ms, and the communication to the main controller via UART is a variable time between 10 and 50 ms. The time for a phase sweep for six samples took about 1.5 seconds.

5 Conclusions

The combined use of PlutoSDR and VCO fulfills the objectives of developing a system that is non-complex to implement and adaptable to different systems. As the communication of this module with the WPT system main controller was made resorting to the RPi, the communication protocol used for this case (UART) can be replaced by another available on the RPi, either wired or wireless, in order to adapt the module.

A Feedback Channel for WPT applications was implemented aiming to communicate the power value from the receiver to the transmitter in order to adjust the beam for the best efficiency. All the components were first tested in a laboratory environment and then the model was integrated with a real WPT system in the anechoic chamber, which allows us to validate the work developed in this context and study how it will be possible to extend the approach to other WPT systems.

6 Acknowledgements

This work is supported by the European Union / Next Generation EU, through Programa de Recuperação e Resiliência (PRR) [Project Nr. 11: New Space Portugal (02/C05-i01.01/2022.PC644936537-00000046)].

References

[1] "The future of bioenergy," *Global Change Biology*, vol. 26, pp. 274–286, 1 2020.

[2] R. Pereira and N. Carvalho, "Quasioptics for Increasing the Beam Efficiency of Wireless Power Transfer Systems," 2022.

[3] N. Shinohara, "History and Innovation of Wireless Power Transfer via Microwaves," *IEEE Journal of Microwaves*, vol. 1, pp. 218–228, 1 2021.

[4] R. Correia, N. B. de Carvalho, G. Fukuday, A. Miyaji, and S. Kawasaki, "Backscatter wireless sensor network with WPT capabilities," 2015, pp. 1–4.

[5] The Code of Federal Regulations (CFR), "eCFR :: 47 CFR Part 15 – Radio Frequency Devices." [Online]. Available: https://www.ecfr.gov/current/title-47/chapter-I/subchapter-A/part-1515.503

[6] K. F. Lee and J. S. Dahele, *Characteristics of microstrip patch antennas and some methods of improving frequency agility and bandwidth*. Institution of Engineering and Technology, 1 1989.

[7] Yilin Mao and Yashwanth R. Padooru and Kai Fong Lee and Atef Z. Elsherbeni and Fan Yang, "Air gap tuning of patch antenna resonance," 2011, pp. 3088–3090.

[8] Asmita Mhamane Sveri's and Pandharpur Meenakshi Pawar, "Designing of Wideband Microstrip Patch Antennas at 2.4 GHz," *International Journal of Computer Applications*, vol. 105, pp. 975–8887, 2014.

[9] Analog devices, "pyadi-iio: Device Specific Python Interfaces For IIO Drivers [Analog Devices Wiki]," 2021. [Online]. Available: https://wiki.analog.com/resources/tools-software/linux-software/pyadi-iio