IMPLEMENTATION OF A QI COMPLIANT WIRELESS POWER SYSTEM FOR AN UNDERWATER PROBE

Heitor M. Santos, Luiz F. O. Chamon, and Cássio G. Lopes

Signal Processing Lab
Electronic Systems Engineering Department
University of São Paulo – Brazil
heitorsantos.91@gmail.com, chamon@usp.br, cassio@lps.usp.br

ABSTRACT

Underwater sensing probes are used in a myriad of applications, for instance, oceanographic profiling. These probes present a design challenge as they are submitted to harsh marine environments and large pressures, which makes their waterproofing intricate. A solution to this issue would be to completely and permanently seal the probe's shell. This, however, complicates the access to the internal circuit, which poses the problem of how the equipment's batteries would be charged. This work addresses this issue by implementing a Qi-compliant wireless power transfer system. Introducing a layer model of the standard, each part of the power transmitter and receiver modules are designed, mounted, and tested. Even though the purposes of this system is battery charging, the wireless power modules described in this white paper could also be used in other applications.

1. INTRODUCTION

Oceanographic research is paramount to the preservation of coastal biomes, also contributing to economic and military interests. In this endeavor, a myriad of sensing instruments are used to map and monitor oceans and lakes, the CTD (Conductivity, Temperature, and Depth) being one of the most commonly used. This equipment is composed of a waterproofed probe equipped with conductivity, temperature, and pressure sensors. The probe is usually attached to a boat by a steel cable and dives sampling these variables at different depths. From these measurements, scientists can obtain the profile of several quantities of interest for their research, such as salinity and water density [1].

The CTD was initially developed in 1960 by the electrical engineer Neil Brown, from Bissett-Berman Corporation. It has since evolved into a more feature-rich equipment, including different sensors (light, current velocity, etc.) and automatic profiling capabilities [2]. Still, some issues have yet to be fully addressed, one of the most important being waterproofing. The use of these instruments in great depths requires costly sealing solutions that can deal with large pressure, since any infiltration, no matter how small, can permanently damage the instrument.

Our laboratory proposed permanently sealing the CTD probe as a solution to this problem. This could be achieved, for example, by making use of an acrylic cast which fully impermeabilizes the internal circuitry. Nevertheless, this raises two additional problems: data access and powering. The former can easily be dealt with using any of the countless wireless communication systems available nowadays. The latter, on the other hand, is more demanding. Even though most probes already rely on batteries to operate, these are usually recharged using a specific connector on the probe's shell, which defies our fully sealed probe solution.

This work addresses this issue by recharging the batteries via wireless power (WP) transfer (inductive charging), allowing the probe's shell to be completely and permanently sealed [3]. This white paper starts giving an overview of WP transfer and the available standards for it. A layer implementation of the Qi standard is then introduced, which has the advantage of facilitating development and increasing the system's robustness. Finally, implementation details are presented and testing results are analyzed and discussed.

2. WP TRANSFER

WP transfer is useful in situations where wiring is inconvenient or even impossible. It consists of supplying energy to a device using air as a conductive medium, by means of electromagnetic waves or magnetic fields. The current application is justified by the inaccessible nature of the batteries due to the permanent sealing of the underwater probe.

The development of WP transfer can be traced back to Nikola Tesla. Though scientists had been studying electromagnetic induction since the early 18th century, Tesla was the first to demonstrate its use for transmitting power wirelessly. In 1891, he lighted a lamp without connecting wires to it, later patenting several other applications of WP [4].

Slow progresses were made in the field of WP during the 1900s, such that in the beginning of the 21th century there

Table 1. Market assessment of WP standards [5]

	WPC	PMA	A4WP
Member Companies	140+ members	80+ members	40+ members
Specification Published	Yes (WPC1.1), public	Yes (PMA 1.1), members only	Yes (v1.0), members only
Approved Tx Types	> 20	In development	In development
Certified Products	160	In development	In development
IC Solution Available	Yes (5 suppliers)	Two in development	None public
Regulatory Approvals	Yes	Yes	No
Infrastructure Play	U.S., Japan, Europe	U.S., Europe	None

were only a few consumer products employing this technology. This scenario, however, is rapidly changing and the WP market has shown a significant growth in recent years. An increasing number of companies have been interested in WP and the development of several WP standards (Section 2.1) has been fundamental in this process [5].

Even though this work is applied to the charging of an underwater probe's battery, WP can be applied to countless electronic consumer products, such as mobile phones, MP3 players, laptops; medical devices, like pacemakers [6]; and even electric vehicles [7].

2.1. WP Standards

Currently, there are three main organizations [5] developing WP transfer standards: the Wireless Power Consortium (WPC), responsible for the Qi standard (see Section 2.2); the Alliance for Wireless Power (A4WP); and the Power Matters Alliance (PMA). So far, only the Qi standard is ready and freely available to the community on the WPC website [8]. A4WP and PMA standards are still under development and are only available to members of the respective groups. Comparisons between the three standard can be found on Table 1.

2.2. Qi WP Standards

WPC is the largest group involved in the creation of WP standards (more than 140 members), presenting the most developed standard so far: the Qi standard [5,9].

Developed since 2008, the Qi standard is based on inductive coupling and magnetic resonance. The current version (1.1) aims at low power devices, defining close-proximity power transfers up to 5W. The standard was named after the Asian philosophy's term "Qi", meaning *vital energy* (referring to the power flow that allows devices to work) [6,9].

3. THE QI LAYER MODEL

The Qi standard does not define the structure of the power transmitters and receivers, only their specifications. In this work, we introduce a layer model for the Qi standard (Figure 1) in order to facilitate the development of the system. Layer designs are considered robust, since each layer can be implemented independently, and have been used in several applications, such as the OSI model and the World Wide Web [10].

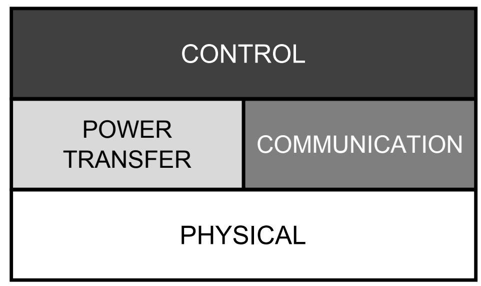


Fig. 1. Qi layer model

3.1. Physical Layer

This layer is responsible for the transduction of electric to magnetic energy. The physical layer is the actual gateway to WP transfer, though it is also involved in the exchange of messages between Qi devices.

The Qi standard describes several transmitter/receiver sets that are adequate for different applications [9]. In this work, a 24 μH and a 15.3 μH coil were chosen for the transmitter and receiver respectively. Cylindrical helical coils with air cores were chosen due to their ease of construction and well-known behavior. The inductors' design was based on Nagaoka's model,

$$L = \pi \mu N \frac{R^2}{\ell} K$$

where L is the self-inductance of the coil, μ is the magnetic permeability of the medium, R is the radius of the coil, N is the number of turns, ℓ is the length of the coil and K is the Nagaoka's factor [11].

3.2. Power Layer

The power layer is responsible for performing the conversions necessary to transfer power, i.e., it is responsible for DC-to-AC conversion in the transmitter and AC-to-DC conversion in the receiver. This layer connects directly to both the source and the load, thus being the layer that indeed retrieves energy from the source and delivers it to the load.

The power layer is also responsible for the sensing of the physical layer. For the purposes of this implementation, it is sufficient to measure the current going through the coils, since the voltage is known a priori. These measurements are required by the Communication layer to receive messages from the receiver module and by the Control layer to adjust the transmitted power.

The Qi standard determines that the operation frequency should be within a 100–205 kHz range [9]. The nominal frequency must corresponds to the resonance of the transmitter-receiver pair, so as to allow for maximum power transfer. This work adopts a nominal frequency of 100 kHz.

In order to adjust the resonant frequency of the transmitter-receiver coils, suitable series capacitors were selected. Using the resonant frequency relation for series LC circuits, namely

$$f = \frac{1}{2\pi\sqrt{LC}} \Rightarrow C = \frac{1}{L(2\pi f)^2}$$

Taking $L_{TX} = 24\mu$H and $L_{RX} = 15.3\mu$H, the inductance of the transmitter and receiver coils, yields

$$C_{TX} = \frac{1}{L_{TX}(2\pi 100 \cdot 10^3)^2} \Rightarrow C_{TX} = 105.54 \text{ nF}$$
$$C_{RX} = \frac{1}{L_{RX}(2\pi 100 \cdot 10^3)^2} \Rightarrow C_{RX} = 165.56 \text{ nF}$$

These values were adopted as an initial estimate of the necessary capacitance. Tuning of capacitors values was later performed in-circuit to improve the resulting resonance.

3.3. Communication Layer

The Qi standard defines a one-way communication protocol from the receiver to the transmitter module. Hence, the receiver can send identification and control messages to the transmitter, but the latter has no way to respond except by controlling the power being transferred. Communication between the modules is used to ensure Qi compliance, determine the device's power requirements, and control the power transfer [9].

The communication protocol relies on a biphase differential signaling. In this scheme, each bit is transmitted in two clock periods [9]. Zeros are encoded using the same level in both periods, whereas ones perform a transition after the first period (Figure 2). The advantage of this coding system is that the message is invariant to polarity inversions: even if the modulated signal is inverted, the received message remains the same.

The message bits are grouped in bytes of 11 bits (Figure 2) consisting of a start bit (0), 8 information bits (from least to most significant), a parity bit (even), and a stop bit (1). These bytes are, then, transmitted in packets described below (Figure 3):

- **Preamble:** sequence of 11 to 25 bits 1 used for synchronization purposes;
- **Header:** one byte that determines the packet type and, implicitly, the message size;
- **Message:** up to 27 bytes carrying the actual information of the packet, i.e., the payload;
- **Checksum:** single byte resulting of the exclusive or of the message and header bytes.

The packets are transmitted using amplitude modulation by switching a capacitive and/or resistive dummy load on the receiver side (Figure 4). The modulation frequency defined by the Qi standard is 2 kHz, i.e., the differential signaling clock is 4 kHz [9].

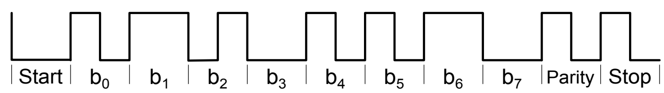


Fig. 2. A Qi byte (0x35) [9]

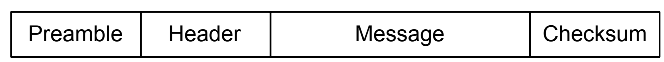


Fig. 3. Configuration for a packet of bytes

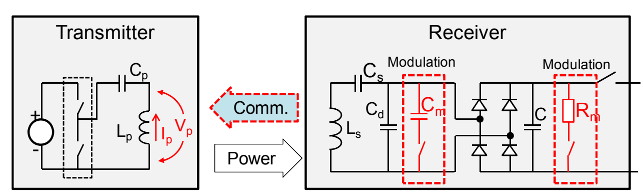


Fig. 4. Diagram of the capacitive dummy load modulator [12]

3.4. Control Layer

The Control layer coordinates the whole WP transfer. It has different roles in the receiver and transmitter. The receiver Control layer is responsible for the messages that the Communication layer delivers to the transmitter. It also compares the current sensing data from the Power layer with the load set point to generate error value messages. The transmitter Control layer manages the WP transfer. It checks the compliance of the receiving device, gathers its identification and configuration informations, and uses the error value messages received to feed a PID controller that adjusts the power sent by the Power layer.

The Qi standard defines a four-phases WP transfer (Figure 5) [9]:

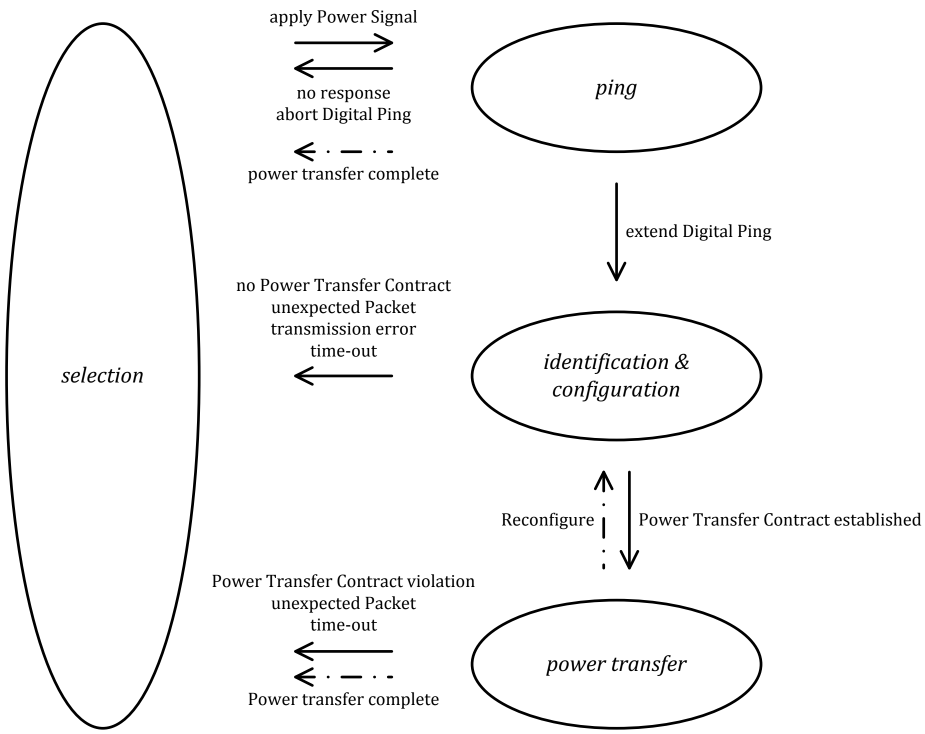


Fig. 5. Phases of the power transfer process and control protocol [9]

- **Selection:** during this initial phase no power is transferred. The transmitter recurrently checks for the presence of an object, usually using short power bursts. As soon as an object is detected, the process follows to the next phase. Whenever the WP transfer is interrupted, the system returns to this phase;
- **Ping:** the transmitter checks if the detected object is a Qi compatible device. To do so, the transmitter starts sending power at a nominal level and waits for a predefined packet. If this packet is not received within a certain time limit, the transmitter aborts the WP transfer;
- **Identification & Configuration:** in this phase, the receiver sends all the information necessary to start a WP transfer. The transmitter can check if it supports the device's version and required power and choose to abort or proceed with the transfer ;
- **Power Transfer:** this is the phase when the actual power transfer takes place. The power is controlled using error value messages from the receiver and adjusting the inverter's operating frequency.

4. IMPLEMENTATION

During the implementation of the Qi standard, the layer design model introduced in the last section was extensively used. All circuits and firmwares were independently developed and tested relying only of their interfaces to other layers. A final integration step was then performed so as to produce the final prototype.

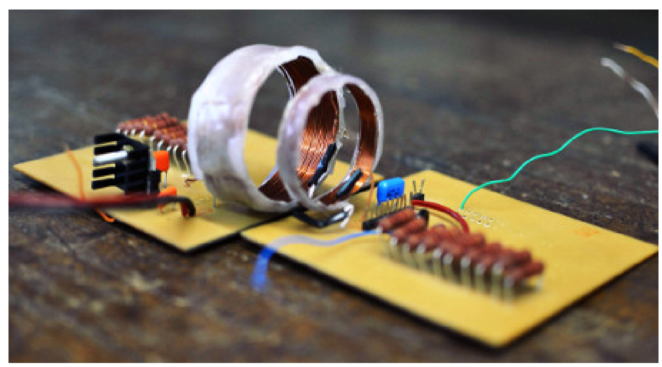


Fig. 6. WP transfer system prototype

The final prototype can be seen in Figure 6 and a detailed block diagram is presented in Figure 7. In the following sections, the implementation of the aforementioned layers is described in more details.

4.1. Microcontroller

In this work, the microcontroller adopted to implement the Qi protocol was the Texas Instruments MSP430. The MSP430 is

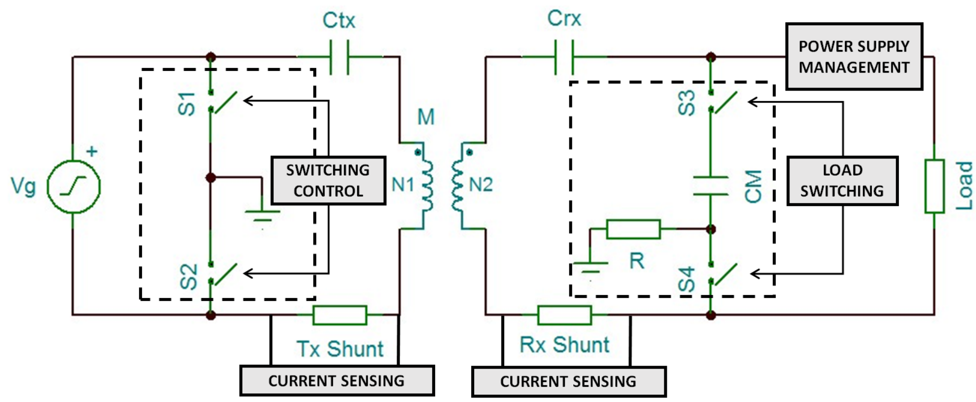


Fig. 7. WP transfer system overview

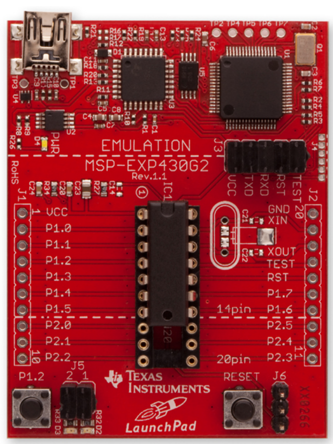


Fig. 8. Texas Instruments' MSP430 LaunchPad

a low power 16-bit RISC microcontroller with embedded 10-bit ADCs, timers, PWM, and UART [13], making it appropriate for the present implementation. Another advantage of this microcontroller is the MSP430 LaunchPad board [14], an evaluation/development module which facilitates its use and test in prototypes (Figure 8).

4.2. Physical Layer

The helical coils constructed for the WP transfer modules can be seen in Figure 6. Their characterization is presented in Table 2, where the theoretical values evaluated in Section 3.1 are compared to measurements of the actual coils. The latter were obtained using a 1 V signal at 100 kHz.

Given the values obtained, the coupling coefficient can be evaluated. Explicitly,

$$k = \frac{M}{L_{TX} L_{RX}} \approx 0.3,$$

where k is the coupling coefficient and M is the mutual inductance of the coils.

Table 2. Comparison between calculated and measured inductance values

Module	Theoretical L (μH)	Measured L (μH)	Measured M (μH)
Transmitter coil	25.4	25.309	5.518
Receiver coil	14.3	14.193	5.518

Table 3. Characterization of the capacitors of the WP transfer coils

Module	Theoretical C (nF)	Nominal C (nF)	Measured C (nF)
Transmitter coil	105.54	120	113.19
Receiver coil	165.56	180	179.40

4.3. Power Layer

So as to guarantee the resonant frequency chosen in Section 3.2, the capacitance was tuned according to the coils inductances. To do so, the theoretical values previously determined were approximated by standardized capacitor values and simulated using SPICE. The selected capacitors are characterized in Table 3 and the assembled circuit frequency response is illustrated in Figure 9. Again, the impedance measurements were performed using a 1 V signal at 100 kHz.

The power layer is also responsible for DC-to-AC and AC-to-DC conversions in the transmitter and receiver modules, respectively. The transmitter inverter produces a square wave from a DC voltage by switching the load between VCC and ground (see *Switching Control* in Figure 7). To do so, this implementation relied on an H-bridge driver IC, which has the advantage of requiring a single signal from the microcontroller and taking care of PWM dead time internally [15]. Hence, the MSP is relieved of this task, simplifying the firmware.

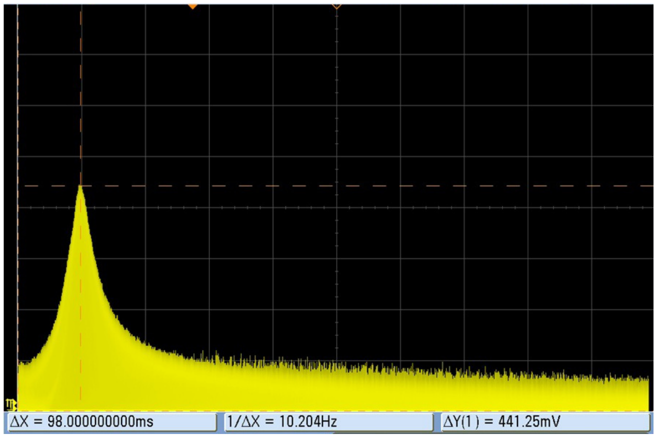


Fig. 9. Frequency response of the transmitter/receiver pair: measured using a sine sweep from 50 to 550 kHz (0.5 kHz/ms). Resonance = 99 kHz

Due to high quality factor of the LC filter formed by transmitter/receiver pair (see Figure 9), the received voltage is approximately sinusoidal. Before it can be delivered to the load, it must therefore be rectified. As a proof of concept, this work adopts a full-bridge diode rectifier. Though there are more efficient solutions, such as those based on silicon-controlled rectifiers (SCR) or switch-mode supplies [16], the diode rectifier is simpler and sufficient for this implementation's purposes.

Finally, this layer must also perform the task of sensing current on both modules. In this development, a low side 1 Ω shunt resistor was used to simplify the design. Even though high side measurements are more reliable in many applications, there would be little gains in this case. Furthermore, high side current sensing requires a more costly differential amplifier to deal with the larger common mode voltages. Before entering the microcontroller's AD converter, the current sensor signal passes through a peak hold to facilitate its amplitude measurements.

4.4. Communication Layer

Contrary to the previous layers, which were implemented mainly in hardware, the communication layer has both hardware and firmware components. This section first describes the receiver side, which from the communication viewpoint transmits messages, then discussing the reception of these messages by the transmitter.

The receiver firmware starts by mounting the packets, appending start, stop, and parity bits to the message, constructing the preamble and the header, and calculating the checksum. Using an interrupt routine, the receiver sends the packet by modulating the dummy load (see Figure 7) using the MOSFET switches shown in Figure 10. This bootstrap circuit is only necessary when the MOSFET transistors' gates are not

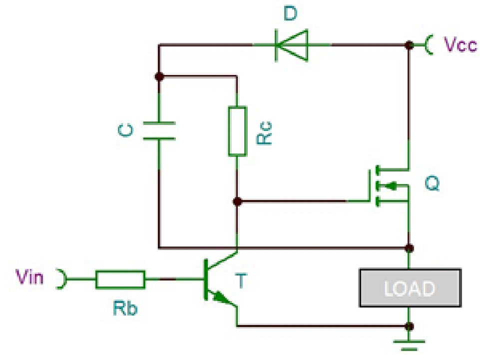


Fig. 10. Bootstrap circuit with MOSFET transistor

logic level, i.e., they cannot be triggered by typical logic voltages. Here, a BJT, which is able to turn on at lower voltages, is used to control the charge and discharge of diode/capacitor voltage doubler, thus enabling the MOSFET to act as a switch. The biphase differential signaling is implemented by the interrupt routine during the load modulation.

The communication layer on the transmitter module is firmware-only, since current sensing information are already captured by the Power layer. The demodulation routine, however, is not as straightforward as the modulation one. While the transmitter is waiting for a message, it samples the current level at approximately 8 kHz, i.e., twice the preamble frequency. As soon as it detects a level shift, the firmware samples the channel at higher speed (about 50 kHz) so as to determine the bit period and align its measurements to a preamble edge (Figure 11a). The firmware then synchronizes to the middle of the bit and starts sampling at normal pace (Figure 11b). The demodulation occurs at the same time as the sampling, so that the transmitter records the demodulated bits.

After the header has been acquired, the transmitter can evaluate the number of bytes in the message. It then proceeds to capture the message and compare the checksums. If the reception is successful, the header and message become available to the Control layer. Otherwise, the Communication layer will reset the process immediately.

Figure 11c illustrates the communication of three packets (ping, identification, and configuration) between the Qi modules.

4.5. Control Layer

The first role of the control layer is that of controlling the WP transfer process flow, i.e., going through the phases described in Section 3.4. The receiver firmware goes straightforwardly through all phases as long as it is receiving power. The transmitter, on the other hand, has the more complicated task of constantly checking whether all requirements of one phase were met before proceeding to the next one. Both flow control were implemented using an array of function pointers traversed by a variable that tracked the current phase. In case of errors (wrong message header, time out, incompatible device etc.), the transmitter microcontroller was reset, thus ending the power transfer and restarting the phases cycle.

The transmitter's control layer has the additional task of adjusting the inverter frequency to control the amount of power transferred to the receiver. To do so, the transmitter uses error messages from the receiver and a PID controller. Explicitly,

$$P(i,j) = e(i,j)$$
$$I(i,j) = \min[\, I(i,j-1) + e(i,j)\cdot t\,;\, I_{\max}\,]$$
$$D(i,j) = \frac{e(i,j) - e(i,j-1)}{t}$$
$$PID(i,j) = [K_P P(i,j) + K_I I(i,j) + K_D D(i,j)]\, S_v$$

where i indexes the outer loop (which starts upon receiving a new error message) and $j = 1, \ldots, J$ indexes the inner loop; $e(i,j)$ is the error, with $e(i,1)$ being the first value received from the power receiver module and $e(i,0) = e(i-1,J)$; K_P, K_I, and K_D are the proportional, integral, and derivative gains, respectively; S_v is the control gain which converts the PID update to the control signal; t is the time it takes for the inner loop to execute; $I_{\max}$ is used to avoid integral windup issues; $I(i,0) = I(i-1,J)$ represent the value of the integral term at the end of the last outer loop iteration [9,17]. The Qi standard suggests that the proportional term alone would be sufficient for this type of implementation [9].

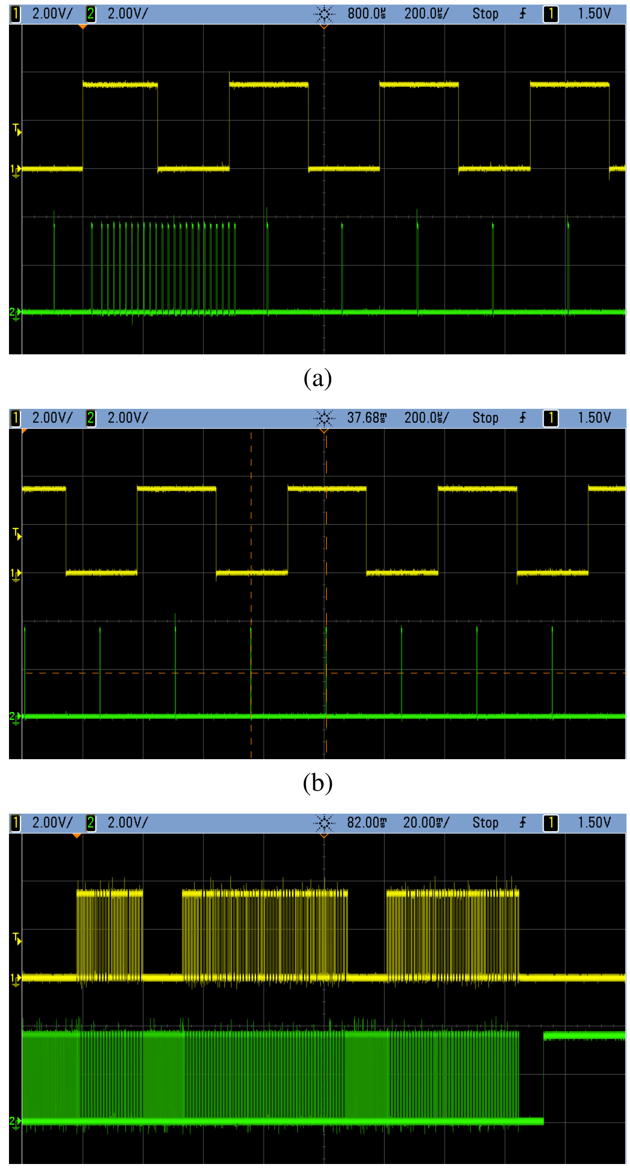
Though the control layer has been fully implemented, the PID controller parameters still requires adjustments to function properly. So far, it has only been validated in debugging simulations.

4.6. Power Supply Management

The WP receiver module is responsible for charging the lithium-polymer (LiPo) battery used to power the underwater probe. This type of battery, however, requires care since its life cycle may be reduced if it is fully discharged or charged too quickly. In some cases, LiPo batteries can incinerate and even explode.

Several dedicated ICs are available to manage this kind of battery. In this work, Microchip's MCP73831 was used [18]. A typical configuration of this IC is introduced in Figure 12.

As the figure shows, the output of the Power layer on the receiver module is connected to one side of the IC, while the battery is connected to the other. Instead of an LED, the STAT pin is used by the microcontroller to determine when it should request the power transfer to end. The 2 kΩ resistor on the PROG pin sets the constant-current charge mode of the IC to 500 mA. If necessary, this pin can be used to manually disable the charging at any moment. Here, however, the receiver module can rely on the undervoltage lock out of the IC.



(a) (b) (c)

Fig. 11. Communication: receiver message (upper yellow curves) and transmitter sampling (lower green curves). The transmitter first synchronizes using the preamble **(a)** and then proceeds to the message **(b)**. Ping, identification, and configuration packets are illustrated in **(c)**.

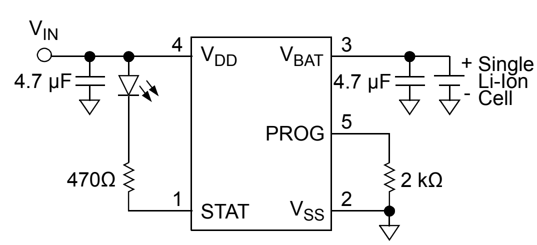


Fig. 12. MCP73831 for LiPo battery charging [18]

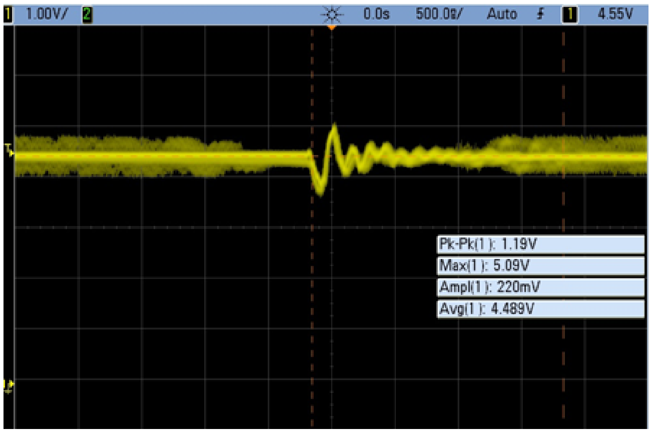


Fig. 13. Rectified received voltage on a $1\ \Omega$ dummy load. Power = 20.15 W

4.7. Integration and PCB design

This last step consists of integrating the layers and making the necessary adjustments to the interfaces so as to enable WP transfer. Since the layers were carefully designed and tested, interfacing them was straightforward. However, tuning the modules parameters is a non-trivial task that depends on a myriad of factors extrinsic to the circuit design, such as components tolerances, parasitics etc. Though the design allowed most adjustments to be made in the firmware, some hardware would, nevertheless, be necessary.

The transmitter and receiver modules printed circuit boards (PCBs) were designed so that the MSP430 Launchpad could be easily connected to them. This was done so as to facilitate system debugging. Once assembled (Figure 6), the system was tested using a $1\ \Omega$ dummy load. In this test, the input voltage was increased up to the point where the circuit started to overheat. The implemented system was able to supply more than 20 W to the receiver module using a 20 V input (Figure 13). Hence, this implementation can perform well above the 5 W required by the Qi standard v1.1. Still, efficiency could be increased by improving the performance of some of the system components (e.g., the coils).

5. CONCLUSION

This white paper details the implementation of a Qi compliant WP transfer device. This device was designed to be used as a charger for the batteries of an underwater probe, though it could easily be adapted to serve other purposes. It starts by describing the main characteristics of the standard and introducing a layer model of the system. The implementation of each layer was then detailed, along with the result of their testings. Though all layers were individually functional, the integration step was only concluded for the Physical, Power, and, partially, for the Control layer. Future works include tuning of the Communication layer and the PID controller parameters; optimization of the coils design to increase the WP transfer efficiency; improvement of the receiver's rectifier to reduce losses; and development of a more precise current sensor.

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