A 700 kHz Ultrasonic Link for Wireless Powering of Implantable Medical Devices

Raffaele Guida, G. Enrico Santagati, Tommaso Melodia,
Department of Electrical and Computer Engineering
Northeastern University, MA 02115, USA
Email: {guidar, santagati, melodia}@ece.neu.edu

***Abstract*—Wireless energy transmission to medical implants via ultrasonic waves is a promising technology with significant potential benefits over systems relying on radio frequency (RF) transmission in terms of (i) charging efficiency (ii) safety concerns. This paper discusses the design of an ultrasonic link to transfer energy from an external acoustic transmitter to an in-body deeply implanted medical device (IMD). Experimental results show that the rectified wave is able to convey enough power to completely charge a $0.22\,\mathrm{F}$ supercapacitor in $210\,\mathrm{s}$.**

***Keywords*—UTET; energy harvesting; IMD**

I. Introduction

Powering implanted electronic systems is a critical challenge in the area of implantable medical devices (IMDs) [1] [2]. Clearly, this is a crucial problem especially for life-saving medical devices like cardiac or neural bio-implants. Currently, the most common ways to provide the energy necessary to power IMDs are batteries and supercapacitors, energy harvesting solutions, and transcutaneous energy transmission (TET). Among the different TET technologies, which include radio frequency (RF) transmission and electromagnetic induction [2], ultrasonic TET (UTET) is particularly promising [3] [4] [5], [6].

Ultrasounds traversing biological tissues can result in phenomena such as cavitation, mechanical stimulation, and temperature increase. In specific cases, depending on the power of the wave and the duration of the exposure, health hazards can arise. For these reasons the FDA regulates the acoustic wave power emissions defining the safety limits for ultrasound transmissions in medical applications [7]. The safety limitations on acoustic power are, however, less constraining with respect to the RF radiation exposure limits [6]. The benefits of using ultrasounds can therefore be grouped in three major categories briefly described below.

Safety. Exposure of human tissues to ultrasounds is considered safer than electromagnetic (EM) radiations. EM waves are significantly absorbed by vital organs (particularly by cardiac and brain tissues) and, as a consequence, the temperature in the exposed area of the body increases and the power transferred to the receiver end of the wireless link is significantly reduced.

Power levels. Higher power intensities can be used for ultrasonic transmissions with no health hazards. For this reason, the FDA allows much higher intensity for acoustic waves ($720\,\mathrm{mW/cm^2}$) in tissues as compared to RF ($10\,\mathrm{mW/cm^2}$), i.e., almost two orders of magnitude higher.

Propagation in human tissues. The significantly lower absorption by biological tissues of ultrasonic waves (e.g., $8-16\,\mathrm{dB}$ for a $10-20\,\mathrm{cm}$ link at $1\,\mathrm{MHz}$, vs $60-90\,\mathrm{dB}$ at $2.45\,\mathrm{GHz}$ as used in Bluetooth) [8] results in much reduced tissue heating, which makes propagation safer; second, from a technical point of view this means that the power losses by absorption are reduced. UTET power transmission efficiency has been reported to be as high as 39% [9]. In addition, there are no electromagnetic compatibility concerns with a crowded RF spectrum[8]. Therefore, wireless recharging of batteries in deep implants via ultrasounds can potentially be much faster than alternative solutions; as a consequence, battery powered implants can last longer or be smaller in size.

In this study, we discuss the design of a wireless energy transfer link for deeply implanted medical devices, where the receiver is able to harvest energy from an ultrasonic transmitter to charge a supercapacitor. In Section II we report the related work and in Section III we describe our system. Experimental results are reported in Section IV followed by conclusions in Section V.

II. Related work

Various theoretical studies [10] and [11] have modeled acoustic propagation in bio-tissue, proving that it is possible to transfer energy from outside the body to an implanted receiver at ultrasonic frequencies. In [10], an acoustic model of the ultrasound propagation is built and validated, paying specific attention to the FDA safety limits to avoid cavitation effects and temperature rise in tissue. In [12], a testbed to study ultrasonic wave propagation in the human body is discussed. The authors show that ultrasounds at $1\,\mathrm{MHz}$ can be used to transfer energy and recharge a lithium battery for power transfer or communication purposes. Moreover, the set-up allows to study the side effects connected with the propagation of mechanical waves through biological tissue and their applicability to clinical scenarios.

Among the most recent works, [6], [11], and [13] focused on the problem of energy transmission via ultrasounds to implantable devices. In [6], a first proof-of-concept of a mm-sized IMD is presented. The system uses a hybrid bi-directional data communication link consisting of ultrasonic downlink and an RF ultra-wideband pulse sequence in the uplink direction. It is demonstrated that ultrasonic power

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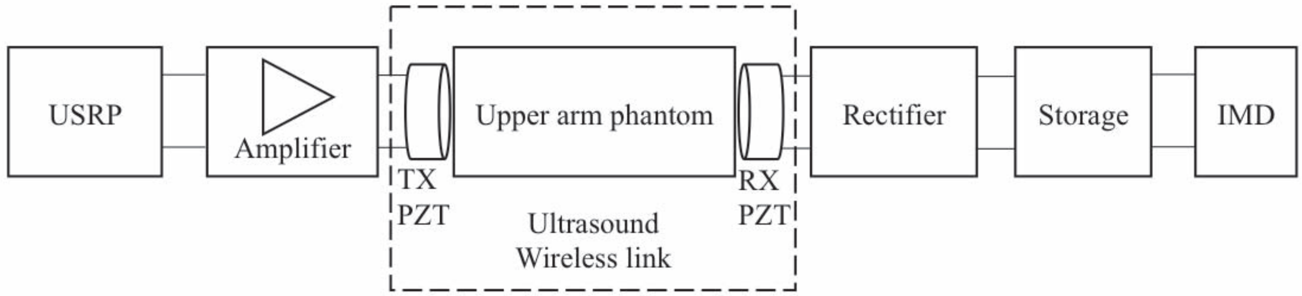

Figure 1. Block schematic of the ultrasonic wireless powering system

transfer can provide high power levels ($100\,\mathrm{W}$ to a few mWs) to mm and sub-mm sized deeply implanted devices.

In [14], the design of an ultrasound link for WPT to deeply-implanted IMDs is presented. The authors define the operating frequency and design a class-E amplifier to drive the array of transmitting transducers. The efficiency of the system measured with and without a phantom is 2.3% and 1.6% respectively. Previous studies have also shown that three geometrical factors can reduce the system's power transfer efficiency, namely the distance between the transmitting and the receiving transducers (resulting in power loss in tissue [15]), the lateral shift and the relative orientation of the two piezoelectric (PZT) devices [9].

III. System description

As shown in Figure 1, the proposed UTET link consists of two thin disk ultrasonic transducers (American Piezo Corporation [16]) with a diameter of $9.5\,\mathrm{mm}$ used for implementing the transmitter and the receiver. The piezoelectric receiver has the same geometrical and electro-acoustic features of the transmitter. Transmitter and receiver are aligned. The power transfer of the ultrasonic link is characterized by means of the Blue Phantom's upper arm tissue phantom [17]. The ultrasonic elements are symmetrically applied at the opposite sides of the phantom's smaller dimension at a distance of $5\,\mathrm{cm}$. The excitation voltage leading the transducer at the transmitting end is a continuous sine wave at $700\,\mathrm{kHz}$, i.e., the resonance frequency of the transducers. The power signal is generated using a USRP N210 software defined radio controlled by a software radio application. The input signal to the transmitter is preamplified using a Mini-Circuits LZY-22+, i.e., a high power amplifier with $43\,\mathrm{dB}$ gain and able to deliver 30 W as output power. This element is necessary to provide higher power levels as the maximum peak-to-peak voltage value of the signal at the output of the USRP is 2 V (peak-to-peak), which might be too small for intra-body energy transfer applications. Nevertheless, the maximum amplitude of the sinusoidal wave entering the amplifier cannot exceed $0.4\,\mathrm{V}$, otherwise the waveform is distorted. The AC source signal applied to the PZT is then converted into mechanical vibrations that propagate through the phantom and impact the surface of the receiving transducer which, in turn, converts it back into an electric AC wave. This signal carries the power available to the implanted device and our goal is to efficiently store it in an implantable battery or supercapacitor. To this purpose, the AC voltage coming from the receiving transducer has to be rectified first. We built a passive full wave diode rectifier whose output is an almost-DC signal with a small ripple that is used to recharge an energy storage device. The behavior of an implantable storage was studied connecting a $0.22\,\mathrm{F}$ ($5\,\mathrm{VDC}$) supercapacitor to the rectifier.

IV. System evaluation and experimental results

The output of the bridge rectifier is the most critical point in the entire link, for its output voltage and current (and more in general power) determine how much and how fast the supercapacitor can be charged. To test the behavior described above, the system was excited with a sine wave oscillating at $700\,\mathrm{kHz}$ and at different amplitude values, up to $400\,\mathrm{mV}$.

We studied the system with four USRP-generated waves respectively of $300\ \mathrm{mV}$, $400\ \mathrm{mV}$, $700\ \mathrm{mV}$ and $800\ \mathrm{mV}$ (all peak-to-peak) to which correspond the following peak-to-peak values at the receiving PZT transducer connected to an open circuit: $10\ \mathrm{V}$, $11.8\ \mathrm{V}$, $23.5\ \mathrm{V}$, $26\ \mathrm{V}$. We also measured the values after the amplifier and found a gain varying between $38\ \mathrm{dB}$ and $40\ \mathrm{dB}$, depending on the input signal. This means that the attenuation in the arm tissue, the transducers conversion inefficiency and the losses due to the mismatch and misalignment between the two transducers summed up to a value between $9.3\,\mathrm{dB}$ and $9.5\,\mathrm{dB}$. The wave is further attenuated during the rectification process, but the impact of the loss is negligible with respect to the attenuation phenomena mentioned above.

In Figure 2 and Figure 3 the voltage drops across the supercapacitor and its input currents measured as functions of time and for different amplitude values of the USRP input waves are reported. The voltage is indicative of the charge accumulated inside the storage element, since the capacitor equation holds.

From these curves, it is obvious that increasing the input voltage to the system is not always the best strategy to recharge the capacitor faster. In fact, what determines the speed of the charging process is the current, and in Figure 3 it can be seen that the current corresponding to the $700\,\mathrm{mV}$ peak-to-peak USRP input wave is initially higher than the current

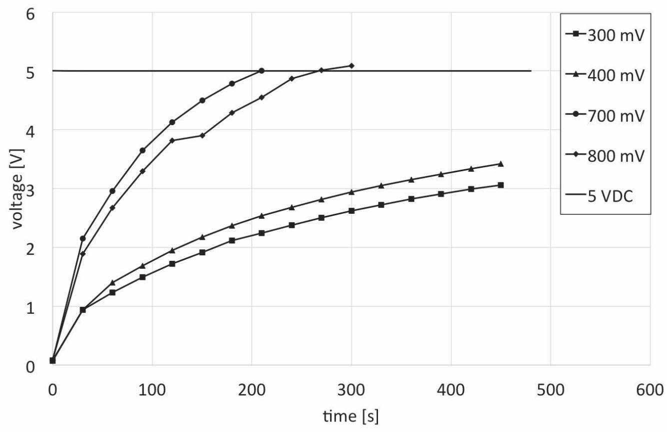

Figure 2. Voltage drops over the supercapacitor during charging phase

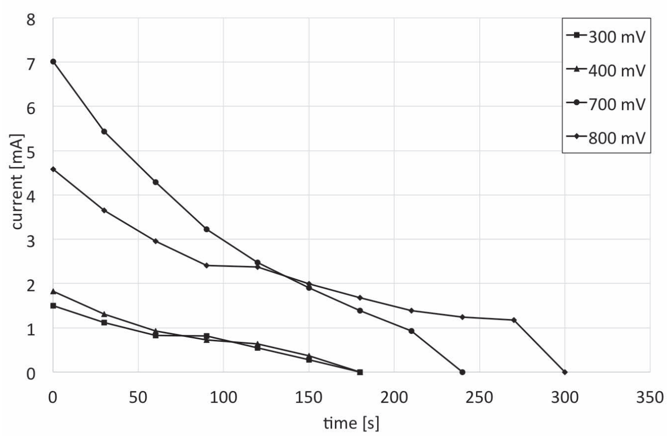

Figure 3. Input currents to the supercapacitor during charging phase

flowing into the supercapacitor with the $800\ \mathrm{mV}$ peak-to-peak signal. As a consequence the charging in the first case reaches the 5 VDC threshold (maximum value allowed by the supercapacitor) $150\,\mathrm{s}$ earlier. For lower voltage values, the charging process can be very slow and take more than 10 minutes to reach the $5\,\mathrm{VDC}$ threshold.

Once we know the IMD (typically represented by a resistive load) requirements in terms of required power, we can evaluate the charge and the voltage drop across the supercapacitor that needs to be reached. By using this voltage value in the curves in Figure 2 and based on the input voltage to the system, we are finally able to predict how long it will take to charge the supercapacitor.

V. Conclusions

In this article, an UTET system to recharge medical devices operating in the human body was proposed. We first described the ultrasonic link, which was built on two identical piezo-electric transducers operating at $700\,\mathrm{kHz}$ and located at the sides of an upper arm tissue phantom. The received signal was rectified and used to charge a supercapacitor. Experimental results showed that the rectified wave is able to convey enough power to completely charge a $0.22\,\mathrm{F}$ supercapacitor in $210\,\mathrm{s}$.

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