Opticon1826, Issue 8, Spring 2010
DOI: http://dx.doi.org/10.5334/opt.081005

BIOMEDICAL TELEMETRY: COMMUNICATION BETWEEN IMPLANTED DEVICES AND THE EXTERNAL WORLD

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Introduction

There have been many important technological achievements in microtechnologies and microsystems in the past fifteen years. These have lead to the design of small, reliable and low-power-consuming biomedical devices that can be implanted inside a patient's body by means of a surgical operation. Contrary to traditional, external medical devices, these implanted devices can sense data from inside the human body in real-time, offering a unique opportunity for early diagnosis and treatment of diseases.

In the most complicated scenario, implanted devices communicate with the external world in terms of both powering and telemetry. Powering is the delivering of energy to the implant from the external world in order to make it work. Telemetry includes data transmission from the implanted device to an external one, and vice versa. Depending on the design, several values of implant dimensions, delivered power, data transmission and error rates can be achieved.

Applications of Implanted Devices

Implanted devices can act as either sensors or stimulators. Sensors measure a biosignal from inside the body and transmit this information to an external device. They can measure body temperature, blood pressure and glucose concentration, for example, and detect respiratory, cardiac and arterial wall movements, the contraction of blood vessels and cardiac pressure disorders. The information received by the external device is post-processed by monitoring units and medical experts who treat the patient accordingly. This allows several diseases, such as cancer or diabetes, to be diagnosed in their very early stages, while critical medical conditions, such as heart attacks or strokes, can be prevented.

Stimulators receive information from the external world (in terms of an external unit operated by doctors) and stimulate specific nerves. Among the common applications of stimulators are microelectrodes for neural recording, used to diagnose and determine treatment for brain disorders. The electrical stimulation of retinal ganglion/bipolar cells creates visual excitation in patients who suffer from retinal diseases such as Retinitis Pigmentosa (RP) and Age-Related Macular Degeneration (AMD). Cochlear stimulators offer people who are severely hard of hearing or even profoundly deaf the hope of restoring the ability to sense sound. Meanwhile, stimulators are used in Functional Electrical Stimulation (FES) to restore function in paralyzed muscles by stimulating the nerves that control them, or the muscles themselves.

Powering the Implanted Device

Implanted devices need energy in order to sense or stimulate. The amount of energy required for the implant to work is small but cannot cease; if the implanted device runs out of energy, it would become useless and have to be substituted by surgical operation.

Early implanted devices were interfaced with wires through the skin in order to receive energy. This way of powering soon proved to be ineffective since it restricted the movements of the patient and increased the chances of infection. Adding a battery to the implanted device is also a prohibitive solution. No matter how small the battery might be, the total size of the implant increases, limiting the possible implant locations. Moreover, battery life is limited and even rechargeable batteries have a limited number of recharge cycles before they become completely useless. One might suggest energy harvesting as being the solution to the powering problem. However, while this makes use of the external environment as a source of energy (temperature, wind, water etc), these sources of energy are unavailable in the case of implanted devices. The use of implanted and external antennae to wirelessly transmit energy to the implant appears to be a suitable alternative. However, parameters such as human safety, power transfer efficiency and simplicity of electronics imply that the operational frequency must be in the frequency range between 1 and 20 MHz. Due to this constraint, the size of the implanted antenna, which is closely related to the electromagnetic radiation frequency, becomes too large to be implanted.

Inductive powering of the implanted device is the most promising solution. A pair of coils, one implanted and one placed outside the human body, form a loosely-coupled transformer, known as the biotelemetry inductive link. When appropriately driven, the external coil creates an electromagnetic field. The implanted coil, which is placed close to the external one, captures a portion of this field and current is produced. Thus, power is transferred to the implant. In order to guarantee human safety, the power transmitted from the external unit must comply with the government safety standards and must not exceed 10 mW/cm^2.

The same biotelemetry inductive link that is used to power the implant can be used to bi-directionally transmit data between the implant and the external device. The implanted and external units along with the biotelemetry inductive link form the biomedical telemetry system.

Typical Biomedical Telemetry System

Figure 1 shows a simplified block diagram of a typical biotelemetry system. At the external unit, a modulator circuit modulates the binary data ("1"s and "0"s) to be transmitted from the external to the implanted (internal) unit. The process modulates a property (amplitude, frequency, phase) of a high frequency carrier signal (usually a sine wave with a frequency of the order of tens of MHz) according to the binary data that is to be transmitted, and is necessary for the transference of the signal. A Power Amplifier (PA) receives and amplifies the modulated signal to produce an adequate transmitting power.

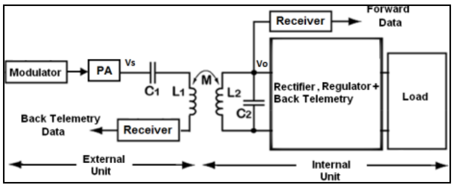

Figure 1. Simplified block diagram of a typical biotelemetry system.

Powering and bi-directional data transmission take place across the biotelemetry inductive link consisting of the mutually coupled external (L_1) and implanted (L_2) coils. The degree of coupling between these two coils can be described in terms of their mutual inductance, $M = k\sqrt{L_1 L_2}$. The coupling factor, k, shows the proportion of the external coil's (L_1) field, which is captured by the implanted coil (L_2).

The external (C_1) and implanted (C_2) capacitors are respectively used to form a tuned-in-series external and a tuned-in-parallel implanted circuit. The purpose of the tuned circuits is to achieve a high voltage at the output of the implanted unit (V_o), compared with the voltage at the input of the external unit (V_s) (that is a high voltage gain) at the frequency of the carrier signal (f_0). For example, assuming a carrier signal frequency of $f_0 = 13.56$ MHz, the magnitude of the voltage gain of the biotelemetry inductive link as well as its dependence on k are shown in Figure 2. The voltage gain is maximized at the resonant frequency, which in this case is $f_0 = 13.56$ MHz, and becomes higher for better coupled coils.

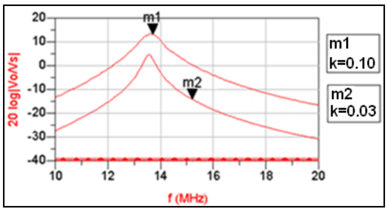

Figure 2. Dependence of the magnitude of the voltage gain on the coupling factor, k.

At the internal unit, the received waveform is demodulated and the originally transmitted binary data is recovered. At the same time, the received waveform is rectified and regulated to deliver an appropriate supply voltage (and thus power) to the implant. The load resistance of the implanted circuits is represented by the block called "Load" in Figure 1. In a real system, the load is time-varying and includes both resistive and capacitive elements. However, for reasons of simplicity, the load is usually considered to be a real resistor (R_l). The internal unit can itself send information back to the external unit. This information will be transmitted via the biotelemetry inductive link and demodulated at the receiver part of the external unit, as shown in Figure 1.

Data Transmission from the Implant to the External Device

Data transmission from the implant to the external device, known as 'uplink transmission', is necessary for both sensors and stimulators. Sensors measure the biosignals and transmit their measurements to the external world (e.g. medical experts, home/hospital monitoring units). Apart from stimulating specific nerves, stimulators can also send feedback to the external unit regarding the condition of the nerves or the implant itself.

Different methods for uplink data transmission are available, but passive telemetry, which is performed by means of load modulation (Load Shift keying, LSK), is the most commonly used technique. Data transmission is achieved by changing the load resistance of the implant, for example by switching a second resistor loading the implant in addition to the load resistor R_l. The substitution of the load resistor changes the current in the implanted device, which in turn changes the current in the external device. This change is sensed at the receiver part of the external device, shown in Figure 1, and is translated into the information which was originally transmitted by the implant.

Data Transmission from the External Device to the Implant

Data transmission from the external device to the implant, known as 'downlink transmission', is also, necessary for both sensors and stimulators. Sensors receive information from the external device and adjust, for instance, their rate of sensing the biosignals or performing uplink transmissions. Stimulators stimulate specific nerves with the intensity and frequency of stimulation that is defined by the external device.

Amplitude Shift Keying (ASK) techniques, which vary the amplitude of the carrier signal according to the binary data to be transmitted, were the first to be used to downlink data to the implant. They were preferred because of the design simplicity of the modulator and demodulator circuits at the external and implanted devices, but the amount of power transferred to the implant and the data rates achieved at the biotelemetry inductive link were too poor.

In order to achieve greater power efficiency and higher data rates, Phase Shift Keying (PSK) techniques, which vary the phase of the carrier signal according to the binary data to be transmitted, might be used instead. Binary Phase Shift Keying (BPSK) is the simplest form of the Phase Shift Keying (PSK). In BPSK, the carrier signal can easily be modulated simply by changing its polarity by means of the binary data signal to be transmitted (a "1" bit means that the carrier will be transmitted, while a "0" bit means that minus the carrier will be transmitted).

System Design

A typical biotelemetry system which downlinks BPSK modulated data to the implanted device is designed in Advanced Design System (ADS), as shown in Figure 3. The system consists of a BPSK modulator circuit as part of the external unit, a Class E Power Amplifier (PA), a biotelemetry inductive link and a BPSK demodulator circuit as part of the implanted unit.

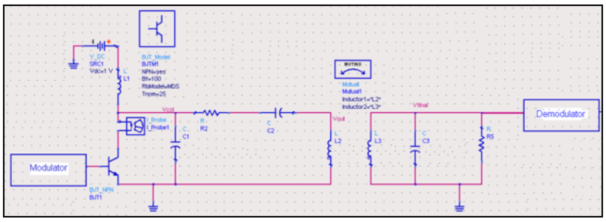

Figure 3. Design of a typical BPSK biotelemetry system in ADS.

An example of the binary signal at the input of the modulator, V1, which will be transmitted via the biotelemetry inductive link ("1"s and "0"s represented as 1V and -1V voltage levels) and the recovered signal at the output of the implant's demodulator, V2, are shown in Figure 4. In the absence of noise, the recovered binary data will be identical to the originally transmitted ones.

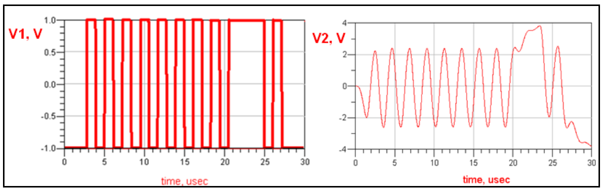

Figure 4. Binary signal to be transmitted, V1 and signal at the output of the implant's demodulator, V2.

Probability of error

In order to evaluate the effect of noise added by the biotelemetry inductive link on the transmitted signal, we now assume that Additive White Gaussian Noise (AWGN) distorts the signal before being received by the implant's demodulator. AWGN is the fundamental source of noise associated with real channels. It is said to be additive because it is added to the desired signal being transmitted. The term "white" refers to the fact that the power spectral density is flat as a function of frequency, meaning that the power of the noise signal is the same at all frequencies. Finally, the probability density function of the noise is a normal distribution, also known as Gaussian distribution. The bit rate and the carrier signal's frequency are considered to be equal to 1 Mbps and 13.56 MHz respectively.

The BPSK biotelemetry system is simulated for two values of k ($k = 0.03, 0.1$). The simulated probability of error curves are depicted in Figure 5. The y-axis of the graph indicates the probability of error, or equivalently the bit error rate (BER). The x-axis represents the signal-to-noise ratio (SNR) per bit, defined as the E_b/N_0 ratio, where E_b is the energy per bit before entering the inductive link channel and N_0 is equal to the noise power (related to the AWGN's variance, σ^2, as $N_0=2\sigma^2$).

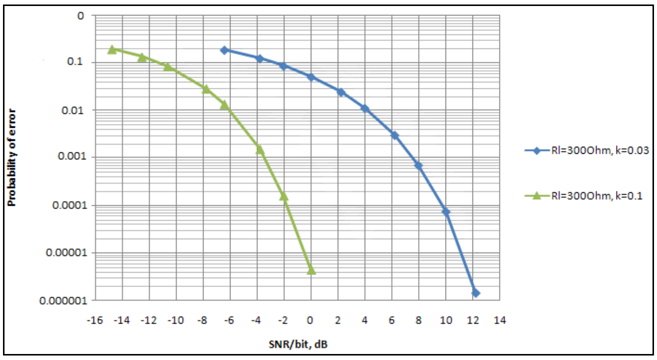

Figure 5: Simulated probability of error curves for BPSK modulated signals in case of a biotelemetry system with k=0.03, 0.1.

Figure 2 indicates that at the resonant frequency (which equals the carrier signal's frequency), the biotelemetry inductive link amplifies the BPSK modulated signal at its input. As a result, due to the presence of the inductive link channel, AWGN is expected to distort an amplified version of the initial BPSK modulated signal. Moreover, Figure 2 shows that the higher the inductive link's coupling factor, k , the more the signal will be amplified at its input. As a result, as the value of k gets higher, AWGN is added to an increasingly amplified version of the signal at the input of the inductive link. This explains why, for higher values of k , the same probability of error can be achieved for lower values of the defined E_b/N_0 ratio.

Conclusions

Implanted devices play an increasingly important role in modern medicine, for both the diagnosis and treatment of diseases. This article has addressed the powering of the implanted devices, as well as the bi-directional communication between the implant and the external world, which can be simultaneously performed via a biotelemetry inductive link. It has also discussed BPSK modulation as a means of modulating the data to be transmitted from the external to the implanted device, concluding that this method achieves fast transmission with very few errors, which keep decreasing for better coupled coils.

Even though there is considerable scientific work on the development of implanted devices that act as sensors or stimulators, further miniaturization of existing implanted devices or the design of new implanted devices that can perform more complicated tasks, such as organ monitoring, remain areas of great scientific research. The improvement of the circuit design to increase the bit rate in both directions and the power delivered to the implant (while at the same time decreasing the error rate and satisfying several security-related issues) is a very fruitful area for future research.

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Acknowledgement

I would like to express my gratitude to Dr Andreas Demosthenous for his supervision and guidance. I am also grateful to the Greek "Foundation of Education and European Culture" that funded my MSc studies at UCL during the academic year 2008-09.

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