ISSN(Online): 2320-9801
ISSN (Print) : 2320-9798

International Journal of Innovative Research in Computer and Communication Engineering

(An ISO 3297: 2007 Certified Organization)

Vol. 4, Issue 3, March 2016

Batteryless Power Supply and Telemetry System for Biomedical Implantable Devices Using CMOS Circuits

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ABSTRACT: Implanted sensors and actuators are most often in contact with sensitive organs such as the heart, arteries, nerves, and the brain. There have been many important technological achievements in CMOS technology 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. In the most complicated scenario, implanted devices communicate with the external world in terms of both powering and telemetry. Electromagnetic radio-frequency (RF) inductively coupled link is a commonly used technique to deliver power to implanted prosthetics. It transmits power to the implanted part at field levels below government safety standards (10 mW/cm^2). The link is intended to power up the receiver, and bidirectionally transmit data at various speeds, within various modulation/demodulation schemes. Low-power CMOS circuits are used to design the inductive RF link and digital demodulator, BPSK demodulators to transmit the data at different rates bidirectionally. This paper presents the characteristics of the inductive RF link and efficient communication systems for high data rate over the link.

KEYWORDS: RF inductively coupled link, CMOS, pass transistor, Class E power amplifier, self-driven synchronous rectifier (SDSR), low dropout (LDO) linear regulator, Load Shift Keying (LSK), BPSK, QPSK.

I. INTRODUCTION

With the rapid development of biomedical circuits and systems during the last few years, high-performance implantable medical devices such as sensors and neuromuscular stimulators play a more and more important role in modern medicine. Implanted medical devices are electronic devices that monitor and diagnose the electromyography (EMG), electrocardiogram (ECG), electroretiuogram (ERG) and electrooculography (EOG) of the patient and send current to various parts of a patient body.

In general, the implanted device consists of two parts: the internal part located underneath the body skin and an external part. *i.e.*, controller. The external part is used for powering the combination and sending data to the outside world. 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. Implantable devices are self-operating devices which adjust their operation depending upon the patient's condition. These devices do not rely on external sources of power.

Thus, low power consumption and high data rate are the main requirements for medical implant devices. In general, the battery less power supply is based on a modulated carrier that is rectified to transcutaneously power the implant. This technology allows patient mobility, improves quality of life, and reduces risk of infection compared to percutaneous wires. Electromagnetic radio-frequency (RF) inductively coupled link is a commonly used technique to deliver power to implanted prosthetics. At present, inductively coupled link technique is the most desirable method for patients, because of its safety, and high power transfer efficiency. Meanwhile, such a link is also employed as a media to transmit data between the external controller and the implanted unit.

This paper discusses a typical biotelemetry link, which consists of two coils, one implanted in the human body and another one being put close but outside the body. The link is intended to power up the receiver, and bidirectionally transmit data at various speeds, within various modulation/demodulation schemes. Regarding the power transfer, circuit topologies will be considered and discussed to achieve high-power efficiency.

II. LITURATURE SURVEY

Most battery less implantable devices consists of a matching network, rectifier, regulator, and band gap reference. Figure 1 shows a typical active battery less implantable system.

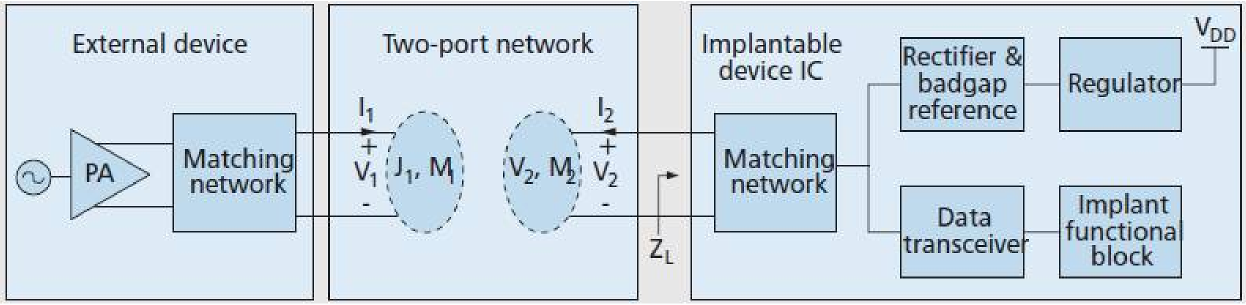


Fig 1: Active battery less implantable system

It consists of an external device that provides power and control signals to the implantable devices, and receives sensed signals from those devices. The coupling between the external and implantable devices is via a pair of transmit and receive antenna structures, which can be modelled by a two-port network. While implants are restricted in size and power consumption, we have freedom in designing the external transmit antenna. These components harvest RF power from the external device and provide a stable reference and supply voltages necessary for the device operation.

Matching Network

The matching network is used to maximize the delivered power for a given pair of transmit and receive antenna structures. The matching network topology can be L, Π, transformer, or a higher-order matching network. The trade-offs are among bandwidth, complexity, and chip area. Since on-chip capacitors often have a much higher quality factor than inductors or bond wires in the low-gigahertz regime, a matching network using only capacitors may have a higher voltage gain and occupy smaller area than a matching network consisting of inductors or a transformer.

III. INDUCTIVE LINK TO DELIVER POWER TO IMPLANTS

The wireless telemetry bio-devices powered by radio frequency (RF) signals, transmit power from the external part to the internal part through an inductive coupling coil and then converted into AC and DC voltages. Figure 2, depicts a block diagram of a typical system dedicated to power implanted electronic devices using an inductive link.

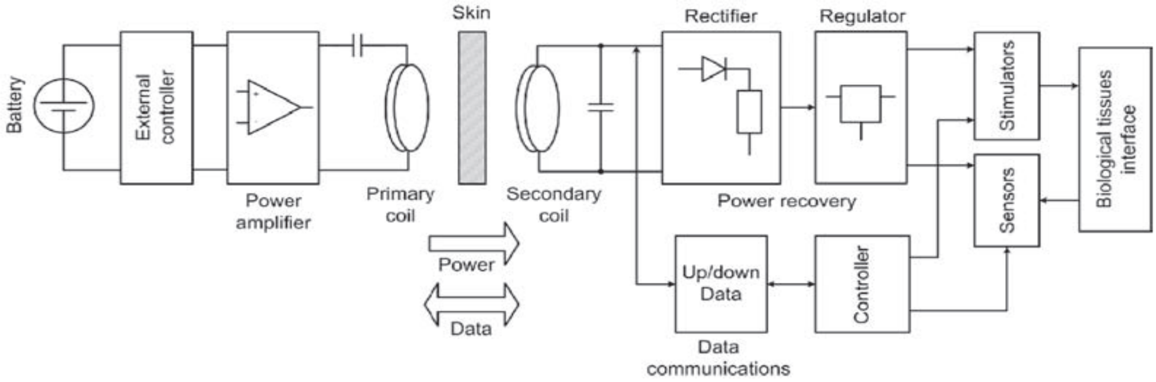


Fig 2: Inductive link to transmit power/data to an implant.

The power amplifier drives an external coil in the RF transmitter (the primary). The implanted coil (the secondary) receives the necessary energy through inductive coupling. A voltage rectifier and a voltage regulator follow for delivering an adequate dc supply voltage to the implanted circuits. The ac voltage induced at the secondary should be high in order to allow the voltage rectifier and voltage regulator blocks to extract the expected dc voltage as well as the energy to power on the whole implant. The most important characteristics to be considered when designing inductively coupled link to transfer energy are the ratio of the output voltage to the input voltage, the power efficiency, the bandwidth, the external power amplifier characteristics, and the load of the implant.

Power Amplifier

A class E power amplifier is recommended for high-power transfer efficiency to the primary. Such amplifier theoretical efficiency reaches 100%. A class E amplifier uses a shunt inductor, a capacitor, and only one power transistor, followed by the series resonant circuit of the link primary The power transistor acts as a low loss switch whose switching frequency is tuned close to the resonant frequency of the link primary circuit. This results in a sinusoidal output waveform.

Power Efficiency

The power efficiency of the link can be determined by considering the reflected impedance from the secondary (receiving coil) to the primary coil adds in series with the primary circuit. At resonance, and at critical coupling coefficient, the reflected impedance is purely resistive, and the corresponding dissipated power in the primary circuit is obtained from

$$P_{in} = \frac{V_{in}^2}{R_p + (\omega M)^2 / (R_s + R_L)|}$$

The power transferred to the secondary is equivalent to the same amount of power delivered to the reflected impedance, the power efficiency $\acute{\eta}_{\mathrm{link}}$ of the inductive link is

$$\eta_{link} = \frac{(\omega M)^2 / (R_s + R_L)}{R_p + (\omega M)^2 / (R_s + R_L)} \cdot \frac{R_L}{R_s + R_L}$$

Power Recovery and Voltage Regulation

The carrier recovered at the secondary is rectified and regulated in order to power up the implant with a stable dc voltage. These steps affect the overall power efficiency of the inductive link. For instance, the voltage regulator power efficiency is calculated as

$$\eta_{reg} = \frac{I_L V_{in\_reg}}{(I_q + I_L)} \approx \frac{V_{in\_reg}}{V_{out\_reg}}$$

Iq is the quiescent current drained by the regulator, and I_{L} is the load current. Since Iq is usually much less than I_{L}, the efficiency $\acute{\eta}_{\mathrm{reg}}$ mostly relies on the dropout voltage ($V_{\mathrm{in\_reg}}$–$V_{\mathrm{out\_reg}}$).

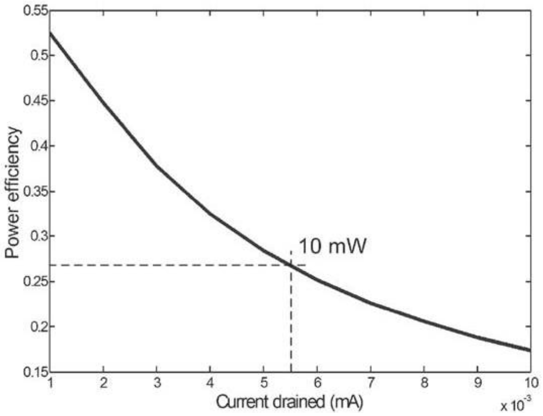


Fig 3: Efficiency of the link according to the current drained by the implanted circuits.

Above figure shows the graph between current drained and the power efficiency obtained by the implanted circuits. The power efficiency is exponentially decaying as the current is increasing.

Rectifier

The rectifier converts the AC signal to a DC voltage that can be used to supply the active circuitry in the implantable integrated circuit (IC). Depending on the received open voltage and the quality factor of the matching network, several rectifier topologies can be employed in implantable devices: diode connected metal oxide semiconductor (MOS), native MOS, and self-driven synchronous rectifier (SDSR) topologies. The critical trade-offs for these rectifier topologies are the on-resistance and reverse conduction current, which limit the efficiency of the rectifier. The RF input voltage amplitude is too low for one rectifier stage to generate sufficient voltage at the output to power up the on-chip circuitry. Compared to other rectifier topologies, SDSR configuration provides a good balance between efficiency and the input voltage at which it can operate.

Low power controller in the Implant functional block

Low power digital circuits can be designed by operating transistors at low supply voltages near sub threshold or even in deep sub threshold region. This limits the maximum operating frequency of logic gates, which, however, is adequate for many biomedical devices designed to capture low frequency physiological signals. The optimal operating condition to achieve best power efficiency for digital circuits is when leakage power equals the dynamic power.

Regulator

The key function of the regulator is to provide a stable supply voltage for on-chip circuitry even as the input voltage or load current experience variations. Existing regulators can be grouped into two main categories: linear regulators and switching regulators. Linear regulators are simple in design but inefficient for high drop-out voltage with large load currents. Switching regulators, on the other hand, can achieve very high efficiency, commonly over 85 percent, and can regulate to either lower, higher, or inverted output voltage as compared to its input.

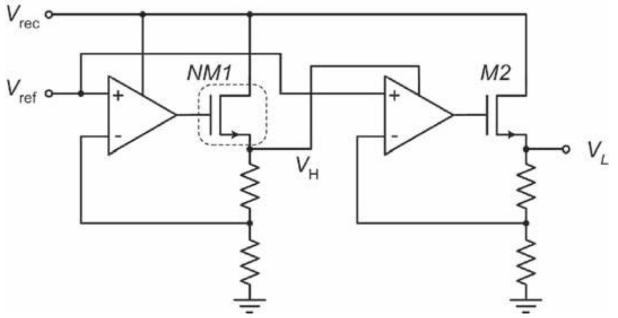


Fig 4: Dual output LDO regulator using a native transistor *NM*1 with a reduced *V*th.

A low dropout (LDO) linear regulator is depicted in Figure 4. It generates two supply voltage levels. A high-level voltage (V_H) is provided for higher-voltage applications, such as stimulators, and a lower one (V_L) supplies other circuitry, such as low-power sensors. Such a regulator employs a pass transistor (*NM*1) to isolate the input and output voltages, and an error amplifier with resistive feedback to correct the difference between the input and output voltages. Regulators using n-type pass devices are often preferred because they show fewer stability problems, better regulation, and lower Ohmic output impedance than their p-type counterparts. Conventional n-type regulators suffer from higher dropout voltage because a higher gate-to-source voltage is required in the pass device. This problem can be alleviated by using a native transistor (*NM*1 in Fig.4), for which the threshold voltage (*V*th) adjustment step is omitted in the fabrication process. By contrast, a regular transistor can be used at the second stage of the dual output regulator since the high-regulated voltage V_H provides sufficient voltage swing at the output of the feedback amplifier.

IV. BIO MEDICAL TELEMETRY SYSTEM

Telemetry includes data transmission from the implanted device to an external one, and vice versa.

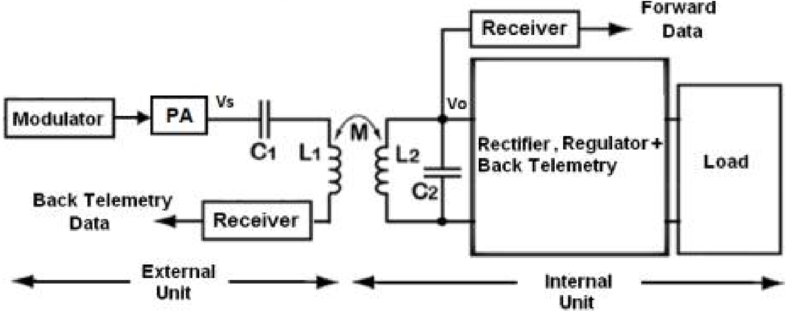


Fig 5: Simplified block diagram of a typical biotelemetry system.

Implantable devices are self-operating devices which adjust their operation depending upon the patient's condition. Figure 5, shows a simplified block diagram of a typical biotelemetry system.

Communication between implanted devices and the external world

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. The Power Amplifier (PA) receives and amplifies the modulated signal to produce an adequate transmitting power. 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.

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). 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.

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 were the first to be used to downlink data to the implant. 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).

BPSK demodulator

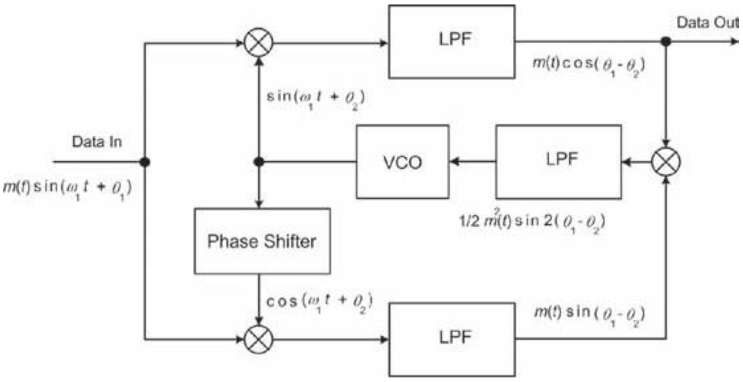


Fig 6: Block diagram of the Costas loop-based BPSK demodulator.

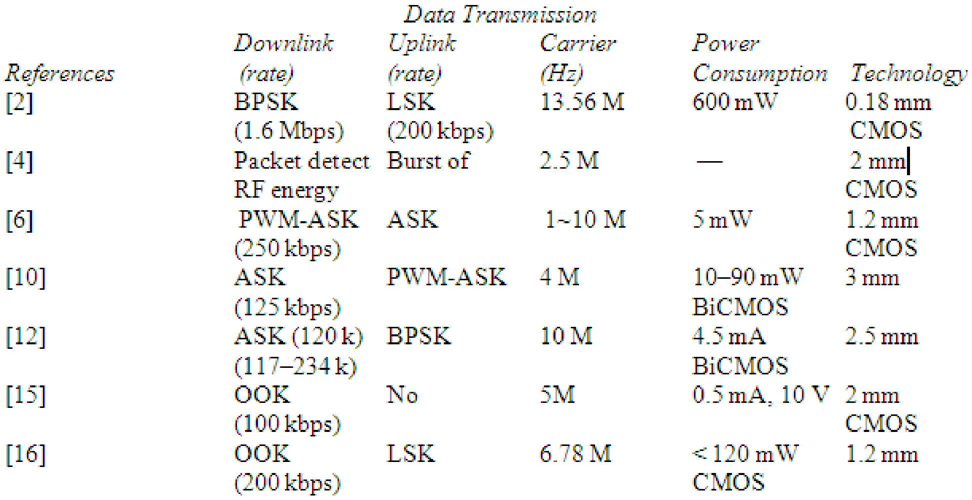
The block diagram of a BPSK demodulator is shown in Figure 6. A mixed-signal (analogue/digital) modulation/demodulation module is used for extracting clock and data signals from a PSK modulated 13.56-MHz carrier. BPSK is a modulation process whereby the input signal shifts the phase of the output waveform between 0° and 180°, which is equivalent to multiplying the carrier with a bit stream of ‘1’ and ‘–1’ representing high and low states, respectively. This demodulation technique is based on the Costas loop due to its especially practical feasibility. It consists of two parallel phase-locked-loops (PLL), whose phase error outputs are multiplied to control the frequency of the oscillator. First, a comparator converts the received carrier in a square waveform. This allows the use of simple digital phase detectors in the two arms of the circuit, because a sinusoidal input signal is considered in place of the square wave, since the low-pass loop filters reject the high-order harmonics. In addition, another comparator is added into the lower branch, which forms a hard-limited Costas loop. A fully differential architecture is adopted in all branches to improve the circuit’s reliability, power supply rejection ratio (PSRR), and noise immunity. The BPSK demodulator has been fabricated in a TSMC 0.18-mm CMOS technology.

QPSK Demodulator

The QPSK scheme improves the results of BPSK , because of its bandwidth efficiency and higher data rate. In both modulation methods, a carrier frequency of 13.56 MHz, which is legally designated for ISM applications, is used. The QPSK is based on two carriers, one in-phase and another in 90° quadrature phase. Their polarities are switched respectively by two binary signals (two-bit data streams). Hence, QPSK has four possible transmitted phases, and it doubles the data rate of BPSK, but without requiring additional bandwidth.

V. RESULTS

Table 1 summarizes the main modulation methods used in wireless implantable systems. All these are simulated by using CMOS technology. Based on the technology power consumption is varying. All the results are shown in below table.



	Data Transmission				
References	*Downlink (rate)*	*Uplink (rate)*	*Carrier (Hz)*	*Power Consumption*	*Technology*
[2]	BPSK (1.6 Mbps)	LSK (200 kbps)	13.56 M	600 mW	0.18 mm CMOS
[4]	Packet detect RF energy	Burst of	2.5 M	—	2 mm CMOS
[6]	PWM-ASK (250 kbps)	ASK	1~10 M	5 mW	1.2 mm CMOS
[10]	ASK (125 kbps)	PWM-ASK	4 M	10–90 mW BiCMOS	3 mm
[12]	ASK (120 k) (117–234 k)	BPSK	10 M	4.5 mA BiCMOS	2.5 mm
[15]	OOK (100 kbps)	No	5M	0.5 mA, 10 V	2 mm CMOS
[16]	OOK (200 kbps)	LSK	6.78 M	< 120 mW CMOS	1.2 mm

Table 1: Modulation Methods and Characteristics of the Reported Inductive Link Circuits.

The above data transmission table shows different uplink and downlink data rates using different CMOS technologies. BPSK is the effective modulation scheme among all of the above. It is having less power consumption with a carrier frequency 13.56MHz. It is implemented by using 180nm CMOS technology.

VI. CONCLUSION AND FUTURE WORK

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. Although much work has been done in the field of wireless communications and wireless powering for biomedical implants, there is still room for improvement and optimization of the entire system. In this article, we have presented typical active implantable device architecture and the associated components.

The design of the demodulator is realized by pure analogue circuits to achieve high speed and low-power consumption. This demodulator has been implemented in a TSMC 0.18-mm CMOS process and simulated using *spectre*. Data rate of up to 4 Mbps can be achieved with a 13.56 MHz carrier at a total power dissipation of 0.75 mW. In Table 1, the performance of the QPSK demodulator is compared with other demodulators.

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BIOGRAPHY

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