Adaptive RF Power Control For Wireless Implantable Bio-Sensing Network To Monitor Untethered Laboratory Animal Real-Time Biological Signals

Nattapon Chaimanonart, Mark D. Zimmerman, and Darrin J. Young
Department of Electrical Engineering and Computer Science
Case Western Reserve University
Cleveland, Ohio, USA
nxc35@case.edu

Abstract—**A wireless implantable adaptive RF power converter system for monitoring real-time biological signals of an untethered small laboratory animal inside a housing cage is developed. The overall prototype sensing system exhibiting a dimension of 6 mm x 6 mm x 2 mm and a weight less than 100 mg can be implanted in the animal abdomen. The implant unit consisting of a tuned 20-turn spiral coil is inductively coupled a 4 MHz RF energy source from an external power amplifier driving a tuned 25 cm x 15 cm, 4-turn RF coil. An on-chip rectifier and linear regulator circuit convert the received AC voltage to a stable 2 V DC supply with 1 mA driving capability. Due to animal's different positions and tilting angles (up to 60 degrees) inside the cage with a 1 cm nominal separation distance between internal and external coils, a large varying RF coupling strength is produced and can be detected by a power sensing circuit. The received RF power level is quantized and processed with other biological data before wireless transmission using frequency shift keying (FSK) scheme. The external power source can adaptively adjust its RF power strength based on the received one-bit power sensing data to achieve a stable and reliable voltage supply for the overall bio-implant microsystem with an optimal power coupling efficiency.**

I. INTRODUCTION

One of the critical biomedical research advancements focuses on identification of genetic variation susceptibility to diseases—such as hypertension, obesity, epilepsy, and cancers—and the ongoing search for new treatments and cures. Researchers often require extensive real-time biological information such as blood pressure, core body temperature, activity, and bio-potential signals from a living test subject, for example, a genetically engineered mouse also known as knock-out mouse due to its high degree of genetic and physiological homology with human beings. Long-term bio-sensing implant systems are employed to obtain the above biological data [1]. However, the small size and weight of a laboratory mouse means that typical pacemaker-size monitoring devices—comparable in size to a mouse—cannot be used. Furthermore, "backpack" systems or systems that tether the mouse to an external power supply and data receiving unit can cause significant alterations in a mouse's behavior, thus distorting the biological data. An implanted battery is also unfeasible due to its relatively large size and mass and limited operating time (~ 100 mAh for a typical coin-cell battery).

Most commercial implant products utilize RF powering to supply the implant system with required power. These products, though, rely on bulky discrete designs consisting of separate sensors, off-chip components, and multiple processing IC's on a circuit board. The discrete approach occupies a significant volume and requires a high level of power dissipation. RF powering typically exhibits low efficiency. Thus, a large implanted coil with a heavy ferrite core is often necessary to meet the high power demand of discrete designs. The coil and core further increase the size and weight of an implanted system, resulting in a final product exhibiting a mass of up to 20-30% of a laboratory mouse body mass. Therefore, a miniaturized, implantable, wirelessly powered bio-monitoring system is highly desirable for advanced biological research. Integrating the powering, signal processing, and data transmission electronics into a single IC results in a distinct improvement in system power dissipation, size and weight [2]. Optimized circuit design, especially with respect to the RF-to-DC power conversion electronics, can eliminate the need for off-chip components, further reducing the size, weight, and parasitics. The low system power requirement allows for a much smaller implanted RF coil without a heavy ferrite core to be used for receiving RF power to supply the implant microsystem.

In classical RF powering designs, the relative position of the internal coil is fixed with respect to the external coil. The case of an implant in an untethered laboratory animal differs from these typical design scenarios in that the inductive coupling factor, and thus the power coupled into the implant, varies drastically over the operating region as the internal coil tilts and changes its position with respect to the stationary external coil. Significant system optimization is, therefore, necessary to achieve the highest possible coupling efficiency and coupling uniformity over the operating region, and to design integrated RF-to-DC electronics that prevent power variations from damaging on-chip components or distorting sensitive bio-signals.

In this paper, an adaptive, intelligent power control system that limits the power consumed by the external amplifier and supplied to the external coil based on the needs of the implant system is proposed and developed. The

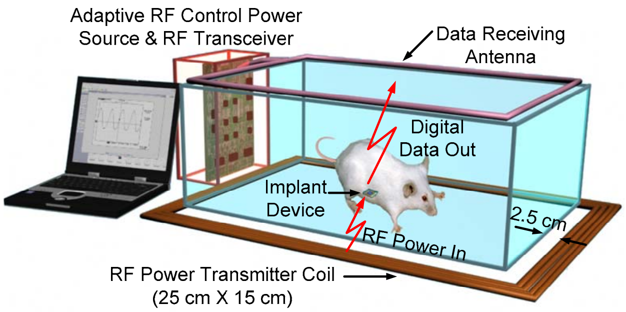
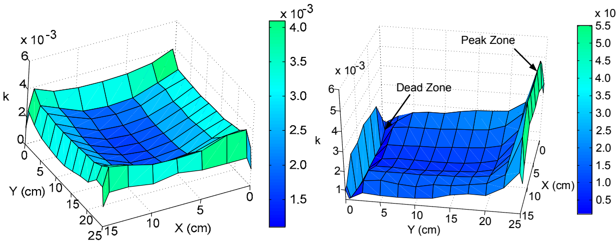


Figure 1. Wireless implantable bio-sensing network with adaptive RF powering capability

prototype system is demonstrated with bench-top measurement results presented.

II. WIRELESS IMPLANTABLE BIO-SENSING NETWORK WITH ADAPTIVE RF POWERING ARCHITECTURE

Figure 1 depicts the overall implantable bio-sensing network. An external adaptive control power source with a transmitting antenna underneath the cage is used to transmit an RF power to the implant unit. The digitized power sensing data together with real-time biological signals can be transmitted to a nearby receiver. A miniature 6 mm x 6 mm x 2 mm implant unit with a total weight less than 100 mg can be implanted inside an untethered mouse abdomen. The wireless implantable system consists of integrated electronics with external passive components, such as RF power receiving coil, data transmitting coil, and filtering capacitors. The RF power receiving coil is wired in a planar spiral configuration around an IC to reduce the overall system thickness for a compact design. The flat thin configuration can provide a better comfortable fit inside the mouse abdomen. Moreover, the total device size and weight are also greatly reduced without the traditional RF power receiving coil containing a magnetic ferrite core. A mouse moving area of 25 cm x 15 cm is chosen for the prototype design, thus the size of the external RF power transmitting coil. For optimally designing the adaptive RF power control system, the coupling factors at different mouse cage locations were characterized by using the prototype RF power receiving coil with a normal 1 cm separation distance from the external coil. An optimal operating condition was determined to use a 4-turn external coil and a 20-turn internal coil with an operating frequency of 4 MHz [3]. *In vitro* experiments were further conducted to demonstrate that the skin absorption of the laboratory animal to an RF signal at 4 MHz had a negligible effect [4]. The measured coupling factor (*k*) with an animal tilting angle of 0° and 60°, which is the worst case considered for the prototype design, are presented in Figure 2a and Figure 2b, respectively. The *k* values vary from 0 to 0.55%, where the minimum (dead-zone) and maximum (peak-zone) occur around the edge of the external coil. The dead-zone can cause an unreliable RF power signal reception, and the peak-zone can result in an excessive power coupling. Therefore, by limiting the cage size at 2.5 cm away from the external coil edge, the dead-zone and peak-zone can be eliminated. Ultimately, with the cage size of 20 cm x 10 cm, *k* values are bounded from 0.078 % to 0.34 %. This operating condition is sufficient to generate a 2 V DC supply with up to 1 mA current driving capability for the integrated electronics over the chosen cage size with an animal tilting angle of up to 60°. A standard CMOS 1.5 μm (2-poly and 2-metal) technology chosen in the prototype design is typically operated at 5 V DC supply. However, since most biological signals exhibit a low bandwidth below 1 kHz, high speed digital electronics are not required. The system DC supply voltage thus can be reduced to 2 V, substantially minimizing system power consumption. The 2 V supply level is a few hundred millivolts greater than the sum of the worst case (slow process) NMOS and PMOS threshold voltages, thus allowing sufficient headroom for standard CMOS design techniques. Still, the large *k* variation results in a significant power dissipation variation of the RF power source. Without the adaptive feedback, implant unit would require a constant external RF power of 18.5 W for an animal being located in the small coupling area. Once moving to a higher coupling region, an excessive received RF power resulting in an excessively large DC voltage as well as ripple can fail the internal electronics. However, with the adaptive feedback, the external power source is expected to dissipate 4.7 W and 20 W for the best-case and worst-case power coupling, accordingly. The received RF power level due to varying coupling factor can be detected by an on-chip power sensing circuit and fed back to adjust the transmitted RF power strength as depicted in Figure 3.



(a) 0° tilting angle (b) 60° tilting angle

Figure 2. Measured coupling factor with the external coil separated from the internal coil by 1-cm

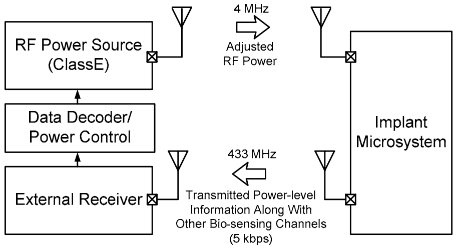


Figure 3. Wireless implantable adaptive RF powering system architecture

III. ADAPTIVE RF-DC POWER COVERTER ELECTRONICS

The simplified overall RF-to-DC converter with power sensing circuits consisting of voltage-doubler, 2 V linear regulator, digital processing circuits and FSK transmitter is presented in Figure 4. The on-chip voltage-doubler is implemented by using diode-connected NMOS devices, MD_1

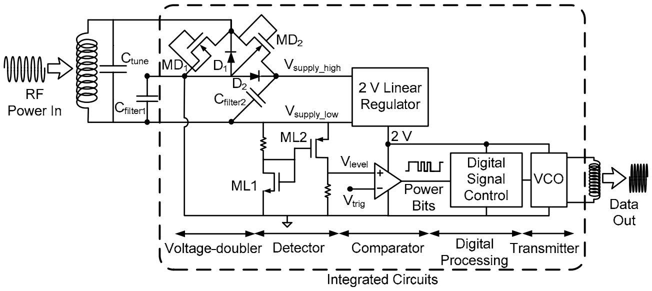


Figure 4. Simplified RF– DC converter with power sensing electronics

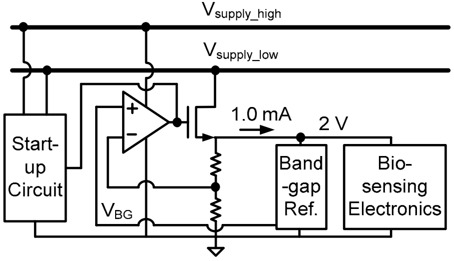


Figure 5. Simplified 2 V linear regulator

and MD_2. A latch-up effect due to the parasitic BJT can be eliminated by keeping MD_1 and MD_2 far from any p^+ regions in the layout. The intrinsic CMOS p-n parasitic diodes, D_1 and D_2, also shown in the figure, do not interfere with the doubler operation. An RF input signal with a peak amplitude of 3.25 V is needed to achieve the regulator turn-on voltage of 2.5 V at V_{supply_low} and 4.5 V at V_{supply_high}. The DC voltage at V_{supply_high} is reduced from the expected doubled-voltage of 5 V due to a voltage drop of 1.25 V across MD_2 caused by the transistor body effect. The two supply voltages, V_{supply_high} and V_{supply_low}, allow the linear regulator to incorporate an NMOS pass device operating in an effective low drop-out configuration without using complicated circuit topology or a PMOS pass device requiring a large compensation capacitor at the output.

An off-chip filtering capacitor of 10 nF, $C_{filter1}$, is used to limit the voltage ripple at 4 MHz on V_{supply_low} at 25 mV_{p-p} for 1 mA DC load current without producing excessive current spikes through the diodes. To produce the same amount of voltage ripple at the same frequency, $C_{filter1}$ can be reduced as the load current decreases [5]. Therefore, for future low power electronics, $C_{filter1}$ could potentially be implemented on-chip. An on-chip filtering capacitor of 110 pF, $C_{filter2}$, is chosen based on the designed current consumption of 16 µA from V_{supply_high}. By operating at 4 MHz, the voltage ripple has negligible signal interference to the low bandwidth biological signals.

The simplified linear regulator is illustrated in Figure 5. The regulator is designed to operate at V_{supply_low} from 2.5 V to 4.5 V, limited by an oxide breakdown of the doubler. Due to mouse movement (<10 Hz), the line regulation or power supply rejection (PSR) of the regulator near DC needs to be properly designed to minimize the variation at 2 V supply. In the prototype, the minimum detectable signal of the designed bio-sensing electronics can be as small as 1 mV or 11-bit resolution from a full 2 V range [6]. If the voltage variation is directly coupled from 2 V supply to a bio-sensing circuit output, line regulation of less than -66 dB is required for the worst-case 2 V variation on V_{supply_low}. The proposed linear regulator employing a voltage reference (bandgap) from the regulated 2 V supply helps achieve -80 dB line regulation without using two regulators cascaded.

Previously published adaptive power control techniques [7] convert the on-chip power level to a digital representation, then transmit this data to an external system, which controls the RF power provided by the external power amplifier. Multiple bits of power information were used to precisely define the desired power level from the external power supply to minimize variation on the implant supply. In our proposed system, utilizing the linear regulator with a high line regulation (-80 dB) is able to reduce power sensing quantization level to 1 bit, therefore, greatly reducing the design complexity of the power sensing circuit. In addition, the 1-bit power level can readily be combined with other bio-sensing data without significantly increasing data transmission bandwidth, which is limited and crucial for low-power system design. The power sensing circuit consists of a comparator that compares the existing V_{level}—output of the V_{supply_low} level detector—to a reference level, V_{trig}. By compensating all process variations, V_{trig} of 0.4 V is chosen such that the comparator triggers when V_{supply_low} reaches to a designed triggering level between 2.5 V and 4.5 V. Using this configuration, a digital power bit is produced by the comparator that is high when V_{supply_low} is greater than the triggering level—indicating more than necessary power received by the implant—and low when V_{supply_low} is less than the triggering level—indicating that sufficient or less than sufficient power is received by the implant. The power status bit is sent by the on-chip 433 MHz FSK transmitter along with other bio-signals data to an external receiver, where the data is decoded and processed. The FSK transmitter is implemented by using a free running LC tank voltage-controlled oscillator (VCO). NMOS/PMOS cross-coupled configuration is chosen to allow one external high-Q tuning inductor to be used with a total current consumption of 120 µA from 2 V supply.

Figure 6 illustrates the operation of the adaptive power control system. When *k* decreases, the power coupled to the implant temporarily drops, causing the power data bit to remain low. The adaptive controlling program steps up the external input power to regain the coupled power in the implant system to a desired level. In this prototype, the transmitting RF power is controlled by adjusting a supply voltage of a class-E amplifier implemented as the external power source. When *k* increases, the external input power is stepped down to a proper level resulting in lower

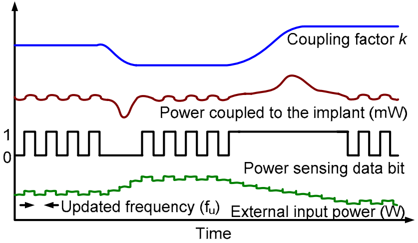


Figure 6. Timing diagram of adaptive powering system

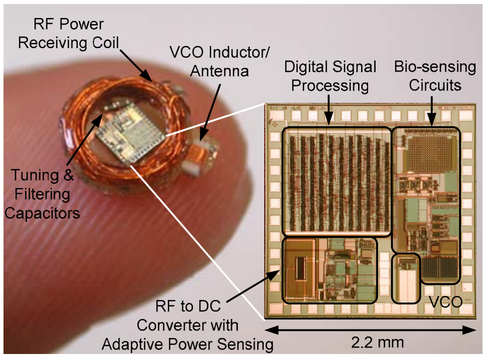


Figure 7. Prototype implantable system

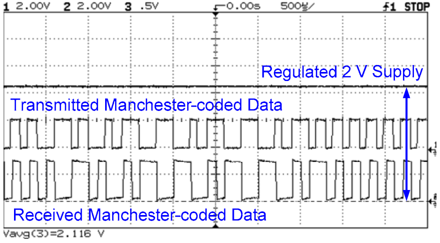


Figure 8. 2V regulated supply with 5 kbps Manchester-coded data telemetry

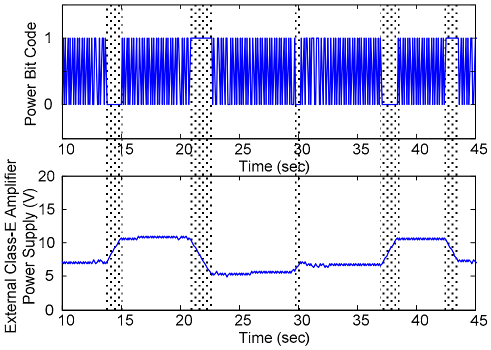


Figure 9. Real-time measured data, (top) extracted power bit, (bottom) tracked external class-E amplifier power supply

external power consumption, thus a reduced RF input power. When k is constant (mouse not moving), the power data bit alternates between a high and low state, causing a steady power with ripple at the step up/down frequency. The adaptive control system will be more sensitive to a mouse movement as this updated frequency, f_u, increases. Since the linear regulator high PSR region (-80 dB) is from DC to 1 kHz, the updated frequency is limited to about 10 Hz to 300 Hz in this design. This updated frequency range is fast enough to track the mouse movement without causing high voltage ripple at the 2 V regulated output.

IV. MEASUREMENT RESULTS

The prototype implantable system consisting of a 1.5-µm CMOS ASIC with RF powering coil, two external filtering capacitors and one VCO tuning inductor/antenna is presented in Figure 7. Figure 8 shows the measured stable regulated DC supply of 2.1 V with 5 kbps transmitted and received Manchester-coded test data. With the miniaturized package, the FSK data transmission range is approximately 15 cm, which can provide a reliable data reception covering the entire cage areas. The linear regulator achieves -85 dB line regulation and -25 dB PSR at 4 MHz as expected. The measured power sensing triggering level at V_{supply_low} is 2.8 V in the prototype design, which falls into the desired range between 2.5 V and 4.5 V. The extracted power bit data together with real-time automatically adjusted class-E amplifier supply voltage is shown in Figure 9. The shaded areas illustrate the change in k due to the implant device movement. In this experiment, the class-E supply voltage can be varied from 2.5 V to 25 V covering the required power in all characterized regions and scenarios with a 0.3 V step voltage at the updated frequency of 10 Hz to ensure a stable 2 V implant supply voltage with a total system current consumption of 160 µA from V_{supply_low} and 13 µA from V_{supply_high}.

V. CONCLUSION

A miniature, implantable, remote RF powering system for a small, untethered laboratory animal inside a cage is developed. An external adaptive powering system is designed and optimized along with an implant bio-sensing device. Microfabricated RF-to-DC electronics with power sensing electronics are designed in CMOS 1.5 µm 2M-2P process. A novel single-bit adaptive powering control system is demonstrated to achieve overall system functionality and requirements.

ACKNOWLEDGMENT

This work is supported by National Science Foundation under contract # EIA-0329811.

REFERENCES

[1] B. Hoit, et al., “Naturally occurring variation in cardiovascular traits among inbred mouse strains,” Genomics, vol. 79, no. 5, pp. 679-685, May 2002.

[2] M. Suster, J. Guo, N. Chaimanonart, W. H. Ko, and D. J. Young, “A wireless strain sensing microsystem with external RF powering and two-channel data telemetry capability,” IEEE International Solid-State Circuits Conference (ISSCC), San Francisco, pp. 380-609, February 2007.

[3] M. Zimmerman, N. Chaimanonart, and D. J. Young, “In vivo RF powering for advanced biological research,” IEEE Engineering in Medicine and Biology Society (EMBS '06), New York, N.Y., pp. 2506-2509, 2006.

[4] N. Chaimanonart, K. Olszens, M. Zimmerman, W. H. Ko, and D. J. Young, “Implantable RF power converter for small animal in vivo biological monitoring,” IEEE Engineering in Medicine and Biology Society (EMBS '05), pp. 5194-5197, September 2005.

[5] N. Chaimanonart and D. J. Young, “Remote RF powering system for wireless MEMS strain sensors,” IEEE Sensors Journal, vol. 6, no. 2, pp. 484-489, April 2006.

[6] Peng Cong, W. H. Ko, and D. J. Young, “Low noise µwatt interface circuits for wireless implantable real-time digital blood pressure monitoring,” to appear in the IEEE Custom Integrated Circuits Conference (CICC), San Jose, California, September 2008.

[7] G. Wang, et al, “A closed loop transcutaneous power transfer system for implantable devices with enhanced stability,” IEEE International Symposium on Circuits and Systems, vol. 4, pp. 17-20, May 2004.