Wireless Charge Recovery System for Implanted Electroencephalography Applications in Mice

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Abstract

Recording electroencephalography (EEG) in multiple mice within one cage is needed not only to allow high throughput testing, but to also maintain normal social and behavioral cues when studying sleep, memory and psychiatric disorders. This work proposes a concept and a blueprint of implementation of a low-power, untethered, fully integrated, implantable system suitable for EEG applications. The system employs two primary components of i) wireless powering through Helmholtz coil around the cage and ii) charge recovery logic (CRL) instead of traditional static CMOS for EEG processing. CRL presents lower power consumption, especially in the low-frequency range typical of EEG. The presented system uses charge recovery principles for the analog circuits as well, enabling improved power savings with respect to existing solutions. Finite element method simulations, or FEM, shows the feasibility of power transmission over a inductive wireless link, designed with the Helmholtz coil over the cage. The roadmap for implementation is described in the system implementation blueprint, identifying the individual building blocks that have been shown to be functional, and shown to be inter-operable with simulations in this work.

1 Introduction

The advantage of studying mice for sleep, memory and psychiatric disorders is the tremendous number of genetic and protein tools available to test associations and mechanisms of various stressors and treatment that can not be performed directly on humans. Electroencephalography provides functional neural assessment to correlate genetic and protein mutations/modifications. Currently, a mouse must be singly housed when undergoing EEG because more than one mouse per cage will result in tethered cords getting tangled or if the power source is mounted on top of the skull, it will get scratched off. Wirelessly powered solutions that eliminate the need for cords and battery are attractive in this regard [1–3]. This emerging area of research is fueled by improvements in the two primary building blocks of the system: 1) wireless powering and 2) electric circuit implementation for EEG processing.

In terms of wireless powering, while printed coils could be a solution for some applications [2], their size makes that approach prohibitive for smaller devices and smaller animals, e.g. mice. Other solutions [3] employ small devices, in the order of $10\,\mathrm{mm}^3$, and uses resonant cavities and high transmission frequencies, in the order of GHz. While the approach is demonstrated to work, its functionality is limited to a simple light delivery system. The system could potentially be modified to include an analog front end, complex logic, and memory, in order to probe and store neural signals, but the off-the-shelf approach in that case would be hard for small animals, e.g. mice, because of the large volume that discrete packages and boards would require. As the complexity of the implanted system increases, a fully integrated solution would scale better in terms of volume and power consumption.

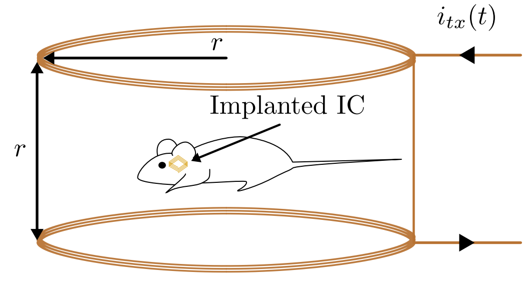


Fig. 1: Simplified representation of the system using an Helmholtz coil

In terms of the circuit implementation, low power electronics is essential for in-vivo applications. Low power electronics requires less energy, enabling smaller form factors in battery to power these electronics or enables the use of less sophisticated wireless power delivery approaches. In both cases (of battery-operated or wirelessly powered systems), the heat dissipated from the circuitry is also directly proportional to the power consumed by the circuits. In this regard, low power electronics is also critical to the heat tolerance of the living host. A common implementation strategy for low power electronics (also in implanted circuits) has been the near-threshold or subthreshold CMOS circuits [4], which operate on a fraction of the voltage of a typical circuit. Another implementation of low power electronics, highly unexplored to date, is charge recovery circuits [5]. An intrinsic characteristic of charge recovery logic (CRL) is that it uses a sinusoidal signal both for timing and power delivery [5], hence eliminating the need for a stable DC supply. Recent work in charge recovery logic has addressed the common shortcomings of these circuits. Most significantly, it is shown that a wireless link can be used to generate the power-clock signal of charge recovery logic in [6], an obstacle commonly thought to be limiting to the wide-spread use. This approach has been shown to produce circuits that are faster than popular near threshold operations, and smaller due to eliminating some circuit components. This work proposes a wirelessly powered implantable EEG system that uses charge recovery principles not only in the logic section but throughout the system. The entire system, for which the blueprint is proposed in this paper, is powered up wirelessly through inductive coupling with transmitters placed in the floor and ceiling of the cage. Although this solution is targeted to mice EEG, such a fully integrated approach could be extended to a wide variety of cyber-physical interfaces.

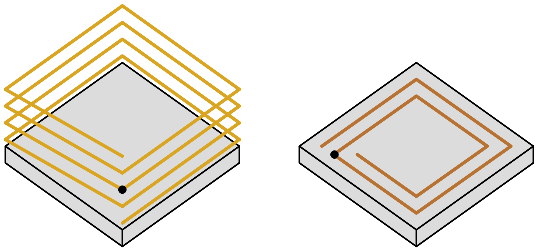
The reminder of this paper is organized as follows. An introduction to charge recovery logic and its advantages are presented in Section 2. The proposed concept of the EEG wireless system is presented in Section 3. Numerical analyses of the feasibility of the wireless link are presented in Section 4. Concluding remarks are presented in Section 5.

2 Background on charge recovery logic

One of the many differences between charge recovery logic and static CMOS (including sub- or near- threshold variants) is that CRL employs one or more signals, called power-clocks, that both deliver power and timing. While a CMOS circuit has one DC source, i.e. V_{DD}, and a clock that synchronize operations throughout the circuit, CRL uses one or more sine-waves to deliver power and timing information [5]. Another key difference is that CRL, as the name implies, recovers or recycles part of the energy used in the system, hence providing substantial power savings. It is well known [7] that the dynamic energy consumption of a complementary logic such as CMOS is $E \propto C_L V_{DD}^2$ where C_L is the load capacitance, and V_{DD} the supply voltage. On the other hand, for charge recovery logic it can be shown [5] that the energy consumption is

$$E \propto 2\frac{C_L^2 V_{DD}^2 R_{ON}}{T} \tag{1}$$

where R_{ON} the on resistance of the switch, and T the period of the power-clock. One of the differences with respect to static CMOS is that T appears in Equation 1. For $T \rightarrow \infty$, i.e. slower power-clock, the energy consumption goes to zero. This is a theoretical limit and the actual energy consumption would not be zero, but Equation 1 shows the trend of CRL energy consumption. As elaborated in [6], CRL offers power savings of up to one order of magnitude at lower frequency. This very low energy profile and the recently discovered interoperability (in [6]) with wirelessly transmitted power make CRL an excellent candidate for replacing CMOS for medical applications such as EEG, ECG, etc, where the signal frequency is low.



(a) External inductor **(b)** Integrated inductor

Fig. 2: Two configurations for the receiving inductor. The inductor can be center-tapped (black dot) in order to obtain the two power-clocks required by charge recovery logic.

3 Blueprint of proposed system

The proposed configuration for the wirelessly powered charge recovery logic system is illustrated in Figure 1 for an in-vivo application. An external coil surrounds the cage in order to wirelessly power the devices implanted on mice. The implanted device, whether it is fully integrated as in Figure 2b or it has an external inductor as in Figure 2a, is completely embed between the scalp and the skull of the mouse, thus avoiding any protrusion jutting from the scalp that can be scratched off by another mouse.

The wireless power transfer mechanism is detailed in Section 3.1. The second component of the proposed system is the implanted circuit, built with charge recovery principles in this paper, detailed in Section 3.2.

3.1 Wireless power delivery

An Helmholtz coil [8] is used in order to generate a spatially constant magnetic field, through an AC current $i_{tx}(t) = I_{tx}\sin(2\pi f_{tx})$. The magnitude of the generated magnetic field B_{tx} can be approximated as

$$B_{tx} = \frac{\mu_0 N I_{tx}}{r}\left(\frac{4}{5}\right)^{3/2} \tag{2}$$

where μ_0 is the vacuum magnetic permeability, N is the number of turns per coil, I_{tx} is the magnitude of the current through the coils, and r is the radius of the coils. For example, for $I_{tx} = 1\,\mathrm{A}$, $r = 10\,\mathrm{cm}$, $N = 100$, the generated magnetic field is $B_{tx} = 900\,\mu\mathrm{T}$. In this case a radius of 10 cm was used to reflect the typical dimensions of a mouse cage. The Magnetic field $B = B_{tx}\sin(2\pi f_{tx})$ translates in a magnetic flux Φ over the receiving coil, and it is equal to

$$\Phi = B \cdot A \tag{3}$$

where A is the area of the coil on the in-vivo system. For example, for a square coil like the one in Figure 2(a) with 3 mm sides, and with the values of the previous example, $\Phi = 9\,\mathrm{nWb}$. According to Faraday's Law, the electromo-

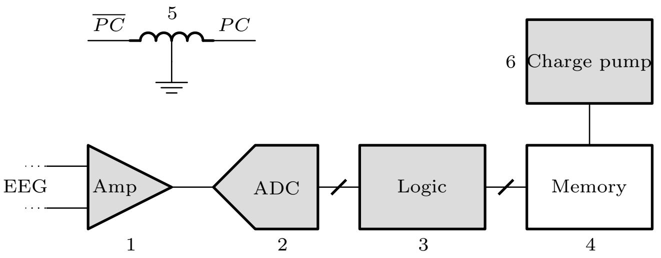


Fig. 3: The proposed implantable integrated circuit

tive force, or EMF, across the receiving coil is

$$\mathcal{E} = -n\frac{d\Phi}{dt} = -nB_{tx}A2\pi f_{tx}\cos(2\pi f_{tx}) = V_{rx}\cos(2\pi f_{tx}) \tag{4}$$

where n is the number of turns of the receiving coil. With the number from the previous examples, $n = 10$, and with a transmission frequency of 1 MHz the induced voltage on implanted coil is $V_{rx} = 0.5\,\text{V}$, i.e. a 1 Vpp signal. The same recovered voltage can be obtained with $n = 1$ and $f_{tx} = 10\,\text{MHz}$, if for example the implanted coil must be as small as possible.

3.2 Implanted IC with charge recovery logic

The proposed implementation of a charge recovery system for EEG applications is shown in Figure 3. The wireless implanted receiving coil, described in Section 3.1, is labeled 5. The building blocks of the wirelessly powered CRL circuit are labeled 1 through 6.

The required functionality of these building blocks (such as amplification, A/D conversion etc.) are known and relatively common implementations exist. The novelty is in the integration of charge recovery implementations of these blocks. Charge recovery implementations of some of these blocks have been presented in literature, whereas some others need continued investigation. The specific implementations of the missing blocks are left to future work; instead, a system integration overview of blocks is proposed here, clearly marking potential design paths for blocks, where available, in existing literature.

The principal parts of the systems are

1. Differential amplifier. Takes the neural signal from the probes and intensifies it, and can be realized in a charge recovery fashion [9].
2. ADC. Converts the amplified signal to a digital value, and some early works exists for a charge recovery implementation [10].
3. Logic. In the simplest form it is a memory addressing block, but many complex functions can be implemented, as shown in Section 4.
4. Non volatile memory. Stores the sampled data indefinitely, e.g. flash memory. It is the only block that does not employ charge recovery principles, as it only stores digital data. The whole addressing and reading circuitry can be charge recovery implemented [11].
5. The center tapped inductors, as shown in Figure 2, that recover the transmitted voltage and produce two power-clock signals of opposite polarity.
6. Charge pump. Boosts the recovered voltage of block 5 to higher level that is suitable for flash memory operation.

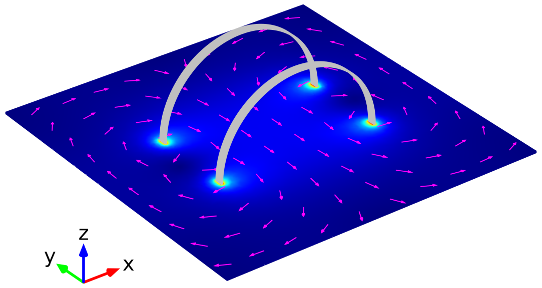


Fig. 4: The simulated magnetic field in the middle of the Helmholtz coil is $B_{tx} \approx 900\,\mu\text{T}$.

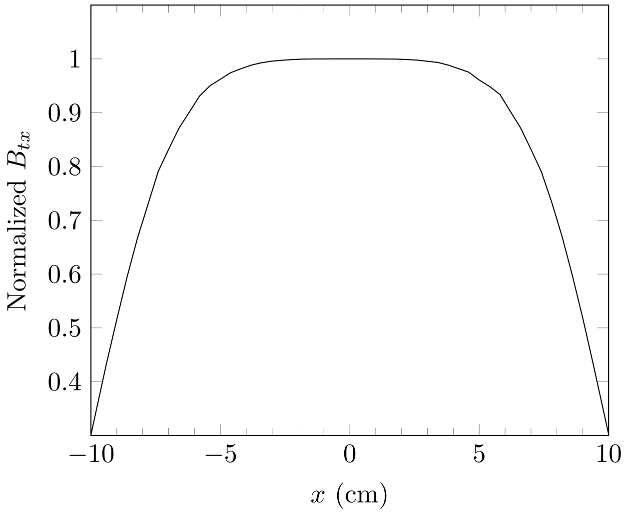
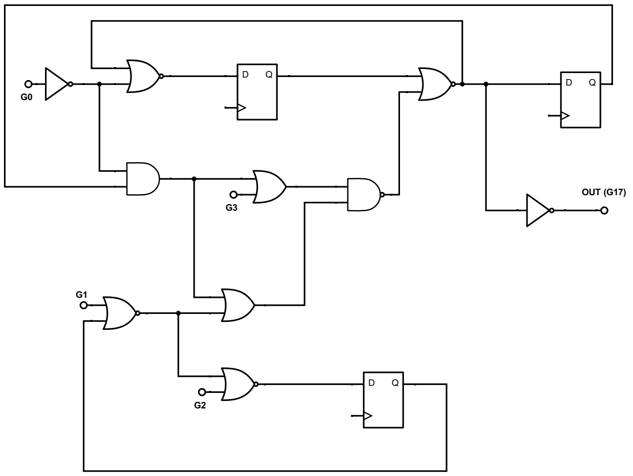


Fig. 5: Magnetic field B along the x coordinate, for $y = z = 0$

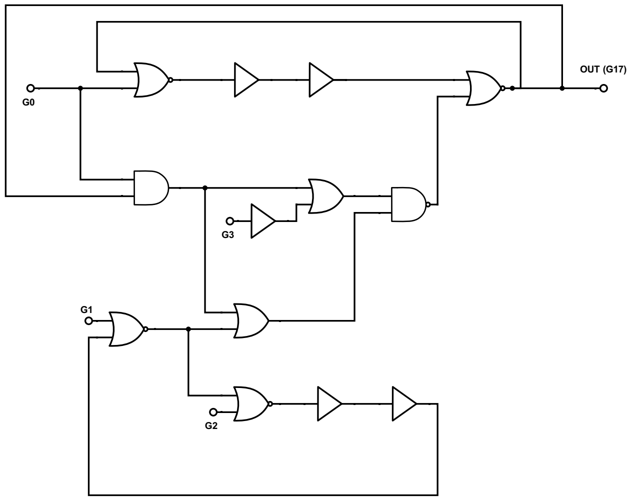
Every component in Figure 3 can be integrated in an IC, hence providing a small implantable device that does not require any wires for its operation. In order to recover the data, the proposed system can be removed from the animal once the memory is full. If the latter is not an option, e.g. for long-term studies, a transmitting antenna could be added to the system in order to recover the data. In that case, the on-chip memory could be superfluous and a passive RFID circuitry could be added to transmit the measured data [12].

4 Experimental setup

Prior to an actual physical prototype, circuit simulations and finite-element method simulations are used to demonstrate the operation of selected building blocks shown in



(a) Static CMOS



(b) Charge recovery logic implementation

Fig. 6: The s27 circuit schematic from ISCAS '89 benchmarks

Figure 3. Simulations with SPICE and FEM analyses are industry standard methods to evaluate circuit implementations and the wireless link, respectively, and are very common in electrical engineering. Both methods have very high fidelity of accuracy.

FEM simulations were carried out in Comsol Multiphysics in order to confirm the theoretical results of Section 3. A 2D axi-symmetric parametric model was set up, and the values from the previous example where used. Figure 4 shows the simulated magnitude and direction of the magnetic field B generated by an Helmholtz coil with the values of the previous example. The simulated magnetic field is approximately $900\,\mu T$ and validates the result obtained from Equation 2. A transient simulation of the Helmholtz coil and the receiving coil shows that the recovered voltage, for a coil with area $9\,\mu m^2$ and $n = 10$, is a 1Vpp sine-wave at $1\,MHz$, as expected from Equation 4.

Figure 5 shows the variability of the magnetic field produced by the Helmholtz coil B_{tx}, when traveling along the x axis. Since the coil is symmetrical around the z axis, This is the magnetic field variability that a mouse would see while moving in the cage. An Helmholtz coil of the previous example, with $R = 10\,cm$ could fit around a circular cage of diameter 18 cm, allowing for enough room for the animal. From Figure 5 it can be seen that 18 cm traveling across the x (and because of the symmetry on the y too) axis causes a decrease in the magnetic field up to 50 % of its highest value. This means that if the recovered voltage is 1 Vpp in the middle of the Helmholtz coil, it goes down to 0.5 Vpp towards the edge of the cage. The implanted system will have to be resilient to such variations, and as showed [6] wirelessly-powered CRL is capable of such flexibility.

As an example of the power savings offered by charge recovery logic, the authors compared CRL and static CMOS implementations for s27, the smallest circuit of ISCAS '89 benchmark suite [13]. Both the CRL and the static CMOS circuits of Figure 6 are implemented in CMOS 65 nm technology. When implemented with CRL, the circuit of Figure 6 consumes one fourth of the power of the static CMOS version, at both 1 MHz and 10 MHz. Other works present improvement in power consumption for circuits from discrete filters [14] to datapath blocks such as adders and multipliers [5].

5 Conclusion

In this work a system for implantable untethered devices for EEG applications is proposed. The focus is in building a blueprint of system integration, with simulations used to demonstrate the feasibility of i) circuit operation and ii) wireless powering, of the proposed system. In particular, the implanted integrated circuit employs charge recovery principles in order to decrease the power consumption of the in-vivo apparatus. Also, the system does not use a resonant inductive link, reducing the complexity of the link design and allowing for flexibility in transmission frequency. The presented work has the potential to be extended to capture other physiological signals including cardiac and respiratory signals, and not only in laboratory and free-range animals, but humans as well – both in the hospital and home monitoring.

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