A Brief Review of Brain Machine Interface with Focus on RFID-inspired System

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Abstract—**In this review, we begin at illustration of the importance of Brain Machine Interface (BMI) technology, then discuss several challenges facing in design, such as powering and wireless communication issues. Radio-frequency identification (RFID) is then reviewed as possible solution. We also review a practical end-to-end RFID-inspired BMI system as example.**

I. Introduction

Brain Machine Interface (BMI) is one of the most challenging multidisciplinary fields, which has drawn tremendous attention from neuroscientists, IC engineers, antenna engineers, biomedical engineers in the last decade.

BMI technology has been viewed as one of the most promising ways to restore the functionality of disable patients, and also one of the most interesting topics in Sci-Fi creations (see *Ghost in the Shell, 1989*). However, although many people pinned their hopes on this technology, there are still lots of challenges remain unsolved to develop a reliable, practical-use BMI application.

One of the challenges lies in the data transfer of detected neural signal, which is also the highlight of this review. Since it is undesirable for customer to penetrate a hole on cranium and connect a wire for data transmission, some research has been devoted to do to this job wirelessly. For this concern, the research of BMI really need the devotion of antenna engineers and electromagnetic scientists.

In this review, we illustrate several considerations of BMI design, with focus on wireless method. In Section II, the overview of BMI technology is given. And we discuss several challenges on such technology development. In Section III, one of the most promising ideas for BMI antennas design, radio-frequency identification (RFID), is reviewed. In Section IV, one recent work is presented as an example for RFID-inspired BMI system.

II. Brain Machine Interface

A. Importance of BMI Technology

Since in 1999, first experimental demonstration showed that ensembles of cortical neurons could control a robotic manipulator [1]. BMIs have been conceived as a new therapy to restore motor control in severely disabled patients. Besides BMIs controlling limb prostheses, some researchers also dedicated to using BMI to restoration of locomotion and speech.

B. Challenges of BMI Design

The BMIs can be simply classified as non-invasive and invasive, depends on whether utilizing invasive (i.e. intracranial) methods of electrophysiological recordings. Each have their own advantages and design concerns.

1) Non-invasive BMIs: Primarily exploiting electroencephalograms (EEGs), non-invasive system can be used to control computer cursor and other devices, providing simple way for paralyzed patients to communicate. These kinds of systems have advantages in safety concern and fewer biocompatibility issues. However, neural signal have a limited bandwidth in this case.

2) Invasive BMIs: As the main topic of this review, invasive BMIs provide the best signal quality, but it also carried risk associated with invasive surgical procedure. Beside all of these, there are several design challenges remain [2]:

a) Operation Frequency: Selection of operation frequency involves several trade-offs. Low frequency is associated with lower loss through biological tissues. However, low frequency limit the communication speed and imply large antennas and circuit components, which are not good for in-body device. The most used frequency is Medical Device Radio Communication Service (MedRadio) band of 403.5 MHz, which is also used in the example in Sec. IV.

b) Wireless Interface: Integration of wireless capabilities into the in-body device is highly critical. Inductive coupling technology can be used, which require inductors within the implant and exterior device that were brought in close proximity. However, it suffers from slow data rates and high sensitivity to misalignments. In-body antennas can avoid aforementioned problems, and the design challenges are mainly related to miniaturization.

c) Powering: Nowadays, in-body device powered by batteries is not desired, because of increased size, safety concerns and frequent replacements or recharging. Batteryless in-body devices draw much attention for these reasons. One solution is using power harvesting techniques, which harvest power from environmental or bodily source. Another one, which will also be discussed later in III, is fully-passive operation, which eliminate power storage requirements of any sort. Exterior interrogator in close proximity is required in fully-passive operation.

d) Biocompatibility: Biocompatibility means that the device operating inside the body won't react with the surrounding tissues. Usually this problem will be solved by the use of biocompatible materials, or coating with thin biocompatible polymers. However these solutions only provide short-term biocompatibility.

III. RFID ANTENNAS FOR BMI DESIGN

As discussed in Section. II-B2b and Section. II-B2c, main challenges about invasive BMIs include powering and wireless communication issues. One of the method to solve this two at once is using radio-frequency identification (RFID) design.

A. Principles of Passive RFID

RFID is a wireless application that utilize RF backscattering to extract information associated with remote objects [3]. Specifically, passive RFID offers several advantages for BMI systems, including low profile, battery less operation, flexible realization. The working principle of passive RFID is shown in Fig. 1. The RFID reader sends a carrier signal f_c, which will be wirelessly received by the RFID tag. Then the RFID tag will activate the IC, and backscatter the mixed signal $f_c \pm f_s$, where f_s is sensed signal. And then demodulation will be utilized.

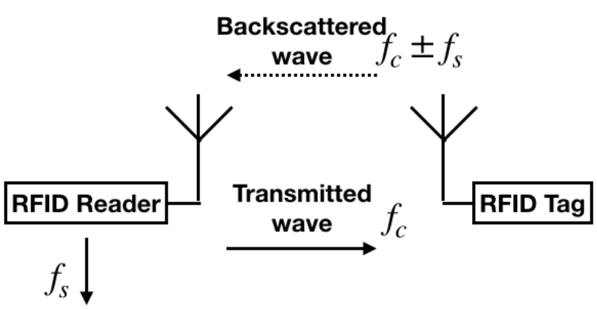

Fig. 1. The principle of passive RFID system

B. Design Considerations of RFID Device

There are several design considerations for RFID devices, particularly for BMIs. Here we discuss some of them.

a) Influence of the Human Body: Biological tissues exhibit frequency-dependent permittivity and loss-tangent that far exceed free space. Anatomically shaped tissue models may be pursued to take into account the presence of biological tissues. These properties may change not only among individuals, but also for same individual in different conditions.

b) Safety against Electromagnetic Fields: RFID technologies need to conform to safety guidelines for specific absorption rate (SAR). The evaluation of the SAR levels associated thus becomes a key design parameter.

IV. EXAMPLE: AN END-TO-END IMPLANTED BRAIN–MACHINE INTERFACE ANTENNA SYSTEM

In the previous sections, we have already shown several design challenges for BMI system, and specifically on design using antennas. We also show that RFID technique might be one of the solution. In this section, we demonstrate how this idea can be applied to practical work. The example demonstrated here is the work from [4].

The system considered applies short-range RFID backscattering technology. Between the reader antenna and implanted antenna, power and data transfer are realized by near-field inductive coupling. Implanted antenna will activate neural recording IC by receiving power. The impedance at the terminal of the implanted antenna according to neural signal will then be used to modulate the reflected signal.

A. Wireless Link Characterization

The power is transferred from reader antenna to implanted antenna using short-range backscattering technology, utilizing near-field inductive links. This method is desirable to transfer power through highly dissipative medium, in this case, human head.

The wireless link can be characterized as a linear two port network, the input and output impedances can expressed as

$$Z_{ta} = Z_{in} = Z_{11} - \frac{Z_{12}Z_{21}}{Z_{22} + Z_{IC}} \tag{1}$$

$$Z_{ra} = Z_{out} = Z_{22} - \frac{Z_{12}Z_{21}}{Z_{11} + Z_s} \tag{2}$$

where Z_s and Z_{IC} denote source and load impedance, Z_{ta} and Z_{ra} denote impedance of transmitting and implanted antennas, respectively. Link power efficiency $G_{p,max}$, defined by maximum ratio of power delivered to the implanted antenna to the power supplied to the reader antenna, can be used to describe effective coupling between antennas.

$G_{p,max}$ will be achieved when $Z_{ta} = Z_s^*$ and $Z_{ra} = Z_{IC}^*$.

The exposure of the tissues to electromagnetic fields needs to be considered. According to FCC regulation, the maximum SAR level should be less than 1.6 W/Kg, which in terms limit the maximum power P_t delivered by the reader antenna. The maximum power available to the implanted device is $P_{L,max} = G_{p,max}P_{t,max}$. The goal of design is to maximize P_L while P_t remaining low enough for regulation.

B. Antenna Design

1) Reader Antenna Design: The goal is to provide high inductive coupling to maximize the link power efficiency, as well as low SAR. The objective can be summarized as follows: 1) high near magnetic field and efficient coupling; 2) low near electric field, since local SAR is proportional to $|E|^2$. Using computer simulation to find the optimum size for reader antenna, while keeping trace width fixed to 3 mm to lower ohmic loss, the result shows that the optimum size for 400 MHz is about 6 mm in inner radius. However, even the optimum configuration is obtained, the solid loop structure give rise to E-field hot spots close to the feeding point, due to nonuniform current distribution within the loop. The E-field hot-spot leads to high local SAR, which is undesired. Prior research showed that partitioning loop antenna into segments and inserting capacitors help E-field hot spots be averaged effectively.

2) Implanted Antenna Design: For applications of implanted near sensing system, the occupied space is a major constraint. Using similar simulation, the optimum values for the link change for different implant sizes can be found, which shows that the optimum size is about 1 mm. Simulations were carried out with the presence of head model. The structure advantages of using cubic or coils were also studied. The cross-sectional area and overall separation remains the same. The result shows the advantages of using cubic structure, also allowing insertion of magnetic core to further enhance inductive coupling [4].

C. Simulation

1) Antennas in Human Head Model and Path Loss: For approximation, human head can be represented by a multilayered lossy dielectric sphere. Considering six-layer head (brain, CSF, dura, skull, fat, skin), four-layer head (brain, CSF, skull, skin), homogeneous head and fully integrated head (with organs and muscles), the simulation can be carried out. Link efficiency is lower in head model than in air, as expected. For interested frequency around 400 MHz, the link power efficiency of two head models agree quite well.

2) Local SAR: In the U.S. standard, the SAR value for partial body exposure regulated by FCC to 1.6 W/Kg. The simulateion with testing excitation 1 W at reader antenna is considered. The maximum SAR is generated in the top skin surface, which is closest to reader antenna [4]. The maximum SAR-compliant trasmit power can be computed as $P_{t,max} = 1.6/\mathrm{SAR}_{max,exc=1w}$, which is about 60 mW or 18 dBm. For fixed maximum received power, while the maximum voltage is also related to the impedance at resonance [4].

D. Estimation of Channel Capacity

Future BMI requires large number of sampling channel for accuracy, spatial- and temporal-resolution., and reliability. It is also required to analysis the power and data transfer in telemetry system.

1) Power Transfer: The link budget gives the energy supplied to the load as $P_L = G_{p,max}P_{t,max}$, where $P_{t,max}$ is the maximum SAR-compliant transmit power and $G_{p,max}$ is the maximum link efficiency. In Section IV-C2, the maximum SAR-compliant transmit power is 60 mW, and the maximum link power efficiency is higher than -20dB [4]. The maximum RF power applied is thus 600 μW. The state-of-the-art RF-to-dc convert efficiency is about 79.9%. Thus, the maximum dc power supplied to the load is about 480 μW, which can supporting existing neural recording IC with up to 96 channels (5 μW/channel).

2) Data Transfer: For data transfer, the theoretical maximum data capacity is given by Shannon's Law: $C = B\log_2(1+\mathrm{SNR})$, where C is the data capacity in bits/second and B is the bandwidth in Hz. Assume the implanted antenna noise temperature T_A is as derived using the full-wave absorption-noise model as 112.24 K [4]. For low-power neural signal of -80 dBm, SNR $= S_i/(kT_AB) =$ 28dB, which satisfies typical wireless link.

E. Summary

In this example, we illustrate several important consideration in BMI design, such as local SAR constraint, influence of human head. The detailed optimization, evaluation and capacity estimation are also performed in original work [4]. The demonstrated end-to-end design and characterizations provide wireless and fully passive telemetry that can be used as multichannel BMIs.

V. Conclusion

In this review, we illustrated the importances and challenges of BMI technology, with focus on RFID-inspired design. We show that how invasive BMIs might outperform non-invasive BMIs in current technological development, and why invasive BMIs facing challenges in powering and wireless communication. RFID technology is then reviewed as possible solution, and several design considerations are mentioned. And then a practical example [4] of end-to-end RFID-inspired BMI system is also reviewed to illustrate how the aforementioned considerations come to the play in practical work.

References

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