

Data Communication Between Brain Implants and Computer

Mingui Sun, Marlin Mickle, Wei Liang, Qiang Liu, and Robert J. Sclabassi

Abstract—Recent advances in neuroscience, microelectronics, and information technology have allowed construction of miniature, but highly intelligent, devices to be implanted within the brain to perform *in vitro* diagnostic and therapeutic functions. However, there exists a significant problem in establishing an effective wireless data communication link between brain implants and external computer. This communication investigates this link and presents a new design using the mechanism of volume conduction of biological tissues. A theoretical model of volume conduction of the head is utilized to compute signal strength in data communication and the result is evaluated by a physical model. The two-way data communication sensitivity of the volume conduction channel is found to be symmetric, as suggested by the reciprocity theorem. A high-performance, α -shaped volume conduction antenna has been designed. Experiments are performed on animals which demonstrate the effectiveness of this volume conduction approach.

Index Terms—Brain-computer interface (BCI), data communication, implantable device, medical device, medical informatics, microelectromechanical device, neural engineering, neural prosthesis, telemetry, volume conduction.

I. INTRODUCTION

There has been active research on brain-computer interface (BCI) with implantable devices [1]. This research has mainly targeted the access/delivery of meaningful signals from/to the human cortex so that information in a bioelectric form can be converted to/from information in a digital form. As a result, sophisticated electrodes and implantable chips performing such conversion have been investigated and several prototypes of these devices have been demonstrated. However, one extremely important problem has not yet been well addressed: How do we pass this information between implanted brain chips and computers? In the current experimental settings, wires are utilized. Clearly, this type of connection involves a high risk of infection. Wireless radio frequency (RF) connection provides an alternative. However, its feasibility is in serious question due to the following limitations: 1) RF antenna and certain circuit elements (e.g., induction coils) increase the size and the mass of the brain implant; 2) the conversion between signal and RF waves requires a considerable amount of energy which is drained from an internal battery within the implant, and this battery is difficult to recharge or replace; and 3) the ionic fluid of biological tissues, such as the cerebrospinal fluid, is highly conductive. As a result, transmitting an RF signal within the head is similar to transmitting a radio wave through an electrically shielded room. Such transmission is possible only when the RF signal is strong and its frequency is relatively low, which requires more energy consumption.

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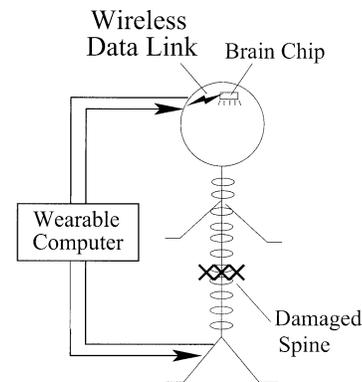


Fig. 1. Wireless data communication establishes a closed-loop information link bypassing the damaged spine (marked by “XXX”).

There exists a natural passageway of information which has been previously overlooked. The ionic fluid in the biological body conducts electrical current which, when intentionally manipulated, is capable of passing information. This conduction is called volume conduction. Electrostatic laws of physics state that a current source within a volume conductor results in an electrical potential distribution within and on the surface of the conductor. This potential can be measured by affixing a pair of stick-on electrodes on the skin surface.

There are only a handful of reports on data communication based on the mechanism of volume conduction. Mackay [2] described an interesting experiment for sending data inside the body of a dolphin to a pair of remotely located electrodes placed in sea water. Recently, Lindsey *et al.* [3] reported an experiment transmitting information from a pair of platinum electrodes implanted within a leg of a cadaver to measure the tension in anterior cruciate ligament grafts.

When compared to the RF approach, the volume conduction approach has the following advantages:

- 1) strong shielding effect of ions in the biological tissue is no longer a problem, instead, these ions are now employed as information carriers;
- 2) electronic circuit associated with the communication system is simple and does not involve bulky components, allowing an aggressive reduction in size and weight;
- 3) system does not require signal conversions to/from RF, increasing energy-efficiency.

Because of these advantages, the volume conduction approach has many potential applications, such as the one shown in Fig. 1.

This paper will first describe theoretical and physical models. Then, a fundamental property concerning channel symmetry in two-way data communication will be presented in terms of the reciprocity theorem. We will also present a design of the volume conduction antenna, results of animal experiments, and data analysis using signal processing techniques.

II. THEORETICAL AND PHYSICAL HEAD MODELS

A key question is: will the volume conduction system have enough sensitivity to pass information reliably through a noisy biological environment? In order to answer this question, we have calculated the signal strength on the scalp using a theoretical volume conduction model of the head.

We coarsely approximate the head by a hypothetical homogenous conductive sphere of 15 cm in diameter. A volume conduction antenna is located at the center of the sphere. This antenna is modeled by a current dipole consisting of a source and a sink separated by a small distance. A pair of external electrodes are located on the surface

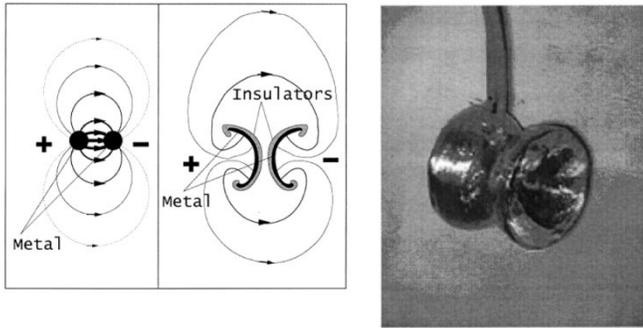


Fig. 2. (left) Artificial current sources of conventional design. (middle) New x antenna design. (right) Actual construction of the antenna.

TABLE I
COMPARISON BETWEEN x ANTENNA AND ELECTRODE PAIR

Received Strength	Signal	x -Antenna		
		Current	Voltage	Power
0.05 mV		130 μA	20 mV	1.3 μW
0.1 mV		242 μA	40 mV	4.84 μW
0.15 mV		393 μA	60 mV	11.79 μW
Received Strength	Signal	Electrode Pair		
		Current	Voltage	Power
0.05 mV		428 μA	600 mV	128.4 μW
0.1 mV		762 μA	800 mV	304.8 μW
0.15 mV		1133 μA	1000 mV	565.5 μW

of the sphere along the same line connecting the source and sink. For this particular configuration, the signal strength v across the external electrodes can be expressed by a very simple expression [4]: $v = 3M/(2\pi\sigma R^2)$, where M , R , and σ are, respectively, the dipole strength, model radius, and conductivity (for soft tissues, $\sigma \approx 1/222 \text{ cm}^{-1} \cdot \Omega^{-1}$ [5]). Note that v is linearly related to M (this linearity holds for the general case regardless the shape and homogeneity in conductivity). To demonstrate the magnitude of v with respect to M , let us assume that the distance between the source and sink is 1.4 cm and a current of 40 μA is emitted by the dipole. Then, $M = 56 \mu A \cdot \text{cm}$ and the voltage across the external electrodes is $v = 105 \mu V$, which represents a reasonable signal strength for the purpose of data communication since, as we know in the RF case, a raw signal from the reception antenna as weak as several microvolts is usually detectable.

In this calculation, we did not consider the effects of the skull whose conductivity is between 26 and 80 times smaller than that of soft tissues [6]. In our previous publications [4], we have derived a computationally efficient algorithm for evaluating surface potential of a spherical model with four conductive layers representing the brain, cerebrospinal fluid, skull, and scalp. Our result based on this algorithm indicates that the signal intensity on the scalp is 88 μV , about 16% less than that computed from the homogenous model.

In order to evaluate our calculations, we physically constructed a model filled with sodium chloride solution with an electrical resistivity of $222 \Omega \cdot \text{cm}$. A dipole antenna and a pair of external electrodes were placed at the same locations as those described previously. The measured voltage at the external electrodes was approximately 13.6% smaller than the calculated result.

III. RECIPROCITY THEOREM

Our system is required to pass information bidirectionally. In this context, it is important to know whether the sensitivity of the information channel varies if the roles between transmission and reception are switched. We have theoretically investigated this problem using a two-port model and applied the reciprocity theorem [7]. A two-port

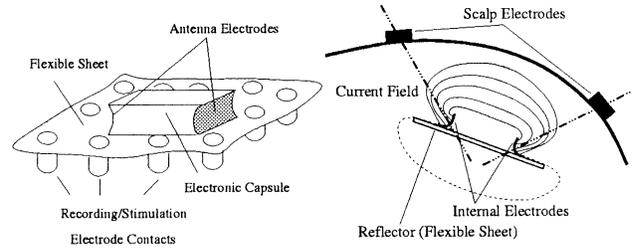


Fig. 3. (left) Structural design of the brain implant. (right) The reflector formed by the flexible sheet blocks most current flux flowing through the brain (dashed curve), while enhancing the current flux (solid curves) in the direction of the reception electrodes on the scalp.

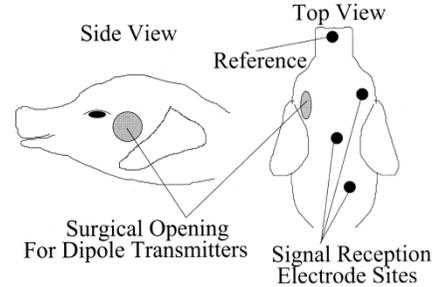


Fig. 4. Surgical site for placement of dipoles (left) and locations of reception and reference electrodes (right).

system is a black box with two pairs of accessible terminals. The theorem states that, if this system is linear, time-invariant, zero-state, nondegenerate, and passive, the two access terminals can be interchanged without altering the system response to a given waveform. With appropriate assumptions, the application of the reciprocity theorem to our problem indicates that, under the same excitation current, the volume-conduction-based data communication system produces the same output regardless of the direction of information flow. We have experimentally verified this property using our physical model. The discovery of this property provides a theoretical foundation for system design.

IV. ANTENNA DESIGN

Dipole electrodes for emitting current within a volume conductor have been available for different applications. Since both metal poles (shown in the left-most panel in Fig. 2) are exposed to the conducting medium, most current flux goes directly from the positive pole to the negative pole. This strong “shorting” current not only wastes power, but also promotes adverse effects interfering with vital organ’s activity. In contrast, the useful far-field, which contributes to the transmission of information, is relatively weak.

A. x Antenna

We have designed a new antenna illustrated in the middle panel of Fig. 2. The black and shaded regions of the “ x ”-shaped antenna indicate a metal layer and an insulator layer, respectively. Since the shorting paths between the two electrodes are blocked by insulation, current is forced to flow along much longer paths. As a result, the far-field is enhanced significantly since, by the definition of a current source, the total amount of current flowing through the volume conductor is the same in both cases. In addition, by selecting the shape of “ x ” and the pattern of the insulation layer on the electrodes, a directional transmission can be obtained. The middle panel illustrates that the flux line lengths in the upper part are longer than those in the lower part due to the asymmetry of the two openings in “ x .” Our actual construction of the x antenna is shown in the right panel.

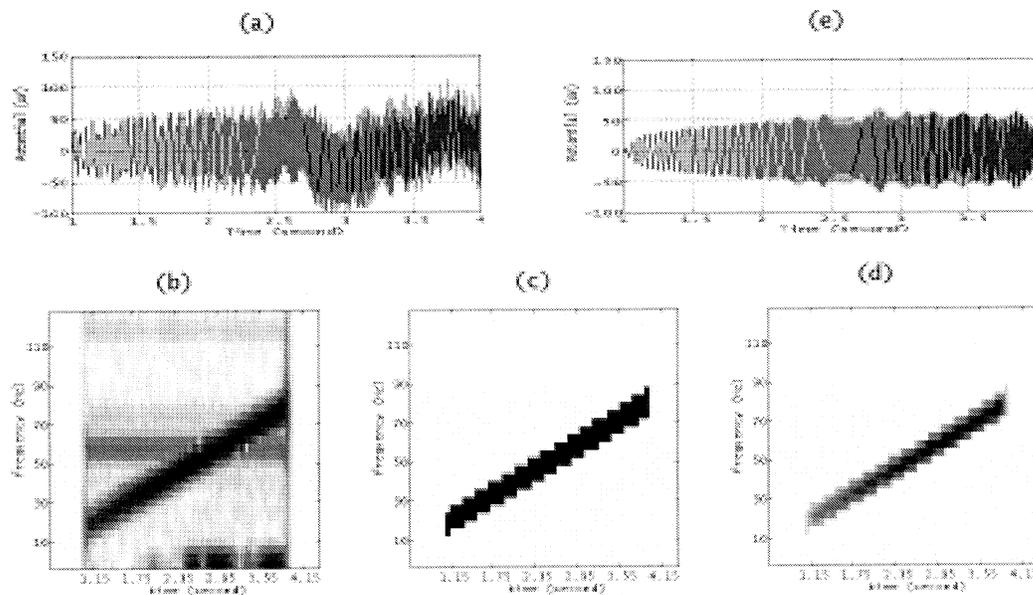


Fig. 5. Gabor time-frequency analysis and synthesis. (a) Recorded data segment corrupted by biological and environmental noise. (b) Amplitude of discrete Gabor coefficients. (c) Mask function for selecting the desired time-frequency component. (d) Gabor coefficients after four iterations. (e) Result of Gabor synthesis.

The new x antenna was compared to the traditional dipole antenna using a spherical conductor model 30 cm in diameter. The diameter of the x antenna was 9 mm and the openings of both antennas were 7 mm. In each case, the antenna was placed at the center of the physical model to transmit a sinusoidal current signal of 1 KHz. The received voltage signal by the external electrodes (15 cm from the antenna) was measured. Table I compares transmission current (in microamperes, peak value), transmission voltage (in microvolts, peak value), and power consumption (in microwatts) for both the x antenna and the traditional electrode pair. The results indicate that, for the same output, the new design requires only 30%–35% of the transmission current, 3%–6% of the transmission voltage, and 1%–2% of the power compared to the traditional design, representing a substantial improvement.

B. Integration of x Antenna With Implantable Device

Since the available space for implanting a device between the brain and the skull is very limited, we have integrated the x -antenna with the implantable device so that it does not occupy additional space. The electronics required for data communication are designed in modular forms and the small-size circuitry is entirely included, along with other circuit modules, within the “electronic capsule” of the implantable device (left panel in Fig. 3). Our structural design of the device for brain implants includes a flexible, transparent, thin plastic sheet embedded with a grid of contacts facing the brain. These contacts measure brain activity and/or perform cortical stimulation. On the top of the flexible sheet (opposite to the site of contacts) lies an electronic capsule which hosts a data communication subsystem, a battery, and an antenna for wireless data transmission and reception. The capsule has a low profile to facilitate subdural implantation. Two of the side panels (one of them is shown as the shaded region) are made concave in shape to form two x -antenna surfaces. Although the side view of the each surface is now rectangular rather than circular, the essential feature of the antenna described in the previous section is retained. For the optimal data transmission, each antenna surface aims at the corresponding scalp electrode (dash-dot lines in the right panel).

In addition to space-saving, our design has the following important features: 1) it employs a relatively large portion of packaging area for the antenna, reducing the current density in brain tissues surrounding the antenna surfaces and improving electrical contact; 2) it increases

the efficiency of the transmitter because of the maximum separation between the two antenna surfaces; 3) the flexible sheet is deformable to conform to the exterior shape of the cortex; and 4) this sheet forms a reflector which strengthens the current field in the direction of reception, and weakens the current flowing through the brain, as depicted in the right panel in Fig. 3. As a result, the undesired brain stimulation by the current-emitting antenna is minimized.

V. ANIMAL EXPERIMENTS

With approval from the Institutional Animal Care and Use Committee, we performed an experiment on a Yorkshire pig which was provided with standard anesthesia and life support. Current sources were surgically implanted within the head. A linear sinusoidal chirp signal in the form $A(t) \sin(\alpha t^2)$ was generated as a sound wave file and played on a computer. A 2.5-V output voltage was obtained at the “audio-out” socket which was connected, after voltage attenuation, to a current drive to excite the dipole antenna connected to the computer. Two such antennas were implanted under the dura with the exposed metal elements in contact with the cortex. After closing the surgical opening, needle electrodes were placed at the locations shown in Fig. 4. Three channels of potential data, all referenced to the electrode on the snout, were then collected (sampling frequency of 256 Hz) repeatedly over a 5-h period.

We intentionally delivered a very low exciting current [$20\text{-}\mu\text{A}$ root-mean-square (rms) value] to each of the implanted dipoles. Noise contamination in the recorded data was significant because of this low-current level [Fig. 5(a)]. Since this signal is highly nonstationary, we applied a discrete Gabor analysis and synthesis technique [8] (reported by us for a different application). Fig. 5(b) shows the image of the amplitude values of the Gabor coefficients (matrix size 33×128). In this image, horizontal and vertical axes represent, respectively, the time and frequency variables. The chirp signal (diagonal component), the 60-cycle interference and its harmonics (horizontal stripes), and the spontaneous EEG in the bottom part of the image can be clearly observed. Panels (c)–(e) show, respectively, the mask function of a special filter with varying frequency characteristics over time, the filtered Gabor coefficients after four iterations, and the reconstructed signal. The noise originally presented in the data has been virtually eliminated [compare (a) and (e)].

VI. CONCLUSION

We have conducted a fundamental investigation on a novel application of volume conduction through biological tissues as a wireless BCI. Both a theoretical model and a physical model have been utilized to study the system sensitivity. An important property of channel symmetry has been found based on the reciprocity theorem. An x -shaped volume conduction antenna has been designed which not only enhances transmission/reception, but also minimizes the space for brain implantation. Our investigation provides a new enabling technology to integrate brain function and the external computing environment with broad applications.

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Probabilistic Methods in BCI Research

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Abstract—This paper suggests a probabilistic treatment of the signal processing part of a brain–computer interface (BCI). We suggest two improvements for BCIs that cannot be obtained easily with other data driven approaches. Simply by using one large joint distribution as a model of the entire signal processing part of the BCI, we can obtain predictions that implicitly weight information according to its certainty. Offline experiments reveal that this results in statistically significant higher bit rates. Probabilistic methods are also very useful to obtain adaptive learning algorithms that can cope with nonstationary problems. An experimental evaluation shows that an adaptive BCI outperforms the equivalent static implementations, even when using only a moderate number of trials. This suggests that adaptive translation algorithms might help in cases where brain dynamics change due to learning effects or fatigue.

Index Terms—Adaptive classification, Bayesian interface, empirical comparison, probabilistic modelling.

I. INTRODUCTION

The brain–computer interface (BCI) used in our paper follows previous work by [3], [7], [8], and [14], and uses surface electroencephalography (EEG) to record brain signals that are converted into computer commands. A good average communication bandwidth of such a system will be in the range of 5–25 b/min [13]. This is sufficient for non-time-critical communication tasks like [3], but clearly not enough for high-bandwidth applications such as control of a powered wheel chair. A probabilistic point of view of current BCI signal processing suggests two modifications that have been found to improve the bandwidth. Probabilistic methods (e.g., [2]) regard all BCI parameters (i.e., features extracted from EEG and all other parameters) as random variables. Inference (i.e., finding the posterior distribution $p(\mathbf{w}|\mathcal{D})$ over model parameters \mathbf{w} given data $\mathcal{D} = \{y_n \forall n = 1 \dots N\}$) and prediction, require two operations.

- 1) Bayes' theorem $p(\mathbf{w}|\mathcal{D}) = p(\mathbf{w})p(\mathcal{D}|\mathbf{w})/p(\mathcal{D})$ converts a prior, $p(\mathbf{w})$, and a likelihood, $p(\mathcal{D}|\mathbf{w})$ into a posterior.
- 2) To obtain model predictions $\hat{y} = \int_{\mathbf{w}} y(\mathbf{w})p(\mathbf{w}|\mathcal{D})d\mathbf{w}$ and the normalization constant $p(\mathcal{D}) = \int_{\mathbf{w}} p(\mathbf{w})p(\mathcal{D}|\mathbf{w})d\mathbf{w}$, we need to calculate marginalization integrals.

We use probabilistic methods to improve two suboptimal aspects of current BCI systems. First, we compare classical time series classification with a probabilistic generalization that uses a joint model for feature extraction and classification. Used in that manner, the probabilistic approach implicitly considers the certainty of information. Empirical tests confirm that this allows us to predict cognitive states with higher accuracy and, thus, to increase the communication bandwidth. The second aspect of probabilistic methods considered in this paper is to use a hierarchical model for inferring the BCI classifier adaptively. Compared with a stationary model, the adaptive BCI shows a statistically significant improvement in communication bandwidth.

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