

# SIGNAL MULTIPLEXING AND MODULATION FOR VOLUME CONDUCTION COMMUNICATION

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## ABSTRACT

Volume conduction communication is an efficient means of transmitting signals within the human body. This paper introduces a multiplexing and modulation method which minimizes circuit complexity, space, and power consumption.

## 1. INTRODUCTION

Medical Implants will continue to grow in sophistication requiring greater computational power and memory, and demanding more space and energy. However, medical implants must be small enough to facilitate implantation because the more power they consume, the more frequent their power supplies require surgical replacement. By establishing a high-fidelity space and power efficient communication channel between the implant and an external computer we can allow most of the processing and memory to lie in a computer external to the patient's body, where space, energy, and computational power are relatively unlimited. This communication channel cannot be implemented with direct wires traversing the skull, as these wires tend to break or cause infections. An effective and efficient telemetry methodology, wirelessly connecting the implant to an external computer must be established. The most commonly employed wireless technology with implants is still radio frequency (RF) telemetry. However, telemetry within a conductive medium, such as a human body, is highly inefficient when using RF, as high frequencies are rapidly dissipated in a conductive medium.

Instead of being hindered by the conductive environment, we propose to embrace the conductivity exploiting a natural communication channel in the human body known as volume conduction. This paper introduces an implementation which achieves efficient space and power communication within a conductive medium by combining multiplexing and modulation blocks operating with an effective low-frequency carrier signal transmitting using volume conduction.

## 2. VOLUME CONDUCTION

Volume conduction occurs naturally in humans; it is the communication channel which allows us to acquire biopotential waveforms on the surface of the body. An active region of the body is characterized by a charge dipole existing across a membrane. An oppositely oriented neighboring dipole generates a current flowing between the active regions through the conductive environment. When this current flows between electrodes attached to the skin (or scalp), a voltage potential proportional to the internal signal can be measured across the two electrodes, thereby acquiring the desired EEG, ECG, EMG, or any other signals, resulting from current sources within the human body.

Fig. 1 illustrates the book-shaped structure of the implantable device. As the volume conduction antennas form two sides of the device, they occupy little space. A voltage generated across these antennas produces a current flow within the body. By placing the device on a non-conducting flexible sheet (possibly an implantable electrode array pad), and by appropriately shaping and directing the antennas we can maximize the percent of current flowing across the external electrodes, thereby increasing the efficiency of transmission [1, 2].

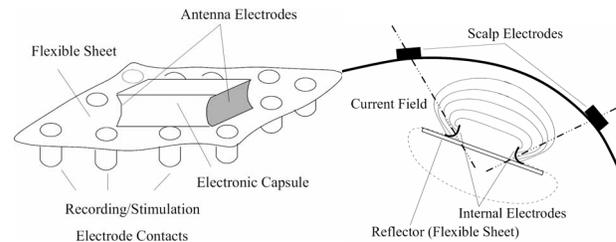


Fig. 1: Implantable device using volume conduction

In order for us to transmit multiple channels of data simultaneously without the signals mixing (i.e. spatial blurring), multiple signals must be combined on a single signal channel via multiplexing. In order to maintain a high-fidelity communication channel the signal must be transmitted using a modulation technique that facilitates

the separation of this signal from all others at the reception site.

### 3. MODULATION

As high frequencies are absorbed greatly by the biological conductive medium, we want to modulate the signal with a low frequency carrier achieving high communication channel efficiency. For implantable devices it is necessary that the implantable communication circuitry consumes minimal power and space. Our modulation technique has been designed to satisfy these requirements.

The modulation block can be implemented with a single solid-state single-pole double-throw (SPDT) switch, which is controlled by a clock as shown in Fig. 2.

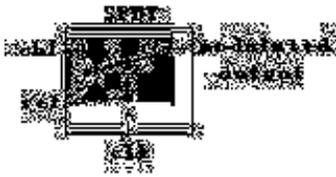


Fig. 2: Single-channel modulation implementation

By periodically switching the output from the input signal to its reference, we generate time-slices of the input signal at the output. This is mathematically equivalent to multiplying the input signal by a periodic sampling pulse. An example using a sinusoid (with dc offset) as the input signal is illustrated in Fig. 3. In the Fourier domain, the resulting output contains replicas of the input signal at its original frequency as well as harmonics of the switching frequency which are scaled according to the carrier's duty cycle (50% for a single input signal). This is a classical modulation technique known as Amplitude Modulation with a Pulse Carrier [4].

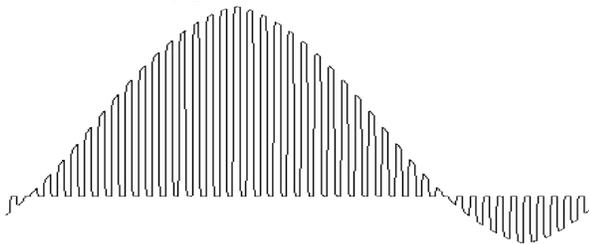


Fig. 3: Modulated sinusoid with offset

Our transmitted signal cannot consist of data at the original frequency range, as the low-frequency noise in the volume conduction channel could then not be subsequently filtered. Transmitting at the original frequency range may also cause inadvertent stimulation. In addition, positive feedback may lead to instability if the device is used as an implantable biopotential amplifier. Hence, at the output of the switch, prior to transmission, we must filter out frequencies within the input signal's bandwidth.

### 4. DEMODULATION

We can detect the carrier frequency of the received modulated signal by computing the Fast Fourier Transform in MATLAB. If there is a large DC offset at the input then the carrier frequency will be the point of the maximum peak in the range of the user-entered approximate carrier frequency. If the offset is low, then we can calculate the carrier frequency by band-pass filtering around the approximate carrier frequency then detecting the largest peak on the left-hand side (LHS) and the right-hand side (RHS) of the approximate carrier frequency. Due to the symmetry of the input signal about the carrier frequency with the LHS corresponding to the negative frequency component of the input signal, and the RHS corresponding to the positive frequency component, we can acquire a precise measurement of the carrier frequency by averaging the frequencies at which the RHS and the LHS peaks occur.

Fig. 4 demonstrates our demodulation technique. After acquiring the first peak in the received signal (i.e. the modulated output, post high-pass filtering), we can demodulate the received signal by plotting each multiple of the time period of the carrier signal (i.e. the inverse of the carrier frequency) at times referenced to the first peak occurrence. The demodulated signal would be a subsequent plot of the sampling points represented by the circles in fig. 4, forming an accurate representation of the original input signal.

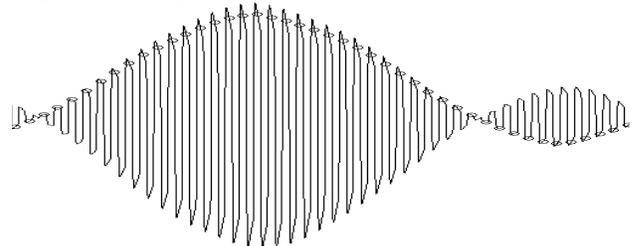


Fig. 4: Demodulating a transmitted single channel signal.

### 5. MULTIPLEXING/MODULATION

Time-division multiplexing can be efficiently implemented using an analog multiplexer and a counter with a clock to realize the commutation as shown in fig. 5. The multiplexed output can be described as the addition of the time-slices of each input channel each with the same carrier frequency and duty cycle of 25% but with a time shift between the slices of half the inverse of the carrier frequency. The inverse of the carrier frequency is the effective sampling period for each input signal. Noticing that the spectra of the output is equivalent to that specified by the amplitude modulation technique with a pulse carrier (with a 25% duty cycle), this output can be considered simultaneously multiplexed and modulated, if we can transmit the signal after high-pass filtering (to remove the

original frequency content of the input signal) and demultiplex the individual input signals from the received transmission. Combining the multiplexing and modulation blocks results in increased power and space efficiency, especially since this design excludes all RF modulation circuitry.

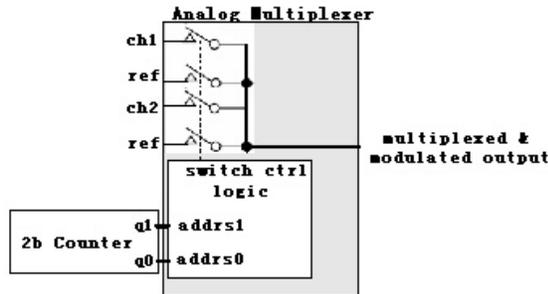


Fig. 5: Two-input-channel time-division multiplexing implementation

## 6. DEMULTIPLEXING/DEMULATION

Attenuation occurring naturally or intentionally during communication may result in distortion, concealment or loss of information in the time domain although other replicas of the input signal still exist at higher frequencies. This loss of low-frequency content is usually prevented by employing an additional modulation block, modulating the multiplexer's output to a higher-frequency range [3]. We have found that this additional modulation is unnecessary but the loss of the low frequency content from the multiplexer complicates demultiplexing.

When low frequencies are attenuated with a cut-off frequency of  $f_L$ , subsequent samples in the time frame ( $1/f_L$ ) are shifted up or down in amplitude making the average voltage for every  $1/f_L$  equal to zero. This shifting is dependent on neighboring data (other input channels). By applying the same demodulation technique as in the single-input case, we would find that the peaks of the modulated signal corresponding to one input signal have developed a correlation (i.e. crosstalk) with the other input signals. This would result in distortion of all input signals.

Recognizing that with the low-frequency cut-off corner (from the required high-pass filtering prior to transmission) much less than the carrier frequency, any amplitude shifting of each input channel time-slice is relatively equivalent to the amount of shifting on the subsequent time-slice. Hence, by interleaving each input signal time-slice with a reference signal, we can recover the original amplitude of each of the input time-slices (eliminating crosstalk interference) by referencing each time-slice to its subsequent reference time-slice.

In a multiplexed/modulated signal, each reference time-slice corresponding to its input slice is delayed by exactly  $(2 * inputs * f_c)^{-1}$  seconds, where  $f_c$  is the

carrier frequency and the variable *inputs* contains the number of input signal channels. Each input signal time-slice is delayed by exactly  $(inputs * f_c)^{-1}$  seconds. (i.e. the sampling period for each input). Hence, for simultaneous demultiplexing and demodulation, we need to first determine the carrier frequency as described in single-channel demodulation. By finding the first peak in the received signal and plotting integer multiples at times referenced to the first peak occurrence, and by referencing the amplitude of each of these samples to its subsequent reference amplitude, we effectively demodulate and demultiplex the first input signal. By delaying each of these samples (and reference points) by half the sampling period, we can recover the other signal channel.

In order to identify which recovered signal is from which input location, we could make a distinguishing mark in the transmitted signal, such as doubling the length of the reference time-slice preceding the first input slice. Note that this would reduce the effective sampling frequency.

## 7. TWO-INPUT-CHANNEL EEG EXAMPLE

This example is included to detail the major procedures and demonstrate the effectiveness of this efficient multiplexing/modulation technique for transmitting real multi-channel signals within a noisy volume conduction channel.

We began by multiplexing the two input signals each which are one second's worth of real EEG data cut off at 85Hz, and shown in fig. 6. The multiplexed/modulated output is shown in fig. 7. This output was then high-pass filtered and added with dominant 60Hz noise, shown in fig. 8, modeling the volume conduction transmission of a two-channel implantable EEG amplifier.

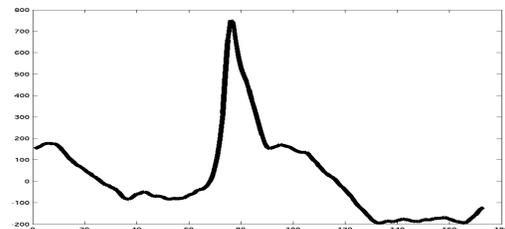


Fig. 6: First input signal (EEG, 1 sec)

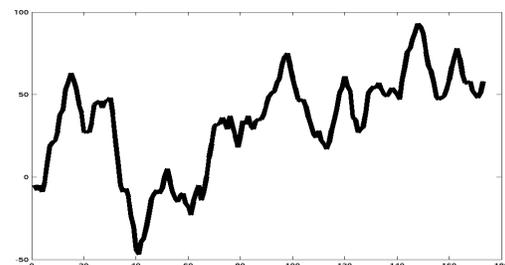


Fig. 7: Second input signal (EEG, 1 sec)

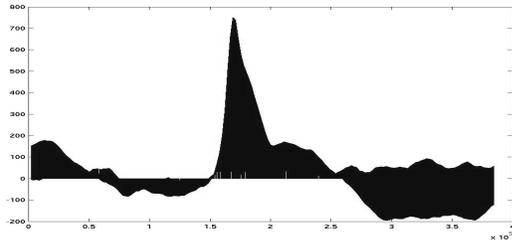


Fig. 8: Multiplexed and modulated output

Fig. 9 represents the signal that would be received after transmission. The output needed to be high-pass filtered prior to transmission. A large 60Hz noise was added to the filtered output, simulating the dominant noise when transmitting through the human body.

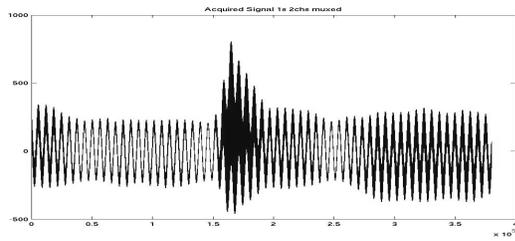


Fig. 9: Received signal

Fig. 10 and fig. 12 show the demultiplexing/demodulating technique for channels one and two, respectively. Fig. 11 provides a close-up view of the recovery process showing two samples (top) with their two amplitude references (bottom). Fig. 13 and fig. 14 plot the recovered points of each channel, which indicate that the original signals in fig. 6 and fig. 7 are recovered with high fidelity.

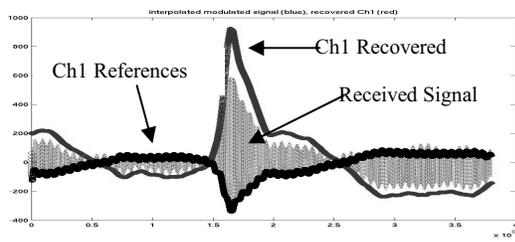


Fig. 10: Demultiplexing/demodulating channel 1

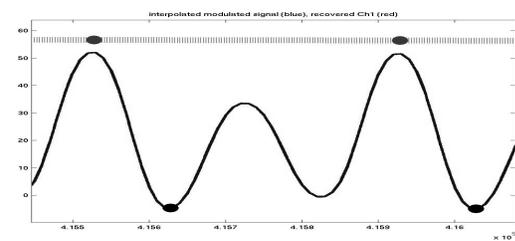


Fig. 11: Demultiplexing/demodulating channel 1

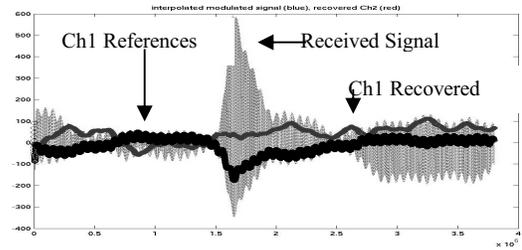


Fig. 12: Demultiplexing/demodulating channel 2

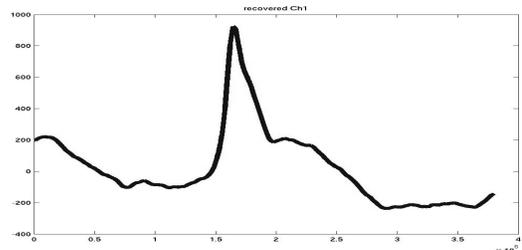


Fig. 13: First channel, recovered

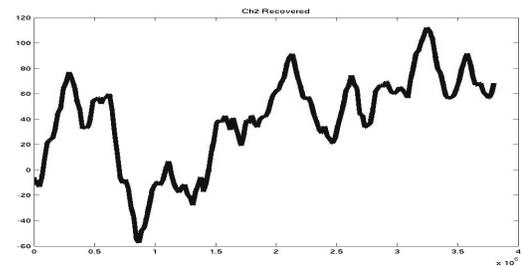


Fig. 14: Second channel, recovered

## 8. ACKNOWLEDGEMENT

This work was supported in part by National Institutes of Health Grants No. EB002099, NS38494 and Computational Diagnostics, Inc.

## 9. REFERENCES

- [1] Sun, M., M. Mickle, W. Liang, Q. Liu, and R. J. Sclabassi, "Data Communication between Brain Implants and Computer," *IEEE Transactions on Neural Systems and Rehabilitation Engineering*, Vol. 11, No. 2, 2003, pp. 189-192.
- [2] Sun M., Q. Liu, W. Liang, B. L. Wessel, P. Roche, M. Mickle, and R. J. Sclabassi, "A Volume Conduction Antenna for Implantable Devices," *IEEE Proc. EMBS'03*, Cancun, Mexico, 2003.
- [3] Oppenheim, A.V., A.S. Willsky, *Signals & Systems*, Prentice Hall, NJ.
- [4] Neuman, M. R., "Biopotential Amplifiers," in *Medical Instrumentation: Application and Design*, J. G. Webster, Ed. New York, NY: Wiley.