# Noise reduction for wireless brain-computer interface signals using polar codes

Hussain K. Chaiel

***Abstract*—**In dependent Brain-Computer Interface (BCI), the normal output pathways of the brain cell activity generate message signals with low signal to noise ratio. Recent works use polar codes to enhance the generated noisy signals and transmit multidimensional BCI commands individually with the aid of addressing words located at the noisy bits of the polar codeword. However, transmission of addressing words through the noisy bits of a long polar code reduces the error correction performance of the BCI system. This work derives the likelihood ratio of the successive cancellation decoder of the polar coded BCI system, which shows that the main reason of degradation in the system performance is the transmission of addressing word via the bits with large number of sum operations of the polar flow graph. Simulation tests used to examine the designed system show an improvement of nearly 10 dB as compared with the conventional wireless BCI system.

***Keywords*—**Brain-Computer Interface (BCI), LLR, Polar codes, SCD.

## I. Introduction

THE voltage fluctuations resulting from ionic current within the neurons of the brain create electrical signals, which transform to communication and control commands using Brain-Computer Interface (BCI). These signals are used to derive some output devices such as wheelchairs, neural prostheses and robots[1], [2]. However, BCI systems are still inflexible (need skin preparation) and noise sensitive. The limitation of skin preparation can be solved with the use of dry electrodes, which are either micro-electromechanical or fabric-based [3]. The first type includes high manufacturing cost, while the second is not suitable for hairy sites [4]. On the other hand, tremendous efforts have made to enhance the BCI noisy signals with the aid of wireless transmission techniques [5], [6]. As compared with the wired BCI, the wireless BCI is smaller in size, more power efficient and has the possibility of transmission of additional signals such as signals used to reduce the movement artifacts [7]. Both academia and industry have made research efforts to design wireless BCI system with high signal to noise ratio. However, the very low amplitude signals of the BCI commands reduce the signal to noise ratio at the receiver input [8]-[11].

Nowadays, polar codes are considered as promising error correction codes.In addition to their applications in coding theory, recent research have shown the importance of such codes to solve problems in the field of communication and signal processing. Data compression [12], broadcast channels [13], wiretap channels [14] and multiple access channel [15], [16] are examples of applying polar codes and polarization operations. The gain of the polar code is represented by its ability to isolate the output bits into noisy (frozen bits) and relatively noise free. Therefore, the transmission of message signal through the noise free bits improves the system performance [17].

Present-day,BCI commands are individually and independently sent via the transmission channel [18], [19]. In this work, we assume that the command signals are multiplexed with the aid of certain addressing word. Both of the multiplexed signal and the addressing word are then polar encoded.The challenge is how toarrange the two digital data, multiplexed signal and the addressing word, at the encoder bits, which finally enhances the performance of the system. The main contributions of this work are summarized in the following points:-

1) This work derives a general relation, which describes the log likelihood ratios (LLRs) at each node of polar graph of the BCI system and this gives an idea about the choice of addressing word location.
2) This paper suggests a procedure to design polar codes suitable for transmitting BCI commands with no reduction in the system performance.

The rest of this paper is organized as follows: the block diagram of BCI transducer is presented in Section II. A derivation of the general form of log likelihood ratios of BCI polar coding is included in Section III. Section IV provides a design procedure of the proposed BCI system. The error correction performance of the suggested BCI system under additive white Gaussian noise is presented in Section V, whileSection VI concludes the paper.

## II. Brain Computer Interface

Brain computer interface (BCI) is a non-muscular communication channel by which the brain activity commands are sent to a computer or used to derive a verity of output devices [20]. The BCI transducer, see Fig.1, acquires the brain signal with very low amplitude in the range of (5-100)\µ volt and it may include one or more of the five rhythms: delta (0.1-3.5Hz), theta (4-7.5Hz), alpha (8-13Hz), beta (14-29Hz) and gamma(≥ 30Hz) [21]. The brain signal is then passed through anotch filter, differential amplifier and cascade of low pass and high pass filters with pass band of (1-100Hz). The notch filter has been designed with center frequency of 50 Hz to remove the interference caused by AC power line signal, while the output signal of the differential amplifier is proportional to the potential difference between any two

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electrodes placed at certain part of the head. The artifact processing unit is used to remove artifacts from the brain signal. Artifacts are either patient related, such as minor body movement and eye movements or technical type such as impedance fluctuations, cable movement and AC power line noise [22]. The output of this unit is converted to digital form using analogue to digital converter (ADC). The sampling frequency of the (ADC) is determined by the speed of the other units and wireless transmitter, but it is normally in the range of (100-1000 KHz). The digital signal is passed through a feature extraction unit. This unit transforms the recorded signals into command signals.Finally, the classifier maps the command signals to classes corresponding to control commands. Linear classifier, neural networks, nonlinear Bayesian and nearest neighbors are types of classifiers used in practice [21], [22].

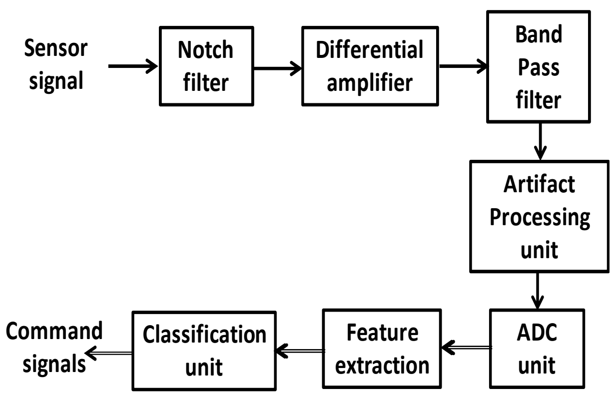


Fig.1 BCI transducer.

## III. LOGARITHMIC LIKELIHOOD RATIO OF THE POLAR CODE BITS

A polar code is an error correction code specified by three-tuple expression $(N, K, F)$,where $N$is the codeword length, $K$ is the number of information bits in each codewordand $F$ is a subset represents the location of the noisy, frozen, bits. Sometimes, the frozen bits are called very bad bits, while the message bits are called very good bits [23] and in the original formulation of [24], the frozen bits are set to zeros.Vector notation used in this work is similar to that used in [25], for example,$x_0^{N-1}$ represents the polar coded BCI vector,$X = [x_0 \quad x_1 \quad \cdots \quad x_{N-1}]$. This vector is constructed with the aid of the generator matrix$G_N$ as, for example in [26]-[29];

$$X = UG_N = UB_N F^{\oplus n} \tag{1}$$

where $N = 2^n$, U is the uncoded BCI command vector, $B_N$ is the bit reversal matrix and $F^{\oplus n}$is the $n^{th}$Kronecker power of the matrix;

$$F = \begin{bmatrix} 1 & 0 \\ 1 & 1 \end{bmatrix} \tag{2}$$

For the communication system shown as in Fig.2, the elements of the two vectors $Y$ and $\tilde{U}$ represent the received and the decoded BCI data respectively.

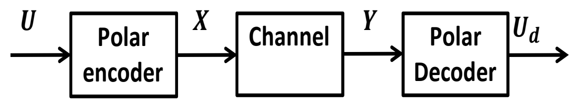


Fig.2 Simple polar coded communication system.

For a simple analysis, let$N = 2$, the vector $U = [u_0 \quad u_1]$ and $X = [x_0 \quad x_1]$. The polar coded vector, $X$, is sent through a channel W. At the receiver side, the elements of the vector $Y = [y_0 \quad y_1]$ represent the receiver bits.

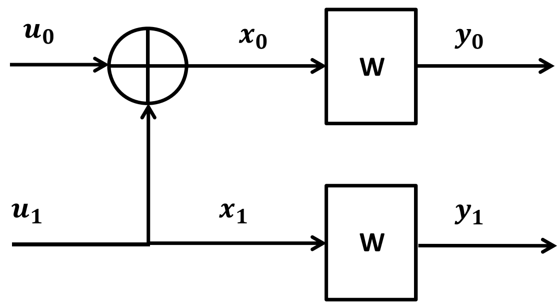


Fig.3 Two-bit polar encoder.

A deterministic successive cancellation decoder (SCD) performs decoding procedure to recover the codeword $\tilde{U} = [\tilde{u}_0 \quad \tilde{u}_1]$ with the use of bit likelihood ratios (LRs) [30], [31]. Fig.4 shows a two-bit successive cancellation decoder.

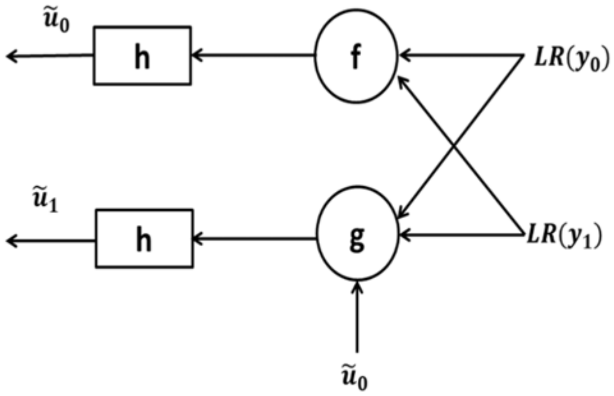


Fig.4 Two-bit successive cancellation decoder.

In fig.4, the functions **f**and **g**is defined as [31]:-

$$\left.\begin{aligned} f(a,b) &= \frac{1+ab}{a+b} \\ g(a,b,\tilde{u}_0) &= a^{1-2\tilde{u}_0}.b \end{aligned}\right\} \tag{3}$$

and **h** is a hard decision unit for final binary output.

For each bit, a likelihood ratio is calculated by:

$$l(x) = \frac{p(y/x = 0)}{p(y/x = 1)} \tag{4}$$

The logarithmic likelihood ratios (LLRs) can be represented by:

$$L(x) = \ln\big(l(x)\big) = \ln\left(\frac{p(y/x = 0)}{p(y/x = 1)}\right) \tag{5}$$

For the sum operation $(u_0 \oplus u_1)$, the LLR becomes [25]:-

$$L(u_0 \oplus u_1) = \frac{1 + l(u_0)l(u_1)}{l(u_0) + l(u_1)} \tag{6}$$

and

$$L(u_0 \oplus u_1) = 2tanh^{-1}\left(tanh\frac{u_0}{2}\ tanh\frac{u_1}{2}\right) \tag{7}$$

Equation(7) can be approximated as [30]:-

$$L(u_0 \oplus u_1)$$
$$= sgn\ L(u_0).sgn\ L(u_1)\ .\min(|L(u_0)|\ , |L(u_0)|)$$
$$= f(u_0, u_1)(8)$$

From Eqs.(4-8), one can conclude that the polar code isolates the two bits into noisy bit, $u_0 \to y_0$, and relatively noise free bit, $u_1 \to y_1$, according to their log likelihood ratios, as follows:

$$LLR(, u_0 \to y_0) = L(x_0) + L(u_0 \oplus u_1) \tag{9}$$

$$LLR(, u_1 \to y_1) = L(x_1) \tag{10}$$

If we assume that $L(x_0) = L(x_1)$, then the LLR ratio for the first bit is larger than that of the second bit and it approaches to the noise margin.

## IV. Logarithmic Likelihood Ratio of ThePproposed System Bits

The proposed system shown as in Fig.4 consists of two units; a multiplexer and a polar encoder. The BCI command signals are multiplexed according to $m$ bits addressing word. Each of the command signals are assumed to be with K bits. The $(K + m)$ bits of the multiplexed signal and the addressing word re encoded with $N$ bits polar code. It is also assumed that the polar encoded data is transmitted through anAdditive White Gaussian Noise (AWGN).

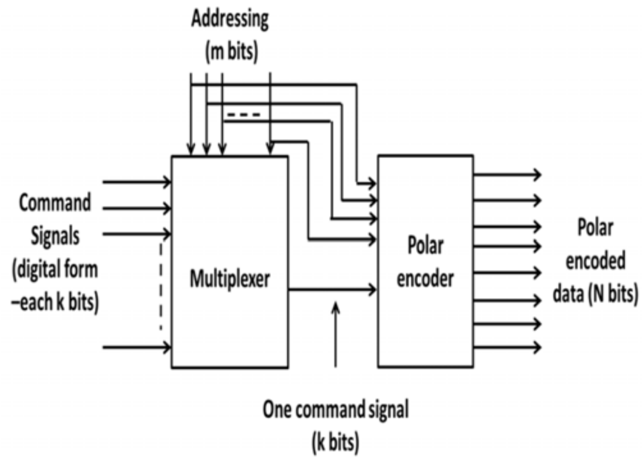


Fig.4. The proposed system.

The transition function of Additive White Gaussian Noise channel with binary bipolar modulation $(x_i = \pm 1)$ has the relation [31];

$$W(y_i/x_i) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{(y_i-(1-2x_i))^2}{2\sigma^2}} \quad ; x_i \in (-1,1) \tag{11}$$

where $x_i$ and $y_i$ represent the $i^{th}$ bit of the input and the output of the channel respectively.
Therefore, LLRs for bipolar data transmitted through AWGN channel can be written as;

$$L(x) = \frac{2y_i^2}{\sigma^2} \tag{12}$$

As a result, the log likelihood ratios at the output of AWGN channel encoded with $N$ bits polar code can be written as:-

$$\left.\begin{array}{c} LLR(, u_0 \to y_0) = \dfrac{2y_i^2}{N\sigma^2} + f(u_0, u_1, \dots\dots, u_{N-1}) \\ \vdots \\ LLR(, u_{N-2} \to y_{N-2}) = \dfrac{2y_i^2}{N\sigma^2} + f(u_0, u_1) \\ LLR(, u_{N-1} \to y_{N-1}) = \dfrac{2y_i^2}{N\sigma^2} \end{array}\right\} \tag{13}$$

This equation shows that the performance of the proposed system under the AWGN depends on the location of the $m$ addressing bits and the $K$ command bits along the codeword of length $N$. The next section includes the designalgorithm of the proposed polar encoding of the BCI commands to improve the system performance.

## V. Design of The Bci Polar Codes

This section proposes a design for a polar encoder to satisfy two objectives. The first is to reduce the probability of error at the decoder output and the other is to locate the addressing words in a suitable part of the transmitted codeword.

The design algorithm of the polar coded BCI system is summarized as;

1) For a certain value of signal to noise ratio, the probability of error ($p_e$) of the uncoded data transmitted through the wireless channel is evaluated.
2) From ($p_e$) and the required probability of error for each bit $p_e(i)$, $1 \leq i \leq N$, of the polar graph, Monte-Carlo simulation tests [32] are used to evaluate the block length N.
3) The number of addressing bits m is determined from the number of BCI commands M, where M=$2^m$.
4) Finally, the frozen bits $N_f$ are determined from ($N_f = N - (m + K)$.

This paper discusses two approaches to locate the addressing word within the block of transmitted data. These approaches are:-

### A. First Approach

In this approach, the $m$ addressing bits are located at the best $m$ noise free bits of the polar code and the other $K$ noise free bits are used for the BCI commands. Fig.5.a shows such arrangement.

### B. Second Approach

The arrangement of the bits in this approach is in opposite of that of the first approach (i.e. the first $K$ bits of the noise free bits are used for message bits, while the other $m$ bits re used for addressing bits. The error correction performance of the system based on this approach may be further improved by repeating the contents of the $m$ addressing bits few times as shown in Fig.5.b(odd times).

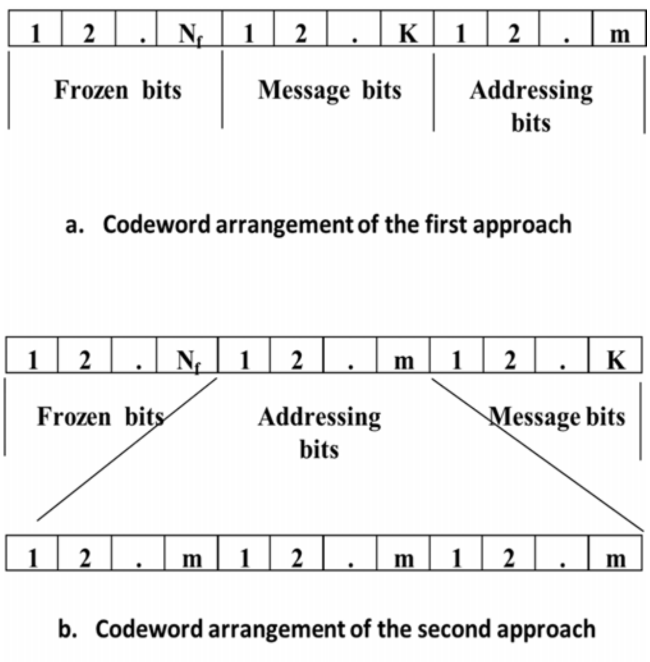


Fig.5 Arrangement of the proposed codeword. (a) for the first approach, (b) for the second approach.

## VI. Simulation Results

This section includes computer simulation tests to examine the error correction performance of the proposed BCI system under AWGN channel. For a signal to noise ratio of (0dB), the Monte-Carlo simulations tests show that (N=1024) is enough to have ($p_e \leq 10^{-10}$)at the noise free bits of the code. The BCI commands and the wireless transmitter data rate are assumed to be (16) and (25Kb/sec) respectively. Therefore, the number of address bits is 4 and there are 25 blocks should be transmitted each second. If the sampling frequency of the BCI signals is (1 KHz), the number of message bits is 40 and so the number of frozen bits is 980. The performance of the proposed system is represented by the relation between the signal to noise ratio in dB and the average error in the transmitted frames (average FER).

Fig.6 presents the error correction performance of the designed BCI system using the two approaches of Section V as compared with the results of [19]. It is clearly appeared that the arrangement of locating the addressing bits at the best noise free bits (approach 1) is the best approach from the error correction performance point of view (10 dB improvement s compared with second approach).

Fig.7 illustrates the improvement in the system performance of the second approach when multiple addressing words are involved. The plot shows 0.5 dB improvement for five-word addressing (approach 2-5) as compared with three-word case (approach 2-3) and so that for the one-word very bad message bits case (approach 2-1). In this case, the number of frozen bits is decreased to 972 and 964 for the three-word and five-word addressing,respectively.

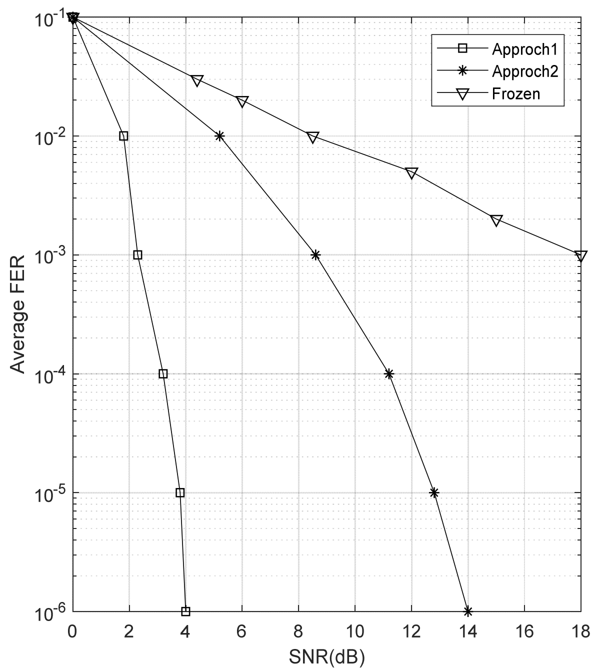


Fig.6Error correction performance of BCI system with very good and very bad bit addressing approach.

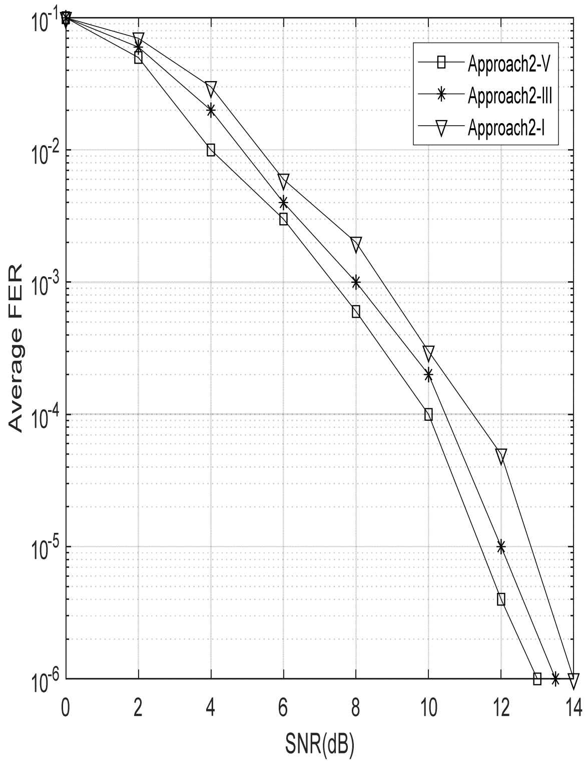


Fig.7Error correction performance of BCI system with very good and very bad bit addressing approach.

## VII. CONCLUSION

The conventional wired BCI system is not sized to transmit control commands to the output devices in real time due to wiring limitation, long preparation time and low available signal to noise ratio. This paper proposes wireless BCI system with polar coding technique to transmit commands to the computer or the output devices in real time. The BCI commands are addressed by a word involved in these commands.Two approaches are used to arrange the addressing word in the transmitted coded data. The first approach locatesthe addressing word at the best noiseless bits of the polar code, while the second approach locates the BCI bits at the best noiseless bits of the code. Simulation results show that the proposed system based on the first approach has a 10 dB improvement in the error correction performance as compared with that based on the second approach.

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