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Exploring the potential of brain signals beyond traditional medical applications

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Abstract. This article proposes a new method for utilizing brain signals by connecting them to the fields of electrical devices and phased arrays. The innovative modulation technique presented in this study goes beyond traditional medical applications of brain waves and has the potential to revolutionize the way we interact with technology. The article highlights the implications of this new approach for various fields, including telecommunication, artificial intelligence, and military applications. The paper also explains the BCI processing algorithm, brain signal extraction and analysis techniques, and electrical device arrangement used in the study. Overall, this paper presents a significant contribution to the field of brain signal research and would be a valuable addition to the IEEE community.

Keyword: EEG-signal, modulation, BCI algorithm, telecommunication.

1. Introduction

Brainwaves is a complex and fascinating topic that involves the study of the electrical activity in the brain. Brainwaves are generated by the interaction of neurons in the brain and can be measured using EEG (electroencephalography) technology. They are defined as vibrating electrical signal in the brain measuring just a very small amount of a volt [1]. The study of brainwaves has many practical applications, including in the fields of medicine, psychology, and neuroscience. Brainwaves can provide important insights into how the brain processes information and how different parts of the brain communicate with each other.

Since early 1875, Richard Caton published his research about the electrical signals that could be detected in the brain of animals using electrodes. EEG has become a popular topic in lots of labs and university. Soon in 1930, scientists successfully define the types of brainwaves into five different frequencies, and named them alpha, beta, dela and theta waves [2].

Gamma waves have the highest frequency among all the known brain waves. It vibrates between 30 to 100hz, which indicates the most active brain activity such as a peak concentration and high levels of problem-solving task. A classic gamma wave is represented in Figure 1 first plot.

Beta waves are considered to be the most normal state for our brain activity [2]. Beta is defined as “fast wave” activity and dominated when people are thinking and making decision. Its frequency range covers from 12-30Hz. Beta waves are also divided into three subsets to further describe different state: Low beta is defined when the frequency within 12-15Hz when brain is thinking; Beta waves define the

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focusing brain state when the frequency is between 15-22Hz; High beta waves indicate an emotion of exciting or anxious. A classic beta wave is represented in Figure 1 second plot.

An alpha brain wave usually indicates the brain activity during quiet thought and deep relaxation, especially usually when the eyes are closed. Its frequency covers from 8Hz to 12Hz. Compared with theta and delta waves, alpha waves tend to be more regular and repeated. A classic alpha wave is represented in Figure 1 third plot.

Theta waves mainly define the brain activity in sleep but are also dominant in deep meditation. It performs as our gateway to learning and memory. Its frequency range covers from 4Hz to 8Hz. A classic theta brain waves may be similar to alpha waves in pattern; however, their frequency and range are quite different, a classic theta wave is plotted in Figure fourth plot.

Delta waves mainly define the brain activity in deepest meditation and dreamless sleep. Its frequency range covers from 0.5Hz to 4 Hz. A classic delta brain waves should be described as low frequency and deeply penetrating, like a drum beat, which is recorded as Figure 1 last plot.

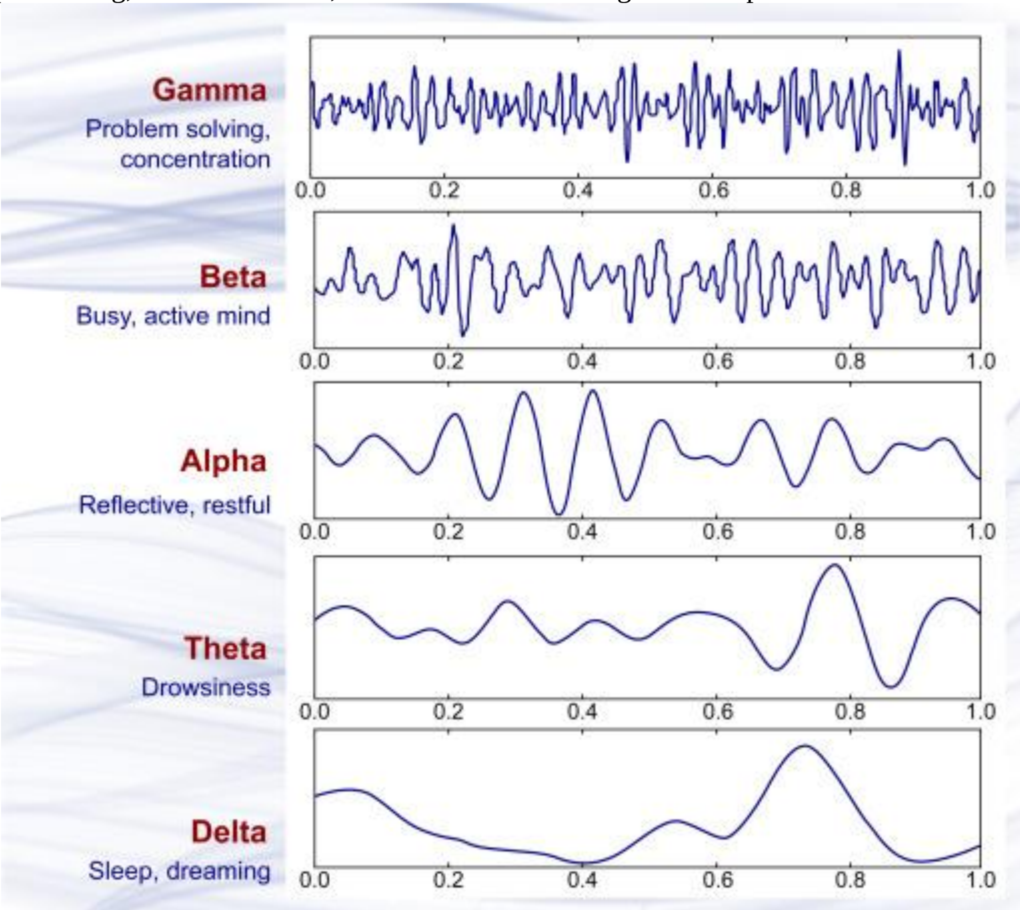

Figure 1. Brainwaves diagram from ScienceDirect [1].

In 1960, the first computerized EEG machine’s development indicated a new era of brain waves has started [2]. The researchers could link the brainwaves with a viewable plot to measure and utilize. Then in 1990, researchers started to explore the potential of brainwaves entrainment for anxiety and depression condition. Which officially tied the brainwaves application with medical treatment.

Moreover, with the development of technology, brainwaves are required in more and more field, even with some traditional industry such as electronic actuators. Electronic actuators have been widely used in various fields, such as automotive industry, aerospace industry, and robotics. With the development of advanced materials and technologies, electronic actuators have become more efficient, reliable, and precise. The future of electronic actuators looks promising, as they continue to play a critical role in many modern technologies.

The main aim of this article is to come up with a new theory to tie the application of electronic actuators with brain activity. By modulating the brainwaves, it will be recoded to send command to electronic actuators to affect the phased array. This interaction is crucial for brain waves research in industry and telecommunication field. It is creative to push the development of brainwaves into a new field which interact with antenna elements. A corresponding block diagram is shown below in figure 2:

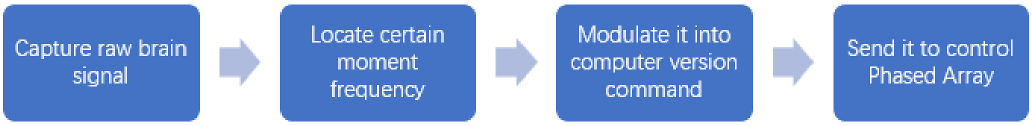

Figure 2. Experiment block diagram.

2. BCI processing algorithm

BCI, which is denoted as the brain computer interface, is a computer-based system that uses, analyzes and transforms brain signal into computer command. In the following, some classic algorithms are summarized with their pros and cons when dealing with frequency-based brain signal.

2.1. Common spatial pattern

The Common Spatial Pattern algorithm, which is also denoted as CSP, is a feature extraction method that uses spatial filters to maximize the discriminability of two classes and address a characterize vector with a clear frequency [3]. The CSP algorithm determines the ratio of variance w^T between two windows with the following expression:

$$w^T = \arg\max\left(\frac{\|wX_1\|^2}{\|wX_2\|^2}\right) \tag{1}$$

Then, the solution covariance matrices will be given by calculating the expression below:

$$R_1 = \frac{X_1X_1^T}{t_1} \text{ and } R_2 = \frac{X_2X_2^T}{t_2} \tag{2}$$

After this step, simulate the diagonalization of these matrix to generate the eigenvectors and eigenvalue and plot them to separate datasets.

This algorithm is capable to extract data from a multi-source brain computer interface dataset and divide them into different kinds of brain waves. Since the brain waves is divided by their frequency, this method is a perfect match to apply to separate the data into frequency domain. However, this method requires a large number of datasets to determine the ratio of variance, when the raw data in this case is not large enough, it would lose accuracy. Therefore, this method won’t be used in this case to separate the data, because when the dataset is unknown, this method cannot meet all the requirements.

2.2. Auto regressive model

The Auto Regressive Model, which is denoted as AR, is an algorithm to forecasts future behavior based on past behavior data. This model is only available when there is a correlation between the time series values and their preceding and succeeding values [4]. Many AR model uses linear combinations of predictors to forecast the future behavior with the following equations:

$$x(n) = -\sum_{i=1}^{P} a_p(i) * x(n-i) + \varepsilon(n) \quad (3)$$

Where $\varepsilon(n)$ is white noise series with deviation variance of σ^2 and mean of 0. P is the level of autoregressive model.

As mentioned above, linear system approximation is the core method that AR model apply, in this case, a method called Frequency selective all-pole modeling can be processing to identify the signal frequency and divide it into different frequency domain. The parameters extraction would normalize the feature stream. However, when AR model is built, the parameter P is very hard to choose to decorrelate the feature stream. If online model designer is applied, the calculation will be too huge (based on the raw signal) to process and identify the level of model. Therefore, this method will not be applied in this topic.

2.3. *The fourier transform*

Before the Wavelet Transform is introduced, the concepts of the Fourier Transform should be known first, since it is an initial idea to decomposing a signal into some sine and cosine waves of specific waves [5]. This Transformation is ideal only for stational signal since it could only represent the frequency information and its magnitude, but it could not reflect when in time this frequency exist. Which makes this transformation hard to deal with complex signal and locate an ideal location. The mathematical expression of the Fourier Transform is shown as:

$$F(\tau, \omega) = \int_{-\infty}^{\infty} f(t) w(t-\tau) e^{-i\omega t} dt \quad (4)$$

In this equation, τ is the translation parameter, w is the window function, f(t) is the observed signal.

Therefore, due to the lack of description about dynamic signal. The Fourier Transform will not be used to separate the brain waves in this case. Its upgrade transformation, the Wavelet Transform will be introduced and apply in this application.

2.4. *The wavelet transform*

Wavelet Transform is a mathematical process for analyzing data where features vary over different features. For signals, features can be frequencies varying over time domain [5]. Specifically speaking, The Wavelet Transform initially uses wavelet, which is a wave-like vibration that is localized in time [6], to separate the electrical signal into different domain corresponding to different Wavelet coefficient. Then, by computing how much of a wavelet is in a signal for a particular scale and location, the algorithm maintains the useful information and eliminate the noise to reorganize the signal. There are two types of Wavelet Transforms are widely used in industry, The continuous Wavelet Transform (CWT) and the Discrete Wavelet Transform (DWT). CWT focuses on every possible wavelet over a range of scales and locations, while DWT only apply a finite set of wavelets with preset particular scales and location to describe the signals. Their definition is given as below:

$$\text{Equation for CWT: } T(a,b) = \frac{1}{\sqrt{a}} \int_{-\infty}^{\infty} x(t) \psi^* \frac{(t-b)}{a} dt \quad (5)$$

$$\text{Equation for DWT: } T_{m,n} = \int_{-\infty}^{\infty} x(t) \psi_{m,n}(t) dt \quad (6)$$

In the above equation, ψ is the selected wavelet equation, x(t) is the observed electrical signal, a reflects the scale of the wavelet to squish or stretch the oscillation and b reflects the location of the wavelet to shift.

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Compared with the Fourier Transform, the Wavelet Transform is more flexible with detailed information, since the Wavelet Transform could extract the frequency and time information simultaneously and there are infinite sets of wavelets can be chosen to suit the given signal. When dealing with frequency-based signal, this method is adequate with reasonable calculation and data required, it is considerable useful in this case when the input signal is limited and there is no further assumption required. Therefore, the Wavelet Transform will be used to process the signal and divide the signal into required frequency domain.

2.5. Power spectral density

The Power spectral density method, which is also denoted as PSD, is a common technology to extract brain signal from raw EEG data as well. It also utilizes the Fourier Transform logic to decomposes an input signal into its constituent frequencies.

Similar to the process of Wavelet transform, PSD will firstly require a preprocess to remove artifacts and noise. Then divide into some small epochs that is typically 1-2 seconds width.[11] Lastly, apply the following formula to plot a function of frequency with the power of signal represented on y-axis and the frequency on x-axis.

$$\mathrm{PSD(t)} = \frac{|\mathrm{FFT(f)}|^2}{2 * \mathrm{delta_f}} \tag{7}$$

Where *delta_f* denotes the frequency resolution, FFT(f) is the Fast Fourier Transformation in specific frequency *f*.

3. Modulation

Modulation is the next process in signal transformation to convert data, which is brain signal in certain frequency range in this case, into some radio waves by adding information to an input signal [7].

3.1. QPSK

QPSK is short for Quadrature Phase Shift Keying. It is a method of phase modulation technique. It applies two information bits as one symbol and selected one of 4 possible initial signal phases shift states. These four phases are $\frac{\pi}{4}, \frac{3\pi}{4}, \frac{5\pi}{4}$ and $\frac{7\pi}{4}$.[7]

The QPSK signal within a symbol duration T_{sym} is defined as:

$$\mathrm{s(t) = A\cos(2\pi f_c t + \theta_n)} \quad , 0 \leq \mathrm{t} \leq \mathrm{T_{sym}}, \mathrm{n} = 1,2,3,4 \tag{8}$$

The parameter n above represents the signal phases, where:

$$\theta_\mathrm{n} = \frac{(2\mathrm{n} - 1)\pi}{4} \tag{9}$$

Compared with other phase shift keying method, QPSK is more efficiency. As noted above, a QPSK symbol can represent two information bits, which are 00, 01, 10 and 11. Which essentially double the transmit efficiency.

3.2. 16-QAM modulation

16-QAM is a type of quadrature modulation as well. However, instead of four states, carrier wave of a fixed frequency can be in one of 16 states of amplitudes and/or phase level.

Compared with QPSK, 16-QAM technique is a higher-level modulation that can modulate signal amplitude and the phase of the carrier signal [8]. It is relatively more efficient compared with QPSK in data transmit. Similarly, when the rank of states increases, its efficiency will accordingly rise in different scheme such as 64-QAM or even 1023-QAM. However, the modulation method is mainly depending on the signal bandwidth, a higher-level states modulation is not always adequate.

4. Brain signal extraction and analyzation

4.1. Brain signal extraction

Single-channel EEG is the easiest method to generate a set of brain signal. It can be used to detect simple brain activity such as sleeping detection [9]. It uses only one electrode to record brain signal. Thus, it can hardly find any mutual connection or link between each area, which makes it hard to be utilized in complex brain analysis. In our case, in order to detect the eye blink, single-channel EEG will be used and place an electrode in FP1 or FP2 position in trier’s forehead to identify the state.

Multi-channel EEG is another method to record brain signal. This method applies a comprehensive way to decode brain activity, which indicate the link between each part in brain [9]. In our experiment, we will use the 10-20 system to locate the electrode. The whole system contains 20 positions around skull, 10-20 represents the electrode’s distance with head skin is around 10% to 20%. This system is one of the most basic methods that used in lab with a high-resolution signal.

4.2. Brain signal analyzation

In this theory, the following modulations are considered to decode the brain signal and transfer to the electrical devices.

Table 1. QPSK modulation design.

Modulation	State (waveform)
00	Eye blink by purpose
01	Left ring finger movement
10	Right ring finger movement
11	Clenched right fist

The first case is defined as eye blink by purpose, which is also the first type of waveform. This state can be detected by a single-channel EEG signal [9]. Eye blink will mostly reflect on the energy increase in delta domain. As the table shown below, during eye blink, whether it is by purpose or normal blink, the energy amplitude in delta domain will increase to seven to eight times high. Which also appears to be the most obviously change in all the brainwaves domains.

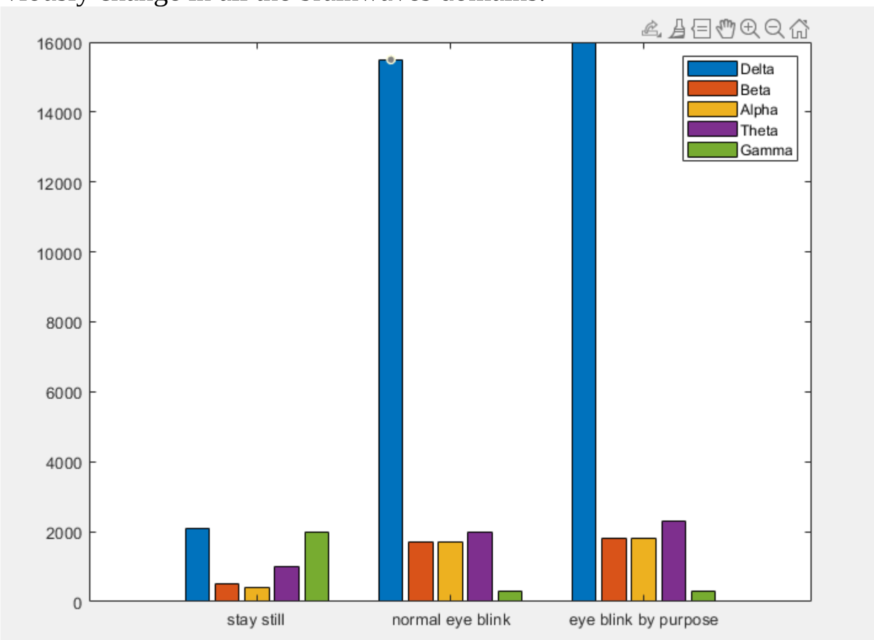

Figure 3. Energy amplitude in different state. Adapted from *CSDN* [9].

Moreover, in order to further more separate the different between the normal eye blink and by purpose, the following data was recorded to identify the amplitude change during two brain activity.

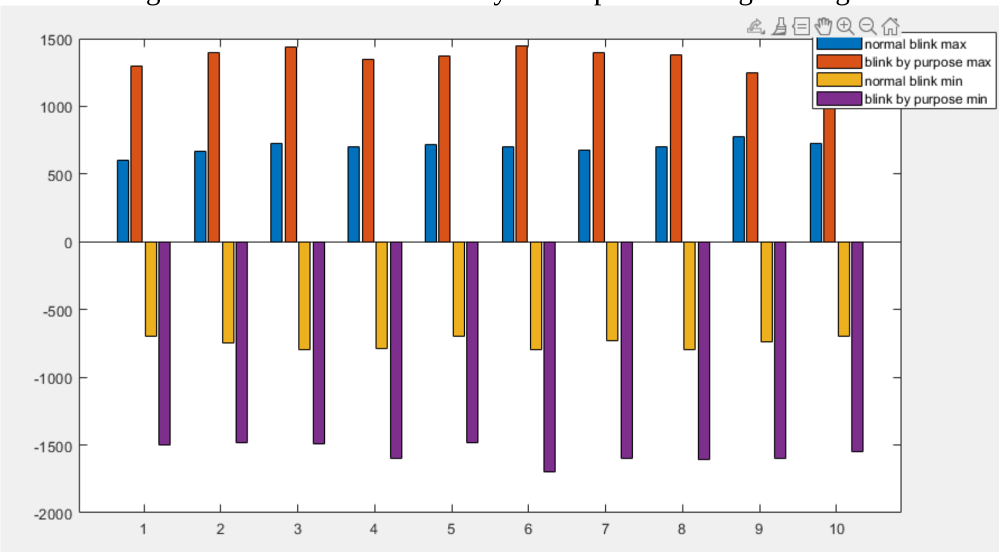

Figure 4. Signal amplitude recorded. Adapted from *CSDN* [9].

It can be obviously observed that the normal eye blink showed a maximum at around 700μV and -1000 μV as minimum. Therefore, during our state detection, we set the threshold at 1000 μV and -1000 μV to detect "Eye blink by purpose".

The second and third states are defined as moving left and right ring finger vertically. These states require multiple-channel EEG signal to detect. Finger movement is a complex activity shown in brain waves compared with eye blink, especially the single ring finger movement. It can be hardly described by a single-channel change. The following equation will be used to indicate the power increase or decrease during the time *t* in the electrode *e* compared with reference power *ref_Power* [15]:

$$\mathrm{ERG}_{\mathrm{ERS(e,t,ref_{Power})}} = \frac{\mathrm{Pow(e,t)} - \mathrm{ref_{Power}}}{\mathrm{ref_{Power}}} \tag{10}$$

A detailed CSP algorithm is required for feature extraction. Usually, 16-channel brain wave extractor is used in lab test, we only required the power change for the following channels, which are also the most active parts in brain during the right ring finger movement.[16] The left ring finger movement have the opposite sensitive channel compared with the following graph according to central line.

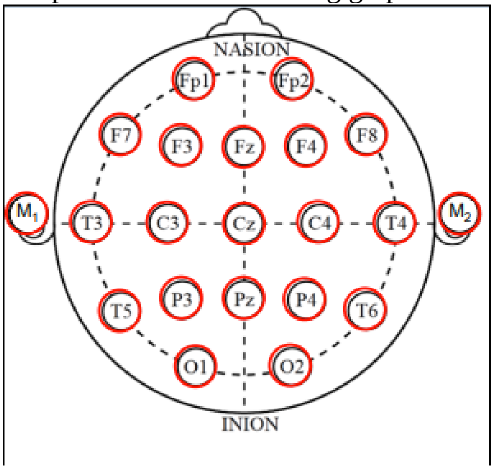

Figure 5. Traditional 16-channel EEG placement from *ERS* [16].

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After filtering the potential noise, the energy change can be found and calculated smoothly. If the power change exceeds 40% threshold increment, the required states will be activated and encode 01 and 10 types of waveforms. This power change limited to beta domain and tested in lab with an 87% of accuracy [9].

The fourth state is defined as right fist clenched. Which is also the most complex description indicated in brain waves. This situation will be denoted by multiple-channel EEG signal as well. It required Power Spectral Density method to transfer the brain wave numerically and change the EEG signal from time-domain to frequency-domain by Fourier Transformation.

This method will be used in every channel in our left brain in beta and gamma domain. Only when we detect an over increment (density change) of 40% in beta domain and 50% in gamma domain, the states will be considered as activated. This number is also considered as the threshold to reduce misread.

5. Electrical device arrangement

5.1. Phased array

Phase array is a technology which arrange the direction or permutation of antenna elements to affect the coming electronical beams or radiation patterns [10]. This is technology is quite popular in telecommunication, radar interface and optical region.

In this case, we are most interested in its function in electronics application. As talked above, in terms of controlling the array, we need to control plenty of antenna elements separately to arrange to a needed surface. By controlling, it means to change the phase difference between each two elements to a constant to achieve an electronical interface. Electronical interface is a physical principle that when two or more than two arrays of electronical beams generate superposition in the same space during overlap and produce a new beam with different frequency or shape.

During the application of telecommunication, we try to utilize this principle and change the element direction and unit distance to generate superposition or cancellation of a coming electrical signal. By achieving this arrangement, we can amplitude or erase a beam. The following plot is a description of how we arrange the direction and unit difference to modify the electronical beam.

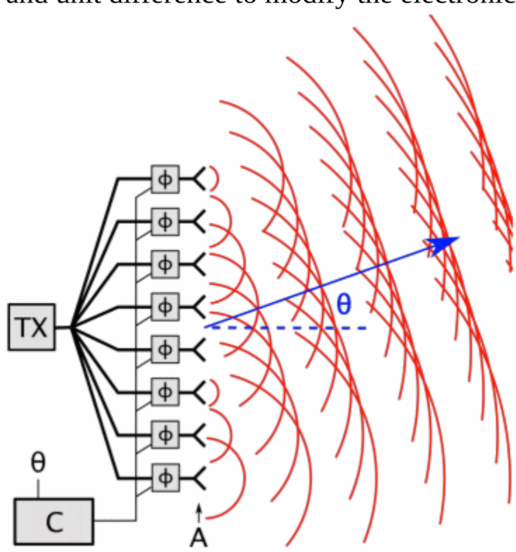

Figure 6. Phased array example.

Phased array can be divided as active phased array and passive phased array. The former utilizes a transmission device in every single antenna element called T/R module to generate its own electronical signal separately.[10] The later, however, apply the same transmitter and receiver with corresponding phased array antenna to achieve arrangement.

5.2. Electrical actuator

Electrical actuator is a device that can generate pulse or attract force. It is drove by electrical magnetic principle, which is formed by coil and iron core [12]. In this experiment, we aim to use it to alter its current amount and direction to affect the magnetic field, which is the phased array in this case. More specifically, by altering the magnetic field in electrical actuator, it could change the antenna direction and radiation amplitude in phased array. Therefore, to achieve the control of any coming electrical beam.

Generally speaking, Electrical actuator utilize its current amplitude and direction to affect the phase difference in phased array. When current increase, the magnetic field in actuator will increase to enlarge the unit difference between antenna element and vice versa.

5.3. Phased array arrangement

Table 2. Corresponding phased array arrangement design.

Modulation	State (waveform)	Phased array arrangement
00	Eye blink by purpose	0 phase difference
01	Left ring finger movement	90 phase difference
10	Right ring finger movement	180 phase difference
11	Clenched right fist	270 phase difference

As discussed above, the phased array utilizes the electrical interface principle to change the physical characteristic of coming beam. When the phase difference is 0, the coming beam and phase array are in the same state, their electrical and magnetic field will change consistently. Which represent the highest energy transmit efficiency [13]. In telecommunication region, 0 phase difference means maximum antenna radiation, it could help the signal gather in a preset direction to improve the signal amplitude and quality. This particular arrangement also minimizes the sidelobe which caused by irregular antenna element to reduce the signal energy loss in unexpected direction.

When the phase difference is 90, the phase relation between the electrical field and magnetic field meets the sine rule. Their peak generates in different period, when the electrical field maximized, the magnetic field is zero and vice versa [13] [9]. This specific arrangement achieves the linear and round polarization which is used to serve MIMO technology. By controlling this relation between the field, it could also jam or strengthen the signal to create Beamforming.

When the phase difference is 180, the signal in antenna elements cancel each other, which will minimize its effect to the coming beam [13] [14]. These characteristics create a method to receive or transmit signal in all direction. Furthermore, when we individually formulate the phase difference in certain area, we could recognize the beam in a specific direction to locate its origin and create a solid channel to communicate. This specific phase difference increases the ability and efficiency of signal transmit in three dimensions.

When the phase difference is 270, it will inverse the signal direction compared with 90-difference. Compared with other phase difference, this arrangement has larger amplitude to react coming beam, which provide it higher chance to read the beam information with less disturb [13] [14]. When raw signal crosses the phased array with 270 phase difference, it will rotate 90 degrees anticlockwise, this rotation makes it easy to trace back the resource of this signal. Which makes this arrangement useful when we try to reverse control the device.

6. Conclusion

This article focuses on a creative modulation method to utilize the brain signal. It is essential to connect the brain signal with another field, the electrical device field and phased array. Currently, when people think about brain signal, they could only see through medical region. Which is too limited to define the function of brain waves. This modulation and new connection could be potentially helpful for the development of telecommunication, artificial intelligence and even military field.

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