A Framework for Brain-Computer Interfaces Closed-Loop Communication Systems

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Abstract. This paper is a review of the brain-computer interface technology and its latest applications on human subjects. The brain-computer interface is an emerging technology that utilizes neurophysiological signals produced through the electrode interactions initiated inside the human brain to control external devices. Research on connecting human brains via brain-computer interfaces has been progressing with a lack of details on the technology used in closed-loop communication, which often leads to rumours, scepticism, and misunderstanding. We aim to alleviate these issues and to this end, we first analyze descriptions of brain-computer interface technology. We then explain the operational mechanisms of existing brain-computer interfaces and how they can perform direct brain-to-brain communication between human subjects separated in different locations. Findings from the literature motivate us to present a closed-loop communication framework that enables the combination of brain-computer interfaces and telecommunication channels such as vocal and text messages. Finally, we discuss the implications and limitations underlying the theoretical findings. The contribution of this paper is to provide a better understanding of emerging technology to support communication and innovation.

Keywords: Brain-computer interface · Brain-to-brain interface · Closed-loop communication · Cryptography

1 Brain-Computer Interfaces

Brain-computer interface (BCI) or brain-machine interface (BMI), is a novel technology that uses neurophysiological signals produced through the electrode interactions initiated inside the human brain to control external devices [5]. The awareness of reading the human brain has been mentioned since the early 20th century as a theoretical concept derived from the combination of Electroencephalography (EEG) and mathematical analysis methods [33]. The neurofeedback and operant conditions of neuroelectric activity are the underpinning of the BCI. In most types of BCI, the biofeedback's EEG signals, or event-related potentials brain signals will be collected and analyzed due to our brain giving the distinguished types of brainwaves for each subject received in biofeedback [18].

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There has been a proliferation of BCI research in the last few decades. Nowadays, both firms and scholars have put forward applications of BCI in various domains to challenge innovation boundaries. Mashat et al. [27] point out that BCI has disruptively changed the way of human interaction to open a new era where empowering human interaction will be lifted to its peak by the BCI technology. Mashat et al.'s [27] argument has several implications. Firstly, with the inauguration of BCI, the way people generally communicate with each other could be significantly disrupted. Secondly, people who have strokes, paralysis, or obstacles with communication ability now can have opportunities to use their brainwaves to express their thoughts. Furthermore, the brain-to-brain interface (BTBI) is a significant breakthrough of the BCI technology when an individual's brainwaves are not only employed to control external devices but to control another one's brain. BCI and its applications thus can open a new era where technology ethics, humanity, and governance need to be seriously reconsideration [1, 29, 42]. These issues are also the challenges of BCI in practice. Communication systems using BCI have been proposed ubiquitously, however, these systems mostly appear in the form of experiments or laboratory tests. Overcoming the barrier of the current legislative framework seems not to be possible for BCI in the near future. Furthermore, as BCI is an advanced technology that has a great potential for both intelligence and commercialization once it is approved to be implemented [23], firms/research teams that develop BCI often keep descriptions of solutions in secret.

In most BCI for closed-loop communication studies, descriptions of experiments and test results are well demonstrated. However, the description of BCI solutions is seldomly seen. This setting raises doubts regarding the reliability of results produced by such nascent technology. Due to these matters, it is often claimed there is not enough scientific evidence on the adverse impact BCI might have on human health in the long term [10]. Considering the numerous obstacles, research on BCI is often attracts rumour and distrust from both industry and academic audiences. Furthermore, studies such as those by Laiwalla and Nurmikko [23], Aggarwal and Chugh [1], and Taschereau-Dumouchel and Roy [44], mostly focus on typical aspects of BCI such as ethics, decoding, and its future. Motivating us to focus our efforts on fulfilling an apparent gap.

With the aim of alleviating the misunderstanding and skepticism of closed-loop communication using brainwaves, this paper is set out as a review of the BCI technology with its latest updates and applications on human objects. To achieve this goal, we will review technical descriptions of a series of relevant studies to illustrate the operational mechanisms of BCI. Specifically, we investigate descriptions of the BCI technology to explain the possibility of direct brain-to-brain communication between human subjects separated in different locations. We then use obtained results to conceptualize a closed-loop communication system that consists of BCI and telecommunication channels such as vocal and text messages.

The rest of the paper proceeds as follows. The next section is a brief discussion of how hypotheses were developed. Next, we will introduce the research methodology in the third section. Theoretical findings will be represented in the fourth sections. We then discuss the implications and limitations underlying theoretical findings in the fifth section before providing the conclusion in the final section.

2 Hypotheses

The aim of this paper is to alleviate the misunderstanding and skepticism of closed-loop communication using brainwaves. We assume that audiences have no prior knowledge of BCI technology. We will focus on the use of brainwaves to conduct closed-loop communication between human subjects. Based on the current achievement of BCI studies and the rapid development of communication technology, we propose two hypotheses: (1) It is possible to conduct communication by the transmission of human brainwaves through a global network between human subjects separated at a great distance; and (2) It is possible to design and implement a telecommunication system that uses human brainwaves to carry on closed-loop communication. From this perspective, we will collect, analyze, evaluate, and represent the review of existing BCI systems used for closed-loop communication to provide proof of concepts. Details of the review method will be provided in the following section.

3 Multidisciplinary Literature Review

While seeking an appropriate review method, we realize that there is a lack of publications regarding BCI system designs due to several restraints such as commercial intelligence, technological protection, and other restrictions. Furthermore, a dominant part of published systems remains in the experiment phases. Because of these issues, it was difficult for us to employ practical approaches such as design science research, action research, field, or case study in investigating the use of the BCI systems. Brewer and Hunter [8] suggest that using one or more approaches would enable the investigation where a single research methodology might not be applicable to analyze the problems. Thus, in this paper we utilize a multidisciplinary literature review method to profoundly analyze the meaning and principle of BCI, brain-to-brain interface (BTBI) as the scientific evidence for the feasibility of establishing a brainwaves telecommunication system. We follow the approach to qualitative research outlined by Mayring [28] in the literature review to develop a search query and analysis framework.

Following the search results, we will carry out in-depth analyses and assessments of the relevant studies on BCI. The article selection is based on the prestigious ranking of published journals and the number of citations. The quality of selected articles thus can be guaranteed. The technical details, operational mechanisms of BCI and closed-loop communication, and how such systems can carry on connections between human subjects via brainwaves will be presented following theoretical findings to provide testing results of the hypotheses.

4 Framework for Brain-Computer Interfaces Closed-Loop Communication Systems

In this section, technical descriptions of BCI, their applications that constitute the breakthrough in direct brain-to-brain communication and BCI and telecommunication systems will be represented through the in-depth analysis of selected literature. Along with the framework for BCI closed-loop communication systems.

4.1 Brain-Computer Interfaces

Theoretical findings indicate that since the 1960s, scholars such as Dewan [14] had identified that, by collecting Electroencephalography (EEG) signals (or simplified as brain signals) recorded from human eye movements and decoding them to become Morse codes, it is possible to conduct commands of turning on and off indoor equipment such as light and television. Following Dewan's [14] perspective, the concept of using observable electrical brain signals to work as carriers of information in human-computer communication has been extended in later research. Vidal [46, 47] implements coloured and patterned visual stimulation to examine a new model of evoked responses in the trichromatic absorbing structure by evaluating the sequential events of short duration in bio-electric potentials and the relation between brain states. This eminent approach subsequently raised the interest in the definitive term BCI throughout the field. Farewell and Donchin [19] shifted the use of BCI to translate the EEG signals into interactive movements in a VRML world. Wolpaw et al. (2000) defined BCI as a communicative system that does not depend on the brain's conventional output pathways of peripheral nerves and muscles. The translational algorithm, which converts the user's brainwaves into output, is the key component of Wolpaw et al.'s BCI. In particular, the user encodes the commands in the electrophysiological input transmitted to the BCI processor that recognizes and translates these commands into the signals then expresses them in external devices. Moreover, the study by Birbaumer [4] proves that multiple types of brain signals have been successfully tested in BCI research. According to Lightbody et al. [25], a BCI system can be constructed basically with five major elements including user, signal acquisition, signal processing, user interface, and application. Based on findings outlined by Lightbody et al. [25], we conceptualize major components of a BCI system in Fig. 1.

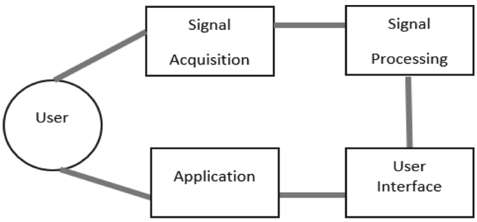

Fig. 1. The major components of a BCI system adapted from lightbody et al. [25]

Nonetheless, a BCI system's components might be varied as it depends on the purposes of the application. Research on BCI used for communication technology has been carried out in recent years. Dewan [15] successfully uses brainwaves to operate a binary digit communication system. In Dewan's system, the user was trained to alter their brain's alpha-wave rhythms – changing the eye movement techniques. The predetermined EEG control signal pattern then corresponded to a Morse code message. In particular, Dewan [15] used a Grass model 7 Polygraph printer to record EEG signals which were transported from the left and right electrodes derivations. These signals then were transferred through a 10c/s bandpass filter to enter the Schmitt stringer which would produce the pulse when the signal's voltage exceeded a threshold to ensure the presence of the pulse for each wave crests when the alpha wave activated. Dewan [15] then injected outputs into a LINC computer which was designed to translate the Morse characters into the alphabet system and displayed the words on the cathode ray tube that was visible to read. Serby et al. [39] proposed a P300-based BCI, which was built on the BCI pattern suggested by Farewell and Donchill [19] regarding a BCI communication system with 36 symbols. The P300-based BCI system uses independent component analysis (ICA) [16] to divide the P300 brainwave source from the ambient sources and filter out the troublesome signals simultaneously. Serby et al.'s [39] BCI system was outstanding for the higher performance of BCI compared with the others at that time. The BCI evaluation indicated that the system delivered reasonable communication effects while maintaining an acceptable level of errors. Similar systems to Serby et al.'s [39] BCI have been applied in subsequent experiments in using brainwaves to conduct virtual commands and robotic controlling [34].

4.2 Brain to Brain Closed-Loop Communication

Closed-loop communication has been well-known as a communication technique that is used to avoid misunderstanding [12]. This technique focuses on repetitive interactions between two objects which establish a loop of communication. Experiments in BCI to allow bidirectional interactions between users were successfully conducted in studies on closed-loop communication over the last decade. O'Doherty et.al [34] employed an invasive method to indicate the competence of the bidirectional communication between a primate brain and an external actuator. It shows the ability to liberate the human brain from physical constraints as both afferent and efferent channels could surpass the subject's body. The study laid a crucial milestone as it opened the new age of brain-machine-brain interfaces which can conduct reciprocal communication between and among neural structures and various external devices. Yoo et al. [52] insist that by using a non-invasive brain-to-brain interface (BTBI), we can establish functional links between two brains. Pais-Vieira et al. [35] develop a BBI to conduct three experiments on real-time sensorimotor information sharing between the brains of two rats. The findings of such experiments indicate that cortical sensorimotor signal patterns, which work as the code of a particular behaviour response, were successfully recorded from the encoder rat and transmitted directly to the brain of the decoder rat to complete a similar behavioural goal. The BTBI was manipulated in three different phases including encoding the detected signals, collecting data of the BCI process, and utilizing the real-time feedback analysis after electrical micro-stimulations. Pais-Vieira et al. [35] implemented the sigmoid function to convert the Z-score value to the number of pulses that were collected in the micro-stimulation pattern. Four distinguished neuron signals were amplified at 20000 to 30000 times and digitized at 40kHz. The data were sorted online afterward in Sort client 2002, Plexon Inc, Dallas, and TX. NEX technologies neuroexplorer version 3.266 was employed to process and analyze data.

One of the pioneer direct BTBI for human objects was presented by Rao et al. [37]. Rao et al. [37] carried out a series of experiments involving connections of two human brains. In these experiments, two users located at two different locations used the BTBI to together complete a virtual task of a computer game in a non-muscle interaction state. Rao et al.'s [37] BTBI system was a combination of an inherent BCI system and transcranial microsimulation (TMS) – an effective non-invasive method for sending commands directly to the user's brain. Specifically, such a BCI system collects EEG signals of the sender and transmits the information via the internet to the receiver's cortex. By using TMS, it allows the sender to conduct a desired motor response in the receiver reflected in the behaviour of the receiver, for example, pressing a button. Rao et al.'s [37] BTBI system was evaluated in three respects including decoding the sender's signals, generating a motor response from the receiver upon stimulation, and achieving a desired goal in the visuomotor task. The findings indicated a possibility of connecting directly human brains for information transmission purposes by a completely non-invasive method.

On the contrary, Grau et al. [21] upgraded the non-invasive stimulation and the BCI to conduct the consciousness transmission between human brains separated at a large distance. Grau et al. [21] extended the distance between two users to be 5000kms to conduct the consciousness transmission from one brain to another appearing as specific flashes of light. The word "hola" and "ciao" were encoded using a 5-bit Bacon cipher and redundancy 7 times to reach a total of 140bits. The signals were transmitted to the receiver's specific occipital cortex site through the transcranial microsimulation (TMS) pulses. The pulses were coded as bit value "1" if the TMS-induced electric field produced phosphenes and bit value "0" if the orthogonal direction did not produce phosphenes. The receiver server confirmed that it was available to receive the sequences of light. Although the messages that the sender and the receiver exchanged were encoded in the phosphenes form [11], the study evidently indicated that there is a possibility of direct mind-to-mind communication between human subjects separated at a great distance. It represents the feasibility of the transformation of traditional language-based communication into a novel type of telepathic communication including emotions and consciousness transmission by a non-invasive method. An upgrade BCI version was suggested to support a bi-directional dialogue between more than two brains or a closed mind-loops, in which the command from one brain is processed and transferred to other brains to conduct the same command. Nevertheless, the study raises concerns about the ethical and legislative responsibilities for this new type of human interrelation.

In another approach, the experiment by Mashat et al. [27] indicate that it is possible to control human muscles by BTBI. As the human brain sends the electrical and chemical messages back and forth, it is believed that the muscle signals can be converted to electromyography signals and transmitted consecutively to the decoder to make the similar muscle movement of the encoder [41, 43]. Mashat et al. [27] examined the approach to the human-to-human closed-loop control by combining the BTBI and muscle-to-muscle interface. Mashat et al. [27] introduce a system in which the artificial elements are connected functionally to the human nerves to control hand motions. Mashat et al. [27] tested such system performance in 6 dyads of healthy subjects with response accuracy results that could indicate the probability of creating a controlled loop by both human and automatic devices. Findings the from above studies have supported our first hypothesis – it is possible to conduct communication by the transmission of human brainwaves through a global network between human subjects separated at a great distance.

4.3 Integration of Brain-Computer Interfaces and Telecommunication Systems

Using the internet to send text messages technology has long been acknowledged as a common high-tech achievement as presented by Vieri, Tomasso, and Vieri [48] and Gabriel [20]. The system developed by Gabriel [20] allows users to send the message to a hardware device through the primary wireless network and subsequently forward it to a host server. This process will transmit the message to the device in the receiving wireless network and to the intended recipient afterward. The connection is conducted via the internet with multidirectional options, for instance, the recipient can send back the messages to the sender's cellular telephone or to a hardware device via email or an HTML-based interface. Vieri, Tomasso, and Vieri [48] propose the design of a communication system that is capable to send and receive text messages through the internet and expressing them in speech form on the recipient's device. A central server combined with software permits users to convert the primary message into vocal form, reach a telephone number, and conduct other commands such as storage, authorization to control, select, check, confirm or identify the website's operational criteria.

Vieri, Tomasso, and Vieri's [48] system for sending and receiving text messages converted into speech consists of the following components:

- A data input device comprised of hardware that allows users to write a text or record a vocal message, access phone numbers, and send to a server.
- An interconnection system consisted of a modem, data transmitting and receiving cards, and apparatus to connect to the satellite. This system works as a connection between the data input device and the server.
- A hardware-server installed a software program to convert text message to voice message, set up for sending out, and link other apps for operation purposes; and common phone to receive the message and give feedback.
- A transmission line to transfer the vocal message such as a telephone line consisting of voice modern or other technological peripherals.

Vocal message communication systems have been used in some research of indirect brain recording regards word pair classification during imagined speech [6, 9, 22, 26, 40]. Pandarinath et al. [36] proposed a high-performance BCI for non-muscle communication which can control the movement of a computer cursor to express the user's thoughts. In addition, Chartier et al. [13] collect articulatory kinetic movements from the human sensorimotor cortex produced when speaking and encode them to track the neural mechanisms underlying articulation. The brain signals of the coordinative movements of the voice producing system such as jaw, tongue, lips, and larynx were recorded while users speak common English sentences. These signals help capture a wide range of articulatory kinematic movement types that can be manifested in movement trajectories with harmonic oscillator dynamics. Chartier et al.'s [13] findings contribute to the understanding of the complex kinematics based on continuous speech production, which has been employed in later studies on neural decoding of spoken sentences [2, 13].

With the aim of removing obstacles in the communication of people with neurological impairments symptoms, Anumanchipalli et al. [2] develop a BCI that translates neural activity into speech (Fig. 2). This upgraded BCI resolves the challenge of decoding speech from neural activity due to the requirements of accuracy and rapid multi-dimensional control of vocal tract articulators when speaking. Such BCI works as a neural decoder that can synthesize the kinematic and sound representations collected from neuron firing activities to become audible speech. The BCI system first decodes the cortical activity into articulatory movement data and converts them into speech acoustics afterward. In Anumanchipalli et al.'s [2] experiments, audiences could hear the synthesized speech properly. Furthermore, it was capable to synthesize the speech when a user mimed the sentence silently proving the possibility of transferring human thoughts into speech.

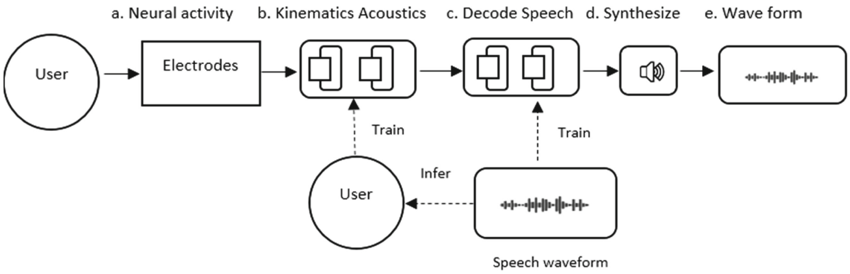

Fig. 2. BCI system to convert brainwaves to speech adapted from anumanchipalli et al. [2]

Assessment results from existing studies have supported our second hypothesis - it is possible that, theoretically, a telecommunication system that uses human brainwaves to carry on closed-loop communication can be established by the combination of BCI and telecommunication methods. In the next section, we will conceptualize findings from the above results to establish a framework for BCI closed-loop communication systems.

4.4 Framework for Brain-Computer Interfaces Closed-loop Communication Systems

Even though studies on vocal message communication systems and BCI have been carried on, extant research has not been clear on the possibility of establishing a telecommunication system. Motivated by such findings from the literature review, we aim to draw a framework that can extend the use of BCI for communication via the integration of a telecommunication system. Anumanchipalli et al. 's [2] BCI system and Vieri, Tomasso, and Vieri's [48] system for sending and converting text messages to speech enables us to conceptualize a framework for sending SMS messages by brainwaves. The system components generally include an EEG headset, EmotivePro Software, internet protocol, and the cellular telephone telecommunication network (Fig. 3). The headset firstly collects users' EEG signals and transfers them to the BCI server via internet. The server then converts neural activities to become kinematics acoustics which can be decoded and synthesized to become speech. The user's speech then will be connected to the smartphone that can recognize sound commands to define the recipient, input content, and conduct the sending out the message to a receiver device.

The proposed framework consists of the below components:

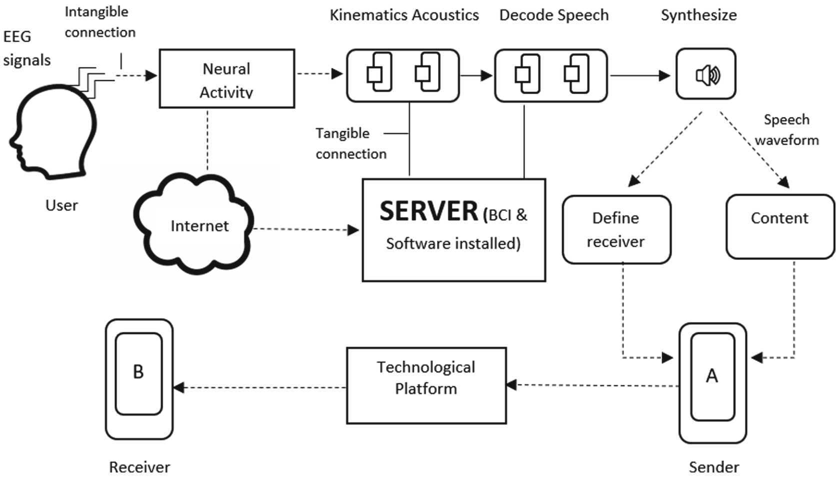

Fig. 3. Framework for sending SMS messages by brainwaves

- The headset that can detect 14 channels (AF3, F7, F3, FC5, T7, P7, O1, O2, P8, T8, FC6, F4, F8, AF4) and 2 references (In the CMS/DRL noise cancellation configuration P3/P4 locations) of EEG signals to ensure the quality of detection process.
- Mobile and computer devices.
- Conditions: All recordings were made in the laboratory condition. All data were recorded directly to the computer and carefully synchronized.
- Languages: English.
- Objects: Two users who voluntarily participate in the experiments.
- Connections: Wi-Fi; Headset connection Bluetooth/ 2.4 GHz band Wi-Fi; Cellular telephone telecommunication network.
- Platform: Voice modem and/or a technological platform make the text completely voice.
- Software: EmotivPro (for signals resolution).
- Data collection: MATLAB, TDT ephys software.
- Data analysis: Python 3.6, Tensorflow 1.4, sklearn 0.20, img-pipe, freesurfer, spm12, Festvox.

The proposed framework in its general form could be seen as an integration of the BCI that is able to translate neural activity into speech while connecting to a telecommunication system that can receive and perform repetitive simple commands.

5 Discussion

Wolpaw et al. [50] figure out that the major factor which interferes with the signal transmission is the noise created by the surrounded environment, i.e., power line electrode activities, and biological noises such as the heartbeat, muscle activity, and eyes movement. Additionally, the progress of BCI performance requires high attention and appreciation of users to achieve the best performance. Furthermore, a BCI connection will fail when the subject is in a paralytic state without eye movements [6, 31]. With the development of BCI technology, signal collection and transmission are more warranted nowadays. However, brain-to-brain communication is even much more complex compared to brain-computer communication, which requires the signal collecting processes to be conducted in strict conditions inside the laboratory [21]. Thus, to bring the brain-to-brain communication system out of the laboratory remains challenging. In addition, the non-invasive brain-to-brain communication system requires complex equipment that only a few organizations can suffice. Overall, BCI research is challenging as it involves an interdisciplinary approach that requires researchers to have a proficiency in mathematics, neurobiology, medical and computer science, engineering, and psychology [30]. The contribution of this paper thus can be seen in delivering a better understanding of emerging technology BCI and the development of a framework for BCI closed-loop communication systems. Notably, the proposed framework is beneficial for both academics and industry in terms of simplifying the presentation complex systems, conceptualizing intangible system connections, and representing a framework to implement BCI to telecommunication systems.

The proliferation of BCI technology has sparked controversies and criticism in recent years. It has been censured for posing a threat to human beings because it constitutes a risk of human mind hacking [49]. Lenca and Andomo [24] believe that the rapid development of neurotechnology applications produces unprecedented feasibility in collecting, accessing, sharing, and processing human brain information. Although several studies have indicated that BCI might evoke brain performance to enhance communication [32, 38]. It raises concerns about the ethical and legislative responses regarding this emerging type of human interaction [29]. Swan [42] introduces the idea of the "cloud mind" or "crowded mind" BCI system which can connect human brains to conduct highly effective interactions to become a network of minds. In this network, individuals' minds (human or machine) could join together in sharing perceptions to achieve a common goal. The study suggests that blockchain technology could be the resolution to warrant the security of cloud-mind collaboration. Yang et al. [51] suggest that we can create an ethical robot based on BCI technology that benefits human beings. Nonetheless, the existing human right might not be sufficient to respond to these new issues, especially in the four key rights such as cognitive liberty, mental privacy, mental integrity, and psychological continuity which would be highly related in the coming decades [24].

In recent years, using the quantum entanglement approach in cryptography for enhancing data security has been implemented in several systems [49], which might be an option for securing BCI data privacy. Einstein [17] indicated that the quantum entanglement process occurs when two particles in different locations can have related properties. The physical phenomenon occurs when the particle groups interact in ways in which the quantum state of each particle cannot be depicted independently of others even between great distances. The quantum state thus must be depicted for the system entirely [7]. Such a process implies a suitable state of occurrence for closed-loop communication via BCI, especially for brain-to-brain communication within a great distance. Research in quantum communication for satellite-to-ground networks has been indicated the possibility of completely secure quantum communication. The communication will be partially entangled in multiple states in which the teleportation was performed only through an end-to-end entangled process [3, 45]. By employing quantum cryptography for information sharing, the human brainwaves data can possibly be secured in a sheer state to avoid the violation of data privacy. The bi-directional signals exchange within more than two brains or the closed mind-loops thus could be secured as an end-to-end information sharing process to protect the information and only can be decoded by recipient systems. This would require further investigations through future research. Our work at this point has provided a theoretical support to the development of advanced technology such as BCI for communication innovation.

6 Conclusion

In summary, utilizing extant literature, we have tested the proposed hypotheses and achieved theoretical findings that indicate the possibility to conduct bidirectional connections between human brains located at a great distance for communication purposes. The telecommunication system that allows sending SMS messages by human brainwaves is also theoretically possible to achieve. The above findings support two proposed hypotheses. Furthermore, this paper uses the theoretical findings to develop a framework BCI closed-loop communication systems that benefits both academics and industry audiences. The limitations of BCI for closed-loop communication are detected as: the noise signals created by the surrounded environment; laboratory requirements; scarcity of equipment and intellectual resources; unknown impacts on mental health; and challenges in ethics, legislation, data privacy, and data security. The primary difference between this paper compared to existing BCI research can be seen in the in-depth review of technical descriptions of BCI and their applications to deliver a better understanding of the complex BCI technology. The findings from this review can help mitigate the scepticism, criticism, and misunderstanding of BCI technology. This paper contributes to common knowledge in terms of supporting communication technology development and innovation. Theoretical findings outlined in this paper can possibly be a foundation for future research towards the development of brain-to-brain telecommunication systems.

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