Review of Wireless Brain-Computer Interface Systems

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1. Introduction

Over the past two decades, the study of the Brain Computer Interfaces (BCI) has grown dramatically. According to Scopus search engine, a search result with the keyword "Brain Computer Interface" returns only two papers for year 1991. But, the same query returns 897 journals and conference papers for year 2011 (date of search: March 14, 2013). BCI systems provide a new communication channel to humans who use it. They measure neurophysiological signals of the human, electroencephalogram (EEG) in particular. EEG based BCI systems are designed to decode the intension of the human user and generate commands to control external devices or computer applications. The human can produce these commands by generating the neurophysiological signals intentionally. This process can become more successful – fast and accurate – through training and practice. This technology allows the users with new experiences which enable a direct communication between the human and the computers or external devices such as home appliances, and prosthetic devices.

The BCI systems consist of two parts, signal acquisition and translation (see page 7 Figure 2). The signal acquisition part contains electrodes, analog circuit and digital system for neurophysiological signal recording and transmission. The translation part is normally computing devices which are equipped with high performance processor such as laptops, PDAs, and smart phones. With an application program, this part performs algorithmic processes such as feature extraction and classification to convert the raw neurophysiological signals into computer readable messages. Depending on the type of connection between the two parts, we can divide BCI systems into two kinds, wired versus wireless BCI systems.

Many conventional BCI systems are wired. With just three electrodes positioned at the occipital lobe, the acquisition part of wired BCI systems generally comes with bulky and heavy amplifiers and preprocessing units. Connection wiring is usually complicated with a large number of cables between the electrodes and the acquisition part. For these reasons, preparation time for measuring EEG signals is typically very long. In addition, user's movement is limited due to cable constraints. Therefore, the application of BCI systems is difficult to escape from laboratory scale experiments. These restrictions make the types of applications for which BCI systems can be made useful be severely limited. Wireless BCI systems are to eliminate the wire connection, between the signal acquisition and the translation part, with the use of a wireless transmission unit such as Bluetooth and Zigbee modules. Removing wire connections, portability of BCI systems is greatly improved. Postures and movements of users wearing the acquisition part of wireless BCI systems are also unimpeded. These desirable aspects of wireless BCI systems promote to go beyond a laboratory scale experiments and to develop everyday-life applications.

With portable wireless BCI systems, various real-life applications are under development now. In the early days of BCI researches, cursor control and speller applications were developed mainly targeted for helping the disabled people. Recently, with growing interest, wireless BCI systems have been applied in entertainments as well. For example, Emotiv and Neurosky companies have recently released their wireless BCI headsets for entertainment uses such as brain gaming and mind monitoring. Moreover, international research groups have applied wireless BCI systems for interesting new applications such as home automation system based on monitoring human physiological states [29], cellular phone dialing [28], and drowsiness detection for drivers [19][20][32].

In this book chapter, we will review recent research trends in wireless BCI systems. In Section 2, we summarize several research topics in wireless BCI systems such as electrodes, embedded systems, user-friendly designs, and novel applications. We then take a closer look into emerging wireless BCI systems designed by BCI researchers, and discuss general BCI systems recently introduced into the market in Section 3. In Section 4, we discuss current challenges and possible future research directions on wireless BCI systems. Finally, we provide concluding remarks in Section 5.

2. Research trends of wireless BCI systems

Wireless brain computer interface (BCI) systems are neurophysiological signal acquisition and processing systems where acquired physiological signals are wirelessly transmitted to the translation unit. Wireless systems, unlike their traditional wired counterparts, are designed to provide convenience in monitoring the neurophysiological signals of users.

Compared to conventional wired BCI systems, wireless BCI systems provide enhanced portability and wearability, facilitated by elimination of the wire connections between the wearable acquisition unit and the translation unit. The translation unit is usually housed in a portable device such as laptops and smart phones. This improvement provides an easy installation process and freedom of postures for users. Furthermore, owing to advanced integrated circuit designs, the components of the wireless BCI systems are small in sizes and efficient in power consumption. Employing these components, the acquisition part of wireless BCI systems can be miniaturized. These advantages allow wireless BCI systems to be shaped in user friendly styles such as baseball caps [14][19][21][29], headsets [16][17][23][25] [27], and headbands [18][20][22][28][30][32]; thus, applying them in various applications such as entertainments and health care becomes easier than ever before.

Even though wireless BCI systems may provide a number of advantages, there are still many issues that need to be resolved including improving signal quality, more compact and stylish system designs, and excavation of useful applications. First, the quality of the measured EEG signals has to be improved for more precise classification of user's intensions. The measured EEG signals are easily contaminated by various noise sources such as the presence of other physiological signals and the power line noise. Moreover, various impediments exist in electrodes-scalp interfaces such as hairs, sweat, and stratum corneum of skin [6]. These obstacles cause deleterious effects in signal measurements with high leakage currents and high contact impedances. Due to these difficulties, EEG signals get easily corrupted and the quality of measured signals is often undesirable. Consequentially, these factors lead to drop of application accuracy. Second, stylish, miniaturized and light

weight wireless BCI systems are necessary for daily life application and long-term wearing. Conventional wired BCI systems are bulky, not user-friendly in system appearances because of their complicated connection between electrodes and signal acquisition part. Multi-channel electrode installation is also inconvenient and time-consuming, usually taking more than 30 minutes.
Thus, the users are easily irritated and long-term monitoring becomes difficult. Third, killer applications are needed. Many researchers and developers introduced various applications related to entertainments and health care. But such contributions are still not enough to make any fundamental change in our life.

To help these issues, research groups are paying attention to the following aspects:
1. Advanced electrodes for measuring clean EEG signals
2. Low-power, miniaturized, portable and wearable BCI systems
3. A *killer* application, an application of such a great value and popularity that it assures the success of the BCI technology.
In this section, we aim to analyze the current status of research and development efforts in these directions.

2.1. New electrodes for EEG signal acquisition
Among the above research topics, the development of advanced EEG electrodes which measure brain signals precisely with low noise is the most important challenge. Practically, the signal acquisition part of general wireless BCI systems only contains a signal acquisition circuit and a micro-processor based embedded system for transmission of the measured EEG signals. For example, a well-known Emotiv EPOC neuro-headset is composed of 14 channel electrodes and a small integrated embedded system powered by an onboard battery for signal conditioning and transmission. In the translation part of wireless BCI systems, analysis of acquired signals is performed either online or offline on a computer or a mobile device which is equipped with high-performance processors. For this segregated structure to work well, signal acquisition part of a wireless BCI system should be devoted to high fidelity signal recording. To provide clear EEG signal acquisition at the electrode-skin interface, development of outstanding electrodes becomes a critical issue. For this reason, many research groups have recently been interested in developing advanced electrodes which can provide low-noise recording, convenience in installation, and comfort even in long-term wearing.

In conventional wired BCI systems, passive electrodes are widely used to measure EEG signals. Generally, these electrodes are disc or ring shaped and are made of Ag/AgCl alloy [10]. Due to their simple structure, it is easy to make them small. However, they have many disadvantages as well. Extra treatments are essential for recording reliable EEG signals because the scalp potentials are only on the order of several micro-volts and thus very noise-sensitive. Treatments are needed, including a hair preparation step and the use of conductive gels or glues for better attachment and higher conductivity. These preparations induce discomfort and require long preparation time. Furthermore, the conductive gels easily desiccate and lose their adhesion. These problems bring about worse contact impedances at electrode-scalp interfaces, causing a large reduction of signal-to-noise ratio. In addition, the quality of recorded signals is sensitive to cable vibrations [17]. For these reasons, the longterm monitoring of EEG signals using passive electrodes is not feasible.

Recently, to overcome the weaknesses of passive electrodes, many researchers have studied advanced electrodes. For examples, research of dry electrodes is active recently. Generally, dry electrodes are defined as those that do not require the use of conductive gels or glues for installation process. Thus, a user can conveniently attach the electrodes to the user's scalp without any hair arrangement. To make dry contact at the electrode-skin interface, researchers employ special materials or shapes in the design of dry electrodes. Extensive research has produced a huge variety of electrode materials and structures, including conductive rubber [8][9], conductive carbon nanotubes [7], micro-tip structures [6], micro-machined structures [14][15][20], non-contact types [4][5], spring-loaded fingers [2][13], bristle structures [3], and conductive foams [27]. The most widely used dry electrode design is a set of contact posts which look like fingers [13][16]. This design has an advantage in contact ability because it is easy to penetrate into the scalp through the hair without an extended hair arrangement. Recently, some research groups have altered this finger design to produce advanced mechanical designs, such as spring-loaded fingers [2] or bristle structures [3]. These designs seem to provide flexibility and geometric adaptation between the sensor and the irregular scalp surface to obtain low interface impedance. To achieve low contact impedance and provide a robust and stable electrical interface, some research groups have employed multi-walled carbon nanotube arrays [7] and micro-tip structures [6], which are able to penetrate the outer skin layer (which is 5 to10 um thick and called the *stratum corneum*).

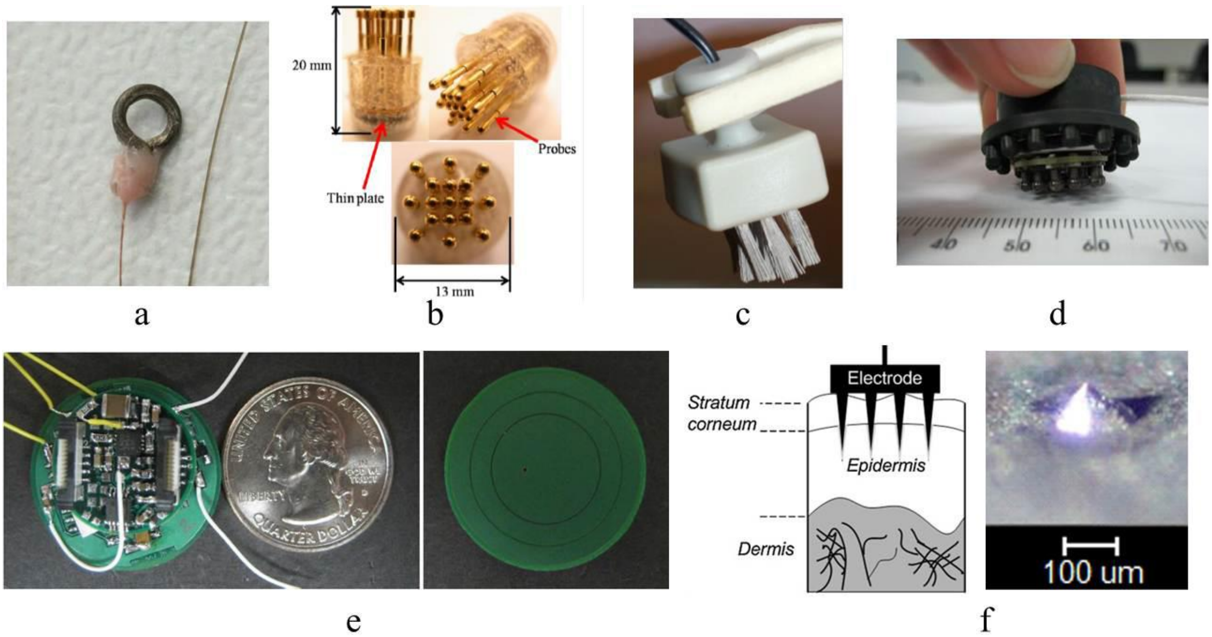

Figure 1. Various EEG electrode types. (a) a miniature passive ring electrode [10] (b) a spring-loaded dry electrode [2] (c) a bristle-type dry electrode [3] (d) the Quasar hybrid EEG biosensor [11] (e) a non-contact-type active dry EEG sensor [4] (f) Diagram of a micro-tip electrode and the pyramidal shape of a micro-tip [6].

While we can reduce the installation time significantly using dry electrodes, the contact impedance between the scalp and the electrodes is higher than that with gel-based passive electrodes due to the absence of conductive gels. Thus, signal quality of dry electrodes would be not better than that of the gel-based passive electrodes. To overcome this drawback, many research groups have been interested in active electrodes. Active electrodes contain amplifier or buffer circuits integrated to the electrodes themselves [1][4][5][7][11][12] [13]. This amplifier or buffer circuits are located between the electrodes and the signal acquisition frontend. They are aimed at impedance conversion. Providing high input impedance on the electrode-amplifier interface, active circuits reduce the distortion of the measured signals. This is desired for dry electrodes which do not use conductive fluids. Also, the low output impedance of the amplifier eliminates artifacts caused by posture changes in mobile environments. Therefore, the quality of measured physiological signals can be remained in a desirable state by the use of active electrodes.

Recent wireless BCI systems are equipped with active dry electrodes to combine the advantages of active and dry electrodes such as convenient installation and high fidelity signals. Because these electrodes provide more robust and stable signal quality in mobile environments, they are suitable for wireless BCI systems. Researchers working on the development of advanced electrodes have produced a variety of active dry electrodes. Valchinov *et al*. Designed body surface electrodes equipped with a biopotential amplifier using two op-amps [1]. Matthews *et al*. designed an ambulatory wireless EEG system using Quasar hybrid biosensors [11][12][13]. In this type of sensors, they employ a special circuit which uses the common mode follower (CMF) technology. This technology provides an ultra-high input impedance to ensure low distortion of the biopotential signals. Chi *et al.* designed and built dry and non-contact electrodes [5]. In their dry electrodes, a unity gain buffer is used to reduce the effects of cable artifacts and external interference. Their non-contact electrodes also integrate discrete circuits to achieve high input impedance. To further optimize the size and power consumption of such electrodes, some researchers have employed customized ASIC designs for amplifiers. Xu *et al.* produce a low-power 8-channel active electrode system [17].
In this system, to reduce the power consumption of voltage buffers in dry electrodes, they designed active electrodes including ASICs based on chopper instrumentation amplifiers.

2.2. Wireless BCI system design and structure

In EEG-based wireless BCI systems, additional signal conditioning is essential to enable the transmission of precise neurophysiological signals. Many noise sources are present such as physiological interferences and power line noise. Physiological interferences are the other biopotential signals such as electromyogram (EMG), electrocardiogram (ECG), and electrooculogram (EOG). They have relatively lager amplitudes around 50uV and up to 20-30mV while the amplitude of EEG signals is much smaller on the scale of roughly 10~100uV. Thus, the EEG signals are easily buried by these physiological signals unavoidably. In the case that the BCI system is connected to a desktop which operate with the electric power outlet, we also have to consider the power line noise as well. The power line noise contaminates the desired EEG signals in the range of 50 or 60Hz. Furthermore, the users of portable wireless BCI systems are usually in an active state making free motions and postures, whereas the users of wired BCI system are asked to stay in a motionless state, while their EEG signals are monitored. Therefore, the measured EEG signals of wireless BCI systems are also subject to heavy motion and vibration artifacts.

To avoid interference from the various noise components and recognize the user's intention correctly, the system must be designed carefully. Figure 2 is the general block diagram of a typical wireless BCI system. In EEG acquisition block of the system, there are two main parts, namely, the analog front end circuit and the digital system.

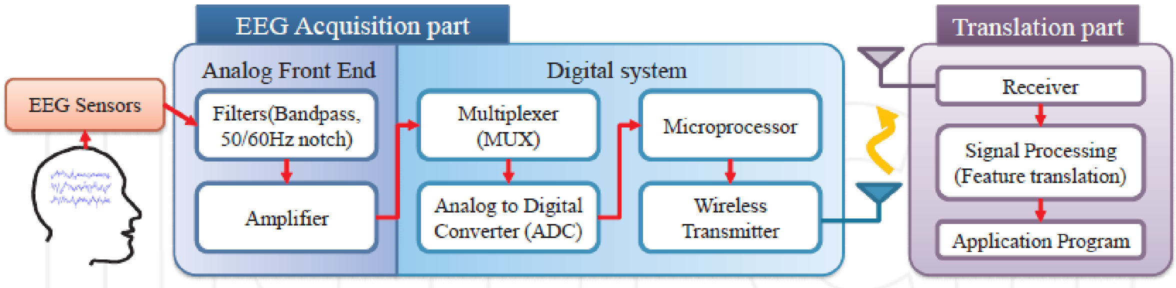

Figure 2. Block diagram of a typical wireless BCI system

In the analog front-end stage, the amplifier and bandwidth limiter circuits are included to make more robust and reliable EEG signals from the sensitive raw signals. Because the amplitude of EEG signals is quiet small, the pre-amplification of the measured EEG signals at the analog front end is extremely important. In this amplification process, many developed wireless BCI systems use operational amplifiers or instrumentation amplifiers. Those amplifiers normally provide a gain ranging from thousands to hundreds of thousands. Amplifica-

tion with high gain provides greater robustness against a variety of noise sources. However, we need to determine a suitable amplification gain to maximize the signal resolution in the analog digital converter (ADC) because the ADC has a restricted input dynamic range. Therefore, the amplification gain of the analog front end varies depending on the components of the digital system.

We also need a frequency filtering procedure to remove various noise components. The EEG signals occupy a narrow bandwidth: normally from 0.1Hz to less than 50 Hz. Thus, filtering is helpful for extracting useful signals from the desired frequency bands. To filter out signals from useless frequency bands, the analog front-end of the system takes both a low-pass filter and a high-pass filter. Especially to filter out the power line noise, a notch filter which eliminates the specific frequency components of signals is also applied in this stage. Those filtering processes are performed using passive or active filtering circuits [24][26].

In the digital system stage, four integrated circuits are included: a multiplexer, an ADC, a microprocessor, and a wireless transmission unit. Generally, most EEG-based wireless BCI systems support multi-channel recording. To measure multi-channel signals simultaneously, a multiplexer is needed to access all of the channels. Because the measured EEG signals are analog signals, an ADC has to be included to process the recorded EEG data on the digital circuits. This integrated circuit transforms the EEG analog signals into discrete digitized data with a specific sampling frequency. The sampling frequency is determined by the

speed of the microprocessor, wireless transmission, and translated frequencies of EEG features.
Formally, researchers and system developers choose the sampling frequency between about 100 Hz and 1000 Hz. The microprocessor makes data packets from the corrected EEG data and hands them over to the wireless transmission unit. The microprocessor also manages the components of the entire system. Some wireless BCI systems load the feature extraction algorithm on the microprocessor to process the EEG signals internally [19][20][21][29][30]. Because the recorded multichannel EEG data is transmitted from the portable EEG acquisition device to the host system, the wireless transmission unit is essential. Regarding the protocol of wireless transmissions, various communication modules are employed for transmission of the measured signals from the signal acquisition unit to the translation unit, such as Bluetooth and IEEE 802.15.4 Zigbee. Bluetooth has many advantages such as sufficient transmission rates and wide accessibility. Thus, many wireless BCI systems employ this transmission module. Including analog front-end and digital system stage, the acquisition unit of wireless BCI systems generally operates onboard power sources such as Li-ion, Li-polymer, and NiMH batteries.

Because the analog front-end and digital system parts have to be loaded in portable and wearable acquisition part of wireless BCI systems, longer operation time and small size are necessary in system specifications. Thus, system developers should choose low-power components with smaller packages. Recently, many semiconductor manufacturers have released low-power microprocessors and integrated analog front end circuits for bio-potential measurements.
For example, Texas Instruments released the ADS129x series integrated circuit solutions [34] for the analog front end of ECG/EEG applications. This series provides up to 8-channel high-resolution ADCs and a built-in programmable gain amplifier (PGA) with low noise and low power consumption features. In the microprocessor area, various ultralow power processors have been released on the market for portable devices. The most
widely used microprocessors are the PIC24 microcontroller series [35], the dsPIC digital signal controller series [36] (manufactured by Microchip Technology) and the MSP430 microcontroller series [37] (manufactured by Texas Instruments). In particular, the dsPIC processor series is applied as the processing unit of the Emotiv EPOC system [38].

Regarding the design approach of system appearance, a variety of designs have been adopted depending on the application purpose and target users. Widely used styles of the acquisition part of wireless BCI systems include headsets [16][17][23][25][27], head bands [18][20] [22][28][30][32], baseball caps [14][19][21][29], and military helmets [13]. In designing the appearance of wireless BCI systems, we need to consider several factors, such as wearability, stability, and convenience of installation. To provide long-term monitoring capability, wearable part of wireless BCI systems has to be light with comfort fitting. Also, convenient installation is necessary to save time in the set up process. Appropriate pressures are also needed to maintain stable electrode positions and low impedance characteristics at the sensor-skin interfaces. Additionally, to allow for the diversity of users' head sizes, the materials used in wireless BCI systems should be flexible, or size adjusters must be added. Various designs of wireless BCI systems are shown in Figure 3.

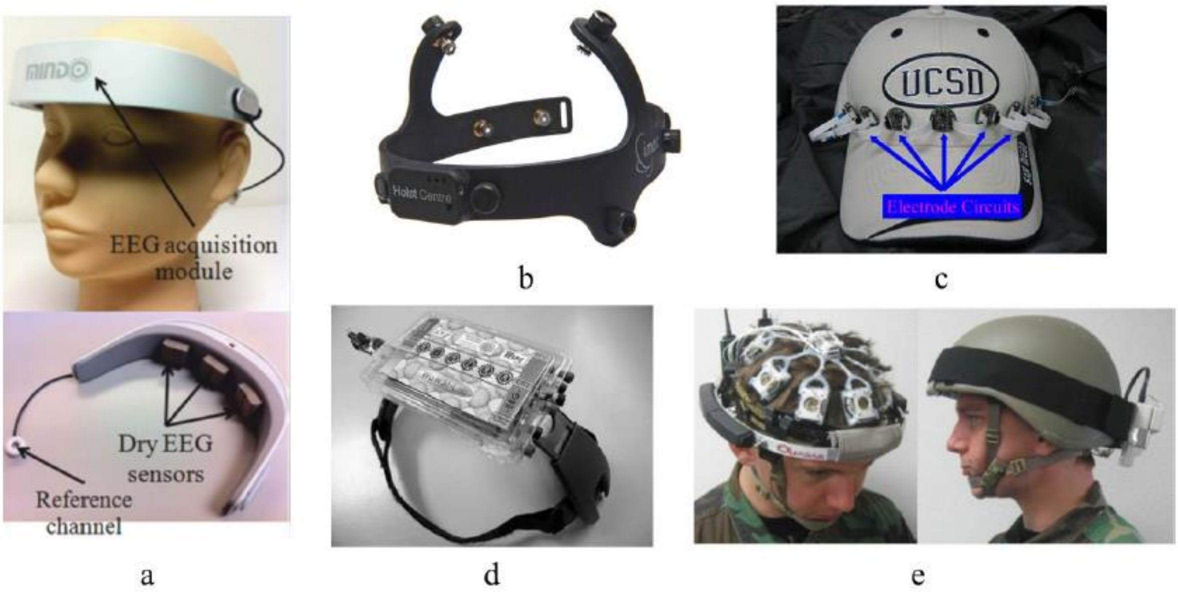

Figure 3. Various designs of wireless BCI systems: (a) wearable EEG acquisition headset [27], (b) 8-channel EEG monitoring headset [16], (c) baseball cap-based EEG acquisition device [14], (d) wireless EEG system for SSVEP application [25], and (e) soldier's Kevlar helmet-based ambulatory wireless EEG system for real-time workload classification [13].

2.3. Signal features and applications

In EEG-based BCI systems, they translate the specific signal features that reflect the user's intentions or cognitive states into commands or feedback signals for controlling of the target applications. For these operations, BCI systems analyze and capture the user's intensions based on detection of ERPs [33] or power spectra changes in specific brain rhythms.

Most research groups have focused on sensorimotor rhythms (SMRs) [39] and event related potentials (ERPs) [40], including visual evoked potentials (VEPs) such as P300 [41] and steady-state visual evoked potentials (SSVEP) [42]. The SMRs are spontaneous responses which can be actively generated by motor imageries, such as the left hand, the right hand, or the foot movements measured by electrodes placed on the scalp over the sensorimotor cortex area. These rhythms appear as suppression or enhancement of the power spectra, called event-related desynchronization (ERD) and event-related synchronization (ERS). The VEPs are behavioral responses which are passively synchronized by the frequency of flickering visual stimulus from the occipital lobe. Because the SMRs and VEPs reflect the user's intensions, we can utilize them as a means to control commands in applications. Moreover, various cognitive states are also studied, such as drowsiness, alertness, and mental focusing [27] [29][30][32]. These cognitive states are related to the power changes of specific rhythms, called alpha, beta, theta rhythms and so on. Several studies have shown that the power of the alpha rhythm has a negative relationship with mental concentration [27][29][30]. Also, researchers have found that when subjects feel sleepy or fall into a deep sleep, the power spectra of alpha and theta bands change depending on these drowsiness conditions [29][30] [32]. Using these relationships, the BCI systems detect the user's cognitive states and provide feedbacks such as focusing indicator [27] and sleep warning [32].

Among the signal features mentioned above, many researchers have chosen VEPs or users'

cognitive states as a means for BCI based controls. The reason is that these features are easy to generate and provide good accuracy in the application of BCI systems. Also, the features of VEPs and cognitive state make it easy to classify users' intentions with a relatively simple feature extraction method, and a small number of electrodes and training session are needed to achieve higher accuracy. Compared with ERPs like VEPs, the SMRs can be generated by voluntary imagination, such as motor imagery, generally require long-term training to achieve higher accuracy in BCI applications. Furthermore, approximately 30% of normal people cannot generate SMRs due to the phenomenon of BCI illiteracy [43].
In the application parts of BCI systems a variety of promising rehabilitation-related applications have already been developed with EEG-based wired BCI systems. Because BCI systems measure and analyze neurophysiological signals, these systems provide practical assistance for patient diagnosis, treatment, and rehabilitation. For example, using BCI systems, long-term monitoring of EEG signals assists the diagnosis of epilepsy and the prediction of epileptic seizures [44]. For people with severe motor disabilities, the P300 speller [41] and wheelchair control [45] applications provide practical assistance in everyday life by providing non-muscular motor functions.

In spite of these useful applications, the dissemination of BCI systems is limited because of the drawbacks of wired BCI systems. Wired BCI systems are generally bulky, complicated, and expensive. Also, the users of wired BCI systems are confined to a limited space without freedom of postures and movements. To overcome these limitations, wired BCI systems are gradually being replaced with the wireless BCI systems.

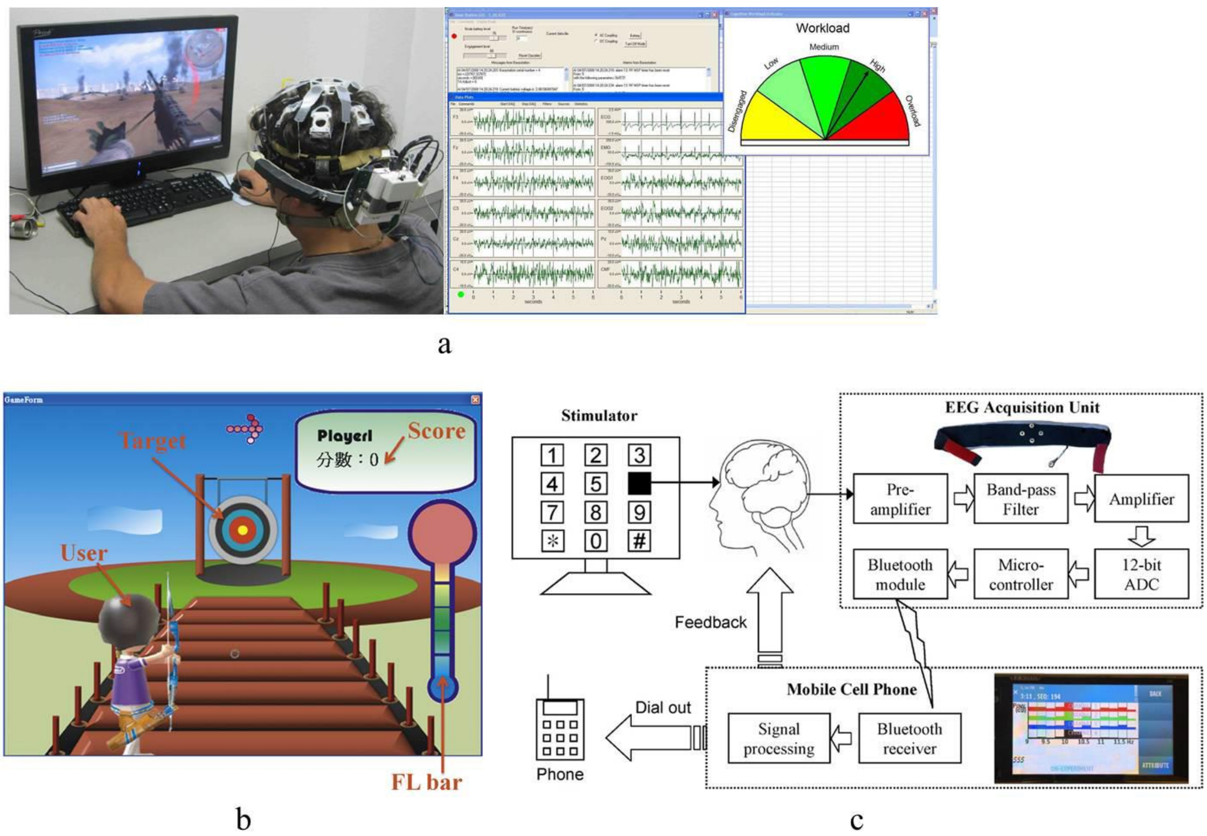

Figure 4. Applications of wireless BCI systems: (a) workload classification application screenshot (data collection and engagement classifier running on the gaming subject) [13],

(b) EEG-based BCI archery game screenshot [27], and (c) SSVEP-based dialing application using smart phone [28].

Recently, with the development of wireless BCI systems, researchers have shifted their focus from applications for disabled people to applications of interest to the general public in the entertainment, smart living environment, and cognitive neuroscience areas. In the entertainment area, Liao *et al.* developed an EEG-based gaming interface based on a real-time focusing detection algorithm with a wireless EEG acquisition device [27]. For smart living environment, Lin *et al.* developed an environmental auto-control system based on human physiological states, such as drowsiness and alertness [29][30]. Similarly, Guge *et al.* Developed a smart home control system based on P300 EEG response [31]. For mobile applications, Wang *et al.* developed a cellular phone dialing application [28]. In cognitive state monitoring, D'Arcy *et al.* developed a diagnostic device which provides an evaluation of an individual's conscious awareness based on various ERP components [33]. In this research,

they found that sensation, perception, attention, memory, and language are properly related with the P1, mismatch negativity (MMN), P300 (tones), P300 (speech), and N400 responses. Also, Matthews *et al.* developed a real-time workload classification system during subject motion with a compact ambulatory wireless EEG system [13]. Figure 4 shows application examples of wireless BCI systems.

3. Review of wireless BCI systems

Over the past 20 years, many research achievements associated with BCI and the neurosciences have been made and they have helped stimulate the interest of the general public.

Owing to the advances in wireless BCI systems, bulky wired biopotential acquisition systems have been replaced with portable and wearable devices. Following this trend, the number of published papers with the topic of wireless BCI systems and (their) applications is being continuously increased. A few commercial companies have developed and released portable wireless EEG acquisition systems with interesting new entertainment applications. Now, measuring brain activity is no longer limited to hospital-based medical diagnostics, but includes more courageous applications aiming at changing the lifestyle of users. In this section, we aim to first review several wireless BCI systems which have appeared in recent research articles. Second, we will introduce several examples of wireless BCI systems which have been lately released into the market for consumer and research usages.

3.1. Wireless BCI systems in scientific papers

In the research field, many research articles have been published in the last decade with the topic of wireless BCI systems. There are some distinct features in them such as the use of dry electrodes and novel applications which we are interested in reviewing in this subsection. For example, see the wireless BCI systems listed in Table 1.

This table shows system specifications

such as the number of channels and operation hours. They are all wireless and wearable systems, some aiming for applications that average people can find useful, including drowsiness detection and workload monitoring. Specifications for each system are optimized

for its own target application.
In what follows, we will briefly review each of the system listed in Table 1

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