

Modeling a Transmission System for Multichannel Biomedical Signals

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Abstract: *Telemedicine brings an undeniable contribution in the improvement of healthcare systems. We studied in this paper, the ability to transmit simultaneously, all channels of a multichannel biomedical signal. We have adopted for this purpose the model of the Code Division Multiple Access (CDMA) system. At the transmitter, we developed the models of the spectral spreading, multiplexing, modulation and amplification. Discrete Walsh functions were chosen to serve as codes. We implemented in the simulations, five propagation models of electric radio waves. At the reception, in addition to the inverse functions to those used in transmission, we particularly studied the synchronization. We have developed a platform to run our algorithms. The results are very encouraging. We believe our models may be taken into account in the development of telemedicine systems.*

Keywords: *CDMA, Multichannel biomedical signals, Radio waves propagation models, Telemedicine.*

I. Introduction

Telemedicine is the aspect of medicine that uses telecommunication systems to transmit medical information (images, reports, records, etc.), in order to obtain remote diagnostics, expert advice, ongoing monitoring of a patient or a therapeutic decision. Telemedicine includes several different applications and the common point is the evaluation of the patient, or patient data, by one or more medical professionals, without direct physical interaction. Telemedicine enables to overcome some difficulties in medicine such as health coverage of isolated areas, and also contribute in improving the quality of healthcare. In fact, to meet the new needs of medical services related to the aging population, lack of hospital staff and the request of home medical care, telemedicine is the recommended solution. The diffusion of mobile technologies as well as advancements in their innovative application to address health priorities has evolved into a new field of electronic health (eHealth) known as mobile health (mHealth) [1]. Mobile technology is helping with chronic disease management, empowering the elderly and reminding people to take medication at the proper time [2]. The penetration of mobile phone networks in many low- and middle-income countries surpasses other infrastructure such as paved roads and electricity. Telemedicine can then be an alternative that would make a significant contribution to public health problems in developing countries. Telemedicine also advocates home medical treatment, self-care and remote diagnosis. Remote monitoring devices enable patients to record their own health measures and send them electronically to physicians or specialists eHealth is the future of healthcare. The transmission of biomedical signals is then a main concern in telemedicine.

Multichannel biomedical signals are usually operated as graphics with multiple plots. We distinguish two main categories of multichannel biomedical signals: multi-lead signals representing the same physiological phenomenon recorded at different positions of the human body, and multi-parameters signals including several physiological parameters recorded synchronously. Fig. 1 shows two cases of multi-lead signals from [3]. To the left is an electrocardiogram (ECG) with twelve standard leads while on the right is an electroencephalogram (EEG) which has 21 leads.

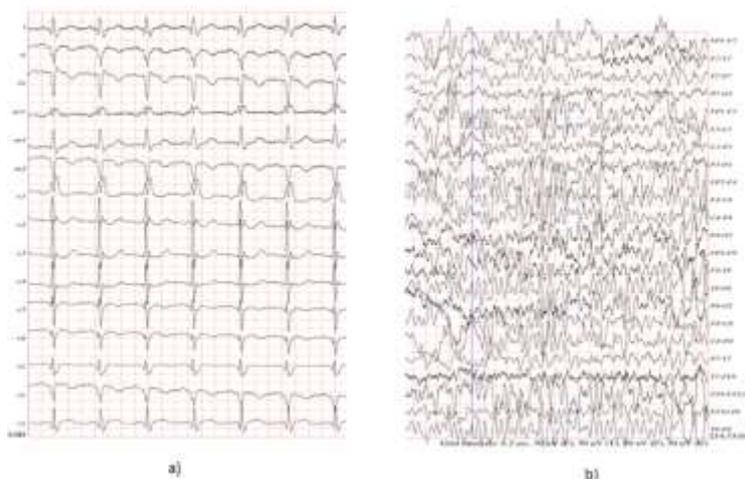


Figure 1: Examples of multi-lead signal from [3]; a) 12 leads ECG; b) 21 leads EEG.

An electrocardiograph measures the electrical activity of the heart in two ways, said horizontal and front (Horizontal plane: by chest leads and Front shot: by limb leads). A 12-lead ECG allows having an overview of the cardiac electrical waves. The 12 leads correspond to 12 angles of cardiac function. Each of the 12 leads represents a particular orientation in space, as indicated below (RA = right arm; LA = left arm, LL = left foot). These leads are divided as follows:

- Six limb leads including the standard Einthoven bipolar leads and the standard Goldberger unipolar leads. The bipolar leads are measured from two electrodes. There are 3 of them (Lead I: RA (-) to LA (+) (Right Left, or lateral); Lead II: RA (-) to LL (+) (Superior Inferior); Lead III: LA (-) to LL (+) (Superior Inferior)). The Goldberger leads use the same electrodes as the Einthoven leads, except that the electrode is regarded as positive pole toward two negative poles formed by the two other electrodes (Lead aVR: RA (+) to [LA & LL] (-) (Rightward); Lead aVL: LA (+) to [RA & LL] (-) (Leftward) and Lead aVF: LL (+) to [RA & LA] (-) (Inferior)).

- Six chest leads known as Wilson unipolar leads: V1, V2, V3, V4, V5 and V6. Leads V1, V2, V3: are Posterior Anterior while Leads V4, V5, V6: are Right Left, or lateral. As Goldberger leads, a measured corresponds to the positive pole while the other precordial leads are negative pole. They record the heart's electrical activity on the horizontal plane and their "precordial" designation indicates to position them near the heart. Examples of signals from 12 lead ECG can be seen in figure 1-a.

The transmission of the ECG through modern telecommunication systems has been an intensive research work in the recent years. The Bluetooth, GSM, internet and various combinations of modern digital telecommunications systems have already been proposed for the transmission of the ECG [4 - 10]. Many works have been devoted in recent years on mobile telephony applications for recording and transmitting Electrocardiogram (ECG) [11-14].

The Electroencephalogram (EEG) is a test based on the measurement of the electrical activity of the brain. This is performed via electrodes placed in contact with the scalp. This clinical examination informs the medical team on the neurophysiological activity of the brain. The EEG allows to measure brain activity with high temporal precision. This examination guide diagnosis or monitoring the effects of treatment. It also allows studying certain sleep disorders. In the internationally standardized 10-20 system usually employed to record the spontaneous EEG, 21 electrodes are located on the surface of the scalp. In addition to the 21 electrodes, intermediate 10% electrode positions are also used. The locations and nomenclature of these electrodes are standardized. Besides the international 10-20 system, many other electrode systems exist for recording electric potentials on the scalp. Bipolar or unipolar electrodes can be used in the EEG measurement [15]. Examples of signals from 21 lead EEG can be seen in fig.1-b.

Clinical examination of the EEG also requires that doctor scrutinize several leads of the signal at the same time. The need to transmit several leads of the EEG arose since the early 60s [16-17]. The pioneer works aimed to transmit just two or three leads. Recent EEG recording systems are wireless: the electrodes are positioned in a helmet including preamplifiers and transmitters. The recorded signals are then instantly transmitted through radiofrequency waves to a central for registration and analysis [18-20]. These new facilities provide the ability to record the EEG of a patient in mobility and in various emotional conditions. The Bluetooth is the transmission protocol the most used in wireless EEG recording systems. Beyond the medical diagnosis, research to explore the human brain and even prediction of human behavior by the computer uses such equipments.

Some multi-parameters biomedical signals from [3] are given in fig.2 and Fig.3. Fig.2 presents a MGH/MF Waveform signals and a CAP Sleep signals. The MGH/MF (Massachusetts General Hospital/Marquette Foundation) recording includes three ECG leads, arterial pressure, pulmonary arterial pressure, central venous pressure, respiratory impedance, and airway CO₂ waveforms. Some recordings include intra-cranial, left atrial, ventricular and/or intra-aortic-balloon pressure waveforms. ECG calibration, pressure zero, pressure calibration, and pressure/catheter frequency response tests are also recorded [3]. The CAP (Cyclic Alternating Pattern) waveforms include at least 3 EEG channels (F3 or F4, C3 or C4 and O1 or O2, referred to A1 or A2), EOG (2 channels), EMG of the submental muscle, bilateral anterior tibial EMG, respiration signals (airflow, abdominal and thoracic effort and SaO₂) and EKG. Additional traces include EEG bipolar traces, according to the 10-20 international system (Fp1-F3, F3-C3, C3-P3, P3-O1 and/or Fp2-F4, F4-C4, C4-P4, P4-O2) [3].

In Fig.3 are shown the CEBS (Combined measurement of ECG, Breathing and Seismocardiogram) and the SHHS (Sleep Heart Health Study) Polysomnography waveforms. In the CEBS, Channels 1 and 2 of the system are devoted to measure conventional ECG (leads I and II respectively) with a bandwidth between 0.05 Hz and 150 Hz, channel 3 is employed to measure the respiratory signal obtained from a thoracic piezoresistive band with a bandwidth of 0.05 Hz to 10 Hz and channel 4 is devoted to acquire the SCG using a triaxial accelerometer and a bandwidth between 0.5 Hz and 100 Hz [3]. The SHHS is a prospective cohort study designed to investigate the relationship between sleep disordered breathing and cardiovascular disease. The full details of the procedures for obtaining polysomnograms are given in [21]. The recording montage consisted of: C3/A2 and C4/A1 EEGs, sampled at 125 Hz; right and left electrooculograms (EOGs), sampled at 50 Hz; a bipolar submental electromyogram (EMG), sampled at 125 Hz; thoracic and abdominal excursions (THOR and ABDO), recorded by inductive plethysmography bands and sampled at 10 Hz; "airflow" sampled at 10 Hz; finger-tip pulse oximetry sampled at 1 Hz; ECG from a bipolar lead, sampled at 125 Hz for most SHHS-1 studies and 250 Hz for SHHS-2 studies; Heart rate derived from the ECG and sampled at 1 Hz; body position; ambient light[3].



Figure 2: Examples of multi-parameters signal from [3]; a) MGH/MF (Massachusetts General Hospital/Marquette Foundation); b) CAP (Cyclic Alternating Pattern) Sleep.

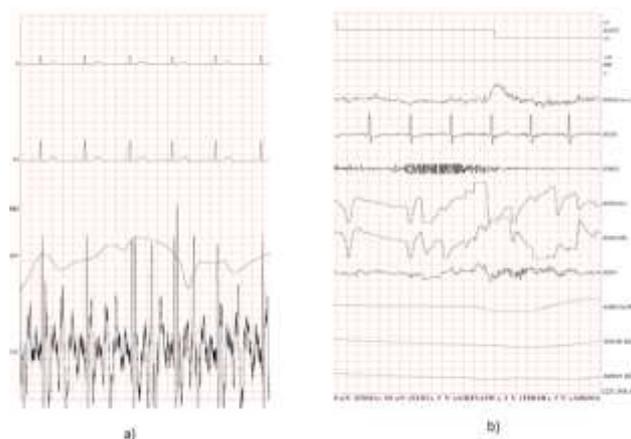


Figure 3: Examples of multi-parameters signal from [3]; a) CEBS (Combined measurement of ECG, Breathing and Seismocardiogram); b) SHHS (Sleep Heart Health Study).

In most cases of wireless transmission of ECG signals, only a single lead of ECG signal is envisaged. Even modern high-performance equipments for ambulatory "Holter" or telemonitoring electrocardiographs are limited to the transmission of a single ECG lead. The range of the transmission distance is limited to few tens of meters. The level of security of information transmitted is very weak and the degradation of the signals is important. Yet, for the diagnosis of certain cardiac pathologies, the physician must use at least twelve ECG leads. He analyses and examines all these leads simultaneously, establishing correlations between them. The literature on the transmission of other multichannel biomedical signal is not abundant. This reflects the fact that researchers do not pay enough interest to this topic. And yet, given the scale that takes telemedicine, we should not overlook this research. We are concerned about the transmission of multichannel physiological signals. Taking inspiration from the CDMA deployed in mobile phones for the simultaneous use of multiple subscribers within the same channel for their communication systems, we developed a transmission model for multichannel biomedical signals that could be implemented in telemedicine.

For the rest of this paper, section 2 is devoted to materials and methods including an overview on CDMA and its synchronization process, the modeling of the transmission units and a brief description of propagation channels models. The results obtained are presented in section 3, starting by the presentation of the platform for simulation, followed by the results obtained at various stages of the transmission and a discussion. The paper ends with a conclusion.

II. Material and Methods

2.1 An overview on CDMA

The CDMA is a technique whereby different users can communicate simultaneously in the same frequency band. The distinction between users is done through codes that are assigned to them and known only by the sender and the receiver. This technique is based on the principle of spectrum spreading by orthogonal or pseudo-orthogonal codes [22, 23]. At the reception, the despreading operation will help to regenerate the baseband signal (or produce an intermediate frequency); other signals (interference) are perceived by the receiver as noise [24, 25]. The principle of the simplified CDMA transmission system is shown in Fig. 4.

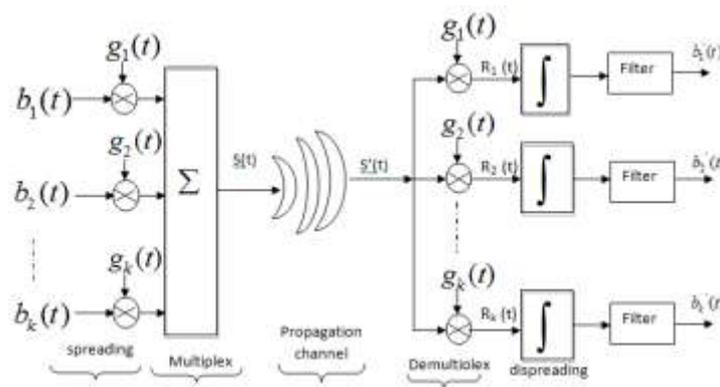


Figure 4: Principle of a simplified CDMA emitter and receiver. $b_k(t)$ is the signal number k , $g_k(t)$ is the code assigned to signal number k , and $s(t)$ is the multiplexed composite signal. $S'(t)$ Composite signal received, $g_k(t)$ code for emitter number k ; $R_k(t)$ image signal of emitter k , extracted from the composite signal; $b_k'(t)$ reconstructed signal of the user k .

The signals b_k are transmitted to the symbol duration rate T . The codes $g_k(t)$ are orthogonal as indicated in equation (1) and have expressions in the form of equation (2).

$$\int g_k(t - nT) g_l(t - n'T)^* = 0 \quad \text{if } k \neq l \quad \text{or } n \neq n' \quad (1)$$

$$g_k(t) = \sum_{m=0}^N c_{k,m} g(t - mT_c) \quad (2)$$

with $T_c = \frac{T}{N}$, denoting the chip period and N is the spreading factor.

$g(t)$ is a shaping filter whose frequency band is equal to $1/T_c$;

The coefficients $c_{k,m}$ are ± 1 , and for a given user, the set of coefficients $c_{k,l}$ for $l = 0, \dots, N-1$ is the code for signal number k .

When $k \neq l$, then
$$\sum_{m=0}^{N-1} c_{k,m} c_{l,m}^* = 0 \tag{3}$$

An important consequence follows:

$$\frac{1}{T} \int g_k(t - nT) g_l(t - n'T)^* dt = \frac{1}{N} \sum_{m=0}^{N-1} c_{k,m} c_{l,m}^* = 0 \quad \text{if } k \neq l \text{ or if } n \neq n'. \tag{4}$$

Multiplexing involves mixing all the spread signals from different users into a single composite signal. The signal obtained after multiplexing is expressed as equation (5).

$$s(t) = \sum_{k=1}^{NB} \left[\sum_{n \in \mathbb{Z}} b_{k,n} g_k(t - nT) \right] \tag{5}$$

Where $b_{k,n}$ form the sequence of the user number k . Thus, to effectively transmit K sequences of symbols at a

frequency $\frac{1}{T}$, it takes at least a frequency band of $\frac{N}{T}$ with $NB \leq N$.

On the reception stage, the waveform received will depend on the nature and characteristics of the link between the emitter and the receiver. When it is synchronous, the complex envelope of the received signal in the case of a single-path channel is given by the equation (6).

$$R(t) = Att. \frac{1}{\sqrt{T}} \sum_{k=1}^k \left[\sum_{n \in \mathbb{Z}} b_{k,n} g_k(t - nT) \right] + \xi(t) \tag{6}$$

Here, Att is the attenuation of the signal when it passes through the channel and $\xi(t)$ represents the noise added to the signal during the transmission. The gain of the amplification can be set to $1 / Att$. The demultiplexing of this signal uses the codes $g_k(t)$. Finally, despreading and filtering retrieve the information to each user. For a given user number k ,

$$b'_k(t) = \frac{1}{\sqrt{T}} \int_{-\infty}^{+\infty} R(t) g_k(t - nT)^* dt = b_{k,n} + \xi_n \tag{7}$$

The differences between the signals emitted $b_k(t)$ and the signals received $b'_k(t)$ depend on the amplitude of the noise and of the type of filter used

2.2 Synchronization process

The Direct Sequence Spread Spectrum (DS-SS) communication systems need synchronization. The main purpose of synchronization irrespective of the specific communication scheme is to estimate and eliminate the time difference between the transmitter and locally generated receiver spreading sequence. Usually in DS-SS system, the problem of synchronization is solved via a two-steps approach: the initial code acquisition (coarse acquisition or coarse synchronization) and the code tracking. The aim of initial code acquisition is to achieve a coarse synchronization between the receiver and the transmitted signal. Its accurately estimate the time difference between the received spreading sequence and its replica generated in the receiver. In Fig. 5-a we have the generic acquisition circuit.

The receiver hypothesizes a phase of the spreading sequence and attempts to despread the received signal using the hypothesized phase. If the hypothesized phase matches the sequence in the received signal, the wide-band spread spectrum signal will be despread correctly to give a narrowband data signal. Then a bandpass filter, with a bandwidth similar to that of the narrowband data signal, can be employed to collect the power of the despread signal. Since the hypothesized phase matches the received signal, the BPF will collect all the power of the despread signal. In this case, the receiver decides that the coarse synchronization has been achieved

and activates the tracking loop to perform fine synchronization. On the other hand, if the hypothesized phase does not match the received signal, the despreader will give a wideband output and the BPF will only be able to collect a small portion of the power of the despread signal. Based on this, the receiver decides this hypothesized phase is incorrect and other phases should be tried.

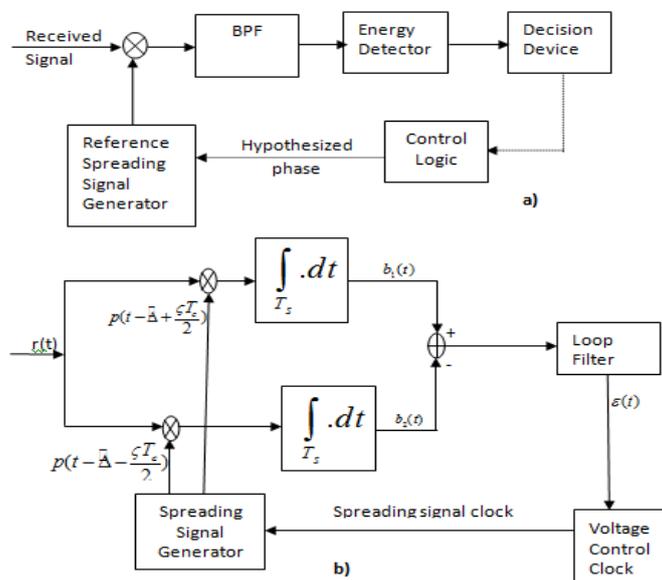


Figure 5: Synchronization process: a) Generic acquisition circuit; b) Early-late gate delay-lock loop

The purpose of code tracking is to perform and maintain fine synchronization. A code tracking loop starts its operation only after initial acquisition has been achieved. A common fine synchronization strategy is to design a code tracking circuitry which can track the code phase in the presence of a small frequency error. After the correct code phase is acquired by the code tracking circuitry, a standard phase lock loop (PLL) can be employed to track the carrier frequency and phase. A common technique for code tracking, namely, the early-late gate delay-lock loop (DLL) as shown in Fig. 5-b.

2.3 Modeling the transmission system

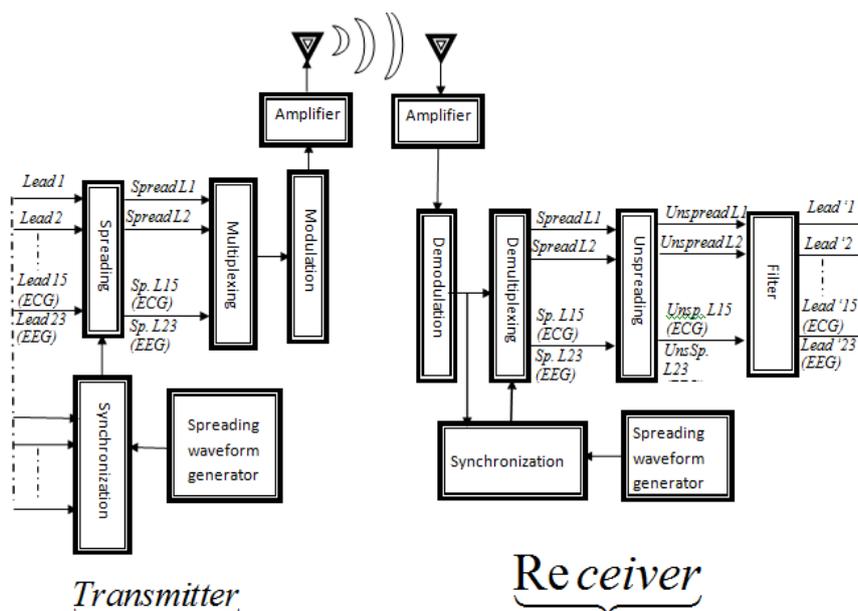


Figure 6: Bloc diagram of the transmission system for multichannel biomedical signals

The bloc diagram of the overall transmission system for multichannel biomedical signals is shown in Fig. 6. It includes the transmitter, the channel and the receiver.

2.3.1 The transmitter

The model of the transmitter comprises seven modules: the acquisition of multichannel signals, code generation and synchronization to signals, the spectral spreading, the multiplexing, the modulation and the transmission. The codes used are the rows of the Walsh matrix. Indeed, the orthogonality property of the binary Walsh functions allows us to use them as codes in the process of CDMA. More details on continue and discrete Walsh functions can be found in [26-27]. The order of the matrix is chosen according to the number of channels of the multichannel signal. The multiplexed signal at a given time is expressed by the equation (8).

$$s(j) = \sum_{k=1}^K b_k(j) \cdot w_{k+1} \tag{8}$$

with $b_k(j)$ the sample number j of the signal b_k and w_{k+1} the Walsh function of order $k+1$ which is here the code assigned to the lead signal b_k .

The spread spectrum will transform narrowband signals into broadband signals. The principle is the same shown in Fig. 4 where the codes $g_k(t)$ are replaced by the lines of the Walsh matrix $W(i, n)$. The signals b_k are from the multichannel biomedical signals (ECGs, EEGs, CAP Sleep, MGH/MF, CEBS and SHHS). To this end, a lead signal d_k , ($k = 1, 2, \dots, 15$ for ECG and $k = 1, 2 \dots 23$ for the EEG) whose length is L , is divided into M segments of length A such that $MA = L$. Each segment is then convolved by the code assigned to that lead signal. For a segment of length A and a code of length B , the convolution produces a spread segment of a length $A + B - 1$. The Walsh matrices generated have i lines ($i = 1, 2 \dots 2^Y$) and n columns ($n = 1, 2 \dots 2^Y$). A sample $d_{k,j}$ is spread with a code $w(i, n)$ and becomes a vector $de_{(k,j,i)}$ of length N such that:

$$de_{(k,j,i)}(n + (j-1) \times 2^Y) = d_{k,j} \times w(i, n) \tag{9}$$

The spread lead signal is a sequence of vectors obtained by varying j . Each lead spread signal is of a duration P . This is done simultaneously on all leads. We then obtain the same number of vector as the number of leads but with wider band spectrum. Since we have many channels, we must ensure that the spread gains of various channels are identical in order to avoid errors at the reception process. The vector of the multiplexed signal comprises the sum of all spread samples at the same rank. The multiplexed vector elements are defined by equation (10).

$$R(m) = \sum_{k=1}^{Nc} de_{(k,j,i)}(m) \tag{10}$$

With $m = 1, 2, \dots, P$, and Nc the number of channels.

The Modulation process is not a primary concern for our work. We adopted to use the frequency modulation. The carrier frequency is set at 2.5 GHz. This is the same range as the values of frequencies used for Bluetooth, wifi or wimax. The last stage of the transmission is a power amplifier with adjustable gain for the management of the transmission distance.

2.3.2 The reception

The Fig. 6 also shows the blocks involved in the reconstitution of multiple channels signals from a single received CDMA signal. An amplifier returns the received signal to a power level sufficient before demodulation. The same Walsh functions used as transmission codes are generated for demultiplexing. The demultiplexing process extracts the images of each lead signal from the composite signal. The correlation of the received composite signal with the codes is carried out. Let R_s be a segment of the received vector, the expression of the vector segment $R_{(ii,s)}$ obtained from demultiplexing using the appropriate code is given by (11).

$$R_{(ii,s)} = R_s \cdot w(ii, n) \tag{11}$$

with $(ii = 1, 2, \dots, N)$.

The signal R_k shown in Fig. 4 are explicitly obtained using equation (12).

$$R_k = d_{(k,j)} \times w(i, n) \cdot w(ii, n) \tag{12}$$

When $i \neq ii$, the orthogonality of the codes implies that $w(i, n) \cdot w(ii, n) = 0$. Thus, the interferences between different channels are cancelled. Only the elements of the signal mapped with the spreading code

$w(i, n)$ appear at the end of this operation. After the demultiplexing, we obtain as many channels signals as in the emission stage, but which are larger in duration, more precisely having the length is $M(A + B - 1)$. Integration is then performed on the demultiplexed signal on a finite period equal to the symbol duration. This allows recovering the initial unstretched band signal. If the spread signal contains noise which has been added during the transmission, a low-pass filtering is performed.

2.3.3 Propagation Channels Models

Radio waves propagate from a transmitting antenna, and travel through free space undergoing absorption, reflection, refraction, diffraction, and scattering. They are greatly affected by the ground terrain, the atmosphere, and the objects in their path, like buildings, bridges, hills, and trees. Thus, the existence of a direct or line-of-sight path between the transmitter and the receiver is highly unlikely. In the Rayleigh Channel there is no direct path. When the direct path exists the channel is called Rician channel. We considered AWGN (Additive White Gaussian Noise), Rayleigh and Rician channels when modeling the radio waves channels.

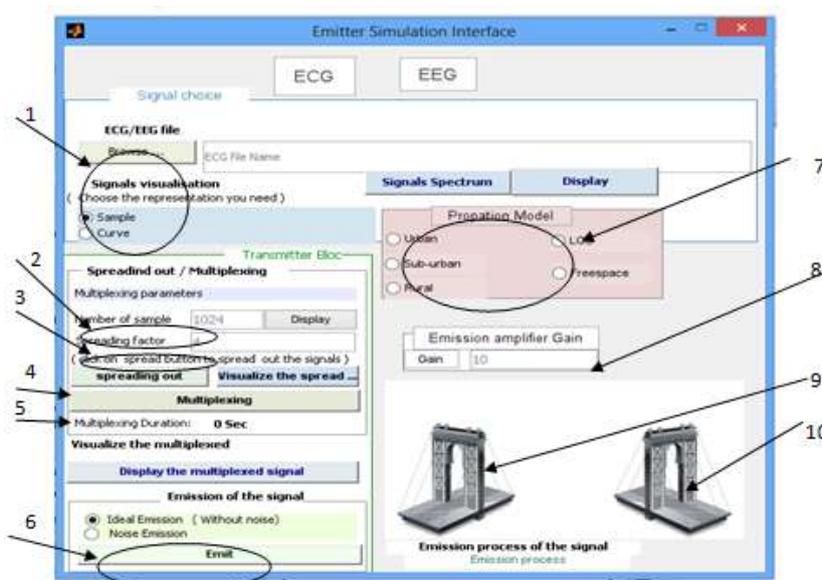
Recording and transmission of biosignals are performed in a hospital, at home and even in the ambulance in the case of accident for example. The environment in this case is made of people (medical personnel, patients and patients' guards), biomedical machines and furniture, walls and buildings, trees, mountains and various particles suspended in the atmosphere. The parameters of this environment fluctuate over time and are not controllable: movement of people, equipment and vehicles, weather conditions, industrial and civil engineering activities. The formulas in radio links are essentially empirical and based on the results of many measurements at various locations around the world. We have integrated into the platform of simulation, five models of propagation: the propagation in free space, the Okuruma - Hata models for urban, sub-urban and rural areas, and the "Line On Sight (LOS)" model. These models and many others are used for the planning and the design of mobile communication systems [25].

III. Results and Discussion

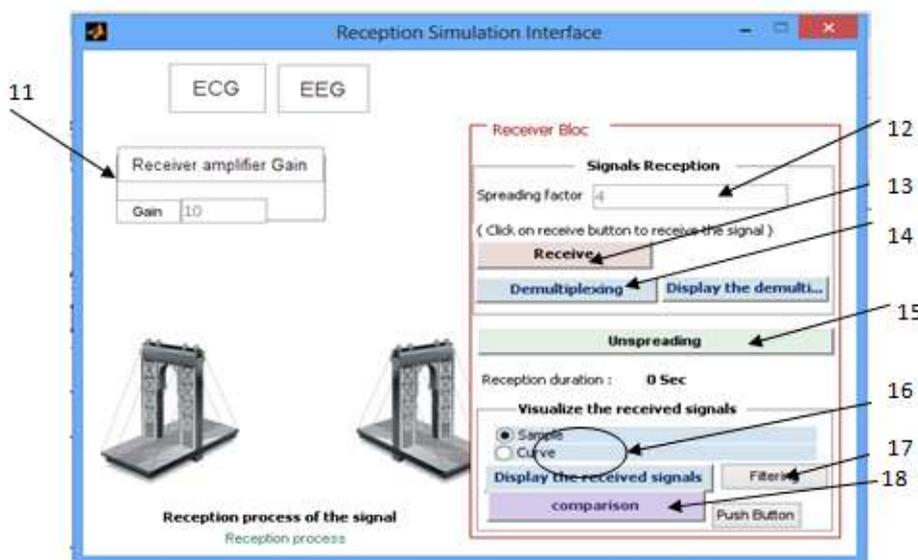
3.1 Platform for simulation

We realized a platform that is used to simulate the transmission of 15 leads ECGs and 23 leads EEGs. The main functions for the simulation interface can be seen in Fig. 7. There are many command buttons and fields that guide the user. The algorithms simulating the various processes that we have described above are implemented and run in the background. We can therefore load data (acquisition), view step by step, the signals obtained at each unit output.

In zone 1, a click on the Browse button allows to specify a path and load the multichannel signal that the user wants to transmit. He can decide to display this signal as sample values or to plot the curve of its evolution. Zone 2 allows us to input the length of segments of signals to be transmitted. This duration in terms of the number of samples must be a power of 2. This duration is identical for all leads. One can display at this level, the selected portions of signals to be transmitted. Field 3 associated with spreading factor is used to define the code length. A number n is entered in this field, such that 2^n is the spreading factor. For the 15-leads ECG signal for example, the minimum dimension of the Walsh matrix which can be used for spreading is 16. Thus, we will enter in the field 3, the number 4. The button 4 sets the spectral spreading. At this level, we can view the spread signals from all the leads. When clicking on the button 5, the algorithm in the background performs the multiplexing operation. The multiplexed composite signal can be displayed by clicking on the button "display the multiplexed signal". Several options for emission and transmission are proposed in Zone 6. The modulation operation is automatic. The user can adjust the transmission power according to the desired range. We can choose a long distance transmission in free space, an average transmission distance in urban, suburban or rural area. The user can consider noise that is added to the modulated signal during transmission. The user can assume that noise is superimposed on the composite multiplexed signal. That noise representing the noise from the electronics used for acquisition and processing, is usually a white Gaussian noise.



(a) Emission platform interface



(b) Reception platform interface

Figure 7: Platform for simulation a) Emitter interface: 1: Acquisition and visualization buttons and fields, 2 - 5: spreading and multiplexing buttons, 6-10: Propagation models, amplifier and emission fields. b) Receiver interface: 12-15: Unspreading and demultiplexing buttons and fields, 16-18: Extraction, filtering and comparison units

The second interface showed in Fig. 7-b gathers the modules of the receiving system. These modules perform the inverse functions to those of the emitting system. It thus contains an adjustable gain amplifier, the demodulator, and buttons for controlling the despreading, the demultiplexing and also the filtering. Here once, you can view the signals at various stages of the system. One can find more details on the platform in the *additional document* attached to this paper.

3.2 Results of the simultaneous transmission of multi-lead ECG/EEG signals

3.2.1 Transmission of 15 leads ECG

In [3], we found ECG records from PTB Diagnostic Database (ptbdb) which are 15-leads ECG signals. For the clarity of display, we plot only signal segments of 1024 samples in length. In Fig. 8 is shown extracts of 15-leads ECG recording ptbdb/patient001/s0010_re. We simulated the simultaneously transmission of these fifteen leads.

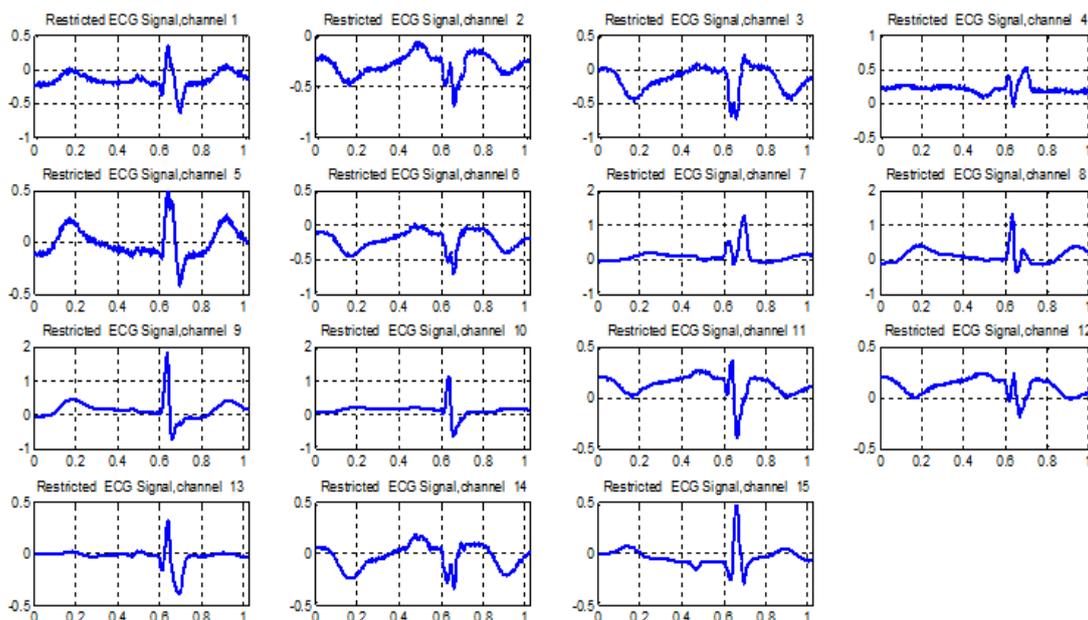


Figure 8: Extracts of a 15 ECG, ptbdb/patient001/s0010_re [3]

The spreading operation enlarges the bandwidth of each lead signal and increases the length of the signal as it can be seen in Fig. 9. The spread leads signals are made of 16,384 samples each.

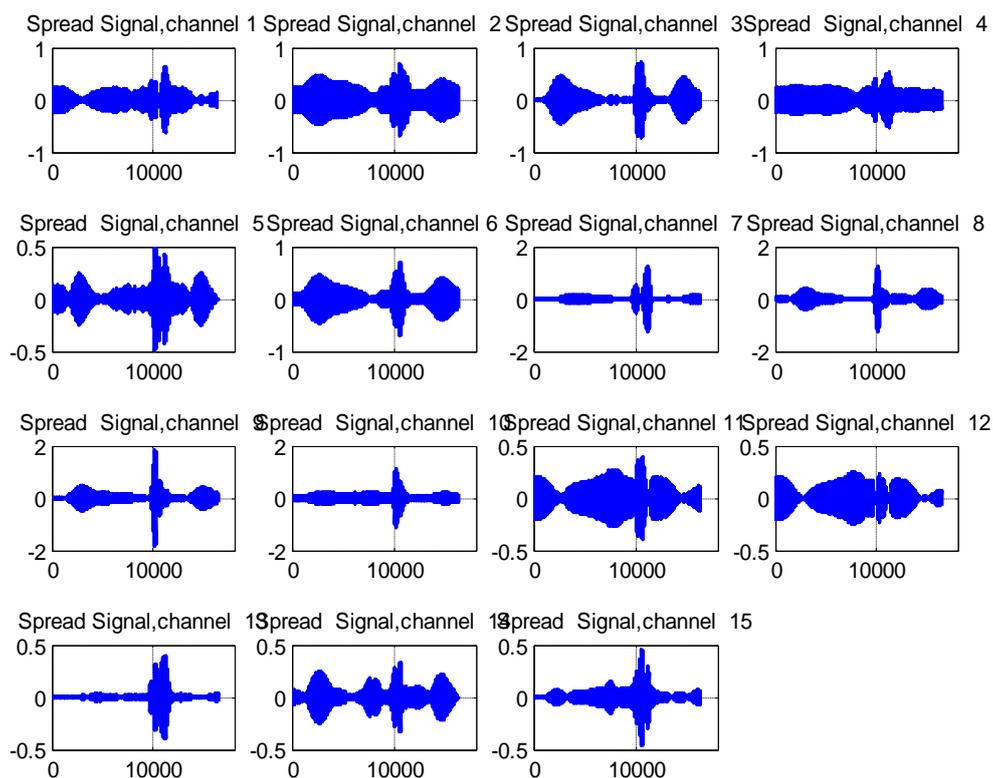


Figure 9: Spread versions of the signals in Fig. 8

The composite multiplexed signal issued from the 15-leads spread signals is shown in Fig. 10. This signal is next frequency modulated with a carrier frequency of 2.5 GHz, the modulated signal is amplified and transmitted over a single radio channel.

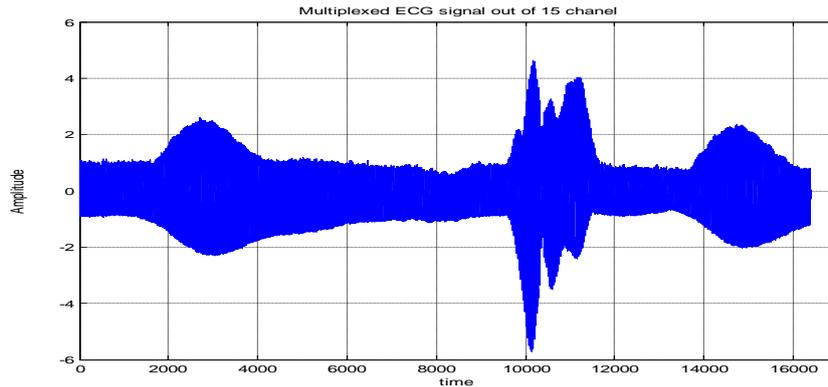


Figure 10: Multiplexed composite signal issued from 15-leads spread ECG in Fig. 9.

In the case of a transmission through an ideal radio channel, and if the noise of the processing electronics is neglected, we obtain after the demodulation and the correlation of the received signal with corresponding codes, the curves of Fig. 11. These signals are demultiplexed, but they remain spread signals.

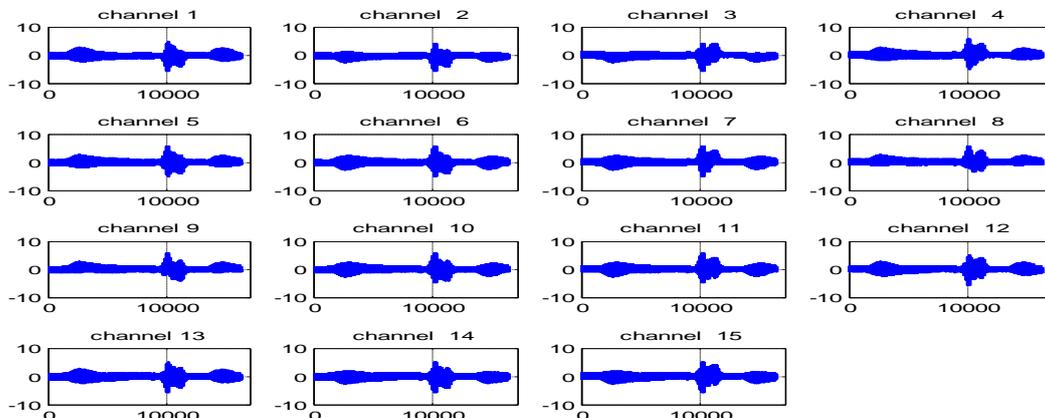


Figure 11: 15-leads demultiplexed and spread ECG from the received signal after demodulation and correlation with codes

When applying to each of the demultiplexed signals, integration over a period of 16 which is the spreading factor, we obtain the signals in Fig. 12. In Fig. 12, the received signals are superimposed to the emitted signals. The received signals and the transmitted signals are identical. The coincidences were such that no one would notice that there were two superimposed curves. We then intentionally added a 0.1 mV DC component to the received signals in order to create an offset and detach them from transmitted signals.

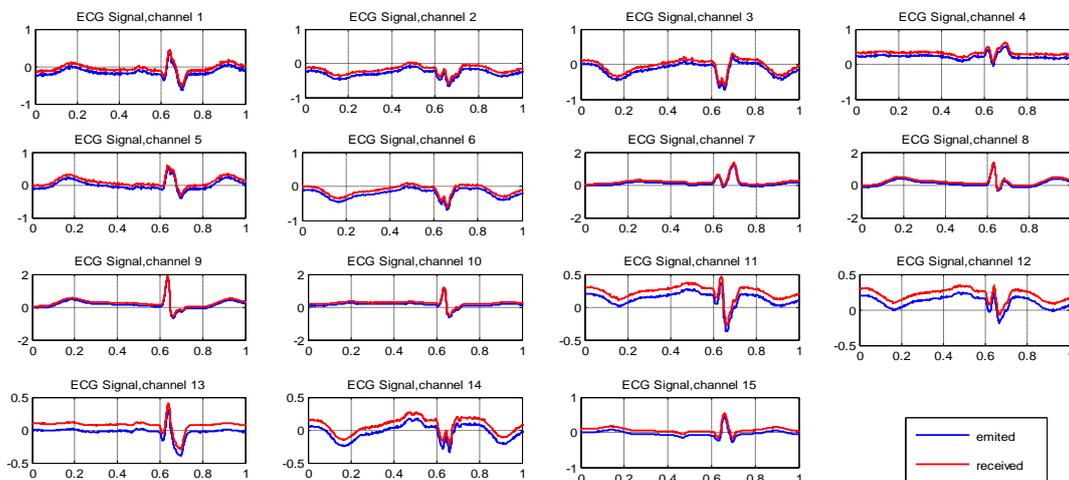


Figure 12: The 15-leads signals received compared to the emitted leads signals of ECG ptbdb/patient001/s0010_re.

When the transmission is done through a real channel, the received signal is weakened due to the complex propagation environment. There is thermal noise and shot noise of various electronic components. We brought all these noises at the output of the multiplexer. We varied the signal to noise ratio (SNR) and observed its influence on the quality of the output signal at the reception stage. For an example, we added a Gaussian white noise to the spread composite signal before modulation. Fig. 13 shows the results obtained with a SNR value of 25 dB. A simple digital Butterworth filter of order 7 is used for denoising. Fig. 13 allows us to appreciate the results obtained after these operations. A DC value of 0.1 mV is also added to the received signal here. The visual assessment does not realize the difference between the transmitted and received signals. Some samples' values for both the original and the received signals are given in Fig. 14. More results on the transmission of 15 leads ECGs can be found in the additional document.

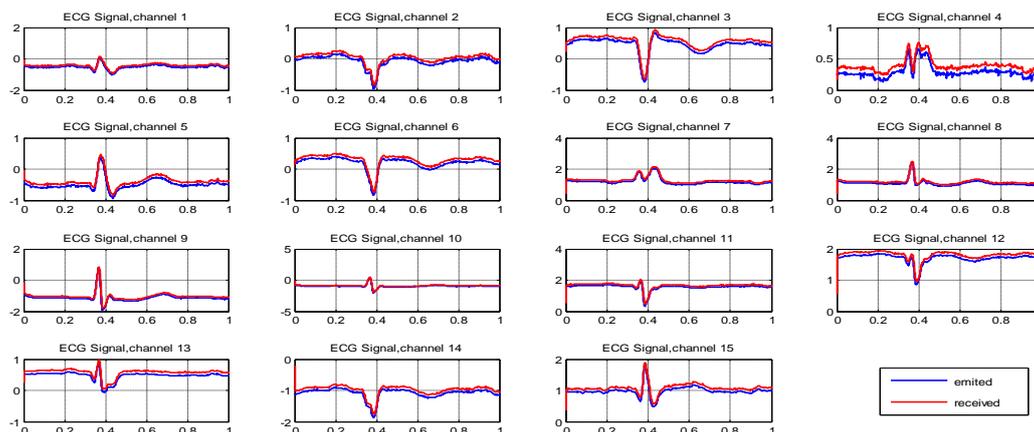
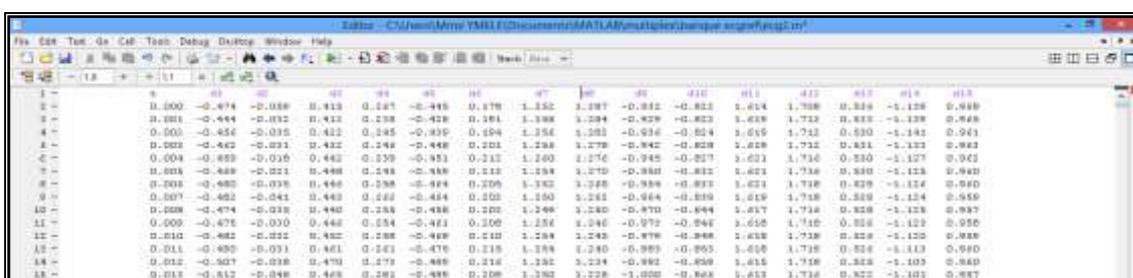
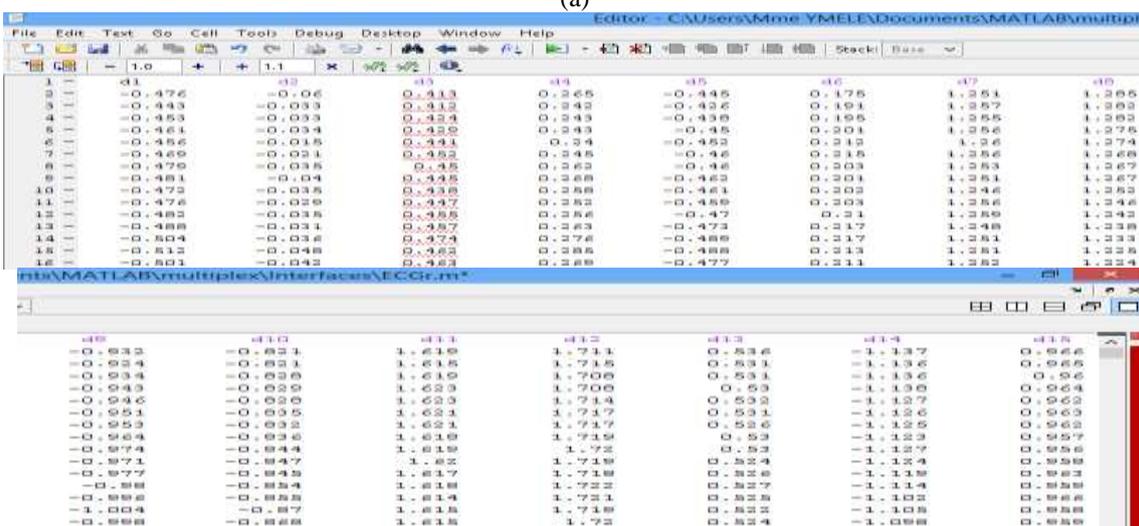


Figure 13: Emitted and received 15 leads ECG signal through noisy transmission system (record ptbdb/patient001/s0014re)



(a)



(b)

Figure 14: Emitted and received ECG data of patient ptbdb/ patient001/S0014-re as sample ; a) Original data of ECG data of patient ptbdb/ patient001/S0014-re as samples, t is time column and d1, d2 ...d23 are different leads; b) Received ECG as samples at 25 dB

3.2.2 Transmission of 23-leads EEG

We also tested our algorithms on the EEG signals of the CHB-MIT Scalp EEG Database (chbmit) included in [3]. As these EEG signals have 23 leads each, we must use at least a Walsh matrix of order of 32, to generate the codes. The spreading factor is then 32. Fig. 15 presents excerpts from the 23-lead EEG record chbmit/chb03/chb03_26.edf. We simulated the simultaneous transmission of this 23-leads EEG by a single CDMA signal.

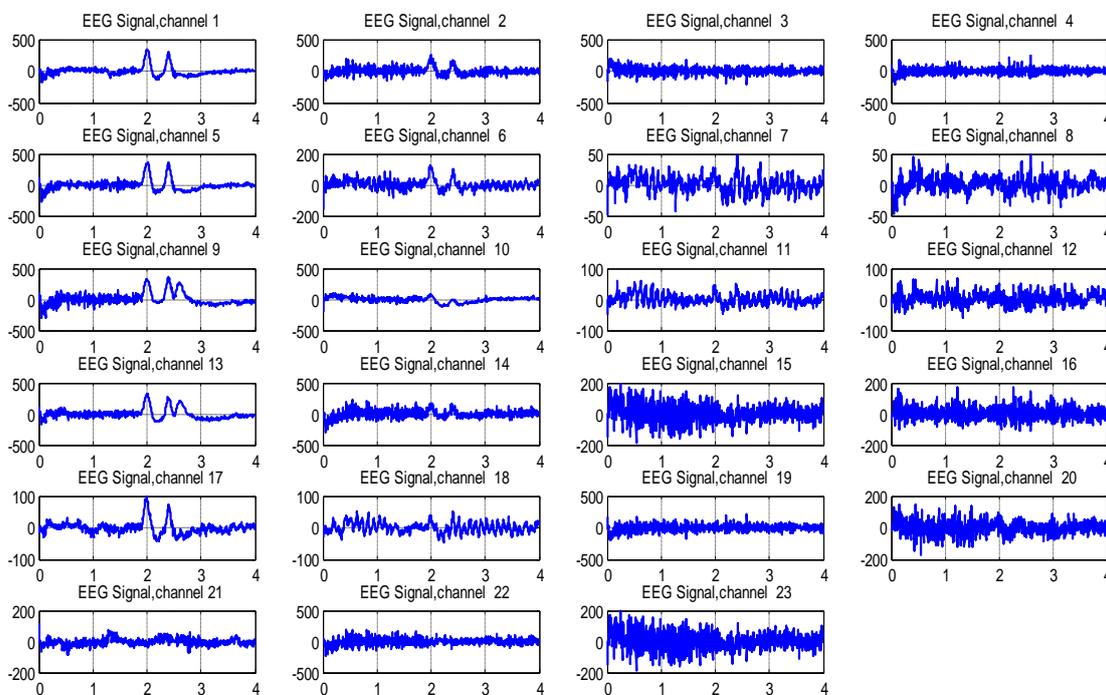


Figure 15 : Short portions of the 23 leads EEG record chbmit/chb03/chb03_26.edf [3]

The spreading of these leads signals with a gain of 32 results in signals shown in Fig. 16. The bandwidth of these leads signals widens and the length of each lead increases. Each lead signal now has 32768 samples. The multiplexing of the 23-leads spread EEG leads to signal in Fig. 17.

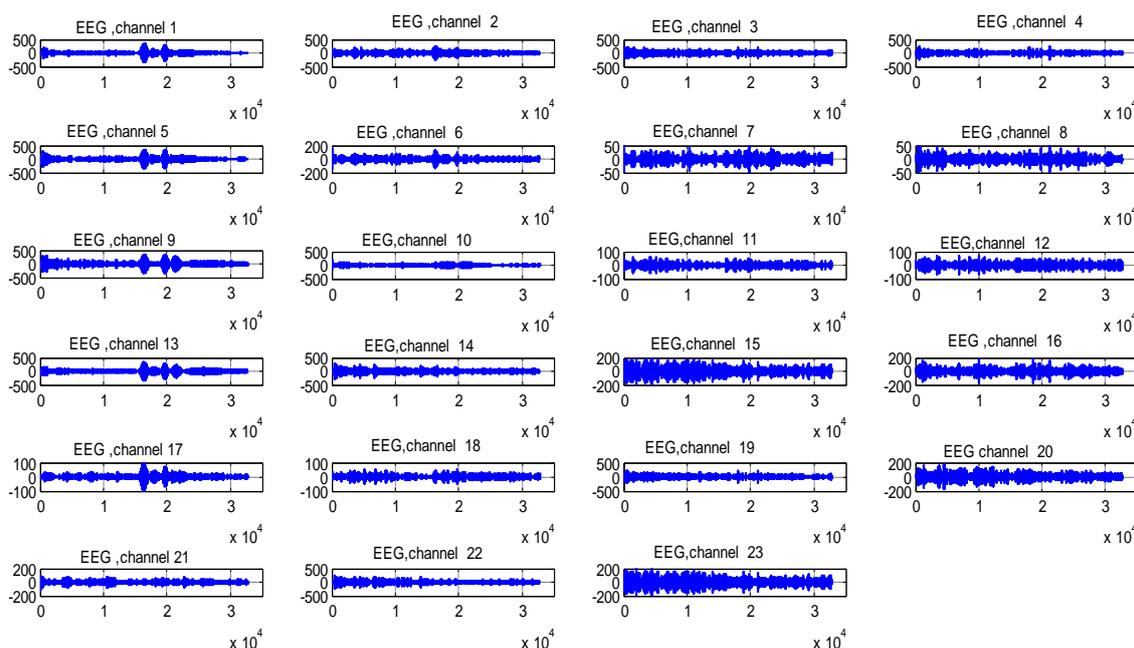


Fig. 16: The 23 channels EEG record chbmit/chb03/chb03_26.edf spread with a gain of 32

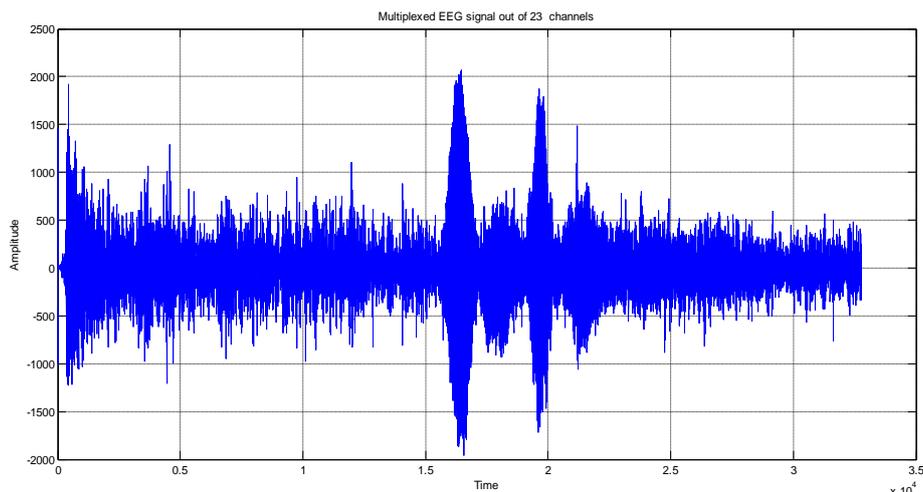


Figure 17: The composite spread EEG obtained after multiplexing signals in Fig. 17.

When the transmission is through a perfect channel and without noise, Fig. 18 shows the demultiplexed signal. For the 23-leads EEG, the integration must be extended over a period corresponding to the spreading factor that is 32. The received signal is identical to the transmitted signal as in the case of ECG signals. It can be seen in Fig. 19, where a shift of 200 μV is intentionally introduced to separate the received signal from the emitted signal as the tracings of the two signals were combined.

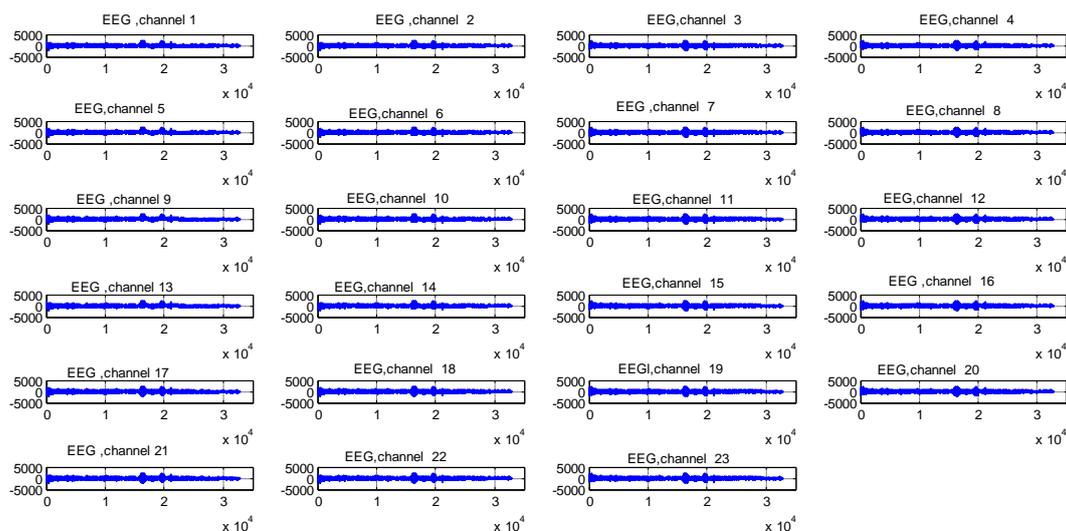


Fig. 18: The 23-leads spread demultiplexed EEG record chbmit/chb03/chb03_26.edf

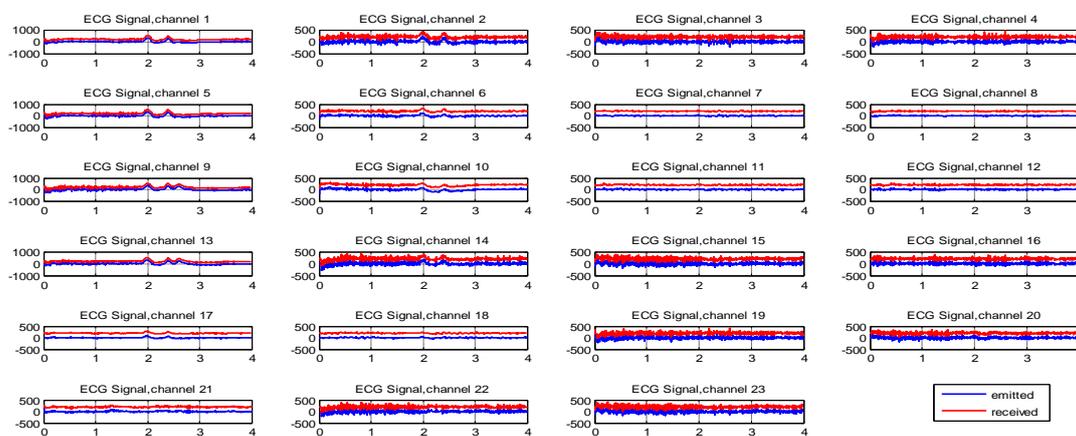


Figure 19: The emitted and the received 23-leads EEG.

Under the same conditions of disturbances by additional Gaussian white noise, but this time on the EEG record chbmit/chb03/chb03_27.edf of [3], we can see in Fig. 20, the superposition of the signals received at different leads with the transmitted signals. The SNR ratio is 25 dB, the leads signals received were filtered using an IIR Butterworth filter of order 7 for denoising.

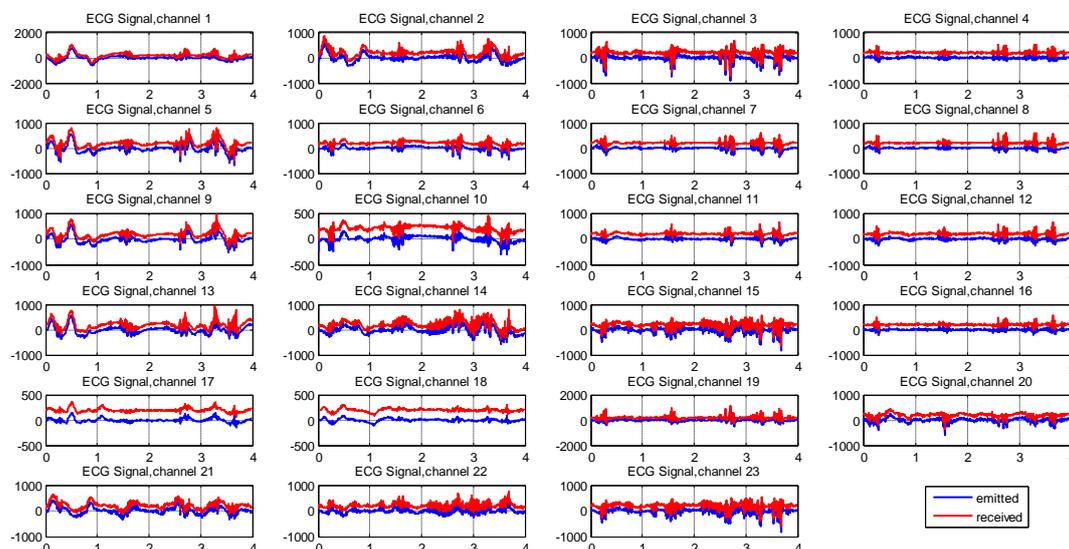


Figure 20: 23-leads emitted and received EEG where transmission is noisy

3.3 Discussion

It follows from the above results that the Walsh functions can be used to spread the multichannel physiological signals such as ECG and EEG. All spread leads signals can next be transformed into a single composite signal by DS-CDMA. The multiplexed signal is modulated, amplified and transmitted. Upon receipt, we can proceed to the inverse operations to restore multichannel biomedical signals. We believe we have achieved our goals. This technique reduces the risk of interference with other signals received while ensuring a high degree of confidentiality. The more the spreading factor is large, the greater is the tolerance to interference and to noise immunity. The spectral spreading increases the flow of transmissions, but the flow of useful information is unchanged after decoding. Also, the spreading does not change the signal strength, but the spectral power density is reduced. The transmission channel is used once for transmitting a composite signal which comprises all leads of a biophysiological signal. There is the advantage not only of reducing the cost and time of transmission, but also in minimizing the distortions and synchronization problems. The simulation results showed that this method is effective even for the transmission of signals heavily contaminated by noise. For comparison purpose, we implemented the transmission of multichannel biomedical signals using the FDMA (Frequency Division Multiple Access). It comes out from theatrical assessment using the PRD (Percent Root square Difference) that our system gives very good results compared to the FDMA. More results and discussion can be found in the *additional document*.

IV. Conclusion

We managed to model and simulate a specific system of transmission of biomedical multichannel signals. We used for this purpose, the CDMA technique where Walsh functions are codes. The results obtained are very encouraging. This paper is then a small contribution to the prospects for telemedicine.

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