Simulation of an optimized technique based on DS-CDMA for simultaneous transmission of multichannel biosignals

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Received: 23 May 2016 / Revised: 29 December 2016 / Accepted: 6 February 2017 / Published online: 28 February 2017
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Abstract Telemedicine is becoming increasingly, with applications in many areas of healthcare, such as home telecare of the elderly, diagnosis at a distance and robotic surgery. The simultaneous transmission of several leads of biomedical signals should be considered in telemedicine, given the many benefits it brings. Code division multiple access (CDMA) is a multiple access technique that enables users to transmit independent information simultaneously within the same bandwidth. The direct sequence CDMA (DS-CDMA) is a variant of the CDMA technique in which a pseudorandom sequence having a higher bandwidth than the information signal is used to modulate the information signal directly. Biomedical signals are confidential; thus, their transmission must be secured. In this paper we propose a protocol similar to DS-CDMA for the simultaneous transmission of all of the leads of some multichannel biomedical signals. We assigned orthogonal codes to different leads of a signal. The convolution of each lead with

the code gives a signal spread over a broad frequency band. All of the spread signals are then mixed to produce a single composite signal. This composite signal is frequency modulated, amplified and transmitted. At the reception, inverse functions to the previous are developed to perform demodulation, demultiplexing and extraction of the physiological signals transmitted. We used the discrete Walsh functions as codes. The results obtained are satisfactory, even in situations where the noise disturbances are significant.

Keywords Biomedical multichannel signals · CDMA transmission · Telemedicine · Walsh functions · ECG · EEG

1 Introduction

Telemedicine uses telecommunications technology to transmit patient medical information (images, reports, records, etc.) to a doctor who is at a distance. Telemedicine enables health care professionals to overcome difficulties in medicine, such as health coverage of isolated areas, and improve the quality of healthcare. In fact, telemedicine is the recommended solution to meet the new needs of medical services related to an aging population, lack of hospital staff, home care requests and the restructuring of the family model. Biomedical information is converted into signals before transmission. Telecare and telehealth systems are subject to many constraints such as low power [1, 2] and bandwidth. The transmission of a one-dimensional and single channel signal is commonly used.

The transmission of the electrocardiogram (ECG) through modern telecommunication systems has been an intensive research work in the recent years. Bluetooth,

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GSM, Internet and various combinations of modern digital telecommunications systems have already been proposed for the transmission of the ECG [3–12]. In most cases of wireless transmission, only a single lead of ECG signal is envisaged. The range of the transmission distance is limited to a few tens of meters. The security level of the information transmitted is weak and degradation of the signals is important. We did not find in the literature, any work on the simultaneous transmission of 12 leads ECGs. Even modern high-performance equipment for ambulatory “Holter” or telemonitoring electrocardiographs are limited to the transmission of a single ECG lead. However, for the diagnosis of certain cardiac pathologies, the physician must use at least 12 ECG leads. They analyze and examine all of the leads simultaneously, establishing correlations between them. Figure 1 demonstrates a record of 12 leads ECG signal taken from [13].

The clinical examination of the electroencephalogram (EEG) also requires that the doctor scrutinize several leads

of the signal at a time. In the early 1960s, during the first steps of medical telemetry through the transmission of biomedical information via the telephone line, the need to transmit several leads of the EEG arose [14]. These pioneering works aimed to transmit just two or three leads. A big step was taken in [15], where eight EEG leads were simultaneously transmitted over a telephone line using frequency division multiplex. With the evolution of the technology, some recent recording systems for biomedical signals are wireless [16]. For recording EEG signals in this case, the electrodes are positioned in a helmet, including preamplifiers and transmitters. The recorded signals are then instantly transmitted through radiofrequency waves to a central location for analysis and archiving [17–19]. These new facilities provide the ability to record the EEG of a mobile patient and in various emotional conditions. Generally, multichannel EEG is considered to be two-dimensional signal and processed like an image by the transmission systems [20].

Fig. 1 Example of 12 lead ECG signal [13]

Figure 2 demonstrates another complex biomedical signal from the Cyclic Alternating Pattern (CAP) database [13], including 3 EEG channels, 2 channels EOG, 2 EMG channels, respiration signals and ECG. The CAP is used to explore periodic EEG activity occurring during sleep and can be transmitted through telecommunication network. There is then a need to put up systems of simultaneous transmission of multiple leads biosignals for telemedicine applications; this justifies the topic of our work.

The problem of simultaneous transmission of several leads of biomedical signals can be considered similar to the multiplexing problem in telecommunication systems. One might naïvely consider a frequency division multiplexing that involves assigning a transmission channel to each lead. Currently, radio communication needs are enormous and resources, in terms of frequency bands available, are very limited. For these reasons, the principle of FDMA (Frequency Division Multiple Access) might not be suitable for the simultaneous transmission of several leads of bioelectric signals. One could also consider forwarding the leads signals, one after the other. The time division multiplex in which the

transmission of the leads signals in the ‘one after another’ method is also not advantageous because there is too much time consumed, and synchronization problems could arise.

We propose to encode multichannel signals, and then convert them into a single channel signal and transmit it once. This technique has the advantage of reducing the time of the transmission and therefore the cost. The other advantage is that it minimizes the distortions due to synchronization problems encountered in other techniques. In this paper, we simulate an optimized technique for the simultaneous transmission of multiple lead ECG and EEG signals, based on the principle of DS-CDMA (direct sequence CDMA). DS-CDMA uses an orthogonal pseudorandom code sequence to redistribute each lead signal over the entire bandwidth. The principle of CDMA is to carry out the convolution of each lead signal with a code in an initial step. In the second step, the spread signals are mixed to form a single composite signal. Various codes used for such purpose are binary functions derived from a family of orthogonal functions [21, 22]. We performed the encoding with Walsh functions [23]. After spreading and multiplexing, the composite signal was then

Fig. 2 Example of Cyclic Alternating Pattern (CAP) signal (record caps1pdb/ins1.edf) [13]

transmitted. The spectral spreading operation jams the signal such that it cannot be intercepted. The confidentiality of information is thus reinforced. At the receiver, the code sequences that served in the emission are also used for the extraction of each lead signal. The problem of synchronization is simplified and multichannel biomedical signals are transmitted and received with less distortion.

The next section is devoted to an overview of the Walsh functions and the principles of the CDMA. The modeling algorithms are explained in the third section. The fourth section is concerned with the presentation of the results and a discussion. A conclusion ends our work.

2 The orthogonal binary Walsh functions and CDMA

2.1 Walsh functions

The binary orthogonal Walsh functions are defined in the space of real numbers. These functions take only two values: +1 and −1. A Walsh function is characterized by position N or by sequence s . In the continuous domain, the rank N is the number of sign changes in the meantime interval $[-1/2, 1/2]$, while the sequence s is half of the average number of zeros per unit time and is expressed as zeros per second (zps or z/s). The analytical expression of a Walsh function of order N is given by (1). Curves for the first ten Walsh functions are shown in Fig. 3.

$$W(N, x) = \text{sgn} \left[\cos a_1 \left(x - \frac{\pi}{2} \right) \prod_{j=2}^{NB} \cos(a_j 2^{j-2} x) \right], \quad (1)$$

where a_j is the digits used for the binary representation of N , thus $N = \sum_{j=1}^{NB-1} a_j 2^{j-1}$, and NB is the integer part of $\log_2(N) + 1$, that is, $NB = E[\log_2(N) + 1]$.

The discrete Walsh functions $W_\gamma(m, n)$, are periodic functions. The period is $M = 2^\gamma$, where γ is the basis of the function. The orthogonality property of the discrete Walsh functions reflects the fact that the scalar product of any two rows or any two columns of the Walsh matrix is always zero (2).

$$\text{For all } m, n \in [0, 2^\gamma - 1], \sum_{i=0}^{2^\gamma-1} W(m, i) \cdot W(n, i) = 0 \quad (2) \\ \text{if } m \neq n.$$

2.2 DS-CDMA

The new generation of mobile communication systems primarily uses CDMA for multiple access [24]. The various types of CDMA techniques are direct sequence CDMA (DS-CDMA), frequency hopping CDMA (FH-CDMA), time hopping CDMA (TH-CDMA) and hybrid CDMA. We chose DS-CDMA because there are no bandwidth divisions while in the FH-CDMA; the reserved bandwidth for transmission is divided into sub-bands according to the codes assigned to users. The same problem arises with TH-CDMA that is transmitted short bursts. DS-CDMA is a technique where different users can communicate simultaneously in the same frequency band, and the distinction between users is performed via assigned codes known only by the sender and the receiver. This technique is based on the principle of spectrum spreading by orthogonal or pseudo-orthogonal codes [25, 26]. At the reception, the despreading operation will help to regenerate the baseband signal; other signals are perceived by the receiver as noise [26, 27].

We denote b_k as the signals to be transmitted at the symbol duration rate using some orthogonal codes $g_k(t)$, whose expressions are in the form of (3):

Fig. 3 Ten Walsh functions in the sequence order

$$g_k(t) = \sum_{m=0}^N c_{k,m} g(t - mT_c), \quad (3)$$

where $T_c = T/N$ denotes 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 or $\frac{1}{\sqrt{2}}(\pm 1 \pm i)$, and for a given user k , the set of coefficients $c_{k,l}$ is then the code.

$$\text{When } k \neq l, \sum_{m=0}^{N-1} c_{k,m} c_{l,m}^* = 0. \quad (4)$$

An important consequence follows:

$$\frac{1}{T} \int g_k(t - nT) g_l(t - n'T)^* dt = \frac{1}{N} \sum_{m=0}^{N-1} c_{k,m} c_{l,m}^* = 0 \text{ if } k \neq l \text{ or if } n \neq n'. \quad (5)$$

The signal obtained after multiplexing is expressed as (6):

$$s(t) = \sum_{k=1}^{NB} \left[\sum_{n \in \mathbb{Z}} b_{k,n} g_k(t - nT) \right], \quad (6)$$

where $b_{k,n}$ forms the sequence for the signal of the user k .

At the CDMA receiver, the complex envelope of the received signal in the case of a single-path channel is given by (7):

$$R(t) = Att. \frac{1}{\sqrt{T}} \sum_{k=1}^k \left[\sum_{n \in \mathbb{Z}} b_{k,n} g_k(t - nT) \right] + \xi(t), \quad (7)$$

where, Att is the attenuation of the signal when it passes through the channel and $\xi(t)$ represents the noise added to the transmitted signal. The demultiplexing of this signal uses the code $g_k(t)$ and the received signals are $b'_k(t)$ expressed by (8):

$$b'_k(t) = \frac{1}{\sqrt{T}} \int_{-\infty}^{+\infty} R(t) g_k(t - nT) dt = b_{k,n} + \xi_n. \quad (8)$$

The differences between the signals emitted $b_k(t)$ and the signals received $b'_k(t)$ depend on the added noise. Finally, despreading and filtering retrieve the information of each user.

3 Transmission modeling and algorithms for simulations

3.1 Modeling the DS-CDMA emission

The model of the transmitter comprises seven modules: the acquisition of multichannel signals, code generation and synchronization, spectral spreading, multiplexing, modulation and transmission. The model is shown in Fig. 4. The codes used are the rows of the Walsh matrix. Indeed, the orthogonality property of the binary Walsh functions enables us to use them as codes in CDMA. The order of the matrix is chosen according to the number of leads of the multichannel signal. The multiplexed signal is expressed by (9):

$$s(j) = \sum_{k=1}^K b_k(j) \cdot w_{k+1}, \quad (9)$$

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

The signals b_k are from the ECG or EEG leads. 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 . A code is then assigned to each

Fig. 4 Block diagram of a CDMA emitter used for the transmission of multichannel biosignals

segment for convolution. When a sample $d_{k,j}$ is spread with a code $w(i, n)$, it becomes a vector $de_{(k,j,i)}$ of length N such that:

$$de_{(k,j,i)}(n + (j - 1) \times 2^j) = d_{k,j} \times w(i, n). \quad (10)$$

The spread lead signal is a sequence of vectors obtained by varying j . We then obtain the same number of vectors as the number of leads but with wider band spectrum. We must ensure that the spread gains of various channels are identical 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 (11):

$$R(m) = \sum_{k=1}^{N_c} de_{(k,j,i)}(m), \quad (11)$$

where $m = 1, 2, \dots, P$, and N_c is the number of leads ($N_c = 15$ for ECG and $N_c = 23$ for EEG).

We used the built in frequency modulation syntax of Matlab. The last stage of the transmission is a power amplifier with adjustable gain for the management of the transmission distance.

3.2 Propagation model for wireless transmission

In radio communication, the signals that propagate through the atmosphere are affected by numerous distortions. The received signal includes the transmitted wave in the direct path and the contributions at the same frequency of the waves reflected and refracted by the environment. Recording and transmission of biosignals was performed in a hospital, at home and even in the ambulance, in the case of accident. The environment includes people (medical personnel, patients and patients' family), 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. The formulas in radio links are essentially empirical and based on the results of many measurements at various locations around the world [28–30].

3.3 Modeling of the reception units

Figure 5 demonstrates the blocks involved in the reconstitution of multiple leads 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 images of leads signals are extracted from the composite signal using the correlation of the received composite signal with the codes. When R_S is a segment of the received vector, the expression of the demultiplexed vector segment $R_{(ii,s)}$ is given by (12):

$$R_{(ii,s)} = R_S \cdot w(ii, n). \quad (12)$$

The orthogonality of the codes ensures that the interferences between the signals of the different leads are cancelled. The received signal is demultiplexed through convolution by the spreading codes. After demultiplexing, we obtained as many leads signals as in the emission stage but they are not unsread. Integration is next performed on a finite period equal to the symbol duration. This enables recovery of the initial narrow band signal. If the dispread signal contains noise that was added during the transmission, low-pass filtering could be performed.

Fig. 5 Block diagram of a CDMA biosignals receiver

3.4 The algorithms for simulation

3.4.1 Emission unit

Let $b(t)$ be the ECG/EEG record having N_c leads. The lead signals are denoted as $b_k(t)$, $k = 1, 2, 3, \dots, N_c$:

- Specify the number of samples to be transmitted for each lead;
- Generate the spreading codes $C_k(t)$. In this case, the length of $C_k(t)$ should be equal to the spreading factor SF ;
- Spread each lead signal $b_k(t)$ by convoluting it with the corresponding $C_k(t)$ to obtain a spread lead signal $b_{ks}(t)$;
- Sum all of the spread lead signals to obtain a single multiplexed signal $s(t)$;
- Modulate the multiplexed signal $s(t)$, amplify it and then transmit.

3.4.2 Reception unit

Let $R(t)$ be the received signal delivered by the channel:

- Amplify and demodulate the signal $R(t)$ to obtain $r(t)$;
- Generate the spreading codes, $C_k(t)$, identical to those used at the transmitter;
- Demultiplex the signal $r(t)$ by convoluting it with the spreading code $C_k(t)$. This operation produces N_c different signals $rd_k(t)$;
- Specify the period T_{int} for the integrator;
- Unspread each $rd_k(t)$ by integration. The unspread lead signals are named $ru_k(t)$;
- Filter each $ru_k(t)$ to eliminate the noise added during the transmission and recover the received lead signals $\tilde{b}_k(t)$;
- Evaluate the PRD between $b_k(t)$ and $\tilde{b}_k(t)$.

3.5 Performance evaluation

To appreciate the results, we performed a comparison between the emitted and received signals. We adjusted the gain of the receiver amplifier to compensate for the weakening due to transmission. We can then appreciate theoretically the error rate of transmission by calculating the PRD (percent root mean difference) of each lead signal, the RMSE (root mean square error) and the STD (standard deviation). The formulas for PRD, RMSE and STD are given by (13), (14) and (15), respectively.

$$PRD = 100 \times \sqrt{\frac{\sum_{i=1}^N (Sr_i - Se_i)^2}{\sum_{i=1}^N Se_i^2}}, \quad (13)$$

$$RMSE = \sqrt{\frac{\sum_{i=1}^N (Sr_i - Se_i)^2}{N}}, \quad (14)$$

where Se_i and Sr_i , are the samples of the emitted and received signals and N is the number of sample of the emitted or received signals.

$$STD = \frac{1}{N} \sqrt{\sum_{i=1}^N (Se_i - Sr_i)^2 - \left[\sum_{i=1}^N (Se_i - Sr_i) \right]^2}. \quad (15)$$

We calculated, for each ECG signal, the average PRD (MPRD) for the 15 leads and for each EEG signal the MPRD for the 23 leads using (16):

$$MPRD = \frac{1}{N_c} \sum_{k=1}^{N_c} PRD(k), \quad (16)$$

where N_c is the number of leads as described in (11); the average RMSE and STD were also calculated.

4 Results and discussion

4.1 Simulation of the simultaneous transmission of 15-lead ECG

We found in [13] 15-lead ECG records from PTB Diagnostic Database (ptbdb). Figure 6 shows 1024 sample extracts of the 15-lead ECG recording ptbdb/patient001/s0014lre. The sampling frequency is 1000 Hz, and the ADC resolution is 16 bits. We simulated the simultaneous transmission of these 15 leads.

The spreading operation enlarges the bandwidth of each lead signal and increases the length of the signal. Each spread lead was then made of 16,384 samples.

The composite multiplexed signal issued from the 15-lead spread signal is shown in Fig. 7. This signal is then frequency modulated, and the modulated signal is amplified before transmission over a single radio channel.

After demultiplexing, the 15 lead ECG signal still remains spread. When integrating each of the demultiplexed signals, we obtain the base band received signals. The received signals and the transmitted signals are identical if no noise was introduced into the processes. The PRD and the MPRD are thus 00.00%.

When the transmission occurs through a real channel, the received signal is weakened due to the complex propagation environment. The channel noise contaminates the signal very little; the information is contained in the argument of the carrier in the case of frequency modulation. There is thermal noise and shot noise of various electronic components. We brought all of this noise 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 example, we added Gaussian white noise to the spread composite signal before

Fig. 6 Extracts from ptbdb/patient001/s0014ire [13]

Fig. 7 Multiplexed composite signal issued from 15-lead ECG after spreading

modulation. Figure 8 demonstrates the results obtained with an SNR of 25 dB. A simple digital Butterworth filter of order 7 was used. Figure 8 enables us to appreciate the

results obtained after these operations. A DC value of 0.1 mV was added to the received signals to create an offset and detachment from the transmitted signals. The

Fig. 8 Emitted and received 15 lead ECG signal (ptbdb/patient001/s00141re) through noisy transmission system (SNR = 25 dB)

visual assessment does not realize some differences between the transmitted and received signals. The theoretical calculation gives a minimum PRD of 0.87% in the lead signal number 14, and the maximum PRD is 4.15% in lead signal number 5. The average PRD (MPRD) is 2.22% for the 15 leads signals. The minimum RMSE is 0.013 mV in leads 2, 10 and 15, and the maximum is 0.0149 mV in lead 4. The average RMSE is 0.0141 mV. The STD values are also negligible: 0.1×10^{-3} mV for the minimum and 0.63×10^{-3} mV for the maximum. The average STD over the patients is 0.35×10^{-3} mV. All of those values are near zero, meaning that the error between the received and the emitted signals is very low. The values for the 15 lead ECG signal are summarized in Table 1.

We conducted simulation tests using signals from a bank with 100 ECGs recorded from different patients. We varied

the SNR ratio from 20 to 85 dB during the simulations. Table 2 presents the PRDs, RMSE and STD obtained with ECG signal record ptbdb/patient034/s01091re at 35, 45, 55, 65 and 75 dB. According to Table 2, the values of PRD, RMSE and STD decrease when the SNR increases. The averages of PRD, RMSE and STD are 0.77%, 4.4×10^{-2} and 9.6×10^{-5} mV at 35 dB, respectively. At 75 dB, the averages of PRD, RMSE and STD are 0.01%, 2.1×10^{-4} and 3.9×10^{-6} mV, respectively, which are negligible compared to those at 35 dB. The results obtained on other ECG signals from that ECG bank are grouped in Fig. 9, where the averages of PRD (named MPRD) in patients depending on the variation of SNR are shown. When observing these curves, we see that for SNR values above 50 dB, the values of MPRD are always less than 0.5%, which confirms the high quality of this transmission

Table 1 PRD, RMSE and STD of received noisy 15 lead ECG signal (SNR = 25 dB)

ECG record ptbdb/patient001/s00141re—SNR = 25 dB								
	Lead1	Lead 2	Lead 3	Lead 4	Lead 5	Lead 6	Lead 7	Lead 8
PRD (%)	2.92	2.58	3.67	2.95	4.15	3.44	1.46	1.60
RMSE (mV)	1.4×10^{-2}	1.3×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.4×10^{-2}	1.3×10^{-2}
STD (mV)	4.1×10^{-4}	6.3×10^{-4}	3.7×10^{-4}	4.3×10^{-4}	2×10^{-4}	4.2×10^{-4}	3.7×10^{-4}	3.1×10^{-4}
	Lead 9	Lead 10	Lead 11	Lead 12	Lead 13	Lead 14	Lead 15	Average
PRD (%)	1.19	1.61	1.12	1.00	3.25	0.87	1.42	2.22
RMSE (mV)	1.4×10^{-2}	1.3×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.4×10^{-2}	1.3×10^{-2}	1.3×10^{-2}	1.4×10^{-2}
STD (mV)	2.5×10^{-4}	2.9×10^{-4}	4.2×10^{-4}	2.5×10^{-4}	1.6×10^{-4}	3.6×10^{-4}	4.1×10^{-4}	3.5×10^{-4}

Table 2 Values of PRD, RMSE and STD of ECG record ptbdb/patient034/s0109lre

ECG record ptbdb/patient034/s0109lre									
SNR (dB)	35			45			55		
Lead	PRD (%)	RMSE (mV)	STD (mV)	PRD (%)	RMSE (mV)	STD (mV)	PRD (%)	RMSE (mV)	STD (mV)
Lead 1	0.92	4.3×10^{-3}	1.1×10^{-4}	0.29	1.4×10^{-3}	6.8×10^{-5}	0.09	4.5×10^{-4}	4.1×10^{-5}
Lead 2	0.25	4.4×10^{-3}	5×10^{-5}	0.07	1.4×10^{-3}	3.8×10^{-5}	0.02	5.1×10^{-4}	1.5×10^{-5}
Lead 3	0.19	4.6×10^{-3}	1.3×10^{-4}	0.06	1.4×10^{-3}	4.6×10^{-5}	0.01	5.4×10^{-4}	1.2×10^{-5}
Lead4	0.66	4.4×10^{-3}	1×10^{-4}	0.21	1.4×10^{-3}	4.3×10^{-5}	0.06	4.5×10^{-4}	1.3×10^{-5}
Lead 5	0.33	4.2×10^{-3}	1.1×10^{-4}	0.1	1.4×10^{-3}	4.4×10^{-5}	0.03	4.9×10^{-4}	8.7×10^{-6}
Lead 6	0.22	4.3×10^{-3}	3×10^{-5}	0.07	1.4×10^{-3}	4.3×10^{-5}	0.02	5.3×10^{-4}	1.7×10^{-5}
Lead7	1.45	4.4×10^{-3}	1.4×10^{-4}	0.45	1.4×10^{-3}	4.3×10^{-5}	0.14	4.8×10^{-4}	2.7×10^{-5}
Lead8	0.87	4.4×10^{-3}	1×10^{-4}	0.27	1.4×10^{-3}	2.6×10^{-5}	0.08	4.9×10^{-4}	1.5×10^{-5}
Lead9	0.52	4.3×10^{-3}	1.4×10^{-4}	0.16	1.3×10^{-3}	4.5×10^{-5}	0.05	4.9×10^{-4}	1.6×10^{-5}
Lead $\times$ 10	1.06	4.5×10^{-3}	1×10^{-4}	0.33	1.4×10^{-3}	4×10^{-5}	0.1	5.1×10^{-4}	1.5×10^{-5}
Lead 11	0.73	4.4×10^{-3}	1.4×10^{-5}	0.23	1.4×10^{-3}	2.9×10^{-5}	0.07	5.3×10^{-4}	1.5×10^{-5}
Lead 12	0.8	4.5×10^{-3}	6.3×10^{-5}	0.25	1.4×10^{-3}	4.2×10^{-5}	0.07	5×10^{-4}	1.3×10^{-5}
Lead 13	2.67	4.3×10^{-3}	1.3×10^{-4}	0.84	1.4×10^{-3}	6.5×10^{-5}	0.26	4.4×10^{-4}	1.3×10^{-5}
Lead 14	0.28	4.2×10^{-3}	1.2×10^{-4}	0.08	1.3×10^{-3}	2.7×10^{-5}	0.02	4.5×10^{-4}	1×10^{-5}
Lead 15	0.55	4.4×10^{-3}	5.4×10^{-5}	0.17	1.4×10^{-3}	6.1×10^{-5}	0.05	4.5×10^{-4}	2.1×10^{-5}
Mean	0.77	4.4×10^{-3}	9.6×10^{-5}	0.24	1.4×10^{-3}	4.4×10^{-5}	0.07	4.9×10^{-4}	1.7×10^{-5}

SNR (dB)	65			75		
Lead	PRD(%)	RMSE (mV)	STD (mV)	PRD(%)	RMSE (mV)	STD (mV)
Lead 1	0.03	1.5×10^{-4}	2.3×10^{-6}	0.01	9.5×10^{-5}	2.8×10^{-6}
Lead 2	0	3×10^{-4}	8.9×10^{-6}	0	2.7×10^{-4}	5.1×10^{-6}
Lead 3	0	3.6×10^{-4}	5×10^{-6}	0	3.4×10^{-4}	4.3×10^{-6}
Lead4	0.02	1.7×10^{-4}	2.2×10^{-5}	0	1.1×10^{-4}	1.9×10^{-6}
Lead 5	0.01	2.5×10^{-4}	4.9×10^{-6}	0	2.1×10^{-4}	4.5×10^{-6}
Lead 6	0	3.3×10^{-4}	1.2×10^{-5}	0	3×10^{-4}	2.9×10^{-6}
Lead7	0.04	2.8×10^{-4}	8.1×10^{-6}	0.01	2.5×10^{-4}	4.4×10^{-6}
Lead8	0.03	2.9×10^{-4}	8.8×10^{-6}	0.01	2.5×10^{-4}	5.8×10^{-6}
Lead9	0.02	2.6×10^{-4}	6.8×10^{-6}	0.01	2.3×10^{-4}	1.8×10^{-6}
Lead $\times$ 10	0.03	3.1×10^{-4}	9.3×10^{-6}	0.01	2.7×10^{-4}	7.5×10^{-6}
Lead 11	0.02	3.2×10^{-4}	6.2×10^{-6}	0.01	3×10^{-4}	6×10^{-6}
Lead 12	0.02	3.1×10^{-4}	8.7×10^{-6}	0.01	2.8×10^{-4}	5.8×10^{-6}
Lead 13	0.08	1.4×10^{-4}	3.6×10^{-6}	0.03	5.9×10^{-5}	1.1×10^{-6}
Lead 14	0	1.5×10^{-4}	4.1×10^{-6}	0	6.5×10^{-5}	1.4×10^{-6}
Lead 15	0.01	1.6×10^{-4}	7.6×10^{-6}	0	8.9×10^{-5}	2.7×10^{-6}
Mean	0.02	2.5×10^{-4}	6.6×10^{-6}	0.01	2.1×10^{-4}	3.9×10^{-6}

system. To perform the evaluation, Table 3 presents the average of RMSE of different patients.

4.2 Simulation of the simultaneous transmission of 23-lead EEG

We also tested our algorithms on the EEG signals of the CHB-MIT Scalp EEG Database (chbmit) included in [13]. These EEG signals have 23 leads. We then used a Walsh matrix of the order 32 to generate the codes. We simulated

the simultaneous transmission of this EEG by a single CDMA signal. After spreading these lead signals with a gain of 32, the bandwidth of the signals widens and the length increases to 32,768 samples. The received signal is identical to the transmitted signal as in the case of ECG signals when no noise was added. Under the same conditions of disturbance, for example additional Gaussian white noise, we can see the superposition of the signals received at different leads with the transmitted signals in Fig. 10. The signals in Fig. 10 are excerpts from the EEG record

Fig. 9 Average MPRD in patients of ptbdb from [13] as functions of SNR

Table 3 The average of RMSE of different ECG patients in data base [13]

SNR	20	25	30	35	40	45	50
patient001/s0016lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient002/s0015lre	2.5×10^{-2}	1.4×10^{-2}	8.0×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient003/s0017lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient004/s0020are	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient004/s0020bre	2.5×10^{-2}	1.4×10^{-2}	8.0×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient005/s0021are	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient005/s0021bre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient005/s0025lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient005/s0031lre	2.5×10^{-2}	1.4×10^{-2}	8.0×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient005/s0101lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient006/s0022lre	2.5×10^{-2}	1.4×10^{-2}	8.0×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient006/s0027lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient006/s0064lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient007/s0026lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient007/s0029lre	2.5×10^{-2}	1.4×10^{-2}	8.0×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient007/s0038lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient007/s0078lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.1×10^{-4}
patient008/s0028lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient008/s0037lre	2.5×10^{-2}	1.4×10^{-2}	8.0×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient008/s0068lre	2.5×10^{-2}	1.4×10^{-2}	8.0×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient009/s0035_re	2.5×10^{-2}	1.4×10^{-2}	8.0×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient010/s0036lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient010/s0042lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient010/s0061lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient011/s0039lre	2.5×10^{-2}	1.4×10^{-2}	8.0×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient011/s0044lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient011/s0049lre	2.5×10^{-2}	1.4×10^{-2}	8.0×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient011/s0067lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}

Table 3 continued

SNR	20	25	30	35	40	45	50
patient012/s0043lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.2×10^{-4}
patient012/s0050lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient013/s0045lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient013/s0051lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient013/s0072lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.1×10^{-4}
patient014/s0046lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient014/s0056lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.5×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
patient014/s0071lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	7.9×10^{-4}
patient015/s0047lre	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}	2.5×10^{-3}	1.4×10^{-3}	8.0×10^{-4}
SNR	55	60	65	70	75	80	85
patient001/s0016lre	4.6×10^{-4}	2.6×10^{-4}	1.6×10^{-4}	1.0×10^{-4}	8.1×10^{-5}	7.2×10^{-5}	6.9×10^{-5}
patient002/s0015lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	8.8×10^{-5}	6.0×10^{-5}	4.6×10^{-5}	4.1×10^{-5}
patient003/s0017lre	4.5×10^{-4}	2.6×10^{-4}	1.5×10^{-4}	9.6×10^{-5}	6.9×10^{-5}	5.8×10^{-5}	5.4×10^{-5}
patient004/s0020are	4.5×10^{-4}	2.6×10^{-4}	1.5×10^{-4}	9.0×10^{-5}	6.2×10^{-5}	4.9×10^{-5}	4.5×10^{-5}
patient004/s0020bre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	8.9×10^{-5}	6.0×10^{-5}	4.7×10^{-5}	4.2×10^{-5}
patient005/s0021are	4.5×10^{-4}	2.6×10^{-4}	1.6×10^{-4}	1.0×10^{-4}	8.0×10^{-5}	7.0×10^{-5}	6.6×10^{-5}
patient005/s0021bre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	9.0×10^{-5}	6.0×10^{-5}	4.8×10^{-5}	4.3×10^{-5}
patient005/s0025lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	8.8×10^{-5}	5.9×10^{-5}	4.5×10^{-5}	4.0×10^{-5}
patient005/s0031lre	4.5×10^{-4}	2.6×10^{-4}	1.6×10^{-4}	1.1×10^{-4}	8.1×10^{-5}	7.0×10^{-5}	6.7×10^{-5}
patient005/s0 $\times$ 101lre	4.5×10^{-4}	2.5×10^{-4}	1.4×10^{-4}	8.4×10^{-5}	5.4×10^{-5}	3.9×10^{-5}	3.3×10^{-5}
patient006/s0022lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	8.8×10^{-5}	5.9×10^{-5}	4.6×10^{-5}	4.0×10^{-5}
patient006/s0027lre	4.5×10^{-4}	2.6×10^{-4}	1.5×10^{-4}	9.7×10^{-5}	7.0×10^{-5}	5.8×10^{-5}	5.4×10^{-5}
patient006/s0064lre	4.4×10^{-4}	2.6×10^{-4}	1.5×10^{-4}	9.3×10^{-5}	6.4×10^{-5}	5.2×10^{-5}	4.8×10^{-5}
patient007/s0026lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	8.9×10^{-5}	5.9×10^{-5}	4.6×10^{-5}	4.1×10^{-5}
patient007/s0029lre	4.5×10^{-4}	2.7×10^{-4}	1.7×10^{-4}	1.1×10^{-4}	9.4×10^{-5}	8.5×10^{-5}	8.3×10^{-5}
patient007/s0038lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	8.6×10^{-5}	5.5×10^{-5}	4.0×10^{-5}	3.5×10^{-5}
patient007/s0078lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	8.6×10^{-5}	5.6×10^{-5}	4.3×10^{-5}	3.7×10^{-5}
patient008/s0028lre	4.5×10^{-4}	2.7×10^{-4}	1.7×10^{-4}	1.2×10^{-4}	9.7×10^{-5}	8.9×10^{-5}	8.6×10^{-5}
patient008/s0037lre	4.5×10^{-4}	2.6×10^{-4}	1.5×10^{-4}	8.9×10^{-5}	6.1×10^{-5}	4.7×10^{-5}	4.2×10^{-5}
patient008/s0068lre	4.5×10^{-4}	2.6×10^{-4}	1.5×10^{-4}	9.6×10^{-5}	7.1×10^{-5}	5.9×10^{-5}	5.5×10^{-5}
patient009/s0035_re	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	9.1×10^{-5}	6.3×10^{-5}	5.1×10^{-5}	4.6×10^{-5}
patient0 $\times$ 10/s0036lre	4.6×10^{-4}	2.6×10^{-4}	1.6×10^{-4}	1.1×10^{-4}	8.5×10^{-5}	7.5×10^{-5}	7.1×10^{-5}
patient0 $\times$ 10/s0042lre	4.5×10^{-4}	2.6×10^{-4}	1.6×10^{-4}	1.1×10^{-4}	8.5×10^{-5}	7.4×10^{-5}	7.0×10^{-5}
patient0 $\times$ 10/s0061lre	4.7×10^{-4}	2.9×10^{-4}	1.9×10^{-4}	1.4×10^{-4}	1.2×10^{-4}	1.1×10^{-4}	1.1×10^{-4}
patient011/s0039lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	9.4×10^{-5}	6.6×10^{-5}	5.4×10^{-5}	5.0×10^{-5}
patient011/s0044lre	4.4×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	9.2×10^{-5}	6.3×10^{-5}	5.1×10^{-5}	4.6×10^{-5}
patient011/s0049lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	9.0×10^{-5}	6.1×10^{-5}	4.9×10^{-5}	4.4×10^{-5}
patient011/s0067lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	8.7×10^{-5}	5.7×10^{-5}	4.3×10^{-5}	3.7×10^{-5}
patient012/s0043lre	4.8×10^{-4}	3.0×10^{-4}	2.2×10^{-4}	1.8×10^{-4}	1.7×10^{-4}	1.6×10^{-4}	1.6×10^{-4}
patient012/s0050lre	4.6×10^{-4}	2.7×10^{-4}	1.7×10^{-4}	1.3×10^{-4}	1.1×10^{-4}	9.7×10^{-5}	9.4×10^{-5}
patient013/s0045lre	4.4×10^{-4}	2.5×10^{-4}	1.4×10^{-4}	8.5×10^{-5}	5.5×10^{-5}	4.0×10^{-5}	3.4×10^{-5}
patient013/s0051lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	9.2×10^{-5}	6.5×10^{-5}	5.4×10^{-5}	4.9×10^{-5}
patient013/s0072lre	4.7×10^{-4}	2.8×10^{-4}	1.9×10^{-4}	1.4×10^{-4}	1.2×10^{-4}	1.2×10^{-4}	1.1×10^{-4}
patient014/s0046lre	4.5×10^{-4}	2.5×10^{-4}	1.5×10^{-4}	8.9×10^{-5}	5.8×10^{-5}	4.6×10^{-5}	4.0×10^{-5}
patient014/s0056lre	4.6×10^{-4}	2.6×10^{-4}	1.6×10^{-4}	1.1×10^{-4}	8.4×10^{-5}	7.5×10^{-5}	7.2×10^{-5}
patient014/s0071lre	4.5×10^{-4}	2.6×10^{-4}	1.5×10^{-4}	9.9×10^{-5}	7.2×10^{-5}	6.1×10^{-5}	5.7×10^{-5}
patient015/s0047lre	4.6×10^{-4}	2.7×10^{-4}	1.8×10^{-4}	1.3×10^{-4}	1.1×10^{-4}	1.0×10^{-4}	1.0×10^{-4}

Fig. 10 23-lead emitted and received EEG where transmission was noisy (SNR = 25 dB)

chbmit/chb03/chb03_27.edf. The sampling frequency of that signal is 256 Hz and the ADC resolution is 11 bits. The SNR ratio is 25 dB; the leads signals received were filtered using an infinite impulse response (IIR) Butterworth filter of order 7. We obtained an MPRD of 7.07%.

We present the values of PRD, RMSE and STD at different leads of the EEG record chbmit/chb03/chb03_22.edf in Table 4. It appears that for the SNR values of 55 dB, the average PRDs, RMSE and STD are 0.17%, 2.38×10^{-2} and 5.30×10^{-4} mV, respectively. Those values decrease when the SNR increases. The results obtained after the simulation using many other EEG signals from [13] are similar to those in Fig. 9. Table 5 presents the average of STD from different patients.

4.3 Comparisons between DS-CDMA and FDMA results

We compared the DS-CDMA transmission technology and FDMA technology in terms of performance in the presence of noise when transmitting multi-lead biomedical signals. Two modulation types (namely, Amplitude Modulation [FDMAam] and Frequency Modulation [FDMAfm]) were used for the FDMA technique. Tables 6 and 7 show PRD values obtained for a signal to noise ratio (SNR) ranging from 20 to 85 dB. In the case of ECG signals, Table 6

demonstrates that for an SNR of 40 dB, the minimum value of the PRD in DS-CDMA is 0.41%, obtained with the patient signal patient030/s0099lre while in FDMAam the minimum value is 5.69%, obtained with the patient signal patient031/s0127lre. In the case of FDMAfm, the minimum value of the PRD is 13.88% obtained with the patient signal patient030/s0099lre. Similarly, the maximum values of PRD are 1.7% in DS-CDMA obtained from the patient's signal patient032/s0106lre, while the maximum PRD values are 8.73% and 40.74%, respectively, for FDMAam and FDMAfm. In general, regardless of the signal and for a given level of signal to noise ratio, the DS-CDMA multiplexing always produces the lowest values of PRD compared with those obtained in FDMA. For example, at an SNR of 50 dB, the PRD obtained on the patient's ECG signal patient030/s0099lre are 0.13% in DS-CDMA, 5.66% in FDMAam and 13.84% in FDMAfm. The results presented in Table 7 confirm the above observations in the case of EEG signals.

4.4 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 lead signals can next be transformed into a single composite signal by DS-CDMA. The multiplexed signal is modulated, amplified

Table 4 The values of PRD, RMSE and STD at different leads of the EEG record chbmit/chb03/chb03_22.edf

SNR (dB)	35			45			55		
Lead	PRD (%)	RMSE (mV)	STD (mV)	PRD (%)	RMSE (mV)	STD (mV)	PRD (%)	RMSE (mV)	STD (mV)
Lead 1	1.92	2.1×10^{-1}	6.2×10^{-3}	0.6	7×10^{-2}	1.9×10^{-3}	0.19	2.4×10^{-2}	7.5×10^{-4}
Lead 2	1.3	2.1×10^{-1}	5.9×10^{-3}	0.41	7×10^{-2}	2.2×10^{-3}	0.13	2.4×10^{-2}	5.5×10^{-4}
Lead 3	1.74	2.2×10^{-1}	6.8×10^{-3}	0.54	7.1×10^{-2}	2×10^{-3}	0.17	2.1×10^{-2}	6.5×10^{-4}
Lead4	2.04	2.2×10^{-1}	6.5×10^{-3}	0.64	7×10^{-2}	2.1×10^{-3}	0.21	2.2×10^{-2}	5.8×10^{-4}
Lead 5	1.13	2.2×10^{-1}	5.6×10^{-3}	0.35	7×10^{-2}	3.1×10^{-3}	0.11	2.5×10^{-2}	7.9×10^{-4}
Lead 6	1.44	2.3×10^{-1}	8.6×10^{-3}	0.45	7.5×10^{-2}	1.3×10^{-3}	0.14	2.4×10^{-2}	5.8×10^{-4}
Lead7	1.9	2.1×10^{-1}	6.7×10^{-3}	0.62	7.3×10^{-2}	2.9×10^{-4}	0.19	2.2×10^{-2}	6.6×10^{-4}
Lead8	2.26	2.1×10^{-1}	6.5×10^{-3}	0.72	7.2×10^{-2}	1.6×10^{-3}	0.23	2.2×10^{-2}	1×10^{-3}
Lead9	1.14	2.1×10^{-1}	6.7×10^{-3}	0.36	7.1×10^{-2}	1.4×10^{-3}	0.12	2.4×10^{-2}	3.3×10^{-4}
Lead $\times$ 10	1.3	2.3×10^{-1}	6.7×10^{-3}	0.41	7.1×10^{-2}	1.6×10^{-3}	0.14	2.4×10^{-2}	7×10^{-4}
Lead 11	1.39	2.1×10^{-1}	6.7×10^{-3}	0.44	7.2×10^{-2}	2.1×10^{-3}	0.15	2.4×10^{-2}	1.4×10^{-4}
Lead 12	1.59	2.1×10^{-1}	7.1×10^{-3}	0.49	7×10^{-2}	2.7×10^{-3}	0.16	2.3×10^{-2}	5.2×10^{-5}
Lead 13	1.95	2.2×10^{-1}	5.4×10^{-3}	0.61	7.2×10^{-2}	2.2×10^{-3}	0.19	2.3×10^{-2}	6.7×10^{-4}
Lead 14	2.14	2.2×10^{-1}	6.7×10^{-3}	0.68	7.3×10^{-2}	1.9×10^{-3}	0.22	2.3×10^{-2}	5.9×10^{-4}
Lead 15	2.05	2.3×10^{-1}	7.2×10^{-3}	0.63	7×10^{-2}	9.3×10^{-4}	0.2	2.2×10^{-2}	5.6×10^{-4}
Lead 16	2.03	2.2×10^{-1}	5.8×10^{-3}	0.64	7.1×10^{-2}	2.1×10^{-3}	0.21	2.2×10^{-2}	7.9×10^{-4}
Lead 17	0.99	2.2×10^{-1}	6.2×10^{-3}	0.31	7.2×10^{-2}	6.6×10^{-3}	0.1	2.6×10^{-2}	2.1×10^{-4}
Lead 18	1.12	2.1×10^{-1}	5.8×10^{-3}	0.35	7.3×10^{-2}	2.5×10^{-3}	0.11	2.4×10^{-2}	4.3×10^{-4}
Lead 19	1.73	2.1×10^{-1}	8.6×10^{-3}	0.54	7×10^{-2}	2.2×10^{-3}	0.17	2.2×10^{-2}	4.2×10^{-4}
Lead 20	1.48	2.2×10^{-1}	6.8×10^{-3}	0.47	7.1×10^{-2}	1.6×10^{-3}	0.16	2.4×10^{-2}	4.9×10^{-4}
Lead 21	1.24	2.2×10^{-1}	4.8×10^{-3}	0.39	7.2×10^{-2}	1.7×10^{-3}	0.12	2.2×10^{-2}	6.9×10^{-5}
Lead 22	2.01	2.3×10^{-1}	8.7×10^{-3}	0.65	7.1×10^{-2}	3.4×10^{-3}	0.21	2.4×10^{-2}	7.4×10^{-4}
Lead 23	2.02	2.2×10^{-1}	5×10^{-3}	0.65	7.2×10^{-2}	3.2×10^{-3}	0.2	2.3×10^{-2}	2.8×10^{-4}
Mean	1.65	2.2×10^{-1}	6.6×10^{-3}	0.52	7.1×10^{-2}	2.2×10^{-3}	0.17	2.3×10^{-2}	5.3×10^{-4}

SNR (dB)	65			75		
Lead	PRD (%)	RMSE (mV)	STD (mV)	PRD (%)	RMSE (mV)	STD (mV)
Lead 1	0.07	8.8×10^{-3}	7.9×10^{-5}	0.04	5.3×10^{-3}	6.9×10^{-5}
Lead 2	0.05	1.1×10^{-2}	7.6×10^{-5}	0.03	9.7×10^{-3}	3×10^{-4}
Lead 3	0.06	8×10^{-3}	1×10^{-4}	0.03	4.3×10^{-3}	1.3×10^{-4}
Lead4	0.08	8.3×10^{-3}	2.6×10^{-4}	0.05	5.4×10^{-3}	1.6×10^{-4}
Lead 5	0.05	1.3×10^{-2}	3.8×10^{-4}	0.04	1.1×10^{-2}	3.5×10^{-4}
Lead 6	0.06	1×10^{-2}	3.1×10^{-4}	0.04	8.2×10^{-3}	2.4×10^{-4}
Lead7	0.07	9.6×10^{-3}	1.7×10^{-4}	0.04	7.2×10^{-3}	2.2×10^{-4}
Lead8	0.08	8.8×10^{-3}	1.7×10^{-4}	0.05	5.7×10^{-3}	1.7×10^{-4}
Lead9	0.05	1.1×10^{-2}	1.9×10^{-4}	0.03	9.6×10^{-3}	2.9×10^{-4}
Lead $\times$ 10	0.08	1.3×10^{-2}	4.2×10^{-4}	0.07	1.1×10^{-2}	3.6×10^{-4}
Lead 11	0.08	1.3×10^{-2}	4.1×10^{-4}	0.07	1.1×10^{-2}	3.5×10^{-4}
Lead 12	0.06	9.9×10^{-3}	2.7×10^{-4}	0.04	7.2×10^{-3}	2.2×10^{-4}
Lead 13	0.07	9.4×10^{-3}	2.9×10^{-4}	0.05	7.1×10^{-3}	2.1×10^{-4}
Lead 14	0.07	8.5×10^{-3}	2.3×10^{-4}	0.04	4.7×10^{-3}	1.4×10^{-4}
Lead 15	0.07	8.5×10^{-3}	2.5×10^{-4}	0.04	5.3×10^{-3}	1.6×10^{-4}
Lead 16	0.08	9.3×10^{-3}	2.2×10^{-4}	0.06	6.2×10^{-3}	1.9×10^{-4}
Lead 17	0.04	1.3×10^{-2}	3.4×10^{-4}	0.03	1.2×10^{-2}	3.8×10^{-4}
Lead 18	0.05	1.2×10^{-2}	2.7×10^{-4}	0.03	1×10^{-2}	3.4×10^{-4}
Lead 19	0.06	7.8×10^{-3}	2.4×10^{-4}	0.03	4.4×10^{-3}	1.3×10^{-4}
Lead 20	0.07	1×10^{-2}	3.5×10^{-4}	0.06	9.1×10^{-3}	2.8×10^{-4}

Table 4 continued

SNR (dB)	65			75		
Lead	PRD (%)	RMSE (mV)	STD (mV)	PRD (%)	RMSE (mV)	STD (mV)
Lead 21	0.05	8.9×10^{-3}	1.7×10^{-4}	0.03	5.8×10^{-3}	1.7×10^{-4}
Lead 22	0.1	1×10^{-2}	3.3×10^{-4}	0.08	8.1×10^{-3}	2.5×10^{-4}
Lead 23	0.07	8.7×10^{-3}	7.7×10^{-5}	0.04	5×10^{-3}	1.4×10^{-4}
Mean	0.07	1×10^{-2}	2.4×10^{-4}	0.04	7.6×10^{-3}	2.3×10^{-4}

Table 5 The average of STD from different patients in data base [13]

SNR (dB)	20	25	30	35	40	45	50
chb01_01.edf	7.2×10^{-2}	3.9×10^{-2}	2.1×10^{-2}	1.1×10^{-2}	6.8×10^{-3}	4.4×10^{-3}	0.23×10^{-3}
chb01_02.edf	4.4×10^{-2}	2.9×10^{-2}	1.9×10^{-2}	8.9×10^{-3}	5.5×10^{-3}	2.4×10^{-3}	1.5×10^{-3}
chb01_03.edf	7×10^{-2}	4.6×10^{-2}	2.6×10^{-2}	1.2×10^{-2}	7.7×10^{-3}	3.9×10^{-3}	2.6×10^{-3}
chb01_04.edf	7.9×10^{-2}	4.4×10^{-2}	2×10^{-2}	1.4×10^{-2}	7.6×10^{-3}	3.7×10^{-3}	2.2×10^{-3}
chb01_05.edf	5.9×10^{-2}	3.1×10^{-2}	1.6×10^{-2}	9.4×10^{-3}	4.6×10^{-3}	3.1×10^{-3}	1.7×10^{-3}
chb01_06.edf	9.2×10^{-2}	5.4×10^{-2}	2.4×10^{-2}	1.3×10^{-2}	8.1×10^{-3}	5.5×10^{-3}	3×10^{-3}
chb01_07.edf	8.8×10^{-2}	4.7×10^{-2}	3×10^{-2}	1.8×10^{-2}	9.1×10^{-3}	5.1×10^{-3}	3.2×10^{-3}
chb01_08.edf	6.2×10^{-2}	3×10^{-2}	1.9×10^{-2}	1.2×10^{-2}	5.7×10^{-3}	3.5×10^{-3}	2×10^{-3}
chb01_09.edf	4.4×10^{-2}	2.8×10^{-2}	1.3×10^{-2}	8.3×10^{-3}	4.3×10^{-3}	2.3×10^{-3}	1.6×10^{-3}
chb01_10.edf	5.13	3.17	1.7×10^{-2}	9.2×10^{-3}	5.5×10^{-3}	3.3×10^{-3}	1.7×10^{-3}
chb01_11.edf	4.8×10^{-2}	2.7×10^{-2}	1.6×10^{-2}	1×10^{-2}	5.3×10^{-3}	2.2×10^{-3}	1.9×10^{-3}
chb01_12.edf	1.6×10^{-1}	1×10^{-1}	5.7×10^{-2}	3×10^{-2}	1.6×10^{-2}	8.9×10^{-3}	4.5×10^{-3}
chb01_13.edf	8.9×10^{-2}	6×10^{-2}	2.7×10^{-2}	1.5×10^{-2}	9.4×10^{-3}	4.8×10^{-3}	2.4×10^{-3}
chb01_14.edf	1×10^{-1}	5×10^{-2}	3.3×10^{-2}	2.1×10^{-2}	1×10^{-2}	4.9×10^{-3}	3×10^{-3}
chb01_15.edf	1.4×10^{-1}	7.9×10^{-2}	4×10^{-2}	2.5×10^{-2}	1.4×10^{-2}	7.9×10^{-3}	4.4×10^{-3}
chb01_16.edf	6.4×10^{-2}	4.1×10^{-2}	2×10^{-2}	1.2×10^{-2}	6.9×10^{-3}	3.7×10^{-3}	2.1×10^{-3}
chb01_17.edf	1.5×10^{-2}	8.9×10^{-2}	4.7×10^{-2}	2.3×10^{-2}	1.4×10^{-2}	8.4×10^{-3}	4.5×10^{-3}
chb01_18.edf	6.0×10^{-2}	3.2×10^{-2}	1.7×10^{-2}	9.3×10^{-3}	5.1×10^{-3}	2.8×10^{-3}	1.2×10^{-3}
chb01_19.edf	8.4×10^{-2}	5.1×10^{-2}	3.1×10^{-2}	1.4×10^{-2}	8×10^{-3}	5.4×10^{-3}	2.5×10^{-3}
chb01_20.edf	5.8×10^{-2}	3.1×10^{-2}	1.8×10^{-2}	9.3×10^{-3}	4.5×10^{-3}	2.8×10^{-3}	1.7×10^{-3}
chb01_21.edf	9.7×10^{-2}	5×10^{-2}	2.6×10^{-2}	1.7×10^{-2}	9.5×10^{-3}	4.4×10^{-3}	2.4×10^{-3}
chb01_22.edf	1.6×10^{-1}	8.2×10^{-2}	4.1×10^{-2}	2.8×10^{-2}	1.3×10^{-2}	8.3×10^{-3}	5.2×10^{-3}
chb01_23.edf	1.1×10^{-1}	5×10^{-2}	3.3×10^{-2}	2.1×10^{-2}	9.6×10^{-3}	6×10^{-3}	3.2×10^{-3}
chb01_24.edf	1.8×10^{-1}	7×10^{-2}	4.7×10^{-2}	2.6×10^{-2}	1.4×10^{-2}	8×10^{-3}	4.7×10^{-3}
chb01_25.edf	8.5×10^{-2}	5.6×10^{-2}	3.1×10^{-2}	1.8×10^{-2}	1×10^{-2}	5.9×10^{-3}	3.1×10^{-3}
chb01_26.edf	2.1×10^{-1}	1.4×10^{-1}	5.8×10^{-2}	3×10^{-2}	1.8×10^{-2}	1.1×10^{-2}	6.2×10^{-3}
chb01_27.edf	9×10^{-2}	5.4×10^{-2}	2.7×10^{-2}	2×10^{-2}	9.2×10^{-3}	4.7×10^{-3}	3.2×10^{-3}
chb01_29.edf	8.1×10^{-1}	4.1×10^{-1}	2.5×10^{-1}	1.1×10^{-1}	8×10^{-2}	4.4×10^{-2}	2.7×10^{-2}
chb01_30.edf	1.3×10^{-1}	7.6×10^{-2}	3.9×10^{-2}	2×10^{-2}	1.3×10^{-2}	7.8×10^{-3}	3.9×10^{-3}
chb01_31.edf	6.7×10^{-2}	3.4×10^{-2}	2.2×10^{-2}	1.3×10^{-2}	7×10^{-3}	4.7×10^{-3}	2.4×10^{-3}
chb01_32.edf	1.1×10^{-1}	5.3×10^{-2}	3.2×10^{-2}	2.1×10^{-2}	1.2×10^{-2}	6×10^{-3}	3.2×10^{-3}
chb01_33.edf	1.3×10^{-1}	6.7×10^{-2}	4×10^{-2}	2.2×10^{-2}	1.3×10^{-2}	9.1×10^{-3}	5×10^{-3}
chb01_34.edf	1.3×10^{-1}	8.5×10^{-2}	4×10^{-2}	2×10^{-2}	1.2×10^{-2}	7.2×10^{-3}	4.1×10^{-3}
chb01_36.edf	7.5×10^{-2}	4.4×10^{-2}	2.6×10^{-2}	1.5×10^{-2}	8.2×10^{-3}	4×10^{-3}	2.7×10^{-3}
chb01_37.edf	1.1×10^{-1}	6.2×10^{-2}	2.9×10^{-2}	1.9×10^{-2}	1×10^{-2}	6×10^{-3}	3×10^{-3}
chb01_38.edf	6.7×10^{-2}	4.5×10^{-2}	2.2×10^{-2}	1.3×10^{-2}	7.7×10^{-3}	4.1×10^{-3}	2.7×10^{-3}
chb01_39.edf	7.6×10^{-2}	4.9×10^{-2}	2.8×10^{-2}	1.4×10^{-2}	9.2×10^{-3}	4.8×10^{-3}	2.2×10^{-3}

Table 5 continued

SNR (dB)	55	60	65	70	75	80	85
chb01_01.edf	1.3×10^{-3}	1.1×10^{-3}	7×10^{-4}	7×10^{-4}	07×10^{-4}	7×10^{-4}	7×10^{-4}
chb01_02.edf	8×10^{-4}	6×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}
chb01_03.edf	1.4×10^{-3}	8×10^{-4}	5×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}
chb01_04.edf	1.4×10^{-3}	7×10^{-4}	6×10^{-4}	5×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}
chb01_05.edf	9×10^{-4}	6×10^{-4}	4×10^{-4}	3×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}
chb01_06.edf	1.5×10^{-3}	9×10^{-4}	6×10^{-4}	4×10^{-4}	4×10^{-4}	3×10^{-4}	3×10^{-4}
chb01_07.edf	2×10^{-3}	1.1×10^{-3}	9×10^{-4}	7×10^{-4}	8×10^{-4}	8×10^{-4}	8×10^{-4}
chb01_08.edf	1.1×10^{-3}	08×10^{-4}	06×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}
chb01_09.edf	8×10^{-4}	5×10^{-4}	5×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}
chb01_10.edf	1.1×10^{-3}	7×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}
chb01_11.edf	1.2×10^{-3}	8×10^{-4}	8×10^{-4}	8×10^{-4}	7×10^{-4}	7×10^{-4}	7×10^{-4}
chb01_12.edf	2.8×10^{-3}	1.9×10^{-3}	1.5×10^{-3}	1.2×10^{-3}	1.1×10^{-3}	1.2×10^{-3}	1.2×10^{-3}
chb01_13.edf	1.6×10^{-3}	1.1×10^{-3}	8×10^{-4}	07×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}
chb01_14.edf	1.7×10^{-3}	1×10^{-3}	6×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}
chb01_15.edf	2.7×10^{-3}	1.3×10^{-3}	9×10^{-4}	7×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}
chb01_16.edf	1.3×10^{-3}	7×10^{-4}	6×10^{-4}	5×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}
chb01_17.edf	2.6×10^{-3}	1.3×10^{-3}	8×10^{-4}	6×10^{-4}	6×10^{-4}	5×10^{-4}	5×10^{-4}
chb01_18.edf	1×10^{-3}	6×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}	4×10^{-4}
chb01_19.edf	1.5×10^{-3}	1×10^{-3}	7×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}
chb01_20.edf	1.1×10^{-3}	8×10^{-4}	6×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}
chb01_21.edf	1.7×10^{-3}	9×10^{-4}	5×10^{-4}	3×10^{-4}	3×10^{-4}	3×10^{-4}	3×10^{-4}
chb01_22.edf	2.8×10^{-3}	1.4×10^{-3}	8×10^{-4}	7×10^{-4}	6×10^{-4}	6×10^{-4}	5×10^{-4}
chb01_23.edf	2.1×10^{-3}	1.2×10^{-3}	9×10^{-4}	7×10^{-4}	7×10^{-4}	7×10^{-4}	7×10^{-4}
chb01_24.edf	2.9×10^{-3}	1.7×10^{-3}	1.3×10^{-3}	1.1×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}
chb01_25.edf	1.5×10^{-3}	9×10^{-4}	6×10^{-4}	4×10^{-4}	3×10^{-4}	3×10^{-4}	3×10^{-4}
chb01_26.edf	3.5×10^{-3}	2×10^{-3}	1.2×10^{-3}	6×10^{-4}	5×10^{-4}	4×10^{-4}	4×10^{-4}
chb01_27.edf	1.9×10^{-3}	1×10^{-3}	6×10^{-4}	4×10^{-4}	3×10^{-4}	3×10^{-4}	3×10^{-4}
chb01_29.edf	2.2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}	2×10^{-2}	1.9×10^{-2}	1.9×10^{-2}
chb01_30.edf	2.7×10^{-3}	2×10^{-3}	1.8×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}	1.7×10^{-3}
chb01_31.edf	1.4×10^{-3}	1×10^{-3}	1×10^{-3}	9×10^{-4}	9×10^{-4}	9×10^{-4}	9×10^{-4}
chb01_32.edf	2×10^{-3}	1.5×10^{-3}	1.1×10^{-3}	1.1×10^{-3}	1.1×10^{-3}	1.1×10^{-3}	1.1×10^{-3}
chb01_33.edf	2.8×10^{-3}	1.7×10^{-3}	1.3×10^{-3}	1×10^{-3}	1×10^{-3}	1×10^{-3}	1.1×10^{-3}
chb01_34.edf	2.8×10^{-3}	2.1×10^{-3}	2×10^{-3}	1.9×10^{-3}	1.9×10^{-3}	1.9×10^{-3}	1.9×10^{-3}
chb01_36.edf	1.5×10^{-3}	9×10^{-4}	6×10^{-4}	6×10^{-4}	5×10^{-4}	5×10^{-4}	5×10^{-4}
chb01_37.edf	2.2×10^{-3}	1.1×10^{-3}	9×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}	6×10^{-4}
chb01_38.edf	1.4×10^{-3}	1.2×10^{-3}	9×10^{-4}	8×10^{-4}	8×10^{-4}	8×10^{-4}	8×10^{-4}
chb01_39.edf	1.7×10^{-3}	1×10^{-3}	8×10^{-4}	7×10^{-4}	7×10^{-4}	7×10^{-4}	7×10^{-4}

and transmitted. Upon receipt, we can proceed to the inverse operations to restore multichannel biomedical signals. We believe we have achieved our goals. The use of orthogonal codes reduces the risk of interference between the various channels of the signal received. The mix up of the signal ensures a high degree of confidentiality. The larger the spreading gain, the greater the noise immunity and the lower the tolerance to interferences. If the disspread signal contains noise that was been added during the transmission, low-pass filtering could be performed. The

spectral spreading increases the flow of transmissions, but the flow of useful information is unchanged after decoding [25]. Additionally, the spreading does not change the signal strength, but the spectral power density is reduced [31]. The transmission channel is used once for transmitting a composite signal that comprises all of the leads of a bio-physiological signal. This provides the advantage of reducing both the cost and the time of transmission. The transmission of all of the lead signals at once reduces synchronization problems. The simulation results

Table 6 Values of PRDs obtained on ECG records with CDMA, FDMAam and FDMAfm transmission technologies

Records	Method	SNR														
		20	25	30	35	40	45	50	55	60	65	70	75	80	85	
patient030/ s0099lre	CDMA	4.13	2.29	1.33	0.73	0.41	0.22	0.13	0.07	0.04	0.02	0.01	0.01	0.01	0	
	FDMAam	12.16	8.43	6.79	6.06	5.77	5.71	5.66	5.65	5.64	5.64	5.64	5.64	5.64	5.64	
	FDMAfm	17.18	14.99	14.3	13.95	13.88	13.86	13.84	13.84	13.83	13.83	13.83	13.83	13.83	13.83	
patient030/ s0099lre	CDMA	13.99	7.71	4.45	2.52	1.41	0.79	0.44	0.24	0.14	0.08	0.04	0.03	0.02	0.02	
	FDMAam	33.63	19.42	12.88	9.61	8.27	7.83	7.67	7.63	7.61	7.6	7.6	7.6	7.6	7.6	
	FDMAfm	43.52	34.65	31.14	29.69	29.33	29.27	29.21	29.17	29.17	29.17	29.17	29.17	29.17	29.17	
patient030/ s0117lre	CDMA	10.39	5.79	3.26	1.84	1.03	0.56	0.33	0.18	0.1	0.06	0.03	0.02	0.01	0.01	
	FDMAam	24.93	15.37	10.29	7.64	6.65	6.11	5.94	5.91	5.88	5.87	5.87	5.87	5.87	5.87	
	FDMAfm	31.46	24.49	21.24	20.59	20.11	20.05	20.02	20.01	20	20.01	20.01	20.01	20.01	20.01	
patient030/ s0153lre	CDMA	13.66	7.76	4.33	2.49	1.37	0.78	0.43	0.24	0.13	0.08	0.04	0.03	0.02	0.02	
	FDMAam	32.21	19.79	13.03	10.02	8.73	8.19	8.05	8.01	7.99	7.99	7.98	7.98	7.98	7.98	
	FDMAfm	41.16	32.25	28.5	27.21	26.79	26.76	26.68	26.68	26.67	26.66	26.67	26.66	26.67	26.67	
patient031/ s0100lre	CDMA	4.88	2.75	1.54	0.85	0.48	0.26	0.15	0.08	0.05	0.03	0.01	0.01	0.01	0.01	
	FDMAam	13.62	9.32	7.34	6.46	6.13	6	5.98	5.95	5.95	5.95	5.95	5.95	5.95	5.95	
	FDMAfm	36.61	34.47	33.6	33.29	33.15	33.14	33.14	33.14	33.14	33.14	33.13	33.14	33.13	33.13	
patient031/ s0114lre	CDMA	11.39	6.35	3.62	2.04	1.13	0.65	0.36	0.2	0.11	0.06	0.04	0.02	0.02	0.01	
	FDMAam	26.79	15.93	10.21	7.51	6.16	5.42	5.27	5.16	5.14	5.14	5.14	5.14	5.14	5.14	
	FDMAfm	41.76	35.09	32.54	31.89	31.69	31.53	31.51	31.49	31.5	31.49	31.49	31.49	31.49	31.49	
patient031/ s0127lre	CDMA	7.78	4.42	2.48	1.39	0.77	0.44	0.24	0.14	0.08	0.04	0.02	0.01	0.01	0.01	
	FDMAam	19.14	11.86	7.84	6.36	5.69	5.35	5.23	5.17	5.19	5.18	5.18	5.18	5.18	5.18	
	FDMAfm	27.65	23.52	22.02	21.26	21.09	21.09	21.05	21.05	21.05	21.05	21.05	21.05	21.05	21.05	
patient032/ s0102lre	CDMA	9.73	5.43	3.09	1.71	0.96	0.53	0.3	0.17	0.09	0.05	0.03	0.02	0.01	0.01	
	FDMAam	22.19	14.29	9.56	7.47	6.62	6.33	6.28	6.25	6.24	6.23	6.23	6.23	6.23	6.23	
	FDMAfm	30.89	24.3	21.9	21.23	20.87	20.76	20.73	20.72	20.73	20.73	20.73	20.72	20.73	20.73	
patient032/ s0106lre	CDMA	17.19	9.64	5.43	3.05	1.7	0.95	0.53	0.3	0.17	0.09	0.05	0.03	0.02	0.02	
	FDMAam	40.15	22.65	14.25	9.65	7.8	6.9	6.48	6.49	6.43	6.44	6.44	6.43	6.43	6.43	
	FDMAfm	60.74	47.21	42.86	40.89	40.74	40.43	40.39	40.38	40.4	40.38	40.38	40.38	40.38	40.38	
patient032/ s0115lre	CDMA	10.15	5.71	3.2	1.8	1.03	0.56	0.31	0.18	0.1	0.05	0.03	0.02	0.01	0.01	
	FDMAam	24.88	15.04	9.9	7.56	6.37	5.88	5.74	5.65	5.61	5.62	5.62	5.62	5.62	5.62	
	FDMAfm	37.04	30.38	28.22	27.25	27	26.99	26.94	26.93	26.93	26.93	26.92	26.93	26.93	26.93	

demonstrated that this method is effective, even for the transmission of signals heavily contaminated by noise. Practically, some difficulties such as transmission interruption, hand over, user identification and mobility management could be encountered. Such problems should be solved through specific software for the management of the overall transmission system.

5 Conclusions

Our goal was to transmit simultaneously, on the same channel, multiple leads of biosignals. The task was then about transforming these multiple leads signals into a single signal covering the entire bandwidth. We wanted to prevent the interception of these signals to

Table 7 Values of PRDs obtained on EEG records with CDMA, FDMAam and FDMAfm transmission technologies

Records	Methods	SNR													
		20	25	30	35	40	45	50	55	60	65	70	75	80	85
chb03/ chb03_17.edf	CDMA	9.63	5.33	2.99	1.71	0.97	0.55	0.33	0.21	0.16	0.13	0.12	0.12	0.12	0.12
	FDMAam	31.92	31.31	31.13	31.05	31.03	31.02	31.02	31.02	31.02	31.02	31.02	31.02	31.02	31.02
	FDMAfm	51.52	49.65	48.84	48.6	48.5	48.5	48.49	48.49	48.49	48.49	48.49	48.49	48.49	48.49
chb03/ chb03_18.edf	CDMA	13.7	7.71	4.3	2.43	1.36	0.77	0.44	0.26	0.16	0.11	0.1	0.09	0.08	0.08
	FDMAam	23.89	22.81	22.4	22.27	22.22	22.21	22.21	22.2	22.2	22.2	22.2	22.2	22.2	22.2
	FDMAfm	74.77	74.7	74.45	74.45	74.5	74.41	74.48	74.44	74.34	74.44	74.4	74.4	74.34	74.4
chb03/ chb03_19.edf	CDMA	9.6	5.37	3.04	1.7	0.96	0.54	0.31	0.18	0.12	0.08	0.07	0.07	0.06	0.06
	FDMAam	20.76	19.82	19.39	19.28	19.25	19.22	19.22	19.23	19.22	19.22	19.22	19.22	19.22	19.22
	FDMAfm	35.28	31.89	30.87	30.48	30.37	30.33	30.31	30.31	30.31	30.31	30.31	30.31	30.31	30.31
chb03/ chb03_20.edf	CDMA	12.18	6.9	3.86	2.17	1.22	0.7	0.41	0.26	0.19	0.16	0.15	0.14	0.14	0.14
	FDMAam	41.81	41.3	41.15	41.14	41.13	41.12	41.12	41.12	41.12	41.12	41.12	41.12	41.12	41.12
	FDMAfm	72.23	71.43	71.59	71.52	71.48	71.47	71.47	71.47	71.47	71.47	71.47	71.47	71.47	71.47
chb03/ chb03_21.edf	CDMA	23.15	13.05	7.41	4.16	2.33	1.31	0.73	0.42	0.24	0.14	0.09	0.07	0.06	0.06
	FDMAam	18.07	16.72	16.21	16.03	15.97	15.94	15.94	15.94	15.93	15.93	15.93	15.93	15.93	15.93
	FDMAfm	63.35	63.09	62.88	62.78	62.77	62.76	62.77	62.77	62.77	62.77	62.77	62.77	62.77	62.77
chb03/ chb03_22.edf	CDMA	9.44	5.4	3.03	1.69	0.96	0.54	0.3	0.17	0.11	0.07	0.06	0.05	0.05	0.05
	FDMAam	15.99	14.62	14.24	14.11	14.07	14.05	14.05	14.05	14.05	14.05	14.05	14.05	14.05	14.05
	FDMAfm	31.98	29.06	28.64	28.09	28.19	28.09	28.08	28.14	28.14	28.15	28.13	28.14	28.14	28.14
chb03/ chb03_23.edf	CDMA	9.35	5.31	2.98	1.67	0.94	0.54	0.32	0.2	0.14	0.11	0.1	0.1	0.1	0.1
	FDMAam	26.06	25.32	25.09	25	24.97	24.96	24.96	24.96	24.96	24.96	24.96	24.96	24.96	24.96
	FDMAfm	47.14	45	44.34	44.12	44.05	44.04	44.03	44.03	44.03	44.03	44.03	44.03	44.03	44.03
chb03/ chb03_24.edf	CDMA	16.68	9.42	5.27	2.97	1.66	0.95	0.54	0.31	0.19	0.13	0.1	0.09	0.08	0.08
	FDMAam	23.89	22.78	22.4	22.28	22.22	22.22	22.21	22.21	22.21	22.21	22.21	22.21	22.21	22.21
	FDMAfm	75.13	75.03	75.12	74.91	75.11	75.04	75.08	75.06	75.08	75.08	75.08	75.08	75.08	75.08
chb03/ chb03_25.edf	CDMA	13.67	7.71	4.3	2.44	1.38	0.77	0.44	0.26	0.16	0.11	0.09	0.09	0.08	0.08
	FDMAam	24.37	23.23	22.83	22.7	22.66	22.64	22.64	22.64	22.64	22.64	22.64	22.64	22.64	22.64
	FDMAfm	81.23	81.61	81.37	81.2	81.23	81.23	81.23	81.28	81.29	81.29	81.29	81.29	81.29	81.29
chb03/ chb03_26.edf	CDMA	13.99	7.84	4.38	2.47	1.39	0.8	0.46	0.28	0.19	0.15	0.13	0.12	0.12	0.12
	FDMAam	33.14	32.47	32.26	32.18	32.15	32.15	32.15	32.14	32.14	32.14	32.14	32.14	32.14	32.14
	FDMAfm	76.28	75.68	75.54	75.4	75.34	75.38	75.37	75.39	75.39	75.39	75.39	75.39	75.39	75.39

ensure confidentiality. The success rates obtained confirm the feasibility of the process. Spectral spreading is already a security key for the transmission. The advantage of this transmission technique lies in the multiplexing, which offers high capacity and

considerable gain in time. The transmission channel does not saturate, and it can be used for other purposes; the cost of transmission is low. We believe that as this technique is improved, it could be integrated into future telemedicine systems.

Compliance with ethical standards

Conflict of interest There is no conflict of interest.

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