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Analysis and Simulation of Coded Hybrid Spread Spectrum Transmitter System

Hany A.A. Mansour and Yongqing Fu
College of Information and Communication Engineering, Harbin Engineering University, Harbin 150001, China

Corresponding Author: Hany A.A. Mansour, College of Information and Communication Engineering, Harbin Engineering University, Harbin 150001, China Tel: +8618746026548

ABSTRACT

The simulation of Direct Sequence/Frequency Hopping Spread Spectrum is discussed by a lot of researches; on the other hand a few researches illustrated the hybrid spread spectrum including Direct Sequence/Frequency Hopping/Time Hopping. In this study, a complete simulation in addition to a mathematical analysis of a coded hybrid Direct Sequence/Frequency Hopping/Time Hopping Spread Spectrum transmitter system is presented. The simulation is performed by using the matlab Graphical User Interface that shows the effect of changing multi values of the system parameters on the transmitted signal.

Key words: Hybrid spread spectrum, direct sequence spread spectrum, frequency hopping and time hopping

INTRODUCTION

Since the Federal Communication Commission (FCC) has been established, its main basis in managing the spectrum allocations was depending on the request-by-request basis, until it has realized that it had no more spectra to allocate (Billa *et al.*, 2012), which gave rise to spread spectrum techniques as one of the available solutions. The main concept of the spread spectrum technique is to modulate (spread) the modulated waveform a second time in such a way to generate an expanded bandwidth signal by means of a code, which is completely independent of the information message. This code used in the receiver in a synchronized way to dispread the received signal and makes the original data recovery (Feher, 2009). Generally, the spread spectrum techniques are classified as direct Sequence Spread Spectrum (DSSS), Chirp Spread Spectrum (CSS), Frequency Hopping Spread Spectrum (FHSS), Time Hopping Spread Spectrum (THSS) and hybrid spread spectrum (Rappaport, 2009).

DSSS expands the signal band width throughout injecting high rate code called the spreading code. This injection process is performed by directly multiplying the original waveform by the spreading code. Since the spreading waveform has a rate much higher than the data rate, the bandwidth of the signal increases. Chirp modulation technique (it can be called also linear frequency modulation) has the concept of increasing the frequency ('up-chirp') or decreasing the frequency ('down-chirp') with the time. In FHSS spreading the spectrum of the data is performed by switching the carrier frequency periodically from one to another according to a specific spreading code (in some cases the hopping is performed in a complete random manner). Generally, the hopping carrier frequencies are spaced apart with the same data modulation bandwidth (Hsiao-Hwa, 2007). THSS is like FHSS, meanwhile the hopping process performed in the time domain according to a specific code. Now-a-days, DS/FH hybrid spread spectrum technique are discussed throughout many papers and has been used widely in communication system, for example in U.S. army's JTIDS (Joint Tactical Information Distribution System) (Wei and Xiaolin, 2010), on the contrast, the DS/FH/TH hybrid spread spectrum technique didn't take the same chance as it rarely discussed and applied due to its complexity.

In this study, a transmitter system based on multi spread spectrum techniques is simulated and mathematically analyzed. The system constructed from coding technique and three kinds of spread spectrum technique, which are the Direct Sequence Spread Spectrum (DSSS), Fast Frequency Hopping Spread Spectrum (FFHSS), in addition to Time Hopping Spread Spectrum (THSS).

SYSTEM MODEL BLOCK DIAGRAM

The whole construction of the hybrid spread spectrum transmitter system can be shown in Fig. 1. The system is constructed from the baseband data unit followed by encoder (error correcting code) unit. Figure 2 shows the encoder type which is a conventional encoder with code rate equal to 2. The output of this encoder is spreaded throughout the spreader unit, which generates a long code PN1 with spreading gain 250 as shown in Fig. 3. The spreaded signal is modulated using Differential Phase Shift Keying (DPSK) module to avoid the ambiguity of the phase that can be occurred if the constellation is rotated by some effect in the communications channel. The modulated signal then will have a bi-polarity transformation and then the hopping frequency is injected through the direct digital oscillator, after that the frequency hopped signal will be transmitted in hopped time windows by using the time hopping unite to the noisy channel. Actually, the frequency interval is default taken to be 10 MHZ, with hopping rate 100 kbps. The frequencies is generated by the direct digital oscillator and the hopping process is completely controlled throughout the sequence PN2. Finally, the coded spreaded frequency hopped signal is transmitted in a certain time windows identified by the code PN3.

Actually, the system is not designed to use only one set of PN1, PN2 and PN3 codes, in other words the system is designed to deal with many groups of these codes called bank of parameters. In the actual case the bank of these parameters or the number of the groups manipulated by the system is set to be 8. This means that we have 8 different PN1 codes, 8 different PN2 codes (and correspondingly 8 different frequencies sets) and finally 8 different PN3 codes. The parameter that identifies which group will be used is a frequency called the unified frequency constructed from 3 binary digits, this frequency is also sent to the receiver to unify the receiving parameters stored in the receiver during the receiving process. This can be clear from Fig. 4 which discuss the parameters groups of the system.

MATHEMATICAL SYSTEM MODEL

For simplicity the analysis will begin considering one parameters group and then it will be generalized for all the parameters groups. To identify the mathematical model of the given system, let the baseband data be represented as:

$$d(t) = \sum_{i=0}^{M-1} x(t - imT_s) \tag{1}$$

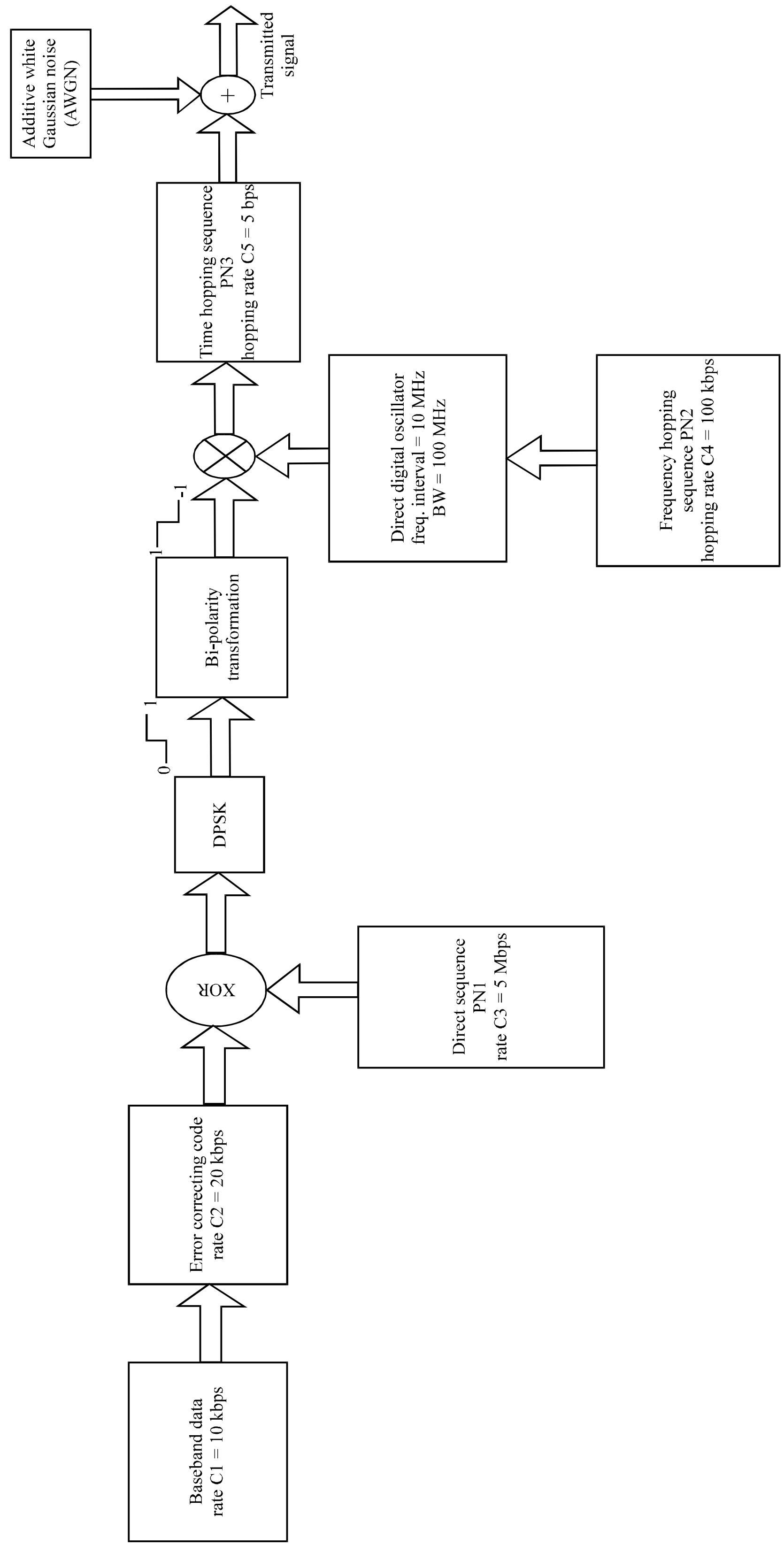

Fig. 1: Block diagram of the hybrid spread spectrum transmitter

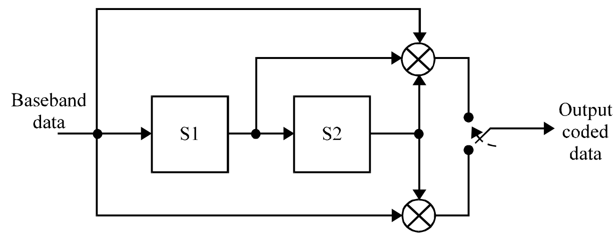

Fig. 2: Block diagram of the conventional encoder

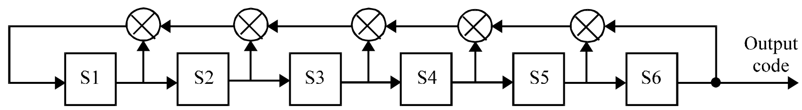

Fig. 3: Block diagram of the linear long code generator

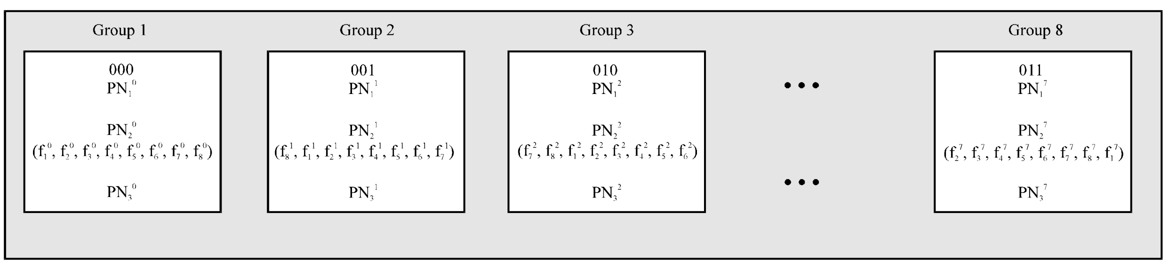

Fig. 4: The bank of the parameters used by the transmitter system

where, M is the number of bits generated during the assigned time frame, x(t) is the rectangular pulse with duration mT_s, m is the number of samples in one bit duration and T_s is the sampling time which equals to the inverse of sampling frequency F_s. This equation can be represented in vector form by a (1×M) vector as:

$$d = [x(0), x(1), \ldots, x(M\text{-}1)] \quad (2)$$

This baseband data is the input to the conventional encoder which has an output that can be represented as:

$$d_c(t) = \sum_{i_c=0}^{M_c-1} x_c(t - i_c m_c T_s) \quad (3)$$

where, M_c is the number of coded bits generated during the same assigned time frame such that $M_c = 2M$, $x_c(t)$ is the coded rectangular pulse with duration m_cT_s, m_c is the number of samples in one coded bit duration with $m_c = m/2$. Also, similarly the vector form of the code data bits will be vector with dimension ($1\times M_c$) as:

$$d_c = [x_c(0), x_c(1), \ldots, x_c(M_c\text{-}1)] \quad (4)$$

As a result, the total spreaded signal can be represented as:

$$S(t) = \sum_{i_c=0}^{M_c-1}\sum_{j=0}^{N-1} z(t - nT_s[2i_c N + j]) \tag{5}$$

where, z(t) is also rectangular pulse with the same duration nT_s, The bi-polar transformation applies the rule of $(-1)^{z(t)}$, in which each 0 will be 1, while each 1 will be -1 to be suitable for modulation with the hopping frequency. To represent the DS-FH signal in the case of using one group parameters, Eq. 5 can be useful as:

$$S_h(t) = S(t)\mathrm{Re}\left[\exp\left(J2\pi[f_c - f_p]\frac{m_c}{G_h}l_n T_s\right)\right] \tag{6}$$

or:

$$S(t) = \sum_{i_c=0}^{M_c-1}\sum_{j=0}^{N-1} z(t - nT_s[2i_c N + j])\mathrm{Re}\left[\exp\left(J2\pi[f_c - f_p]\frac{m_c}{G_h}l_n T_s\right)\right] \tag{7}$$

where, f_c is the carrier frequency taken to be 2.4 GHz. f_p is the hopping frequency taking the values of {0, f_h, $2f_h$, $3f_h$, ..., $7f_h$} according to the controlled code sequence PN2, where f_h is the frequency interval which sets to be 10 MHZ as mentioned before. G_h can be considered as the hopping spreading gain, which is the ratio between the hopping rate and the coded bit rate (in our case $G_h = 5$). It is cleared that each bit will be modulated with 5 different frequencies, which mean that each frequency will take $\frac{1}{5}m_c T_s$ part of each bit. This part is determined by the factor l_h, in which l_h can be represented as:

$$l_h = a \text{ for, } N\left(\frac{a-1}{G_h} + (e-1)\right) + 1 \le \text{number of chips} \le \left(\frac{a}{G_h} + (e-1)\right),\ a = 1, 2, \ldots, 5,\ e = 1, 2, \ldots, M_c \tag{8}$$

Taking into consideration the different parameters groups, this means that there are 8 different sequences of PN2 each of which has a corresponding 8 different frequencies sets, these sets of frequencies can be represented as:

$$F = [f(1), f(2), \ldots, f(8)]^T \tag{9}$$

Each set of these frequencies sets has the same frequencies values but with different orders, in other words:

$$f(1) = (f_c, f_c\text{-}f_h, f_c\text{-}2f_h, f_c\text{-}3f_h, f_c\text{-}4f_h, f_c\text{-}5f_h, f_c\text{-}6f_h, f_c\text{-}7f_h)$$
$$f(2) = (f_c\text{-}7f_h, f_c, f_c\text{-}f_h, f_c\text{-}2f_h, f_c\text{-}3f_h, f_c\text{-}4f_h, f_c\text{-}5f_h, f_c\text{-}6f_h)$$
$$\vdots$$
$$f(8) = (f_c\text{-}f_h, f_c\text{-}2f_h, f_c\text{-}3f_h, f_c\text{-}4f_h, f_c\text{-}5f_h, f_c\text{-}6f_h, f_c\text{-}7f_h, f_c)$$

Then, the general expression of the whole spreaded frequency hopped signal can be expressed as:

$$S_{kh}(t) = S_k(t)\mathrm{Re}\left[\exp\left(J2\pi f(k)\frac{m_c}{G_h}l_h T_s\right)\right] \tag{10}$$

or:

$$S_{kh}(t) = \sum_{i_c=0}^{M_c-1}\sum_{j=0}^{N-1} z_k(t - nT_s[2i_cN + j])\mathrm{Re}\left[\exp\left(J2\pi f(k)\frac{m_c}{G_h}l_h T_s\right)\right] \tag{11}$$

Finally, the time hopping process of the spreaded frequency hopping signal can be expressed considering only one group as:

$$S_t(t) = S_h(t)w(l_cT_s) \tag{12}$$

or:

$$S_t(t) = \sum_{i_c=0}^{M_c-1}\sum_{j=0}^{N-1} z(t - nT_s[2i_cN + j])\mathrm{Re}\left[\exp\left(J2\pi f[f_c - f_p]\frac{m_c}{G_h}l_h T_s\right)\right]w(l_tT_s) \tag{13}$$

where, $w(l_tT_s)$ is the time window in which the signal will be transmitted. This time window has 200 msec duration which means that for each second there is one section from different 5 sections is available to send the message through. The chosen section is determined throughout the factor l_t, which has a number of samples equal to F_s/G_t and identifies which section containing these samples according to the sequence PN3, where G_t is the time hopping gain. According to this definition, l_t can be expressed as:

$$(a-1)\frac{f_s}{G_t} \le l_t \le a\frac{f_s}{G_t},\ a = 1, 2, \ldots 5 \tag{14}$$

SIMULATION SYSTEM DESIGN OF CODED HYBRID SPREAD SPECTRUM TRANSMITTER

The main idea is to design a software program which has the ability to change and accept different input parameters values for the presented hybrid transmitter system and gets the different output results in the form of displayed curves and numerical outputs results. In other words, the main target is to enable the user to study the effect of changing the different input parameters values on each other and on the transmitted signal. Figure 5 illustrates a brief layout for the simulation interface showing that the program interface basically divided into three main sections, the input parameters section, the displaying section and the numerical output parameters section.

In the input parameters section, the input parameters are divided into groups. The first I/P group represents the Base Band (BB) data parameters, which contain the base band data rate and the number of transmitted bits. The user can controls the BB rate by selecting the desired rate

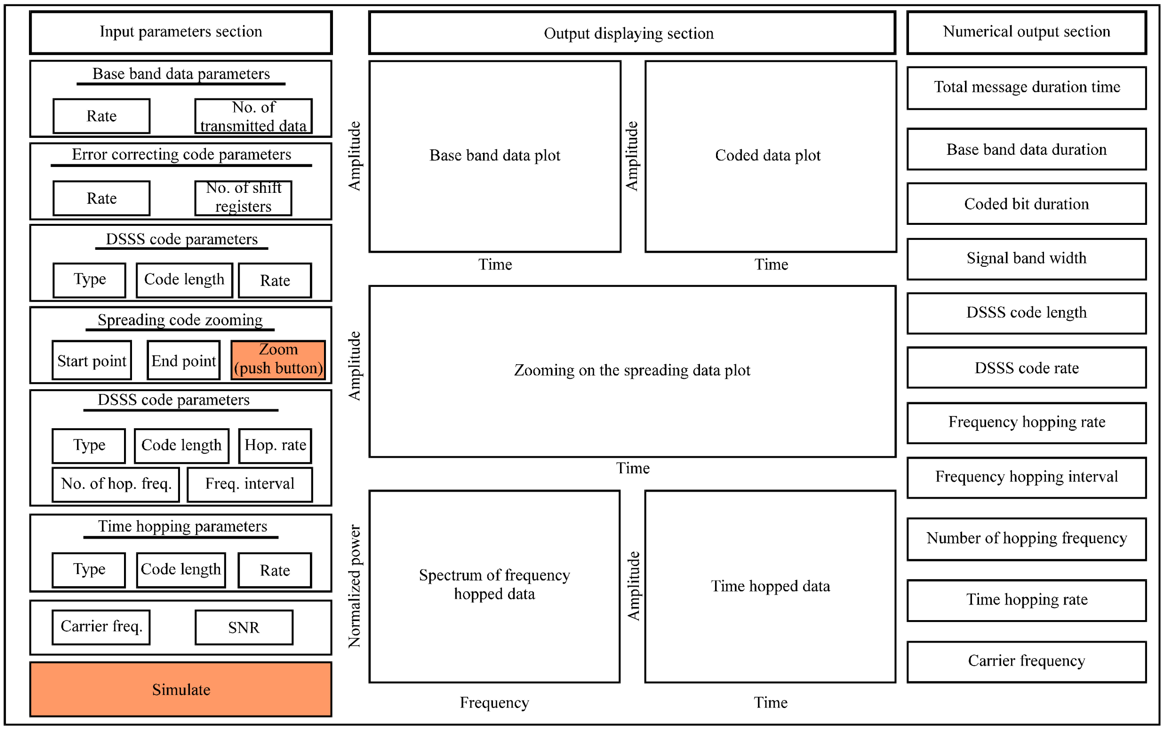

Fig. 5: GUI interface layout

Table 1: Parameter values of rate 1/2 conventional codes

			B(d_f+i) for i = 0, 1, ..., 6						
K	d_f	Generators	0	1	2	3	4	5	6
3	5	5, 7	1	4	12	32	80	192	448
4	6	15, 17	2	7	18	49	130	333	836
5	7	23, 35	4	12	20	72	225	500	1324
6	8	53, 75	2	36	32	62	332	701	2342
7	10	133, 171	36	0	211	0	1404	0	11,633
8	10	247, 371	2	22	30	148	340	1008	2642
9	12	561, 763	33	0	281	0	2179	0	15,035
10	12	1131, 1537	2	21	100	186	474	1419	3542

(from 10 to 100 kbps) and select the number of the transmitted bits (from 10 to 5000 bits), these two parameters mainly calculate the total message time duration, ofcourse as the number of transmitted bits increases the total message duration increases and consequently the complexity increases.

The second I/P group represents the Error Correcting Code (ECC) parameters, in which the user can control the ECC rate to be 2, 3, or 4 and the number of shift registers (from 3 to 10) used in generating the ECC according to the selected code rate. Table 1-3 show the parameter values of the conventional codes with rates 2, 3 and 4 and its generator polynomials in octal form (Torrieri, 2005).

The third group shows the DSSS code parameters, which contains the DSSS code type, the DSSS code length and the DSSS code rate. The code type contains three different types, the PN sequence, the Gold sequence and the long code generated in Fig. 3. If the user selects the PN or the

Table 2: Parameter values of rate 1/3 conventional codes

			B(d_f+i) for i = 0, 1, ..., 6						
K	d_f	Generators	0	1	2	3	4	5	6
3	8	5, 7, 7	3	0	15	0	58	0	201
4	10	13, 15, 17	6	0	6	0	58	0	118
5	12	25, 33, 37	12	0	12	0	56	0	320
6	13	47, 53, 75	1	8	26	20	19	62	86
7	15	117, 127, 155	7	8	22	44	22	94	219
8	16	225, 331, 367	1	0	24	0	113	0	287
9	18	575, 673, 727	2	10	50	37	92	92	274
10	20	1167, 1375, 1545	6	16	72	68	170	162	340

Table 3: Parameter values of rate 1/4 conventional codes

			B(d_f+i) for i = 0, 1, ..., 6						
K	d_f	Generators	0	1	2	3	4	5	6
3	10	5, 5, 7, 7	1	0	4	0	12	0	32
4	13	13, 13, 15, 17	4	2	0	10	3	16	34
5	16	25, 27, 33, 37	8	0	7	0	17	0	60
6	18	45, 53, 67, 77	5	0	19	0	14	0	70
7	20	117, 127, 155, 171	3	0	17	0	32	0	66
8	22	257, 311, 337, 355	2	4	4	24	22	33	44
9	24	533, 575, 647, 711	1	0	15	0	56	0	69
10	27	1173, 1325, 1467, 1751	7	10	0	28	54	58	54

Gold sequence, the code length menu will be considerable while the code rate menu will be inconsiderable, since the PN and Gold codes has periodic lengths, in this case the code length also represents the spreading code rate. On the other hand if the user selects the long code (which has not a restricted length) the code length menu will be inconsiderable while the code rate menu will be considerable. The available code lengths for the PN and Gold codes are 7, 15, 31, 63, 127 and 255, while the available spreading code rate for the long code case is from 1 to 10 Mbps.

The fourth group represents the frequency hopping parameters, which contains five different submenus (code type, code length, hopping rate, number of hopping frequency and frequency interval). In the code type submenu, the user can select the type of the PN2 code which can be PN-sequence or Gold sequence. The code length can be selected to be 8, 16 or 32. The user can select the hopping rate to be a value from 100 to 500 kbps. Here, we can note that the minimum value of the hopping rate (100 kbps) is equal to the maximum available value of the BB data rate to ensure the fast frequency hopping property. The available numbers of hopping frequencies are from 5 to 10 and the user can select the frequency interval to be from 10 to 50 MHZ. Here there is important note which is in case the user selects number of hopping frequencies greater than 8 (9 or 10), the code length must be also greater than 8, since the code with length 8 enable only 8 different hopping frequencies.

The fifth group is the time hopping parameters, which enable the user to select the type of the PN3 code to be PN-sequence (PN) or Gold sequence, the other submenu identifies the code length which is the same as that of the frequency hopping parameters (8, 16 and 32), finally the time hopping rate which can be set to be 4, 5, 8, or 10 such that if the hopping rate is selected to be 10, then the code length must be greater than 8 (16 or 32), since the code with length 8 enable only 8 different time hopping locations.

The sixth group represents the carrier frequency and the value of the Signal to Noise Ratio (SNR). The carrier frequency can be set to be from 1.2 to 2.4 GHz with step length = 0.2 GHz, also an important note must be mentioned here that the sampling frequency used in this program is function of the carrier frequency (sampling freq. = twice the carrier freq.) this mean that as the value of the selected carrier frequency increases, the processing time of the program increases due to the large sampling frequency value. The SNR can be selected to be a value from six different values which is -20, -10, 0, 10, 20 or infinity dB, which mean that the transmission performed without noise.

The remaining group is the spreading code zooming parameters, which enable the user to make a zooming on any duration part of the spreaded coded data to check the spreading code in this time duration. The user inserts the start point and the end point manually then presses the zoom pushbutton; the spreading code will be plotted during the selected time duration. Traditionally, there is no need to say that the value of the start point must be less than the end point and the two values must be within the total time duration of the transmitting message, if any values is selected out of these constrains, the program will generate an error message to make the user attention to the wrong value.

The second main section of the simulation interface is the plotting (displaying) section which contains five different plots. The first plot (upper left) represents the amplitude of the selected number of the base band data bits against the time, as mentioned before the total message duration is specified according to the selected BB data rate and the selected number of the transmitted bits. The second plot (upper right) shows amplitude of the coded data (encoder output) against the time during the same total message duration. In Fig. 6 the number of the coded bits is equal to the BB data bits multiplied by the ECC rate. The third plot (middle) illustrates the zooming part of the selected spreading code during the selected zooming period, which is specified by the values of the start and the end point. The fourth plot (lower left) discusses the spectrum of the transmitted signal in the frequency domain, this figure also clarifies the carrier and hopping frequencies values, in addition to the total signal band width according to the selected values of the carrier frequency and frequency hopping parameters. The last figure (lower right) represents the amplitude of time hopped signal according to the selected time hopping rate and the SNR value.

The third main section of the simulation interface represents some numerical results that can help the user in studying and evaluating the system performance. These results contains the total message duration (msec), which is equal to that of the first and second figures, the next result shows the BB data bit duration (msec) which is the inverse of the BB data rate. The third result gives the value of the coded bit duration which equals to the BB data bit duration divided by the ECC rate, this value can be helpful in setting the end point of the Spreading code zooming, in other words if the user wants to discuss one period of the spreading code, he can set any value for the start point and the end point will be the start value plus the coded bit duration value. The next result calculates the total band width of the transmitted signal according to the selected number of hopping frequency and the frequency interval. The fifth result clears the type of the spreading code and its selected length, the following result calculates the rate of the spreading code according to its type, such that if the selected code is PN or Gold code then the rate will be its length multiplied by the coded data rate, while in case of the long code the rate will be the selected value of the rate box in the DSSS code parameters group. The next two boxes show the frequency hopping interval and the number of hopping frequency. Finally the time hop rate and the carrier frequency are cleared in the last two boxes.

ANALYSIS OF THE PROGRAM SIMULATION AND SIMULATION RESULTS

Here, we will perform two different experiments to evaluate the simulation program and the presented transmitter system performance. In the first experiment, the input parameters will be selected randomly without noise to prove that the simulation system working correctly, while in the second experiment the input parameters will be selected according to the given values of the transmitter system to prove that the presented transmitter system is correct.

Experiment 1: In this experiment the input parameters values are selected to be as follows: BB data bit rate 40 kbps, number of transmitted bits 10 bit. The ECC rate is 4 the number of shift registers is 8. For the DSSS parameters, the spreading code type is PN code with length 15. The frequency hopping code type is Gold code with length 16, the hopping rate is 400 kbps with 10 hopping frequencies and frequency hopping interval 40 MHZ, the time hopping code type is Gold code and the time hopping rate is 10 bps. The SNR value is infinity which means that there is no noise and the carrier frequency is selected to be 1.6 GHz.

Figure 6 shows the results of the GUI simulation according to the previous given input parameters; the first figure (upper left) plots 10 bits of the BB data with rate 40 kbps which results total message duration 0.25 msec as cleared in the first cell of the output results. The BB bit duration will be 0.025 msec as cleared in the second O/P cell. Since the ECC rate is 4, then the number of the coded data will be 40 bit plotted in the same total message duration as shown in the second figure (upper right) and consequently the coded bit duration will be 0.00625 msec (0.025/40) as cleared in the third cell. The zooming parameters are set to show the whole DSSS waveform which has spreading code length 15, so the start and the end points are set to be 0 and 0.25, respectively to contain the total message duration and the spreading code is plotted in Fig. 3 (middle) with its parameters cleared in cells 5 and 6 in the output parameters section. Since the number of the hopping frequencies is 10 and the hopping interval is 40 MHZ, the total transmitted signal BW will be 360 MHZ as cleared in cell 4 and the spectrum of the transmitted signal is discussed in Fig. 4 (lower left). In Fig. 4, we can see 10 different spectral with 40 MHZ spacing starting with the carrier frequency which set to be the largest frequency, to ensure that the

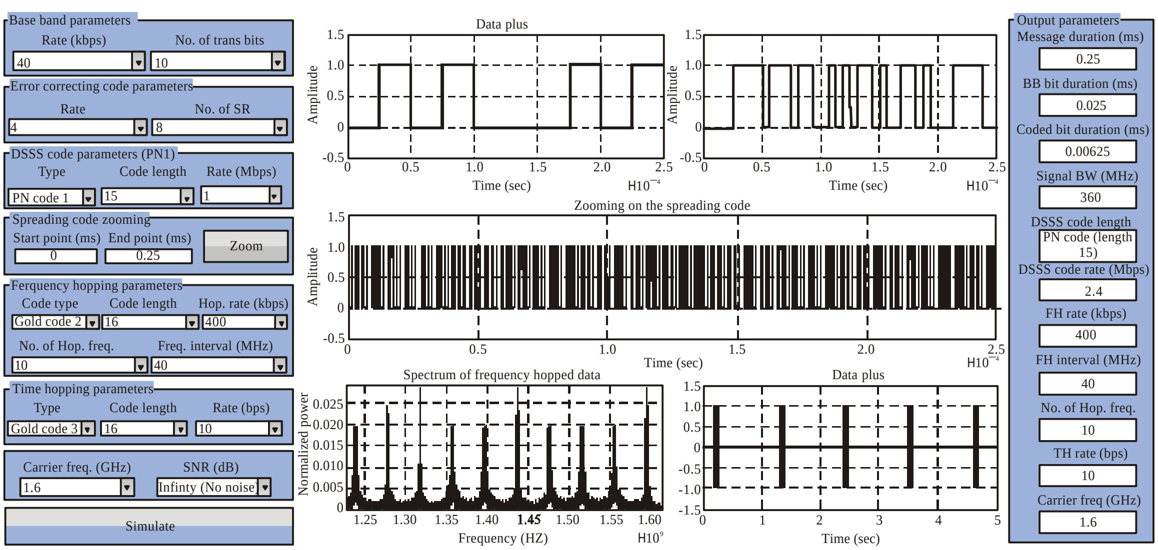

Fig. 6: GUI with random input parameters values

sampling frequency value will avoid the frequency folding property. The last plot (lower right) illustrates the time hopping transmitted signal, in which the hopping rate is selected to be 10 bps which mean that each second is divided into 10 parts and the signal hop on one part of these 10 parts according to the hopping code (Gold code 3). The numerical output parameters show that its results are corresponding to the plotted figures and to the input parameters values which indicate that the simulation is working perfectly.

Experiment 2: In this experiment the default parameters value of the presented transmitter system are set to discuss the performance of the presented system as follows: the BB data bit rate 10 kbps, the number of transmitted bits is 20 bit. The ECC rate is 2, the number of shift registers is 3. For the DSSS parameters, the spreading code type is long code with rate 5 Mbps. The frequency hopping code type is PN code with length 8, the hopping rate is 100 kbps with 8 hopping frequencies and frequency hopping interval 10 MHZ. the time hopping code type is PN code and the time hopping rate is 5 bps. The SNR value is -10dB and the carrier frequency is set to be 2.4 GHz.

Figure 7 shows the results of the GUI simulation according to transmitter system default parameters; the BB data figure shows 20 bits and since the rate is 10 kbps the total message duration will be 2 msec as cleared in the first cell of the output results. The second cell in the output section identifies the duration of one BB bit as 0.1 msec, which equal to the inverse of

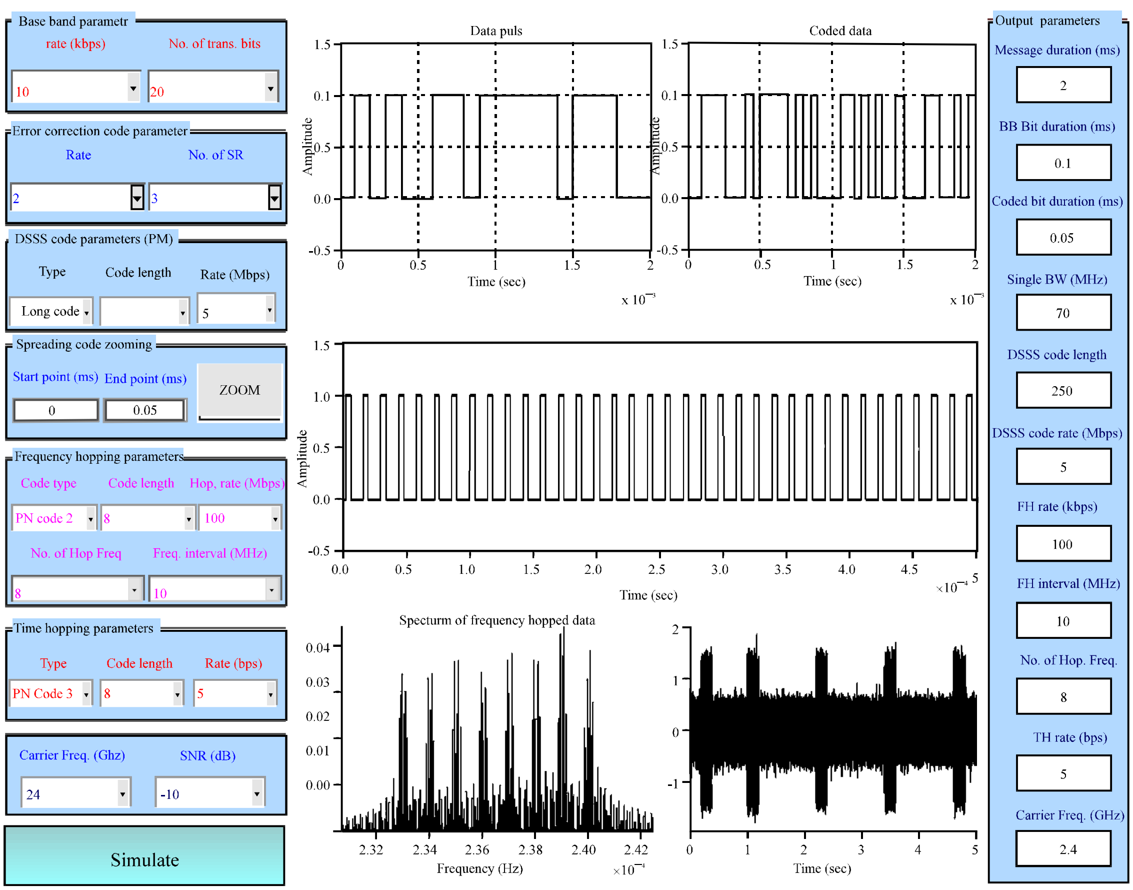

Fig. 7: GUI with default transmitter system parameters values

the BB data rate. Since the ECC rate is 2, then the number of the coded data will be 40 bit plotted in the same total message duration as shown in the second figure and consequently the coded bit duration will be 0.05 msec (0.1/2) as cleared in the third cell. The zooming parameters are set to show one period of the spreading code which has length 250 (5 Mbps/20 kbps), so the start and the end points can be set to be 0 and 0.05, respectively (end value = start value+coded bit duration) and the spreading code is plotted in Fig. 3 as its parameters are cleared in cells 5 and 6 in the output parameters. Since the number of the hopping frequencies is 8 and the hopping interval is 10MHz, the total transmitted signal BW will be 70 MHZ as cleared in cell 4 and the spectrum of the transmitted signal is discussed in Fig. 4. Figure 4 show, that the carrier frequency is shifted to be 2.4 GHz according to the selected input value. The last plot illustrates the noisy time hopping transmitted signal, in which the hopping rate is selected to be 5 bps which mean that each second is divided into five parts and the signal hop on one part of these five parts according to the hopping code (PN code 3). From these results we can conclude that the presented transmitter system is working correctly and that the performance of the presented system is perfect.

CONCLUSION

In this study, a coded DSSS/FFH/TH transmitter system is mathematically analyzed and simulated. The system is constructed from conventional coding technique with code rate 2 and three different spread spectrum techniques which are DSSS, FFHSS and THSS. The paper presents a detailed explanation of the system block diagram, in addition to the mathematical analysis of the whole system. Finally, some of the results for the different stages was showed and discussed throughout the simulation by using the matlab Graphical User Interface (GUI) with different input parameters. According to the illustrated results, we can conclude that the presented system of hybrid SS transmitter is correct.

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