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Design and performance analysis of frequency hopping OFDM based noise reduction DCSK system

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ABSTRACT

The reference chaotic signal in the differential chaos shift keying (DCSK) system causes both bit error rate (BER) and security performance degradation. In this paper, a frequency hopping orthogonal frequency division multiplexing based noise reduction DCSK (FH-OFDM-NR-DCSK) system is proposed to enhance both the BER and security performance of the OFDM-DCSK system. This system combines the advantages of both FH-OFDM-DCSK and NR-DCSK. Rather than creating β separate chaotic samples to utilize as a reference sequence, β/P chaotic samples are created and then replicated P times. Moving average filters of size P are applied after the frequency hopper to average the repeated chips of the reference and data-bearing signals. A new frequency hopping pattern is designed depending on the chaotic map on which the matrix pattern is designed efficiently. The performance of the proposed system is examined, and bit error rate analytic equations of the FH-OFDM-NR-DCSK system over an AWGN and two-path Rayleigh fading channel are derived. The simulation results show that the theoretical BER expressions and simulation performance match. The findings show that for the same spreading factor, the proposed system outperforms the DCSK and FH-OFDM-DCSK when P>1. This method decreases noise variance and improves BER without adding to the system's complexity.

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1. INTRODUCTION

In the past few decades, chaos-based communication systems have attracted a significant amount of interest due to the benefits afforded by the chaotic signal, such as non-periodic, noise-like, wideband, impulse-like auto-correlation and very low cross correlation. It also performs well in multipath environments and has immunity to jamming and interception. Coherent and non-coherent communication schemes are the two basic forms of chaos-based communication schemes. To demodulate the transmitted bits, a coherent receiver requires a synchronized copy of the chaotic carrier created by the transmitter. Chaotic synchronization still exists as a channeling issue. As a result, research on coherent systems is restricted [1].

The generation of chaotic carriers at the receiver is not required for non-coherent systems. As a consequence, non-coherent systems have attracted a great deal of attention. A lot of schemes have been produced, among which non-coherent DCSK is the most suitable one due to its simple transmitter and receiver, as well as its good noise and multipath performance [2]–[4]. In DCSK, half the bit duration time is spent sending a non-information-bearing reference [5]. Therefore, this architecture's data rate is significantly lower than other systems using the same bandwidth, resulting in energy waste. Half of each bit's energy is dissipated by the reference sequence. A substantial volume of research is being conducted to address the DCSK scheme's weaknesses, permutation-based DCSK was introduced in [6]. The bit rate was made undetectable by the frequency spectrum. This minimized the similarity between the reference and data samples in a DCSK system, hence data security was improved. Yang and Jiang [7], define high-efficiency DCSK (HE-DCSK) was presented as a way to improve bandwidth efficiency. The system requires wideband RF delay lines, which are difficult to fabricate in CMOS technology [8]. Improved DCSK (I-DCSK) [9], phase-separated DCSK (PS-DCSK) [10], and short reference DCSK (SR-DCSK) [11], M-ary DCSK system with code index modulation [12] were proposed.

Kaddoum and Gagnon [13], presented a code shifted differential chaos shift keying (CS-DCSK) to solve the problem of RF delay in DCSK systems. Kaddoum and Soujeri [14], suggest noise reduction DCSK (NR-DCSK) to improve DCSK's bit error rate (BER) performance. The reference and information-carrying signals are both p-times repeated. At the receiver, an average filter is used to reduce the noise. This system improves the BER of the DCSK system. However, this system is inefficient in terms of energy and bandwidth. To boost data rates and improve energy efficiency, Kaddoum *et al*. [15] proposed a multicarrier DCSK (MC-DCSK) approach that enables multi-carrier transmission. In this method, a chaotic reference sequence is transmitted over a predefined subcarrier frequency while multiple modulated data streams are transmitted over the remaining subcarriers. However, it requires the use of parallel matched filters and usually requires a large amount of bandwidth.

Inspired by the MC-DCSK system, Li *et al.* [16] presented an OFDM-DCSK system as a substitute for reducing the system's complexity of the multi-carrier DCSK system. Using IFFT and FFT on the transmitter and receiver, respectively, in comparison to [15], this strategy has succeeded in lowering complexity as well as improving bandwidth efficiency. In [17], [18] studied sort reference quadrature chaos shift keying (SR-QCSK) and orthogonal chaotic vector shift keying (OCVSK) were combined with an OFDM technique, respectively. However, the security of OFDM systems is compromised since the chaotic carrier is sent on a predetermined subcarrier. An eavesdropper might use this flaw to decode the transmitted data. Liu *et al*. [19] proposed index modulation and M-ary PSK Aided OFDM-DCSK as a method for increasing energy efficiency. To enhance the security of the OFDM system, a frequency hopping sequence is used to distribute chaotic reference chips to different subcarriers in a random manner. This system is named FH-OFDM-DCSK [20]. In this paper, we propose a frequency-hopping OFDM-NR-DCSK (FH-OFDM-NR-DCSK) to take advantage of both the NR-DCSK [14] and the FH-OFDM-DCSK systems [20]. This system combines the security, energy, and bandwidth efficiency of FH-OFDM-DCSK with the good BER performance of the NR-DCSK system. The purpose of this research is to enhance the BER without increasing the system's complexity. Only β/P is produced instead of β chaotic samples, and each chip of reference and information-bearing signals is repeated p times. Moving average filters of size P are employed at the receiver to average the signal, minimizing the noise variance and enhancing the BER.

The rest of the paper is organized in the following way: section 2 proposes the FH-OFDM-NR-DCSK scheme. The theoretical BER analysis of the proposed system under a two-path Rayleigh fading channel and an AWGN channel is presented in section 3. The results of the simulations are presented in section 4 to demonstrate the improvement in BER. Finally, we conclude the paper in section 5.

2. FH-OFDM-NR-DCSK SCHEME

In this section, the transmitter and the receiver structure of the FH-OFDM-NR-DCSK system are presented.

2.1. FH-OFDM-NR-DCSK transmitter structure

Figure 1 shows the transmitter structure of FH-OFDM-NR-DCSK system. Firstly, the binary data is converted to bipolar symbol ∈ {-1, 1} through Mapping function, and then passed to a serial to parallel (S/P) converter, $d_i \in \{-1,1\}$, (i=1, 2..............., M), where M is the number of parallel transmitted bits. Then every bit is modulated by a chaotic signal. The k^{th} sample of the i^{th} reference and data modulated sequence $u_{i,k}$ is written as:

$$u_{i,k}=\begin{cases} x_k & for\ i=0 \\ d_i x_k & for\ i=1,..,M \end{cases} ,\ k=1,...,\beta/P \quad (1)$$

where x_k is the k^{th} chip of the reference chaotic sequence and β/P is the length of the sequence. Due to its simplicity and high performance, the chaotic signal is generated using the second-order Chebyshev polynomial function (CPF) [9], which is provided as:

$$x_{k+1}=1-2x_k^2\ ,\ k=1,..,\beta/P \quad (2)$$

where, $x_k \in$ (-1,1). Because the chaotic sequences have been normalized, their mean values are all zero, and their mean squared values are one, E[x_k]=0, E[x_k^2]=1. With various initial values, different chaotic sequences result.

Every sample of $u_{i,k}$ is P-times repeated to become the spreading factor β. Let the $u_{i,\lceil k'/P \rceil}$ represents a $u_{i,k}$ element of i^{th} chip repeated P times, k'=1,...,β and $\lceil * \rceil$ denotes the ceiling operation. The repeated reference sequence, $u_{0,\lceil k'/P \rceil}$, and the repeated sequence of the M information-carrying chips, $u_{i,\lceil k'/P \rceil}$, are arranged in matrix $A^{(M+1)\times\beta}$ according to:

$$A = \underbrace{\begin{bmatrix} u_{0,1} & \cdots & u_{0,1} & u_{0,2} & \cdots & u_{0,2} & \cdots & u_{0,\beta/P} & \cdots & u_{0,\beta/P} \\ u_{1,1} & \cdots & u_{1,1} & u_{1,2} & \cdots & u_{1,2} & \cdots & u_{1,\beta/P} & \cdots & u_{1,\beta/P} \\ u_{2,1} & \cdots & u_{2,1} & u_{2,2} & \cdots & u_{2,2} & \cdots & u_{2,\beta/P} & \cdots & u_{2,\beta/P} \\ \vdots & \vdots & & & & & \vdots & & & \\ u_{M,1} & \cdots & u_{M,1} & u_{M,2} & \cdots & u_{M,2} & \cdots & u_{M,\beta/P} & \cdots & u_{M,\beta/P} \end{bmatrix}}_{\beta \text{ columns (groups of } P)} \quad M+1 \text{ rows}$$

the matrix A is passing through a 2D frequency hopping function. Frequency hopping is performed to distribute reference and information-bearing chips equally across all occupied subcarriers. Algorithms 1-2 are used to demonstrate how the frequency hopping function is operated. The output sample of the frequency hopping function, is expressed as:

$$b_{i,k'} = u_{f(i,k'),k'} \quad , k'=1,..,\beta \tag{3}$$

where $f(*)$ represents the frequency hopping operation and $b_{i,k'}$ is the resultant sample. The output of frequency hopping operation is applied to IFFT function to produce the n^{th} OFDM modulated sequence which is expressed as:

$$t_{n,k'} = \frac{1}{\sqrt{N}} \sum_{i=0}^{N-1} b_{i,k'}\, e^{\frac{j2\pi,k'n}{N}} , n=0,..,M \tag{4}$$

where N is the IFFT points, N=M+1. And M, k', n, and i, respectively, are the number of data subcarriers, the chaotic chip time slot index, the index of the IFFT-modulated symbols in a chip time slot, and the subcarrier index. The resultant OFDM symbols are transmitted over the channels after P/S conversion and a cyclic prefix is added to prevent inter-symbol interference (ISI) [21].

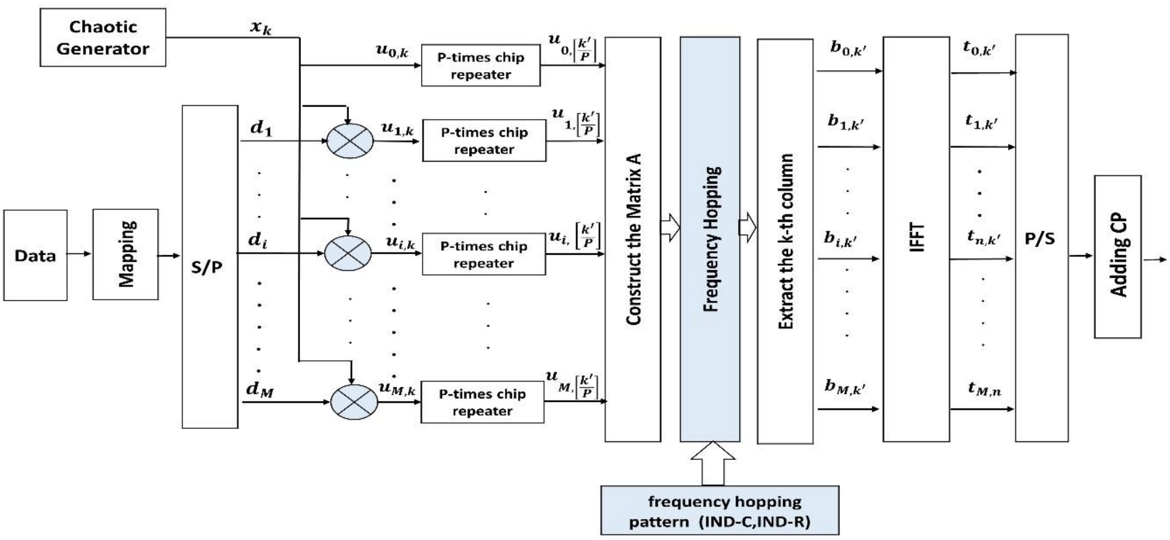

Figure 1. FH-OFDM-NR-DCSK transmitter

2.1.1. 2D frequency hopping pattern generation and operation

The frequency hopping pattern is generated using the index of the chaotic sequence generated from the logistic map described in (2). First, determine the initial value of the chaotic map x_o. Second, sort the chaotic sequence $\{x_o\ x_1 \dots\dots\dots\dots\ x_N\}$, where N is the length of the sequence. Finally, the decimal number that determines the positions is defined as the frequency hopping pattern. $\{q_o\ \ q_1 \dots\dots\dots\dots q_N\}$ dented by IND. Algorithm 1 describes the pseudo code of the 1D frequency hopping sequence generator using MATLAB program.

Using Algorithm 1, we generate two sequences with different initial values, $IND\_C^{(M+1)\times\beta}$ and $IND\_R^{(M+1)\times\beta}$. IND_C is used to permute each k^{th} column vector, while IND_R is used to permute each i^{th} row vector of the matrix A. The output matrix is the frequency hopping matrix, $B^{(M+1)\times\beta}$. The pseudo code of the 2D frequency hopping function is described in Algorithm 2. Similar to Liu *et al.* [20], to transmit the secret keys, we use the uncoordinated direct sequence spread spectrum approach established in [22].

Algorithm 1: generating frequency hopping sequence, IND

```
Input:  xo   <--initial value of the chaotic map
             N <-- size of the sequence array
Output: IND<-- Array of N integers number
LOOP Process
for n = 0 to N-1 do
x_{n+1}=1-2 x_n^2               //generating chaotic sequence
end for
for I = 0 to N-1 do      //sorting (x) and takes the indices
S = I
        for J = I + 1 to N-1 do

          If (x[J] < x[S]) then
              S = J
          end if
       IND[I]=S             //Save the indices in an array
       end for
tem = x[I]
x[I] = x[S]
x[S] = tem
end for
return IND
```

Algorithm 2: 2D Frequency hopping (FH) function:

```
Input: matrix A^(M+1)×β    <--represents input matrix of FH
       IND_C^(M+1)×β       <-- FH-sequence for each column
       IND_R^(M+1)×β       <-- FH-sequence for each row
Output: matrix B           <-- represents output matrix of FH
LOOP Process for each column
for C = 0 to β-1 do          // takes all the β columns
  for I = 0 to M do          // The loop for column chips
  BC [I, C] = A[IND_C[I, C],C] // Changing each column separately
  end for
end for
LOOP Process for each row
 for J = 0 to M do             // Take all the M rows
   for T = 0 to B-1 do         // The loop for row chips
 B[J, T] = BC[J, IND_R [J, T]] // Changing each row separately
  end for
 end for
 return B
```

2.2. FH-OFDM-NR-DCSK receiver structure

For our evaluation, we employed a widely known channel model in spread spectrum wireless communication systems. The model is based on a two-ray Rayleigh channel as shown in Figure 2, which is quite common in wireless communication [14], [19], [23]. The first path is the line of sight (LOS) with gain α_1 and time delay $\tau_1 = 0$. And the second path has a gain of α_2 and a time delay of τ_2.

The received symbols are applied to the FFT module for OFDM demodulation after serial to parallel conversion and CP removal to produce the following sequence:

$$b`_{i,k'} = \frac{1}{\sqrt{N}} \sum_{n=0}^{M} r_{n,k'}\, e^{\frac{-j\,2\pi ki}{N}}, k' = 1,\dots,\beta \quad (5)$$

where $r_{n,,k'}$ is the received symbol in the time domain. The signals are obtained in the frequency domain following the FFT transform. The OFDM demodulated symbols are then sent to the frequency de-hopping module. By regenerating the same frequency hopping pattern employed in the transmitter with the same initial values and reversing the operation that has been done by the transmitter, the chaotic modulated signals are restored to their original structure $u`_{i,\left\lceil\frac{k'}{P}\right\rceil}$, k'=1,.., β. The structure of the receiver is shown in Figure 3.

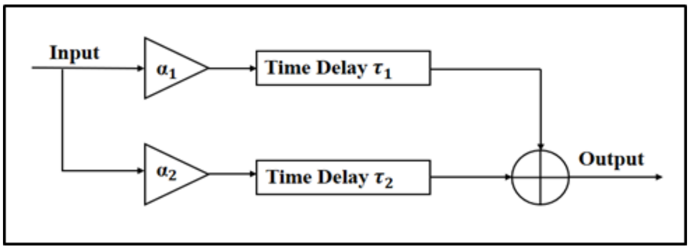

Figure 2. Two path Rayleigh fading channel model

Moving average filters of size P are used at the receiver to take the average of P-repeated symbols. The reference chips decode the M-information baring signals using correlators. The sent data is then recovered by decision circuits.The output of moving average filter with a period of P is described as follows:

$$u`_{i,k} = \frac{1}{P}\sum_{p=0}^{P-1} u`_{i,\left\lceil\frac{k'}{P}\right\rceil+p} \tag{6}$$

The channel coefficients are considered to be constant over the transmission duration of an OFDM-DCSK frame since the channel is assumed to have slow fading. As a result, the cannel frequency response is no longer affected by the subcarrier index or the k^{th} OFDM symbol [15]. The k^{th} , *k=1,..,β/P* received symbol at the i^{th} subcarrier before the multiplier of the decision variable is given by:

$$\acute{u}_{i,k} = \alpha_1 d\ d_i x_{i,k-\tau_1} + \alpha_2\ d_i x_{i,k-\tau_2} + \frac{1}{P}\sum_{p=0}^{P-1}\eta_{i,k+p} \tag{7}$$

where $\frac{1}{P}\sum_{p=0}^{P-1}\eta_{i,k+p}$ is a complex Gaussian noise after passing to an average filter corresponding to i^{th} subcarrier and k^{th} chip of the chaotic sequence. It has a zero mean and variance of No [24]. The real and imaginary parts of the complex noise are independent, with equal variance of No/2 [20].

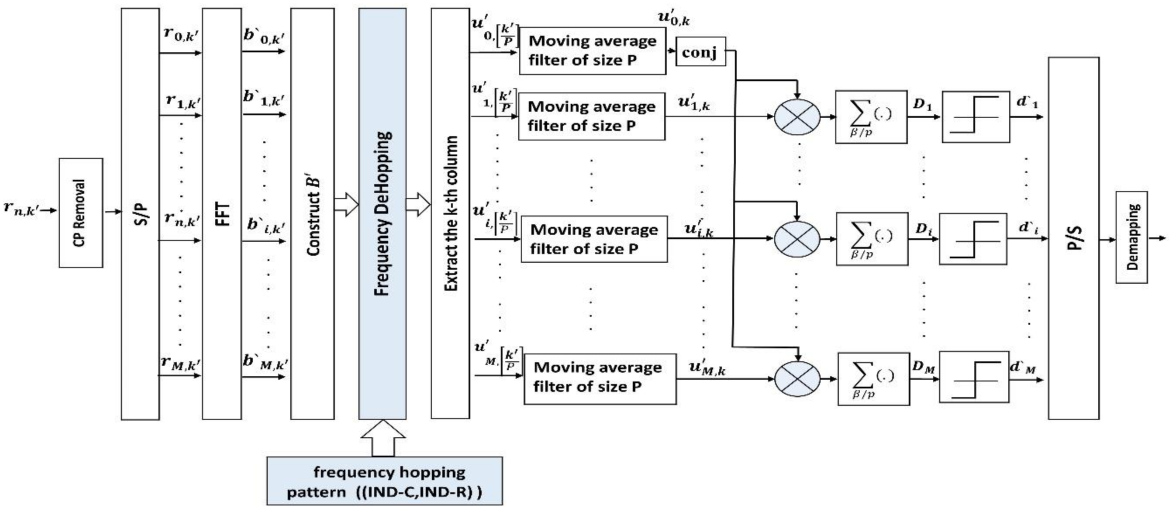

Figure 3. FH-OFDM-NR-DCSK receiver

3. PERFORMANCE ANALYSIS

In this part, we first calculate the suggested FH-OFDM-NR-DCSK scheme's energy efficiency. The BER performance under a two-path Rayleigh fading and AWGN channel is then derived using the Gaussian approximation method.

3.1. Energy efficiency

Because β/P chaotic chips are utilized to modulate M data bits, the system's energy efficiency is improved when compared to the NR-DCSK system. E_{data} and E_{ref} represent the energies utilized to send data bits and reference chips, respectively. In a conventional DCSK system, the transmitted bit energy, E_b, is provided by:

$$E_b = E_{data} + E_{ref} \tag{8}$$

we also assume that the data and the reference have the same energy.

$$E_{data} = E_{ref} = T_C \sum_{k=1}^{\beta} x_k{}^2 \tag{9}$$

And the transmitted bit energy,

$$E_b = 2\ T_C \sum_{k=1}^{\beta} x_k{}^2 \tag{10}$$

For the sake of simplicity, assume T_C=1, where T_C is the chaotic chip time duration. In NR-DCSK the reference length is reduced by factor of 1/P however, every chaotic is repeated p times, therefore the NR-DCSK has same energy as conventional DCSK.

$$E_{ref} = P \sum_{k=1}^{\beta/P} x_k{}^2 \tag{11}$$

One reference energy E_{ref} is shared by M transmitted bits in our FH-OFDM-NR-DCSK system. The transmitted energy for a given bit:

$$E_b = E_{data} + \frac{E_{ref}}{M} = \frac{M+1}{M} E_{data} = \frac{P(M+1)}{M} \sum_{k=1}^{\beta/P} x_k \tag{12}$$

Energy efficiency is calculated using the data energy to bit energy ratio (DBR) [14]:

$$DBR = \frac{E_{data}}{E_b} \tag{13}$$

The DBR of conventional DCSK and NR-DSCK systems is 1/2, which means that the reference is sent using half of the bit energy E_b.The DBR for the FH-OFDM-NR-DCSK system is M/(M+1). The reference energy is less than 4% of the total energy of the transmitted bit when M exceeds forty. Therefore, when compared to the NR-DCSK system, the FH-OFDM-NR-DCSK system has a higher energy efficiency.

3.2. BER derivation

In order to derive BER performance in this analysis, the Gaussian approximation (GA) approach is used, which can be evaluated for large spreading factors [25]. The mean and variance of the observation signal must be examined. We may conclude that various chaotic sequences created by different initial conditions are independent of each other because of the sensitive to initial conditions property [1]. Furthermore, the Gaussian noise and the chaotic sequences are independent. When the spread factor is large, chaotic signals traveling over several channels with various delay times are independent [26]. The equation below is actually true for large value of β/P:

$$\sum_{n=1}^{\beta/p} x_{n-\tau_k} x_{n-\tau_j} \approx 0 \quad for\, k \neq j \tag{14}$$

In our calculations, we assume that the delay is significantly less than the reference duration $0<\tau<<\frac{T_C\beta}{P}$, a scenario in which the ISI can be neglected [14].

For the sake of simplicity, we will use a chip with a duration of one (Tc=1). The observation signal D_i for the i^{th} subcarriers due to a two-path Raleigh fading channel is provided by:

$$D_i = \Re\left\{\sum_{k=1}^{\beta/P} \acute{u}_{i,k} \cdot \left(\acute{u}_{0,k}\right)^*\right\} \quad (15)$$

where $\Re$ is the real value, ( )* is the conjugate operation. The i^{th}bit is decoded by comparing the observation signal D_i to zero threshold.

$$D_i = \Re\left\{\sum_{l=1}^{L} \sum_{k=1}^{\beta/P} \left(\alpha_l d_i x_{k-\tau_l} + \frac{1}{P}\sum_{p=0}^{P-1}\eta_{i,k+p}\right) \cdot \left(\alpha_l x_{k-\tau_l} + \frac{1}{P}\sum_{p=0}^{P-1}\eta_{0,k+p}\right)^*\right\} \quad (16)$$

where L represents the number of paths, α_l represents the channel coefficient of the l^{th} path, and τ_l represents the delay of the l^{th} path. we consider a two-path channel with first path τ_1=0 is LOS path. And the τ_2 is the delay of second path.

$$D_i = \underbrace{\Re\left\{\sum_{l=1}^{2} \sum_{k=1}^{\frac{\beta}{P}} d_i|\alpha_l|^2 {x_k}^2\right\}}_{A1} + \underbrace{\Re\left\{\sum_{l=1}^{2} \sum_{k=1}^{\frac{\beta}{P}} \left(\alpha_l d_i x_{k-\tau_l} \frac{1}{P}\sum_{p=0}^{P-1}\eta^*_{0,k+p}\right)\right\} + \Re\left\{\sum_{l=1}^{2} \sum_{k=1}^{\frac{\beta}{P}} \left(\alpha_l d_i x_{k-\tau_l} \frac{1}{P}\sum_{p=0}^{P-1}\eta_{i,k+p}\right)\right\}}_{A2} + \underbrace{\Re\left\{\sum_{k=1}^{\beta/P} \left(\frac{1}{P}\sum_{p=0}^{P-1}\eta_{i,k+p} \frac{1}{P}\sum_{p=0}^{P-1}\eta^*_{0,k+p}\right)\right\}}_{A3} \quad (17)$$

A1 is useful information, A2 and A3 identify the interference that arises from Gaussian noise. Let E_b represent the transmitted bit energy for a particular data sequence and given as:

$$E_b = \frac{P(M+1)}{M}\sum_{k=1}^{\beta/P} {x_k}^2 \quad (18)$$

The mean of the observation signal D_i

$$E[D_i] = \frac{M}{P(M+1)} d_i \sum_{l=1}^{2} |\alpha_l|^2 E_b \quad (19)$$

The variance of a random variable Cp with P independent and identically distributed (i.i.d) Gaussian samples of c samples reduce [14] to:

$$Var\,[Cp] = \frac{Var[c]}{P} \quad (20)$$

The three elements of D_i are independent to each other. As a consequence, the variance of D_i is equal to the sum of these parts.

$$\mathrm{Var}\,[A1] = 0 \quad (21)$$

$$\mathrm{Var}\,[A2] = \frac{M}{P(M+1)}\sum_{l=1}^{2} |\alpha_l|^2 E_b \frac{No}{2P} + \frac{M}{P(M+1)}\sum_{l=1}^{2} |\alpha_l|^2 E_b \frac{No}{2P} = \frac{M}{P^2(M+1)} \sum_{l=1}^{2} |\alpha_l|^2 E_b No \quad (22)$$

$$\mathrm{Var}\,[A3] = \frac{\beta}{2P} \cdot \frac{No}{P} \cdot \frac{No}{P} = \frac{\beta No^2}{2P^3} \quad (23)$$

where E[ ] denotes the mean and Var[ ] denotes the variance. Because chaotic chip energies are deterministic variables, the decision variable at the correlator's output is a random Gaussian variable by means of the central limit theorem [27]. Therefore, the probability of bit error may be expressed:

$$BER(\alpha_l) = \frac{1}{2} p_r(D_i < 0|d_i = +1) + \frac{1}{2} p_r(D_i > 0|d_i = -1) = \frac{1}{2} erfc\left(\frac{E[D_i]|d_i=+1}{\sqrt{2.Var[D_i]|d_i=+1}}\right) \quad (24)$$

where $erfc(x)$ denotes the complementary error function, which is given as:

$$erfc(x) = \frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-z^2} dz \quad (25)$$

For the FH-OFDM-NR-DCSK system, the BER equation is:

$$BER(\alpha_l) = \frac{1}{2} erfc\left(\left[\frac{2(M+1)No}{M\sum_{l=1}^{2}|\alpha_l|^2 E_b} + \frac{\beta}{P}\left(\frac{(M+1)No}{M\sum_{l=1}^{2}|\alpha_l|^2 E_b}\right)^2\right]^{-\frac{1}{2}}\right) \quad (26)$$

Many techniques have been studied for determining the BER of chaotic systems, with the Gaussian approximation being the most generally used, which treats the transmitted bit energy E_b as constant [28]. For large spreading factors, this assumption offers a decent approximation of the performance. Based on this, the FH-OFDM-NR-DCSK system's total BER expression may be simplified as follows:

$$BER(\gamma_b) = \frac{1}{2} erfc\left(\left[\frac{2(M+1)}{M\gamma_b} + \frac{\beta}{P}\left(\frac{(M+1)}{M\gamma_b}\right)^2\right]^{-\frac{1}{2}}\right) \quad (27)$$

where $\gamma_b = \sum_{l=1}^{2} |\alpha_l|^2 \frac{E_b}{No} = \gamma_1 + \gamma_2$, $\gamma_1 = {\alpha_1}^2 \frac{E_b}{No}$, $\gamma_2 = {\alpha_2}^2 \frac{E_b}{No}$. And the average of $\gamma_1 and\ \gamma_2$ are denoting by $\overline{\gamma_1}$ =E $[\gamma_1]$= $E[{\alpha_1}^2]\frac{E_b}{No}$ and $\overline{\gamma_2}$ =E $[\gamma_1]$= $E[{\alpha_2}^2]\frac{E_b}{No}$ respectively. The probability density function of γ_b was represented in [3] as:

$$f(\gamma_b) = \begin{cases} \frac{\gamma_b}{\overline{\gamma_1}^2}.\ e^{-\gamma_b/\overline{\gamma_1}} & E[{\alpha_1}^2] = E[{\alpha_2}^2] \\ \frac{\gamma_b}{\overline{\gamma_1}^2 - \overline{\gamma_2}^2}\ .\ \left(e^{-\gamma_b/\overline{\gamma_1}} - e^{-\gamma_b/\overline{\gamma_2}}\right) & E[{\alpha_1}^2] \neq E[{\alpha_2}^2] \end{cases} \quad (28)$$

Finally, by averaging the conditional BER, the BER may be established.

$$\text{BER}= \int_0^\infty BER(\gamma_b)\ f(\gamma_b)d\gamma_b \quad (29)$$

The bit error performance of the system will be evaluated using this formula in the next section. It is possible to obtain the BER expression of FH-OFDM-NR-DCSK over AWGN by setting $\alpha_1 = 1$, α_2=0 and $\gamma_b = \frac{E_b}{No}$ in (27) and become:

$$BER = \frac{1}{2} erfc\left(\left[\frac{2(M+1)}{M}\frac{No}{E_b} + \frac{\beta}{P}\left(\frac{(M+1)}{M}\frac{No}{E_b}\right)^2\right]^{-\frac{1}{2}}\right) \quad (30)$$

It is worth noting that when P=1, the system's BER is comparable to that of FH-OFDM-DCSK [20].

4. SIMULATION RESULTS AND DISCUSSIONS

To evaluate the BER performance of the FH-OFDM-NR-DCSK system obtained in this paper and compare it to the DCSK and FH-OFDM-DCSK schemes, simulation results under AWGN and two-path Rayleigh fading channels validate and support the obtained BER equations. Figure 4 shows the BER performance over the AWGN channel with β=300 for the DCSK, FH-OFDM-DCSK and FH-OFDM-NR-DCSK with p=1,5 and 25 As expected, when p=1, the system is identical to that of FH-OFDM-DCSK. BER improves when p>1. This improvement is due to the averaging operation performed on the received signal, which decreases the noise power. In comparison to P=1, the gain in Eb/No at BER=10-4 for P=5 is 2.65 dB and for P=25 is 4.55 dB.

However, this trend does not hold true for all p values. We can clearly observe in Figure 5, which depicts the relationship between BER and P for different values of β, that when P is increased, the BER decreases until a certain value is reached, at which point the BER improvement stops. The reason behind this is that when P is increased, the noise is added to all the repeated chips of the reference and information-bearing signal, resulting in an increased noise level.

Despite the fact that small β values produce decent results, for large P numbers, we may be pushed to use moderate and high values, so the condition in (14) remains valid. Figure 6 demonstrates the proposed FH-OFDM-NR-DCSK system's BER performance for various P values as well as for the DCSK and FH-OFDM-DCSK under two-path Rayleigh fading for a spreading factor of β=300, FH-OFDM-DCSK, P=1, 5, and 30. The first and second paths, with delay spread of 0 and 2, have power gains of E(α_1^2)=2/3 and E(α_2^2)=1/3, respectively. As previously stated, the improvement in FH-OFDM-NR-DCSK performance is proportional to the value of P.

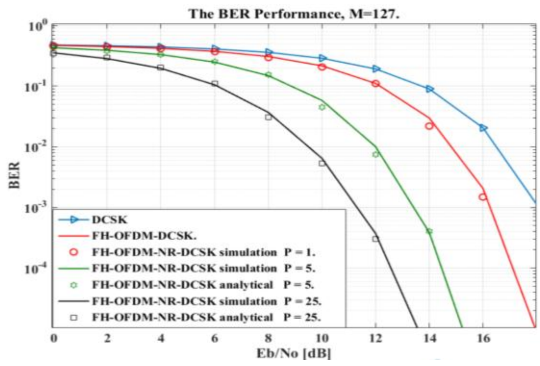

Figure 4. The BER performance over the AWGN channel with β=300 for the DCSK, FH-OFDM-DCSK, and FH-OFDM-NR-DCSK with P=1,5 and 25

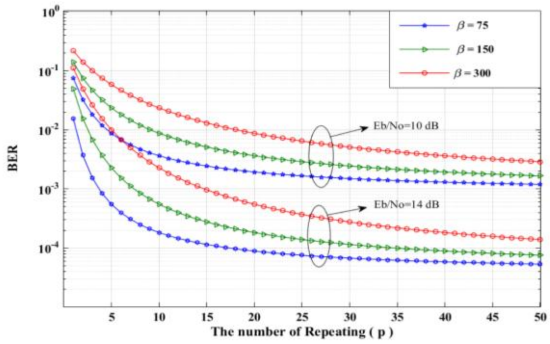

Figure 5. The BER performance of FH-OFDM-NR-DCSK verse the number of repeating (P) for different values of β

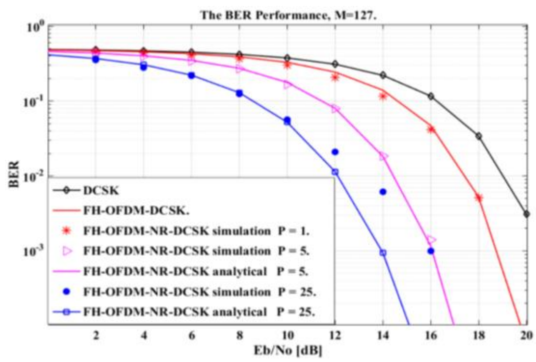

Figure 6. The BER performance under two path Rayleigh fading channel with β=300 and N=128, of the DCSK, FH-OFDM-DCSK and FH-OFDM-NR-DCSK with P=1,5 and 25

The analytical BER matches the simulation results for small and moderate values of P. However, for large values, the BER in simulation is higher than that in theory. This error is due to the fact that when P is large, the condition of P<< $\frac{T_C\ \beta}{\tau}$ is not fulfilled. As a consequence, ISI emerges. In comparison to P=1, the gain in Eb/No at BER=10^{-4} for P=5 is 2.65 dB and not increased for P=25 because of the effect of ISI. In both the Rayleigh fading channel and AWGN, the system outperforms DCSK and FH-OFDM-DCSK in terms of BER. The findings indicate that the system is effective at reducing noise, resulting in an improvement in BER.

Figure 7 shows how legitimate users and eavesdroppers perform in terms of BER. Lower BER and reliability can be obtained since the frequency hopping sequence is known to legitimate users. Eavesdroppers, on the other hand, can hardly learn the right keys that are used to generate the frequency hopping sequences, therefore they would be unable to extract the information even if they had only one right key or did not have both, due to the high BER.

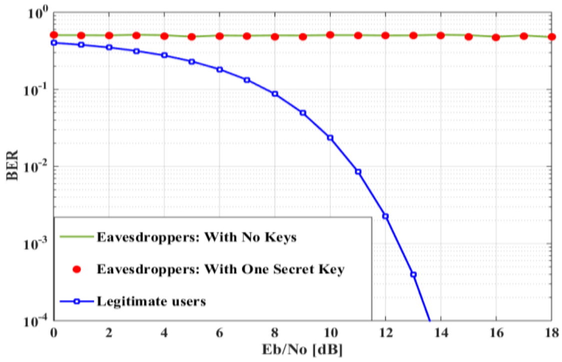

Figure 7. The BER performances of legitimate users and eavesdroppers

5. CONCLUSION

In this paper, a frequency hopping OFDM based noise reduction DSCK (FH-OFDM-NR-DCSK) has been proposed. This system is non-coherent, energy and bandwidth efficient, and has better BER than DCSK as well as FH-OFDM-DCSK. Frequency hopping is used to produce two-dimensional scrambling, which solves the DCSK security issue while also providing frequency and time diversity. This system uses moving average filters, which improve the SNR at the receiver. Instead of using β chaotic samples, β/P samples are used and each chip is repeated p-times. The noise variance was decreased by a factor of 1/P as a result of this approach. The system is energy efficient, with a DBR of M/(M+1). When M exceeds forty, the reference energy is less than 4% of the total energy of the transmitted bit. The performance of the proposed system is examined, and bit error rate equations for an AWGN and two-path Rayleigh fading channels are developed. The simulation results match the theoretical BER expressions, showing the accuracy of our method and supporting our approximations. To compare the proposed system's performance to that of the DCSK and FH-OFDM-DSCK, the simulated BERs are plotted with the same spreading factor, and the results demonstrate that the suggested system outperforms the DCSK and FH-OFDM-DSCK when P>1. We conclude that this system has succeeded in improving the BER performance without increasing the system's complexity.

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