Performance study of chaos-based DSSS and FHSS multi-user communication systems

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***Abstract*—Deployment of wireless sensor networks (WSNs) with a large number of nodes have reinstated interest in spread spectrum (SS) technologies as they allow to establish multiple access for nodes with simple hardware and limited power budget. Chaotic spreading is one of the still insufficiently explored areas which can lead to higher security and lower multiple access interference (MAI). This research is intended to bring new information about the performance of binary direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS) communication systems which employ chaos-based spreading codes and compare them against classical systems employing m-sequences. Unlike existing research, this investigation is based on the simulation of passband communication systems with up/down-conversion and respective filtering. Performance comparison in terms of bit error ratio (BER) versus signal-to-noise ratio (SNR) at the different number of users and MAI dependence on carrier frequency offset among users in case of additive white Gaussian noise (AWGN) channel are presented. Obtained results highlight several scenarios where chaotic-sequences-based binary DSSS and FHSS systems have advantages over classical solutions.**

***Index Terms*—Code division multiplexing, Communication systems, Passband, Wireless communication, Frequency hopping, Multiple access interference, Binary sequences, Chaos**

I. Introduction

Increasing interest in wireless sensor networks (WSNs) and internet of things (IoT) solutions is determined by the growing role of automation and machine intelligence as one of the key sources of well-being, sustainability, and development [1]. Communication technologies employed in WSNs vary a lot and strongly depend on the distance between sensor nodes, the intensity of the communication, availability of the resources, such as energy and frequency spectrum, and coexistence issues [2]. In the spread spectrum (SS) systems the processing gain which is achieved by sacrificing the transmission bandwidth allows achieving high robustness of the communication in applications with poor propagation conditions, low signal-to-noise ratio (SNR) and limited hardware capabilities. SS technology has been well-known for decades, however, a rise of WSNs paved the way to develop novel spreading schemes, including ones that employ chaos for the generation, synchronization, and encryption of the signals.

This paper is devoted to comparing chaos-based direct sequence spread spectrum (DSSS) and frequency hopping spread spectrum (FHSS) systems with classical ones employing m-sequences. Comparison is made using passband MATLAB Simulink models, i.e. including the radio frequency (RF) part.

This paper is organized as follows: Section II is devoted to the literature review and assessment of state-of-the-art (SoA) in the area of chaos-based SS, Section III explains chaos-based SS concept. While Section IV describes Simulink passband communication system models, Section V presents the obtained results and provides the analysis of them. Finally, Section VI draws overall conclusions about the research.

II. Related work

The first papers with the idea of using chaotic spreading sequences are dated back to 1994 [3], [4]. One of the first papers where chaos-based code division multiple access (CDMA) was analyzed is [5] whereas in [6] chaotic frequency hopping code division multiple access (FH-CDMA) is considered. While first researches mostly employed popular and simple generation methods, such as Logistic equation, later researches employed much more advanced methods, such as decimated samples continuous-time chaos signals [7], 3-dimensional chaotic maps [8], chaotic not only sequence itself but also the duration of the sequence [9] or spreading factor [10], [11]. In a research paper [12] it is proposed to use multiple orthogonalized chaotic sequences for non-sinusoidal subcarriers, therefore providing higher bandwidth. Converting this solution into a multiple access system would require inspection of inter-carrier interference at a non-zero shift.

Detailed and thorough mathematical models of binary chaos-based direct sequence code division multiple access (DS-CDMA) communication systems with wideband channels for the first time were presented in [13]. Closed-form formulas for the probability of bit error in single-user and multi-user scenarios. It was shown that an increasing number of users significantly degrades system performance. To address this problem publications [14], [15] propose a method for search and selection of optimized chaotic spreading codes which perform well at a certain number of simultaneous users.

Complete receiver solution for chaotic DSSS is presented in [10]. Paper [16] provides a theoretical analysis of chaos-based DS-CDMA communication system with multiple frequency-selective channels, i.e. multiple-input multiple-output (MIMO). Finally, opportunities for the unauthorized interception of chaotic DSSS are analyzed in [17].

III. System descriptions

A. Direct-Sequence Spread Spectrum System

Block diagram of asynchronous DSSS transmitter and receiver pair is shown in Fig. 1. This diagram is divided into the transmitter, common communication channel, and receiver parts. Transmitter has its own transmission start moment τ, randomly generated information bits $b(t)$ with bit period T_b and unique chaos-based spreading sequence $c(t)$ has chip duration T_c. Information bits $b(t)$ are spread by multiplying each information bit by a spreading sequence $c(t)$. An example of a product of the multiplication with a 7-chip long spreading sequence is shown in Fig. 2.

Multiplication product is up-converted to the carrier frequency and sent to the common communication channel. While the transmitted signal propagates through the common communication channel, additive white Gaussian noise (AWGN) noise $\eta(t)$ and propagation delay τ_L are added. In the case of AWGN channel, the signal $r(t)$ at the receiver's input is the sum of the transmitted signal and noise $\eta(t)$:

$$r(t) = b(t)c(t) + \eta(t) \tag{1}$$

In the multi-user system the common communication channel with n transmitters each having unique spreading sequence $c_i(t)$ and information bits $b_i(t)$. The received signal $r(t)$ is the sum of all transmitted signals and noise $\eta(t)$:

$$r(t) = \sum_{i=1}^{n} b_i(t)c_i(t) + \eta(t) \tag{2}$$

Received signal $r(t)$ is demodulated and despread by multiplying the received signal with local spreading sequence $c(t)$, resulting in signal $z(t)$. Spreading sequence $c(t)$ is bipolar and alternates between 1 and –1. If the receiver and transmitter are using identical and synchronized spreading sequences, then after despreading we get:

$$z(t) = c^2(t)b(t) + c(t)\eta(t) = b(t) + c(t)\eta(t) \tag{3}$$

because $c^2(t) = 1$. Despread signal $z(t)$ from the multi-user communication channel will always give a sum of information bits, noise, and correlated signals from other transmitters, that can be considered as additional noise called multiple access interference (MAI):

$$z_1(t) = b_1(t) + \sum_{i=2}^{n} b_i(t)c_i(t)c_1(t) + c_1(t)\eta(t) \tag{4}$$

Since detection is based on the correlation, after the despreading, integration is applied :

$$U = \int_0^{T_b} b(t) + c(t)\eta(t)dt \tag{5}$$

To convert U values into information bits $b(t)'$, threshold detector is used. This detector compares U values to zero. The correctness of the detector depends on noise power and MAI in the channel.

B. Frequency-hopping Spread Spectrum System

In FHSS system, the carrier frequency of the transmitter changes in a predefined manner multiple times during the symbol (bit) interval. This helps mitigate MAI in the multiuser communication channel when transmitted signals interfere with each other if carrier frequencies do not differ. Moreover, frequency hopping allows for overcoming frequency-selective fading. FHSS can be obtained by adding a frequency modulator at the output of DSSS baseband transmitter and in the case of binary DSSS, the obtained signal is equivalent to frequency shift keying (FSK). Demodulation of the binary FHSS signals can be performed by ordinary FSK receiver, which, in turn, can employ frequency modulation (FM) demodulator. It is worth mentioning that the employment of a full-scale FM demodulator for demodulation of FSK is not the best solution.

C. Generation of binary chaos-based spreading sequences

For spreading and despreading information bits in SS communication systems, binary spreading sequences can be used. In this paper, sequences are obtained from chaotic sequences that are generated by an algorithm that uses a logistic one-dimensional (1D) map with $\lambda = 4$ and $x \in (0; 1)$:

$$x_{\text{n+1}} = \lambda x_n(1 - x_n). \tag{6}$$

The initial value of x_0 is chosen randomly where $x \in (0; 1)$. Different initial x_0 values yield completely different sequences. The result of the Logistic map generates continuous values between 0 and 1, and conversion into discrete binary form is performed by applying the threshold rule:

$$c_n = \begin{cases} 1, x_n \geq \Theta \\ 0, x_n < \Theta \end{cases} \tag{7}$$

where $\Theta = 0.5$, conversion to binary sequence c_n can be performed. This process is illustrated in Fig. 3.

The binary chaos-based discrete-time sequence is then converted into a bipolar sequence by changing all 0 to –1, so it can be used in the spread spectrum system's multiplications. The continuous-time signal $c(t)$ is obtained by switching between the discrete values of c_n.

Using the aforementioned approach it is possible to generate a very large number of different binary sequences. However, not all of them will perform well in the multi-user SS communication system. To achieve optimal performance, the chaos-based sequences have been selected using the methodology presented in [15]. The obtained binary sequences are given in Table I.

IV. Simulation environment

A. Passband DSSS System Simulation.

Two passband DSSS and FHSS system simulations are made in MATLAB Simulink in accordance with the block diagram shown in Fig. 1. Simulink block-scheme of passband DSSS system which employs binary phase shift keying (BPSK) is shown in Fig. 4. This block scheme comprises two transmitters, receivers and bit error ratio (BER) counters,

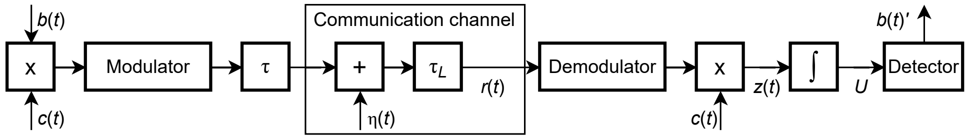

Fig. 1. Block diagram of asynchronous DSSS transmitter and receiver pair.

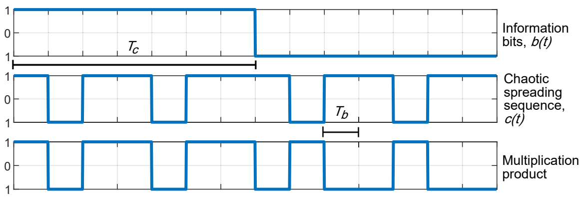

Fig. 2. Multiplication product of the information bits $b(t)$ and chaos-based spreading sequence $c(t)$.

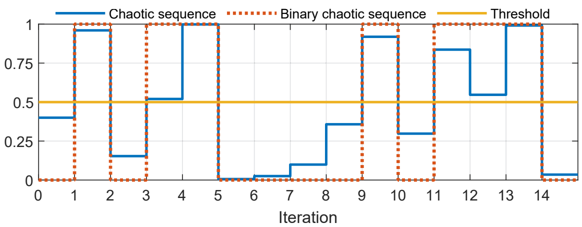

Fig. 3. Binary chaos-based sequence generation where $x_0 = 0.4$.

and a common communication channel with AWGN noise. Transmitters and receivers are almost identical, except for using different binary chaos-based spreading or pseudo-noise (PN) sequences. Transmitters start at the same time having equal transmission start moments, therefore, perfect sequence synchronization is assumed. Transmitter and receiver block-schemes are shown respectively in Fig. 5 and Fig. 6.

The transmitter is sending original data that is generated by the Bernoulli binary generator, and this data is converted to a bipolar signal so that it can be spread with chaos-based or PN sequence before BPSK modulation. Each transmitter sends its own data, defined by the generator's seed. This data is then modulated using a 50 kHz passband BPSK modulator, which is implemented from baseband BPSK modulator and up-conversion circuitry.

The receiver's bandpass filter is necessary to limit noise at the receiver's input. This filtered band is down-converted to the baseband using multiplication with a real 50 kHz sinewave signal. The obtained product is then filtered using a lowpass filter and down-sampled. Downsampled signal is then demodulated by baseband BPSK demodulator and multiplied by delayed chaos-based or PN sequence. Despread signal is integrated and detected, obtaining the received bits $b'(t)$ that can be compared to the original bits $b(t)$ using error rate calculation.

TABLE I
SELECTED BINARY SEQUENCES

1 -1 1 1 1 1 -1 1 -1 -1 1 1 1 1 -1 -1 -1 -1 -1 -1 1 -1 1 1 -1 -1 -1 -1 -1 1 -1 -1 1 1 -1 1 1 1 1 1 -1 -1 1 1 1 1 1 1 -1 -1 -1 1 1 1 1 1 -1 -1 -1 1 1 -1 -1
-1 1 1 1 -1 1 -1 1 -1 -1 -1 1 1 1 1 -1 1 1 1 -1 1 -1 1 1 1 1 -1 -1 -1 1 1 -1 -1 1 -1 1 -1 1 -1 -1 -1 1 -1 -1 1 1 -1 -1 1 1 -1 -1 -1 -1 1 1 1 1 -1 1 1 -1 -1
1 1 -1 1 1 1 1 1 1 1 -1 -1 1 -1 1 -1 -1 -1 -1 -1 -1 -1 -1 1 -1 -1 -1 1 1 1 1
1 -1 1 -1 1 1 1 1 -1 -1 1 -1 1 1 -1 1 -1 1 1 -1 1 1 1 1 -1 1 -1 -1 1 1 1
1 -1 1 1 -1 1 1 -1 1 -1 -1 1 1 -1 1
1 -1 1 1 1 -1 -1 1 1 1 -1 1 1 1 -1

TABLE II
SIMULATION PARAMETERS.

Parameter	Value		
Length of spreading sequences L_c	15	31	63
Data bit frequency, $1/T_b$, Hz	100	50	25
Chip frequency $1/T_c$, Hz	1500	1550	1575
User 1 carrier frequency	50 kHz		
User 2 carrier frequency	50 – 110 kHz		
FHSS FM frequency deviation	25 kHz		

FHSS modulated system's transmitter, and receiver Simulink diagrams are similar to those using DSSS just frequency modulation and demodulation blocks must be added. Transmitter's block-scheme is shown in Fig. 7 and receiver's block-scheme is shown in Fig. 8.

The main difference between DSSS and FHSS systems is the absence of explicit upconversion and downconversion in FHSS system. This is because FM built-in upconverter/downconverter in Simulink "Passband FM" blocks are used. FM frequency deviation is set to 25 kHz for every simulation. Parameters for the DSSS and FHSS simulations are presented in Table II.

V. RESULTS AND DISCUSSION

A. Comparison of BER versus SNR

In the system with 2 users, BER is calculated for each user, and a mean value is obtained. Chaos-based spreading and PN sequences of 15, 31, and 63-chip lengths are used. Passband DSSS simulations with BPSK modulation and FHSS simulation are tested with each sequence type and length. Each presented figure legend is used to show results obtained for simulated systems that use predefined sequence's length in chips, chaos-based or PN sequence's type, DSSS or FHSS modulations. It can be seen in Fig. 9 and Fig. 10 that employment of the chaos-based spreading sequences gives approximately the same BER values as PN sequences.

In the case of two users using a common communication channel with equal carrier frequencies and DSSS modulation, employed chaos-based spreading sequences produce worse results at the sequence length of 63 chips than same length

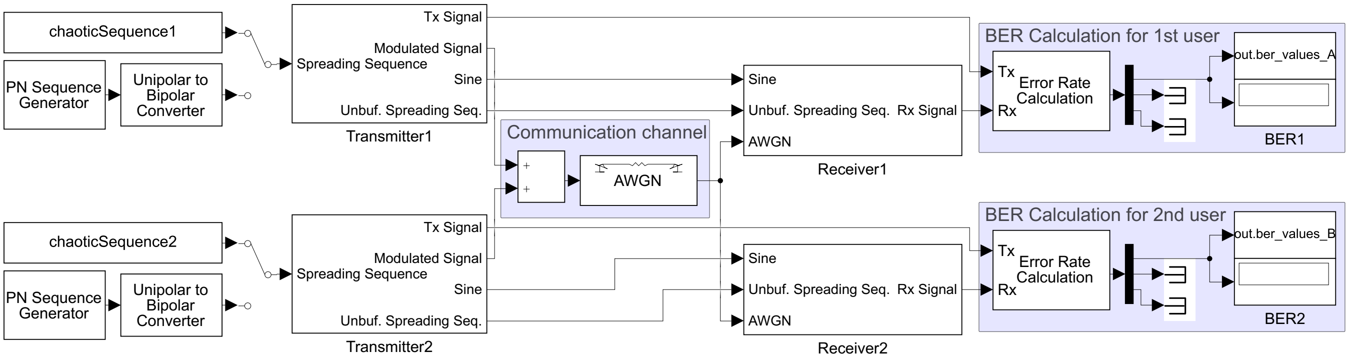

Fig. 4. Simulink block-scheme of two user DSSS.

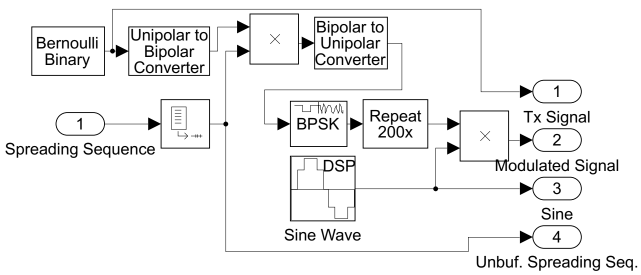

Fig. 5. Simulink block-scheme of DSSS transmitter.

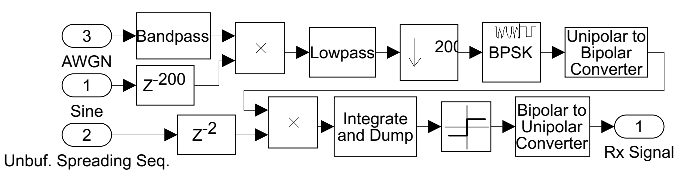

Fig. 6. Simulink block-scheme of DSSS receiver.

PN sequences, which can be seen in Fig. 11. 15-chip chaos-based and PN sequences give equal results, but at the length of 31 chips starting from SNR of –14 dB, the selected chaos-based sequence gives better results than PN sequence.

It can be seen in Fig. 12 that selected chaos-based sequences perform better than PN sequences at sequence lengths of 31 and 63, having a smaller mean BER value in two user

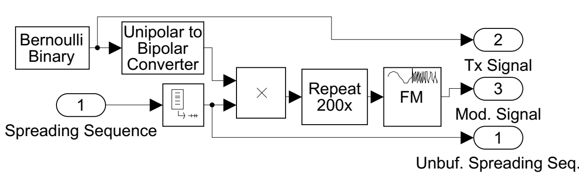

Fig. 7. Simulink block-scheme of FHSS transmitter.

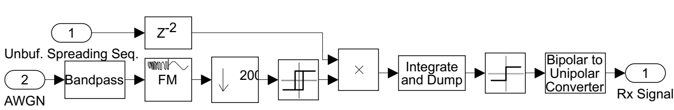

Fig. 8. Simulink block-scheme of FHSS receiver.

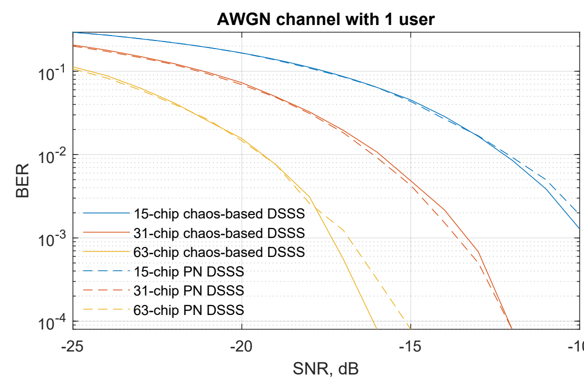

Fig. 9. BER results of DSSS simulation.

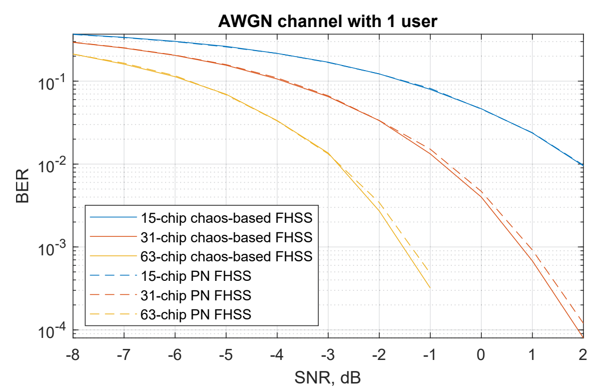

Fig. 10. BER results of FHSS simulation.

communication channel when SNR > –2 dB, transmitting on the same carrier frequency. Similar to DSSS modulation results, FHSS systems give equal results when using 15-chip chaos-based and PN sequences.

B. Assessment of BER versus the frequency offset between users

In the series of simulations, it was assessed how much chaos-based spreading mitigates MAI. For this purpose, in the multi-user communication system, one user gradually changed carrier frequency, and BER was assessed.

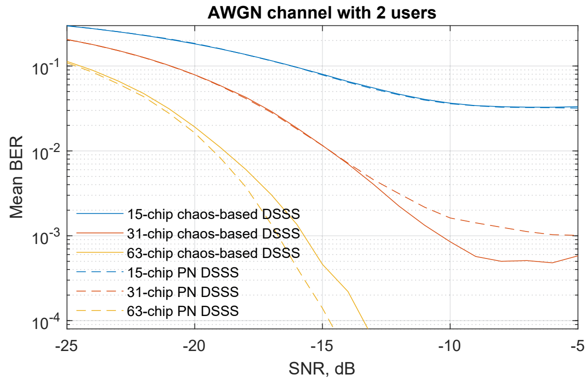

Fig. 11. BER results for simulation with 2 users using DSSS.

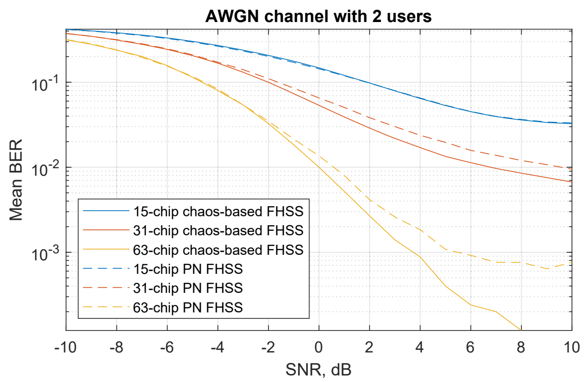

Fig. 12. BER results for simulation with 2 users using FHSS.

It can be seen from Fig. 13, that in DSSS modulated system BER of each user gradually decreases to the single user system's BER values when the carrier frequency difference between transmitters is around 20 kHz. If we look at the power spectral density (PSD) of the transmitted signal shown in Fig. 15, and the frequency response of the filter at the input of DSSS receiver shown in Fig. 14, we can conclude that there is no threshold effect and interference gradually decreases and single-user performance is approached when filtered parts of the spectra stop to overlap.

By adjusting the carrier frequency of the second user in

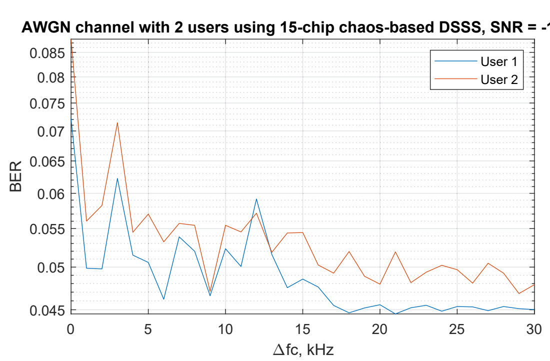

Fig. 13. BER results for simulation with 2 users using DSSS and 15-chip chaos-based sequence at SNR = –15 dB.

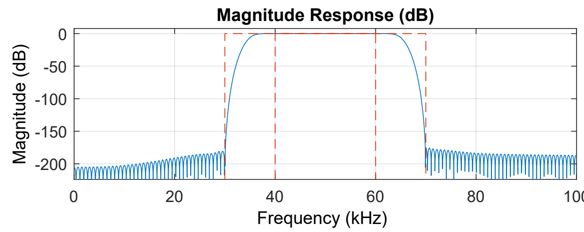

Fig. 14. Frequency response of bandpass filter at the input of DSSS receiver

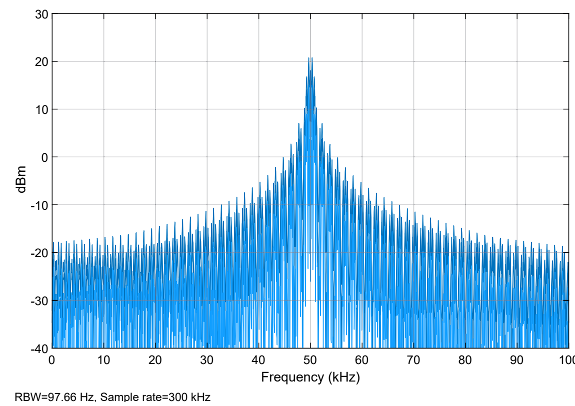

Fig. 15. Power spectral density at the output of DSSS transmitter.

FHSS modulated system, the mean BER changes, decreasing to the values of the single-user system when the frequency difference exceeds 50 kHz, which can be seen in Fig. 16. The PSD of the transmitted binary FHSS signal is shown in Fig. 18, whereas the receiver's bandpass filter's magnitude response, tuned to 50 kHz carrier frequency, is shown in Fig. 17. From these figures can be concluded that systems strongly interfere with each other unless filtered parts of their spectra stop overlapping. There is a clearly observable threshold effect.

VI. Conclusions

This paper is devoted to the performance assessment and comparison of spread spectrum (SS) communication systems that employ binary chaos-based spreading sequences. The per-

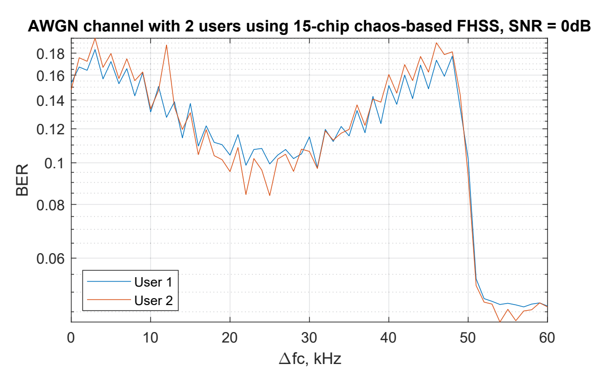

Fig. 16. BER for simulation with 2 users using FHSS and 15-chip chaos-based sequence at SNR = 0 dB.

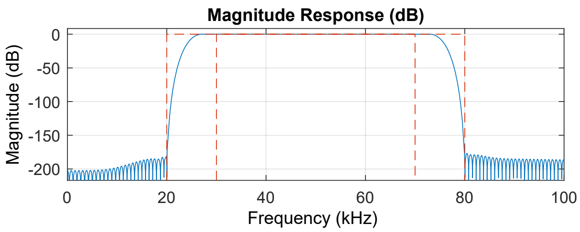

Fig. 17. Frequency response of bandpass filter at the input of FHSS receiver.

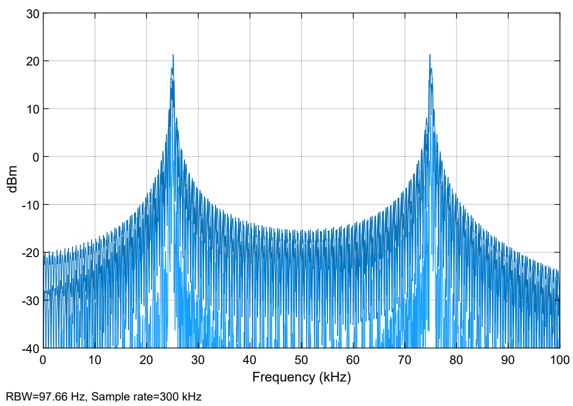

Fig. 18. Power spectral density at the output of FHSS transmitter.

formance is estimated using MATLAB Simulink simulations of passband communication systems.

Simulations have shown that in the case of single-user direct sequence spread spectrum (DSSS) and systems selected chaos-based sequences perform similarly to pseudo-noise (PN) sequences. This confirms the results presented in [5]. The same effect is observable in single-user frequency hopping spread spectrum (FHSS) systems too.

In the multi-user scenarios, there are configurations when binary chaos-based sequences lead to significantly lower multiple access interference (MAI). The selected sequences, shown in Table I, in two-user mode provide equal or better performance than PN sequences in case of 31-chip DSSS and all configurations of binary FHSS.

In the case of a small spreading factor (15 or less), chaos-based spreading sequences do not provide sufficient user isolation, and other multiple-access techniques, such as frequency division multiplexing (FDM) are required. A relatively high level of MAI is observed in the cases of partial frequency spectrum overlapping among the users. In binary FHSS mode even small overlapping of frequency spectra leads to unacceptable MAI.

Employment of non-binary chaos-based spreading sequences, especially in the case of FHSS, potentially could lead to new and valuable results.

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