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Research Article

# Transmitting the Chaotic Masked Audio Signal from a Single Channel

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Sprott chaotic system

**Abstract:** Data security is very crucial for communication systems. Encryption methods are frequently used to ensure security. Chaotic oscillators are used for the encryption of data because they produce signals that do not repeat themselves. Identical chaotic oscillators should be used and synchronized with each other in order to perform encryption and decryption processes healthily. In this study, the encrypted data and synchronization signal are transmitted to the receiver side using the frequency division multiplexing (FDM) method to realize the synchronization between two chaotic oscillators. High-frequency keying is used to increase the encryption quality of the signal to be encrypted on the transmitter side. Proportional-Integral-Derivative (PID) control is used to provide synchronization between two chaotic oscillators. The correlation test, peak signal to noise ratio (PSNR), mean square error (MSE) and spectral entropy were used to determine the accuracy relationship between the original signal and the decryption signal. As a result, simulation programs and numerical analysis verified the encryption success and reliability of the created system.

# Tek Bir Kanaldan Kaotik Maskelenmiş Ses Sinyalinin İletilmesi

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**Anahtar Kelimeler**
Frekans bölmeli çoğullama (FBÇ),
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Kaotik maskeleme ses sinyali,
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Sprott kaotik sistemi

**Öz:** Veri güvenliği iletişim sistemleri için çok önemlidir. Güvenliği sağlamak için şifreleme yöntemleri sıklıkla kullanılmaktadır. Kaotik osilatörler, kendilerini tekrar etmeyen sinyaller ürettikleri için verilerin şifrelenmesi için kullanılır. Şifreleme ve şifre çözme işlemlerinin sağlıklı bir şekilde yapılabilmesi için aynı kaotik osilatörler kullanılmalı ve birbirleri ile senkronize edilmelidir. Bu çalışmada, iki kaotik osilatör arasındaki senkronizasyonu gerçekleştirmek için frekans bölmeli çoğullama (FBÇ) yöntemi kullanılarak şifrelenmiş veri ve senkronizasyon sinyali alıcı tarafına iletilmiştir. Verici tarafında şifrelenecek sinyalin şifreleme kalitesini artırmak için yüksek frekanslı anahtarlama kullanılır. Oransal-İntegral-Türevsel (OIT) kontrol, iki kaotik osilatör arasında senkronizasyon sağlamak için kullanılır. Orijinal sinyal ile şifre çözme sinyali arasındaki doğruluk ilişkisini belirlemek için korelasyon testi, tepe sinyali gürültü oranı (TSGO), ortalama kare hatası (OKH) ve spektral entropi kullanıldı. Sonuç olarak oluşturulan sistemin şifreleme başarısı ve güvenilirliği simülasyon programları ve sayısal analizler ile doğrulanmıştır.

## 1. Introduction

Chaotic signals never repeat themselves periodically during the oscillation process, and chaotic signals are nonlinear. Because of these features, they have been used extensively in communication systems to prevent message signals from being masked and unauthorized users from accessing data (Lorenz, 1963; Chua, 1993; Sprott, 2000). The masking of the data with chaotic signals has also brought about the synchronization problem on the receiver side. Although the transmitter and receiver sides have identical chaotic oscillators, the difference between the oscillators in real-time operation occurs. Various synchronization studies have been conducted to eliminate this difference (Pecora & Carroll, 1990; Almeida et al., 2006; Yau, 2008; Atan, 2016; Elkholy et al., 2016). Due to the synchronization process, more than one transmission channel is used on the receiver and transmitter sides in chaotic communication systems (Kiani-B et al., 2009; Sheu et al., 2010; Vafamand et al., 2018). Many multiplexing methods are used to reduce the number of transmission channels. There are analogue and digital multiplexing methods such as Frequency-division multiplexing (FDM), Wavelength-division multiplexing (WDM), Time-division multiplexing (TDM), Code-division multiplexing (CDM) (Wu, 2010; Feng et al., 2010; Han et al., 2013; Sofi et al., 2017). FDM, one of the analogue multiplexing methods, is based on the principle that the signals to be carried in a transmission channel are placed and transported on the frequency band in accordance with the guard bands (Wu, 2010). The placement of the signals on the frequency band is realized by double side-band amplitude modulation (Pursley, 2002; Rao, 2018). In this study, mask and decoding processes were performed for two speech signals and two music signals. In the following sections, the experimental methods of the study, the proposed encryption scheme, synchronization, simulation and the results of security analysis methods such as Histogram Analysis, Spectral Entropy, Correlation Test, PSNR and MSE Test are given.

Today, frequency division multiplexing has different applications. Frequency division multiple access (FDMA) system is used to transmit image data using chaotic interleaving (Mehallel et al., 2021). In addition, Orthogonal frequency division multiplexing (OFDM) is used for multiplexing on 4G mobile lines. OFDM has also been used to transmit chaotic-based encrypted audio signal and used multi-carrier chaotic Communication (Chen et al., 2019; El-Zoghdy et al., 2020). Generalized frequency division multiplexing (GFDM) is a multi-carrier method for the secure transmission of data for the next generation communication band, 5G (Kumar et al., 2021). Another usage area of GFDM is for underwater systems to communicate with each other. In the study, acoustic communication of underwater systems was provided (Hebbar & Poddar, 2020). GFDM has been used not only in unencrypted but also in encrypted communication systems. For example, GFDM has been used in a structure based on the encoding of audio signals in hyperchaotic systems (Ameen & Hreshee, 2022).

## 2. Material and Methods

### 2.1. Audio signal masking in FDM

In the FDM method, masking and transmitting the audio signal can be achieved by increasing the width of the guard band. The guard band shown in Figure 1 is used to reduce the interference of signals in the same channel.

The guard bands in frequency division multiplexing allow signals to be separated from each other with eighth-order Butterworth filters at the receiver side. (Andrew, 1976). The wall effect of the Butterworth filter order is shown in Figure 2. Increasing the filter order contributes to separating signals transmitting the same channel.

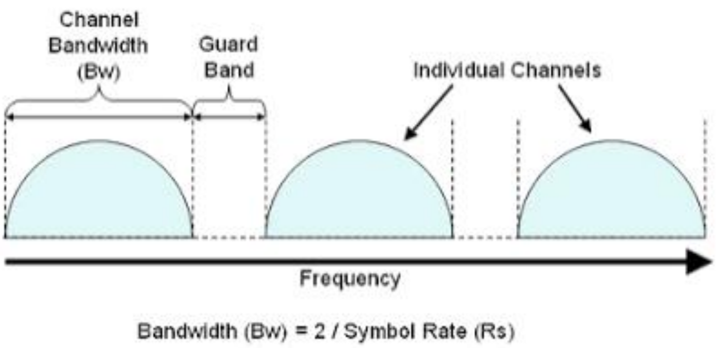


Figure 1. FDM channels and guard band relationship.

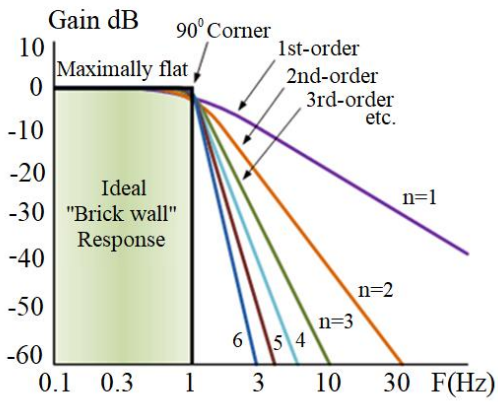


Figure 2. The wall effect of the Butterworth filter order.

## 2.2. Chaotic system

The Sprott chaotic oscillator, which is generally preferred, is chosen for masking the audio signals. For this purpose, the chaotic switching method was used in our system.

### 2.2.1. Sprott chaotic system

The mathematical expressions of the Sprott chaotic oscillator are given in Eq.1 (Chen et al., 2008; Almalı & Dikici, 2016).

$$
\begin{gathered}
x' = y' \\
y' = z' \\
z' = a.x + b.y + c.z + 2sign(x)
\end{gathered} \tag{1}
$$

$x$, $y$ and $z$ are the chaotic signals in equation 1. The initial values of the variables $x$, $y$ and $z$ are taken as $x(0) = 0$, $y(0) = 1$ and $z(0) = 0$ and $a$, $b$ and $c$ coefficients are taken as $a = -1.2$, $b = -1$ and $c = 0.6$. Figure 3 shows the x-y chaotic attractor and initial conditions of the Sprott chaotic system.

Chaotic signals show a very sensitive behaviour against the $a, b$ and $c$ coefficient values used in Eq. 1.

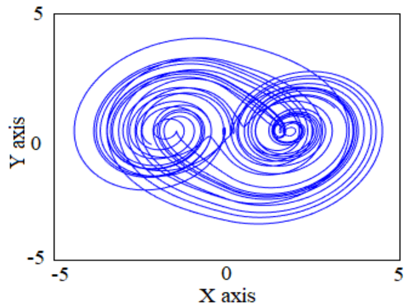


Figure 3. X-Y Sprott chaotic signals attractor.

### 2.2.2. Chaotic based key system

The general structure of a chaotic based key system is shown in Figure 4:

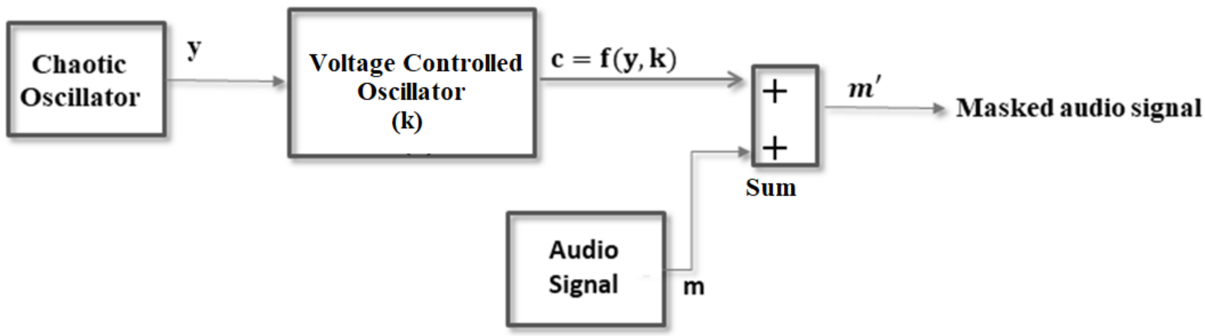


Figure 4. Chaotic base key system.

Thanks to the random key, the distortion of the data is increased, the signal of the data is entirely distorted, and its intelligibility is wholly eliminated. The random key minimized the data security problem and enabled the data to be encrypted.

## 2.3. Proposed masking scheme

The general structure of the FDM-based chaotic masking system is shown in Figure 5. This system's general purpose is to communicate between the receiver and the transmitter over a single channel.

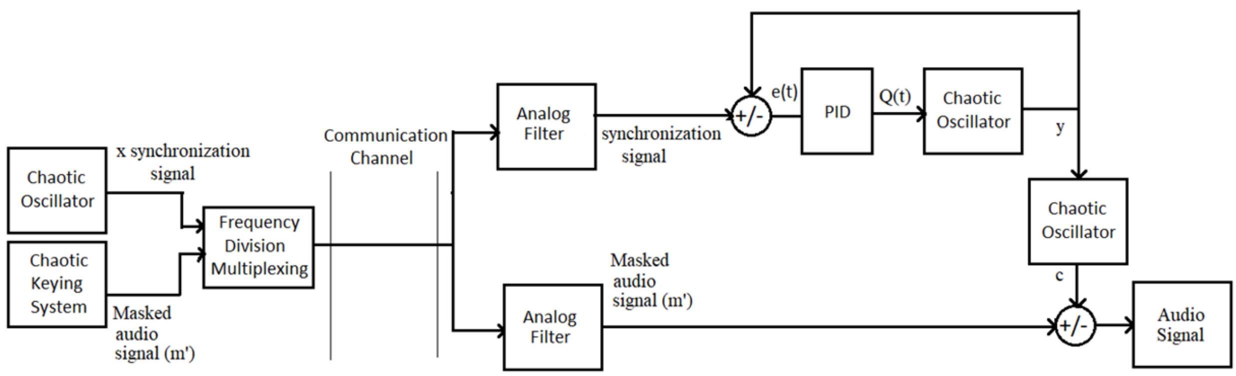


Figure 5. Chaotic masking system.

In order to eliminate unauthorized users' access to data in the transmission channel and the mathematical expression of the chaotic encryption system in Figure 5 is given in Eq. 2 and Eq. 3.

$$c = f(y, k) \tag{2}$$

$$m' = f(c, m) \tag{3}$$

In equations, c is the chaotic random key of the y chaotic signal, and k is the function of keying. The key c is obtained to encrypt the message signal (m). The message signal is encrypted, and m' masked audio signal is obtained by the key. In contrast, in algorithmic key-based encryption, random key generation is performed using a voltage-controlled oscillator depending on the dynamics of the Sprott chaotic oscillator (Keuninckx et al., 2017).

### 2.4. Synchronization

PID controller is used to synchronising identical chaotic oscillators in the system. Kp, Ki and Kd values, which are the coefficients of the PID controller, were found by trial and error with PID tuning. In order to find the Kp, Ki and Kd coefficients, the adjustment in the properties of the PID block diagram on MATLAB/Simulink was used, considering the rise time, the overshoot and how fast it reached the reference value. In this block diagram, it is possible to set how fast the system will respond or have robust behavior. In order to make the synchronization fast, it is crucial to reach the reference value quickly. The reason for this is to prevent data loss in communication. It is shown in Figure 6. The values found are Kp = 21.12, Ki = 11.81 and Kd = 7.65, respectively. The expressions of the chaotic oscillator used on the receiving side are given in Eq. 4 (Vaidyanathan et al., 2015; Almalı & Dikici, 2016).

$$\begin{aligned} x' &= y \\ y' &= z + Q(t) \\ z' &= a.x + b.y + c.z + 2sign(x) \end{aligned} \tag{4}$$

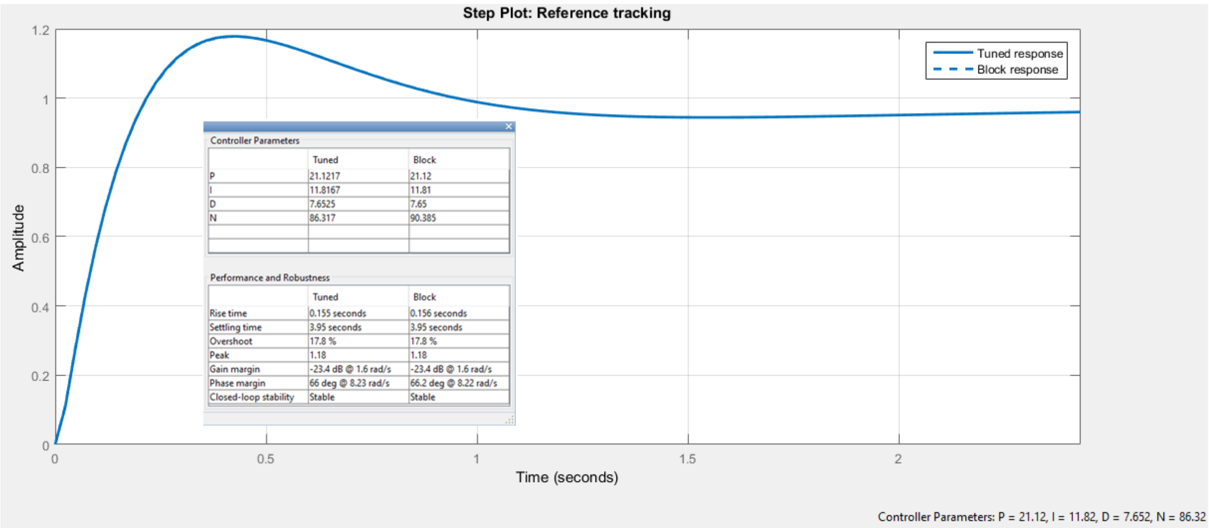


Figure 6. Synchronization of chaotic oscillators.

The only difference between the two chaotic oscillator equations is the $Q(t)$ value obtained from the PID output to synchronize the $y$ signal. The standard PID controller model of $Q(t)$ value is given in Eq. 5.

$$Q(t) = Kp.e(t) + Ki.\int e(t) + Kd.\frac{d(e(t))}{dt} \tag{5}$$

$$e(t) = X_m(t) - X_s(t) \tag{6}$$

$X_m(t)$ is x master chaotic signal and $X_s(t)$ is x slave chaotic signal. Master and slave chaotic signals are written in $Q(t)$.

## 3. Results

The following methods were used to test the safety and success of the masking and decoding method applied to the audio signal;

- Histogram Analysis
- Spectral Entropy
- Correlation Test
- PSNR and MSE Tests

### 3.1. Simulation of masking and decrypting

In this section, encryption and decryption processes were performed. It was observed that the audio signals were completely distorted, and the original audio signal was obtained after the synchronization provided during decoding. The original, masked and decoded versions of four different audio signals, including selected speech and music, as examples are given in Figure 7 and Figure 8.

Figure 7 and Figure 8 shows the original, masked and decoded versions of audio and music signals. Here, it has been observed that synchronization must be provided to reach the actual signal on the receiver side. It is seen that the encrypted state of the signal continues for a particular time until the synchronization is achieved. After synchronization, an intelligible sound was received on the receiver side. As the synchronization time increases, the data loss on the receiver side will also increase.

### 3.2. Histogram analysis

In this study, histogram analysis was performed to examine the distribution of original, masked, and decoded voice data. Histogram analysis shows the relationship between the similarity of the original, masked and decoded audio signals (Lagmiri et al., 2018; Huang et al., 2019). Figure 9 and Figure 10 show histogram plots of the original, masked and decoded signals of Speech 1, Speech 2, Music 1 and Music 2. When the histogram plots of the audio signals were analyzed, changes in masking were also observed due to the success of random switching. It has been observed that the success of speech signals in both masking and decoding processes is higher than that of music signals. Because the data distribution of the music signal is different from the data distribution of the speech signal. In addition to the human voice, the music signal also includes the sound of musical notes. Different amplitudes and rapid changes in music signals cause distortions in amplitude modulation.

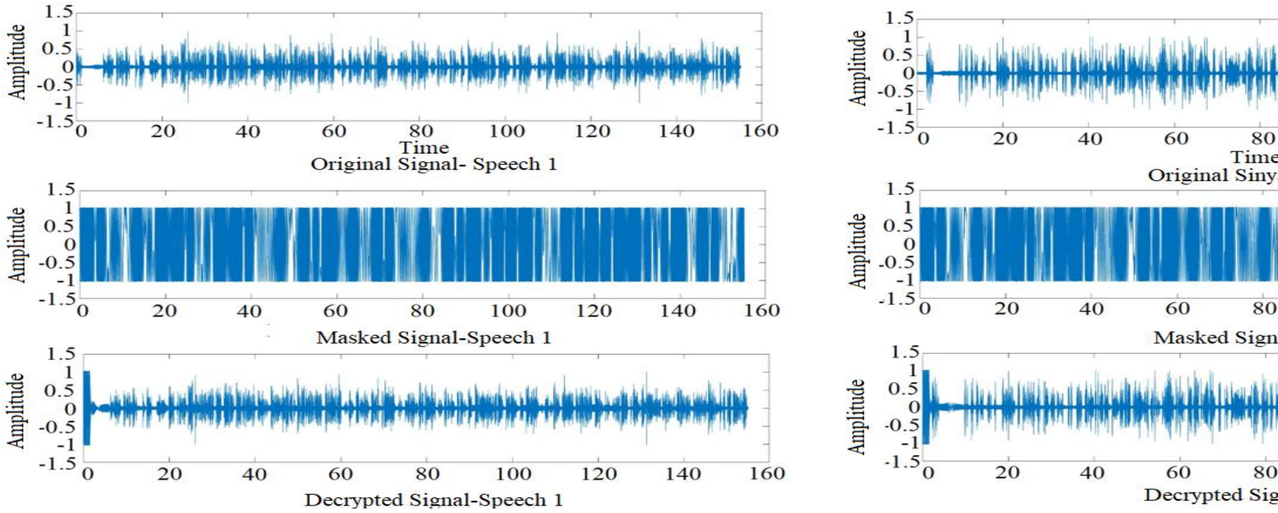


Figure 7. Audio (speech tests) signals.

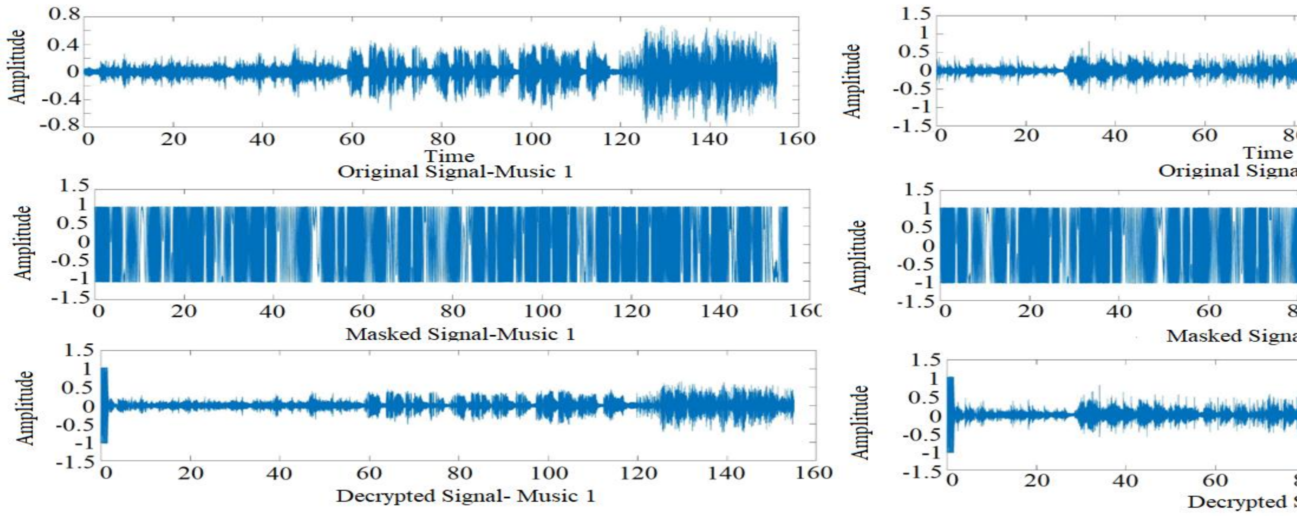


Figure 8. Audio (music tests) signals.

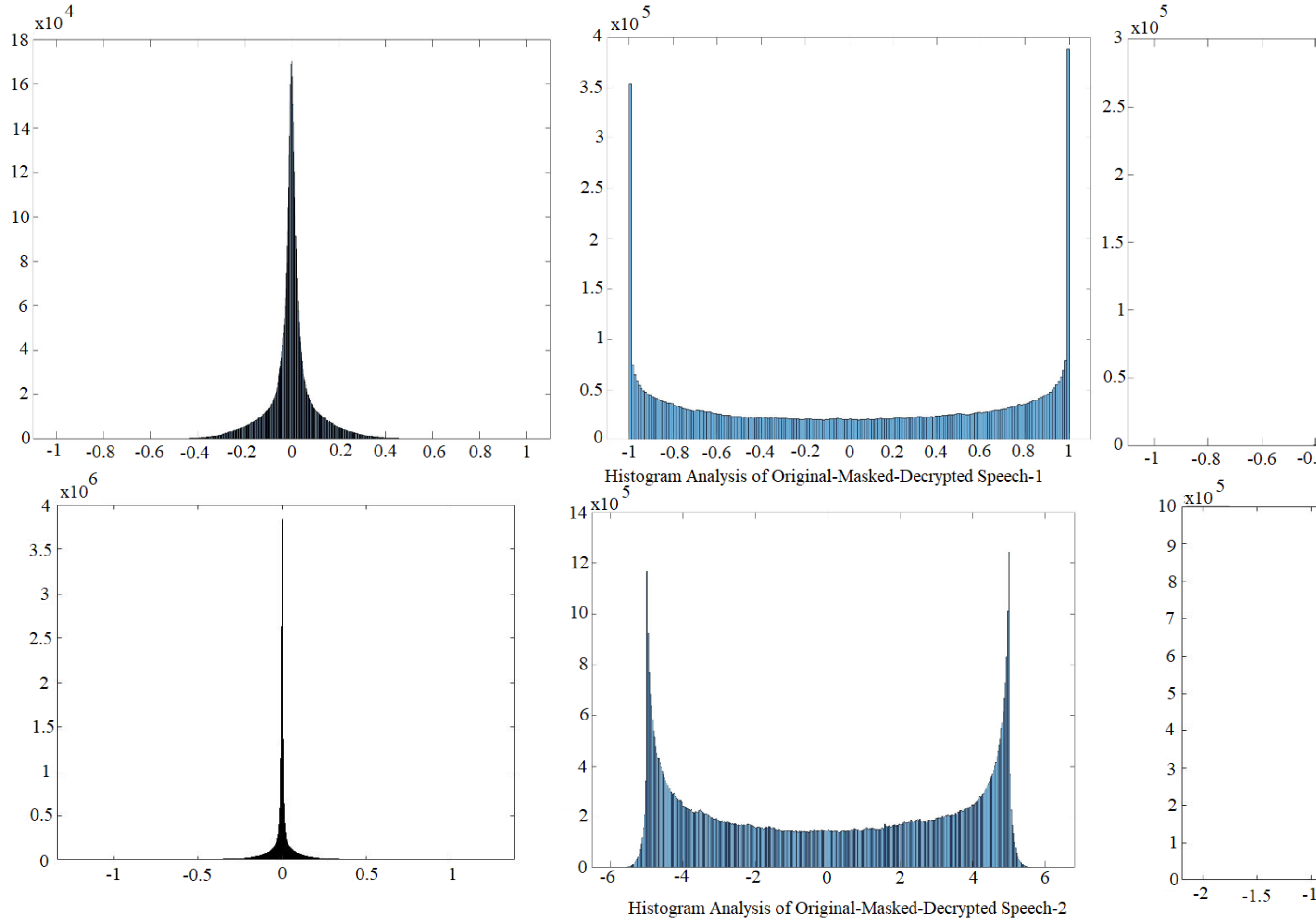


Figure 9. Histogram analysis of speech signals.

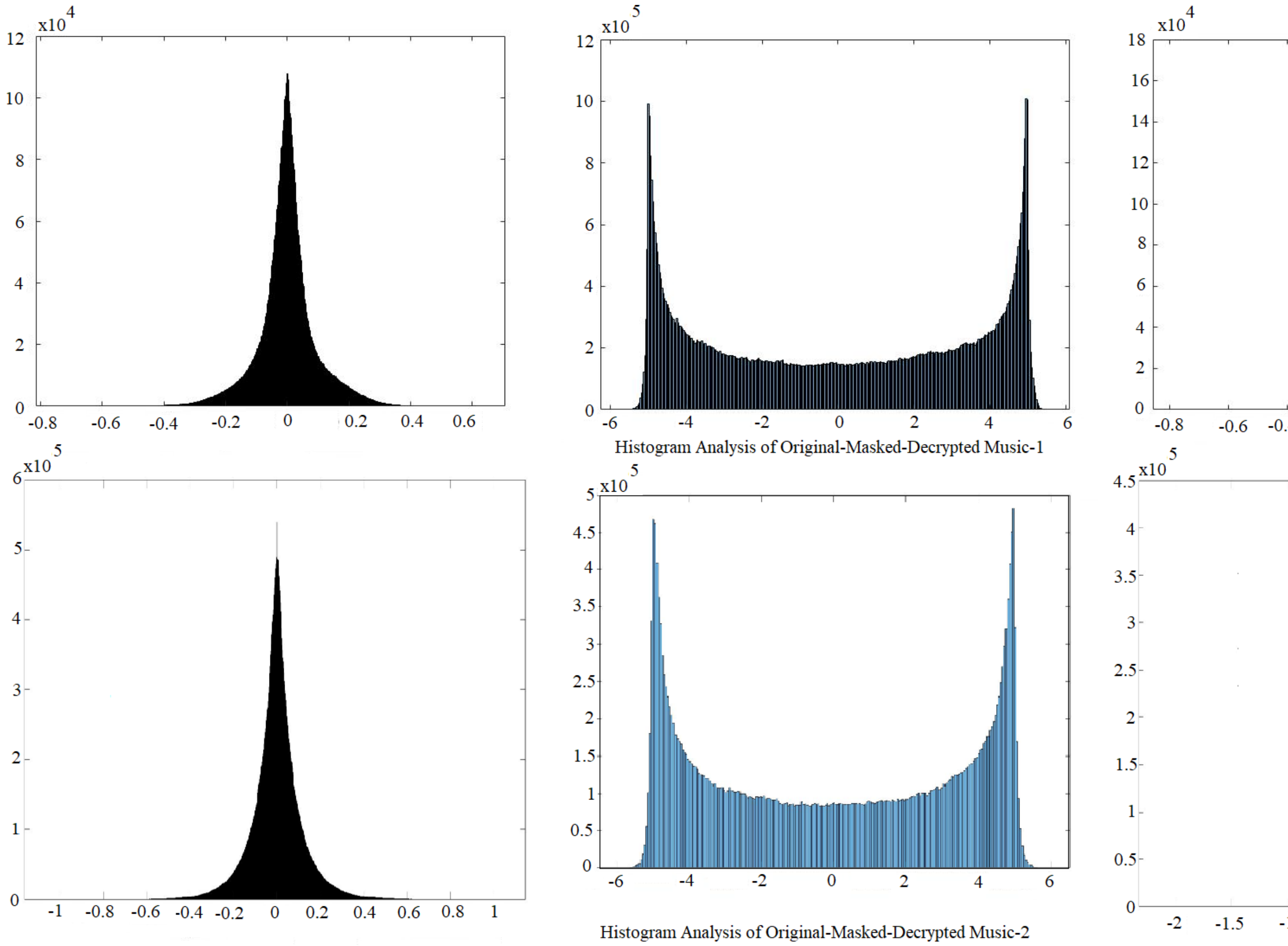


Figure 10. Histogram analysis of music signals.

### 3.3. Spectral entropy of audio signals

Spectral entropy is used to detect the region and movement of silences and speech activities in audio data. Thus, it is revealed whether the compared data belong to the same audio data (Toh et al., 2005). In spectral entropy graphs, the entropies of the original audio signals and the decoded audio signals locally alternate in value and motion. Masked signals do not resemble the original signal regarding value and movement. In the simulation, the difference between the decoded and original signals after synchronization is eliminated. The spectral entropy of the signal is shown in Figure 11 and Figure 12.

### 3.4. Correlation tests

Correlation test is a method used to examine the relationship between data. It can take values between -1 and 1. The correlation value close to -1 means a negative relationship, close to 1 means a positive relationship, and close to 0 means no relation between them (Sathiyamurthi & Ramakrishnan, 2017; Lagmiri et al., 2018). The mathematical expression of correlation is given in Eq. 7.

$$r_{xk} = \frac{c_{xk}}{\sqrt{V(x).V(k)}} \tag{7}$$

While $c_{xk}$ gives the covariance between the two data, $V(x)$ gives the variances of the original signal and $V(k)$ gives the variances of the masked signal. Correlation values are given in Table 1 to explain the relationship between the different audio signals used in the study and the masked and decrypted signals.

Table 1. Correlation of signals

| Correlation | Original/Masked | Original/Decrypted |
|---|---|---|
| Speech 1 | 0.1226 | 0.8200 |
| Speech 2 | 0.1463 | 0.8220 |
| Music 1 | 0.1172 | 0.8221 |
| Music 2 | 0.1505 | 0.7999 |

The correlation value determines the level of relationship between the signals. A value of 0.7 and above indicates that the relationship between the signals is positive and strong, and a value between 0-0.3 indicates that the relationship is positive and weak (Rumsey, 2016; Sathiyamurthi & Ramakrishnan, 2017; Lagmiri et al., 2018). In the correlation values obtained in this study, it was found that there was a robust relationship between the original and the decrypted signal and a weak relationship between the original and the masked signal. These correlation values were adequate according to the reference ranges given above.

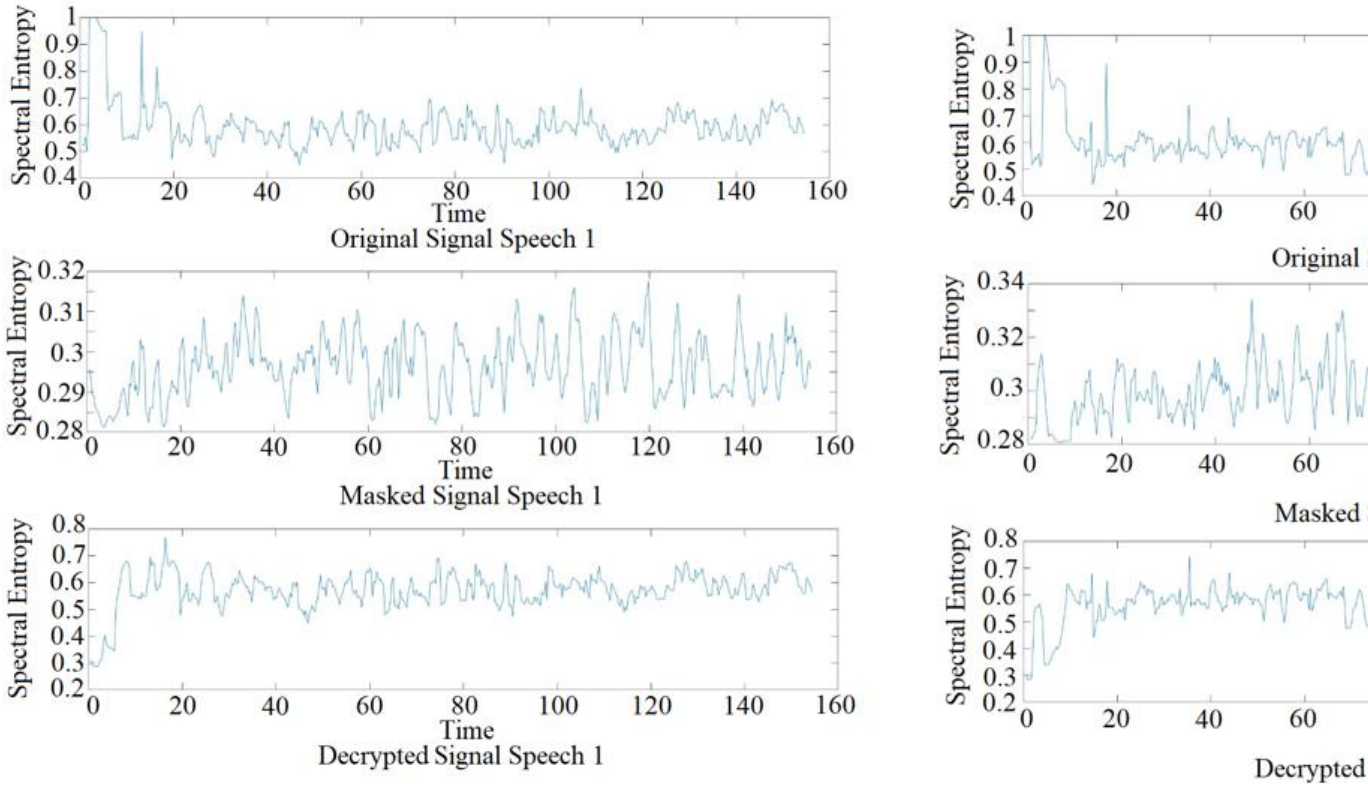


Figure 11. Spectral entropy of Speech signals.

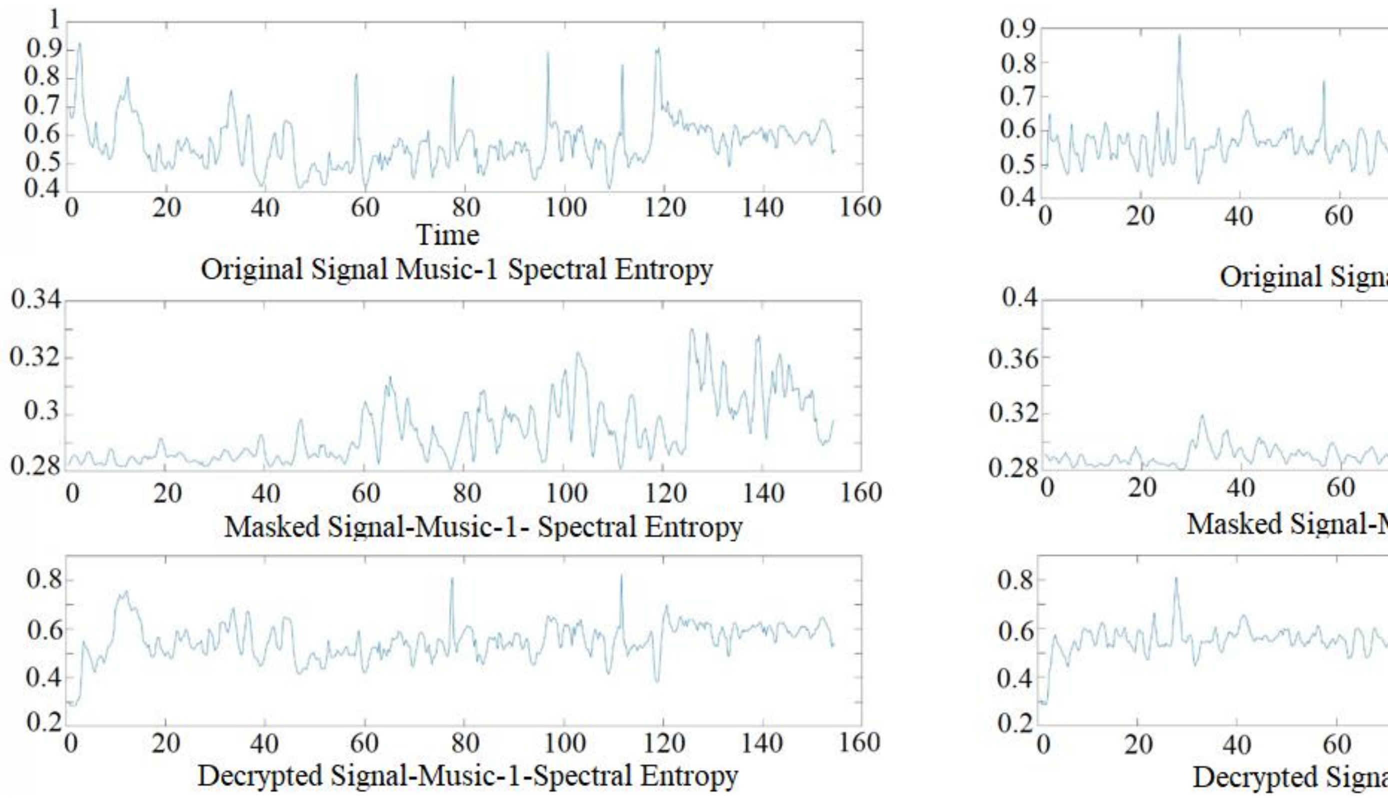


Figure 12. Spectral entropy of music signals.

### 3.5. PSNR and MSE tests

The PSNR test is the ratio between the maximum power that the original audio signal can reach and the strength of the encrypted audio signal. This ratio can also be made with the sound decrypted or with the original sound. However, this ratio should be low between original/ masked and high between original / decrypted (Sathiyamurthi & Ramakrishnan, 2017; Lagmiri et al., 2018). The mathematical expression used in calculating the PSNR value in Eq. 8 and the PSNR values of the different audio signals used in this study are given in Table 2.

$$PSNR = 10log\frac{n.x^2}{\|x-k\|^2} \tag{8}$$

Table 2. PSNR test of audio signals

| | **Speech 1** | **Speech 2** | **Music 1** | **Music 2** |
|---|---|---|---|---|
| Original/Decrypted | 25.73 | 24.74 | 32.62 | 31.07 |
| Original/Masked | 3.14 | 3.16 | 3.09 | 3.10 |

In Eq. 8, $n$ is the number of data, x is the original signal, and k is the masked signal. The high PSNR test value is due to the low MSE value between the original and decrypted signals. Similarly, the high PSNR value between the original and the masked is due to the high MSE (Almalı & Dikici, 2016). The PSNR test and MSE values were measured between 15-25 seconds of audio signals MSE values of the studied audio signals are presented in Table 3.

Table 3. MSE test of audio signals

| **MSE** | **Speech 1** | **Speech 2** | **Music 1** | **Music 2** |
|---|---|---|---|---|
| Original/Decrypted | 0.0027 | 0.0037 | 5.40e-04 | 7.81e-4 |
| Original/Masked | 0.9296 | 0.4826 | 0.4902 | 0.4893 |

When the mean squared error is close to or zero, the two data are considered to have a high similarity rate or the data to be the same. As can be seen in Table 3, it was observed that the mean of error squares between the original and decoded audio and music signals was low and close to zero. This gives the result that the decryption process is successful. Likewise, when the original and masked audio signals were compared, it was observed that the mean squared error value approached 1 and the two data were different from each other due to the increase in the amount of error, that is, the masking process was performed successfully.

PSNR value is used for sound quality comparison. The higher the PSNR value, the higher the sound quality. When the original and decoded music and audio signals were compared in terms of PSNR value, it was seen that the value did not fall below the acceptable values of 20-25 dB and the decoding process was successful. Likewise, when the original and masked signals were compared, it was concluded that the PSNR value was low and the encryption process was successful.

## 4. Discussion and Conclusion

In this study, four different audio signals are masked with the help of a signal from a chaotic oscillator. The masked audio signal and a second chaotic signal to synchronize the system were transmitted over a single channel with the FDM method. In this method, signals are placed in the frequency spectrum using DSB-SC amplitude modulation. In addition, shielding bands have been created to prevent overlap between signals. The synchronization of the second identical chaotic oscillator was achieved on the receiver side using the split synchronization signal PID controller. The masked audio signal was decrypted using the resulting chaotic signal. Some tests such as histogram analysis, PSNR, MSE, correlation test and spectral entropy were performed for the four different audio signals sampled. The distribution of masked and decoded audio data with the original audio data was examined in histogram analysis charts. It was observed that the data distribution of the original signal was similar to the decoded signal, with differences from the masked signal. It was seen in histogram analysis that masking and decoding in speech signals were more successful.

The masking process in the music signals was not as successful as the speech signals and was reflected in the MSE values. The mean frame error between the original music and the decoded music was lower than the speech signals, which is attributed to the ease of unmasking the music signals. For the original/decrypted signals, the MSE was calculated as 0.0027 for Speech 1 and 5.40e-04 for Music 1. Similarly, this effect was observed in PSNR values. It was observed that the PSNR values of the music signals were higher than the speech signals. For decoded signals, the PSNR of Speech 1 was calculated as 25.73, while the PSNR of Music 1 was calculated as 32.62.

The typical PSNR test value is between 20 and 40 (Thomos et al., 2005). Since the MSE values between the decoded and original audio signals are not zero, the PSNR value value between the original and decrypted is infinite. Spectral entropy was used to track the region and movement of the audio signals. In the spectral entropy simulations, it has been observed that the original and decoded audio signals are in the same ranges and follow each other. When the spectral entropies of the original and masked signals were compared, it was determined that the intervals and movements were different from each other.

Finally, correlation analysis was performed on the voice data. In the correlation test, the relationship between the signals was examined. The correlation test value between 0.1 and 0.3 indicates a weak and positive relationship, and values between 0.7 and 1 indicate a strong relationship. It was determined that the audio data had a positive and weak correlation between the original and masked signals and a positive and strong correlation between the original and decoded signals. In correlation tests of the Speech 1 signal, it was determined to be 0.1226 between the original and masked signals and 0.82 between the original decoded signals. Other correlation test values were found to be close to these values. It can be inferred from the results obtained in the study that the proposed system is reliable and successful in encryption. In addition, it is thought that using a single channel to transmit the masked audio signal and synchronization signal to the receiving side will provide public telephones and AM, FM broadcasting practical benefits in communication systems for analogue signals. It provides communication security, and slow narrowband fade is prevented.

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