Security enhancement for OFDM-UWOC system using 3-layer chaotic encryption and chaotic DFT precoding

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Security is one of the key issues in communications, but it has not attracted much attention in the field of underwater wireless optical communication (UWOC). This letter proposes a UWOC encryption scheme with orthogonal frequency division multiplexing (OFDM) modulation, based on the three-layer chaotic encryption and chaotic DFT (Discrete Fourier Transform) precoding. The three-layer chaotic encryption processes are bitstream diffusion, IQ (In-phase/Quadrature) encryption, and time-frequency scrambling. With multi-fold data encryption, the scheme can create a keyspace of $9.7 \times 10^{17}$, effectively resisting brute force attacks (BFAs) and chosen-plaintext attacks (CPAs). A 3-Gbps encrypted OFDM signal is successfully transmitted over a 7-meter water channel.

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1. Introduction

To meet the increasing demand for underwater activities, such as ocean explorations and rescue missions, underwater wireless sensor networks (UWSNs)¹⁰ are expected to be widely used in the near future. Underwater radio frequency (RF) signals are critically attenuated, and the transmission rate of underwater acoustic communication (UAC) is very low. By contrast, underwater wireless optical communication (UWOC) has the characteristics of high bandwidth and low latency, which plays a significant supplementary role in fulfilling the requirements of UWSNs.

UWOC is customarily regarded as highly secure compared with UAC since the light source is highly directional and has limited penetration distance in common waters⁸-³⁴. Thus UWOC has been less investigated to figure out and solve potential security issues, and its research activities mainly focus on improving data rate, transmission distance and link alignment⁶. From a wireless coverage perspective, security and privacy are also important in accessing information⁷.

A UWOC system does not inherently provide a secure transmission link, making it easy for attackers to capture information. In seawater, especially for the long-reach transmission, the scattering effect will make the received light spot much larger than the detection area, thereby increasing the risk of signal eavesdropping. Besides, eavesdroppers can place a mirror or diffraction grating somewhere between the transmitter and receiver to tap light from the line-of-sight beam. To reduce the difficulty of alignment, omni-directional light source and wide-beam laser diode (LD) are also widely used in UWOC, which undoubtedly increase the probability of information leakage. Simultaneously, potential attackers may also use the non-line-of-sight channel formed by the scattered light, with increased concealment. Currently, there are not many solutions available to address UWOC security. Underwater quantum communication generally supports a low communication rate (< 1 Kbit/s)¹³-¹⁵. Ref [16] and [17] used phase deflection and higher-order modulated stream to encrypt data respectively. Chaotic encryption technology has excellent pseudo-randomness and sensitivity to initial conditions. In [18], optical discrete multi-tone (DMT) data was encrypted by digital chaos, which verified the feasibility of chaotic encryption in UWOC. The above-mentioned encryption schemes¹⁶-¹⁸ have a low encryption dimension and a small key space, which are vulnerable to attack after statistical analysis. Furthermore, they all failed to consider the extremely threatening chosen-plaintext attacks (CPAs), thereby not enough for higher safety requirements.

In this letter, we present a security-enhanced OFDM scheme based on 3-layer chaotic encryption and chaotic discrete Fourier transform (DFT) precoding in a UWOC system, which can simultaneously guarantee sufficiently high security and transmission performance. The application of multiple hyperchaotic maps and multi-fold data encryption can improve the key space, and reduce the risk of the scrambling method and chaotic model being destroyed by statistical analysis. Multiple hyperchaotic maps generate masking factors, implementing bitstream diffusion encryption, IQ (In-phase/Quadrature) encryption, time-frequency dimensional scrambling, and chaotic DFT precoding in OFDM. The chaotic DFT precoding matrix is generated to reduce the peak to average power ratio (PAPR) and bit error rates (BERs). The chaotic DFT precoding
matrix is obtained by introducing chaotic sequences into the standard DFT matrix for phase encryption and column permutation. Hence, it is more difficult to crack than the encrypted DFT matrix in ref [18] and [23]. To verify the feasibility of the scheme, a 3-Gbps encrypted 16-QAM OFDM signal is successfully demonstrated over a 7-m UWOC link. The encryption system is tested and analyzed to have higher security with a key space of $9.7 \times 10^{132}$ and can resist brute force attacks (BFAs) and CPAs, achieving the higher confidentiality of information transmission.

2. Principles

The concept of the proposed security-enhanced OFDM system for UWOC based on 3-layer chaotic encryption and chaotic DFT precoding is shown in Fig. 1. The key-driven hyperchaotic maps are used to generate masking factors. It has been proved that signals encrypted by low-dimensional chaotic maps are not always safe[10]. Hyperchaotic maps can generate dynamic trajectories with more randomness in high dimensional space and require more key parameters to recover. Hence, it is much more difficult for eavesdroppers to steal information from hyperchaotic encrypted signals than low-dimensional ones. At the transmitter, the input data is encrypted by bidirectional diffusion and then mapped to QAM for IQ encryption. Subsequently, the OFDM frame is further scrambled in the time-frequency dimension[25,26]. Finally, chaotic DFT precoding is employed to reduce the PAPR. The application of multi-hyperchaotic encryption can effectively hide the original information and increase the keyspace. The signal demodulation and decryption operation at the receiver is the reverse of the transmitter.

**2.1 Diffuse encryption**

Bidirectional diffusion in cryptography makes each bit in the plaintext affect many bits in the ciphertext. Here, a 4-dimensional (4D) hyperchaotic Chen system is applied to generate chaotic sequences for bidirectional diffusion[20]:

$$\begin{align*}
\dot{x}_1 &= a_1 (y_1 - x_1) + u_1 \\
\dot{y}_1 &= d_1 x_1 - x_2 x_3 + c_1 y_1 \\
\dot{x}_2 &= x_1 y_2 + b_1 z_1 \\
\dot{y}_2 &= y_1 z_2 + r_1 u_1
\end{align*}$$

(1)

When $a_1=35$, $b_1=3$, $c_1=12$, $d_1=7$, and $0.085 \leq r_1 \leq 0.798$, the system is in a chaotic state. From Eq. (1), four chaotic sequences $X_t = \{x(t), y(t), z(t), u(t)\}$, and $U_t = \{u(t)\}$ can be obtained. The key1 of bidirectional diffusion is \{0.016, 0.01, 0.01, 0.01\}. The specific diffusion process is as follows:

**Step 1.** Original data and chaotic sequence pre-processing. To improve the efficiency of processing data, the original bit stream is first converted into a data stream $P$ with $t (t=8)$ bits as a unit, and the length of $P$ is denoted as $L_P$. A new chaotic sequence $S_1$ is composed of sequences $X_t$ and $Z_t$, and the combination process is $S_1 = \{X_t(j), Z_t(j)\} j=1, 2, ..., L_{P/2}$. Similarly, $Y_t$ and $U_t$ form a new sequence $S_2$. The sequences $S_1$ and $S_2$ have the same length as $P$ does, and they are further processed as:

$$\begin{align*}
K_1(t) &= \text{mod}(\text{floor}(|S_1(t)| - \text{floor}(|S_1(t)|)) \times 10^{15}), 2^8) \\
K_2(t) &= \text{mod}(\text{floor}(|S_2(t)| - \text{floor}(|S_2(t)|)) \times 10^{15}), 2^8)
\end{align*}$$

(2)

The function mod($x, 2^8$) returns the remainder divided by $2^8$, floor($x$) is rounding down. $K_1$ and $K_2$ sequences, both with the length of $L_P$, consist of integers in the range of 0–255.

**Step 2.** Utilize $K_1$ to encrypt the plaintext $P$ by the XOR operation to form the encrypted data $C_1$.

$$C_1(i) = C_1(i-1) \oplus P(i) \oplus K_1(i)$$

(3)

Where “$\oplus$” is bitxor operation, and $i=1, 2, ..., L_{P}$. When $i=1$ is a particular case, we set $C_1(0)$ to 112 in the experiment.

**Step 3.** Let $C_1'(0) = C(L_P)$ and use Eq.(4) to get bidirectional diffusion of $C_1'$.

$$C_1'(i) = C_1'(i-1) \oplus C_1(i) \oplus K_2(i)$$

(4)

Step 2 can diffuse the plaintext into the ciphertext to different degrees but fail to spread globally due to the single direction of the diffusion, and the following plaintext cannot be diffused to the preceding ciphertext. Hence, using bidirectional diffusion, each binary plaintext information is fully diffused into the ciphertext to generate an utterly dynamic ciphertext. When the plaintext is changed, the entire ciphertext will produce irregular changes, which can effectively resist the CPAs.

**2.2 IQ encryption**

Then the first layer of encrypted data $C_1'$ is converted to binary data for QAM mapping to obtain symbol sequence $W$. The hyperchaotic logistic mapping is used for IQ encryption and is defined as[21]

$$\begin{align*}
x_{n+1} &= 4\lambda x_n (1 - x_n) + \gamma y_n \\
y_{n+1} &= 4\lambda y_n (1 - y_n) + \gamma x_n
\end{align*}$$

(5)

Where $\gamma = 0.1$, and $\lambda_1, \lambda_2 \in [0.65, 0.9]$. The values of the generated sequences $X_2 = \{x(t)\}$, and $Y_2 = \{y(t)\}$ range from 0 to 1. The key2 of IQ encryption in the second layer is $\{\lambda_1=0.9, \lambda_2=0.9, x_0(0)=0.01, y_0(0)=0.12\}$. To generate IQ-encrypted sequences, the post-processing of $X_2$ and $Y_2$ to obtain the sequences $R$ and $I$ are described as

$$\begin{align*}
R(i) &= 1 - \text{round}(X_2(i)) \times 2 \\
I(i) &= 1 - \text{round}(Y_2(i)) \times 2
\end{align*}$$

(6)

Where $R(i), R(i) \in [1,1]$ and two sequences $R$ and $I$ are used to encrypt the real and imaginary parts of the QAM symbol, respectively.
The encryption for the \(k\)th QAM symbol \(W_k\) in the symbol sequence can be expressed as:
\[
C_k(k) = \text{Re}(W_k) \cdot R(k) + j \cdot \text{Im}(W_k) \cdot I(k)
\] (7)

### 2.3 Time-frequency dimensional scrambling

After completing the IQ encryption in the second layer, the OFDM frames are scrambled in the time-frequency dimension\(^{[27,28]}\), as shown in Fig. 2. The third layer of encryption and chaotic DFT precoding apply a hyperchaotic Lorenz system, which is defined as follows:\(^{[22]}\):
\[
\begin{align*}
\dot{x}_1 &= a_1 (x_1 + y_1) \\
\dot{y}_1 &= c_1 x_1 y_3 - x_1 z_3 + u_3 \\
\dot{z}_1 &= x_1 y_3 - b_3 z_1 \\
\dot{u}_1 &= d_1 x_1 
\end{align*}
\] (8)

Where \(a_1=10\), \(b_1=8/3\), \(c_1=28\), and \(d_1 \in [0, 21.75]\), and key3 is \(\{d_1=5, x_1(0)=3.5, y_1(0)=2.2, z_1(0)=1.7, u_1(0)=4.6\}\). Four chaotic sequences \(X_1, Y_1, Z_1\) and \(U_1\) are generated by Eq. (8). \(X_1\) is used for frequency-domain (row) permutation, and \(Y_1\) is applied for time-domain (column) permutation. The dimension of sequences \(X_1, Y_1\) is \(M \times L\), where \(M\) is the number of effective subcarriers and \(L\) is the number of symbols effectively transmitted in the OFDM frame.

The data matrix after IQ encryption can be expressed as
\[
Q_{M \times L} = \begin{bmatrix} Q_{11} & Q_{12} & \cdots & Q_{1L} \\
Q_{21} & Q_{22} & \cdots & Q_{2L} \\
\vdots & \vdots & \ddots & \vdots \\
Q_{M1} & Q_{M2} & \cdots & Q_{ML} \end{bmatrix} = \begin{bmatrix} F_1 \\
F_2 \\
\vdots \\
F_M \end{bmatrix}
\] (9)

Eq. (9) defines the row vectors of the data matrix as \(F_1, F_2, \ldots, F_M\). Before the time-frequency permutation, the sequence \(X_1\) is partitioned into \(L\) parts, and then each part is ranked in ascending order separately to return and record the dynamic indexes. \(L\) position index sequences obtained by \(X_1\) are used to reorder the frequency-domain data of the L OFDM symbols respectively to realize row scrambling operation. The frequency-domain scrambled matrix can be represented by column vectors \(T_1, T_2, \ldots, T_L\). The same operation is used to process \(Y_1\) to obtain \(M\) position index sequences and then scramble time-domain data of \(M\) subcarriers respectively. Time-frequency permutation is similar to bit interleaving, which can reduce the BER to some extent in the case of burst noise.

![Fig. 2. Schematic diagram of time-frequency scrambling\(^{[27]}\).](image)

**2.4 Chaotic DFT precoding**

In this work, chaotic DFT precoding is adopted to reduce PAPR and extra increase the security of UWOC\(^{[18]}\). Chaotic DFT precoding can be realized by applying a combination of row-column phase encryption and column scrambling to the conventional DFT precoding matrix. The conventional DFT precoding matrix \(D\) can be defined as\(^{[23]}\):
\[
D_{m,l} = \frac{1}{\sqrt{M}} e^{-j2\pi(m-1)(l-1)/M}, 0 \leq m, l \leq M-1
\] (10)

Where \(m\) and \(l\) are the row and column index of the standard DFT matrix.
\[
D^c_{m,l} = \frac{1}{\sqrt{M}} e^{-j2\pi(m-Z_3(l)l-1)/M}, 0 \leq m, l \leq M-1
\] (11)

According to the above equation, the standard DFT matrix of \(M \times M\) is row-phase encrypted using \(M\) different values in the sequence \(Z_3\) generated by Eq.8, i.e., each row is subtracted by a different value \(Z_3(l)\), while the column-phase is encrypted using a constant \(a=6.35\), which is from \(Z_0\). Finally, the sequence \(U_3\) is used to perform a column scrambling on the whole of the phase-encrypted DFT matrix \(D^c\) to obtain our final chaotic encrypted DFT matrix \(D^c:\). Column scrambling of the DFT matrix is equivalent to input data scrambling.

**Table 1. The computation complexity of encryption schemes**

<table>
<thead>
<tr>
<th>Scheme</th>
<th>Our (^{[19]})</th>
<th>ref (^{[19]})</th>
<th>ref (^{[18]})</th>
</tr>
</thead>
<tbody>
<tr>
<td>Real-valued multiplication</td>
<td>0</td>
<td>(N^2)</td>
<td>0</td>
</tr>
<tr>
<td>Complex-valued multiplication</td>
<td>(M^2 + N^2)</td>
<td>(M^2)</td>
<td>(M^2 + N^2)</td>
</tr>
<tr>
<td>Addition</td>
<td>(M(M-1)+N(N-1))</td>
<td>((2M-1)+N(N-1))</td>
<td>(M(M-1)+N(N-1))</td>
</tr>
</tbody>
</table>

Compared with other single and common chaotic mappings, the multiple hyperchaotic mappings used have more dimensions, leading to increased complexity and security of the UWOC encryption system, similar to the 7D chaotic mappings applied in \(^{[19]}\). However, once the encryption system is implemented in practical applications, we do not need to iterate multiple hyperchaotic systems or update the key sequence frequently until the key of the UWOC system changes. In this case, the major computation complexity would only come from the encryption at the system level\(^{[18,19]}\), as shown in Table 1. Here, the number of effective subcarriers is set to \(M\), the IFFT size is \(N\), and only one OFDM symbol is used. In contrast, if we want to change the security key frequently to enhance the security of the UWOC further, the computational complexity of the hyperchaotic mapping iterations needs to be considered, as shown in Table 2.

**Table 2. The computation complexity of chaos systems**

<table>
<thead>
<tr>
<th>Chaos maps</th>
<th>Our chaotic systems</th>
<th>7D-chaos (ref (^{[19]}))</th>
<th>Chaos maps (ref (^{[18]}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Addition</td>
<td>104</td>
<td>221</td>
<td>5</td>
</tr>
<tr>
<td>Multiplication</td>
<td>110</td>
<td>118</td>
<td>10</td>
</tr>
<tr>
<td>Sine function</td>
<td>0</td>
<td>4</td>
<td>2</td>
</tr>
</tbody>
</table>

As mentioned above, there is a trade-off between security and complexity. It is worth mentioning that the UWOC encryption method in this letter does not introduce any additional optical module, and all the encryption and decryption operations are performed in the DSP, so the impact of the iterations of chaotic mapping is small\(^{[24,25]}\). Moreover, an extra layer of encryption for communication
systems represents an additional security guarantee. We believe that the study of using multiple hyperchaotic mappings to encrypt UWOC systems is worthwhile.

3. Experimental setup

The experimental setup of the proposed high-security OFDM system for UWOC based on 3-layer chaotic encryption and chaotic DFT precoding is shown in Fig. 3. At the transmitter, the bit streams are encrypted and loaded into an arbitrary waveform generator (AWG, Tektronix 70002A) at a sampling rate of 3.125 GSamples/s. The voltage amplitude of the output signal is appropriately adjusted using an amplifier (AMP) and a variable electronic attenuator (ATT). Subsequently, the encrypted signal is superimposed on a bias tee (Bias-T) with a direct current (DC) of 0.3414 A, so that the drive signal operates within the linear region of the blue LD. The blue light is collimated by a collimating lens (CL) and emitted into a 7-m water tank filled with tap water. At the receiver, the blue light is incident on an avalanche photodiode (APD210) after passing through a focusing lens (FL) and a variable optical attenuator (VOA). Finally, the detected encrypted signals are captured via a mixed signal oscilloscope (MSO, Tektronix MSO71254C) at a sampling rate of 25 GSamples/s and processed offline by a PC. The final data transmission rate is about 3 Gbps. Table 3 shows the detailed OFDM parameters of the UWOC system.

![Fig. 3. The experimental setup. Insets: (a) the transmitter module, (b) the water tank, (c) the receiving module.](image)

**Table 3. Parameters of the OFDM-UWOC system**

<table>
<thead>
<tr>
<th>OFDM parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Modulation format</td>
<td>16-QAM</td>
</tr>
<tr>
<td>Number of effective subcarriers</td>
<td>256</td>
</tr>
<tr>
<td>Inverse fast Fourier transform (IFFT) size</td>
<td>1024</td>
</tr>
<tr>
<td>Number of cyclic prefix (CP)</td>
<td>64</td>
</tr>
<tr>
<td>Number of subcarriers for gap near DC</td>
<td>8</td>
</tr>
<tr>
<td>Number of OFDM symbols</td>
<td>520</td>
</tr>
</tbody>
</table>

4. Performance and safety analysis

The PAPR and BER are utilized to evaluate the performance of our encryption scheme. Besides, image transmission is a typical digital communication application, so we tested the encryption scheme with image data to visualize the encryption performance. The complementary cumulative distribution functions (CCDFs) of PAPRs for the original and encrypted data are shown in Fig. 4.

![Fig. 4. Performance of PAPR for (a) original image data and (b) the 3-layer encrypted data under different conditions.](image)

The PAPR decreases along with the autocorrelation coefficient of the input data reduction before the N-IFFT operation. Fig. 4 show that the chaotic DFT matrix can significantly reduce the PAPR of the original image and the 3-layer encrypted data. Compared with the original image using the standard DFT method, the chaotic DFT scheme obtains a PAPR reduction of about 1.7 dB (CCDF: 1×10⁻⁴) owing to multiple scrambling operations. The PAPR performance of the image data after 3-layer chaotic encryption is very close to that of the pseudo-random bit sequence (PRBS), where the order of PRBS is 2⁶. Due to the relatively low autocorrelation of encrypted data, both the chaotic DFT and standard DFT matrix can achieve a PAPR reduction of about 2.6 dB (CCDF: 1×10⁻⁴). In Fig. 5(b), the BERs of the 3-layer encrypted data using standard DFT and chaotic DFT are almost the same.

It can be further verified that our scheme can be used in UWOC with high confidentiality and solid BER performance. Fig. 5 shows BER curves and constellation diagrams of the original image and the encrypted data. The legal receiver can correctly recover the data using correct private key. In contrast, illegal receivers always obtain a BER of about 0.5 and cannot decrypt the message, even if they obtain most of the correct key, with only a slight difference of 10⁻¹⁵ from β₀(0) of key 1. In the case of BFAs, the attacker receives an annularly distributed constellation since the chaotic DFT has the effect of phase encryption as in Fig. 5(a), which perceives the encryption operation in the UWOC link. In general, the attacker utilizes all possible methods to restore the normal constellation diagram. However, the proposed UWOC system is still highly secure.
with multiple chaotic encryptions because they cannot easily detect the encryption operations in the bitstream, QAM and time–frequency domain.

The randomness of chaotic systems and their high sensitivity to initial conditions are the basis of our encryption algorithm. Multiple hyperchaotic mappings can create a larger key space and increase the difficulty for attackers to crack. According to the IEEE floating-point standard[26], the computational precision of a 64-bit double-precision number is approximately $10^{15}$. Thus the key space of the whole encryption system can be approximately calculated as $(0.798-0.0085) \times 10^{15} \times (10^{15})^{3} \times [(0.9-0.65) \times 10^{15}]^{3} \times 21.75 \times 10^{15} \times (10^{15})^{3} \times 0.9923 \times 10^{79}$. It takes at least $9.08 \times 10^{155}$ years to obtain the correct key by exhaustive enumeration with the $3.386 \times 10^{4}$ TFlop/s computation speed of the Tianhe-2 supercomputer[18]. The key space of our encryption method is large enough to resist BFAs.

It is worth noting that two-layer encryption without diffusion has a better BER performance than three-layer encryption in Fig5. (b). Owing to the XOR operation in the diffusion, which associates the front and back plaintexts, noise accumulation will happen when the ciphertext is decrypted. However, diffusion encryption can generate dynamic ciphertexts to resist the most threatening and aggressive CPAs, so the performance penalty is acceptable. In this paper, to obtain a higher information security and ensure transmission performance, chaotic DFT precoding is adopted to compensate for the loss, even improving the reception sensitivity by about 1dB.

![Fig. 5. BER curves of normal and illegal receiver for (a) original image data (b) the 3-layer encrypted data.](image)

To verify the anti-CPAs ability of our encryption system, we give the variations of the ciphertext when changing 1 bit of the plaintext, as shown in Figure 6. The 10th bit of the original binary plaintext has been changed in Fig. 6(a). And Fig. 6(b) indicates great difference between the new ciphertext obtained after the corresponding plaintext change and the original one in the same OFDM subcarrier, implying that the plaintext information has been sufficiently spread out to nearly all the data during the ciphertext generation process in the OFDM-based UWOC system. For clarity, Fig. 6(b) only shows the difference of ciphertext change on the first 60 OFDM subcarriers. Consequently, the proposed encryption system can mixup the relationship between the original data and the ciphertext to resist CPAs.

![Fig. 6. (a) Change 1 bit in plaintexts; (b) The difference of ciphertext change on the first 60 OFDM subcarriers.](image)

5. Conclusion

In this letter, we have proposed a security-enhanced OFDM scheme for UWOC using 3-layer chaotic encryption and chaotic DFT precoding. Although there is a trade-off between security and system complexity, the experiment in this paper validates the transmission performance and feasibility of this scheme, which is also an additional way to achieve UWOC secure transmission. The three-layer encryption operations of OFDM symbols are diffusion, IQ encryption, and time–frequency scrambling in turn. Finally, chaotic DFT precoding compensates for BER deterioration, and the key space reaches $9.7 \times 10^{159}$. Our encryption system can resist brute force attacks, statistical attacks, and chosen-plaintext attacks, which has great potential for UWOC systems in future with higher security requirements.

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Reference

4. Y. Huang, C. Tsai, Y. Chi, D. Huang, and G. Lin, “Filtered multicarrier OFDM encoding on blue laser


