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I-HPO-CDSK: An improved chaotic communication scheme for high reliability and effectivity

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Abstract
By transmitting 2-bits orthogonal information signal in parallel, compared with phase-orthogonality CDSK (PO-CDSK), high-data-rate PO-CDSK (HPO-CDSK) has double spectral efficiency. Unfortunately, the additional information will cause more noise interference during correlation detection in HPO-CDSK. The study of HPO-CDSK is extended and improved HPO-CDSK (I-HPO-CDSK) is proposed to obtain high reliability and effectiveness. By virtue of the theorem that the integral of the sine and cosine functions in a period is 0, in I-HPO-CDSK, 3-bits information can be transmitted in parallel and will not cause ISI components. Moreover, compared with HPO-CDSK, I-HPO-CDSK can decrease noise interference. Results show that, due to less interference and 3-bits information transmitting in parallel, I-HPO-CDSK has better BER performance and spectral efficiency than those of previous chaotic communication schemes, such as PO-CDSK and HPO-CDSK.

1 INTRODUCTION

With the advantage in wideband and aperiodic, chaotic signals are well researched for spread-spectrum digital communication system [1]. Moreover, by introducing the chaotic theory, the cognitive radio networks can also improve its network security [2]. According to whether carrier restoration is needed in the demodulation, chaotic modulation can be sorted as coherent and noncoherent chaotic communication systems. In a coherent system, the chaotic carrier is needed to restore during the coherent demodulation. Because the key of carrier restoration, the synchronisation mechanism, performs poorly in coherent demodulation, it will make the reliability low in the demodulation. Therefore, from the 1990s, lots of scholars have gradually focused on the noncoherent chaotic communication scheme which does not need carrier restoration in the receiver.

In 1996, Kolumban proposed the classic noncoherent chaotic communication scheme named differential-chaos-shift-keying (DCSK). In DCSK, one frame obtains two equal time slots. The time delay module is applied to repeat the reference signal which is transmitted in the first time slot and bear the information bit in the second time slot [4]. Because DCSK needs half frame to transmit the reference signal, compared with coherent chaotic communication schemes, its spectral efficiency is half. The switch in the time delay module also makes its hardware stability lower. In recent decades, there are many improved
schemes based on DCSK. In reference-modulated DCSK (RM-DCSK) and high-efficiency DCSK (HE-DCSK) [5, 6], 2-bits information can be transmitted in parallel. Results show that RM-DCSK and HE-DCSK have good performance in spectral efficiency and security without high hardware complexity. However, because there is no strict orthogonality between the parallel transmitting chaotic signals, the intrasignal interference (ISI) will be produced when the information-bearing signal correlates to the reference signal.

In 2000, correlation-delay-shift-keying (CDSK) is proposed as another classic noncoherent chaotic communication scheme by Sushchik [7]. Because the reference signal and the information-bearing signal are transmitted in parallel, CDSK has double spectral efficiency than that of DCSK. Meanwhile, because no switch is needed in CDSK, compared with DCSK, CDSK transmitter has better hardware stability. However, due to no strict orthogonality between information-bearing signal and reference signal, the ISI component is emerged when the information-bearing signal correlates to the reference signal in the demodulation. To keep the spectral efficiency advantage and enhance the BER performance, based on the mechanism of CDSK, the improved versions [8–13] are proposed in two ways, namely enhancing the information component or decreasing the ISI component.

As an improved chaotic communication scheme based on CDSK, by enhancing the information component in the demodulation, generalised CDSK (GCDSK) can greatly improve the BER performance [8]. In GCDSK, the information-bearing signal can be sent multiple times by the additional time delay modules at the transmitter. As a result, the information component can be enhanced during the demodulation at the receiver. However, the ISI component and hardware complexity are also increased by the additional time delay modules.

Aiming to eliminate the ISI component and decrease noise interference in CDSK, the improved chaotic schemes are proposed in [9–13]. In reference-adaptive CDSK (RA-CDSK) [9], the information bit is carried by the reference signal. Due to less ISI and double spectral efficiency, the BER is lower than that of CDSK. Unfortunately, because it is not strictly orthogonal between different chaotic signals, the ISI component will be produced when new chaotic signal is introduced as the reference in RA-CDSK. Based on the Walsh coding working mechanism, the ISI component can be eliminated in the CDSK with no intrasignal interference (CDSK-NII) [10] and its multiple access version [11]. However, its hardware complexity is also increased. By virtue of quadrature sinusoidal wavelets, the ISI component can also be eliminated in phase-orthogonality CDSK (PO-CDSK) [12]. Moreover, compared with CDSK-NII, the hardware complexity is lower. Similar to PO-CDSK, high-data-rate PO-CDSK (HPO-CDSK) can also eliminate the intrasignal interference [13]. Furthermore, by sharing the time slot to 2-bits information, where quadrature sinusoidal wavelets assure their separation, the data-rate of this scheme is double as that of PO-CDSK. Nevertheless, the noise interference will also be enlarged with the increase of spectral efficiency.

2 | SYSTEM MODEL

2.1 | I-HPO-CDSK TRANSMITTER

To further decrease the noise interference and enhance the spectral efficiency, based on the mechanism of HPO-CDSK, improved HPO-CDSK (I-HPO-CDSK) is proposed in this paper to obtain high reliability and effectivity. By virtue of the theorem that the integral of the sine and cosine functions in a period is 0, in I-HPO-CDSK, 3-bits information can be transmitted in parallel and will not cause ISI component. Moreover, compared with HPO-CDSK, I-HPO-CDSK can decrease noise interference. Results show that, due to less interference and 3-bits information transmitting in parallel, I-HPO-CDSK has better BER performance and spectral efficiency than those of previous chaotic communication schemes, such as PO-CDSK and HPO-CDSK.
As depicted in Figure 2, because 3-bits information are parallelly transmitted in 1-HPO-CDSK, the transmitter of 1-HPO-CDSK is divided into three branches. Two transmitting conditions of these three branches are considered:

1) When \( l = 0 \), the switches (T1, T2, T3, T4) are downward. Three parallel chaotic signals (the chaos generator output \( x(t) \), the product of cosine wave \( 2 \cos 2\pi f_0 t \) and \( x(t) \), the product of sine wave \( 2 \sin 2\pi f_0 t \) and \( x(t) \)) are delivered to the transmitter antenna and time delay module, respectively.

2) When \( 1 \leq l \leq \Theta \), during the \( \delta \)-th multiframe, the switches (T1, T2, T3, T4) are upward. The information bit \( d_{m,l} \) (m=1, 2 or 3) is carried by the output of time delay module and delivered to the corresponding transmitted antenna.

The transmitted signal in the \( r \)-th frame is given by

\[
s(t) = \begin{cases} 
  1 \leq l = 0 \\
  \begin{aligned}
  &d_{1,l} \left( \prod_{i=0}^{l-1} d_{1,l-i-1} \right) \times (t - \beta t_C) \\
  &+ 2d_{2,l} \left( \prod_{i=0}^{l-1} d_{2,l-i-1} \right) \times (t - \beta t_C) \\
  &\cos (2\pi f_0 (t - \beta t_C)) \\
  &\sin (2\pi f_0 (t - \beta t_C))
  \end{aligned}
\end{cases}
\]

where \( \xi(t) \) is AWGN which has zero mean and power spectral density of \( N_0/2 \).

During the \( j \)-th frame in the \( \delta \)-th multiframe, the outputs of integral function are:

\[
w_{1,\delta,j,k} = \int_{(\delta \Theta+1)/(\beta t_C)+(k+1)T_C}^{(\delta \Theta+1)/(\beta t_C)+kT_C} [s(t) + \xi(t)] dt,
\]

\[
w_{2,\delta,j,k} = \int_{(\delta \Theta+1)/(\beta t_C)+(k+1)T_C}^{(\delta \Theta+1)/(\beta t_C)+kT_C} \cos (2\pi f_0 t + \xi(t)) dt,
\]

\[
w_{3,\delta,j,k} = \int_{(\delta \Theta+1)/(\beta t_C)+(k+1)T_C}^{(\delta \Theta+1)/(\beta t_C)+kT_C} \sin (2\pi f_0 t + \xi(t)) dt.
\]

Then, the delayed signal will be applied as the reference component, the correlator outputs are given by the sum

\[
\gamma_{1,\delta,j} = \sum_{k=1}^{\beta} w_{1,\delta,j,k} y_{1,\delta,j-1,k},
\]

\[
\gamma_{2,\delta,j} = \sum_{k=1}^{\beta} w_{2,\delta,j,k} y_{2,\delta,j-1,k},
\]

\[
\gamma_{3,\delta,j} = \sum_{k=1}^{\beta} w_{3,\delta,j,k} y_{3,\delta,j-1,k}.
\]

According to the results shown in Equations (6)–(10), the estimated information bit is judged as “+1” or “−1”.

\[
d'_{1,\delta,j} = \begin{cases} 
  +1 & y_{1,\delta,j} \geq 0 \\
  -1 & y_{1,\delta,j} < 0
\end{cases}
\]

\[
d'_{2,\delta,j} = \begin{cases} 
  +1 & y_{2,\delta,j} \geq 0 \\
  -1 & y_{2,\delta,j} < 0
\end{cases}
\]

\[
d'_{3,\delta,j} = \begin{cases} 
  +1 & y_{3,\delta,j} \geq 0 \\
  -1 & y_{3,\delta,j} < 0
\end{cases}
\]

### 3 | PERFORMANCE ANALYSIS

### 3.1 | AWGN channel

Because \( f_0 \) is a multiple of \( 1/T_C \) and \( f_0 >> (1/T_C) \),

\[
\int_{(\delta \Theta+1)/(\beta t_C)+(k+1)T_C}^{(\delta \Theta+1)/(\beta t_C)+kT_C} \sin (2\pi f_0 t - \beta t_C) dt = 0.
\]
To illustrate the work mechanism of I-HPO-CDSK, according to Equations (5)–(7), the outputs of integral function are considered as the following two conditions:

1. if \( l = 0 \)
   (1) for the first branch, as seen in Equation (17)
   (2) for the second branch, as seen in Equation (18)
   (3) for the third branch, as seen in Equation (19)

2. if \( 1 \leq l \leq \Theta \)
   (1) for the first branch, as seen in Equation (20) and Equation (21)
   (2) for the second branch, as seen in Equation (22) and Equation (23)
   (3) for the third branch, as seen in Equation (24) and Equation (25)

We assume \( \xi_{\delta,l,k} \) is the AWGN which has zero mean and power spectral density of \( N_0/2 \). Based on the Chebyshev map, which is widely used in conventional chaotic communication schemes such as HE-DCSK, I-DCSK and MC-DCSK, we can obtain following conclusions:

\[
E[y_{1,\delta,l}] = \beta d_{1,\delta,l} E[\mu] = \beta d_{1,\delta,l} P_t, \tag{26}
\]

\[
E[y_{2,\delta,l}] = \beta d_{2,\delta,l} E[\mu] = \beta d_{2,\delta,l} P_t, \tag{27}
\]

\[
E[y_{3,\delta,l}] = \beta d_{3,\delta,l} E[\mu] = \beta d_{3,\delta,l} P_t. \tag{28}
\]

As illustrated in [14], in Equation (27) and Equation (28),

\[
P_t = E[\mu] = E[x_{\delta,0,k}^2] = 0.5. \tag{29}
\]

In the conditions as shown in Equation (21), Equation (23), Equation (25), we have the conditional variance of \( y_{1,\delta,l}, y_{2,\delta,l}, y_{3,\delta,l} \) as follows:

\[
\text{Var}[y_{1,\delta,l}] = \beta \left( \text{Var}[x_{\delta,0,k}^2] + 2P_t(N_0/2 + N_0^2/4) \right), \tag{30}
\]

\[
\text{Var}[y_{2,\delta,l}] = \beta \left( \text{Var}[x_{\delta,0,k}^2] + 2P_t(N_0/2 + N_0^2/4) \right), \tag{31}
\]

\[
\text{Var}[y_{3,\delta,l}] = \beta \left( \text{Var}[x_{\delta,0,k}^2] + 2P_t(N_0/2 + N_0^2/4) \right), \tag{32}
\]

where \( \text{Var}[x_{\delta,0,k}^2] = 0.125 \), \( N_0/2 = \text{E} \left[ \sum_{k=1}^{\beta} s_{\delta,l,k}^2 \right] \).

Compared with CDSK [7], in Equations (30)–(32), we can find that the ISI component is eliminated. Although there are 3-bits transmitted in one time slot, compared with HE-DCSK [6] and HPO-CDSK [13], the noise component is slightly lower.

When the spreading factor \( \beta \) is large, the distribution of correlator outputs in Equations (26)–(32) can be approximated as Gaussian. Under the AWGN case, based on Gaussian approximation [15], the BER expression of I-HPO-CDSK is

\[
\text{BER}_{\text{I-HPO-CDSK}} \approx \frac{1}{2} \text{erfc} \left( \frac{E(y_{1,\delta,l})}{\sqrt{2 \text{Var}(y_{1,\delta,l})}} \right),
\]

\[
= \frac{1}{2} \text{erfc} \left( \frac{E(y_{2,\delta,l})}{\sqrt{2 \text{Var}(y_{2,\delta,l})}} \right),
\]

\[
= \frac{1}{2} \text{erfc} \left( \frac{E(y_{3,\delta,l})}{\sqrt{2 \text{Var}(y_{3,\delta,l})}} \right),
\]

\[
= \frac{1}{2} \text{erfc} \left( \frac{2\beta \left( \text{Var}[x_{\delta,0,k}^2] + 2P_t(N_0/2 + N_0^2/4) \right)^{-1/2}}{\beta^2 P_t^2} \right),
\]

\[
= \frac{1}{2} \text{erfc} \left( \frac{2\psi + 2 \left( \frac{E_b}{N_0} \right)^{-1} + \frac{\beta}{2} \left( \frac{E_b}{N_0} \right)^{-2}}{\psi} \right)^{-1/2}, \tag{35}
\]

where \( \psi = \frac{\text{Var}[x_{\delta,0,k}^2]}{P_t^2} \).

\[
E_b \text{ means the average bit energy in one frame}
\]

\[
E_b = \beta P_t. \tag{37}
\]
3.2 Rayleigh multipath fading channel

Under the Rayleigh multipath fading channel, the received signal can be depicted as

\[ r(t) = \sum_{i=1}^{N} A_i(t) s(t - \tau_i) + \xi(t), \]

(38)

where \( N \) means the number of fading paths, \( A_i(t) \) means the \( i \)-th propagation path coefficient, \( \tau_i \) is the \( i \)-th time delay.

We assume the path coefficient is slow fading, \( A_i(t) \) is considered as the constant, Equation (38) can be written as

\[ r(t) = \sum_{i=1}^{N} A_i \tau_i (t - \tau_i) + \xi(t). \]

(39)

Because the time delay \( \tau_i \) is much smaller, the intrasignal interference between multipath can be ignored.

The instantaneous signal-to-noise ratio (SNR) of the \( i \)-th path, denoted as

\[ \gamma_i = \frac{(E_b/N_0)A_i^2}{\sum_{i=1}^{N} A_i^2}, \]

(40)

and the instantaneous SNR per bit at the receiver, denoted as

\[ \gamma_b = \frac{(E_b/N_0)A_i^2}{\sum_{i=1}^{N} A_i^2}. \]

(41)

Based on Equation (35) and Equations (40)–(41), under Rayleigh multipath fading channel, the conditional BER as a function of \( \gamma_b \) is given by \([16]\)

\[
\text{BER}_{1-HPO-CDSK} \text{ Rayleigh}(\gamma_b) = \frac{1}{2} \text{erfc} \left\{ \frac{E(\gamma_1,\gamma_b) - \gamma_b}{\sqrt{2 \text{Var}(\gamma_1,\gamma_b)}} \right\},
\]

(42)

\[
= \frac{1}{2} \text{erfc} \left\{ \frac{E(\gamma_2,\gamma_b) - \gamma_b}{\sqrt{2 \text{Var}(\gamma_2,\gamma_b)}} \right\},
\]

(43)

Based on above conclusions, under Rayleigh multipath channel, the BER performance expression is

\[
\text{BER}_{1-HPO-CDSK} \text{ Rayleigh} = \int_0^{+\infty} f(\gamma_b) \text{BER}_{1-HPO-CDSK} \text{ Rayleigh}(\gamma_1,\delta,\gamma_b) \, d\gamma_b,
\]

(44)

\[
= \int_0^{+\infty} f(\gamma_b) \text{BER}_{1-HPO-CDSK} \text{ Rayleigh}(\gamma_2,\delta,\gamma_b) \, d\gamma_b,
\]

(45)

\[
= \int_0^{+\infty} f(\gamma_b) \text{BER}_{1-HPO-CDSK} \text{ Rayleigh}(\gamma_3,\delta,\gamma_b) \, d\gamma_b.
\]

(46)

3.3 Spectral and energy efficiencies analysis

From \([13]\), we have known the spectral and energy efficiencies comparison between several previous chaotic communication systems. Based on the same preconditions, we can get the following conclusions which can be seen in Table 1:

1) In one multiframe, since I-HPO-CDSK occupies \((\Theta + 1)\) frames to transmit \(3\Theta\) bits, the spectral efficiency is \(3\Theta/(\Theta + 1)\).

2) In one multiframe (including \((\Theta + 1)\) frames), because only \(\Theta\) frames are occupied to transmit information signal in I-HPO-CDSK, the energy efficiency is \(\Theta/(\Theta + 1)\).
TABLE 1  Spectral and energy efficiencies comparison between chaotic communication systems

| Systems   | Spectral Efficiency | Energy Efficiency |
|-----------|---------------------|-------------------|
| DCSK      | $1/\beta$           | 1/2               |
| CDSK      | $1/\beta$           | 1/2               |
| HE-DCSK   | $1/\beta$           | 2/3               |
| PO-CDSK   | $\theta/(\theta+1)\beta$ | $\theta/(\theta+1)$ |
| HPO-CDSK  | $2\theta/(\theta+1)\beta$ | $2\theta/(2\theta+1)$ |
| I-HPO-CDSK| $3\theta/(\theta+1)\beta$ | $\theta/(\theta+1)$ |

FIGURE 4  Simulation and BER expression, for $\beta = 100, 200, 300$, under an AWGN channel

Clearly, although its energy efficiency is slightly inferior than that of HPO-CDSK, I-HPO-CDSK has the best spectral when $\theta > 1$.

4 | SIMULATION RESULTS

To evaluate the analysis in Section 3, we plot the comparison curves between I-HPO-CDSK and various systems. As illustrated in Section 3, Chebyshev map is adopted here where its generation function is $x_{k+1} = 4x_k^3 - 3x_k$, the initial value $x_0 = 0.1$. In the following figures, simulation result is marked as (S), the theory result is marked as (T).

Under AWGN channel, the relationship between BER performance and $E_b/N_0$ lever is shown in Figure 4, the $E_b/N_0$ level spans from 0 dB to 16 dB, the spreading factor $\beta = 100, 200$ and 300. As verified in Equations (30)–(32), due to no ISI component in the correlator output, simulation results perfectly validate the analytical BER expression given in Equation (35). Moreover, because bigger spreading factor will cause more noise interference during the correlation detection in the receiver, the BER when $\beta = 100$ is lower than that of when $\beta = 300$.

FIGURE 5  Simulation and BER expression with different $E_b/N_0$ lever, for $\beta = 100, 200, 300$, under Rayleigh multipath fading channel on model I when $\tau_1 = 0$ and $\tau_2 = 2$

FIGURE 6  Simulation and BER expression with different $E_b/N_0$ lever, for $\beta = 100, 200, 300$, under Rayleigh multipath fading channel on model II when $\tau_1 = 0$ and $\tau_2 = 2$

Figures 5 and 6 evaluate the effect of Rayleigh multipath channel on BER performance. Here, two models are considered in the following. In model I, two fading paths have the same power gain, $E[\lambda_1^2] = E[\lambda_2^2] = 0.5$. In model II, two fading paths have the different power gain, $E[\lambda_1^2] = 0.8$ and $E[\lambda_2^2] = 0.2$. The multipath delay is set as $\tau_1 = 0$ and $\tau_2 = 2$. Because multipath interference can be ignored when the multipath delay is much smaller than the spreading factor. Consequently, in Figures 5 and 6, the I-HPO-CDSK simulation curves excellently agree with the analytical results which are computed by Equation (48).

Under AWGN channel and Rayleigh multipath fading channel when $\tau_1 = 0$ and $\tau_2 = 2$, the BER comparison with different $E_b/N_0$ lever between I-HPO-CDSK, CDSK and DCSK are
presented in Figure 7, the BER comparison between I-HPO-CDSK and HE-DCSK, PO-CDSK, HPO-CDSK are presented in Figure 8. Because I-HPO-CDSK can thoroughly eliminate the ISI component during the demodulation, compared with CDSK and HE-DCSK, it has better BER performance. Due to needless of half frame to transmit the reference signal, compared with DCSK, I-HPO-CDSK has six times spectral efficiency and two times energy efficiency. It is also found that, as seen in Section 3.1, because the noise component in our demodulation is slightly lower, our BER performance outperforms that of PO-CDSK and HPO-CDSK in AWGN channel and Rayleigh multipath fading channel.

Under AWGN channel and Rayleigh multipath fading channel when $\tau_1 = 0$ and $\tau_2 = 2$, the BER comparison with different spreading factor $\beta$ between I-HPO-CDSK, CDSK and DCSK are presented in Figure 9, the BER comparison between I-HPO-CDSK and HE-DCSK, PO-CDSK, HPO-CDSK are presented in Figure 10. It can also be observed in these figures that, with different $\beta$, the BER performance of I-HPO-CDSK appears to be better than that of other chaotic communication schemes, which is actually the result of no ISI component and reduced noise component in the correlator output of I-HPO-CDSK.

Under Rayleigh multipath fading channel on model I, the BER comparison with different $E_b/N_0$ lever between I-HPO-CDSK and other schemes is presented in Figure 11 when $\tau_1 = 0$ and $\tau_2 = 10$. With the same preconditions and multipath time delay, since less noise interference and no intrasignal...
interference in the demodulation of I-HPO-CDSK, its BER performance is the best. Because the BER performance of chaotic scheme will be seriously influenced when the multipath time delay approaches or exceeds the spreading factor. As seen in Figure 10, when $\tau_1 = 0$ and $\tau_2 = 10$, the BER performance of all schemes with $\beta = 600$ is better than those with $\beta = 60$.

5 | CONCLUSION

Based on the mechanism of HPO-CDSK, in this paper, we have proposed an improved HPO-CDSK (I-HPO-CDSK) to decrease the noise interference and enhance the spectral efficiency. Under AWGN and Rayleigh multipath fading channel, the theoretical BER expression of the proposed system is analytically studied and the simulations are performed. Theoretical analysis and simulations show that, by sharing the time slot to 3-bits information, compared with HPO-CDSK, this system gains a higher data-rate. Due to less interference, I-HPO-CDSK has better BER performance than those of previous chaotic communication schemes, such as HE-DCSK, PO-CDSK and HPO-CDSK.

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APPENDIX A

\[
\begin{align*}
\mathcal{W}_{1, \delta, \theta, k} &= \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} \left[ \chi(t) + \xi(t) \right] \, dt \\
&= \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} \chi(t) + 2 \chi(t) \cos (2\pi f_0 t) + 2 \chi(t) \sin (2\pi f_0 t) + \xi(t) \, dt \\
&= \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} \chi(t) + \xi(t) \, dt \\
&= \mathcal{N}_{\delta, \theta, k} + \mathcal{N}_{\delta, \theta, k} \\
\mathcal{W}_{2, \delta, \theta, k} &= \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} \left[ \cos (2\pi f_0 t) \chi(t) + \xi(t) \right] \, dt \\
&= \cos (2\pi f_0 t) \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} \chi(t) + 2 \chi(t) \sin (2\pi f_0 t) \, dt + \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} 2 \chi(t) \cos (2\pi f_0 t) \, dt \\
&= \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} \chi(t) \left[ 1 + \cos (2\pi f_0 t) \right] + \xi(t) \, dt \\
&= \mathcal{N}_{\delta, \theta, k} + \mathcal{N}_{\delta, \theta, k} \\
\mathcal{W}_{3, \delta, \theta, k} &= \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} \left[ \sin (2\pi f_0 t) \chi(t) + \xi(t) \right] \, dt \\
&= \sin (2\pi f_0 t) \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} \chi(t) + 2 \chi(t) \cos (2\pi f_0 t) \, dt + \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} 2 \chi(t) \sin (2\pi f_0 t) \, dt \\
&= \int_{(\delta \Theta+1) \Omega T_C + (k+1) \Omega T_C} \chi(t) \left[ 1 - \cos (2\pi f_0 t) \right] + \xi(t) \, dt \\
&= \mathcal{N}_{\delta, \theta, k} + \mathcal{N}_{\delta, \theta, k}
\end{align*}
\]
\[ w_{1,\beta, \cdot k} = \int_0^{\beta T_C + (k+1) T_C} \left[ \xi(t) + \xi(t) \right] dt \]  

(20)

\[ \begin{align*}
&= \int_0^{\beta T_C + (k+1) T_C} \left( \prod_{i=0}^{l-1} d_{1,\beta, i} \right) x(t - \beta T_C) dt \\
&+ \int_0^{\beta T_C + (k+1) T_C} 2 \cos \left( 2\pi f_0 (t - \beta T_C) \right) d_{3,\beta, i} \left( \prod_{i=0}^{l-1} d_{2,\beta, i-1} \right) x(t - \beta T_C) dt \\
&+ \int_0^{\beta T_C + (k+1) T_C} 2 \sin \left( 2\pi f_0 (t - \beta T_C) \right) d_{3,\beta, i} \left( \prod_{i=0}^{l-1} d_{3,\beta, i-1} \right) x(t - \beta T_C) dt \\
&+ \int_0^{\beta T_C + (k+1) T_C} \xi(t) dt
\end{align*} \]

(21)

\[ \begin{align*}
&= \sum_{k=0}^{\beta} \left[ d_{1,\beta, i} \left( \prod_{i=0}^{l-1} d_{1,\beta, i-1} \right) x_{0,0,k} + \bar{x}_{0,0,k} \right] \left[ \left( \prod_{i=0}^{l-1} d_{1,\beta, i-1} \right) x_{0,0,k} + \bar{x}_{0,0,k} \right] \\
&= \sum_{k=1}^{\beta} \left[ d_{1,\beta, i} \left( \prod_{i=0}^{l-1} d_{1,\beta, i-1} \right) x_{0,0,k} + \bar{x}_{0,0,k} \right] \left[ \left( \prod_{i=0}^{l-1} d_{1,\beta, i-1} \right) x_{0,0,k} + \bar{x}_{0,0,k} \right] \\
&= \sum_{k=1}^{\beta} \left[ d_{1,\beta, i} \left( \prod_{i=0}^{l-1} d_{1,\beta, i-1} \right) x_{0,0,k} + \bar{x}_{0,0,k} \right] \left[ \left( \prod_{i=0}^{l-1} d_{1,\beta, i-1} \right) x_{0,0,k} + \bar{x}_{0,0,k} \right] \\
&= \int_0^{\beta T_C + (k+1) T_C} \left[ \cos (2\pi f_0 t) x(t) + \xi(t) \right] dt \\
&= \int_0^{\beta T_C + (k+1) T_C} \left[ \cos (2\pi f_0 t) x(t) \right] dt \\
&+ \int_0^{\beta T_C + (k+1) T_C} 2 \cos \left( 2\pi f_0 (t - \beta T_C) \right) d_{2,\beta, i} \left( \prod_{i=0}^{l-1} d_{2,\beta, i-1} \right) x(t - \beta T_C) dt \\
&+ \int_0^{\beta T_C + (k+1) T_C} 2 \sin \left( 2\pi f_0 (t - \beta T_C) \right) d_{2,\beta, i} \left( \prod_{i=0}^{l-1} d_{2,\beta, i-1} \right) x(t - \beta T_C) dt \\
&+ \int_0^{\beta T_C + (k+1) T_C} \xi(t) dt
\end{align*} \]

(22)
\[ y_{3,\delta,j} = \sum_{k=1}^{\beta} w_{3,\delta,j,k} w_{3,\delta,j-1,k} \]

\[ = \sum_{k=1}^{\beta} \left[ d_{3,\delta,j} \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) x_{3,0,j,k} + \xi_{3,\delta,j,k} \right] \left[ \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) x_{3,0,j,k} + \xi_{3,\delta,j-1,k} \right] \]

\[ = \sum_{k=1}^{\beta} \left[ d_{3,\delta,j} \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) x_{3,0,j,k} + d_{3,\delta,j} \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) x_{3,0,j,k} + d_{3,\delta,j-1} \right] \left[ \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) x_{3,0,j,k} + \xi_{3,\delta,j-1,k} \right] \]

\[ w_{3,\delta,j,k} = \int_{(\delta \beta + 1) + i/\beta \tau_{C} + (k+1)\tau_{C}} \sin(2\pi f_{0}(t) \tau(t) + \tau(t)) \, dt \]

\[ = \sin \left( 2\pi f_{0} \right) \int_{(\delta \beta + 1) + i/\beta \tau_{C} + (k+1)\tau_{C}} d_{1,\delta,j} \left( \prod_{i=0}^{l-1} d_{1,\delta,j-1} \right) \tau(t = \beta \tau_{C}) \, dt \]

\[ + \int_{(\delta \beta + 1) + i/\beta \tau_{C} + (k+1)\tau_{C}} 2d_{2,\delta,j} \left( \prod_{i=0}^{l-1} d_{2,\delta,j-1} \right) \tau(t = \beta \tau_{C}) \cos \left( 2\pi f_{0} \right) \, dt \]

\[ + \int_{(\delta \beta + 1) + i/\beta \tau_{C} + (k+1)\tau_{C}} 2d_{2,\delta,j} \left( \prod_{i=0}^{l-1} d_{2,\delta,j-1} \right) \tau(t = \beta \tau_{C}) \sin \left( 2\pi f_{0} \right) \, dt \]

\[ d_{3,\delta,j} \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) \tau(t + \xi_{3,\delta,j,k}) \]

\[ y_{3,\delta,j} = \sum_{k=1}^{\beta} w_{3,\delta,j,k} w_{3,\delta,j-1,k} \]

\[ = \sum_{k=1}^{\beta} \left[ d_{3,\delta,j} \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) x_{3,0,j,k} + \xi_{3,\delta,j,k} \right] \left[ \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) x_{3,0,j,k} + \xi_{3,\delta,j-1,k} \right] \]

\[ = \sum_{k=1}^{\beta} \left[ d_{3,\delta,j} \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) x_{3,0,j,k} + d_{3,\delta,j} \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) x_{3,0,j,k} + d_{3,\delta,j-1} \right] \left[ \left( \prod_{i=0}^{l-1} d_{3,\delta,j-1} \right) x_{3,0,j,k} + \xi_{3,\delta,j-1,k} \right] \]