Experimental validation of carrier waveform inter-displacement modulation with software defined electronics platform

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1 Introduction

In modern communications application scenarios, the conventional Phase Shift Keying (PSK) modulation is not only to satisfy the demand of the explosive growth in data traffic, but also difficult to adapt to the complex electromagnetic environment for high communication performance. The communication system is restricted by several channel constraints, such as complex multipath propagation, large attenuation, low available bandwidth, serious Doppler effect, time-varying characteristic and ambient noise, which significantly deteriorated BER performance of the conventional communications systems [1]. Linear Frequency Modulation (LFM) signal has been widely used in communications applications in recent two decades, it is mainly due to the fact that LFM signal shows attractive advantages, including good anti-jamming performance, low probability of intercept and Doppler effect insensitivity [2].

The hybrid waveform of LFM and PSK modulation for joint waveform of communication and radar system has aroused ongoing and growing research interest in recent years [3–5]. The LFM-PSK can be regarded as modulating PSK signal on LFM carrier [6,7], and improving the communication performance of LPS-PSK system by utilizing the excellent detection and parameter estimation performance of LFM [8,9]. In Ref. [10], the LFM signals are modulated by Binary Phase Shift Keying (BPSK), the information bit is expressed by the phase of LFM signal. In Ref. [11], the binary information bits are transmitted by using LFM signals with the same frequency slope and various initial frequency, which hides the communication signal in radar signal, thus reducing the interception probability of the transmitted signal. Reference [12] combined Multiple Shift Keying (MSK) modulation with LFM signal, and considered the LFM signal as the carriers of the MSK to improve the communication data rate [13]. A simple way to obtain higher speed is to use multi-carrier modulation [14,15], the Bit Error Rate (BER) and communication rate are analyzed in Refs. [16–18]. The performance improvement schemes have attracted lots of attention in the field of
wireless communication [19], especially the use of artificial intelligence and deep learning methods [20]. The echo state network (ESN) and convolutional neural network (CNN) with deep learning structure are trained to predict the future symbol(s) in order to reduce the inter-symbol interference in the chaotic baseband communication system [21, 22]. To further reduce the computational complexity, the ESN is trained to predict the decoding threshold for decoding the symbol [23], along the same line, a genetic algorithm based support vector machine is trained to decode the information bit directly [24]. In Ref. [25], the LFM signals are combined with deep neural network to replace the adaptive equalizer-based receiver, which effectively improves the communication system performance. However, the increased bit data rate in the conventional communications systems at the cost of the complexity, and the modulation method is sensitive with the frequency offset of the carriers. With the increase of modulation order and the number of carriers, the communication performance decreases rapidly, which leads to a high BER in poor channel [26] and deteriorates the effective throughput of the communications system [27]. The normal Direct Sequence Spread Spectrum (DSSS) communication systems have significantly enhanced the anti-interference, anti-fading and anti-multipath propagation performance of the communication systems to improve the communication reliability in poor channels. However, the DSSS communication systems reduce the attainable data rate due to use of pseudo-random spread spectrum sequence. In this work, a novel Carrier Waveform Inter-Displacement (CWID) modulation based on LFM-PSK system is proposed. In the proposed CWID modulation, the main idea is to increase the difference among different symbols’ carrier waveforms, which introduces additional constellation map to increase the communication rate. The CWID modulation is suitable for M-ary PSK modulation, which can achieve higher data transmission rate with low BER as compared to the conventional MPSK and LFM-MPSK. Therefore, the proposed CWID modulation not only obtains better anti-interference and anti-multipath propagation performances, but also avoids the problem of low data rate faced by DSSS systems. The contributions of this work are given as follow: (i) a new CWID modulation scheme is proposed which offers higher Bit Transmission Rate (BTR) as compared to its competitors; (ii) a Software Defined Electronics (SDE) radio testbed has been implemented on an FPGA-based Wireless open-Access Research Platform (WARP) and a Graphical User Interface (GUI) has been designed for the SDE platform. The performances of the proposed CWID, LFM-MPSK and FSK radio links have been evaluated in practical application environments.

This paper is organized as follows: The proposed CWID scheme is introduced in Sect. 2. The simulation results and performance comparison of CWID, LFM-MPSK and MPSK is given in Sect. 3. The GUI, experimental configuration and testing results are reported in Sect. 4. Finally, some concluding remarks are given in Sect. 5.

2 CWID communication system configuration

2.1 LFM-MPSK communication system

The modulated signal of the LFM-MPSK communication system is given as [28]

$$ s(t) = A \sum_{k=1}^{N} \text{rect} \left( \frac{t - (k - 1) T_b}{T_b} \right) \cdot \exp \left( j 2\pi \left( f_0 t + B / T_b t^2 \right) + \phi_k \right) $$

(1)

where $s(t)$ is the modulated signal, $A$ is the amplitude of the signal, $N$ is the number of symbols, $T_b$ is the duration of the modulated signal for one bit, $f_0$ is the initial frequency, $B$ represents the bandwidth, $\phi_k$ is the initial phase of the $k$th symbol, and the window $\text{rect} (\cdot)$ is

$$ \text{rect} (t) = \begin{cases} 1, & 0 < t \leq T_b \\ 0, & \text{others} \end{cases} $$

(2)

Select the initial phase $\phi_k$ are 0, $\frac{\pi}{2}$, $\pi$ and $\frac{3\pi}{2}$, respectively. The basic carrier waveforms for LFM-4PSK are shown in Fig. 1, where $A = 1$, $f_0 = 0.1 \text{MHz}$, $B = 2.9 \text{MHz}$ and $T_b = 4 \text{μs}$. 

Fig. 1 An example of carrier waveforms in the LFM-4PSK modulation.
2.2 CWID modulation

The block diagram of the proposed CWID transmitter is given in Fig. 2, the main idea of the CWID modulation is to maximize the difference among different basic carrier waveforms by re-ordering the position of inter-sub-waveforms in each symbol.

The $s_{w_i}$ in the basic carrier waveform is given by

$$s_{w_i} = s \left( t_{i-1} < t_i, \phi_k \right), \ 1 \leq i \leq M \quad (3)$$

where $s \left( t, \phi_k \right)$ is given in Eq. (1) with initial phase $\phi_k$. $M$ is the modulation order, the basic carrier waveform is split into $M$ groups at each peak of the waveform, and the duration of each sub-waveforms are shown in Fig. 3a. In CWID modulation, the information bits $(a_1, a_2, \ldots, a_{\log_2(M)})$ and $(b_1, b_2, \ldots, b_{\log_2(M)})$ are transmitted, separately, within $T_b$ of the modulated signal. The initial phase $\phi_k$ is given by $\phi_k = \alpha \frac{2\pi}{M}$, and $\alpha = \sum_{l=1}^{\log_2(M)} a_l 2^{l-1}$ is a decimal number calculated by the first half transmitted bits. The modulated signal is given by

$$S(t) = \left[ SW_1, \ldots, SW_j, \ldots, SW_M \right], \ 1 \leq j \leq M \quad (4)$$

where $SW_j = s_{w_i} \mod (\beta + j - 1, M) + 1$, mod $(\cdot, \cdot)$ is the remainder operator, $\beta = \sum_{l=1}^{\log_2(M)} b_l 2^{l-1}$ is calculated by the second half information bits.

The basic carrier waveform represents first half information bits '01' in Fig. 1 is used as an illustration. The initial phase is $\phi_k = \frac{n\pi}{2}$ for $M = 4$ and $\alpha = 1$. The carrier waveform is split into 4 groups at each peak of the waveform, i.e., $s_{w_1}, s_{w_2}, s_{w_3}$ and $s_{w_4}$, respectively, as shown in Fig. 3a. Assume that the second half information bits are '10', then $\beta = 2$, $S(t) = [s_{w_3}, s_{w_4}, s_{w_1}, s_{w_2}]$. The sub-waveforms are reorganized using the rule in Eq. (4), as shown in Fig. 3b and Table 1. The main idea of maximizing the difference between two basic carrier waveforms is that the same sub-waveform will not appear in the same place of any two different basic carrier waveforms, such as $s_{w_1}$ is located in the 1st place in the basic carrier waveform, then, $s_{w_1}$ should not be located in 1st place in the other basic carrier waveforms by re-ordering the sub-waveforms, we have 4 different groups for different symbols by using one symbol of the original LFM-4PSK waveform. The proposed modulation method introduces the position modulation by re-ordering the position of inter sub-waveforms among different basic carrier waveforms and serves as the modulated signal of 4-CWID with initial phase $\frac{n\pi}{2}$, as shown in Fig. 4. The transmitted signal is sent to the radio channel after Digital/Analog Converter (DAC) and up-conversion.

The block diagram of the CWID receiver is shown in Fig. 5. The received signal is down converted to remove carrier frequency, and then correlated with different reference signals, which are composed of reorganizing sub-waveforms with different initial phases. The maximum likelihood deci-

**Table 1** Reorganize sub-waveforms for the basic carrier waveform

| Symbols | 1st place | 2nd place | 3rd place | 4th place |
|---------|-----------|-----------|-----------|-----------|
| 01–00   | $s_{w_1}$ | $s_{w_2}$ | $s_{w_3}$ | $s_{w_4}$ |
| 01–01   | $s_{w_2}$ | $s_{w_3}$ | $s_{w_4}$ | $s_{w_1}$ |
| 01–10   | $s_{w_3}$ | $s_{w_4}$ | $s_{w_1}$ | $s_{w_2}$ |
| 01–11   | $s_{w_4}$ | $s_{w_1}$ | $s_{w_2}$ | $s_{w_3}$ |

Fig. 2  Block diagram of the CWID transmitter

Fig. 3  a The basic carrier waveform generated by LFM-4PSK with $\frac{n\pi}{2}$ initial phase and b the constellation of CWID
The basic carrier waveform of the 4-CWID modulation with initial phase $\frac{\pi}{2}$.

![Fig. 4](image)

Block diagram of the CWID receiver.

![Fig. 5](image)

Fig. 4 The basic carrier waveform of the 4-CWID modulation with initial phase $\frac{\pi}{2}$.

Fig. 5 Block diagram of the CWID receiver.

**3 Simulation results and performance analysis**

In this section, the BER performance of the proposed CWID, LFM-MPSK and conventional MPSK modulations are compared in both Additive White Gaussian Noise (AWGN) channel and wireless multipath fading channel, respectively, with different symbol energy to noise power spectral density noise ($E_s/N_0$). The initial frequency $f_0 = 0.1 \text{ MHz}$, bandwidth $B = 2.9 \text{ MHz}$, symbol duration $T_b = 4 \mu\text{s}$ and sampling frequency $f_s = 40 \text{ MHz}$, the parameters configuration and the corresponding bit transmission rate is shown in Table 2. The frequency spectral are shown in Fig. 6, where Fig. 6a and b are the spectra of the 4-CWID and LFM-4PSK, respectively. It can be seen that the two methods have identical bandwidth. The Spectral Efficiency (SE) can be computed by

$$SE_{CWID} = \frac{\text{data rate}}{\text{total bandwidth}} = \frac{\log_2 (M) + 2}{T_b B}.$$  \hspace{1cm} (5)

Similarly, the spectral efficiency of LFM-PSK is

$$SE_{LFM-PSK} = \frac{\log_2 (M)}{T_b B}.$$  \hspace{1cm} (6)

It can be found that $SE_{CWID} > SE_{LFM-PSK}$ for the same modulation order $M$, symbol duration $T_b$ and bandwidth $B$.

In the AWGN channel, the simulation BER curves are shown in Fig. 7a. It can be found that the 4-CWID is slightly worse than that of LFM-4PSK and 4PSK, because the decision distance of CWID is reduced by re-ordering sub-waveforms as compared with LFM-MPSK and MPSK. It deteriorates the performance of CWID, but provides a higher bit transmission rate. When the CWID, LFM-MPSK and MPSK are configured with the same bit transmission rate (namely $M = 4$ in CWID, $M = 16$ in LFM-MPSK and MPSK), the performance of M-CWID is significantly superior to that of LFM-MPSK and MPSK. Moreover, the bit transmission rate of CWID can be further improved by increasing the number of sub-waveforms in the carrier waveforms.

In the multipath fading channel, a three-ray channel with power gains $E_1 = 0.6$, $E_2 = 0.3$, $E_3 = 0.1$ and excess delays $\tau_1 = 0$, $\tau_2 = 20 \mu\text{s}$, $\tau_3 = 120 \mu\text{s}$, respectively, is used for simulation test. The simulation results are shown in Fig. 7b. It can be found that LFM-MPSK achieves significantly better BER performance than MPSK because the LFM signal is used in LFM-MPSK system which helps to mitigate multipath fading and jamming. The proposed CWID inherits the advantages of LFM, it not only has quadrupled the bit transmission rate as compared to LFM-4PSK and 4PSK, but also shows lower BER than MPSK. The BER performance shows that the M-CWID outperforms the LFM-MPSK and MPSK with the identical bit transmission rate.

The BER performance of the CWID with different modulation order $M$ is shown in Fig. 8, where the blue solid line, dashed line and dotted line with square marks are the BER curves in the AWGN channel with modulation order 4, 8 and 16, respectively. The red solid line, dashed line and dotted line with circle marks are the BER curves in the multipath fading channel with the corresponding modulation order, respectively. The simulation results show that, with the increasing of modulation order, the BER performance degrades and the communication data rate increases gradually, as shown in Table 2. Moreover, due to the distortion of the received signal, the BER performance significantly deteriorates in the multipath fading channel as compared to that in the AWGN channel.

In order to verify the performance of the proposed method and its competitors in different scenarios, the performance comparison in the underwater acoustic channel are sim-
Table 2  Parameters of different modulation schemes considered in performance comparison

|               | BTR (kbps) |     |     | bandwidth | $f_s$  | $T_b$  |
|---------------|------------|-----|-----|-----------|--------|--------|
|               | $M = 4$    | $M = 8$ | $M = 16$ |           |        |        |
| CWID          | 1000       | 1250 | 1500 | 0.1 MHz-3 MHz | 40 MHz | 4 $\mu$s |
| LFM-MPSK      | 500        | 750  | 1000 | 0.1 MHz-3 MHz | 40 MHz | 4 $\mu$s |
| MPSK          | 500        | 750  | 1000 | 1.5 MHz   | 40 MHz | 4 $\mu$s |

Fig. 6  Spectra of the modulated a 4-CWID and b LFM-PSK

Fig. 7  The BER performance of the CWID, LFM-MPSK and MPSK modulations in a BER versus $E_s/N_0$ in AWGN channel and b BER versus $E_s/N_0$ in wireless multipath fading channel
Fig. 8 The BER performance versus the $E_b/N_0$ in the CWID with different modulation orders.

Moreover, the lower modulation order and packet length, the better PER performance for all modulation schemes. The point to be noticed here is that the LFM-16PSK, 8PSK and 16PSK cannot be directly used in the underwater acoustic channel, because their PER tends to 1 even under a small PL, as shown in Table 4 and Fig. 9.

4 Experimental evaluation based on software defined electronics (SDE) platform

In the experimental test, two FPGA-based Wireless open-Access Research Platforms (WARP) are used as RF HW transformers to implement the radio link test. The SDE platform includes two Xilinx Virtex-6 LX240T FPGAs for digital signal processing, two MAX2829 chips for dual-channel and 2.4 GHz/5 GHz dual-channel transceiver with maximum transmission power 20 dBm. The photo of WARP and its block diagram are shown in Fig. 10a and b, respectively.

The photo of the SDE platform is shown in Fig. 11a, where the baseband signal is generated on the Laptop. A universal GUI is designed to configure the communications systems parameters, as shown in Fig. 11b. The panel includes the following four parts:

- Parameter configuration panel is used to configure the parameters, like the frame structure, pilot length, the number of test bits, TX baseband/RF gain, RX baseband/RF gain, carrier frequency, modulation order, spread spectrum gain and oversampling rate, etc;
- The methods selection panel is used to select method to be tested as shown in the block 2 in Fig. 11(b). The test frame has been conducted by all tested modulation schemes as shown in Fig. 12;
- The Run and Stop buttons with online and offline models. The transmitted test frame generated from Laptop is fed into the TX RF HW transformer and is radiated by an TX antenna to pass through the real radio channel. It is

| Parameter name                  | Parameter value | Parameter name                  | Parameter value |
|---------------------------------|-----------------|---------------------------------|-----------------|
| Sea depth $h$                   | 150 m           | Seabed sound speed $c_1$        | 1650 m/s        |
| Temperature of seawater $T$     | 20° C           | seawater density $\rho$         | 1023 kg/m$^3$   |
| Transmitter depth $d_1$         | 30 m            | seabed density $\rho_1$         | 1500 kg/m$^3$   |
| Receiver depth $d_2$            | 50 m            | seawater salinity $S$           | 35 ppt          |
| Propagation distance $R$        | 1200 m          | transducer RMS movement $\sigma_d$ | 0.25 m      |
| Seawater sound speed $c$        | 1539 m/s        | number of multiple paths        | 5              |
| 1 surface/bottom reflections $s_b$ | 1 1           | 3 surface/bottom reflections $s_b$ | 4 3          |
| 2 surface/bottom reflections $s_b$ | 3 2            | 4 surface/bottom reflections $s_b$ | 3 4          |
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Fig. 9  a BER performance and b PER performance comparison in the underwater acoustic channel between the CWID and its competitors

Table 4 The BER and PER performance of the CWID and its competitors

|          | BER ($E_b/N_0 = 25$ dB) | PER (PL = 64) | PER (PL = 128) | PER (PL = 256) |
|----------|--------------------------|---------------|----------------|----------------|
| 4-CWID   | $5.00 \times 10^{-7}$    | $3.20 \times 10^{-5}$ | $6.40 \times 10^{-5}$ | $1.28 \times 10^{-4}$ |
| 8-CWID   | $8.50 \times 10^{-5}$    | $5.40 \times 10^{-3}$ | $1.08 \times 10^{-2}$ | $2.15 \times 10^{-2}$ |
| 16-CWID  | $4.30 \times 10^{-3}$    | $2.42 \times 10^{-1}$ | $4.25 \times 10^{-1}$ | $6.70 \times 10^{-1}$ |
| LFM-4PSK | $1.00 \times 10^{-6}$    | $6.40 \times 10^{-5}$ | $1.28 \times 10^{-4}$ | $2.56 \times 10^{-4}$ |
| LFM-8PSK | $1.70 \times 10^{-3}$    | $1.03 \times 10^{-1}$ | $1.96 \times 10^{-1}$ | $3.53 \times 10^{-1}$ |
| LFM-16PSK| $9.23 \times 10^{-2}$    | $9.98 \times 10^{-1}$ | $1.00$          | $1.00$          |
| 4PSK     | $2.00 \times 10^{-6}$    | $1.28 \times 10^{-4}$ | $2.56 \times 10^{-4}$ | $5.12 \times 10^{-4}$ |
| 8PSK     | $7.13 \times 10^{-2}$    | $9.91 \times 10^{-1}$ | $1.00$          | $1.00$          |
| 16PSK    | $1.52 \times 10^{-1}$    | $1.00$          | $1.00$          | $1.00$          |

Fig. 10 Photos of a the FPGA-based WARP and b the functional block diagram of the WARP

picked up by the RX RF HW transformer and is send to the receiver, the receiver uses the Pilot signal to perform synchronization and to identify the start of a new modulation frame, then, the received signal is decoded at the Laptop to calculate the BER;

– The display panel is used to display the experimental BER curves and the progress bar.

Figure 13a shows the modulated signal of the proposed CWID in the FPGA, where the symbol duration $T_b = 4 \mu$s
Fig. 11 Photos of (a) the experimental link hardware configuration and (b) the designed GUI for parameter configuration.

Fig. 12 The frame structure conducted by parameter configuration panel.

and sampling frequency $f_s = 40$ MHz. Figure 13b shows the experimental BERs performance of the CWID, LFM-MPSK and MPSK in a real radio channel. The test distance between the TX RF HW transformer and the RX RF HW transformer is constant and the signal-to-noise ratio (SNR) is varied by changing the transmission power from 0dBm to 20dBm. Generally speaking, the higher the transmission power, the higher the SNR, if the noise level is not changed too much. The corresponding channel parameters estimation is performed using Least Squares algorithm, the result is given in Fig. 13c, where the delay unit $T_c = 1\mu s$.

From Fig. 13b, it can be seen that the BER performance of the 4-CWID and LFM-4PSK are slightly better than that of 4PSK, because the LFM signal has better anti-interference ability as compared to the conventional sinusoidal signal used by 4PSK. The 4-CWID demonstrates slightly worse performance than LFM-4PSK due to the reduced constellation mapping distance caused by the additional data information mapping. However, the 4-CWID provides double bit transmission rate as compared to LFM-4PSK and 4PSK. With the increasing of modulation order in LFM-MPSK and MPSK, their bit transmission rate can be equal to that of the proposed 4-CWID, but the BER performance of the comparison methods with the same data transmission rate becomes even worse as compared to that of the 4-CWID. The experimental results show the similar trend as the simulation ones.

5 Conclusions

In this work, a CWID scheme based on LFM-MPSK modulation is being proposed for high bit transmission rate in complex wireless channel. The proposed CWID introduces the difference among the basic carrier waveforms by re-ordering the inter-displacement of sub-waveforms. The CWID modulation is more appropriate for M-ary modulation, which could achieve a higher transmitting bit rate with a low BER. The BERs performance of the proposed CWID, LFM-MPSK and MPSK are analyzed by numerical simulation in AWGN and wireless multipath fading channel. The simulation results show that the CWID is obviously superior to its comparison schemes under the identical bit transmission rate. Moreover, a SDE platform is designed on FPGA-based WARPs to implement a real radio link. A GUI is designed for the SDE platform, which can simplify the process of system parameters configuration without designing a brand new hardware or reconfiguring testing frame structure.
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(a) The modulated signal of CWID in FPGA; (b) the SDE platform developed to test the BER performance of the proposed CWID and its competitors in a real radio channel; (c) the estimated channel parameters

The experimental results verify the effectiveness and superiority of the CWID scheme as compared with its competitors.

Declarations

Conflict of interest The authors declare that they have no conflict of interest.

References

1. Bai, C., Ren, H. P., Celso, G., & Baptista, M. S. (2018). Chaos-based underwater communication with arbitrary transducers and bandwidth. *Applied Sciences, 8*(2), 162. https://doi.org/10.3390/app8020162
2. Zhang, Z. P., Mike, W., Nowak, M. J., Lomonte, L., & Wu, Z. Q. (2017). Mixed-modulated linear frequency modulated radar-communications. *IET Radar Sonar and Navigation, 11*(2), 313–320. https://doi.org/10.1049/iet-rsn.2016.0249
3. Nartasilap, N., Salim, A., Tuninetti, D., & Devroye, N. (2018). Communications system performance and design in the presence of radar interference. *IEEE Transactions on Communications, 66*(9), 4170–4185. https://doi.org/10.1109/TCOM.2018.2823764
4. Chen, L., Ai, H. Z., Zhuang, Z. J., & Shang, C.(2018). Real-time multiple people tracking with deeply learned candidate selection and person re-identification. In *IEEE international conference on multimedia and expo (ICME18)*. San Diego: IEEE. https://doi.org/10.1109/ICME.2018.8486597
5. Wang, S. S., Liu, Z., Xie, R., & Wang, J. J. (2021). VCR-LFM-BPSK signal design for countering advanced interception technologies. *Journal of Systems Engineering and Electronics, 32*(2), 380–388. https://doi.org/10.23919/JSEE.2021.000031
6. Bekar, M., Baker, C. J., Hoare, E. G., & Gashinova, M. (2020). Joint MIMO radar and communication system using a PSK-LFM waveform with TDM and CDM approaches. *IEEE Sensors Journal, 21*(5), 6115–6124. https://doi.org/10.1109/JSEN.2020.3043085
7. Bekar, M., Baker, C. J., Hoare, E. G., & Gashinova, M. (2020). Realization of a joint MIMO radar and communication system using a PSK-LFM waveform. In *IEEE radar conference (RadarConf20)*. Florence: IEEE. https://doi.org/10.1109/RadarConf2043947.2020.9266699
8. Li, J., & Dai, Y. Z. (2020). Fast parameter estimation of LFM-BPSK composite modulation and symbol recovery. *Radar & ECM, 40*(2), 14–19. https://doi.org/10.19341/j.cnki.issn.1009-0401.2020.02.004
9. Song, J., Liu, Y., & Xue, Y. Y. (2013). Parameter estimation and recognition of hybrid modulated signal combining BPSK with LFM. Journal of Nanjing University of Aeronautics & Astronautics, 45(2), 217–224. https://doi.org/10.3969/j.issn.1005-2615.2013.02.010

10. Liu, Z. P., Zhang, W. K., & Xu, S. F. (2013). Implementation on the integrated waveform of radar and communication. In International conference on communications, circuits and systems (ICCCAS13) (pp. 200–204). Chengdu: IEEE. https://doi.org/10.1109/ICCCAS.2013.6765318

11. Yang, H. T., Zhou, Y., Gu, Y. B., & Zhang, L. R. (2019). Design of integrated radar and communication signal based on multicarrier parameter modulation signal. Journal of Radars, 8(1), 54–63. https://doi.org/10.12000/JR18001

12. Chen, X. B., Wang, X. M., Xu, S. F., & Zhang, J. (2011). A novel radar waveform compatible with communication. In International conference on computational problem-solving(IICCP11), (pp. 177-181).Chengdu: IEEE. https://doi.org/10.1109/IICCPS.2011.6092272

13. Zhang, W. K., & Liu, Z. P.(2013). Design and implementation of modulator of a novel radar waveform compatible with communication. In International workshop on microwave and millimeter wave circuits and system technology (MMWCST13)(pp. 357-360). Chengdu: IEEE. https://doi.org/10.1109/MMWCST.2013.6814653

14. Li, B. S., Zhou, S. L., Stojanovic, M., Freitag, L., & Willett, P. (2008). Multicarrier communication over underwater acoustic channels with nonuniform Doppler shifts. IEEE Journal of Oceanic Engineering, 33(2), 198–209. https://doi.org/10.1109/JOE.2008.920471

15. Ren, H. P., Guo, S. L., Bai, C., & Zhao, X. H. (2021). Cross correlation and chaotic shape-forming filter based quadrature multi-carrier differential chaos shift keying communication. IEEE Transactions on Vehicular Technology, 70(12), 12675–12690. https://doi.org/10.1109/TVT.2021.3119176

16. Scheibhiffer, W., Feger, R., Haderer, A., Scheibhiffer, S., & Stelzer, A. (2016). In-chip FSK communication between cooperative 77-GHz radar stations integrating variable power distribution between ranging and communication system. International Journal of Microwave & Wireless Technologies, 8(4/5), 825–832. https://doi.org/10.1017/S1759078716000088

17. Nowak, M., Wicks, M., Zhang, Z. P., & Wu, Z. Q. (2016). Co-designed radar-communication using linear frequency modulation waveform. IEEE Aerospace and Electronic Systems Magazine, 31(10), 28–35. https://doi.org/10.1109/MAES.2016.1502326

18. Sun, F. L., Jiang, Z. T., Shen, J., & Zhu, J. Y. (2019). Parameters estimation of LFM-BPSK hybrid signal in low SNR. Guidance & Control, 40(2), 28–35. https://doi.org/10.3969/j.issn.1671-0576.2019.02.006

19. Bai, C., Zhao, X. H., Ren, H. P., Kolumban, G., & Grebogi C. (2021). Double-stream differential chaos shift keying communications exploiting chaotic shape forming filter and sequence mapping. IEEE transactions on wireless communications, early access. https://doi.org/10.1109/TWC.2021.3135043

20. Zhang, C., Patras, P., & Haddadi, H. (2019). Deep learning in mobile and wireless networking: A survey. IEEE Communications Surveys & Tutorials, 21(3), 2224–2287. https://doi.org/10.1109/COMST.2019.2904897

21. Ren, H. P., Yin, H. P., Bai, C., & Yao, J. L. (2020). Performance improvement of chaotic baseband wireless communication using Echo State Network. IEEE Transactions on Communications, 68(10), 6525–6536. https://doi.org/10.1109/TCOMM.2020.3007757

22. Ren, H. P., Yin, H. P., Zhao, H. E., Bai, C., & Grebogi, C. (2021). Artificial intelligence enhances the performance of chaos-based wireless communication. IET Communications, 15(11), 1467–1479. https://doi.org/10.1049/ietcom.212612

23. Yin, H. P., Bai, C., & Ren, H. P. (2021). Echo state network based symbol detection in chaotic baseband wireless communication, prepringarXiv: 2103.08159.

24. Ren, H. P., & Yin, H. P. (2021). Direct symbol decoding using GA-SVM in chaotic baseband wireless communication system. Journal of The Franklin Institute, 358(12), 6348–6367. https://doi.org/10.1016/j.jfranklin.2021.06.012

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