Designing Anti-Jamming Receivers for NR-DCSK Systems Utilizing ICA, WPD, and VMD Methods

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Abstract—In this brief, we consider an advanced noise reduction differential chaotic shift keying system in which a single antenna source communicates with a single antenna destination under the attack of a single antenna jammer. We design an anti-jamming receiver for the considered system. Particularly, we propose a variational mode decomposition—独立component analysis—wavelet packet decomposition (VMD-ICA-WPD) structure, in which VMD method is first exploited to generate multiple signals from the single received one. Second, ICA method is applied to coarsely separate chaotic and jamming signals. After that, WPD method is used to finely estimate and mitigate jamming signals that exist on all outputs of ICA method. Finally, an inverse ICA procedure is carried out, followed by a summation, and the outcome is passed through the conventional correlation receiver for recovering the transmitted information. Simulation results show that the proposed receiver provides significant system performance enhancement compared to that given by the conventional counterparts.

Index Terms—Chaotic communication, anti-jamming receiver, independent component analysis, wavelet packet decomposition, variational mode decomposition, bit-error-rate.

I. INTRODUCTION

A

S AN alternative to pseudo-random noise (PN) sequences used in conventional spread spectrum systems, which have poor cross-correlation and low security level, chaotic communication (CC) is proposed in [1]. The basic idea of CC is to replace PN sequences by chaotic sequences. CC systems can be categorized as coherent and non-coherent ones, among which the non-coherent CC systems have been widely considered and investigated in the literature due to its simplicity [1]. In addition, among various non-coherent CC systems, differential chaotic shift keying (DCSK) is the fundamental and most studied one. The performance of the DCSK system under the additive white Gaussian noise (AWGN), multipath fading, and single-tone jamming environments are extensively investigated in [2]–[4].

Although the DCSK system is largely investigated, it has several drawbacks, i.e., low data rate, high-energy consumption, and high complexity. To alleviate these drawbacks, several advanced alternatives have been proposed. Particularly, high-efficiency DCSK (HE-DCSK) [5], improved DCSK (I-DCSK) [6], and short reference DCSK (SR-DCSK) [7] systems are proposed to improve the data rate and enhance the spectral efficiency of the DCSK system. In addition, in [8], a reference modulated DCSK (RM-DCSK) system is presented to improve the transmission reliability and reduce the complexity of the DCSK system. Moreover, in [9], a noise reduction DCSK (NR-DCSK) system is introduced to reduce the noise variance present in the received signal, and thus, enhance the system performance. Furthermore, multiple access and coded DCSK systems are presented in [10]–[12]. Recently, effects of broad-band, partial-band, tone, and sweep jamming on the performance of the NR-DCSK system are extensively investigated in [13].

The performances of the DCSK and the NR-DCSK systems under jamming environments are studied in [4] and [13], however, how to mitigate the effects of jamming on the performances of CC systems is still an open question. Since the inherent AJ capabilities of CC systems may not work effectively when the jamming power is much larger than that of chaotic signals, designing additional jamming mitigation techniques for CC systems is of paramount importance. One of the common practices to mitigate jamming signals in wireless communication systems is to use fixed or adaptive notch filters (NFs) [14], [15]. While fixed NFs do not perform well if jamming frequency is not known or time variant, adaptive NFs incur high complexity because they use multiple sampling frequencies and adaptively weight filters to identify jamming frequencies. If multiple receiving antennas are available, jamming signals can be mitigated through nulling [16]. However, in this case, direction of arrivals of jamming signals must be estimated first, which leads to high cost and computational complexity. The other simple and promising alternatives are to use independent component analysis (ICA) [17], [18] and wavelet packet decomposition (WPD) methods [19], [20]. The advantage of the ICA method lies in the fact that it does not require prior information of jamming frequency and type. In addition, the WPD method provides a detailed representation of a signal in the time-frequency domain which is greatly useful for jamming estimation and mitigation.

We observe that although the ICA and the WPD methods can be readily applied to CC systems and may provide good AJ performance, there are still spaces for improvement.
Particularly, since the ICA method cannot tell which output is the desired signals, additional resources are required to transmit pilots together with the legitimate signal for the purpose of signal identification at the destination. In addition, the ICA method is not applicable to a system having a single-antenna destination because it requires that the number of input signals is at least equal to the number of independent sources. Moreover, the ICA and the WPD methods can also be combined together to enjoy advantages of both methods for jamming estimation and mitigation.

Motivated by the aforementioned observations, in this brief, we consider a single input single output NR-DCSK system, and design a novel AJ receiver for it. Specifically, we propose a correlation receiver with variational mode decomposition-ICA-WPD (VMD-ICA-WPD) structure, in which we exploit the VMD technique [22] to generate multiple signals from the received one, from which the ICA and the WPD methods can then be applied. In addition, in the proposed receiver, we apply the WPD method on all outputs of the ICA method, then an inverse ICA procedure and a summation are carried out to obtain an estimation of the transmitted signal. This means that we do not need to identify which output of the ICA method is which, and thus, leads to system complexity reduction. We extensively simulate the AJ performance of the proposed receiver and show that it significantly outperforms conventional counterparts.

II. SYSTEM MODEL

We consider the NR-DCSK system consisting of a source \( S \), a destination \( D \), and a jammer \( J \). Each node is equipped with a single antenna. While \( S \) is sending information to \( D \), \( J \) tries to disrupt \( D \)’s reception by emitting jamming signals. The transmitted signal of the \( p \th \)th bit, \( b_l \), is expressed as [9]

\[
x_l^p = \begin{cases} 
\frac{x_l}{\beta} & \text{if } 0 < k \leq \beta, \\
\beta \frac{x_l}{b_k^p \beta}^{\frac{1}{\beta}} & \text{if } \beta < k \leq 2 \beta, 
\end{cases}
\]

where \([\cdot]\) denotes the ceiling operator. In other words, each bit duration is divided into two equal time slots, one for transmitting a reference sequence (RS) of length \( \beta \) and one for sending an information-bearing sequence (IBS). To generate RS, a chaotic generator first generates \( \beta/P \) chaotic samples. Then, each chaotic sample is replicated \( P \) times. In addition, IBS is either RS (if the bit being sent is +1) or an inverted version of RS (if the bit being sent is −1).

The received signal at the destination is given by

\[
r_k^l = \frac{1}{P} \sum_{p=1}^{P} \sum_{k=1}^{\beta} h_{v,k}^l x_{k-l,p} + \frac{1}{P} \sum_{p=1}^{P} \sum_{k=1}^{\beta} g_{v,k}^p f_{t-p-t_l}^l + n_k^l, 
\]

where \( n_k^l \) and \( n_k^l \) respectively denote the jamming signal and the additive white Gaussian noise (AWGN) at \( D \), \( h_{v,k}^l \) and \( t_{v,k}^l \) (\( g_{v,k}^p \) and \( \rho_{v,k}^p \)) are the fading coefficient and the time delay of the \( v \th \) path channel from \( S \) to \( D \) (\( J \) to \( D \)), and \( V_1 \) (\( V_2 \)) is the number of paths from \( S \) to \( D \) (\( J \) to \( D \)). The channels are assumed to be independent block fading, which stay the same for a block of transmission and independently change from one block to another.

We consider sweep and tone jamming, which are widely used against wireless communication systems [13]. A sweep jammer emits a narrow-band signal which has a time-varying frequency. A common sweep jamming based on sinusoidal signal and linear sweep method and its discrete baseband version are expressed as [13]

\[
j(t) = \sqrt{2P} \sin(2\pi f_{\text{start}}t + \pi \Delta f t^2 + \theta_{sw}), \quad (3)
\]

\[
j_k^l = \sqrt{2P} \sin(\frac{kF_{\text{start}}}{\beta} + \pi \frac{k^2 \Delta F}{4\beta^2} + \theta_{sw}), \quad (4)
\]

where \( \Delta f = \frac{f_{\text{stop}} - f_{\text{start}}}{T_{sw}} \), \( f_{\text{start}} \) and \( f_{\text{stop}} \) are starting and stopping frequencies, \( \Delta f \) and \( T_{sw} \) are sweep rate and time, \( \theta_{sw} \) denotes an initial phase, \( F_{\text{start}} = f_{\text{start}}T_{sw} \), \( \Delta F = \Delta f T_{sw}^2 \), \( T_{sw} \) is the bit duration, and \( P \) is the jamming power.

On the other hand, a tone jammer places single or multiple jamming tones in the target signal’s spectrum. The continuous and discrete baseband tone jamming signals are expressed as

\[
j(t) = \sum_{m=1}^{M} \sqrt{2P_m} \sin(2\pi f_{m}t + \theta_m), \quad (5)
\]

\[
j_k^l = \sum_{m=1}^{M} \sqrt{2P_m} \sin(\frac{\pi kF_m}{\beta} + \theta_m), \quad (6)
\]

where \( f_m = f_m T_{sw} \), and \( P_m, f_m, \) and \( \theta_m \) are the power, frequency, and the initial phase of the \( m \th \) tone.

III. CONVENTIONAL RECEIVERS

A. Conventional Correlation Receiver [13]

The conventional correlation receiver for the NR-DCSK system is illustrated in Fig. 1. The received signal \( r_k^l \) is first fed into a block moving average filter (BMAF) which has a block size of \( P \). Secondly, the output of the BMAF is correlated with its replica which is delayed by \( \beta/P \) samples, and then the outcome is summed over \( \beta/P \) samples. Finally, the sum is passed through a threshold detector to recover the transmitted information. Mathematically, the output of the BMAF can be written as

\[
\hat{r}_k^l = \sum_{v=1}^{V_1} h_{v,k}^l x_{k-l,v}^l + \frac{1}{P} \sum_{v=1}^{V_2} g_{v,k}^p f_{t-p-t_l}^l + n_k^l,
\]

In addition, the decision variable \( B_l \) is given by

\[
B_l = \sum_{k=1}^{\beta/P} \left( \sum_{v=1}^{V_1} h_{v,k}^l x_{k-l,v}^l + \frac{1}{P} \sum_{v=1}^{V_2} g_{v,k}^p f_{t-p-t_l}^l \right) + \frac{1}{P} \sum_{v=1}^{V_2} g_{v,k}^p f_{t-p-t_l}^l + n_{k+l}.
\]

\[
B_l = \sum_{k=1}^{\beta/P} \left( \sum_{v=1}^{V_1} h_{v,k}^l x_{k-l,v}^l + \frac{1}{P} \sum_{v=1}^{V_2} g_{v,k}^p f_{t-p-t_l}^l \right) + \frac{1}{P} \sum_{v=1}^{V_2} g_{v,k}^p f_{t-p-t_l}^l + n_{k+l}.
\]
B. Correlation Receiver With WPD

Combining the WPD method [20] and the conventional correlation receiver readily gives a correlation receiver with WPD, as shown in Fig. 2. An estimation of the jamming signal $\tilde{j}$ is obtained by using the denoise capability of the WPD method, in which the jamming signal is treated as the major one and the chaotic signal is considered as noise.

The basic idea of the WPD method is that it decomposes the input signal into approximation and detailed parts, which are further split into other approximation and detailed parts, and the process is repeated. The WPD method can also be interpreted as a multi-resolution analysis, i.e., a $L$ level decomposition of the input signal into the scaling and the wavelet functions, which are respectively expressed as $\phi[k] = \sqrt{2} \sum n h[n] \phi[2k - n]$ and $\psi[k] = \sqrt{2} \sum g[n] \psi[2k - n]$. Consequently, the input signal can be reconstructed as [21]

$$r^j_k = \sum_{m=1}^L \sum_{n \in \mathbb{Z}} c_{m,n} \phi_{m,n} + \sum_{m=1}^L \sum_{n \in \mathbb{Z}} d_{m,n} \psi_{m,n}, \quad (9)$$

where $c_{m,n} = \langle x, \phi_{m,n} \rangle$, $d_{m,n} = \langle x, \psi_{m,n} \rangle$, $\phi_{m,n} = 2^{-m/2} \phi(2^{-m}k - n)$, $\psi_{m,n} = 2^{-m/2} \psi(2^{-m}k - n)$, and $\langle x, y \rangle$ denotes the inner product between $x$ and $y$. $c_{m,n}$ and $d_{m,n}$ here are called the wavelet coefficients.

For a denoising purpose, an appropriate threshold should be selected. Among various options, the common threshold is as follows [19], [20]

$$\gamma = \delta \sqrt{2 \ln(N \ln(N))} / \ln(2), \quad (10)$$

where $\delta = \text{MAD}/0.675$, MAD is the median absolute deviation of the wavelet coefficients, and $N$ is the length of the input signal. Then, if a wavelet coefficient exceeds $\gamma$, we set it to zero. Thereafter, an estimation of the jamming signal is obtained by applying the inverse WPD procedure on the modified wavelet coefficients. Finally, the estimated jamming signal is removed from the received signal, and the outcome is fed into the conventional correlation receiver for recovering the transmitted information.

IV. Correlation Receiver With VMD-ICA-WPD

In this section, we will propose a novel correlation receiver with VMD-ICA-WPD which is suitable for a single-antenna destination and can provide advantages of both the ICA and the WPD methods for the jamming estimation and mitigation purpose. Particularly, we exploit the VMD method to separate chaotic and jamming signals. Therefore, if we use a signal identification block to identify chaotic signal and remove the other one, we may loss sufficient amount of the transmitted information bits. A pseudo-code of the proposed receiver can be expressed as in Algorithm 1, shown in the next page.

Here, one may ask that (1) why we do not use a signal identification block to identify which output of the ICA method is chaotic signal and which output is jamming one, and (2) why we do not directly combine the de-jammed signals, i.e., the ones are inputs of the inverse ICA block, and feed the outcome to the conventional correlation receiver? The reason of not using a signal identification block to select the separated chaotic signal is that the ICA method is applied on signals that are decomposed from the single received one, and thus, we expect that the ICA may not satisfactorily separate chaotic and jamming signals. Therefore, if we use a signal identification block to identify chaotic signal and remove the other one, we may loss sufficient amount of the transmitted information.
Algorithm 1 Correlation Receiver With VMD-ICA-WPD

```
1: procedure VMD
2: Input: a block of the received signal r
3: Initialize \( v_n^1, w_n^1, m \leftarrow 0, N = 10 \) modes
4: while not converged do
5:    Update \( v_n \), \( w_n \), and dual ascent \( \lambda^m \)
6:    \( v_n^{m+1} \leftarrow \arg \min_{v_n} \mathcal{L}(v_n^{m+1}, v_n^{m+1}, \lambda^m) \)
7:    \( w_n^{m+1} \leftarrow \arg \min_{w_n} \mathcal{L}(w_n^{m+1}, w_n^{m+1}, w_n^{m+1}, \lambda^m) \)
8:    \( \lambda^{m+1} \leftarrow \lambda^m + \tau (r - \sum_n v_n^{m+1}) \)
9: Output: \( V_1 = \sum_{n=1}^{5} v_n, V_2 = \sum_{n=6}^{10} v_n \)
10: procedure ICA
11: Input: \( R = [V_1 \ V_2]^T \)
12: Centering: \( R_1 = R - \text{mean}[R] \)
13: Whitening: \( R_2 = C^{-1/2} R_1 \), where \( C = E[R_1 R_1^H] \)
14: for \( p = 1:2 \) do
15:    while not converged do
16:        Initialize \( w_p \)
17:        \( w_p^+ \leftarrow E[R_2 g(w_p^T R_2)] - E[g'(w_p^T R_2)] w_p \)
18:        where \( g(x) = x^3, g'(x) \) is its derivative.
19:        Decorrelation: \( w_p^{+} \leftarrow w_p^+ - \sum_{i < p} w_i w_p \)
20:        Normalizing: \( w_p = w_p^+/\|w_p^+\| \)
21: Output: \( [I_1 \ I_2]^T = W^{H} R \), where \( W = [w_1 \ w_2]^T \)
22: procedure WPD
23: Decompose \( I_1 \) and \( I_2 \) to L detailed level.
24: If a wavelet coefficient exceeds \( \gamma \), thresholds it to zero
25: \( [\hat{j}_1, \hat{j}_2] \) = inverse WPD of the modified coefficients
26: \( W_1 = I_1 - \hat{j}_1, W_2 = I_2 - \hat{j}_2 \)
27: procedure INVERSE ICA
28: \( [H_1 \ H_2]^T = W^{-1}[W_1 \ W_2]^T \)
29: \( Il = I_1 + I_2 \)
30: procedure CORRELATION-BASED DECODING
31: Input \( Il \) and output \( \ldots \hat{b}_i \ldots \)
```

In summary, by integrating the VMD method, the proposed receiver can overcome the limitation of a correlation receiver with ICA on the required number of input signals. In addition, the proposed receiver can provide advantages of both the ICA and the WPD methods on jamming estimation and mitigation. Moreover, in the newly designed receiver, we do not need to identify which output of the ICA method is the chaotic or the jamming signal, and thus, we do not need to send pilots together with the chaotic signal. It means that with the proposed receiver, the system resources can be used more efficiently.

V. SIMULATION RESULTS

The simulation setting follows the system model presented in Section II with \( \beta = 200 \) and \( P = 20 \). In addition, logistic generator is used for generating chaotic samples, i.e., \( \chi_{k+1} = 1 - 2\chi_k^2 \). Moreover, two-path Rayleigh fading channels with an average power gain of 1/2 are used. The time delays of the channels are varying according to the uniform distribution between zero and \( \chi \), where \( \chi \ll \beta \). Noting that the two-path channel model is commonly used in recent works on CC systems [6], [7], [9], [12].

In Fig. 4, we simulate the BER performance of the NR-DCSK system versus JSR with \( \text{Eb/N}0 = 30 \) dB. We compare the system performance provided by the proposed receiver with that given by the correlation receiver with WPD and the conventional correlation receiver. As a benchmark comparison, the performance of the PI-DCSK system [12] is also included. It is first shown that the conventional correlation receiver gives the worst performance over the whole JSR range. In addition, we observe that the proposed receiver provides a similar performance to that given by the correlation receiver with WPD in the low SJR region, i.e., \(-20 \text{ to } -10\) dB. However, as JSR increases, the proposed receiver gives a much better performance than that of the one with WPD. More specifically, at BER = 10^-7, the proposed receiver provides around 8 dB gain compared to the correlation receiver with WPD. Moreover, the aforementioned trend also holds for the case under tone jamming, which implies that the proposed
receiver is robust against different types of jamming. Finally, it is noted that the PI-DCSK system provides a slightly better performance than that of the NR-DCSK system with the conventional correlation receiver.

We present a comparison of BER and runtime of the three receivers versus the number of transmitted bits with JSR = 0 dB and Eb/N0 = 20 dB in Fig. 5. It is shown that, in terms of BER, the proposed receiver provides a much better BER than that given by the correlation receiver with WPD and the conventional correlation receiver. In addition, in terms of runtime (or decoding latency), the conventional correlation receiver has the fastest runtime, followed by that of the correlation receiver with WPD and the proposed one. In other words, there exists a tradeoff between BER and decoding latency of the three receivers. However, we observe that the runtime of the proposed receiver and the correlation receiver with WPD linearly scale with the number of transmitted bits. Therefore, we believe that the proposed receiver is applicable for practical systems.

VI. CONCLUSION

In this brief, we proposed a correlation receiver with VMD-ICA-WPD for the NR-DCSK system. In the proposed receiver, the VMD method is first used to generate multiple signals from a single received one, which alleviates the limitation of the ICA method on the required number of input signals. Secondly, the ICA method is applied to the outputs of the VMD method, followed by the WPD method. The WPD method is applied on all outputs of the ICA method to estimate and mitigate jamming signals. Finally, the inverse ICA procedure and the summation operation are carried out, and the outcome is fed into the conventional correlation receiver for decoding transmitted information. We showed that the proposed receiver significantly outperforms the conventional counterparts.

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