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Communication with unstable basis functions

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ABSTRACT

Work by Corron et al. [1,2] represented a chaotic signal as a set of basis functions, and built a matched filter for the resulting signal. This paper makes use of basis functions without an underlying chaotic system. Matched filtering is still possible, allowing communication in noisy environments, but the resulting signals can be broad band, which is useful for producing signals that are hard to detect. The receiver design retains the simplicity of Corron et al. [1,2], which is good when weight, power consumption or bandwidth are constraints on the receiver.

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1. Introduction

Chaotic signals can be broad band and unpredictable, which makes them attractive for low probability of detection (LPD) communications. In LPD communications, security is gained not by encryption (although encryption is possible) but by the difficulty of detecting the presence of the signal. A primary requirement for LPD communications is that the power spectrum of the signal is broad and flat.

Chaotic signals can have broad power spectra. Unfortunately, the properties that make chaos useful for LPD communications also mean that detecting chaotic signals in a noisy communications channel is difficult. Typically, LPD communications require that the signal power be the same size or lower than the background noise power.

There has been much work on the use of chaos for communication [3–20]. While there are methods for synchronizing two chaotic systems [21], these methods are sensitive to noise, so most recent chaotic methods avoid the synchronization by using non coherent techniques [22]. Recently there has been a resurgence in the field motivated by applications in mobile communications, low probability of detection communications, and new techniques such as orthogonal frequency division multiplexing.

Recent work by Corron et. al. demonstrated a chaotic system for which an exact analog filter could be designed [1,2]. The design of the particular chaotic system allowed the chaotic output signal to be described as a linear combination of basis functions. Encoding information on the chaotic signal altered the particular linear combination. For these basis functions, an analytically derived matched filter existed, so encoded information could be recovered from the transmitted signal by passing this signal through the matched filter. Matched filtering is an effective way to communicate in the presence of noise. The system of Corron et. al. [1,2] could be produced entirely as an analog circuit, which is a potential advantage for circuits that needed to operate at high speeds, or for transmitters that needed to be lightweight and use little power.

The system of Corron et. al. [1,2] had some disadvantages for LPD communications. The output chaotic signal was relatively narrow band; broad band signals are better for LPD systems. Allowing the chaotic system to run freely produced a series of basis functions that overlapped with each other, causing inter-symbol interference. The system described here seeks to produce a signal with a broader spectrum and eliminate the inter-symbol interference.

The important concept that is retained from Corron et. al. [1,2] is the idea of a signal that can be created from a set of basis functions and filtered by a linear matched filter. The basis functions in [1,2] are related to the output of an unstable oscillator, so their matched filter used the same oscillator but with the sign of the damping reversed, so that the oscillator was stable.

The system described here used the concept of basis functions produced by an unstable oscillator, but the method here is a hybrid of analog and digital methods. The output of an unstable oscillator is difficult to reproduce, so this method used a set of N stable linear oscillators driven by an impulse to produce N impulse waveforms. The impulse waveforms were then time reversed to produce signals that mimicked signals from an unstable oscillator. This time reversal required digital processing, so the method described here is not entirely analog.

An additional step in this method is that the set of N time reversed waveforms were then rotated to produce a set of N orthogonal waveforms. The orthogonal waveforms allowed multiple data streams to be transmitted in the same bandwidth. The receiver matched filter used the stable version of the unstable circuits, as

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in the approach of Corron et. al. [1,2], but the stable oscillator circuits were then followed by a rotation matrix to make a complete matched filter.

The transmitter in this method requires some digital processing, but the receiver does not. While digital circuits have many advantages in terms of reproducibility, stability and ease of design, converting signals between analog and digital adds cost and complexity, and limits the possible signal bandwidth. The transmitter, while requiring some digital technology, is still relatively simple, so this method for low probability of detection communication has some advantages where signal bandwidth, power consumption or system weight are limiting factors.

2. Linear basis functions

In theory, the linear basis functions could be produced by an unstable set of oscillators

$$\begin{aligned} \frac{dx_i}{dt} &= \alpha_i y_i \quad i = 1 \ldots N \\ \frac{dy_i}{dt} &= \alpha_i((\beta/\alpha_i)y_i - x_i) \end{aligned} \tag{1}$$

where $\beta > 0$ causes the system to be unstable and α_i sets the oscillator frequency. Scaling the damping β by the time scale factor α_i makes all the unstable oscillators have the same bandwidth. There are N total oscillators.

In practice, in an actual analog circuit, it is difficult to get reproducible waveforms from an unstable circuit. The alternative approach used in this work instead uses stable circuits, as described in Eq. (2).

$$\begin{aligned} \frac{dx_i}{dt} &= \alpha_i y_i \quad i = 1 \ldots N \\ \frac{dy_i}{dt} &= \alpha_i(-(\beta/\alpha_i)y_i - x_i + d(t)) \end{aligned} \tag{2}$$

In Eq. (2), the damping factor $\beta < 0$. The term $d(t)$ is a driving signal. The driving term is set to $d(t=0) = 1$ and $d(t) = 0$ for $t \neq 0$, so that the output signal, $x(t)$, is the impulse response of Eq. (2). The waveforms from the stable oscillators are then reversed in time to produce linear basis functions

$$b_i(t) = x_i(t_{step} \times l_b - t) \tag{3}$$

where l_b is the length of the basis function and t_{step} is the integration time step.

The time reversal means that the basis functions must be either simulated or digitized from a circuit and played back by a digital to analog convertor. Figure 1 shows a typical set of linear basis functions $b_i t$ from a simulation. The length of the basis functions was $l_b = 1000$ points, the integration time step was 0.01 s, and the value of β was 0.6.

2.1. Orthogonal basis functions

The linear basis signals $b_i(t)$ are not orthogonal, so they must be transformed into an orthogonal basis. The set of N linear basis signals of length l_b are loaded into an $l_b \times N$ matrix $\mathbf{B}_l$. $\mathbf{B}_l$ is decomposed by a singular value decomposition:

$$\mathbf{B}_l = \mathbf{U}\mathbf{S}\mathbf{V}^T \tag{4}$$

where $\mathbf{U}$ is an $l_b \times N$ matrix and S is a diagonal $N \times N$ matrix of singular values. The $N \times N$ matrix V will be used as a rotation matrix. The orthogonal basis functions $\chi_i(t)$ are obtained from the linear basis functions $b_i(t)$ by applying the rotation

$$\mathbf{X} = \mathbf{B}_l \mathbf{V} \tag{5}$$

where the individual basis functions $\chi_i(t)$ are the rows of $\mathbf{X}$.

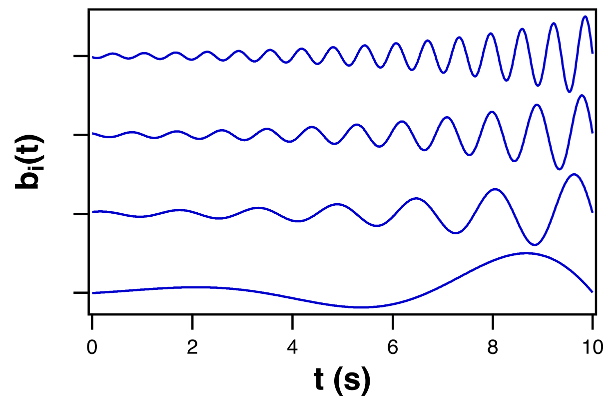

Fig. 1. Typical linear basis functions $b_i(t)$ for $\beta = 0.6, t_{step} = 0.01$ and $l_b = 1000$. The basis functions have been normalized to have a maximum value of 1, and they have been shifted on the y axis for plotting. From bottom to top, the value of α_i is 1, 4, 7 and 10.

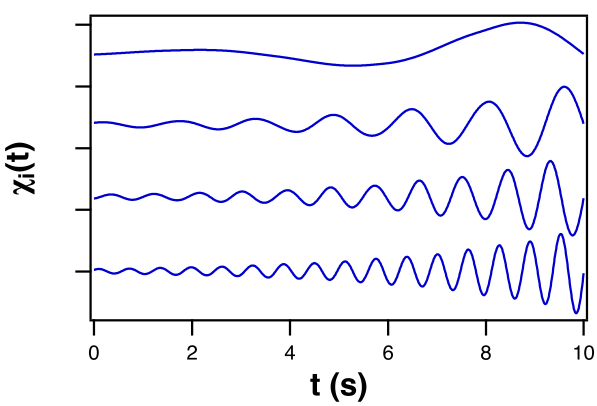

Fig. 2. Orthogonal basis functions $\chi_i(t)$ generated from the linear basis functions in Fig. 1). The basis functions have been renormalized to have a root mean square amplitude of 1, and they have been offset in the y axis for plotting. From bottom to top, the value of α_i is 1, 4, 7 and 10.

Fig. 2 shows the orthogonal basis functions $\chi_i(t)$ obtained from the linear basis functions in Fig. 1. The orthogonal basis functions are all normalized to have the same root mean square (RMS) amplitude.

3. Data encoding

Data will be transmitted by multiplying each of the N orthogonal basis functions by ± 1 and summing. The orthogonality will be used at the receiver to undo the sum and recover the individual basis functions. The length of the transmitted signal $s_t(t)$ will be $K \times l_b$, where the total number of data bits to be transmitted is $N \times K$.

The information to be transmitted consists of a set of binary bits $\rho_i(k), i = 1 \ldots N, k = 1 \ldots M$ where $\rho_i(k) = \pm 1$ The index i refers to the particular basis function while k indicates the particular data interval of length l_b.

To encode the binary information for data interval k, each of the orthogonal basis functions is multiplied by the corresponding binary bit $\rho_i(k)$ and summed to produce the transmitted signal $s_t(k)$:

$$s_t(k) = \sum_{i=1}^{N} \rho_i(k)\chi_i. \tag{6}$$

Fig. 3 is a block diagram of the analog transmitter.

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