Robust, Chaos-Based Communication Using Neural-Networks

W. Citko, A. Luksza, W. Sienko
Dept. of Electrical Engineering
Maritime Academy of Gdynia
81-225 Gdynia, ul. Morska 83,
Poland
e-mail: wcitko@wsm.gdynia.pl

Abstract
This paper presents how can one generate a rich enough set of chaotic signals or random sequences with adequate, for CDMA communications, correlation properties using neural network based chaotic associative memories.

Keywords: chaotic associative memories, chaos generators, chaos-based communication systems.

1. Introduction

Novel engineering applications of chaos have recently been described in the literature. They may be grouped under two following classes:

- Synthesis of chaotic signals, exploiting the noise-like waveform of chaotic signals. This class of applications includes signal masking and spread-spectrum communications.
- Analysis of chaotic signals, exploiting the so called dynamic modelling (Haykin, 1995)

The subject matter of this paper falls under the first class. In particular, the purpose of this paper is to show how to employ neural net based chaotic associative memories as a sources of spreading pseudo-random sequences in SS/CDMA communication systems. It is known that the introduction of deterministic chaos into communication systems offers some improvements, compared to conventional solutions. Regarding such systems, the three following problems must be addressed:

1. Synchronisation of chaotic generators.
2. Correlation properties of the set of signals generated by chaotic systems.
3. Implementation of chaotic generators.

After the synchronisation of chaos was established (Pecora, 1990; Cuomo, 1997; Halle, 1993; Pyragas, 1993; Parlitz, 1996; Rulkow, 1992; Abarbanel, 1996), there has been a great deal of interest in employing sychronised chaos in communication systems. However, the synchronisation schemes based on identical and generalised synchronisation do not demonstrate adequate robustness in realistic channels. Hence, we assume that implementable solutions of chaos based CDMA systems should be based on digital chaos generators. The synchronisation problems can be then solved similarly as in conventional PN sequence generators, assuming that replica of transmitter generator there is on receiver side.

Currently, it seems that the main problem with chaos based communication theory can be formulated as follows: How can one generate a rich enough set of chaotic signals or random sequences with adequate correlation properties, which fulfills the demands of realistic communication systems. Previous results on chaotic spreading signals stated that a chaotic generator supports an enormous number of system users by changing the initial conditions. However, numerical experiments show that the trajectories with different initial conditions eventually coincide with high probability (Cong, 1998). Hence it is currently unclear how to design a chaos generator producing rich set of signals mentioned above, taking into account the limitations of digital hardware implementations. However, solutions which are known from the literature (Andreyew, 1997) propose to employ special chaotic systems 1-D and N-D maps with stored information as sources of pseudo-random code sequences for spread-spectrum communication, but the map generators involve high-precision multipliers and are more complicated than conventional shift register generators.

In our work we claim that large-scale neural networks can be used as the natural source of chaotic signals. Indeed, every such a structure with memory **M** consisting of N-neurons, provides N-uncorrelated binary sequences (output of neurons) and/or N analog chaotic signals (state of the neural network). Moreover, every such a N-neuron network with a fixed structure can be seen as a source of an enormous number of uncorrelated chaotic signals by changing only one external parameter, namely the level of input bias I_B.

2. Passive neural network structure based chaos generators

It has been recently shown how to design the very large scale associative oscillatory/chaotic memories using passive neural networks. A starting point for such a design is a memory **M** given as a set (matrix) of binary {-1, +1} column vectors. The memory **M** can be seen as an information set, such as an alphabet of symbols, pictures etc.(Luksza, 1998; Citko, 1997).

Most of chaotic neural architectures rely on using the chaotic neurons. Hence, such chaotic neural networks can be seen as nets of coupled chaotic oscillators. In our design, an oscillatory structure is derived from static passive neural networks by changing the function of only one neuron. Due to such a solution, the procedures for implementing static, large-scale associative memories provide the tool for designing oscillatory/chaotic large-scale associative memories. It means that static associative memory can be easily changed to a chaotic generator. It is interesting to note that a memory $\mathbf{M} = [\mathbf{m}_1, \mathbf{m}_2, \ldots, \mathbf{m}_r]$, where $\mathbf{m}_i$ are colum (n x 1) vectors with components -1 and $+1$ of basis static neural network, must contain at least two degenerate (unentangled) states, i.e. there are two vectors $\mathbf{m}_k$ and $\mathbf{m}_l$ in Hamming distance equal 2 only. The power spectra of such hyper chaotic generators exhibit some typical features, namely a set of narrow peaks filled by background noise. Many natural sources of chaotic oscillations have such a type of spectra, i.e. correlated noise.

Concluding, we show how given memory $\mathbf{M}$ can be encoded by correlated noise using large-scale neural networks. It is clear that a set of memories $\mathbf{M}_k$, $k = 1, \ldots, q$ can be encoded by set of chaos generators G_k preserving the correspondence $\mathbf{M}_k \leftrightarrow G_k$, $k = 1, \ldots, q$. As an example of the above design, let us consider a chaos generator with underlying memory matrix $\mathbf{M}_1$ given by (1):

$$\mathbf{M}_1 = \begin{bmatrix} -1 & -1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 & -1 & 1 & 1 \\ 1 & 1 & -1 & 1 & 1 & 1 & -1 & -1 & -1 & 1 & -1 & -1 \\ -1 & 1 & 1 & 1 & -1 & 1 & -1 & 1 & -1 & -1 & -1 & 1 \\ -1 & -1 & 1 & 1 & 1 & 1 & -1 & -1 & -1 & -1 & 1 & 1 \end{bmatrix}^T \tag{1}$$

The power spectrum of this 12 neuron net based generator $G_1(\mathbf{M}_1)$ is shown in Fig. 1.

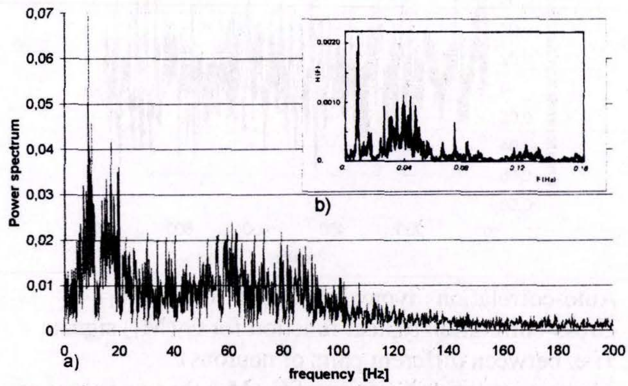

Fig. 1. a) Power spectrum of chaos generator $G_1(\mathbf{M}_1)$
b) Power spectrum of B-Z reaction

The similarity between the power spectrum of designed generator and power spectrum of chaotic oscillations in famous Belousov-Zhabotinskii reaction (Roux, 1980) is worth noting.

It should be noted that every $G_k(\mathbf{M}_k)$ generator can be seen as a source of N (number of neurons) uncorrelated signals. To point out this fact, the same correlation functions of these signals have been analysed and compared with Gold sequences. Fig. 2 shows the normalised, typical auto- and cross-correlation functions found in $G_1(\mathbf{M}_1)$ generator. For comparison, the same functions for Gold (L=511) shift register generator are shown in Fig. 3.

a) b)

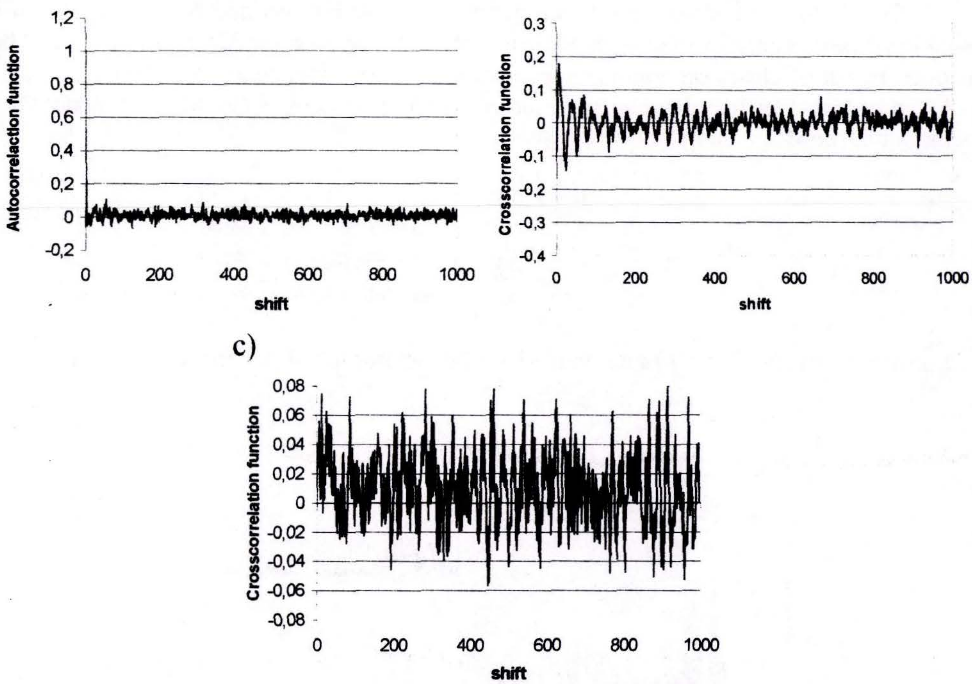

Fig. 2. a) Auto-correlation typical function for $G_1(\mathbf{M}_1)$
b) Cross-correlation typical function for $G_1(\mathbf{M}_1)$ signals (i.e. between different pairs of neurons).
c) Cross-correlation function of $G_1(\mathbf{M}_1)$ for two values of input bias I_B and 0.99 I_B (for the same neuron)

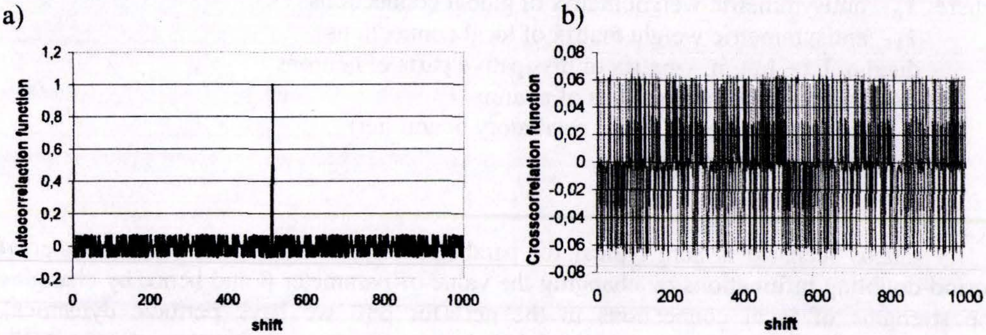

Fig. 3. a) Auto-correlation function for Gold generator (L = 511)
b) Cross-correlation function for Gold generator

Summarising, the chaotic generator presented in this paper can be treated as a flexible source of a very rich set of signals adequate for using in spread spectrum CDMA communication systems.

3. On mechanism of chaos generation

The general structure of neural networks used as chaos generators is shown in Fig.4.

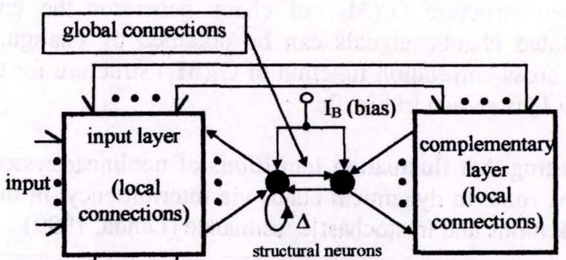

Fig. 4. General structure of neural network based chaos generators.

It resembles the double LEGION structure presented in paper (Wang, 1995; Terman, 1995) State space description of our chaos generators is given by:

$$\dot{\mathbf{x}} = \mathbf{T}_g\boldsymbol{\Theta}(\mathbf{x}) + \left(\mathrm{diag}[0,\ldots,0,\Delta,0,\ldots 0] - \mathrm{diag}[\omega_{oi}]\right)\mathbf{x} + \beta\mathbf{T}_l\boldsymbol{\Theta}(\mathbf{x}) + \mathbf{I}_B \tag{2}$$

where: $\mathbf{T}_g$ – antisymmetric weight matrix of global connections
$\mathbf{T}_l$ - antisymmetric weight matrix of local connections
diag[ω_{oi}], i= 1,..., n, - matrix of dissipative parts of neurons
Θ(x)-sigmoidal characteristics of neuron
Δ-swiching parameter (>0 for oscillatory neural net)
β –bifurcation parameter
I_B – input bias

Chaos scenario is here typical for parabolic map, i.e. one observes a number of period-doubling bifurcations by changing the value of parameter β and hence by changing the strengths of local connections in the net (for β=0 we have periodic dynamics). Moreover, the Lyapunow spectrum exhibits two positive exponents pointing out the hyperchaotic character of attractor. Independent from this scenario, the structure of Eq.(2) allows us to formulate the following conjecture:

Conjecture

1. The dynamics of the neural network from Fig.4. is determined by periodic flow for β=0. Raising the strengths of local connections, some neurons oscillate like Brownian particles, making the whole flow aperiodic. Thus, the component equal $\beta \mathbf{T}_l \boldsymbol{\Theta}(\mathbf{x})$ in Eq.(2) can be seen as a fluctuation force in the diffusion process. It is indeed the case when noise of internal origin induces aperiodic oscillations in the neural networks. Hence one obtains explanation for small values of cross-correlation functions observed in $G_k(\mathbf{M}_k)$ generators.
2. For given structure $G_k(\mathbf{M}_k)$ of chaos generator the enormous number of uncorrelated chaotic signals can be obtained by changing the input bias I_B (typical cross-correlation function of $G_1(\mathbf{M}_1)$ structure for two values of bias I_B and 0.99 I_B is shown in Fig. 2c.

It is worth noting that fluctuation transitions of nonlinear systems can have a dominant role in the route to dynamical chaos via intermittency, in the excitation of noise-induced oscillations and in stochastic resonance (Landa, 1999).

4. Concluding comments

The chaos generators presented in this paper are very flexible and rich sources of signals appropriate for chaos-based SS/CDMA communication systems. Moreover, they are currently implementable by using DSP processors. For example, practically implemented 12-neurons chaos generators are attainable on ADSP-21062 processor (Dudziak, 1998).

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