Claims of the Ph.D. Thesis

PERFORMANCE ANALYSIS OF CHAOTIC COMMUNICATIONS SYSTEMS

Gábor Kis

Budapest University of Technology and Economics
Department of Measurement and Information Systems

Advisor:
dr. Géza Kolumbán
Candidate of Technical Science

Budapest
2003

Introduction

The phenomenon of chaos emerging in deterministic nonlinear dynamical systems is a type of random-like behavior, without showing any regularity at first observation. However, a detailed analysis of a chaotic signal or time series analysis of a chaotic sequence shows that the chaotic signals follow the dynamics of the system.

The well-known steady-state behaviors of a dynamical system are the equilibrium, periodic, and quasi-periodic states. From a practical point of view chaos is a bounded signal generated by a nonlinear, usually low-order, deterministic system, which does not belong to any of the steady-state behaviors given above [PC89].

Chaotic systems are usually characterized by their sensitive dependence on initial conditions, which is defined as follows. Let J be an interval, and suppose that $f : J \to J$. Then f has sensitive dependence on initial conditions at x, if there is an $\epsilon > 0$, such that for each $\delta > 0$, there is a y in J and a positive integer n such that

$$|x - y| < \delta \quad \text{and} \quad |f^{[n]}(x) - f^{[n]}(y)| > \epsilon$$

From a practical point of view, this means that two trajectories emerging from different initial conditions diverge and become uncorrelated even if the initial conditions are arbitrarily close to each other.

Other important properties of chaotic signals and systems exploited in engineering are [PC89, Che99]:

- Sensitive dependence on the parameter values. Consider two chaotic systems with almost identical parameters. Then two trajectories emerging from the same initial conditions diverge even if the parameter mismatch between the two systems is arbitrarily small.
- The consequence of these two properties is that the behavior of chaotic systems can be predicted only for a short time period.
- Trajectories and output signals of chaotic systems are bounded.
- Power spectral density of a chaotic signal covers a wide frequency band.
- The average, average power, and power spectral density of a chaotic signal are time-invariant.
- Chaotic signals can be generated by simple circuits in arbitrary frequency band and at arbitrary power level.

The chaotic signals can be used in communications as carriers transmitting the digital information and as spreading codes in spread spectrum communications. The basic idea of chaotic modulation schemes is that the information to be transmitted is mapped directly to a wide-band chaotic signal. Consequently, a new type of spread spectrum systems having low complexity can be implemented using chaotic communications systems. Because of the wide-band property of the transmitted chaotic signal, these systems are not sensitive to the frequency-selective fading caused by multipath propagation.

Objectives of the research

In the past few years the research done in the field of chaotic communications has studied the following possible applications:

- secure communications systems using chaos;
- application of chaotic signals as spreading codes in conventional spread spectrum communications systems;

- analog and digital chaotic modulation schemes.

At the beginning the research in the field of modulation schemes considered only the coherent analog and digital modulation schemes. As a result, a large number of techniques have been proposed for chaotic synchronization [CP91, CO93, Has95, SCC97, WC94] which is a type of chaotic carrier recovery. However, the analysis of synchronization techniques showed that the methods developed are very sensitive to channel noise, parameter mismatch, and signal distortion caused by the communication channel [CY00]. Because of the sensitivity of chaotic synchronization, various techniques have been proposed in which there are no need for synchronization to perform the communication [ASG00, KKC97, KKC98, KK00, STV00].

The digital chaotic modulation schemes can be divided into three categories:

[1] Modulation schemes developed using heuristic arguments which cannot be treated with the theory of conventional communications systems. These techniques include, for example, the inverse system approach [FHS96] and chaotic masking [ea92].

[2] Methods in which the exact knowledge of the chaotic system generating the transmitted signal is used to perform the demodulation. In this case the information on the dynamics of chaotic system is exploited [HS00, MF00, Sch98].

[3] Modulation techniques in which the digital information to be transmitted is mapped directly to chaotic basis functions. An example of these methods is chaotic switching [KKJK02] which is a special type of chaos shift keying [DKH93] modulation.

The modulation schemes developed in a heuristic manner have been analyzed by means of simulations. The results of these simulations have shown that the noise performance of these systems lags far behind that of conventional modulation schemes.

The methods exploiting the dynamics of chaotic system may have better noise performance than the previous techniques. However, even a small improvement in noise performance requires a much more complex detector configuration.

Those techniques in which the information is mapped directly to chaotic basis functions show similarity to conventional modulation schemes. The noise performance of these schemes can be determined exploiting this analogy.

Considering a chronological order, digital modulation schemes using chaotic basis functions were proposed as follows. The first scheme with a coherent receiver called chaos shift keying (CSK) was introduced in 1992 [PCK+92]. Many other chaotic digital modulation schemes based on heuristic recognitions were proposed in the following years [FHS96, HGO93, SK95, WC93, Yan95]. A survey of the state of the art was presented at IEEE ISCAS conference in 1995 [Has95]. The first chaotic modulation scheme developed using communications approach was the differential chaos shift keying (DCSK) technique published by Kolumbán and Vizvári in 1996 [KVSA96]. The optimized version of this scheme is the frequency-modulated differential chaos shift keying (FM-DCSK) modulation scheme [KKJK98]. Since then, the methods of communication theory [KKC97, KKC98, KK00] and statistical analysis [ASG00, STV00, AGS98, SGK+00] have been applied to chaotic digital modulation schemes, culminating in the development of chaotic counterparts for conventional modulation schemes, and a theoretical classification and an understanding of correlator-based chaotic modulation schemes [Kol00]. The state of the art has been summarized in three publications [KKJK02, Ken00, KRS00].

The most important properties of chaotic communication systems are as follows. Chaotic communications systems can be used in indoor radio environments and wireless local area networks (WLAN), where the main problem is the selective fading caused by multipath propagation and not the thermal noise of the receiver. This problem can be solved by spreading the spectrum of the signal over a wide frequency band.

In chaotic modulation schemes the digital information to be transmitted is mapped to a wide-band chaotic signal in such a way that the bandwidth of transmitted signal is much larger than the bit rate. In this sense chaotic communications is a special type of spread spectrum systems. The main advantages of chaotic communication systems are:

- Since chaotic signals can be generated by simple circuits in any frequency band and at arbitrary power levels, a low-cost and low-complexity spread spectrum system can be implemented by means of chaotic modulation schemes.
- FM-DCSK modulation scheme does not require a linear channel.
- FM-DCSK system can transmit pure "0" and "1" sequences, i.e., there is no need for scrambler circuit.
- Similarly to conventional spread spectrum systems, chaotic communications systems can operate in presence of frequency selective fading caused by multipath propagation because the transmitted modulated signal is spread over a wide frequency band.
- Due to the low power spectral density of transmitted signal, chaotic communications systems cause low level of interference in other narrow-band systems sharing the same frequency band.

Consequently, low-cost spread spectrum systems can be implemented using chaotic modulation schemes. The price of low cost is that chaotic communications systems have several disadvantages:

- Since robust chaotic synchronization technique is not yet available, chaotic basis functions cannot be recovered at the receiver. In order to overcome this problem, differentially coherent demodulation technique is used in the built chaotic communications systems. The application of this technique offers a very robust demodulator but it has no processing gain and has a bit worse noise performance.
- Another problem arises due to the fact that chaotic signals of finite duration are not orthogonal: the chaotic communication systems in the original form cannot offer multiple access capability. However, a limited multiple access capability can be achieved by exploiting the orthogonality of Walsh functions.

To summarize the main properties of chaotic communications systems, we claim that chaotic modulation schemes offer a robust, low-cost, and low-complexity spread spectrum system which can offer limited services compared to conventional SS systems.

The importance of research done in the field of chaotic communications was recognized by the U.S. Army Research Office (ARO). Because of the importance of this research field, the launch of a Multidisciplinary University Research Initiative (MURI) was proposed by U.S. ARO [LZC96, dig98]. This project was started in 1998.

Meantime, an Esprit Open FET project entitled "Innovative Signal Processing Exploiting Chaotic Dynamics" (INSPECT) financed by European Commission was launched in 1997 [inn01]. The aim of this project was to find applications of chaos in communications and watermarking. Research groups of seven European universities were collaborating in the INSPECT Project towards the following goals

- Application of chaotic sequences as spreading codes in conventional spread spectrum communications systems;
- Design and implementation of a chaotic digital communication system;
- Application of chaotic signals for watermarking of digital pictures.

Budapest University of Technology and Economics was represented in the INSPECT Project by the Chaotic Systems Team of the Department of Measurement and Information Systems. As a member of this team, I was working towards the PhD degree in the framework of INSPECT and OTKA T020522/1996 projects. The duty of our team was the

- Development of the modulation scheme;
- Determination of theoretical noise performance;
- Elaboration of the optimum transmitter and receiver structures for the prototype chaotic radio system;
- System level design of the radio;
- Development of an ultra fast chaotic communications system simulator. The simulator has been also used in the design of integrated circuits for the prototype radio system.

The project was completed successfully in 2001. We have proposed the FM-DCSK modulation scheme for implementation and determined the structure of the transmitter and receiver. Based on our system level design and simulation, a prototype wireless local area network (WLAN) FM-DCSK radio was built by the Helsinki University of Technology, which operates in the 2.4-GHz Industrial Scientific and Medical (ISM) band. The custom-made integrated circuit for the FM-DCSK modulator was designed and implemented by the research group of Centro Nacional de Microelectrónica (Seville).

Of the duties of our team in the INSPECT Project, I was responsible for the

- Development of multilevel and multiple access capable FM-DCSK systems;
- Determination of low-pass equivalent model of possible modulation schemes, of which the implemented scheme has been chosen;
- Development of a fast simulator based on the low-pass equivalent model for the analysis of the different modulation schemes;
- Detailed analysis of FM-DCSK modulation scheme: the bit error rate (BER) was to be determined for different propagation conditions including AWGN channel and various multipath environments;
- Elaboration of the receiver structure to be implemented and determination of the receiver parameters.

Since my research was related to the these tasks of the Project, the main goals of my PhD studies were as follows. My first aim was the development multilevel and multiple access FM-DCSK schemes because these services are required in wireless local area networks. At the time of the determination of the modulation scheme to be implemented, no theoretical results on the noise performance of chaotic modulation schemes were available. The comparative analysis of different schemes had to be performed by means of simulations. Therefore my second goal was the implementation of a fast simulator which can be used to calculate the bit error rate. To reduce the simulation time I had to derive the complex low-pass equivalent model of the chaotic modulation schemes. Using the simulator I had to analyze the selected FM-DCSK scheme in propagation conditions that are typical in indoor radio environments and wireless local area networks. I have determined the effect of receiver parameters on the BER; taken into account the maximum implementation loss and the receiver complexity, I have chosen the system parameters for the implemented receiver.

I have completed my PhD studies at the Department of Measurement and Information Systems of BUTE. During the analysis of chaotic communications systems I encountered many problems of signal processing which also appear in measurement. To solve these problems I used the textbook of measurement edited by Prof. Schnell and written by the members of BUTE-DMIS [Sch94], in particular, the chapters on measurement data processing [Dob94] and signal analyzers [Kol94] were of great help.

One main application of chaotic communications is the indoor radio systems, where the main problem is the selective fading similar to mobile communications. Therefore during the analysis of chaotic communications systems I used the results of Prof. Pap (Department of Telecommunications) achieved in the field of mobile communications [Pap99].

I have surveyed the main properties of conventional modulation schemes before I analyzed chaotic ones. To do this I used different books including the one written by Prof. Frigyes (Department of Broadband Infocommunication Systems) which discusses the theoretical and practical aspects of digital microwave transmission [FSV80].

In my PhD studies I used the results of my advisor, Géza Kolumbán, in the field of chaotic communications. Since the FM-DCSK modulation scheme [Kol02] invented by him has been used in the implementation of the INSPECT radio system, I mostly analyzed this scheme in my work. In the FM-DCSK modulator the basis functions are generated by combining a frequency-modulated chaotic waveform with the first two Walsh functions. These basis functions are orthonormal. The demodulation at the receiver is performed by a differentially coherent detector, i.e., it is based on the sign of the correlation between the two segments of transmitted signal. The bit error rate of FM-DCSK is expressed as [Kol00]:

$$BER = \frac{1}{2^{BT}} \exp\left(-\frac{E_b}{2N_0}\right) \sum_{i=0}^{BT-1} \frac{\left(\frac{E_b}{2N_0}\right)^i}{i!} \sum_{j=i}^{BT-1} \frac{1}{2^j} \binom{j+BT-1}{j-i} \tag{1}$$

where the energy per bit and the power spectral density of channel noise are denoted by E_b and N_0, respectively. The RF bandwidth and bit duration are given by $2B$ and T, respectively. I used (1) to derive a number of theoretical results in my work.

Another important approach which I used in my research was the Fourier analyzer concept [KLS03] introduced for chaotic communications. Starting from this description I derived the energy detector configuration for the FM-DCSK scheme. The Fourier analyzer concept is based on the fact that the detector observes the received signal over the finite interval $(0, T]$, i.e., for the length of the bit duration. Consequently, the transmitted signal can be transformed to a periodic signal with period T by repeating the signal. If the Fourier coefficients of basis functions are not accurately known at the receiver, then the demodulation can be performed only by a noncoherent detector. This can be done by using the generalized maximum likelihood (GML) decision rule. In this case the demodulation is performed by determining the energies of received signal measured in the subspaces of each basis functions. The decision is made in favor of that symbol which subspace receives the greatest energy.

Methods used

Although the chaotic signals are generated by deterministic systems, their behavior can be predicted only for short run due to their sensitive dependence on initial conditions. Therefore I used the stochastic signal model introduced in the literature to analyze chaotic signals [Sch94].

I calculated the expected value, variance, autocorrelation and cross-correlation functions of chaotic signals using the stochastic signal model. Theoretically, the cross-correlation of two chaotic signals started from different initial conditions is zero. However, finite-length chaotic signals are only approximately uncorrelated.

In binary FM-DCSK known from the literature, the orthogonality is ensured by the combination of chaotic signals and the first two Walsh functions [Kol02]. I used this approach to develop multilevel and multiple access capable FM-DCSK systems. I proposed an orthonormal signal set of M elements by combining the chaotic signal with the first M Walsh functions, i.e., by extending the FM-DCSK modulation to a larger signal set. This signal set can be used for the implementation of an M-ary modulation scheme or a multiple access scheme having $M/2$ binary channels. Due to the orthogonality of basis functions, the BER is not degraded by increasing M provided that all users are synchronized.

I have shown that in the multiple access FM-DCSK systems that exploit the orthogonality of chaotic signals, the BER is degraded by increasing the number of users.

Modulation schemes can be analyzed by determining the observation signal, i.e., the input signal of the decision device. Thus, their bit error rate can be derived [Hay94]. I analyzed the multilevel and multiple access capable FM-DCSK systems using this approach. I have derived the expression for the observation signal and compared it to that of binary and single-user FM-DCSK. I have analyzed the terms of observation signals and shown that for certain parameter settings the observation signals of binary single-user and multiple access capable FM-DCSK systems are equivalent. Since the BER is known for single-user binary FM-DCSK, I could determine the bit error rate of multilevel and multiple access capable FM-DCSK systems based on this equivalence.

I have analyzed the different chaotic modulation schemes by means of simulations. If the simulation is performed directly in the RF band then the sampling frequency of simulations has to be extremely high. The simulation time can be reduced by using the complex low-pass equivalent model of the modulation schemes. In this model each RF signal is represented by its complex envelope [Ric82]. The low-pass equivalent model contains all the information about the RF system and its simulation requires much lower sampling frequency.

Since the simulator operates in the discrete time domain, I transformed each block to its discrete-time equivalent. For example, I determined the discrete-time equivalent of the filters using the bilinear transformation. I used the additive white Gaussian noise model applied to the analysis of communications systems. I implemented the simulator in Matlab environment and wrote the numerically intensive computations in C subroutines.

I have analyzed the implemented FM-DCSK system under multipath propagation conditions using channel models of indoor radio systems and wireless local area networks. I performed the simulations by means of the multipath channel models developed by Personal Communication Services (PCS) Joint Technical Committee (JTC) [PL95].

During the design of the FM-DCSK receiver I determined the values of the parameters such that I evaluated their effect on the noise performance. I have derived the expression of observation signal in presence of frequency error and shown that the effect of frequency error on the bit error rate can be reduced by decreasing the bit duration. I have also determined the variance of observation signal as a function of the sampling frequency of the correlators and derived an approximate expression for the bit error rate. During this derivation I approximated the observation signal by Gaussian distribution. I modeled the effect of quantization by means of the quantization noise approach known from the literature [Sch94] and derived the approximate expression using this model.

I verified all the theoretical results by simulations.

Claims

Claim I: Improved versions of FM-DCSK modulation scheme

The main application of FM-DCSK communication system is the wireless local area networks, where systems have to offer multiple access capability. In many applications multilevel modulation schemes are needed to improve the data rate. These problems both can be solved by developing large orthonormal signal sets.

I/1. I have developed an FM-DCSK signal set exploiting the orthogonality of chaotic signals and a detector structure to implement a multiple access scheme (Section 4.1 of the thesis, related publications of the author: [10], [32])

The idea of the method proposed is that the autocorrelation function of chaotic signals decays rapidly, and two infinitely long chaotic signals started from two different initial conditions are orthogonal. Exploiting this fact I developed a signal set having approximately orthogonal elements by segmenting the transmitted signal.

I have proposed a detector structure for the demodulation of this signal set by modifying the FM-DCSK receiver. Due to the approximate orthogonality of the elements of the signal set, each receiver is sensitive to the signal of the corresponding transmitter.

I have derived the bit error rate of the system proposed using (1):

$$BER = \frac{1}{2^{BT}} \exp\left(\frac{-E_b}{2N_0 + \frac{1}{B}\sum\limits_{u=2}^{U} P_{s_u}}\right) \sum_{i=0}^{BT-1} \frac{1}{i!}\left(\frac{E_b}{2N_0 + \frac{1}{B}\sum\limits_{u=2}^{U} P_{s_u}}\right)^{i} \sum_{j=i}^{BT-1} \frac{1}{2^j}\binom{j+BT-1}{j-i} \tag{2}$$

where the number of users is given by U and the power of the transmitted signal of uth user is denoted by P_{s_u}. I have shown that the disadvantage of this method is that the level of interference in the channel increases and the bit error rate is degraded when the number of users is increased.

I/2. I have introduced an orthonormal signal set by combining a chaotic signal and Walsh functions (Section 3.3.1, [6], [40])

Since finite length chaotic signals are only approximately orthogonal, the BER of the system discussed in the previous point is degraded by increasing U. The two basis functions of binary FM-DCSK are exactly orthogonal and the orthogonality in ensured by the first two Walsh functions. Therefore I have proposed a set of orthogonal basis functions having M elements, in which the basis functions are generated by combining a chaotic signal and the first M Walsh functions. This set of basis functions can be used to construct either an M-ary multilevel modulation scheme or a multiple access capable system having $U = M/2$ binary channels.

I/3. I have developed a coherent detector based on the recovery of chaotic basis functions for multiple access capable FM-DCSK (Section 4.2.1, [6])

I have proposed a technique for the recovery of orthogonal basis functions in the multiple access FM-DCSK system. The demodulation is performed by a coherent receiver using the recovered versions of chaotic basis functions.

I have derived the expression of observation signal and shown that the bit error rate of each FM-DCSK channel is improved by increasing the number of users. The reason is that the level of noise is reduced by averaging performed in the basis function recovery block.

I/4. I have introduced the energy detector configuration for multilevel and multiple access FM-DCSK systems (Section 3.3.2, [40])

Using the GML decision rule and the Fourier analyzer concept, I have proposed an energy detector configuration for the demodulation of FM-DCSK signals. I have shown that in binary case the bit error rate of energy detector is equal to that of differentially coherent detector, while in the M-ary case the energy detector has a better noise performance. The reason of lower BER in the M-ary case is that the detection is based on a symbol consisting of M bits. Using (1) I have determined the BER of this detector:

$$BER = \frac{1}{2^{2BT/M}} \exp\left(-\frac{E_b}{2N_0}\right) \sum_{i=0}^{2BT/M-1} \frac{\left(\frac{E_b}{2N_0}\right)^i}{i!} \sum_{j=i}^{2BT/M-1} \frac{1}{2^j} \binom{j+2BT/M-1}{j-i} \tag{3}$$

Claim II: Implementation of a fast simulator for the analysis of chaotic communication systems, determination of the noise performance of FM-DCSK in indoor radio environments

I have developed a fast system-level simulator to calculate the bit error rate of the FM-DCSK system implemented in the framework of the INSPECT Project. To speed up the simulator, I have determined the complex low-pass equivalent models of different chaotic communications systems.

The bit error rate is calculated in the simulator in an iterative way. I have derived a theoretical expression for the block length to be transmitted in one iteration.

Using the simulator I have analyzed the INSPECT FM-DCSK system in detail. I have determined the bit error rate using standard multipath channel models developed for wireless local area networks and indoor radio environments.

II/1. I have determined the complex low-pass equivalent model of chaotic communications systems (Section 5.1, [3], [4], [7], [22], [29], [30], [31], [41], [42])

Although the low-pass equivalent models of conventional communications systems are known, these models cannot be applied directly to chaotic systems. The following chaotic modulation schemes known from the literature are considered in the thesis: CSK+AM/DSB-SC, COOK+AM/DSB-SC, DCSK+AM/DSB-SC, DCSK+FM, and FM-DCSK. Using the analytic signal approach, I have derived the complex low-pass equivalent models for these modulation schemes. Since the RF carrier is removed from the model, the simulation time is reduced considerably if these low-pass equivalent models are used.

II/2. I have determined the block length transmitted in one iteration in the simulator (Section 5.2.3, [7], [24], [27], [29], [30], [31])

The bit error rate is calculated in an iterative way in the simulator. Since the chaotic signal generator subroutine is relatively slow, no new chaotic signal is generated in each iteration, but the same frequency-modulated chaotic signal is used in each iteration.

The chaotic FM signal transmitted in one iteration has to be long enough to represent an infinitely long signal, i.e., the error in the BER due to the finite length has to be negligible. The transmitted signal is considered to be long enough if its power spectral density approximates that of an infinitely long signal with a sufficiently small error. This problem is of importance in multipath propagation because in this case the bit error rate depends on the shape of the spectrum.

I have determined the maximum mean square error of power spectral density estimation for a frequency-modulated chaotic signal:

$$\epsilon_{max} = \frac{2}{\Delta f T_e} + 0.052 \left(\frac{\Delta f}{B}\right)^4 \tag{4}$$

where the bandwidth of band-pass filter used in the estimation is denoted by Δf, and the length of signal block transmitted in one iteration is given by T_e. Δf depends on the frequency response of multipath channel, and for indoor channels $\Delta f \leq 74.77$ kHz. If the maximum of mean square error is equal to 0.002, then the length of signal to be transmitted in one iteration is $T_e = 13.375$ ms.

II/3. I have determined the bit error rate of FM-DCSK system in WLAN and indoor radio applications (Section 5.4, [3], [4], [7], [25], [26], [31], [35], [44], [45])

In wireless local area networks and indoor radio systems the main problem of communications is the frequency-selective fading caused by multipath propagation.

Using the simulator and the channel models developed for WLAN [AB00, HW01], and indoor radio environments [PL95] by Personal Communication Services (PCS) Joint Technical Committee (JTC), I have evaluated the BER of INSPECT FM-DCSK system under these propagation conditions.

The average degradation of bit error rate compared to AWGN channel are summarized in the Table below for worst-case propagation conditions, i.e., when the attenuation of the channel is larger than 100 dB.

Type of environment	Average degradation of bit error rate
WLAN	4.8 dB
Office	8.3 dB
Residential	6.8 dB
Commercial	9.8 dB

By means of these simulations I have shown that the FM-DCSK radio system is very robust and it can be applied in WLAN and indoor radio systems.

Claim III: System-level design of the INSPECT FM-DCSK receiver, determination of the main system parameters

The design of the receiver of FM-DCSK radio implemented in the INSPECT Project is discussed here. According to the decision of the INSPECT consortium, the prototype FM-DCSK radio has been implemented using the PRISM II chipset of Intersil [Int99].

The main problem of the receiver design was how to implement the FM-DCSK demodulator using PRISM II integrated circuits. I have shown that the FM-DCSK detector can be transformed to an equivalent detector, which can be implemented using the chipset.

During the design I have determined the main parameters of the receiver. I have examined the effect of phase- and frequency error on the operation of the receiver. I have determined the sampling frequency of the correlators and the resolution of A/D converter.

III/1. I have transformed the FM-DCSK detector in such a way that it could be implemented using PRISM II chipset (Section 6.2, [3], [4], [7], [22], [29], [30], [31], [41], [42]) PRISM II chipset is used to implement wireless transceivers. The receiver of this chipset is based on a superheterodyne architecture, which offers a safe solution to the implementation of FM-DCSK receiver. The analog part of PRISM II, i.e., the quadrature mixer, provides the quadrature components of the received signal. The demodulation is performed by using the digitized versions of these signals.

The theoretical block diagram of FM-DCSK detector consists of a radio-frequency correlator and a decision circuit. I have transformed this block diagram to that of an equivalent detector and have shown that the demodulation can be performed using the quadrature components generated by PRISM II.

III/2. I have determined the effect of phase- and frequency error (Section 6.3.1)

Since the demodulation in FM-DCSK is performed without carrier recovery, the phase- and frequency error between the oscillators at the transmitter and receiver degrades the noise performance. I have derived the expression of the observation signal as a function of phase- and frequency error. I have shown that the observation signal depends exclusively on the frequency error. Furthermore, I have shown that both the observation signal and the bit error rate depend on $\Delta\omega T$, i.e., the effect of frequency error can be reduced by decreasing the bit duration.

III/3. I have determined the sampling frequency of correlators (Section 6.3.2)

An important question of the receiver design is the determination of the sampling frequency of correlators. I have derived an approximate expression for the bit error rate as a function of the sampling frequency:

$$BER = \frac{1}{2}\text{erfc}\left(\frac{E_b f_{corr}}{\sqrt{2\text{Var}[z]}}\right) \tag{5}$$

where the sampling frequency is denoted by f_{corr}. The variance of observation signal is obtained as

$$\begin{aligned}\text{Var}[z] = \sum_{h=-\frac{N_s}{2}+1}^{\frac{N_s}{2}} \left(\frac{N_s}{2} - |h|\right) \Big(\left[R_{s_I}(h) + R_{s_Q}(h)\right] \left[2R_{n_{I_f}}(h) + R_{n_{I_f}}(h - N_s/2) + R_{n_{I_f}}(h + N_s/2)\right] \\ + 2(R_{n_{I_f}}(h))^2 + 2R_{n_{I_f}}(h + N_s/2) R_{n_{I_f}}(h - N_s/2) \Big)\end{aligned} \tag{6}$$

where the autocorrelation functions of the quadrature components of the transmitted signal are denoted by $R_{s_I}(h)$ and $R_{s_Q}(h)$. The autocorrelation function of the in-phase component of the filtered noise is given by $R_{n_{I_f}}(h)$. Based on these theoretical results, I have set the sampling frequency of the correlators to 20 MHz.

III/4. I have determined the resolution of the quantizer (Section 6.3.3, [33], [34])

Since the quadrature components of the received signal are digitized before demodulation, another important question is the determination of the resolution of the quantizer. I have modeled the effect of quantization by the quantization noise known from the literature [Kol94]. Based on this model and using (1), I have derived an approximate expression for the BER of FM-DCSK:

$$BER = \frac{1}{2^{B_{eq}T}} \exp\left(-\frac{E_b}{2(N_0 + N_{0_q})}\right) \sum_{i=0}^{B_{eq}T-1} \frac{\left(\frac{E_b}{2(N_0+N_{0_q})}\right)^i}{i!} \sum_{j=i}^{B_{eq}T-1} \frac{1}{2^j} \binom{j + B_{eq}T - 1}{j - i} \tag{7}$$

where

$$\frac{E_b}{N_0 + N_{0_q}} = \frac{E_b/N_0}{1 + 2(E_b/N_0/T + 2B)/(3 \cdot 4^{R_r} f_{corr})}$$

and

$$B_{eq} = \frac{1 + 2(E_b/N_0/(2BT) + 1)/(3 \cdot 4^{R_r})}{1/B + 4(E_b/N_0/(2BT) + 1)/(3 \cdot 4^{R_r} f_{corr})}$$

where the resolution of the quantizer is denoted by R_r and the sampling frequency is given by f_{corr}. Using these results I have set the resolution of the quantizer to 6 bits.

Practical applications of the results

Most of the results achieved in my PhD studies have been used in the INSPECT Project during the design and implementation of the chaotic communication system [inn01]. Based on the system design completed by our group, the FM-DCSK radio system has been built by the research groups of Helsinki University of Technology and Centro Nacional de Microelectrónica (Seville). The main parameters of the implemented radio are:

- data rate: 500 kbit/sec;
- carrier frequency: 2,474 GHz (ISM frequency band);
- total RF bandwidth: 17 MHz;
- bit error rate: 10^{-3} at E_b/N_0 =14,5 dB;
- superheterodyne architecture.

In FM-DCSK, the transmitted signal is a wide-band signal and the level of power spectral density is low; therefore this system can be used in indoor radio applications operating in the ISM frequency bands. Due to its novelty, the FM-DCSK communication system has been patented in 1999 [KKKJ99].

The multilevel and multiple access FM-DCSK systems proposed by me provide a solution to the requirements emerging in indoor radio systems. The main advantages of the solutions proposed are that the bit error rate is reduced by increasing the number of levels and users. Furthermore, the improved versions of the modulator and demodulator blocks can be implemented easily.

The low-pass equivalent models of different chaotic modulation schemes have been used directly in the implemented simulator. Due to the application of these models, the simulator developed is very fast; it operates with a speed of 500 bit/sec using a normal PC.

The simulator played an important role in each stage of the Project. When the modulation scheme to be implemented was selected, the different schemes were analyzed and compared using simulations. The FM-DCSK system selected for implementation was analyzed by means of simulations for different parameter values under various propagation conditions. The parameters of the implemented system have been determined based on simulations and theoretical results. There were no theoretical results available for the multipath performance; therefore I have shown by simulations that the FM-DCSK system is very robust and can be used in indoor radio environments. A modified version of the simulator was used in the INSPECT Project to test the integrated circuit developed by the research group of CNM. The simulation results have been verified by measurements performed on the implemented radio system.

The design of the FM-DCSK receiver and the determination of the main parameters are presented in the third part of the thesis. The radio receiver has been implemented using the architecture and parameter values proposed in the thesis. The radio-frequency circuits, i.e., the RF mixer and the quadrature IF mixer, have been implemented using the ICs of Intersil PRISM II chipset. The channel filter operating at IF is implemented by a surface acoustic wave filter. The demodulation performed after the analog-to-digital conversion is done by two digital correlators implemented by FPGA device. The values of sampling frequency and resolution determined in the thesis have been used in the implemented circuits.

The receiver designed in the thesis has been built by the research group of Helsinki University of Technology led by Prof. Veikko Porra; the photo of the receiver is shown in Fig. 1. The operation of the built FM-DCSK radio has been demonstrated at ECCTD conference in 2001.

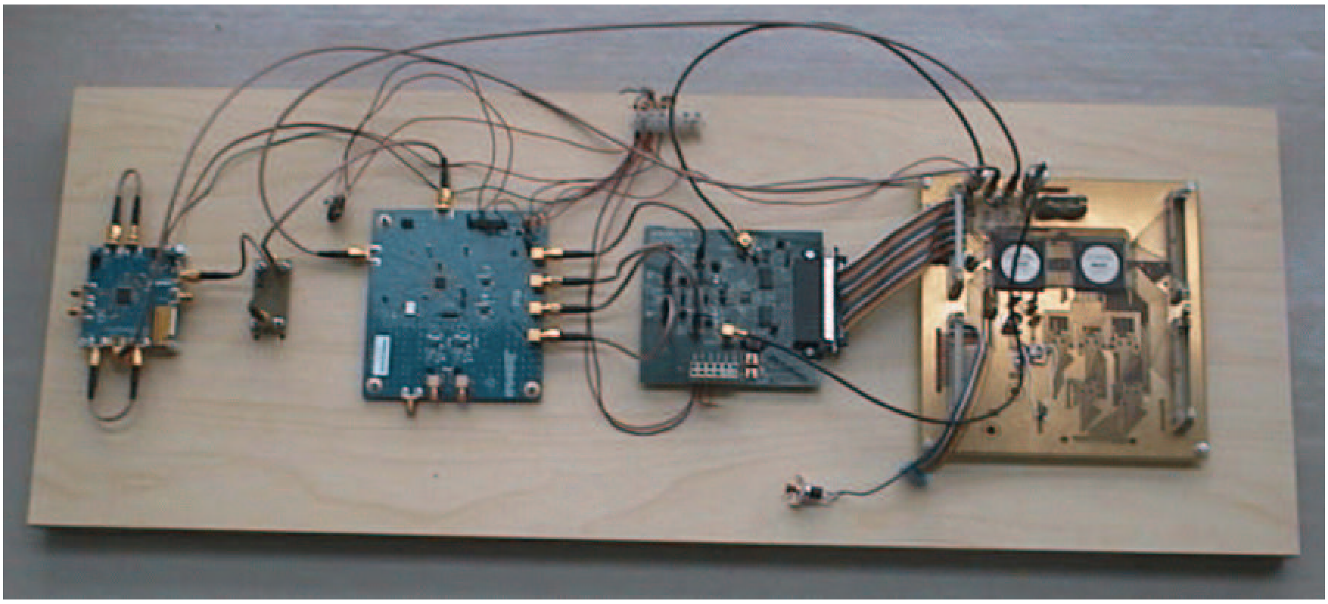

Figure 1: The receiver of FM-DCSK radio system implemented by Helsinki University of Technology.

Full list of publications

International journal papers

[1] G. Kolumbán, G. Kis, Z. Jákó, and M. P. Kennedy, "FM–DCSK: A robust modulation scheme for chaotic communications," *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, vol. E81-A, no. 9, pp. 1798–1802, Oct. 1998.

[2] G. Kis and Z. Jákó, "Noise reduction in DCSK modulation schemes," *Journal of Signal Processing, Special Section on Nonlinear Signal Processing*, vol. 4, no. 1, pp. 71–78, January 2000.

[3] M. P. Kennedy, G. Kolumbán, and G. Kis, "Chaotic modulation for robust digital communications over multipath channels," *Invited tutorial in the Special Issue of Int. J. Bifurcation and Chaos*, vol. 10, no. 4, pp. 695–718, 2000.

[4] M. P. Kennedy, G. Kolumbán, G. Kis, and Z. Jákó, "Performance evaluation of FM–DCSK modulation in multipath environments," *IEEE Trans. Circuits and Systems–Part I: Fundamental Theory and Applications*, vol. 47, no. 12, pp. 1702–1711, Dec. 2000.

[5] Z. Jákó and G. Kis, "Application of noise reduction to chaotic communications: A case study," *IEEE Trans. Circuits and Systems–Part I: Fundamental Theory and Applications*, vol. 47, no. 12, pp. 1720–1725, Dec. 2000.

[6] G. Kolumbán, M. P. Kennedy, Z. Jákó, and G. Kis, "Chaotic communications with correlator receiver: Theory and performance limit," *Proceedings of the IEEE*, vol. 90, no. 5, pp. 711–732, May 2002.

Bookchapter published abroad

[7] G. Kolumbán, M. P. Kennedy, and G. Kis, "Performance evaluation of FM–DCSK," in *Chaotic Electronics in Telecommunications*, M. P. Kennedy, R. Rovatti, and G. Setti, Eds., pp. 185–220. CRC Press LLC, Florida, 2000.

International patent

[8] M. P. Kennedy, G. Kolumbán, G. Kis, and Z. Jákó, "Binary digital communication system using a chaotic frequency-modulated carrier," *Irish patent number: S80913*, granted on June 1 1999.

Papers in international conferences

[9] G. Kolumbán, A. Hasegawa, T. Endo, and G. Kis, "Direct signal generation for chaos communication and chaotic measurement by analog PLL," in *Proc. IEEE–ISCAS'97*, Hong Kong, June 9–12 1997, vol. II, pp. 901–904.

[10] G. Kolumbán, M. P. Kennedy, and G. Kis, "Multilevel Differential Chaos Shift Keying," in *Proc. NDES'97*, Moscow, Russia, June 26–27 1997, pp. 191–196.

[11] G. Kolumbán, M. P. Kennedy, and G. Kis, "Determination of symbol duration in chaos-based communications," in *Proc. NDES'97*, Moscow, Russia, June 26–27 1997, pp. 217–222. S 2

[12] G. Kolumbán, M. P. Kennedy, and G. Kis, "Performance improvement of chaotic communications systems," in *Proc. ECCTD'97*, Budapest, Hungary, Aug. 30–Sept. 3 1997, pp. 284–289. S 2

[13] G. Kolumbán, G. Kis, M. P. Kennedy, and Z. Jákó, "FM–DCSK: A new and robust solution for chaotic communications," in *Proc. NOLTA'97*, Honolulu, USA, Nov. 29–Dec. 2 1997, pp. 117–120. S 2

[14] M. P. Kennedy, Z. Jákó, G. Kis, and G. Kolumbán, "Chaotic communications systems for unlicenced radio applications," in *Proc. NOLTA'97*, Honolulu, USA, Nov. 29–Dec. 2 1997, pp. 120–124.

[15] Z. Jákó, G. Kis, G. Kolumbán, and M. P. Kennedy, "Design of large signal set for DCSK modulation," in *Proc. Sixth IEE Conference on Telecommunications*, Edinburgh, UK, March 29–Apr. 1 1998, pp. 44–48.

[16] G. Kis, Z. Jákó, M. P. Kennedy, and G. Kolumbán, "Chaotic communications without synchronization," in *Proc. Sixth IEE Conference on Telecommunications*, Edinburgh, UK, March 29–Apr. 1 1998, pp. 49–53.

[17] M. P. Kennedy, G. Kolumbán, G. Kis, and Z. Jákó, "Recent advances in communicating with chaos," in *Proc. IEEE–ISCAS'98*, Monterey, USA, May 31–June 3 1998, vol. IV, pp. 461–464.

[18] G. Kolumbán, M. P. Kennedy, G. Kis, and Z. Jákó, "FM–DCSK: A novel method for chaotic communications," in *Proc. IEEE–ISCAS'98*, Monterey, USA, May 31–June 3 1998, vol. IV, pp. 477–480. S 1

[19] G. Kis, "Required bandwidth of chaotic signals used in chaotic modulation schemes," in *Proc. NDES'98*, Budapest, Hungary, July 16–18 1998, pp. 113–117.

[20] G. Kis and G. Szabó, "Optimization of decision thresholds for M-ary DCSK modulation," in *Proc. NDES'98*, Budapest, Hungary, July 16–18 1998, pp. 185–187.

[21] N. Lorenzo, M. P. Kennedy, G. Kolumbán, and G. Kis, "A comparison of the noise performance of Pecora-Carroll and H synchronization," in *Proc. NDES'98*, Budapest, Hungary, July 16–18 1998, pp. 249–252.

[22] G. Kolumbán and G. Kis, "Performance evaluation of FM–DCSK modulation scheme," in *Proc. NOLTA'98*, Le Regent, Crans-Montana, Switzerland, Sept. 14–17 1998, pp. 81–84.

[23] G. Kis and G. Kolumbán, "Constraints on chaotic oscillators intended for communications applications," in *Proc. NOLTA'98*, Le Regent, Crans-Montana, Switzerland, Sept. 14–17 1998, pp. 883–886.

[24] G. Kis, "Fast simulator for analysis of chaotic communications systems," in *Proc. IWK'98*, Ilmenau, Germany, Sept. 21–24 1998, vol. I, pp. 38–43.

[25] M. P. Kennedy, G. Kolumbán, and G. Kis, "Application of chaotic modulation in multipath environments," in *Proc. COST 254*, Neuchatel, Switzerland, May 5–7 1999, p. 13.

[26] M. P. Kennedy, G. Kolumbán, and G. Kis, "Simulation of the multipath performance of FM–DCSK digital communications using chaos," in *Proc. IEEE–ISCAS'99*, Orlando, USA, May 30–June 2 1999, vol. IV, pp. 568–571.

[27] G. Baldwin, M. P. Kennedy, G. Kis, and G. Kolumbán, "FM–DCSK radio system simulator," in *Proc. ISSC'99*, NUI Galway, Ireland, June 24–25 1999, pp. 425–432.

[28] G. Baldwin and G. Kis, "Quantification of intersymbol interference effects in an RF FM–DCSK system," in *Proc. NDES'99*, Ronne, Bornholm, Denmark, July 15–17 1999, pp. 169–172.

[29] G. Kis and G. Baldwin, "Modeling and simulation issues in RF chaotic communications," in *Proc. NDES'99*, Ronne, Bornholm, Denmark, July 15–17 1999, pp. 173–176.

[30] G. Kis and G. Baldwin, "Efficient FM–DCSK radio system simulator," in *Proc. ECCTD'99*, Stresa, Italy, Aug. 29 – Sept. 2 1999, pp. 884–887. S 2

[31] G. Kolumbán, G. Kis, M. P. Kennedy, and G. Baldwin, "Ultra-fast simulator developed in MATLAB environment to evaluate multipath performance of FM–DCSK RF system," in *Proc. ICECS'99*, Paphos, Cyprus, Sept. 5–8 1999, vol. III, pp. 1725–1729.

[32] Z. Jákó, G. Kis, and G. Kolumbán, "Multiple access capability of the FM–DCSK chaotic communications system," in *Proc. NDES'2000*, Catania, Italy, May 18–20 2000, pp. 52–55.

[33] M. P. Kennedy and G. Kis, "Elaboration of system specification for a WLAN FM–DCSK telecommunications system," in *Proc. NDES'2000*, Catania, Italy, May 18–20 2000, pp. 160–164.

[34] G. Kis, "Evaluation of interference performance of FM–DCSK communications system," in *Proc. NDES'2000*, Catania, Italy, May 18–20 2000, pp. 204–207.

[35] G. Kolumbán and G. Kis, "Multipath performance of FM–DCSK chaotic communications system," in *Proc. IEEE–ISCAS'2000*, Geneva, Switzerland, May 28 – 31, 2000, vol. IV, pp. 433–436.

[36] Z. Jákó and G. Kis, "On the effectiveness of noise reduction methods in DCSK systems," in *Proc. IEEE–ISCAS'2000*, Geneva, Switzerland, May 28 – 31, 2000, vol. IV, pp. 437–440.

[37] G. Kis, "Performance of fast and slow chaotic frequency hopping modulation in WLAN applications," in *Proc. ISSC'2000*, NUI Dublin, Ireland, June 29–30 2000, pp. 149–156.

[38] M. P. Kennedy, G. Kis, and Z. Jákó, "Optimum receivers for CSK and DCSK," in *Proc. NOLTA'2000*, Dresden, Germany, September 17–21 2000.

[39] Z. Jákó, D. Fournier-Prunaret, V. Guglielmi, and G. Kis, "Non-redundant error correction in FM-DCSK chaotic communications systems," in *Proc. ECCTD'01*, Espoo, Finland, Aug. 28 – 31 2001, vol. II, pp. 193–196.

[40] G. Kolumbán and G. Kis, "Reception of *M*-ary FM-DCSK signals by energy detector," in *Proc. NDES'03*, Scuol, Switzerland, May 18–22 2003, pp. 133–136.

Papers in Hungarian conferences

[41] G. Kis, "Development of communication system model for FM–DCSK modulation," in *Proc. 5th PhD Mini–Symposium*, DMIS TUB Budapest, Hungary, Feb. 4–5 1998, pp. 14–15.

[42] G. Kis, "FM–DCSK moduláción alapuló kaotikus adatátviteli rendszer modellje és analízise (Low-frequency model and analysis of FM–DCSK chaotic communication system)," in *Proc. Kandó Kálmán Műszaki Főiskola XV. Tudományos Ülésszak*, Budapest, Hungary, May 7–8 1998, pp. 87–92.

[43] G. Kolumbán, G. Kis, and Z. Jákó, "Kaotikus adatátviteli rendszerek (Data transmission using chaotic carriers)," in *Proc. Kandó Kálmán Műszaki Főiskola XV. Tudományos Ülésszak*, Budapest, Hungary, May 7–8 1998, pp. 81–86.

[44] G. Kis, "Performance of FM–DCSK communication system for multipath radio channel," in *Proc. 6th PhD Mini–Symposium*, DMIS TUB Budapest, Hungary, Feb. 3–4 1999, pp. 40–41.

[45] G. Kis, "Evaluation of multipath and interference performance of FM–DCSK chaotic communications system," in *Proc. 7th PhD Mini–Symposium*, DMIS TUB Budapest, Hungary, January 27–28 2000, pp. 18–19.

Citations

Number of citations by independent authors: 52
Number of citations in Science Citation Index: 41
Number of citations by independent authors in Science Citation Index: 16

References

[AB00] R. L. Abrahams and W. R. Bomstad. Multipath performance of a direct sequence 2.4 GHz 11 Mb WLAN PCMCIA assembly with diversity antennas. Technical report, Intersil Corporation, http://www.intersil.com/design/prism/papers/, 2000.

[AGS98] A. Abel, M. Götz, and W. Schwarz. Statistical analysis of chaotic communication schemes. In *Proc. IEEE–ISCAS'98*, volume IV, pages 465–468, Monterey, USA, May 31–June 3 1998.

[ASG00] A. Abel, W. Schwarz, and M. Götz. Noise performance of chaotic communication systems. *IEEE Trans. Circuits and Syst. I*, 47(12):1726–1732, December 2000.

[Che99] G. Chen. Chaos, bifurcations, and their control. In J. G. Webster, editor, *Wiley Encyclopedia of Electrical and Electronics Engineering*, pages 194–218. Wiley, New York, 1999.

[CO93] K. M. Cuomo and A. V. Oppenheim. Circuit implementation of synchronized chaos with applications to communications. *Phys. Rev. Lett.*, 71(1), July 1993.

[CP91] T. L. Carroll and L. M. Pecora. Synchronizing chaotic circuits. *IEEE Trans. Circuits Syst.*, 38(4):453—456, April 1991.

[CY00] C. C. Chen and K. Yao. Stochastic calculus based numerical evaluation and performance analysis of chaotic communication systems. *IEEE Trans. Circuits and Systems–Part I: Fundamental Theory and Applications*, 47(12):1663–1672, Dec. 2000.

[dig98] Digital Communication Devices based on Nonlinear Dynamics and Chaos. Multidisciplinary University Research Initiative (FY1998, Topic #13) sponsored by: Army Research Office, Department of Defense, 1998. URL address "http://rfic.ucsd.edu/chaos/".

[DKH93] H. Dedieu, M. P. Kennedy, and M. Hasler. Chaos shift keying: Modulation and demodulation of a chaotic carrier using self-synchronizing Chua's circuits. *IEEE Trans. Circuits and Syst. II*, 40(10):634–642, October 1993.

[Dob94] T. P. Dobrowiecki. *Jelek és rendszerek méréstechnikája (L. Schnell Editor)*, chapter Mérési adatok feldolgozásának alapvető módszerei. Műegyetemi Kiadó, Budapest, 1994. in Hungarian.

[ea92] A. V. Oppenheim et al. Signal processing in the context of chaotic signals. In *Proc. IEEE–ICCASP'92*, volume IV, pages 117–120, 1992.

[FHS96] U. Feldmann, M. Hasler, and W. Schwarz. Communication by chaotic signals: The inverse system approach. *Int. J. Circuit Theory Appl.*, 24:551–579, 1996.

[FSV80] I. Frigyes, Z. Szabó, and P. Ványai. *Digitális mikrohullámú átviteltechnika.* Műszaki Könyvkiadó, Budapest, 1980. in Hungarian.

[Has95] M. Hasler. Engineering chaos for secure communication systems. *Phil. Trans. R. Soc. Lond.*, 353(1710):115–126, 1995.

[Hay94] S. Haykin. *Communication Systems.* John Wiley & Sons, New York, 3rd edition, 1994.

[HGO93] S. Hayes, C. Grebogi, and E. Ott. Communicating with chaos. *Phys. Rev. Lett.*, 70(20):3031–3034, May 1993.

[HS00] M. Hasler and T. Schimming. Chaos communication over noisy channel. *Int. J. Bifurcation and Chaos*, 10(4):719–735, April 2000.

[HW01] K. Halford and M. Webster. Multipath measurement in wireless LANs. Technical report, Intersil Corporation, http://www.intersil.com/design/prism/, October 2001. File Number AN9895.1.

[inn01] Innovative Signal Processing Exploiting Chaotic Dynamics (INSPECT). Esprit #31103 Open FET Programme sponsored by the European Union, 1997–2001. URL addresses "www.cordis.lu/esprit/src/31103.htm" and "www.mit.bme.hu/research/chaos/projects.html".

[Int99] Intersil Corporation. *PRISM II Chip Set Overview 11MBPS SiGe*, February 1999. File Number AN9837, http://www.intersil.com/design/prism/.

[Ken00] Special issue on noncoherent chaotic communications, Guest Editors: M.P. Kennedy and G. Kolumbán. IEEE Trans. Circuits and Systems–Part I: Fundamental Theory and Applications, 47(12), Dec. 2000.

[KK00] G. Kolumbán and M. P. Kennedy. The role of synchronization in digital communication using chaos–Part III: Performance bounds for correlation receivers. *IEEE Trans. Circuits and Systems–Part I: Fundamental Theory and Applications*, 47(12):1673–1683, December 2000.

[KKC97] G. Kolumbán, M. P. Kennedy, and L. O. Chua. The role of synchronization in digital communications using chaos – Part I: Fundamentals of digital communications. *IEEE Trans. Circuits and Systems–Part I: Fundamental Theory and Applications*, 44(10):927–936, Oct. 1997.

[KKC98] G. Kolumbán, M. P. Kennedy, and L. O. Chua. The role of synchronization in digital communication using chaos–Part II.: Chaotic modulation and chaotic synchronization. *IEEE Trans. Circuits and Systems–Part I: Fundamental Theory and Applications*, 45(11):1129–1140, Nov. 1998.

[KKJK98] G. Kolumbán, G. Kis, Z. Jákó, and M. P. Kennedy. FM–DCSK: A robust modulation scheme for chaotic communications. *IEICE Transactions on Fundamentals of Electronics, Communications and Computer Sciences*, E81-A(9):1798–1802, Oct. 1998.

[KKJK02] G. Kolumbán, M. P. Kennedy, Z. Jákó, and G. Kis. Chaotic communications with correlator receiver: Theory and performance limit. *Proceedings of the IEEE*, 90(5):711–732, May 2002.

[KKKJ99] M. P. Kennedy, G. Kolumbán, G. Kis, and Z. Jákó. Binary digital communication system using a chaotic frequency-modulated carrier. *Irish patent number: S80913*, granted on June 1 1999.

[KLS03] G. Kolumbán, F. C. M. Lau, and M. Small. A new description of chaotic waveform communications: The Fourier analyzer approach. In *Proc. ECCTD'03*, volume III, pages 241–244, Cracow, Poland, September 1-4 2003.

[Kol94] I. Kollár. *Jelek és rendszerek méréstechnikája (L. Schnell Editor)*, chapter Jelanalizátorok. Műegyetemi Kiadó, Budapest, 1994. in Hungarian.

[Kol00] G. Kolumbán. Theoretical noise performance of correlator-based chaotic communications schemes. *IEEE Trans. Circuits and Systems–Part I: Fundamental Theory and Applications*, 47(12):1692–1701, Dec. 2000.

[Kol02] G. Kolumbán. *Kaotikus jelek adatátviteli alkalmazása: Lehetőségek és elvi korlátok.* MTA, Budapest, 2002. Akadémiai doktori értekezés, in Hungarian.

[KRS00] M. P. Kennedy, R. Rovatti, and G. Setti, editors. *Chaotic electronics in telecommunications.* CRC Press, Boca Raton, Florida, 2000.

[KVSA96] G. Kolumbán, B. Vizvári, W. Schwarz, and A. Abel. Differential chaos shift keying: A robust coding for chaotic communication. In *Proc. NDES'96*, pages 87–92, Seville, June 1996.

[LZC96] J. Lavery, J. Zavada, and M. Ciftan. Toward a new digital communication technology based on nonlinear dynamics and chaos. Strategic Assessment Report, U.S. Army Research Office, Research Triangle Park, NC, November 1996.

[MF00] G. M. Maggio and O. De Feo. T-CSK: A robust approach to chaos-based communications. In *Proc. NDES'2000*, pages 37–41, Catania, Italy, May 18–20 2000.

[Pap99] L. Pap. *A mobil hírközlés alapjai, elektronikus jegyzet.* BME, Budapest, 1999. in Hungarian.

[PC89] T. S. Parker and L. O. Chua. *Practical Numerical Algorithms for Chaotic Systems.* Springer Verlag, New York, 1989.

[PCK+92] U. Parlitz, L. O. Chua, Lj. Kocarev, K. S. Halle, and A. Shang. Transmission of digital signals by chaotic synchronization. *Int. J. Bif. Chaos*, 2:973–977, 1992.

[PL95] K. Pahlavan and A. H. Levesque. *Wireless Information Networks.* Wiley, New York, 1995.

[Ric82] S. O. Rice. Envelopes of narrow-band signals. *Proceedings of the IEEE*, 70:692–699, 1982.

[SCC97] J. A. K. Suykens, P. F. Curran, and L. O. Chua. Master-slave synchronization using dynamics output feedback. *Int. J. Bif. Chaos*, 7(3), 1997.

[Sch94] L. Schnell. *Jelek és rendszerek méréstechnikája.* Műegyetemi Kiadó, Budapest, 1994. in Hungarian.

[Sch98] J. Schweizer. The performance of chaos shift keying: Synchronization versus symbolic backtracking. In *Proc. IEEE–ISCAS'98*, volume IV, pages 469–472, Monterey, USA, May 31–June 3 1998.

[SGK+00] W. Schwarz, M. Götz, K. Kelber, A. Abel, T. Falk, and F. Dachselt. Statistical analysis and design of chaotic systems. In M. P. Kennedy, R. Rovatti, and G. Setti, editors, *Chaotic electronics in telecommunications.* CRC Press, Boca Raton, Florida, 2000.

[SK95] J. Schweizer and M. P. Kennedy. Predictive Poincaré control. *Phys. Rev. E*, 52(5):4865–4876, November 1995.

[STV00] M. Sushchik, L. S. Tsimring, and A. R. Volkovskii. Performance analysis of correlation-based communication schemes utilizing chaos. *IEEE Trans. Circuits and Syst. I*, 47(12):1684–1691, December 2000.

[WC93] C. W. Wu and L. O. Chua. Transmission of digital signals by chaotic synchronization. *Int. J. Bif. Chaos*, 3(6):1619–1627, 1993.

[WC94] C. W. Wu and L. O. Chua. A unified framework for synchronization and control of dynamical systems. *Int. J. Bif. Chaos*, 4(4):979–998, 1994.

[Yan95] T. Yang. Recovery of digital signals from chaotic switching. *Int. J. Circuit Theory Appl.*, 23(6):611–615, 1995.