# Performance Evaluation of FM-DCSK Modulation in Multipath Environments

Michael Peter Kennedy, *Fellow, IEEE*, Géza Kolumbán, *Senior Member, IEEE*, Gábor Kis, *Student Member, IEEE*, and Zoltán Jákó, *Student Member, IEEE*

***Abstract*—Kolumbán [1] has shown that, under specified conditions, the noise performance of frequency-modulated differential chaos shift keying (FM-DCSK) in a single-ray additive white Gaussian noise (AWGN) channel is independent of the shape of the underlying waveform. This paper discusses the qualitative features of the FM-DCSK system and characterizes the performance of this system in standard reference multipath channels.**

***Index Terms*—Chaotic communications, chaotic modulation, low-pass equivalent model, multipath performance.**

## I. Introduction

In CHAOTIC communications systems, the digital information to be transmitted is mapped to inherently wide-band signals. In this sense, these systems offer a novel solution to spread spectrum communications.

Although the noise performance of known chaotic digital modulation schemes in single-ray additive white Gaussian noise (AWGN) channels [2] lags behind that of conventional modulation schemes based on periodic waveforms, the performance degradation of chaotic modulation schemes is less under certain propagation conditions where coherent reception is impossible. In particular, frequency-modulated differential chaos shift keying (FM-DCSK) [3], [4] offers robustness against multipath and channel imperfections.

The objective of this paper is to provide a detailed performance evaluation of the FM-DCSK system in multipath environments. We focus on a particular FM-DCSK system, which has been developed in the framework of a long term research project sponsored by the European Commission.

The spectral properties of an FM-DCSK signal are first discussed, and then the characteristic features of the FM-DCSK system are identified. Next, the noise performance of FM-DCSK is evaluated.

One of the most important potential applications of FM-DCSK is in data communications over multipath channels. A tapped delay line model of a multipath channel is introduced and the qualitative and quantitative behavior of FM-DCSK in multipath channels is determined. The data of the multipath channel used in our simulations correspond to a typical wireless local area network (WLAN) application.

The Personal Communication System Joint Technical Committee (PCS JTC) has developed comprehensive channel models for simulating the multipath performance of radio systems for indoor applications; models are available for typical indoor office, residential, and commercial environments [5]. In Section V-D, we present results for the multipath performance of FM-DCSK in these propagation environments.

Manuscript received December 20, 1999; revised September 5, 2000. This work was supported in part by the Hungarian–French Intergovernmental S & T Cooperation Program 1999–2000 under Contract NP-1856/98 and Contract F29/98, and by the European Commission under the Open LTR initiative, Esprit Project 31103-INSPECT.

M. P. Kennedy is with the Department of Microelectronic Engineering, University College, Cork, Ireland.

G. Kolumbán, G. Kis, and Z. Jákó are with the Department of Measurement and Information Systems, Budapest University of Technology and Economics, H-1521 Budapest, Hungary.

Publisher Item Identifier S 1057-7122(00)10642-7.

## II. Spectrum of Transmitted FM-DCSK Signal

In the FM-DCSK modulation scheme, the binary information to be transmitted is mapped to a wide-band signal. The objectives of spreading the transmitted signal are twofold: to overcome the multipath propagation problem and to reduce the transmitted power spectral density in order to minimize interference with other radio communications in the same frequency band.

This section shows how FM-DCSK signals can be generated. The FM-DCSK technique spreads the RF signal to be transmitted and reduces its average power spectral density. In an FM-DCSK modulator, a chaotic signal is fed into an FM modulator to generate a wide-band RF band-pass signal with constant power; DCSK modulation is then applied to this wide-band signal.

Let the chaotic spreading signal be generated by a discrete-time chaotic circuit, which is sampled with period $T_{\rm chip}$. Throughout this work, we consider an implementation of the Bernoulli shift map:

$$x[(k+1)T_{\rm chip}] = 2x[kT_{\rm chip}] \bmod 1.$$

The output of the chaotic signal generator is offset by $-0.5$ V (to have zero mean), scaled by 2 (to lie in $[-1\,{\rm V}, 1\,{\rm V}]$), and quantized to ten bits (corresponding to 1024 different levels). The quantized signal is converted into the continuous-time domain by a zero-order hold circuit, as shown in Fig. 1, where $T$ denotes the bit duration. The hold time is determined by the *chip rate*. In our simulations, the chip rate is 20 MHz.

The output of the zero-order hold circuit is a piecewise continuous chaotic signal, which we denote by $m(t)$. This signal is applied to the input of an FM modulator, whose output $y(t)$ is defined by

$$y(t) = A_c \cos\left(2\pi\left[f_c t + k_f \int_0^t m(\tau)\, d\tau\right]\right)$$

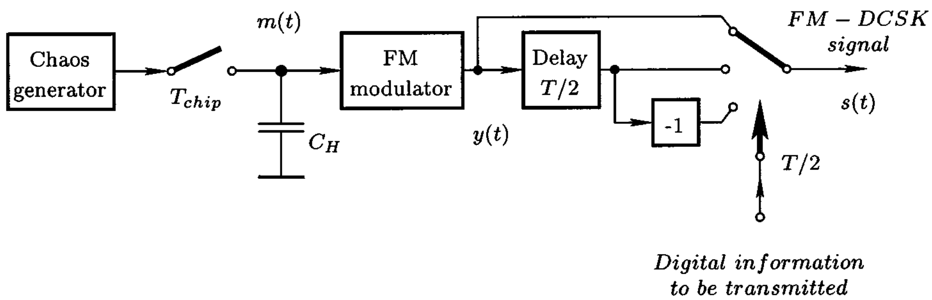


Fig. 1. Block diagram of FM-DCSK transmitter including the zero-order hold circuit.

where $A_c$ and $f_c$ denote the amplitude and center frequency of the FM modulator output, respectively, while $k_f$ is the gain of modulator. In our simulations, $A_c = 1$ V, $f_c = 36$ MHz, and $k_f = 7.8$ MHz/V.

The modulator gain $k_f$ has been chosen such that the RF bandwidth of the FM-DCSK signal is 17 MHz when the chip rate is 20 MHz. This corresponds to the channel allocation of the IEEE 802.11 WLAN standard.

Simulated spectra of the chaotic FM modulator output and the FM-DCSK signal are plotted in Fig. 2 for the FM-DCSK transmitter. The digital information to be transmitted is modeled by a random binary sequence.

To illustrate the relationship between the bit duration and the skirt of the FM-DCSK signal, Fig. 2(b) shows spectra for $T = 2$ $\mu$s and $T = 16$ $\mu$s. Inspecting Fig. 2(b), we conclude that by choosing appropriate values for the chip rate and peak frequency deviation of the FM modulator, DCSK modulation does not cause periodic components in the spectrum, but it does increase the skirt considerably.

To minimize interference with other radio channels, the power generated outside the 17 MHz RF bandwidth has to be kept as low as possible. The skirt can be lowered by increasing the bit duration, but increasing $T$ reduces the attainable data rate and degrades the noise performance [1]. Alternatively, the unwanted skirt can be suppressed, without reducing the data rate, by means of a band-pass filter at the transmitter.

In the FM-DCSK system, the instantaneous frequency of the transmitted signal is constant only for a very short time interval (the chip time). Thus, the transmitted energy is never concentrated about a certain frequency; rather, it is spread continuously over the entire RF channel bandwidth. If this signal interferes with a narrow-band radio channel in the same band, then it simply increases the background "noise level," and so reduces the quality of that channel, but it does not interrupt it. In this respect, the spectral properties of the FM-DCSK system are qualitatively similar to those of a direct sequence (DS) spread spectrum system. If the power spectral density of the FM-DCSK system remains under the noise floor of the other narrow-band users then its presence may not even be noticed.

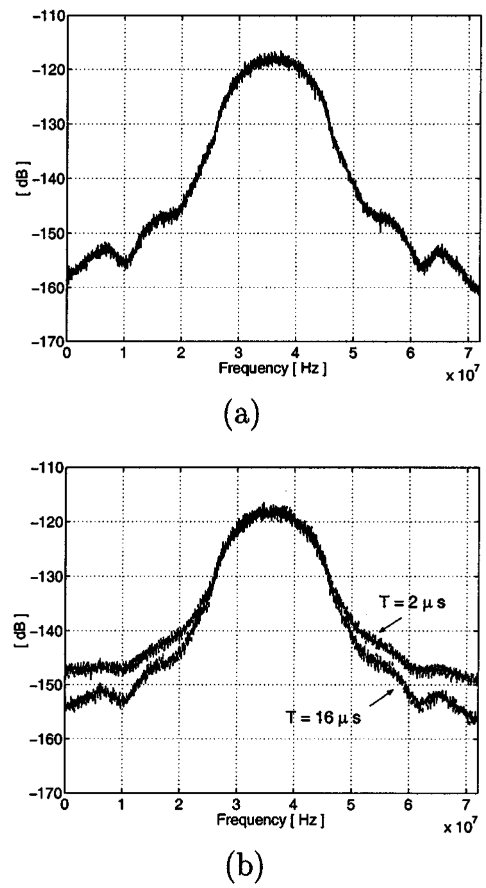


Fig. 2. Output spectra of the (a) FM and (b) DCSK modulators in an FM-DCSK system. $T$ is set to 2 $\mu$s and 16 $\mu$s to illustrate the effect of bit duration on the height of the skirts.

## III. Tools for System Performance Evaluation

Chaotic communications systems present several challenges for the system developer. Most importantly, theoretical results for the noise performance of FM-DCSK have only recently become available [1]. Even with these results, the performance of an FM-DCSK system can still be determined analytically only in the simplest case of a single-ray AWGN channel [2], where an ideal channel filter is used. Determination of the system performance under various propagation conditions and for nonideal system and circuit parameters, and the support of circuit and subsystem development all require a comparative performance evaluation by computer simulation.

The block diagram of a differentially coherent FM-DCSK RF system is shown in Fig. 3, where $z_i$ is the observation signal, and $r(t)$ and $z(t)$ denote the input and output of the FM-DCSK demodulator, respectively. The FM-DCSK signal is mixed up to 2.4 GHz for operation in the 2.4 GHz ISM band. The modulator's RF output $s(t)$ is therefore centered at 2.4 GHz. The system performance can be evaluated by computer simulation

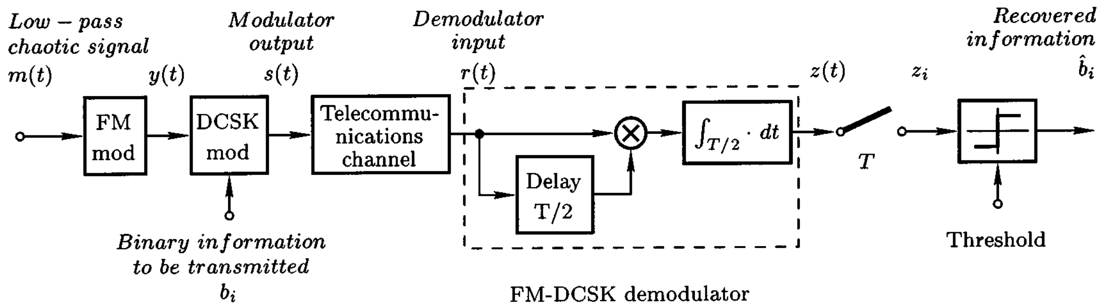


Fig. 3. Block diagram of an FM-DCSK RF system.

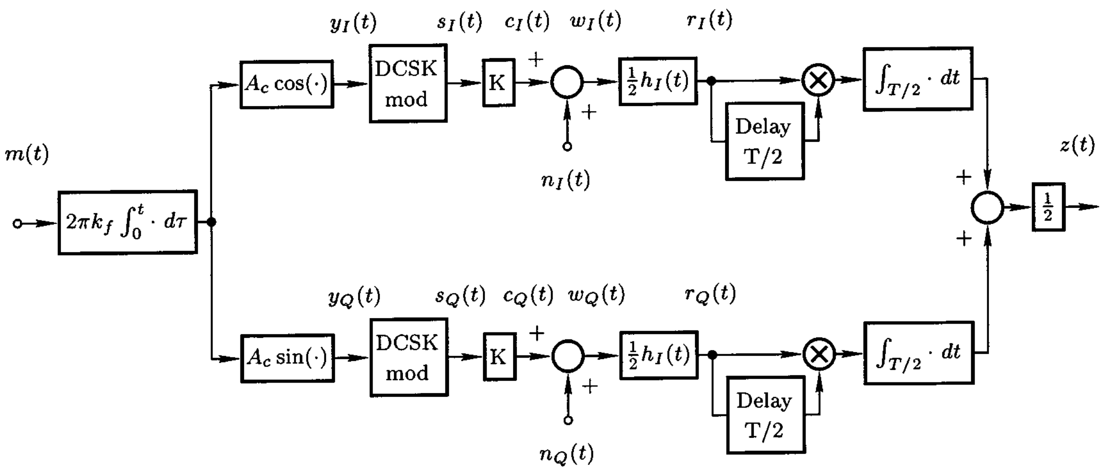


Fig. 4. Low-pass equivalent model of the FM-DCSK chaotic communications system in Fig. 3.

directly in the RF domain, or a low-frequency equivalent model can be developed [6].

Figure 4 shows the low-pass equivalent of the FM-DCSK RF system shown in Fig. 3. The details of the transformation can be found in [6]. In the figure, each signal is replaced by its complex envelope; the indexes $I$ and $Q$ denote the in-phase and quadrature components of the complex envelopes [2]. The complex envelope of the channel noise is denoted by $\tilde{n}(t) = n_I(t)+jn_Q(t)$ and the complex impulse response of the channel filter is given by $\tilde{h}(t) = h_I(t) + jh_Q(t)$. To minimize the simulation time, channel selection is performed by a zero-phase channel filter [7] for which $h_Q(t) = 0$. The attenuation of the telecommunications channel is denoted by $K$.

Note that the low-pass equivalent model gives directly the relationship between the two low-pass signals $m(t)$ and $z(t)$ which are needed in the simulation. The carrier frequency has been removed completely and only slowly-varying low-pass signals appear in the equivalent model so simulation time is minimized.

Channel models for specific simulations will be discussed in Sections IV and V.

## IV. Noise Performance of FM-DCSK

In a digital communications system, the analog sample functions carrying the information pass through a telecommunications channel, in which they are corrupted by noise and may also suffer from distortion and multipath effects. The demodulator must decide, on the basis of the corrupted and distorted received signal, which bit was most likely transmitted. When wrong decisions are made, bit errors occur. The quality of a digital communications system is characterized by the bit error rate (BER) which quantifies the average number of bit errors for specified channel conditions.

In this section, the noise performance of FM-DCSK is compared with that of FSK and GFSK, assuming a linear band-pass channel with AWGN and using a tenth-order channel filter. The channel model, including multipath effects, is shown in Fig. 5. In this section, only a single-ray channel is considered; the effects of multipath on the performance of FM-DCSK will be discussed in Section V.

### A. Relationship Between SNR and BER

To characterize the performance of a digital communications scheme, one must determine the BER as a function of the ratio of the signal energy per bit $E_b$ to the noise spectral density $N_0$. However, in a physical system, the signal to noise ratio (SNR), rather than $E_b/N_0$, can be measured. Knowing the total bandwidth of the RF channel selection filter $2B$ and the bit duration $T$, the SNR at the input of the demodulator can be related to $E_b/N_0$ as follows:

$$\mathrm{SNR} = \frac{P_{\mathrm{signal}}}{P_{\mathrm{noise}}} = \frac{E_b}{N_0}\frac{1}{2BT}. \tag{1}$$

A digital communications system is typically expected to perform with a BER of less than $10^{-3}$. In many applications, such

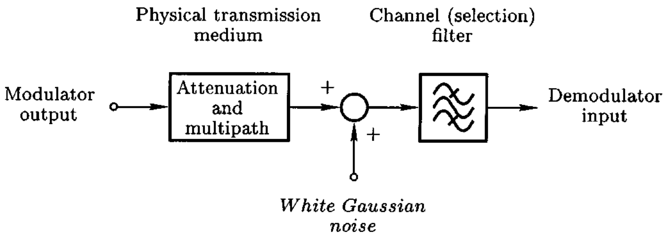


Fig. 5. Model of AWGN RF channel including the effects of multipath.

as a wireless local area network, the SNR may be as low as 0 dB in the worst case [8], [9].

### B. Noise Performance in an AWGN Channel

An analytical expression for the noise performance of the continuous-time FM-DCSK modulation scheme in a linear AWGN channel and assuming an ideal band-pass channel filter has recently been derived [1]. If a real channel filter is used, then the noise performance in the AWGN channel model becomes slightly worse, as shown in Fig. 6, where the BER is plotted as a function of $E_b/N_0$ for the following system parameters: bit duration $T = 2$ $\mu$s and RF channel bandwidth $2B = 17$ MHz. These parameters have been selected to obtain a WLAN system with a data rate of 500 kb/s and with IEEE 802.11-compliant channel spacing.

For a given $E_b/N_0$, the required SNR at the demodulator input can be calculated from (1). For comparison, the noise performance of the noncoherent frequency shift keying (FSK) [2] and Gaussian FSK [8] modulation schemes are also plotted in Fig. 6.

Note that the noise performance of these modulation schemes is much worse than that of coherent binary phase shift keying (BPSK) or coherent FSK modulation (see [2], for example). However, recall that FM-DCSK is suitable for special applications such as WLAN and industrial applications, indoor radio, and mobile communications, where the synchronization requirements of coherent demodulators cannot be satisfied, where the transmitted power spectral density must be low to avoid interfering with other telecommunications systems, and where multipath propagation and industrial disturbances limit the performance of a telecommunications system. In these applications, the noise performance is an important, but by no means the most important, system parameter. Other properties of the modulation scheme, such as robustness to channel nonidealities, are more significant.

In these applications, FM-DCSK has many advantages.

- The demodulation is performed without carrier synchronization.
- It is not sensitive to the particular waveform transmitted, so there is no need for complicated control circuitry in the chaotic signal generator to keep the parameters of the chaotic signal constant in the presence of temperature variations, aging, etc.
- Because both the reference and information-bearing parts of the FM-DCSK signal pass through the same telecommunication channel, it is not sensitive to channel distortion.

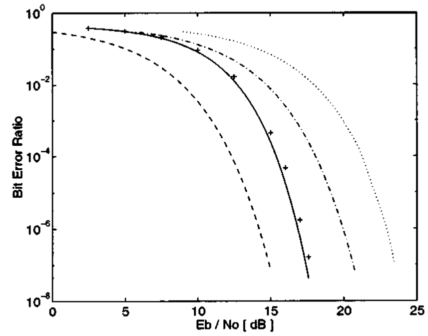


Fig. 6. Noise performance of noncoherent FSK (dashed curve), FM-DCSK and GFSK modulation schemes. For FM-DCSK both the theoretical (solid curve) and simulated ("+" marks) results are plotted. For GFSK the performance is given for two modulation indices: $\beta = 0.31$ (dash-dot curve) and $\beta = 0.22$ (dotted curve).

- It can operate over a time-varying channel if the variations in the channel parameters are negligible over half the bit duration.
- It can transmit pure "0" and "1" sequences, i.e., there is no need for a scrambler circuit.

## V. Operation in a Multipath Environment

In many applications such as WLAN, mobile communications, and indoor radio, the received signal contains components which have traveled from the transmitter to the receiver via multiple propagation paths with differing delays; this phenomenon is called *multipath propagation* [2], [10].

The components arriving via different propagation paths may add destructively, resulting in deep frequency-selective fading. Conventional narrow-band systems fail catastrophically if a *multipath-related null*, defined below, coincides with the carrier frequency.

In the applications mentioned above, the distance between the transmitter and receiver is relatively short, i.e., the attenuation of the telecommunications channel is moderate. The effect which limits the performance of communications in such an environment is not the additive channel (thermal) noise $N_0$, but deep frequency-selective fading caused by multipath propagation. In these applications, the most important system parameter is the sensitivity to multipath.

Figure 6 shows that the noise performance of FM-DCSK in a single-path AWGN channel is better than that of GFSK, but it is much worse than that of coherent modulation schemes. However, FM-DCSK has potentially lower sensitivity to multipath, because the demodulation is performed without carrier synchronization and the transmitted signal is a wide-band signal which cannot be completely canceled by a multipath-related null.

This section first evaluates the performance degradation of the FM-DCSK modulation scheme by computer simulation for the simplest case where two propagation paths are present with an excess delay of 75 ns. This excess delay, i.e., the difference between the propagation times along the two paths, is typical for office buildings in WLAN applications [8].

A more sophisticated and comprehensive model for the simulation of radio propagation in different mobile applications has been recommended by the PCS JTC [5]. In Section V-D, the multipath performance of FM-DCSK is evaluated for the most important indoor applications including office, residential, and commercial environments.

### *A. Model of Multipath Channel*

The tapped delay line model of a time-invariant multipath radio channel having $N$ propagation paths is shown in Fig. 7. The radiated power is split and travels along the $N$ paths, each of which is characterized by a delay $T_l$ and gain $k_l$, where $l = 1, 2, \ldots, N$.

If a narrow-band telecommunications system is considered, then in the worst case two paths exist and the two received signals cancel each other completely at the carrier frequency $\omega_c$, i.e.,

$$\Delta\tau\omega_c = (2n+1)\pi, \qquad n = 0, 1, 2, 3, \ldots$$

where $\Delta\tau = T_2 - T_1$ denotes the excess delay of the second path.

Let the two-ray multipath channel be characterized by its frequency response shown in Fig. 8. Note that the multipath-related nulls, where the attenuation becomes infinitely large, appear at

$$f_{null} = \frac{2n+1}{2\Delta\tau}, \qquad n = 0, 1, 2, 3\ldots \tag{2}$$

Let the bandwidth of fading be defined as the frequency range over which the attenuation of the multipath channel is greater than 10 dB. Then, the bandwidth of multipath fading can be expressed as

$$\Delta f_{\text{null}} \approx \frac{0.1}{\Delta\tau}. \tag{3}$$

Equations (2) and (3) show that the center frequencies of the multipath-related nulls, the distances between them, and their bandwidths, are determined by $\Delta\tau$; a shorter excess delay accentuates the problem.

In WLAN applications, the typical values of $\Delta\tau$ are 91 ns for large warehouses and 75 ns for office buildings [8]. If $\Delta\tau = 75$ ns, then the distance between two adjacent multipath-related nulls is 13.33 MHz. In the case of the three IEEE 802.11-compliant telecommunications channels in the 2.4-GHz ISM band [8], if off-the-shelf channel selection filters are used, then the RF bandwidth of the FM-DCSK signal should be 17 MHz. This means that at most two multipath-related nulls may appear in any of the three channels.

Equation (2) shows that the frequencies of the multipath-related nulls are determined by the excess delay $\Delta\tau$ of the second path. The number of multipath-related nulls appearing in a WLAN channel and their positions relative to the FM-DCSK center frequency also depend on the exact value of $\Delta\tau$. In a real application, $\Delta\tau$ may vary, thus changing the frequencies of the multipath-related nulls. To quantify this effect in the following, but using the same multipath channel for every simulation, the excess delay of the second path is kept constant, but the center frequency of the FM-DCSK signal is varied.

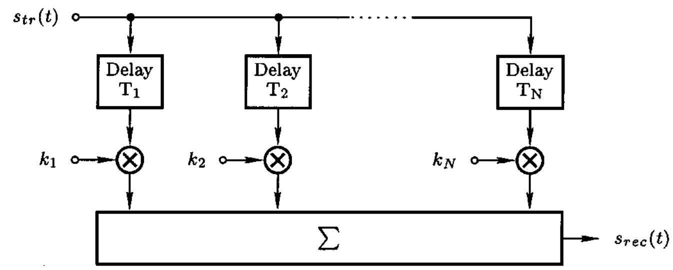


Fig. 7. Tapped delay line model of an RF multipath radio channel.

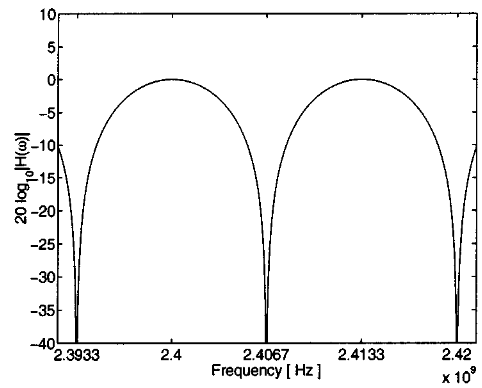


Fig. 8. Magnitude of frequency response of a two-ray multipath channel.

### *B. Qualitative Behavior of FM-DCSK in a Two-Ray Multipath Channel*

To illustrate the effect of the two-ray multipath channel on the received signal, Fig. 9 shows the spectra of the transmitted and received signals of the FM-DCSK system for $T = 2$ $\mu$s and RF bandwidth $2B = 17$ MHz, when $\Delta\tau = 75$ ns. The two possible extreme cases are shown in the figure; in the first case, the multipath-related null coincides with the center frequency of the FM-DCSK signal, while in the second case the two nulls appear symmetrically about the center frequency. Due to the rounded shape of the FM-DCSK spectrum, the loss in the received energy per bit $E_b$ is almost the same in both cases. We expect, therefore, that the multipath performance of FM-DCSK experiences low sensitivity to the relative positions of the center frequency and the multipath-related nulls.

It follows from the frequency response of the two-ray multipath channel shown in Fig. 8 that the required RF bandwidth of an FM-DCSK transmission depends on the worst case excess delay $\Delta\tau$ to be considered in a given application. A shorter delay requires larger transmission bandwidth. This effect can be seen clearly in Fig. 10, where $\Delta\tau$ has been reduced from 75 to 25 ns. In this case, if the multipath-related null coincides with the center frequency of the FM-DCSK signal then almost the entire energy per bit is lost, resulting in a very poor BER.

### *C. Quantitative Behavior of FM-DCSK in a Two-Ray Multipath Channel*

Fig. 8 shows qualitatively why conventional narrow-band systems can fail catastrophically to operate over a multipath channel. Due to high attenuation appearing about the multipath-related nulls, the SNR becomes extremely low at the input of the receiver. Consequently, the demodulator cannot operate.

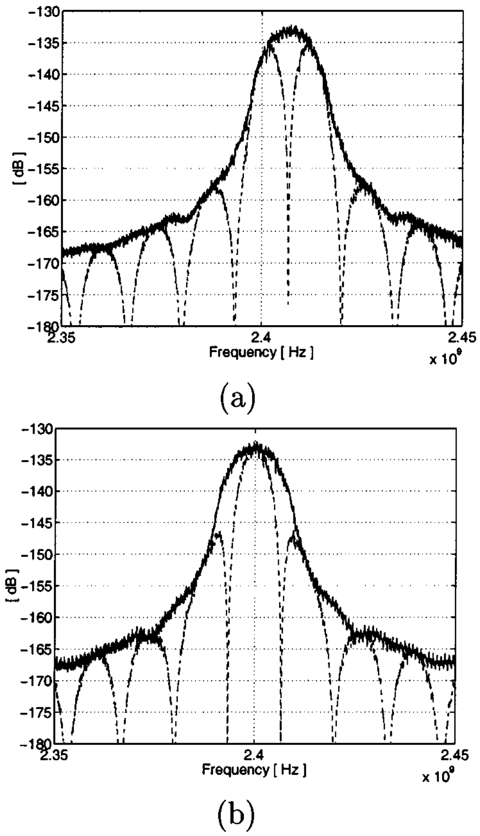


Fig. 9. The transmitted (solid curve) and received (dashed curve) spectra of an FM-DCSK system (a) when the center frequency of the FM-DCSK signal coincides with a multipath-related null and (b) when two nulls appear symmetrically about the center frequency.

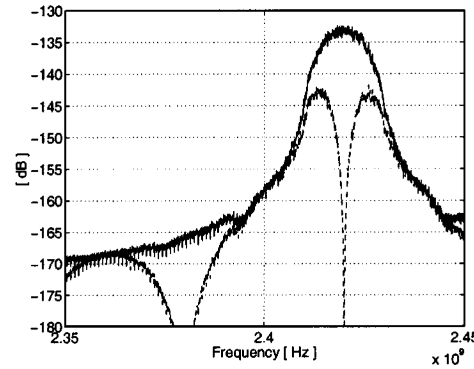


Fig. 10. The transmitted (solid curve) and received (dashed curve) spectra of an FM-DCSK system if the excess delay of the second path is 25 ns.

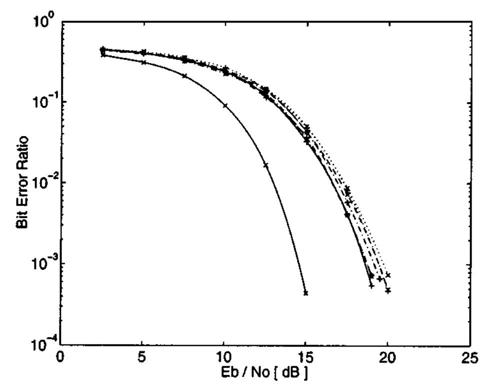


Fig. 11. Performance degradation caused by two-ray multipath propagation in an FM-DCSK system. To change the relative positions of the multipath-related nulls, the center frequency of the FM-DCSK transmission was varied from 2.4 GHz to 2.412 GHz in steps of 2 MHz. For comparison, the noise performance of FM-DCSK without multipath (solid curve with "×" marks) is also shown.

The situation becomes even worse if a carrier recovery circuit is used because a typical carrier recovery circuit, such as a phase-locked loop, cannot synchronize with the carrier unless the input signal level exceeds a certain threshold.

In the FM-DCSK system, the power of the radiated signal is spread over a wide frequency range. The appearance of a multipath-related null means that part of the transmitted power is lost but the system still operates. Of course, the lower SNR at the input of the demodulator results in a worse BER. The special feature of FM-DCSK that it does not use carrier synchronization to perform the demodulation makes it even more robust against multipath.

*1) Degradation due to Multipath with Equal Attenuation of Both Paths:* The performance degradation of the FM-DCSK system due to multipath propagation is shown in Fig. 11, where $\Delta\tau = 75$ ns. The solid curve marked with $\times$s shows the noise performance without multipath propagation. To determine the multipath performance in this example, we assume that the transmitted signal can propagate via two paths, the gain of each path being equal to 0.5.

We noted above that the relative positions of the multipath-related nulls and the center frequency of the FM-DCSK signal might influence the multipath performance. This effect is apparent in Fig. 11, where the model of the multipath channel was fixed, as shown in Fig. 7, but the center frequency of the FM-DCSK signal was varied from 2.4 to 2.412 GHz in steps of 2 MHz.

If a bit error rate of $10^{-3}$ is required, then the average loss due to multipath is only 4.8 dB and the variation in the loss is less than 1.2 dB. These results confirm our conjectures in 1997 [11] and 1998 [12] that the FM-DCSK modulation scheme could outperform conventional narrow-band modulation schemes under poor propagation conditions.

*2) Degradation due to Multipath with Unequal Attenuation of Both Paths:* Figure 11 shows the system performance achieved when two propagation paths exist and both of them suffer equal attenuation. The degradation in system performance is less if the attenuations of the two paths are different; this is illustrated in Fig. 12, where the difference between the attenuations of the two paths is 10 dB. The performance degradation has been determined for different FM-DCSK center frequencies; the dashed and dotted curves correspond to the best and worst cases, respectively. Under these propagation conditions the average performance loss is only 2.5 dB at BER $= 10^{-3}$.

*3) Performance Degradation in terms of Bandwidth:* The bandwidth of the transmitted FM-DCSK signal has the strongest influence on the multipath performance of the system. This effect is illustrated in Fig. 13, which shows the worst case performance degradation in the FM-DCSK system when the RF bandwidth is reduced to 8 MHz. The attenuations along the two

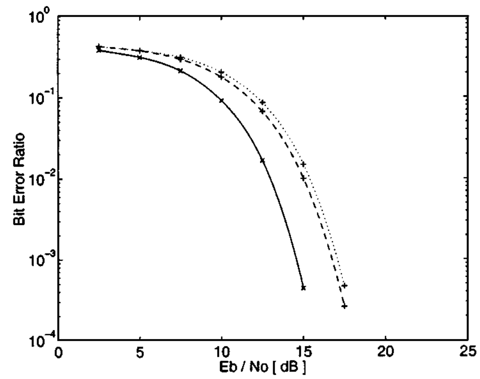


Fig. 12. Performance degradation of FM-DCSK due to multipath propagation when the attenuation of one propagation path is 10 dB higher than that of the other. The dashed and dotted curves correspond to the best and worst cases, respectively. For comparison, the noise performance of FM-DCSK without multipath (solid curve with "×" marks) is also shown.

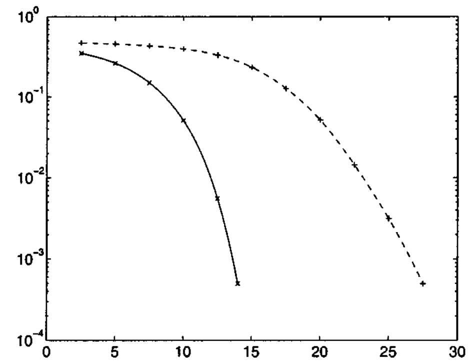

Fig. 13. Worst-case performance degradation caused by two-ray multipath propagation in an FM-DCSK system when the RF bandwidth is reduced to 8 MHz (dashed curve with "+" marks). For comparison, the noise performance of FM-DCSK with 8 MHz RF bandwidth and without multipath is also shown (solid curve with "×" marks).

propagation paths are the same, the multipath-related nulls coincide with the center frequency of the FM-DCSK signal, and $\Delta\tau = 75$ ns. The performance degradation is about 7.5 dB at $\text{BER} = 10^{-3}$. Recall that it was 4.8 dB when the bandwidth of the FM-DCSK signal was set to 17 MHz. As expected, the reduced bandwidth results in poorer system performance.

### *D. Quantitative Behavior of the FM-DCSK in PCS JTC Channels*

The PCS Joint Technical Committee has recommended a comprehensive multipath channel model to check and compare the performance of personal communications and mobile telecommunications systems in both indoor and outdoor applications [5]. In indoor applications, considered here, channel models have been developed for office, residential and commercial environments.

Each channel profile is given by the tapped delay line model shown in Fig. 7. To describe the various propagation conditions, three different channel profiles, denoted by channels $A$, $B$, and $C$, are given for each area. The JTC model assumes that the channel profile and the channel attenuation are correlated, and it provides a statistical procedure for selecting the channel profiles as a function of attenuation.

Let the probabilities of selecting channel profiles $A$, $B$, and $C$ be denoted by $P(A)$, $P(B)$, and $P(C)$, respectively. In the JTC recommendation, these probabilities are given as a function of channel attenuation.

The piecewise-linear curves that relate the probability of selecting a particular channel profile to the channel attenuation are shown in Fig. 14. In addition to the probabilities $P(A)$, $P(B)$, and $P(C)$, the curves are characterized by two parameters $PL_1$ and $PL_2$ which correspond to the channel attenuation at the two breakpoints of the piecewise-linear curves. Note that the probabilities $P(A)$, $P(B)$, and $P(C)$ for a given attenuation are given by the distance between the bounding curves.

Fig. 14 shows, in a qualitative manner, the selection of channel profile probabilities. The exact values of the five parameters $P(A)$, $P(B)$, $P(C)$, $PL_1$, and $PL_2$ are given in Table I for the indoor office, residential and commercial areas.

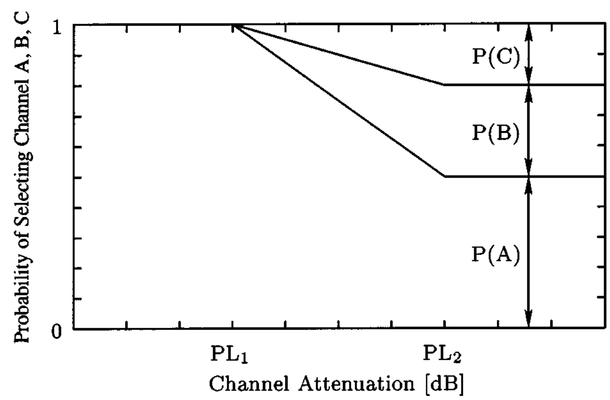


Fig. 14. Probabilities of selecting channel profiles $A$, $B$ and $C$ as a function of channel attenuation in the JTC multipath channel model.

More details on the JTC multipath channel model are given in [5].

*1) Performance Degradation in Office Area:* FM-DCSK communications systems are potentially suitable for applications in indoor office areas, for example, to implement wireless local area networks. The excess delays and attenuations of each tap in channel profiles $A$, $B$ and $C$, are given in Table II.

If the attenuation of the radio channel is less than 60 dB (see Table I) then only channel profile $A$, i.e., a three-ray multipath channel, has to be considered. The performance degradation of FM-DCSK in this channel is shown in Fig. 15. The dashed and dash-dot curves show the best and worst results, respectively, as the FM-DCSK center frequency is varied. The average loss in system performance is 5.8 dB at $\text{BER} = 10^{-3}$.

The propagation conditions in channels $B$ and $C$ are much worse. To illustrate this effect, the frequency response of channel profile $C$ is shown in Fig. 16. Note that due to its many propagation paths with widespread excess delays and high attenuation, the channel has a large attenuation over the whole FM-DCSK frequency band; it also suffers from many multipath-related nulls.

In the worst case, the attenuation of the radio channel is greater than 100 dB and channel profiles $A$, $B$, and $C$ have to be considered with probabilities of 50%, 45%, and 5%, respectively, in the simulations, as shown in Table I. The

TABLE I
PARAMETERS OF THE JTC MULTIPATH CHANNEL MODELS FOR INDOOR OFFICE, RESIDENTIAL AND COMMERCIAL AREAS

| Area | $P(A)$ (%) | $P(B)$ (%) | $P(C)$ (%) | $PL_1$ (dB) | $PL_2$ (dB) |
|---|---|---|---|---|---|
| Office | 50 | 45 | 5 | 60 | 100 |
| Residential | 60 | 35 | 5 | 50 | 75 |
| Commercial | 50 | 45 | 5 | 60 | 100 |

TABLE II
EXCESS DELAYS AND ATTENUATIONS OF THE TAPS IN THE THREE CHANNEL PROFILES RECOMMENDED FOR THE INDOOR OFFICE AREA BY THE PCS JOINT TECHNICAL COMMITTEE

| | Channel A | | Channel B | | Channel C | |
|---|---|---|---|---|---|---|
| Tap | Excess Delay (nsec) | Relative Attenuation (dB) | Excess Delay (nsec) | Relative Attenuation (dB) | Excess Delay (nsec) | Relative Attenuation (dB) |
| 1 | 0 | 0 | 0 | 0 | 0 | 0 |
| 2 | 50 | -3.6 | 50 | -1.6 | 100 | -0.9 |
| 3 | 100 | -7.2 | 150 | -4.7 | 150 | -1.4 |
| 4 | | | 325 | -10.1 | 500 | -2.6 |
| 5 | | | 550 | -17.1 | 550 | -5.0 |
| 6 | | | 700 | -21.7 | 1,125 | -1.2 |
| 7 | | | | | 1,650 | -10.0 |
| 8 | | | | | 2,375 | -21.7 |

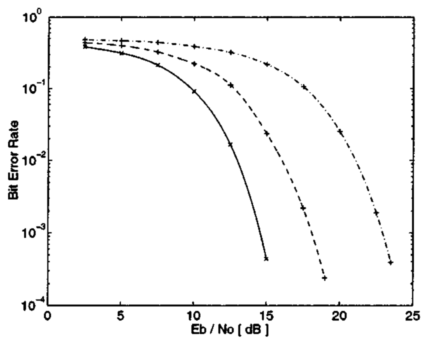


Fig. 15. Performance degradation in an FM-DCSK system caused by channel profile $A$ in the indoor office application. The dashed and dash-dot curves show the best and worst results when the FM-DCSK center frequency is varied. For comparison, the noise performance without multipath (solid curve with "×" marks) is also plotted.

performance degradation of an FM-DCSK system in this environment is shown in Fig. 17. The dashed, dash-dot, and dotted curves correspond to different FM-DCSK center frequencies: b2.4 GHz, 2.41 GHz, and 2.42 GHz, respectively. Note that the average loss in system performance is only 11.2 dB at BER $= 10^{-3}$, even in this worst case situation.

*2) Performance Degradation in Residential Area:* The indoor residential area is another possible application environment for FM-DCSK communications systems. The excess delays and attenuations for the taps in channel profiles $A$, $B$, and $C$ are given in Table III.

Table I shows that, in the worst case, the channel attenuation becomes greater that 75 dB and channel profiles $A$, $B$, and $C$ have to be considered with probabilities of 60%, 35%, and 5%, respectively. The performance degradation of an FM-DCSK system in this environment is shown in Fig. 18. The dashed and dash-dot curves give the best and worst noise performance as

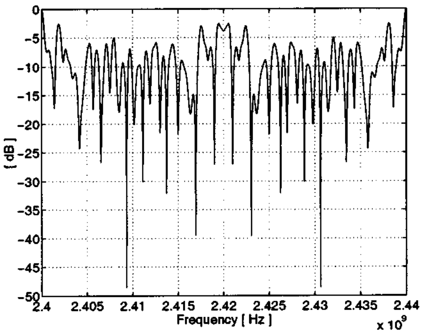


Fig. 16. Magnitude of the frequency response of channel profile $C$ defined by the JTC recommendation for an indoor office area.

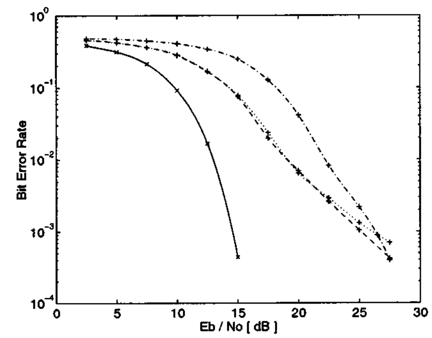


Fig. 17. Worst-case performance degradation in an FM-DCSK system when the channel attenuation exceeds 100 dB in the indoor office application. For comparison, the noise performance without multipath (solid curve with "×" marks) is also plotted.

TABLE III
EXCESS DELAYS AND ATTENUATIONS OF THE TAPS IN THE THREE CHANNEL PROFILES RECOMMENDED FOR THE INDOOR RESIDENTIAL AREA BY THE PCS JOINT TECHNICAL COMMITTEE

| | Channel A | | Channel B | | Channel C | |
|---|---|---|---|---|---|---|
| Tap | Excess Delay (nsec) | Relative Attenuation (dB) | Excess Delay (nsec) | Relative Attenuation (dB) | Excess Delay (nsec) | Relative Attenuation (dB) |
| 1 | 0 | 0 | 0 | 0 | 0 | -4.6 |
| 2 | 50 | -9.4 | 50 | -2.9 | 50 | 0 |
| 3 | 100 | -18.9 | 100 | -5.8 | 150 | -4.3 |
| 4 | | | 150 | -8.7 | 225 | -6.5 |
| 5 | | | 200 | -11.6 | 400 | -3.0 |
| 6 | | | 250 | -14.5 | 525 | -15.2 |
| 7 | | | 300 | -17.4 | 750 | -21.7 |
| 8 | | | 350 | -20.3 | | |

the FM-DCSK center frequency is varied. The average loss in system performance is only 10.5 dB at BER $= 10^{-3}$, even in this worst case situation.

*3) Performance Degradation in Commercial Area:* The third potential application environment for FM-DCSK for which a JTC channel model has been developed is the indoor commercial area. The excess delays and attenuations for each tap are given in Table IV.

In the worst case, the attenuation of the radio channel exceeds 100 dB. Usage of channel profiles $A$, $B$, and $C$ have to be considered with probabilities of 50%, 45%, and 5%, respectively, as given in Table I. The performance degradation of an FM-DCSK system in this environment is shown in Fig. 19. The dashed and dash-dot curves show the best and worst result as the FM-DCSK

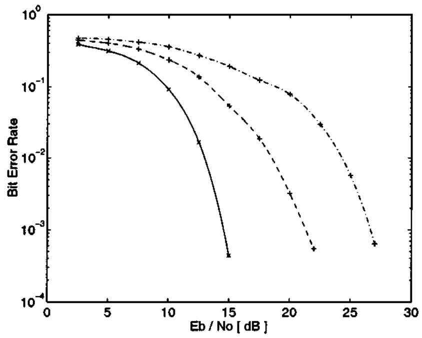


Fig. 18. Best- (dashed) and worst-case (dotted) performance degradation in an FM-DCSK system when the channel attenuation exceeds 75 dB in the indoor residential application. For comparison, the noise performance without multipath (solid curve with "×" marks) is also plotted.

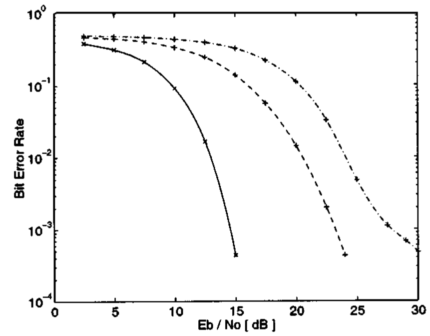


Fig. 19. Worst-case performance degradation in an FM-DCSK system when the channel attenuation exceeds 100 dB in the indoor commercial application. For comparison, the noise performance without multipath (solid curve with "×" marks) is also plotted.

TABLE IV
EXCESS DELAYS AND ATTENUATIONS OF THE TAPS IN THE THREE CHANNEL PROFILES RECOMMENDED FOR THE INDOOR COMMERCIAL AREA BY THE PCS JOINT TECHNICAL COMMITTEE

| | Channel A | | Channel B | | Channel C | |
|---|---|---|---|---|---|---|
| Tap | Excess Delay (nsec) | Relative Attenuation (dB) | Excess Delay (nsec) | Relative Attenuation (dB) | Excess Delay (nsec) | Relative Attenuation (dB) |
| 1 | 0 | 0 | 0 | -4.6 | 0 | 0 |
| 2 | 50 | -2.9 | 50 | 0 | 50 | -0.4 |
| 3 | 100 | -5.8 | 150 | -4.3 | 250 | -6.0 |
| 4 | 150 | -8.7 | 225 | -6.5 | 300 | -2.5 |
| 5 | 200 | -11.6 | 400 | -3.0 | 550 | -4.5 |
| 6 | | | 525 | -15.2 | 800 | -1.2 |
| 7 | | | 750 | -21.7 | 2,050 | -17.0 |
| 8 | | | | | 2,675 | -10.0 |

center frequency is varied. The average loss in system performance is 11.0 dB at BER $= 10^{-3}$ in this worst case situation.

## VI. SUMMARY

In chaotic modulation schemes, the transmitted signal is a wide-band signal. The objectives of using a wide-band signal as the carrier are twofold: 1) to overcome the multipath propagation problem, and 2) to reduce the transmitted power spectral density in order to avoid interfering with other radio communications. In this sense, chaotic communications systems offer a novel solution for spread-spectrum communications.

Of the chaotic modulation schemes published to date, FM-DCSK offers the best robustness against multipath and channel imperfections. Although FM-DCSK belongs to the SS communications family, it differs from conventional direct sequence spread spectrum (DS-SS) and frequency hopping spread spectrum (FH-SS) systems in a few basic respects.

- The narrow-band carrier is not spread by an extra spreading code but the carrier into which the digital information is mapped is a wide-band signal.
- Because chaotic signals are not periodic, the problems which appear in conventional SS systems due to the finite length of the spreading code do not exist in FM-DCSK.
- Except for timing recovery, demodulation of the transmitted bit stream is performed without synchronization in FM-DCSK, making this system much more robust against channel imperfections than modulation schemes which require carrier synchronization.
- At present, only a very limited CDMA capability can be achieved with the FM-DCSK modulation scheme [13].

In this paper, we have evaluated the performance of the FM-DCSK modulation scheme for different propagation conditions. Because the shape of the transmitted spectrum has the strongest influence on the multipath performance and interference caused to other radio channels, we have first analyzed in detail the shapes of the spectra observed at different points in the FM-DCSK modulator.

Due to the wide-band property of chaotic basis functions, FM-DCSK offers excellent multipath performance. We have determined by simulation the performance of an FM-DCSK radio system which has been designed for a WLAN application and which operates in the 2.4 GHz ISM frequency band with an IEEE 802.11-compliant channel spacing. Our results show that FM-DCSK performs extremely well over a radio channel suffering from multipath attenuation. If two propagation paths with equal attenuation are present, $\Delta\tau \geq 75$ ns, and the bandwidth of the FM-DCSK signal is 17 MHz, then the average performance loss is less than 5 dB for FM-DCSK. We re-emphasize that conventional narrow-band systems fail catastrophically under these conditions.

The PCS JTC has developed comprehensive channel models for simulating multipath performance in indoor applications. Models are available for the indoor office, residential, and commercial environments. In Section V-D, we have quantified the multipath performance of FM-DCSK in these reference propagation environments. The average loss in FM-DCSK system performance varied from 5.8 to 11.2 dB in these applications.

## REFERENCES

[1] G. Kolumbán, "Theoretical noise performance of correlator-based chaotic communications schemes," *IEEE Trans. Circuits Syst. I*, vol. 47, pp. 000–000, Dec. 2000.
[2] S. Haykin, *Communication Systems*, 3rd ed. New York: Wiley, 1994.
[3] 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.
[4] 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, HI, USA, Nov. 29–Dec. 2, 1997, pp. 117–120.
[5] K. Pahlavan and A. H. Levesque, *Wireless Information Networks*. New York: Wiley, 1995.
[6] G. Kolumbán, "Performance evaluation of chaotic communications systems: Determination of low-pass equivalent model," in *Proc. NDES'98*, Budapest, Hungary, July 16–18, 1998, pp. 41–51.

[7] A. V. Oppenheim, A. S. Willsky, and I. T. Young, *Signals and Systems*. Englewood Cliffs, NJ: Prentice-Hall, 1983.

[8] C. Andren, "A comparison of frequency hopping and direct sequence spread spectrum modulation for IEEE 802.11 applications at 2.4 GHz," Intersil Corporation, http://www.intersil.com/prism/papers/, 1997.

[9] S. Jost and C. Palmer, "New standards and radio chipset solutions enable untethered information systems: *PRISM*™ 2.4 GHz "Antenna-to-bits" 802.11 DSSS radio chipset solution,", [online]. Available: http://www.intersil.com/prism/papers/, 1998.

[10] R. C. Dixon, *Spread Spectrum Systems with Commercial Applications*, 3rd ed. New York: Wiley, 1994.

[11] 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 Syst. I*, vol. 44, pp. 927–936, Oct. 1997.

[12] ——, "The role of synchronization in digital communication using chaos—Part II: Chaotic modulation and chaotic synchronization," *IEEE Trans. Circuits Syst. I*, vol. 45, pp. 1129–1140, Nov. 1998.

[13] 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.

**Michael Peter Kennedy** (S'84–M'91–SM'95–F'98) received theB.E. (electronics) degree from the National University of Ireland in 1984, and the M.S. and Ph.D. degrees from the University of California at Berkeley in 1987 and 1991, respectively, for his contributions to the study of neural networks and nonlinear dynamics.

He worked as a Design Engineer with Philips Electronics, a Postdoctoral Research Engineer at the Electronics Research Laboratory, UC Berkeley, and as a Professeur Invité at the EPFL, Switzerland. From 1992 to 1999, he was on the faculty of the Department of Electronic and Electrical Engineering at University College Dublin (UCD), where he taught electronic circuits and computer-aided circuit analysis, and directed the undergraduate Electronics Laboratory. He was appointed Professor and Head of the Department of Microelectronic Engineering at University College Cork in 1999. He has published over 180 articles in the area of nonlinear circuits, holds two patents, and has taught courses on nonlinear dynamics and chaos in England, Switzerland, Italy, and Hungary. His research interests are in the simulation, design, and analysis of nonlinear dynamical systems for applications in communications and signal processing.

Dr. Kennedy received the 1991 Best Paper Award from the International Journal of Circuit Theory and Applications, was the IEE Kelvin Lecturer in 1997, was made a Fellow of the IEEE in 1998, received the Best Paper Award at the European Conference on Circuit Theory and Design in 1999, and was awarded the IEEE Circuits and Systems Society Golden Jubilee Medal and the IEEE Third Millenium Medal in 2000. He served as Associate Editor of the IEEE TRANSACTIONS ON CIRCUITS AND SYSTEMS PART I from 1993 to 1995 and PART II since 1999.

**Géza Kolumbán** (M'92–SM'98) received the M.S. and Ph.D. degrees from the Technical University of Budapest and the C.Sc. degree from the Hungarian Academy of Sciences in 1976, 1990, and 1990, respectively. After his graduation, he was employed as a Research Engineer by the Fine Mechanical Enterprise, Hungary, where he developed local generators, microwave transistor power amplifiers and VCO circuits for high-capacity microwave analog radio relay systems. He joined the Research Institute for Telecommunications, Hungary, in 1980, where he was involved in many system engineering projects such as SCPC-type satellite telecommunications system, microwave satellite up- and down-converters, low-capacity microwave digital radio system, etc. He led a group of engineers developing frequency synthesizers and local generators for frequency hopping spread spectrum and satellite systems. He spent one year (1991–1992) with Bilkent University in Turkey and another year (1992–1993) with the Eastern Mediterranean University in Cyprus. He returned to the Budapest University of Technology and Economics (called Technical University of Budapest before 2000) in 1993, where he is employed as an Associate Professor at the Department of Measurement and Information Systems. He has been a Visiting Researcher to the Electronics Research Laboratory, UC Berkeley, University College Dublin, EPFL, Switzerland, and TU Dresden, Germany. His current research and professional interests include nonlinear dynamics of different-type phase-locked loops, frequency synthesis by sampling phase-locked loop, mixed signal processing, computer simulation of complex systems, chaotic communications, and applications of chaotic signals in measurement engineering.

**Gábor Kis** received the M.S. degree in 1997 from Budapest University of Technology and Economics (formerly Technical University of Budapest), Budapest, Hungary, where he is currently working toward the Ph.D. degree in the Department of Measurement and Information Systems, Budapest University of Technology and Economics. He was a Visiting Researcher at University College Dublin in 1999. His research interests include chaotic behavior of the analog phase-locked loop, design and simulation of telecommunications systems, wireless communications systems, and chaotic communications.

Mr. Kis won the "Schnell László" scholarship offered to the best Ph.D. students in 1998 and in 2000. In September 1998, he won the "1998 Prize for Engineering and Technology" offered by The D. N. Chorafas Foundation.

**Zoltán Jákó** received the M.S. degree from the University "Transylvania" Brasov, Romania, in 1995. He is currently working toward the Ph.D. degree in the Department of Measurement and Information Systems, Budapest University of Technology and Economics, Budapest, Hungary.

He was a Visiting Researcher at University College Dublin in 1999. His current research interests include the chaotic behavior of analog phase-locked loops, cleaning noisy chaotic signals, chaotic communications, and CAD systems.

Mr. Jákó won the "Schnell László" scholarship in 1998. Also in 1998, he won the Best Ph.D. Studen Prize from the Telecommunications and Telematics for Higher Education Foundation. In September 1999, he won the "1999 Prize for Engineering and Technology" offered by The D. N. Chorafas Foundation.