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ESSENCE AND ADVANTAGES OF FM-DCSK VERSUS CONVENTIONAL SPREAD-SPECTRUM COMMUNICATION METHODS*

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Abstract. Frequency-modulated differential chaos shift keying (FM-DCSK) is essentially a technique that combines modulation with a spread-spectrum property for communications. It is also an effective technique similar to recent multiantenna methodologies that can make use of multipath effects, thereby achieving an excellent anti-multipath fading capability. Through analysis and simulation, this paper reports some essential characteristics and advantages in the system performance of the newly proposed M-ary FM-DCSK technology. The basic design of the M-ary FM-DCSK-based chaotic spread-spectrum communication system and a comparison with its conventional equivalent are presented. It is shown that the former is not only robust in multipath fading environments and simple in implementation, but also flexible in adjusting system parameters and trading-off several effects among bandwidth efficiency, energy efficiency, data rate, and error performance. It is demonstrated that the FM-DCSK technique is promising for the next generation of wireless communication systems as an excellent modulation and spread-spectrum scheme candidate.
Key words: Communication, M-ary FM-DCSK, anti-multipath fading, chaotic spread-spectrum, bandwidth efficiency, energy efficiency, error performance.

1. Introduction

Chaotic communication theory introduces chaotic modulation schemes into communication systems, which differ from conventional modulation algorithms in that the former applies nonperiodic chaotic signals as the carrier [1], [2]. In chaotic communications, even for the same bit or symbol, the modulated signals

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to be transmitted are varied, quite different from conventional communication schemes. Owing to its inherent broadband nature, which has promising potential superiority in anti-frequency-selective fading, chaotic communications have attracted considerable attention since the time it was put forward [3], [4], [6]. To date, several chaotic modulation schemes have been proposed, among which FM-DCSK is proven to have the best noise performance, which results from the orthogonality of the basis functions assured by the Walsh functions used. In order to ensure constant bit energy, frequency-modulated chaotic signals serve as the carrier in this scheme.

During the past few years, the study of the FM-DCSK technique has been limited to the binary case, which is superior to some conventional modulation schemes in additive white Gaussian noise (AWGN) channels. Over multipath channels, which usually lead to frequency selective fading, the FM-DCSK technique is competent for digital communications, although at the cost of some acceptable increase of transmission power, while conventional ones can fail completely [4]. Recently, the so-called M-ary FM-DCSK modulation scheme was suggested and studied [5]. Through Fourier analysis using the generalized maximum likelihood (GML) rules, the separation of the basis functions in the frequency domain was proposed as a detection scheme for M-ary FM-DCSK.

Differing from existing works, we view the FM-DCSK technique essentially as a technique that combines modulation and the spread-spectrum property. We therefore believe that its system analysis should be compared to conventional modulation along with the spread-spectrum method, not just to be compared to modulation alone. Moreover, FM-DCSK is an active technique, in some ways just like the current multiantenna technology, making use of the multipath feature to improve system performance without compensatory measures such as channel estimation, channel equalization, rake reception, and so on. Through simulation and analysis, we revealed the essence and found some advantages of the FM-DCSK technique versus its conventional equivalent systems. We found that the former is not only robust in a multipath fading environment and simple in implementation, but is also flexible in adjusting system parameters and trading-off several effects among bandwidth efficiency, energy efficiency, data rate, and error performance. In this paper, we will demonstrate that the FM-DCSK technique is promising for the next generation of wireless communication systems, and is an excellent modulation and spread-spectrum scheme candidate.

The rest of the paper is organized as follows. Section 2 reviews the basic principle of the M-ary FM-DCSK technique, while Section 3 analyzes and illustrates some essential characteristics and performance of this new technique. Section 4 compares two spread-spectrum communication systems, M-ary FM-DCSK and the conventional one, through design, simulation, and analysis. Finally, Section 5 concludes the paper with a future research outlook.

2. Basic principle of M-ary FM-DCSK

2.1. Modulation of M-ary FM-DCSK

Following [5], the modulated M-ary FM-DCSK signal to be transmitted is expressed by M orthogonal basis functions as follows:

$$s_m(t) = \sum_{j=1}^{N} s_{mj} g_j(t), \qquad 0 \le t \le T. \tag{1}$$

Here T is the symbol duration and $m = 1, 2, \ldots, M$, $N \le M$.

As for binary FM-DCSK, the two basis functions are

$$g_1(t) = \begin{cases} +(1/\sqrt{E_b})c(t), & 0 \le t < T/2, \\ +(1/\sqrt{E_b})c(t - T/2), & T/2 \le t < T, \end{cases}$$
$$g_2(t) = \begin{cases} +(1/\sqrt{E_b})c(t), & 0 \le t < T/2, \\ -(1/\sqrt{E_b})c(t - T/2), & T/2 \le t < T, \end{cases} \tag{2}$$

and, accordingly, with vector coefficients

$$s_1 = (s_{11} \quad s_{12}) = (\sqrt{E_b} \quad 0),$$
$$s_2 = (s_{21} \quad s_{22}) = (0 \quad \sqrt{E_b}). \tag{3}$$

Here $c(\cdot)$ is the modulated chaotic carrier, E_b is the bit energy, and T is the bit duration. As can be seen, binary FM-DCSK modulation transmits a reference segment and its repeated or reverse segment of the frequency-modulated chaotic signal segment, according to the digital information "1" or "0". It follows the first two Walsh functions:

$$W_2 = \begin{bmatrix} +1 & +1 \\ +1 & -1 \end{bmatrix} \begin{matrix} \ldots & w_1, \\ \ldots & w_2. \end{matrix} \tag{4}$$

Here the two row vectors w_1 and w_2 are the weights to be multiplied with the frequency-modulated carrier segment when the digital information is "1" and "0", respectively.

In the modulation of M-ary FM-DCSK, first, a $\log_2 M$ binary bit stream should be mapped to an M-ary symbol, and then a reference chaotic segment and $M - 1$ information bearing segments are transmitted. The relationship of the reference segment with the information bearing segments varies from symbol to symbol, which is defined by the first M Walsh functions. Take $M = 4$ as an example. The first four Walsh functions are

$$W_4 = \begin{bmatrix} +1 & +1 & +1 & +1 \\ +1 & -1 & +1 & -1 \\ +1 & +1 & -1 & -1 \\ +1 & -1 & -1 & +1 \end{bmatrix} \begin{matrix} \ldots & w_1, \\ \ldots & w_2, \\ \ldots & w_3, \\ \ldots & w_4. \end{matrix} \tag{5}$$

Accordingly, the four basis functions are

$$g_1(t) = \begin{cases} +(1/\sqrt{E_s})c(t), & 0 \le t < T/4, \\ +(1/\sqrt{E_s})c(t - T/4), & T/4 \le t < T/2, \\ +(1/\sqrt{E_s})c(t - T/2), & T/2 \le t < 3T/4, \\ +(1/\sqrt{E_s})c(t - 3T/4), & 3T/4 \le t < T, \end{cases}$$

$$g_2(t) = \begin{cases} +(1/\sqrt{E_s})c(t), & 0 \le t < T/4, \\ -(1/\sqrt{E_s})c(t - T/4), & T/4 \le t < T/2, \\ +(1/\sqrt{E_s})c(t - T/2), & T/2 \le t < 3T/4, \\ -(1/\sqrt{E_s})c(t - 3T/4), & 3T/4 \le t < T, \end{cases} \tag{6}$$

$$g_3(t) = \begin{cases} +(1/\sqrt{E_s})c(t), & 0 \le t < T/4, \\ +(1/\sqrt{E_s})c(t - T/4), & T/4 \le t < T/2, \\ -(1/\sqrt{E_s})c(t - T/2), & T/2 \le t < 3T/4, \\ -(1/\sqrt{E_s})c(t - 3T/4), & 3T/4 \le t < T, \end{cases}$$

$$g_4(t) = \begin{cases} +(1/\sqrt{E_s})c(t), & 0 \le t < T/4, \\ -(1/\sqrt{E_s})c(t - T/4), & T/4 \le t < T/2, \\ -(1/\sqrt{E_s})c(t - T/2), & T/2 \le t < 3T/4, \\ +(1/\sqrt{E_s})c(t - 3T/4), & 3T/4 \le t < T, \end{cases}$$

with

$$\begin{aligned} s_1 &= (s_{11} \quad s_{12} \quad s_{13} \quad s_{14}) = (\sqrt{E_s} \quad 0 \quad 0 \quad 0), \\ s_2 &= (s_{21} \quad s_{22} \quad s_{23} \quad s_{24}) = (0 \quad \sqrt{E_s} \quad 0 \quad 0), \\ s_3 &= (s_{31} \quad s_{32} \quad s_{33} \quad s_{34}) = (0 \quad 0 \quad \sqrt{E_s} \quad 0), \\ s_4 &= (s_{41} \quad s_{42} \quad s_{43} \quad s_{44}) = (0 \quad 0 \quad 0 \quad \sqrt{E_s}). \end{aligned} \tag{7}$$

Here E_s is the symbol energy and T is the symbol duration.

One can similarly describe the implementation process of an arbitrary M-ary FM-DCSK modulation.

2.2. Demodulation of M-ary FM-DCSK

The noise performance of a modulation scheme mainly depends on two factors: the separation of elements of the signal set and the detector configuration. Due to the difficulty of exact recovery and complete synchronization of chaotic carriers, and before M-ary FM-DCSK was proposed, the demodulation of binary FM-DCSK employed a simple differential coherent detection. This detection consists of multiplying the received signal by its $T/2$ delayed version, integrating the results between $T/2$ and T, and making a decision of this integral value by using a zero threshold: if the integral value is greater than zero, "1" is detected; otherwise, "0" is chosen.

For M-ary FM-DCSK, the differential detection technique cannot be applied, because it has several information-bearing segments. It was explained in [5] that the separation of the basis functions for FM-DCSK in the frequency domain relies on Fourier analysis and on the GML decision rules. It was shown that the result is optimal over an AWGN channel. Consider the observation space constructed based on Fourier analysis. Each basis function defines a subspace in the observation space. The received signal is projected onto the subspace of each basis function and the energies measured in the different subspaces are then determined. The decision is made in favor of the subspace and, consequently, in favor of the symbol that receives the greatest energy. This is the principle of the GML decision rules [5]. Modifying and simplifying this rule through Parseval's theorem, the energy calculation can be mapped to the time domain. It can be shown that the energy expression of the received signal elements for binary FM-DCSK can be extended to M-ary FM-DCSK, resulting in

$$E_{j,m} = \frac{1}{N}\int_{T-T/N}^{T}\left[\sum_{i=0}^{N-1}\tilde{r}_m\left(t - i\frac{T}{N}\right)\cdot w_{j,N-i}\right]^2 dt, \qquad N \le M, \quad j = 1, 2, \ldots, M. \quad (8)$$

Here T is the symbol duration, $\tilde{r}_m(\cdot)$ is the received signal, and $w_{j,N-i}$ is the corresponding element in the Walsh function that is the multiplying weight during modulation. Next, one needs to find the j that maximizes $E_{j,m}$ ($j = 1, 2, \ldots, M$), and then to make a decision on that symbol. The block diagram of the demodulation process for M-ary FM-DCSK is illustrated in Figure 1.

3. Essential characteristics of M-ary FM-DCSK

In order to explain why we view FM-DCSK as a technique that combines modulation with the spread-spectrum property, we demonstrate some essential characteristics of FM-DCSK through system-level simulation and system-parameter analysis. The simulation environment used is a **MATLAB7.0/PC** platform.

3.1. FM-DCSK is a spread-spectrum technique

FM-DCSK has the feature of spread-spectrum in the frequency domain. If the bandwidth of a signal before spreading is W, and the bandwidth of the signal after spreading is W_{ss}, then the spread-spectrum factor is defined as $\beta = W/W_{ss}$. Note that $W = 1/T$, $W_{ss} = 1/T_c$, and $\beta = T/T_c$, where T is the symbol duration and T_c is the chip duration of the spreading signal.

Figure 2 illustrates the bit error rate (BER) of M-ary FM-DCSK over an AWGN

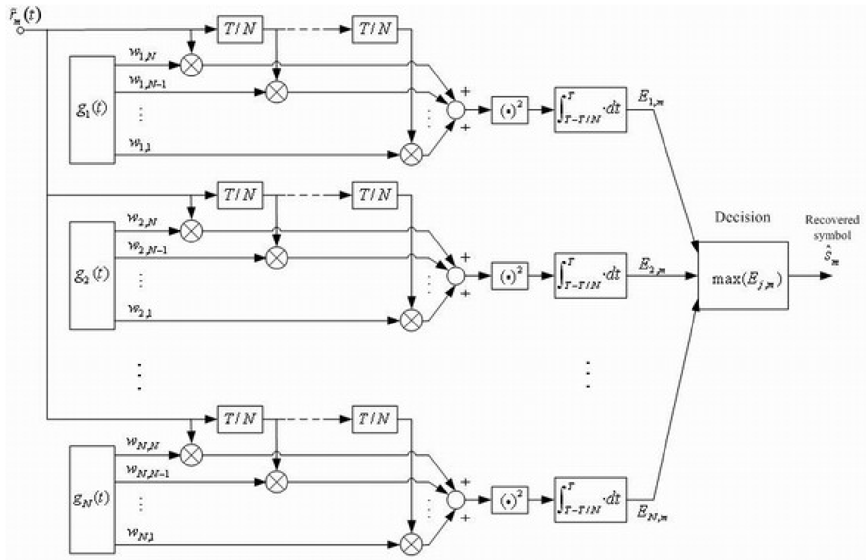

Figure 1. Configuration of the M-ary FM-DCSK detector.

channel with $\beta = 2, 4, 8, 16$, respectively. Figure 3 illustrates the BER of M-ary FM-DCSK over a Rayleigh flat fading channel with $\beta = 2, 4, 8, 16$, respectively. Figure 4 illustrates the BER of M-ary FM-DCSK over a multipath fading channel with $\beta = 2, 4, 8, 16$, respectively. The common parameters used include $M = 2$ and a chaos generator using the Bernoulli map. The parameters of the multipath fading channel include a multipath number of three, a power distribution of [0.4, 0.4, 0.2], and delays of $[0, 1/\beta \cdot T/M = T/2\beta, 2/\beta \cdot T/M = T/\beta]$.

From Figures 2–4, it can be seen that with an increase of β, the performance degrades over the AWGN and the flat fading channels, while the performance actually improves over the multipath fading channel. The improvement is indeed visible over the multipath fading channel and, at the same level of BER, the required E_b/N_0 over the multipath fading channel is smaller than that over the flat fading channel. This proves that FM-DCSK can achieve good error performance by sacrificing some spectral resources under a multipath fading environment, in which it has potential superiority. In conclusion, FM-DCSK has some advantages in performance over some channels under severe transmission conditions.

3.2. FM-DCSK is a modulation technique

Figure 5 shows the error performance of M-ary FM-DCSK over an AWGN channel with $M = 2, 4, 8$, respectively. Figure 6 shows the error performance of M-ary FM-DCSK over a Rayleigh flat fading channel with $M = 2, 4, 8$, respectively.

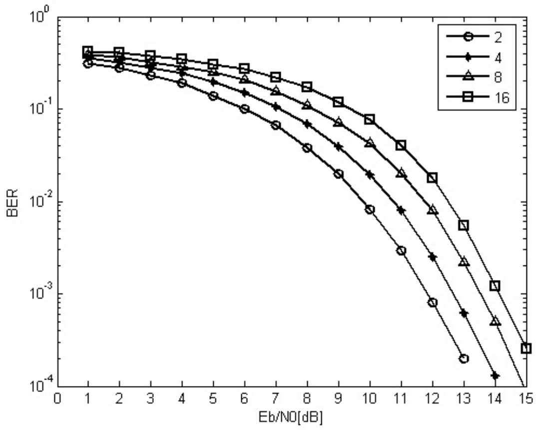

Figure 2. Influence of the spread-spectrum factor on FM-DCSK over an AWGN channel with $\beta = 2, 4, 8, 16$.

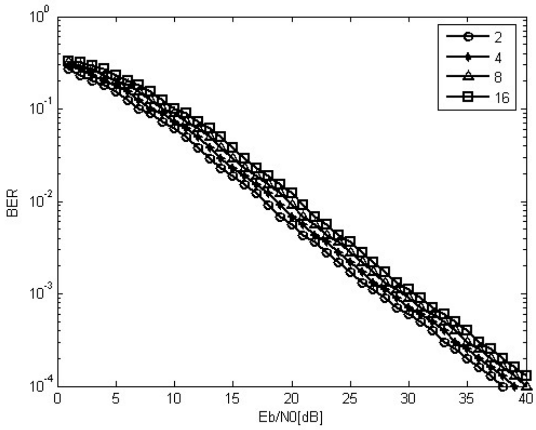

Figure 3. Influence of the spread-spectrum factor on FM-DCSK over a Rayleigh flat fading channel with $\beta = 2, 4, 8, 16$.

Figure 7 shows the error performance of M-ary FM-DCSK over a multipath fading channel with $M = 2, 4, 8$, respectively. The common parameters used include the spread-spectrum factor $\beta = 8$ and a chaos generator using the Bernoulli map. The parameters of the multipath fading channel are the same as those in Section 3.1.

From Figures 5–7 it can be seen that the performance of M-ary FM-DCSK is improved as M increases. This improvement is more prominent over the fre-

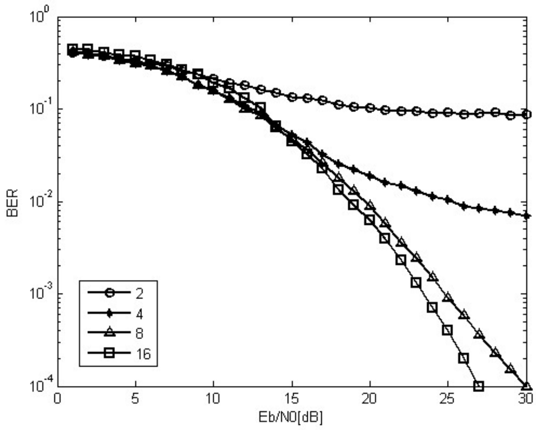

Figure 4. Influence of the spread-spectrum factor on FM-DCSK over a multipath fading channel with $\beta = 2, 4, 8, 16$.

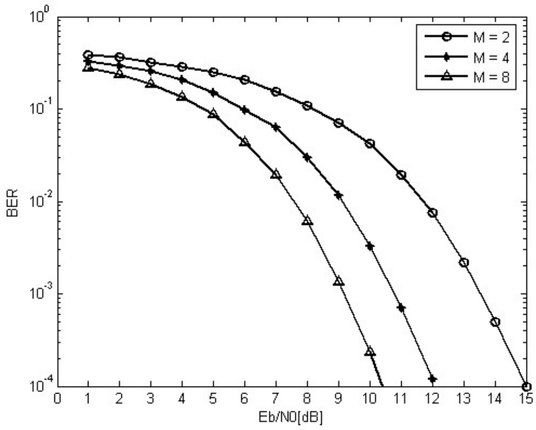

Figure 5. Influence of M on M-ary FM-DCSK over an AWGN channel with $M = 2, 4, 8$.

quency selective channel than over the flat fading channel. Actually, the overall performance over the frequency selective channel is better than that over the flat fading channel. This demonstrates once again that FM-DCSK is an active technique making use of the multipath effects, showing its potential capability for anti-multipath fading. Accounting for the results given in Section 3.1, the increase in the system parameters M and β can contribute to the improvement in the performance of anti-multipath fading. Therefore, we consider FM-DCSK as a technique that combines modulation with the spread-spectrum property.

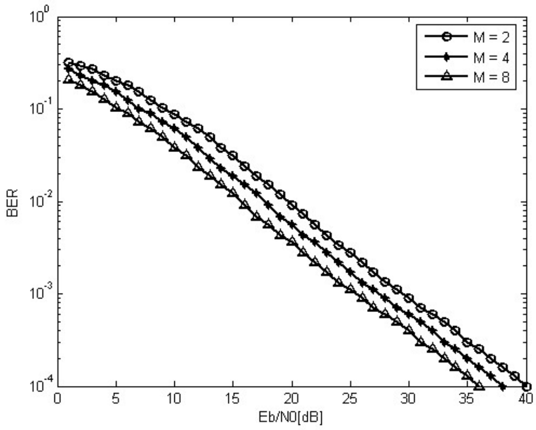

Figure 6. Influence of M on M-ary FM-DCSK over a Rayleigh flat fading channel with $M = 2, 4, 8$.

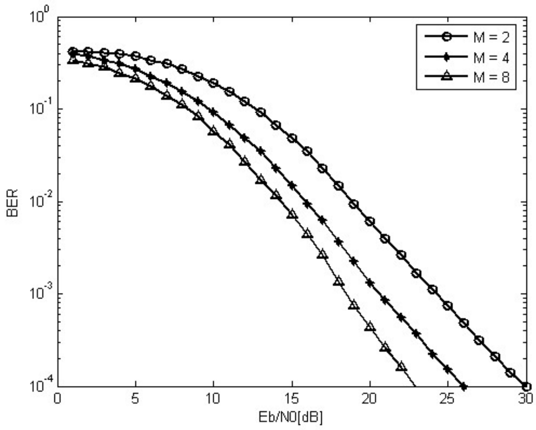

Figure 7. Influence of M on M-ary FM-DCSK over a multipath fading channel with $M = 2, 4, 8$.

3.3. Bandwidth efficiency comparison between MPSK and M-ary FM-DCSK

Figure 8 illustrates the bandwidth efficiency of the M-ary phase shift keying (MPSK) scheme over an AWGN channel and that of M-ary FM-DCSK over an AWGN channel and over a multipath fading channel with $\beta = 8$. The bandwidth efficiency of MPSK over a multipath fading channel is excluded here because its BER is no better than 0.1 on the chosen range of E_b/N_0.

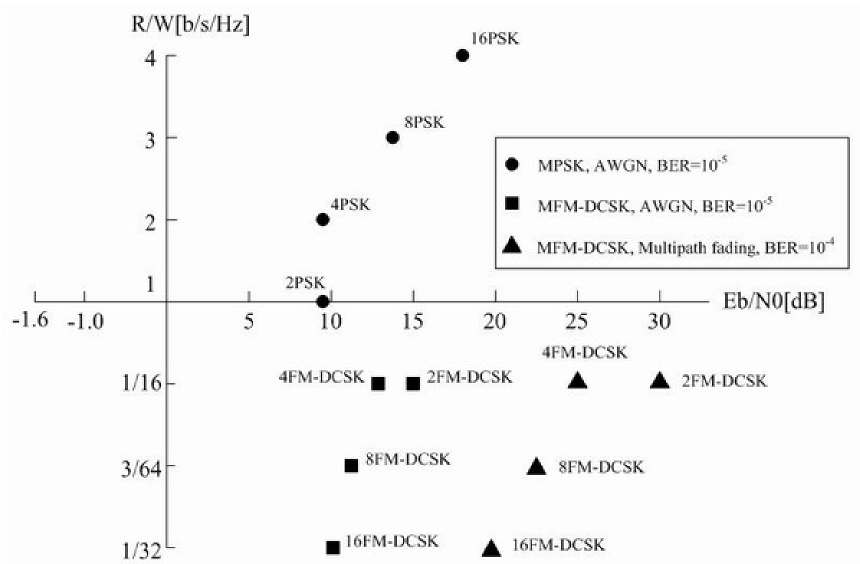

Figure 8. Bandwidth efficiency of MPSK and M-ary FM-DCSK.

From Figure 8 it can be seen that the bandwidth efficiency of M-ary FM-DCSK decreases with the increase of M over both AWGN and multipath fading channels. The reason is that M-ary FM-DCSK is an orthogonal modulation scheme with the spread-spectrum property, whose bandwidth efficiency is $\log_2 M/(M \cdot \beta)$. Note that the bandwidth efficiency of MPSK increases with increasing M over the AWGN channel. The reason is that MPSK is a nonorthogonal modulation method, whose bandwidth efficiency is $\log_2 M$. Over a multipath fading channel, the BER of MPSK is no better than 0.1 over the chosen range of E_b/N_0. Hence, the robust performance of FM-DCSK in a multipath fading channel is quite obvious. Over channels under severe transmitting conditions, M-ary FM-DCSK still works well, and its BER performance can be improved by sacrificing some spectral resources, while MPSK fails even if spectral resources are sacrificed.

4. Performance comparisons between chaotic and conventional spread-spectrum systems

Given that FM-DCSK is a technique combining modulation with the spread-spectrum property, our concern is whether or not the FM-DCSK-based chaotic spread-spectrum system is better than conventional spread-spectrum systems, and, if so, in what sense and by how much.

In this section, we provide some detailed comparisons through system design

Table 1. Architectures of two spread-spectrum (SS) systems

<table>
<tr><th></th><th>System 1</th><th>System 2</th></tr>
<tr><td>Name</td><td>Conventional SS system</td><td>Chaotic SS system</td></tr>
<tr><td>Error-correcting coding scheme</td><td>Convolutional codes</td><td>Convolutional codes</td></tr>
<tr><td>Modulation scheme</td><td>MPSK</td><td rowspan="2">M-ary FM-DCSK</td></tr>
<tr><td>Spread-spectrum scheme</td><td>Gold direct spreading</td></tr>
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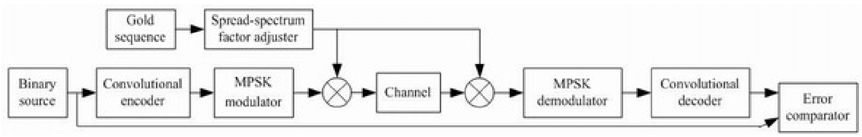

Figure 9. Conventional spread-spectrum communication system.

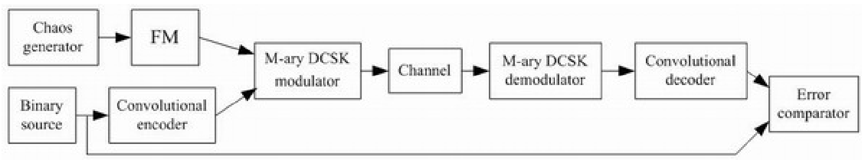

Figure 10. Chaotic spread-spectrum communication system based on FM-DCSK.

and simulation. We mainly compare an M-ary FM-DCSK-based system with a direct spread-spectrum system that employs the MPSK modulation technique, since the latter conventional spread-spectrum and modulation techniques are widely used in the second and third generations of mobile communication systems. In our study, the simulation environment used is an **SPW4.8/Solaris8/ C language** platform.

The architectures of the two spread-spectrum systems are displayed in Table 1. The block diagrams of the two spread-spectrum systems are illustrated in Figures 9 and 10, respectively.

Throughout the simulations, the common parameters used include a spread-spectrum factor of 8 and a chaos generator using the Bernoulli map. Figure 11 shows the BER performance of System 1 and System 2 with $M = 2, 4$, respectively, over an AWGN channel. Other parameters used include a (2, 1, 5) convolutional code, where 2 is the length of code bits, 1 is the length of message bits, and 5 is the constraint length. Figure 12 shows the BER performance of

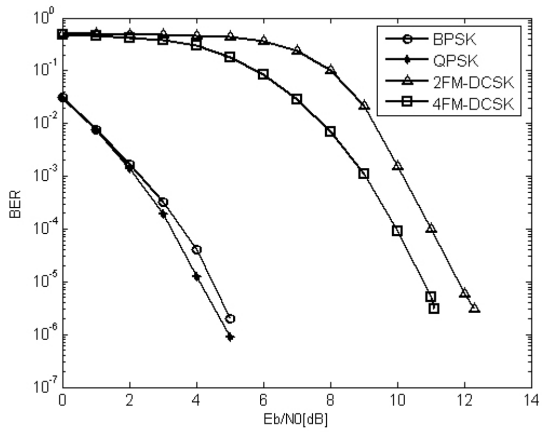

Figure 11. BER performance of the two systems over an AWGN channel with $M = 2, 4$.

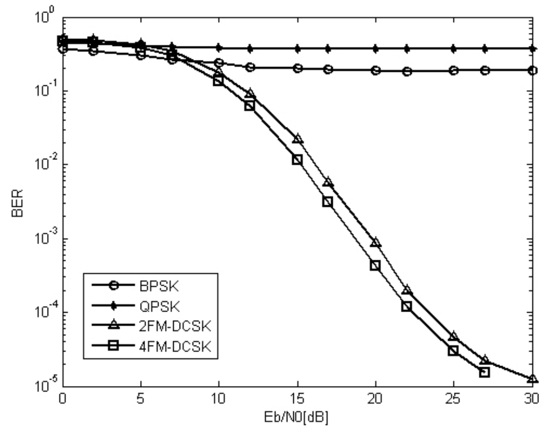

Figure 12. BER performance of the two systems over a multipath fading channel with $M = 2, 4$.

System 1 and System 2 with $M = 2, 4$, respectively, over a multipath fading channel. The parameters of the convolutional code are the same as in Figure 11. Figure 13 shows the BER performance of the two binary systems with (2, 1, 5) and (3, 1, 5) convolutional codes, respectively, over the AWGN channel. Figure 14 shows the BER performance of the two binary systems with (2, 1, 5) and (3, 1, 5) convolutional codes, respectively, over the multipath fading channel. The multipath channel parameters include a multipath number of three, a power distribution of [0.6, 0.2, 0.2], and delays of $[0, 1/\beta \cdot T/M = T/2\beta, 2/\beta \cdot T/M = T/\beta]$.

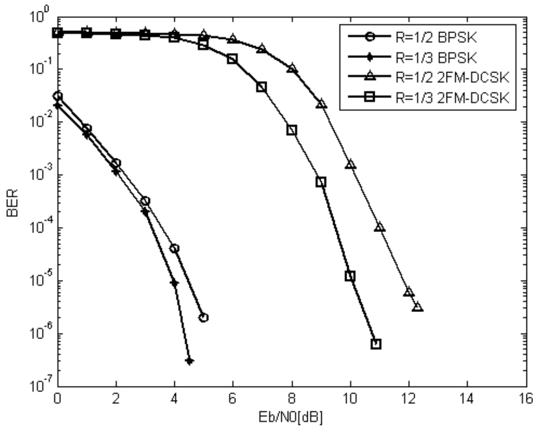

Figure 13. BER performance of the two binary systems over an AWGN channel with code rate $R = \frac{1}{2}, \frac{1}{3}$.

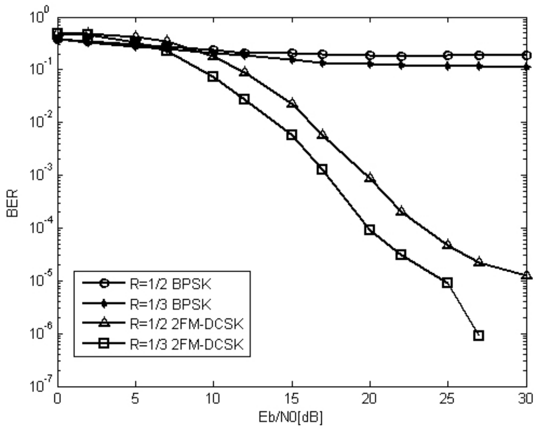

Figure 14. BER performance of the two binary systems over a multipath fading channel with code rate $R = \frac{1}{2}, \frac{1}{3}$.

From Figures 11–14 we found that over the AWGN channel the performance of the chaotic spread-spectrum system is not as good as that of the conventional spread-spectrum system. However, over the multipath fading channel, the conventional system without compensatory measures cannot even guarantee normal communications, while the chaotic system can satisfy the digital communication requirement as long as it is supplied with greater transmission power, which nevertheless is acceptable. This means that the chaotic system is more suitable for mo-

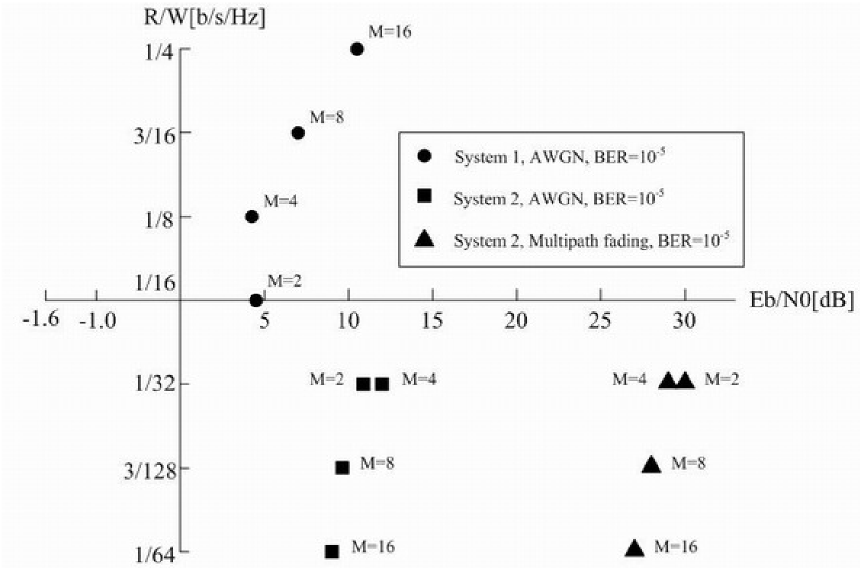

Figure 15. Bandwidth efficiency of the chaotic spread-spectrum system and the conventional spread-spectrum system.

bile data transmission services. Meanwhile, we also found that over a multipath fading channel, the conventional spread-spectrum system is insensitive to the code rate. This system does not satisfy the normal communication requirement unless some channel compensatory measures or extra reception techniques are acquired. In contrast, the chaotic system is sensitive to the code rate, which provides another opportunity to improve the overall performance of the communication system by lowering the data rate or bandwidth efficiency.

At this point, it should be noted that for chaotic spread-spectrum systems, a trade-off and balance among modulation, spread spectrum, and coding can be dynamically maintained for better system performance according to the practical situation at hand.

In our simulations, we also observed some other interesting phenomena. Under the conditions of $\beta = 8$ and $R = \frac{1}{2}$, Figure 15 describes the bandwidth efficiency of System 1 over an AWGN channel and that of System 2 over an AWGN channel as well as a multipath fading channel. Similar to Section 3.3, System 1 over a multipath fading channel is not displayed here.

From Figure 15 it is clear that with increasing M, the bandwidth efficiency of System 1 increases over the AWGN channel, while that of System 2 decreases over both AWGN and the multipath fading channels. This is because the bandwidth efficiency of System 1 is $R \cdot \log_2 M/\beta$ and that of System 2 is $R \cdot \log_2 M/(M \cdot \beta)$. Over the multipath fading channel, the BER of System 1 is no better than

0.1 on the chosen range of E_b/N_0, while System 2 still works well. Obviously, compared to conventional spread-spectrum systems, where the modulation and spread-spectrum scheme are designed separately, System 2 reduces the dependence on reception techniques and channel compensatory measures. The trade-off among bandwidth efficiency, energy efficiency, and BER performance of the chaotic system is superior to that of conventional systems in terms of hardware complexity, energy efficiency, and BER performance. Therefore, we believe that the former is more suitable for adaptive requirements.

5. Conclusions

In conventional communication systems suffering from severe multipath fading, where modulation and spread-spectrum schemes are designed separately, a certain level of fundamental communication quality cannot be guaranteed if no additional compensatory measures are introduced. This separate design practice appears to be a passive approach. However, compensations such as channel estimation, channel equalization, rake reception, etc., will unavoidably increase hardware complexity, which is very undesirable in some applications such as mobile communications. In contrast, M-ary FM-DCSK, as a technique that combines modulation with the spread-spectrum property, can provide satisfactory communication quality without increasing hardware complexity over a multipath channel under severe conditions, with the cost of using higher but acceptable transmission power. In addition, the good anti-multipath fading performance of chaotic FM-DCSK communication systems costs only certain bandwidth resources. Overall, this combined design methodology is shown to be an active approach and a valuable technology, in some sense similar to the current multiantenna systems design idea. Furthermore, the additional transmitting power can be reduced for the same level of communication quality if some simple compensation is added to the chaotic spread-spectrum communication system.

The introduction of M-ary FM-DCSK into wireless communication systems has led to a new trade-off strategy, namely, balancing among energy efficiency, BER performance, hardware complexity, and bandwidth efficiency. Unlike conventional trade-off strategies, where only the former three factors were considered, one is now concerned with the bandwidth efficiency as well. Obviously, the new trade-off strategy has the advantage of having more flexibility in design, which is suitable for future mobile communication systems that require more flexibility in order to implement more functional components.

Reviewing of the transmission environments and service types for the fourth generation of mobile communication systems, we believe that FM-DCSK is a promising candidate.

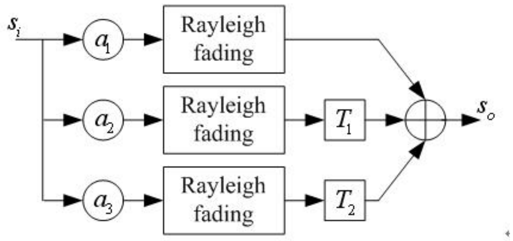

Figure 16.

6. Mathematical models of Rayleigh flat fading and multipath fading channels

6.1. Rayleigh flat fading channel

The pdf of Rayleigh distribution can be expressed as $f_X(x) = (x/\sigma^2)e^{-x^2/2\sigma^2}$, $x \geq 0$. Generate the envelope $a = \sigma\sqrt{-2\ln x}$, where x is a random variable satisfying (0, 1) uniform distribution. Also generate the phase p, which is another random variable satisfying $(0, 2\pi)$ uniform distribution. The complex random sequence with the envelope of a and phase of p is then multiplied to the transmitting sequence. Thus, the transmitting signal is destroyed by a Rayleigh flat fading channel.

6.2. Multipath fading channel

Three paths of the transmitting signals with different Rayleigh fading and different time delays are added to form the signal destroyed by a multipath fading channel. Here, the total power of the three paths of signals equals that before entering the channel. A block diagram (Figure 16) is used to illustrate this situation (note that no matter what kind of fading channel is used here, the AWGN is also added).

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