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CHAOTIC MODULATION AND DEMODULATION TECHNIQUES: A SURVEY

Chandrika B.K[1], Shrikant S. Tangade[2]
Dept. of Electronics and Communication
REVA Institute of Technology and Management, Bangalore

Abstract: Physical-layer encryption using chaotic system is a new concept for secure communication. This is mainly due to their unpredictability and simplicity of implementation over conventional secure communications systems. This paper presents survey of different types of chaotic modulation and demodulation techniques. The techniques are chaos masking (CM), Chaos Shift Keying (CSK), Chaos On-Off Keying (COOK), and Differential Chaos Shift Keying (DCSK) and comparison of chaos techniques in terms of noise performance and BER.
Index terms: Chaos masking, CSK, COOK, DCSK.

I. INTRODUCTION

The rapid increase of the wireless applications, especially in military and commercial use, has been prompting a corresponding increasing demand for transmission security. Currently, several secure communication schemes and cryptosystems, such as public key encryption, quantum cryptography and quantum telecommunication, chaotic communications, have been proposed. Chaos communication is rather a new field in the communication research. It evolved from the study of chaotic dynamical systems, not only in mathematics, but also in physics or electrical engineering somewhere at the beginning of 1990 [6]. Prior to this period, the evolution of chaos has caused much euphoria among the mathematicians and physicists, while the engineering community has observed the development with skepticism. Chaotic signals are irregular, aperiodic, uncorrelated, broadband, and impossible to predict over long times. As chaos is a pseudo-random signal with wide bandwidth and it is unpredictable for a long term, it can be used as carrier to securely hide the confidential message. These properties coincide with the requirements for signals applied in conventional communication systems, in particular spread spectrum communications, multi-user communications, and secure communication. The basic idea of digital communication using a chaotic carrier is that the bits are mapped to sample functions of chaotic signals emanating from one or more chaotic attractors. In order to avoid periodicity, the symbols are mapped to the actual nonperiodic outputs of chaotic circuits and not to parameters of certain known sample functions. The principal difference between a chaotic carrier and a conventional periodic carrier is that the sample function for a given symbol is nonperiodic and is different from one symbol interval to the next. Thus, the transmitted waveform is never periodic, even if the same symbol is transmitted repeatedly. This paper presents chaotic modulation and demodulation techniques are chaos masking CSK, COOK, and DCSK. Comparison of CSK, COOK, DCSK in terms of noise performance, BER.

II. CHAOS SHIFT KEYING

Chaos shift keying (CSK) was first proposed by Parlitz et al. [1992] and Dedieu et al. [1993]. As mentioned before, the idea is to encode digital symbols with chaotic basis signals. Figure 1 shows the block diagram of a typical CSK digital communication system. The operating principle can be described as follows. The transmitter consists of two chaos generators f and g, producing signals c1(t) and c2(t), respectively. If a binary +1 is to be sent during the interval [(l - l)n, ln), c(t) is transmitted, and if -1 is to be sent, c(t) is transmitted. In its originally proposed form, the CSK system works on the basis of the self-synchronizing property of chaotic systems. The receiver structure is shown in Fig. 2, in which the incoming signal is used to drive two self-synchronization subsystems f and g, which are matched to f and $\tilde{g}$, respectively. Assume that the filters at the transmitter and receiver are distortionless and the channel is perfect. When the transmitted signal is c(t), the subsystem will be synchronized with the incoming signal while $\tilde{g}$ does not, and vice versa. Therefore, by measuring the difference between the incoming signal and the output of the self-synchronization subsystems, the transmitted symbol can be estimated. Results show that the systems work well under a noiseless condition. In communications, correlation is a generic process that is used to evaluate the likeness between two signals. Clearly, for the CSK system mentioned above, instead of measuring the synchronization error, we may directly evaluate the correlation between the transmitted signal and the replica basis signals to identify the transmitted symbol. Thus, a correlator plus a decision maker form a generic coherent receiver for the CSK system.

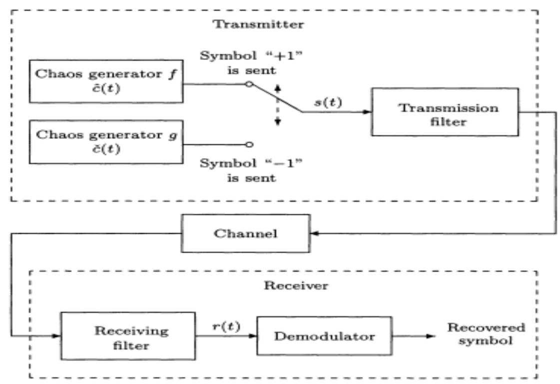


Figure 1: CSK Modulation

A. Coherent Demodulation Based on Correlation

Coherent detection of CSK signals using correlator-based receivers was studied in detail by Kolumban et ai. [1998a]. Figure 2 shows the block diagram of a correlator-based coherent CSK demodulator. The two synchronization circuits attempt to recover the two chaotic signals c(t) and c(t) from the received corrupted signal r(t). An acquisition time Ts is assumed for the synchronization blocks to lock to the incoming signal. The reproduced chaotic functions are then used to correlate with the received signal during the remainder of the bit duration. Then, the outputs of the correlators are sampled and compared. Consider the lth received symbol. The outputs of the correlators at the end of the symbol period are given by

$$\hat{o}(lT_b) = \int_{(l-1)T_b+T_s}^{lT_b} r(t)\hat{c}(t)\,dt$$
$$\check{o}(lT_b) = \int_{(l-1)T_b+T_s}^{lT_b} r(t)\check{c}(t)\,dt. \quad (2)$$

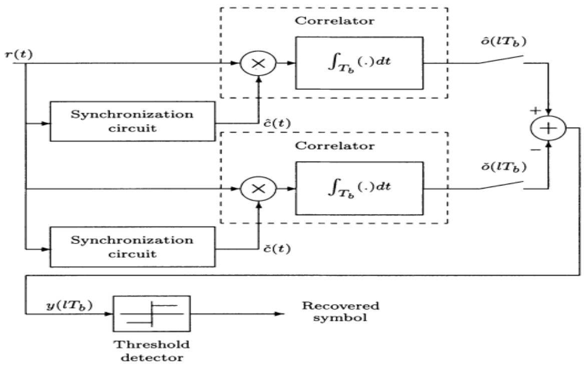
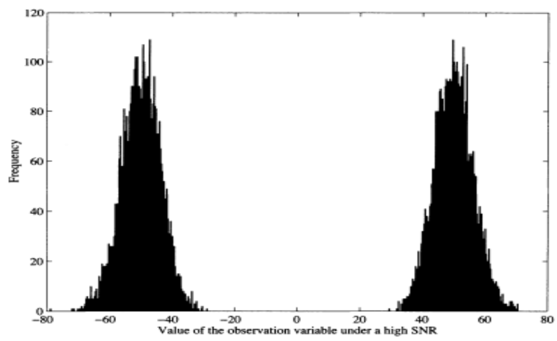


Figure 2: CSK Demodulation

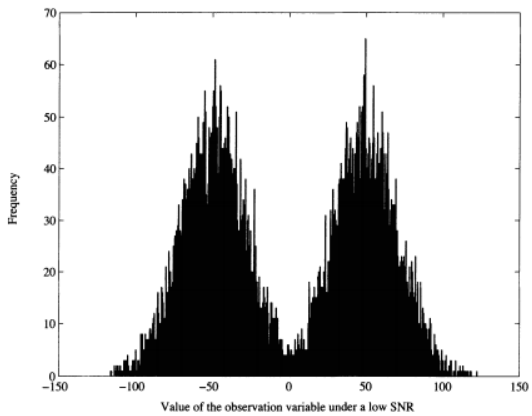
The input to the threshold detector at this instant is

$$y(lT_b) = \hat{o}(lT_b) - \check{o}(lT_b). \quad (1)$$

If y(ln) is positive, a +1 is decoded for the lth symbol. Otherwise, a -1 is decoded. To gain some insights into the demodulation process, the histograms of y(lTb) are helpful. Assuming that the filters are distortionless and the synchronization time Ts is negligible compared to the bit period, we may plot the histograms of y(ln) for different signal-to-noise ratios (SNRs),figure (3a) and (3b) shows histogram of coherent CSK under high and low SNR.



(a)



(b)

Fig.3. Histograms of the observation variable for a coherent CSK system for (a) high SNR, and (b) low SNR.

B. Non-Coherent Demodulation Based on Bit Energy Calculation

In non-coherent CSK demodulation, the chaotic basis signals are not available at the receiver. Detection has to be done based on some distinguishable property of the basis signals. One such property is the bit energy which can be deliberately made different for different symbols in the modulation process [3]. Suppose chaotic basis signals with different bit energies are used to represent the binary symbols. If a binary +1 is to be sent during the interval [(l- 1)n, ln), a chaotic basis signal c(t) with mean bit energy Ec is transmitted, and if -1 is to be sent, a chaotic basis signal c(t) with mean bit energy Ec is transmitted. To generate the chaotic signals with different bit energies, we may employ two chaos

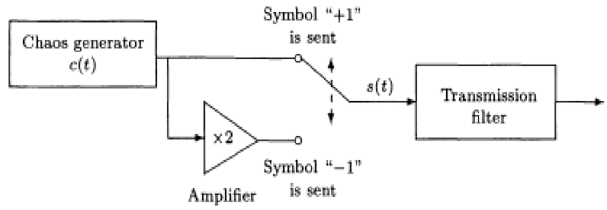


Fig. 4. CSK transmitter sending different average bit energies for different symbols

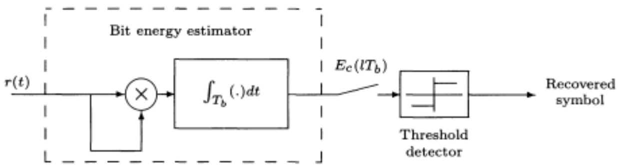


Fig. 5 CSK receiver based on bit energy estimator.

generators with different average bit energies. Alternatively, the same chaos generator can be used to produce two signals of different bit energies by using two amplifiers of different gains, as shown in Fig. 4. At the receiving end, the bit energy can be estimated by a square-and-integrate process such as the one shown in Fig. 5. Assume that only additive noise corrupts the transmitted signal and the noise power is limited by the receiving filter, i.e.,

$$r(t) = s(t) + n'(t) \quad (3)$$

where s(t) denotes the transmitted signal and n'(t) is the noise component at the output of the receiving filter. For the lth received symbol, the sampled output of the correlator, or equivalently the received bit energy E_c(ln), is given by

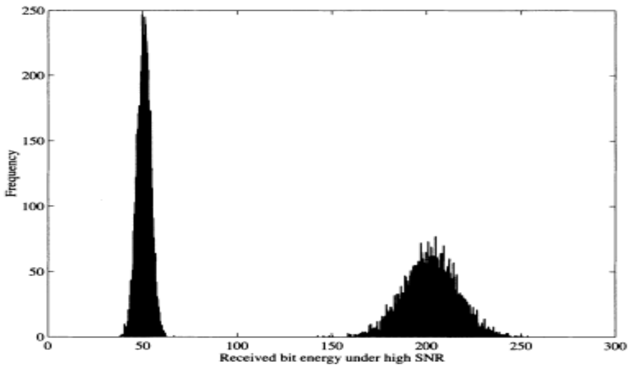
$$\begin{aligned} E_c(lT_b) &= \int_{(l-1)T_b}^{lT_b} r^2(t)\, dt \\ &= \int_{(l-1)T_b}^{lT_b} s^2(t)\, dt + 2\int_{(l-1)T_b}^{lT_b} s(t)n'(t)\, dt \\ &\quad + \int_{(l-1)T_b}^{lT_b} [n'(t)]^2\, dt. \end{aligned} \quad (4)$$

When the SNR is high, the second and third integrals in (4) are negligible compared with the first one. Therefore, Ec(ln) is approximately equal to either one of the following two bit energies:

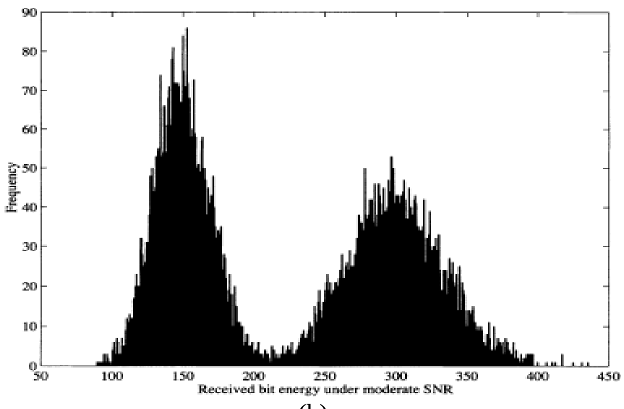
$$\hat{E}_c(lT_b) = \int_{(l-1)T_b}^{lT_b} \hat{c}^2(t)\, dt \quad (5)$$

$$\check{E}_c(lT_b) = \int_{(l-1)T_b}^{lT_b} \check{c}^2(t)\, dt. \quad (6)$$

However, in the CSK system, due to the non-periodic nature of chaotic signals, the bit energy for the same symbol is time-varying (i.e., varying from bit to bit), as illustrated by the histogram shown in Fig. 4 (a) and 4(b)for the high SNR and low SNR case.



(a)



(b)

Fig.4. Histograms of the observation variable for a non coherent CSK system for (a) high SNR, and (b) low SNR.

III. CHAOS ON-OFF KEYING.

Chaos On-Off Keying is similar to CSK in all respects except that only one chaotic signal is used in transmission of message signal. When the message signal is bit 1, the chaotic signal is transmitted, but when the message signal is bit 0 no signal is transmitted. The modulation process is thus as simple as turning on and off a chaos generator. Clearly, the bit energy of the transmitted signal takes either a positive value or zero, depending on the symbol sent. The demodulation can be done in a non-coherent manner using a simple bit-energy estimator.

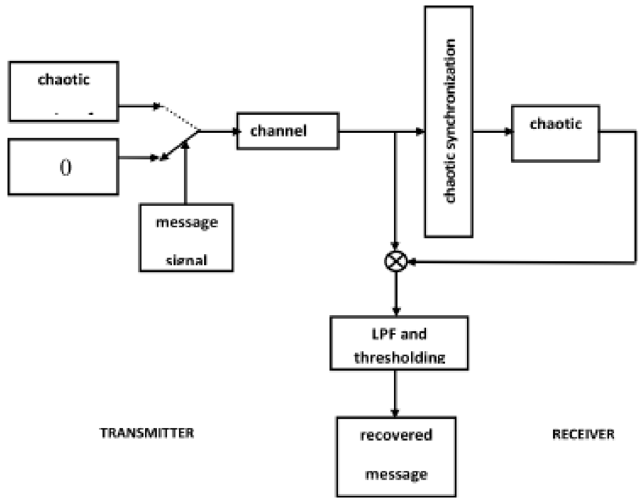


Figure 5: CSK ON-OFF keying

IV. CHAOTIC MASKING

In chaotic masking, two identical chaotic are used one at the transmitter end and the other at the receiver as shown in figure 6.Chaotic Mask signal ĉ(t) which is subtracted from the transmitted signal r(t) to obtain the recovered message signal m(t). Assuming a noise free channel and perfect synchronization between the two chaotic systems, s(t)= r(t), c(t)= ĉ(t) and m(t)=m̂(t). For higher security of the message signal, Yang reported that the message signal is typically made about 20dB to 30dB weaker than the chaotic signal [7].

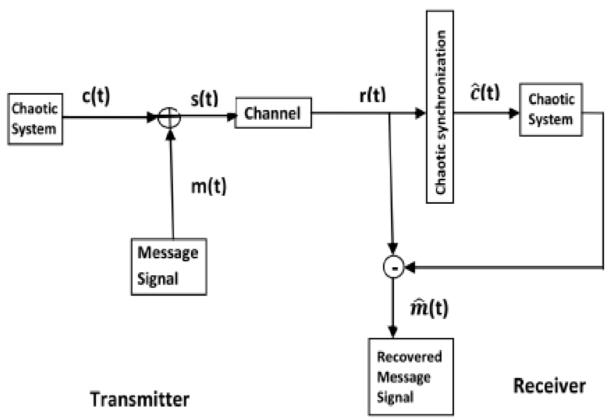


Fig. 6: Chaotic Masking

V. DIFFERENTIAL CHAOS SHIFT KEYING

In Differential Chaos Shift Keying, no synchronization is required as compared to other scheme discussed earlier. When propagation conditions are so poor that it is impossible to recover basis functions by chaotic synchronization, a differential chaos shift keying (DCSK) and a differentially coherent correlation receiver may be used [9]The same chaotic signal used at the transmitter (called reference signal) is transmitted and used to demodulate the message signal at the receiver end. This is illustrated in Fig. 8.In this scheme, every bit is transmitted two sample functions. The first sample function serves as the reference while the second one carries the information. Thus, bit 1 is sent by transmitting the reference signal twice in succession and bit 0 is sent by transmitting the reference signal followed by an inverted copy of the reference signal. The two sample functions are correlated in the receiver and the decision is made by thresholding [2]. When "1" is transmitted and

$$s(t) = \begin{cases} c(t) & \text{for } (l-1)T_b \le t < (l-1/2)T_b \\ c(t - T_b/2) & \text{for } (l-1/2)T_b \le t < lT_b \end{cases} \qquad (7)$$

When "-1" is transmitted

$$s(t) = \begin{cases} c(t) & \text{for } (l-1)T_b \le t < (l-1/2)T_b \\ -c(t - T_b/2) & \text{for } (l-1/2)T_b \le t < lT_b \end{cases} \qquad (8)$$

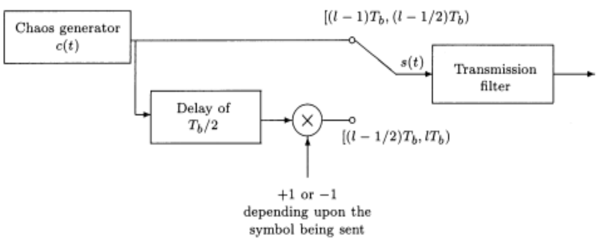


Fig. 7. DCSK modulator.

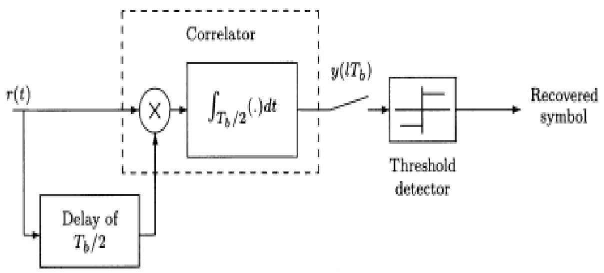


Fig. 8. DCSK demodulator.

At the receiver, the correlation between the reference sample and the data sample is evaluated. This can be done by correlating the incoming signal with a half-symbol-delayed version of itself, as shown in Fig. 2.10. The output of the correlator at the end of the lth symbol duration is given by

$$y(lT_b) = \int_{(l-1/2)T_b}^{lT_b} r(t)r(t - T_b/2)\, dt. \qquad (9)$$

Assuming that the transmitted signal is contaminated by additive noise, the correlator output is given by

$$y(lT_b) = \int_{(l-1)/2)T_b}^{lT_b} [s(t) + n'(t)][s(t - T_b/2) + n'(t - T_b/2)]\, dt \qquad \text{10)}$$

$$\begin{aligned} = & \int_{(l-1/2)T_b}^{lT_b} [s(t)s(t - T_b/2)]\, dt + \int_{(l-1/2)T_b}^{lT_b} [s(t)n'(t - T_b/2)]\, dt \\ & + \int_{(l-1/2)T_b}^{lT_b} [n'(t)s(t - T_b/2)]\, dt \\ & + \int_{(l-1/2)T_b}^{lT_b} [n'(t)n'(t - T_b/2)]\, dt \qquad (2.1\text{(} \end{aligned}$$

where n'(t) is the noise component at the output of the receiving filter. The first term in can be positive or negative, depending on whether a +1 or -1 has been transmitted. Also, all other integral terms have a zero mean. Thus, the threshold of the detector can be set optimally at zero, which is independent of the noise level.Figure 9(a) shows the distribution of the correlator output under a high SNR environment.The centres of the two clusters corresponding to the two symbols are located at equal distance from zero..

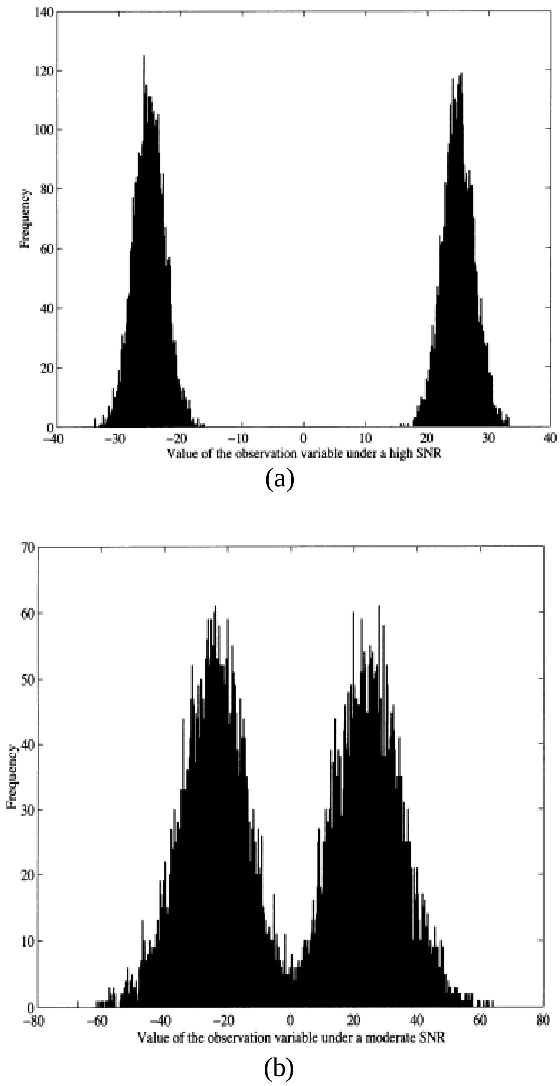


Fig.9. Histograms of the observation variable for a non coherent DCSK system for (a) high SNR, and (b) low SNR

Thus, setting the threshold at zero is sufficient to differentiate the two symbols.If the channel is noisy, however, the two clusters widen and overlap each other, as shown in Fig. 9(b). Thus, although errors are inevitable, the optimal threshold remains at zero

VI. COMPARISON OF CSK, COOK, DCSK

In COOK for sysmbol 1 chaotic signal is transmitted and for sysmbol 0 no signal is transmitted.It has better noise performance than compared to CSK.COOK limitation is high BER than compared to the main advantage of DCSK over CSK is that both the reference and information-bearing components of the transmitted signal pass through the same channel so they undergo the same transformation. This transformation does not change the correlation that carries the information, provided that the time-varying channel remains almost constant for the symbol duration. Because there is no need for synchronization, the DCSK technique can be used even under poor propagation conditions. However, the symbol rate is halved compared with a synchronization-based receiver in which synchronization is maintained. Recall, however, that the synchronization time of a coherent receiver is wasted no information can be carried during this interval. If each symbol must be synchronized independently and the synchronization time is comparable to the correlation time then a DCSK system can in principle operate at the same symbol rate as synchronization based coherent receiver, with the added advantage of superior performance under poor propagation conditions. Thus, synchronization-based recovery of chaotic basis functions from a noisy received signal offers superior performance to DCSK in terms of data rate only if synchronization can be maintained. This advantage is lost if the modulation technique requires the loss and recovery of synchronization at the beginning of every new symbol or if poor propagation conditions make it impossible to maintain synchronization.

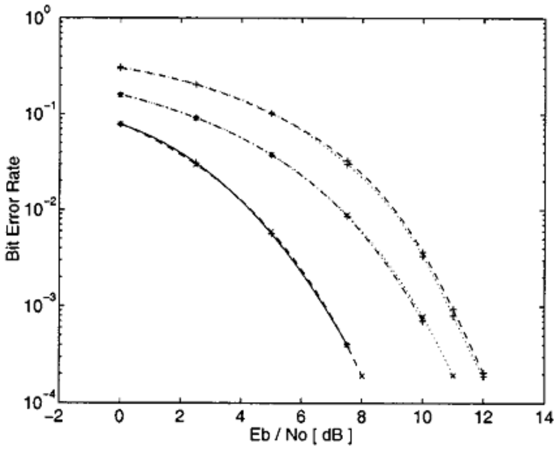


Fig.10. Simulated optimum noise performance of CSK modulation with coherent demodulation (solid curve with "+" marks [left]), COOK with noncoherent demodulation (dashed curve with "+" marks [right]), chaotic switching with orthonormal basis functions and coherent demodulation (dash-dot curve with "+" marks [center]), and chaotic switching with DCSK basis functions and a differentially coherent receiver (dotted curve with "+" marks [right]). The noise performance curves for BPSK (dashed curve with "X" marks [left]) and coherent FSK (dotted curve with "X" marks [center]) are also shown, for comparison.[2] Figure 10 shows comparison noise performance of coherent CSK, non coherent CSK, non coherent COOK, DCSK. It shows that DCSK has less BER then compared to other modulation. Thus, although errors are inevitable, the optimal threshold remains at zero. This is clearly an advantage of DCSK over the non-coherent CSK discussed earlier. Furthermore, DCSK is almost insensitive to channel distortion. This is because the channel usually does not vary much within a symbol period and both the reference and data samples are thus subject to the same distortion. The main drawback of DCSK, however, is that it can only transmit at half the data rate of the other systems because it spends half of the time transmitting the non-information-bearing reference samples. One possible way to increase the data rate is to use a multilevel demodulation scheme [3].The price to pay, however, is a more complicated system and a possibly degraded bit error performance due to the attenuation of the channel.

VII. CONCLUSIONS

In this paper we have discussed about CSK, COOK, DCSK, chaotic masking and compared. The basis function can be easily generated at the receiver if the propagation conditions are so good that the basis function can be regenerated at the receiver, then orthonormal chaotic basis functions digital modulation schemes using conventional orthonormal basis functions can achieve similar levels of noise performance [20] from an implementation perspective is the ease with which the basis functions can be regenerated. If the propagation condition are poor it is very difficult maintain synchronization and hence coherent demodulation cannot be used in such cases non coherent methods are better choice. Non-coherent CSK under high SNR thresholding shift problem occurs. COOK has better noise performance than compared to CSK.COOK limitation is high BER than CSK, DCSK. DCSK eliminates the need of synchronization based recovery and offers best possible performance for a chaotic digital modulation scheme. DCSK are used to combat the problem of thresholding shift problem of non coherent CSK.DCSK are insensitive to channel distortion. Only DCSK limitation is is that it can only transmit at half the data rate of the other systems because it spends half of the time transmitting the non-information-bearing reference samples. One possible way to increase the data rate is to use a multilevel demodulation scheme [3].

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