Wireless Chaos-Based Communication Systems: A Comprehensive Survey

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***Abstract*—Since the early 1990s, a large number of chaos-based communication systems have been proposed exploiting the properties of chaotic waveforms. The motivation lies in the significant advantages provided by this class of non-linear signals. For this aim, many communication schemes and applications have been specially designed for chaos-based communication systems where energy, data rate and synchronization awareness are taken into account in most designs. Recently, the major focus, however, has been given to the non-coherent chaos based systems to benefit from the advantages of chaotic signals and non-coherent detection and to avoid the use of chaotic synchronization which suffers from weak performance in the presence of additive noise. This paper presents a comprehensive survey of the entire wireless radio frequency chaos-based communication systems. It outlines first the challenges of chaos implementations and synchronization methods, followed by comprehensive literature review and analysis of chaos-based coherent techniques and their applications. In the second part of the survey, we offer a taxonomy of the current literature by focusing on non-coherent detection methods. For each modulation class, the paper categorizes different transmission techniques by elaborating on its modulation, receiver type, data rate, complexity, energy efficiency, multiple access scheme and performance. In addition, this survey reports on the analysis of trade-off between different chaos based communication systems. Finally, several concluding remarks are discussed.**

***Index Terms*—Chaos-based communication systems, chaos implementation, chaotic synchronization, coherent systems, non-coherent systems, applications, performance analysis.**

NOMENCLATURE

ADC Analog-to-Digital Converter
ANC Analog Network Coding
ARQ Automatic Repeat Request
BER Bit Error Rate
BPSK Binary Phase Shift Keying
CARQ Cooperative Automatic Repeat Request
CC Cooperative Communication
CD Cooperative Diversity
CDSK Correlation Delay Shift Keying
CM-DCSK Continuous Mobility DCSK
CMOS Complementary MetalOxideSemiconductor
COOK Chaos-based On Off Keying
CPF Chebyshev Polynomial Function
CPM Chaotic Parameter Modulation
CS Complete Synchronization
CSD Chaotic Symbolic Dynamics
CS-DCSK Code-Shifted Differential Chaos Shift Keying
CSK Chaos Shift Keying
DCSK Differential Chaos Shift Keying
DCSK-CD Differential Chaos Shift Keying Cooperative Diversity
DCSK/S Simplest Version of Enhanced DCSK
DCSK/SP Shortest path DCSK
DCSK/SP Spanning tree DCSK
DDCSK Differentially Differential Chaos Shift Keying
DS-CDMA Direct Sequence Code Division Multiple Access
DWSCS Discrete Wheel-Switching Chaotic System
E-COOK Ergodic Chaotic On-Off Keying (E-COOK)
E-CSK Ergodic Chaos Shift Keying
EGC Equal Gain Combining
FDMA Frequency Division Multiple Access
FPGAs Field Programmable Gate Arrays
FM-DCSK Frequency Modulated Differential Chaos Shift Keying
FSO Free Space Optical
GCDSK Generalized Correlation Delay Shift Keying
GS Generalized Synchronization
HCS-DCSK High data rate Code-Shifted Differentially Differential Chaos Shift Keying
HE-DCSK High-Efficiency Differential Chaos Shift Keying
I-DCSK Improved Differential Chaos Shift Keying
IR Iterative Receiver
ISM Industrial, Scientific and Medical
LPI Low Probability of Interception
LS Lag Synchronization
LTE Long Term Evolution
M-DCSK M-ary Differential Chaos Shift Keying
MC-DCSK Multi Carrier Differential Chaos Shift Keying
MIMO Multiple Input Multiple Output
MR-DCSK Multi Resolution Differential Chaos Shift Keying
NIST National Institute of Standards and Technology
NR-DCSK Noise reduction DCSK
OCVSK Orthogonal Chaotic Vector Shift Keying
OFDM Orthogonal Frequency Division Multiplex
OFDM-DCSK Orthogonal Frequency Division Multiplex DCSK
OMCs Orthogonal Multi-Codes
PAPR Peak-to-Average Power Ratio
PCM Pulse Code Modulation
PDF Probability Density Function
PDMA Permutation Division Multiple Access
PMA-DCSK Permutation Multiple Access Differential Chaos Shift Keying
PN Pseudo-Noise

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PRBS	Pilot Random Binary Sequence
PNC	Physical layer Network Coding
PRS	Projective Synchronization
PS	Phase synchronization
PS-DCSK	Phase Separated Differential Chaos Shift Keying
PWL	Piece Wise Linear
QCSK	Quadrature Chaos Shift Keying
RF	Radio Frequency
RM-DCSK	Reference Modulated Differential Chaos Shift Keying
SIMO	Single Input Multiple Output
SNR	Signal-to-Noise Ratio
SR-DCSK	Short Reference DCSK
SS	Spread Spectrum
STBC	Space-Time Block Code
TDMA	Time Division Multiple Access
UWB-DCSK	Ultra Wide Band Differential Chaos Shift Keying
WC	Walsh Codes
WCC	Woven Convolutional Code

I. Introduction

THE field of chaos-based communication systems has attracted a great deal of intense interest, initiated by Shannon's 1947 recognition that a noise-like signal with a waveform of maximal entropy results in an optimized channel capacity in communications [1] and further solidified by Chuas 1980 implementation of a practical chaotic electrical circuit [2]. Basically, chaotic maps due to their high sensitivity upon initial conditions have the potential to generate theoretically infinite number of very low cross-correlated signals. Owing to their wideband characteristics, chaotic signals have proved to be one of the natural candidates for multi-user spread-spectrum modulation schemes [3]–[8]. An information theoretic analysis of the potential of chaos in digital communication schemes is given in [9] underlining that there is no fundamental principle that speaks against the use of chaos in digital communications. Some of these chaos-based modulations provide the same advantages as conventional spread-spectrum modulations do, including mitigation of fading in time varying channels [10], jamming resistance along with low probability of interception (LPI) [11] and secure communications [12]. Additionally, many studies have been done on reducing multi-user interference and the peak-to-average power ratio (PAPR), showing that chaos-based sequences outperform Gold and many other independent, identically distributed sequences in multi-user spread-spectrum communication systems [13], [14].

Two classes of chaos-based communication systems have been proposed and studied:

- Chaos-based communication systems with coherent detection: In these schemes, a synchronized copy of the chaotic signal is generated at the receiver side and the detection is performed by exploiting this replica in different methods to recover the transmitted data [15]–[17].
- Chaos-based communication systems with non-coherent detection: In these schemes, data recovery is performed by detecting features of the received signal and without the need of the channel state information or the regeneration of any local chaotic signal at the receiver side [3], [18], [19].

With coherent reception, like the one used in chaos shift keying (CSK), chaos-based direct sequence code division multiple access (DS-CDMA) and chaotic symbolic dynamic (CSD) modulation systems [3], [4], [20]–[22], the chaotic signal is used to carry the data information signal while chaotic synchronization is required at the receiver side in order to regenerate an exact replica of the chaotic sequence to demodulate the transmitted bits [23]–[25]. The widely studied systems in this modulation class (i.e. coherent detection) is the chaos-based spread spectrum systems. In brief, for such systems, application of chaotic sequences consists roughly of replacing the conventional binary spreading sequences, such as Gold or pseudo-noise (PN) sequences, by chaotic sequences. Nowadays, PN sequences are widely used in DS-CDMA. Aside the good correlation properties of these sequences, the main weakness is the limited security; indeed, they can be reconstructed by a linear regression attack because of their short linear complexity [26], [27]. This limited security can be overcome by using chaotic signals instead of conventional PN sequences, since chaotic signals can be considered as non-periodic signals with an infinite number of states [28].

Because some chaotic synchronization models exhibit a poor performance in noisy environments [3], [29], demodulation poses a real challenge for chaotic communications with coherent receivers. On the other hand, with non-coherent receivers, like differential chaos shift keying (DCSK) systems or chaos-based on off Keying (COOK) systems chaotic signal generation and synchronization are not required on the receiver side to recover the transmitted data [3], [30]. Based on this important advantage, a growing number of research have been conducted in this area where many novel non-coherent chaos-based communication systems are proposed.

A. Related Surveys

Although chaos-based communication systems have been studied before, the literature still lacks a survey that provides the readers coming from different backgrounds with a comprehensive coverage of the topic. For instance, in [31], a comprehensive survey on analog chaotic secure communication systems is presented and a taxonomy is provided. The taxonomy analyzes different models of chaotic secure communication systems with the corresponding synchronization methods. In [32] the authors focus on three analog chaos-based secure communication systems and analyze different types of attacks. Furhtermore, a recent survey that analyzes wireless chaos-based communication schemes and provides the readers with recent achievements in this research area does not exist and the most recent surveys in the field are only found in textbooks like [3], [19], [33], [34]. While these books are the closest to the work that we present in this paper, it is noteworthy to mention that the work we present in this paper is a continuation and an update of recent achievements in the field with emphasis on different applications of such schemes. Thus, our intention from this work is not limited to survey

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different chaotic schemes but rather to provide a taxonomy of the different proposed approaches.

In this paper, we mark our contribution by:

1) Providing a brief overview of the properties of non-linear maps, then explaining several synchronization methods and their applications to RF chaos-based coherent communication systems.
2) Presenting a classification of coherent chaos-based communication schemes. We further discuss different modulation techniques, and provide their advantages and disadvantages. We also present various applications in which these schemes are used.
3) Developing a literature taxonomy of non-coherent schemes by covering new materials in this active research area. We further present different non-coherent detection techniques and discuss their advantages and disadvantages. In addition, we present recent different applications of these non-coherent schemes in wireless communications.

B. Paper Organization

The rest of this survey is organized as follows. In Section II, we present a brief overview of the chaos implementation, noise cleaning and widely used synchronization methods in this field. In Section III, we provide an exhaustive discussion on coherent detection schemes. A literature review and a taxonomy on non-coherent detection techniques is depicted in Section IV. Finally, future research works, concluding remarks and highlighted outcomes are stated in Section V.

II. Chaotic signal generation, noise cleaning and synchronization methods

A. Chaotic maps implementation

Since the 1980's, many popular chaotic maps, such as the Chebyshev polynomial function (CPF) map, the piece wise linear (PWL) chaotic map, the chaotic Markov map, the tent map, etc., have been developed and used in many applications [35]. Such systems are called dynamical because they have memory of their past. For example, 1D discrete-time autonomous chaotic dynamical systems can be described by a mapping function $f : S \rightarrow S$ (i.e. S denotes the state space) and evaluated by a defining vector field and the initial condition x_0 as follows

$$x_{k+1} = f(x_k, \mu) : x \in S \subseteq R^K, \quad (1)$$

where x_k is state variable sampled at the k^{th} sampling instant, $f(\cdot)$ is the iterative function that describes the dynamics of the system, and μ is the vector of the parameters determining the system dynamics.

The discrete-time representation of dynamical systems can easily give us an understandable perspective of chaotic signals generation. In other words, the discrete-time representations eases the study of a dynamical system using an iterative function whose output is a new state variables by using the current state variables as its input. The sampling period determines the intervals whereby the state variables are updated. In contrast, continuous dynamic systems like differential equations [36], [37] generate continuous (i.e analog) chaotic signals with potentially unknown periods [36]. For instance, Chua's circuit is widely used to generate an analogue chaotic signal [38].

Owing to their special properties, *sensitive dependence upon initial condition*s, non-linear dynamical systems are capable of generating theoretically, an infinite number of uncorrelated chaotic signals by using slightly different initial values in the same system. This means that two nearby starting initial conditions can lead to two entirely uncorrelated trajectories of the state variables [36].

Recent studies on chaos theory have proven that the characteristics of chaotic systems can not be perfectly preserved if chaotic maps are implemented on digital signal processing platforms. This is because chaotic maps that are implemented on a digital platorm, i.e. a computer, will have their chaotic state values fall into a finite number of sates as a result of quantization, so their dynamical trajectories become periodic (i.e periodic loop) causing degradation in their principal chaotic behavior [39]. On the other hand, it might be desirable to have a relatively small number of quantisation levels for low hardware complexities.

Consequently, to overcome major drawbacks resulting from quantizing and to keep the number of bits low, a strict methodology is indispensable to improve the quality of the chaotic signal and to guarantee a high level of security and randomness [40]. Many implementation methods are proposed in the literature to enhance the randomness quality of chaotic signals and to increase its periodic loop [40]–[46].

An original approach which consists of a cascade of different maps that allows the generation of a huge number of chaotic sequences with richer state spaces and higher periodic loops and which is useful for cryptographic applications is evaluated in [47] which also creates a substantial increase in the overall system complexity. Additionally, two different implementations of high-performance true-random number generators which use a discrete-time chaotic circuit as their entropy source are presented in [41]. The proposed system has been developed from a standard pipeline analog-to-digital converter (ADC) design, modified to operate as a set of piece-wiselinear chaotic maps which makes the proposed circuit perfectly suitable for embedding in cryptographic applications.

In [42], the implementation of discrete-time chaotic generators is studied and evaluated. This study focuses on power consumption, resource usage, and maximum execution frequency of implementations for two common Field Programmable Gate Arrays (FPGAs). In [48] reverse-time chaos is used to realise hardware chaotic systems that can operate at speeds equivalent to existing state-of-the-art while requiring significantly less complex circuitry. An alternative approach to generate chaotic signals with good randomness properties and low complexity is studied in [44], [45]. In their work, a novel discrete chaotic map named zigzag map that demonstrates an excellent chaotic behaviour is introduced. To implement this map, two circuit implementations based on the switched current technique as well as the current-mode affine interpolation of the breakpoints are used. They show that the proposed zigzag map passes all of the national institute of standards and technology tests, NIST

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$800-22$ statistical randomness tests. In [46], a discrete wheel-switching chaotic system (DWSCS) technique is presented. Implemented on FPGA circuits, this technique is based on changing the controlling sequence of the wheel switch which allows DWSCS to generate a large number of new chaotic sequences from a set of existing chaotic maps.

B. Noise cleaning for chaotic signals

When used in wireless communication systems, chaotic signals are corrupted by additive noise. Therefore, to enhance the performance of the chaos-based modulations schemes, the signal-to-noise ratio must be enhanced. Further, since chaotic signals demonstrate a noise-like behaviour, linear filters are no longer useful for this task. Moreover denoising chaotic time series or extracting chaotic time series from a mixture with a noise component is a challenging open problem. Hence, the performance of any noise cleaning algorithm strongly depends on the amount of available *a priori* information.

Profiting from the *a priori* knowledge of chaotic dynamic systems, many approaches are proposed to reduce or clean the noise present in this class of non-linear signals. In [49]–[51], an original discrete-time Kalman filtering implementation is proposed to estimate the states of noisy chaotic samples. In fact, Kalman filtering is a widely known state-space estimator that provides recursive minimum mean-squared error estimates for linear systems embedded in Gaussian noise. Furthermore, the latter cannot be used directly to estimates non-linear state space models. Therefore, an approximate solution is required which allows the extension of Kalman filtering framework to nonlinear state-space models, as is done in [49], [51]. Moreover, in [49] a receiver for chaos-based spread spectrum system is developed using two Extended Kalman filters for joint synchronization and decoding processes. As this types of filtering is based on the idea of obtaining an estimate of the noisy signal that is as close as possible to the noise-free signal in the mean-squared error sense [52], Wiener filter can also be used for this task. This filtering technique is used in many works to reduce the noise in chaotic signals [51], [53].

In the same vein, adaptive signal processing methods are proposed in [54]–[58] to reduce the noise and enhance the overall performance of the communication system. Hence, the filtering process which utilizes the *a priori* chaotic map f (i.e $x_{k+1} = f(x_k)$) is considered as an optimization problem in which the cost function C having the form

$$C\left(\hat{x}, r\right) = c_1\left(\hat{x}, r\right) + \Gamma c_2\left(\hat{x}\right), \tag{2}$$

is minimized [54]. The function $c_1(\cdot,\cdot)$ measures the closeness between the estimated (i.e filtered) point $\hat{x}_k$ and the noisy received point, $c_2(\cdot)$ is a constraint function indicating how well the estimated orbit fits and Γ is the weight function. The optimal solution for equation (2) is obtained by iterative methods named as method I and method II proposed in [54]. Based on the work of Lee *et al*, Z. Jákó showed in his works [55], [56] that both methods are closely related to the standard gradient method. These noise reduction algorithms are exploited by the same author later to propose new detector designs specially for non-coherent transmit reference schemes to enhance the BER performance. Two approaches were adopted with the noise reduction algorithms. The first one is about cleaning the reference signal while the second approach considers filtering the reference as well as the data carrier signals. [57], [58].

C. Synchronization methods

Synchronization is a vital process to design coherent communication schemes. Many synchronization methods have been proposed in the literature for chaos-based communication systems. In this survey we will briefly summarize these techniques in order to give the readers an idea regarding the challenge in coherent chaos-based communication system design. Therefore, we can categorize these methods into two classes as follows:

1) Chaos synchronization techniques [59]–[65]
2) Conventional synchronization approaches applied to chaos-based communication systems [23]–[25], [66], [67]

In the first category of synchronization, master and slave systems are used for this purpose where a coupling chaotic signal transmitted from the master unit is used to drive the slave system forcing this latter to generate an exact synchronized replica of the coupling signal. The second category of synchronization extends from conventional wireless communication systems such as phase and sampling synchronization to chaos-based coherent communication systems. In this category of synchronization, the chaotic generator at the receiver side must have the same initial condition used at the transmitter side. The aim of these synchronization techniques is to eliminate the drift of clock at the receiver in order to generate synchronized chaotic sequence. The following subsections will present these techniques and the recent works done in these areas.

1) ***Chaos synchronization****:* A major challenge with coherent chaos-based communication systems is the chaotic synchronization at the receiver side [68]. To achieve this goal, many chaotic synchronization methods were proposed in the literature. Yamada and Fujisaka were the first to study this phenomena in [69], followed by Afraimovich et al in [70]. However this topic started to inspire major interest when Pecora and Carroll introduced their method of chaotic synchronization and suggested its application to secure communications [59]. In the proposed approach, a master and a slave system are required, with a single signal of the master system driving the slave system [59], [71]. Hence, a typical master-slave system that consists of two chaotic systems. The two systems are described by the same set of differential equations, with the same parameter values. It was shown in [59] that the chaotic synchronization occurs when the output of at least one of the coupled differential equations of the first chaotic system is available to the second chaotic system. Thus, one chaotic system is said to drive the other chaotic system by the time-series signal generated from one of its differential equations. The driving chaotic system is known as the master system and the driven chaotic system is known as the slave system. The concept of master-slave synchronization scheme has also been investigated in [60], [61]. According to the literature in this field [62]–[65], [72], four types of driving modes of coupled generators are identified. Table I summarizes the identified types in the following manner

Driving type	Description
Directional driving	One chaotic system (generator) is used as the source of driving transmitting one or more driving signals to the other generators. [73]
Bidirectional driving	Two chaotic systems are coupled and driven with each other in a mutual way. [74]
Network coupling	Many chaotic systems are coupled with each other. This is named a complex dynamic network. [75]
External driving	External signals drive the chaotic systems present in a network to establish synchronization.[76]

TABLE I: Different driving types

Applied in the communication field, one or more driving signals are transmitted from the master system (transmitter) to the slave system (receiver) through the communication channel in order to synchronize the slave system. This process forces the slave system to follow the master system by generating an exact replica of the transmitted signal (driving signal), leading to chaos synchronization. This concept is widely used in analog chaos-based communication systems and for secure communications [77]–[79]. These chaos synchronization methods which are proposed in [80]–[83] can be summarized as in Table II.

Sync. method	Description
Complete synchronization (CS)	Also called identical synchronization. In CS a complete agreement of the trajectories of the master and slave systems exists. [80]
Generalized synchronization (GS)	Generalized form of CS, for which the slave systems trajectory converges to the master's one in the sense of a one-to-one mapping f. [81]
Projective synchronization (PrS)	A special case of GS with the one-to-one mapping involved being a simple linear function $f(x) = \alpha x$. [82]
Phase synchronization (PS)	The slave system converges to the same phase of the master system, though their trajectories are not the same.[76]
Lag synchronization (LS)	A time-delayed version of CS for which the slave system coincides with the time-delayed dynamics of the master system. [84]

TABLE II: Chaos synchronization methods

*2) **Conventional synchronization approaches applied to chaos-based communication systems** :* Applied to wireless communications field, the master-slave synchronization shows poor performance in noisy environments [34], [85]. Therefore, coherent communication systems using this chaos synchronization approach on the receiver side show poor performances [85]. Further, over frequency selective channels, the demodulation process is particularly difficult. On the other hand, since the major application of chaotic signals are in ultra wide band and SS systems, another approach extends the synchronization method used for conventional spread spectrum (SS) system to chaos-based communication schemes. In conventional SS systems, the synchronization method uses PN codes to solve the problem in two steps: First, the acquisition process aligns the local sequence to the received sequence by reducing the time uncertainty [26]. Second, code tracking is enabled to carry out a fine alignment between codes.

The application of such a synchronization technique for chaos-based spread spectrum systems is investigated in [23], [66], [67], [86]. Jovic *et al* [24] have proposed a robust synchronization method which uses the pilot random binary sequence (PRBS) to perform in synchronous multi-user chaos-based DS-CDMA systems. It was shown in [87] that the PRBS does not result in significant improvements in the acquisition process when used instead of the chaotic pilot signal. On the other hand, using the chaotic pilot has the benefit of leading to complete masking, since all broadcasting signals are chaotic. It is also simpler since it does not require PRBS generators in the transmitter and receiver. An improvement to this approach was developed in [87] using the chaotic signal as a pilot signal. This synchronization technique can be used for synchronous multi-users communications. The performances in [87] are evaluated for a Rayleigh fading channel. Further improvements and a detailed implementation, as well as a multiplicative approach for the code-assisted pilot, are reported in [25]. The chaotic pilot code is also used in [25] and the synchronization method works for both asynchronous and synchronous transmission cases.

The challenge in implementing this class of conventional synchronization technique depends on the implementation and the generation of the chaotic waveform at the receiver side. To reach this goal, two approaches can be adopted. The first approach requires the implementation of a chaotic map at the receiver side with the same initial conditions as at the transmitter. The second approach consists of generating the chaotic codes (real or quantified values) then storing them into the transmitter and the receiver.

Since the chaotic generator is very sensitive to initial conditions, a small precision error in implementing the latter can lead to generating a different replica and makes synchronization impossible. Note that errors may be generated from digital circuits either at the transmitter or the receiver side and can emerge in the form of numerical precision error, quantizing error, etc. Therefore, the second approach can solve the implementation problem of the chaotic maps and avoid the problem of sensitivity to initial conditions by generating the waveform first, then storing the codes in the transmitter and receiver. Therefore, the latter approach requires extra memory to make it feasible.

III. Chaos-Based coherent modulation schemes

Chaos-based communication systems are classified in two categories according to the type of reception used: coherent or non coherent [8], [88]–[91]. Table III summarizes different modulation classes and their corresponding proposed chaos-based modulation schemes.

In this section we will present different coherent modulation designs and we will address the recent works done concerning each of these systems. Various methods have been presented to encode data using chaotic signals. The additive combination of a chaotic sequence and a low level data signal, or equivalently, additive chaotic masking, is not an effective way to hide the statistical characteristics of the data signal. Two of such effective schemes are chaos shift keying (CSK) modulation

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Class	Analog	Digital
Coherent	Chaotic masking Chaotic modulation	Chaos Shift Keying Symmetric CSK Chaos based CDMA Quantized chaos based CDMA Chaotic symbolic dynamics
Non-Coherent	On Off Keying	Differential CSK FM DCSK Ergodic CSK Quadrature CSK M-DCSK DCSK-WC PMA-DCSK HE-DCSK CS-DCSK UWB-DCSK PS-DCSK RM-DCSK MC-DCSK DDCSK I-DCSK

TABLE III: Modulations classes

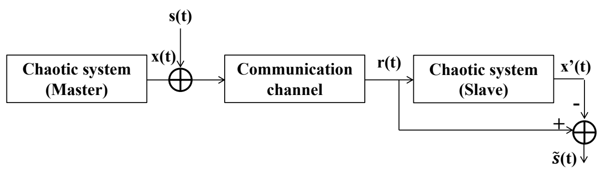

Fig. 1: Chaotic masking system model

and chaotic symbolic modulation. In this part of the paper we will describe these modulation methods and we will highlight their advantages as well as their drawbacks.

A. Coherent analog modulations

1) ***Chaotic masking****:* The widely used and explored modulation in analog domain is the chaotic masking analysed in [92]. As shown in Fig. 1, the analog signal (information) $s(t)$ is added to the transmitted chaotic signal $x(t)$. At the receiver side, thanks to chaos synchronization, the receiver reconstructs the original chaotic signal and the analog information is recovered by subtracting the reproduced chaotic signal from the incoming signal. Furthermore, other techniques that are proposed to improve the chaotic masking modulation are discussed in [93] [94].

The security aspects of such modulation are doubtful against some attacks. In fact, an attacker can have useful information from the transmitted signal helping him to construct the dynamics of the master system. Moreover, the addition of the message $s(t)$ to the chaotic signal $x(t)$ leads to a power change in the resultant signal. Hence, an attacker can estimate the transmitted information by observing the power of the transmitted signal. Therefore, reducing the power of the message $s(t)$ compared to the driving signal cannot essentially eliminate this security defect without changing the encryption structure [32].

2) ***Chaotic modulation****:* As shown in Fig. 2, instead of adding directly the message $s(t)$ to the chaotic signal as in chaotic masking, in chaotic modulation, the analog information is injected directly into the chaotic system to alternate its

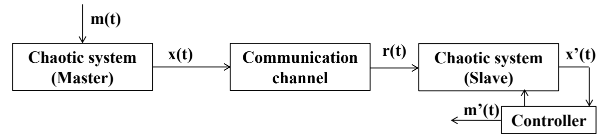

Fig. 2: Chaotic modulation system model

dynamic model. Hence, the generated chaotic signal contains the analog information. At the receiver side, the receiver detects the change in the dynamic behavior of the chaotic signal and recovers the analog information [95].

Compared to chaotic masking schemes, chaotic modulation schemes can exactly recover the message signal $s(t)$ (in an asymptotical manner) if some conditions are satisfied [32] and can yield a better performance than chaotic switching systems.

Moreover, if the chaotic system is carefully designed, the chaotic modulation technique can even be used to transmit more than one message signal $s(t)$. Therefore, the main disadvantage of this technique is the dependence on the controller and the requirement that each chaotic system should have a new controller design. Moreover, in certain cases the controllers may not even exist which causes a serious drawback for this technique [32], [95], [96].

B. Coherent digital modulations

1) ***Chaos Shift Keying****:* Chaotic switching which is also named chaos shift keying modulation was first proposed in [16]. As shown in Fig. 3, the main idea of this modulation is to encode the information into two chaotic generators. At the transmitter side, two different chaotic systems f and g are used during the active transmission interval of the bits $+1$ and -1, respectively. Note that either f or g is active at a time. That is to say, the chaotic generator f is activated during the transmission of the bit $+1$, while the chaotic generator g is activated otherwise. Two coherent receiver types are proposed for this modulation technique [97].

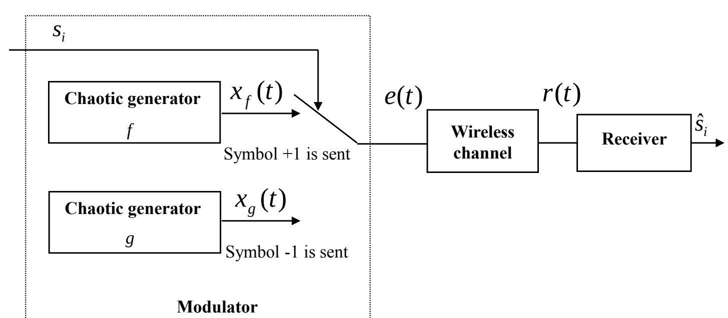

Fig. 3: CSK communication system

The first receiver type shown in Fig. 4, uses the incoming signal to drive two self-synchronizing subsystems of $\tilde{f}$ and $\tilde{g}$. Hence, when the chaotic system f is activated to transmit the bit +1, the subsystem of $\tilde{f}$ at the receiver side under ideal conditions will be synchronized with the incoming signal and generates an exact replica of the chaotic signal f. Therefore, by measuring the difference (error) between the incoming signal and the output of the self-synchronizing subsystems, the transmitted symbol can be estimated [16].

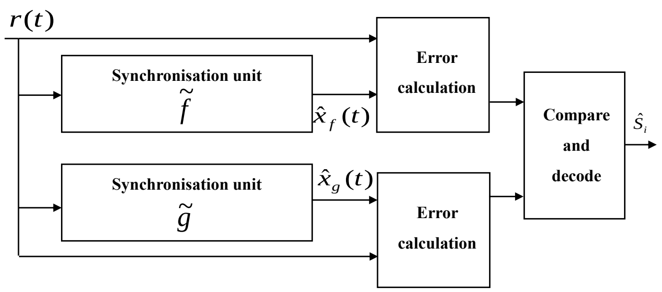

Fig. 4: Synchronization-error-based CSK demodulator

The second type of receiver employs a correlator to recover the transmitted bits instead of measuring the synchronization error as in the first receiver class [85]. As shown in Fig. 5 two synchronization circuits attempt to recover the two chaotic signals $x_f(t)$ and $x_g(t)$ from the received corrupted signal $r(t)$. The generated chaotic signals are then used to correlate with the received signal during the remainder of the bit duration. The outputs of the correlators are then sampled and compared to recover the data.

In conclusion, chaotic systems due to their dynamic properties tend to oppose synchronization. In spite of being deterministic, chaotic systems are extremely sensitive to their initial conditions. Therefore, the two trajectories of two identical but independent chaotic systems starting from nearly the same initial points quickly diverge in phase space [37]. Therefore, in practice, it is almost infeasible to design and implement identical, synchronized chaotic systems and thus the application to coherent communication systems over wireless channels remains a challenge. Finally, because of the use of chaotic synchronization, the application of CSK systems in its present form is limited.

*2) **Chaos based DS-CDMA**:* In some references this modulation is named also CSK [28]. Therefore, CSK and chaos-based DS-CDMA are equivalent when the receiver can generate an exact replica of the chaotic signal at the receiver side (i.e perfect chaotic synchronization for CSK system) and use

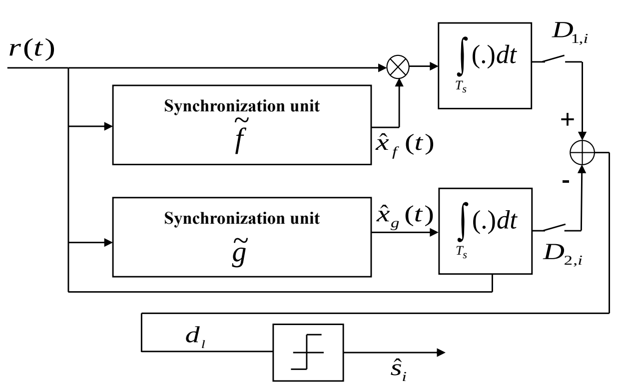

Fig. 5: Correlator-based coherent CSK demodulator

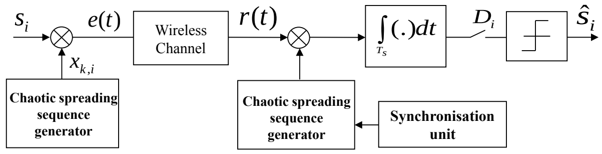

Fig. 6: Simplified baseband equivalent of chaos-based DS-CDMA transmission.

it to despread the received data. As shown in Fig. 6, the data information symbols ($s_i = \pm 1$) with period T_s are spread by a chaotic sequence x_k. A new chaotic sample (or chip) is generated at every time interval equal to T_c ($x_k = x(kT_c)$).

In order to demodulate the transmitted bits, the received signal is first multiplied by the local chaotic sequence, and then integrated over a symbol duration T_s. Finally, the transmitted bits are estimated by comparing the value of the decision variable at the output of the correlator to a predefined threshold.

Many research works have been interested in this class of coherent spread spectrum modulation. In the following subsection we provide an overview of the early works regarding the chaotic spreading sequence design and the performance analysis of the proposed system and finally we discuss the advantages and disadvantages of this modulation.

a) Chaotic spreading sequences design: The literature under this category is rich, many papers studied and evaluated the chaotic spreading sequences from different angels. Generally, two different approaches have been adopted for using the chaotic signal in digital communications systems. The first uses the real value of the chaotic signal to modulate the transmitted bits, whereas the second quantises the chaotic signal before using it to transmit.

In [14], [86], [98]–[103], the authors analysed the correlation properties and the synchronization performances of the quantified version of chaotic signal. Moreover, they designed new binary chaos-based sequence and they showed that when particular chaotic generators are used the expected performance is not worse than that of a well-behaving communications system [102], [104]–[106].

On the other hand, the real values of chaotic sequences were analysed under various scenarios [5], [6], [103], [107]–[112]. Correlation properties were studied [107]–[110] and some designed chaotic sequences were proposed [111], [113] and used to optimize the error performance of the communication system. Each type of chaotic sequence has its advantages and drawbacks. In fact, the quantified sequence gives better performance in terms of bit error rate and synchronization than the real values one because the amplitude of such sequence has just two values $+1$ or -1 which makes the instantaneous energy of the signal constant. Therefore, this approach leads to a loss of chaotic signal properties and decreases the security of the communication system. Finally, any implementation of any of these two approaches on digital signal processor platforms must take into account the implementation problems of chaotic maps discussed in the previous section.

b) Performance analysis: The challenge in the performance analysis of chaos-based spread spectrum (SS) systems

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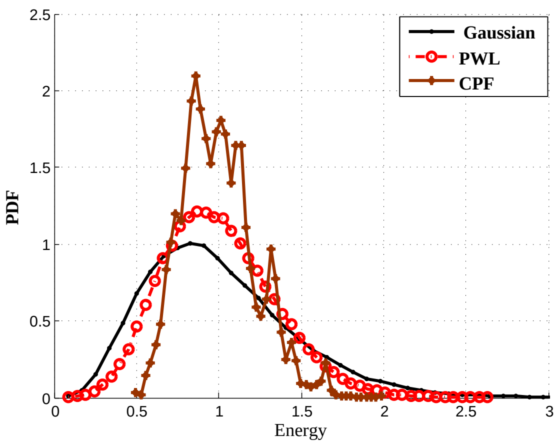

Fig. 7: Normalized histogram of the energy distribution at the output of a chaos-based DS-CDMA system for PWL, CPF and Gaussian sequences for spreading factor equal to 10.

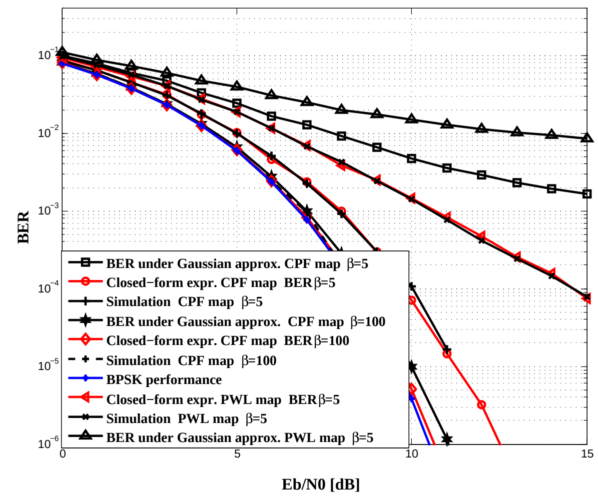

Fig. 8: Simulated and analytical BER performances of Chaos-based DS-CDMA using CPF and PWL chaotic sequences under AWGN channel for a spreading factor equal to $\beta = 5$ and $\beta = 100$

is present when the real valued chaotic sequence is used to convey the information. Therefore, for the binary chaotic sequence case, the same conventional approach used in wireless communications can be extended to compute the performance of chaos-based communication system [114]. Note that when the real-valued chaotic sequence is used to convey the data, the bit energy is no longer constant at the output of the transmitter and change from a bit to another. A histogram of the bit energy distribution for different chaotic sequences is shown in Fig. 7.

Many different assumptions have been considered to compute the bit error rate or symbol error rate performance, for chaos-based communication systems when the real value chaotic sequence is used. In [115], the BER is computed by analogy with binary spread spectrum systems by considering a constant transmission bit energy. This approximation yields a very imprecise BER performance for small spreading factors, i.e. short chaotic sequences. Indeed, because of the non-periodicity of chaotic signals, the transmitted bit energy after spreading by the chaotic sequence varies from one bit to another (i.e see Fig. 7).

A second widely used approach to compute the BER relies on a Gaussian approximation [28], [105], [116], [117]. The idea of this approximation consists of considering the sum of random variables at the output of correlator as a Gaussian variable. This approach cannot be always considered as realistic, since the chaotic signals are generated from a deterministic generator. This approximation can then lead to inaccurate BERs for small spreading factors, but is valid for sufficiently high spreading factors [28].

Another BER computation approach was developed by *Lawrance et al* in [118] for a chaos based-communication system. In this method, the transmitted bit energy is not considered constant. A Gaussian approximation is again considered, but it only models the additive noise and the multiple access interference. This approach takes into account the dynamic properties of the chaotic sequence by integrating the BER expression for a given chaotic map over all possible chaotic sequences for a given spreading factor. The latter is compared to the BER computation methodology proposed in [28] and seems more fitted to match the exact BER. But as mentioned in [118], this method is insightful and either perfectly exact or nearly exact, but presents an important computational cost.

Moreover, another accurate approach was developed in [119]–[121] to compute the exact BER performance without assuming the constant bit energy hypothesis. The main idea of this approach consists of first computing the probability density function (PDF) of the chaotic bit energy, and then deriving the BER by integrating with respect to the PDF of the bit energy. However, when the analytical expression of the PDF is difficult to derive (example of CPF in Fig. 7), the analytical integration becomes intractable, and the only remaining option would be to carry out a numerical integration.

As shown in Fig. 8, the single-user BER performance using CPF and PWL maps are plotted for spreading factor values of 5 and 100 respectively. The PDF distribution of the generators in Fig. 7 is a qualitative indication concerning the expected BER performance. Based on the PDF distributions of Fig. 7, we can find that the CPF sequence will give better results in terms of BER than the other sequences because the CPF sequence has lower distribution values for low energies. In contrast, the PDF energy of the Gaussian distributed sequence has higher distribution values for low energy which leads to a worse performance. On the other hand, as discussed in the previous paragraph, we can observe that exact BER performance without assuming the constant bit energy hypothesis gives better results than the Gaussian approximation when the spreading factor is low and the equivalent precision for high spreading factor.

To conclude this part, an example to show the excellent correlation properties of chaotic codes is illustrated in Fig.

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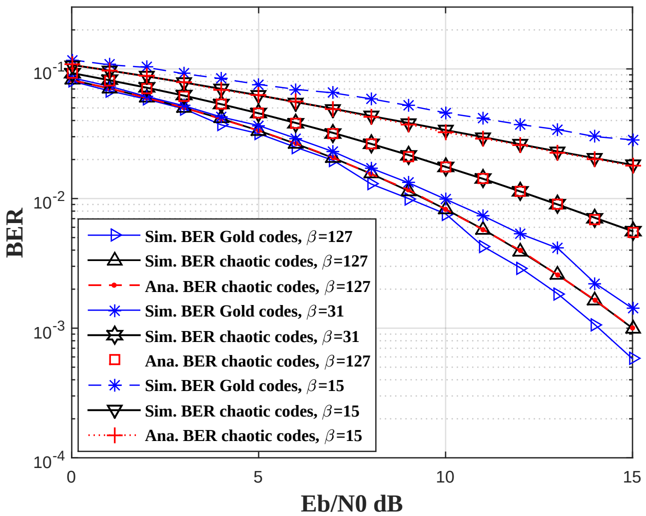

Fig. 9: Simulated and analytical BER upper bounds for chaos-based DS-CDMA system and simulated BER for DS-CDMA system using Gold codes for 3 users, spreading factors β = 15; 31; 127 and channel gain K = 2 dB. [123]

9. Different BER curves compare the performance of multi-user chaos-based DS-CDMA and conventional DS-CDMA systems. The two systems are compared for identical spreading factor, transmitted power, wireless channel and number of users. The first system uses CPF chaotic codes map while the second one uses the Gold codes as spreading sequence. The performance is obtained over flat fading Rician channel. One can see that for a low spreading factor ($\beta = 15$), the chaos-based system gives better performance results as compared to Gold sequences. Indeed, for such values of the spreading factor, the cross-correlation between two chaotic sequences is lower than that between two Gold sequences [122]. Finally, when the spreading factor is high ($\beta = 127$), the correlations are still similar, and the variance of the bit energy for the chaos-based DS-CDMA system is much reduced. Consequently, the performances of both systems become very close. Hence, to obtain low BERs, higher spreading factors must be considered, for any system (chaotic or not). The use of chaotic sequences instead of other spectrum spreading codes improves the security of transmission for a very small BER performance degradation, especially when the spreading factor is high.

*3) **Chaos Symbolic dynamics modulation**:* Recently, chaotic symbolic dynamics modulation have been used for secure communication applications [22], [90], [124], [125] and [126]. The principle of symbolic dynamics was first applied to digital communications in [127] [128]. This modulation scheme partitions a chaotic phase space into arbitrary regions and labels each region with a specific symbol, the resultant trajectories can be converted into a symbolic sequence. In this type of modulation, data information symbols are used to represent the trajectory of the chaotic map rather than generating chaotic sequences directly by iterating equation (3) to modulate the transmitted symbols such that

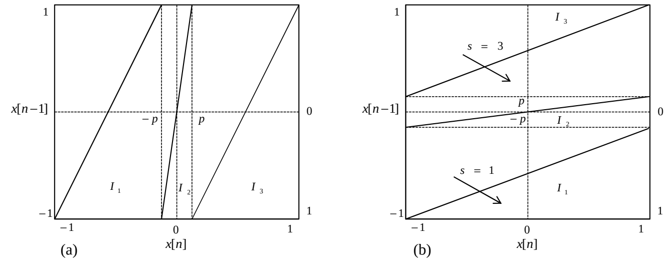

Fig. 10: (a) State space of modified Bernoulli shift map, (b) Inverted modified Bernoulli shift map.

$$x[n] = f(x[n-1]), \quad x[n] \in I, \tag{3}$$

where $f(\cdot)$ is a non-linear and non-invertible chaotic map and I is the phase space.

The state space I of the chaotic map $f(\cdot)$ is partitioned into N disjoint regions, $I = \{I\}_{i=1}^{N}$, such that $I_i \cap I_j = 0$ for $i \neq j$ and $\cup_{i=1}^{N} I_i = I$. Note that this partition is not unique. For any sequence generated by iterating (3), if we can assign N alphabets ($\mathbf{s} = [s_1; ...; s_N]$) to each of the disjoint regions, the dynamics of the system can be represented by a sequence of finite alphabet **S**. This sequence is called the symbolic dynamics of the system.

Bernoulli shift map is used as an example to explain the principle of this modulation. Therefore, many other maps can achieve the similar goal. As shown in Fig. 10, by partitioning a chaotic phase space to arbitrary regions, and labeling each region with a specific symbol, the trajectories can be converted to a symbolic sequence. The parameter shown in Fig. 10, ($0 \leq p < 1$), controls the width of the middle region of the map and the chaotic behaviour of the generated sequences.

On the other hand, because of the sensitivity to the initial conditions of the chaotic map, the sequence diverges rapidly, making the demodulation a real challenge. By iterating from a final condition $x[N]$ onto the inverse function of (3) (f^{-1}), the initial condition is contained in the set $\cap_{n=0}^{N-1} f^{-n}(I_i)$ [129]. When N tends to infinity, the set contains a single initial condition which shows a direct relation between the chaotic sequence and an infinite symbolic sequence. This is called backward iteration, and is well detailed in [90]. Under backward iteration, the chaotic map becomes contracting, thus alleviating the problem of chaos synchronization since there is less sensitivity to initial conditions. Hence, by using backward iteration, a long sequence will eventually converge toward an initial condition $x[0]$ (independent of the last sample $x[N]$) when guided by the sequence of symbols [129].

The synchronization performance of CSD modulation is analyzed in [124], [126], [130]. The enhancement of the spectral efficiency of this modulation class is presented in [131], [132]. Moreover, channel coding techniques combined with symbolic dynamics are studied in [133]–[135] and the feasibility of having this modulation in multiple inputs multiple outputs (MIMO) systems or combined with spread spectrum systems are evaluated in [130], [136].

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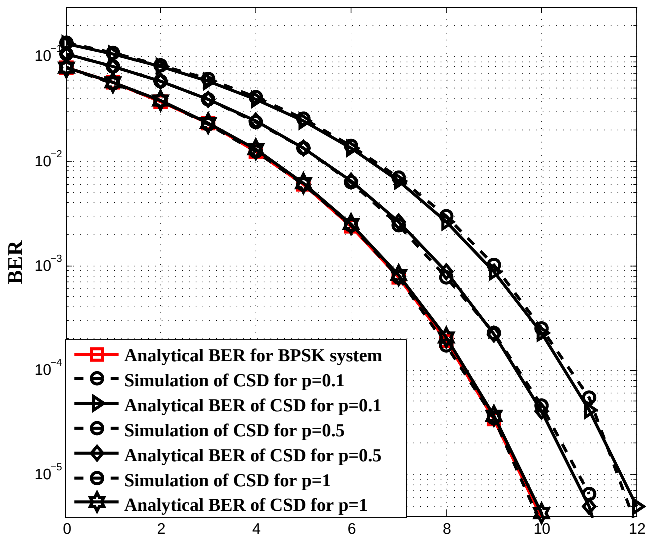

Fig. 11: Theoretical and simulation BER performance given in [137] for the values of $p = 1$, 0.5 and 0.1.

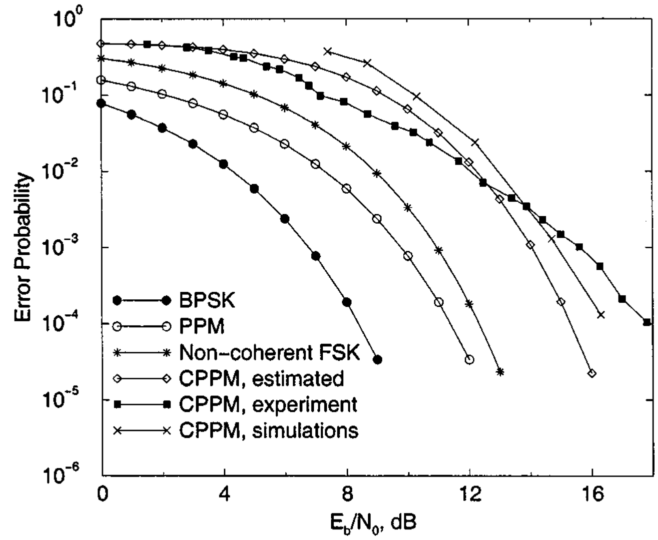

Fig. 12: Error probabilities of ideal BPSK, noncoherent FSK, and ideal PPM systems compared to the performance of the CPPM system. [139]

Moreover, this method can offer better performance than other conventional chaos-based modulation schemes. It is also shown how this system can be improved by means of reducing the amount of security, although there is some trade-off between this reduction and the overall performance of the system. As we can see in Fig. 11, the performance of this modulation class is similar to binary phase shift keying (BPSK) when $p = 1$.

Finally, this class of coherent modulation is very promising in terms of performance, security, and synchronization robustness. In addition, error correction coding techniques, multi-user access and new designs of chaotic maps with iterative receivers can be the future research axes for this communication method to improve its data rate and performance.

*4) **Chaotic-pulse-position modulation**:* Another coherent chaos-based modulation system named Chaotic-Pulse-Position Modulation (CPPM) is proposed and analysed in several papers [138], [139]. This communication scheme is based upon chaotic signals in the form of pulse trains where intervals between the pulses are determined by chaotic dynamics of a pulse generator. The pulse train with chaotic inter-pulse intervals is used as a carrier. Binary information is modulated onto this carrier by the pulse position modulation method, such that each pulse is either left unchanged or is delayed by a certain time, depending on whether $'0'$ or $'1'$ is transmitted. By synchronizing the receiver to the chaotic-pulse train we can anticipate the timing of pulses corresponding to $'0'$ and $'1'$ and thus can decode the transmitted information. A multi-user extension of CPPM system is discussed in [139]. On the other hand, as shown in Fig. 12, the proposed CPPM performs worse than BPSK, non-coherent FSK, and the ideal pulse-position modulation (PPM) system. Therefore, by using chaotic pulse and non periodic intervals between the pulses, CPPM system provides low probability of intercept and low probability of detection. In addition, this design improves the privacy only by adding little circuit complexity. Finally, compared to other impulse systems, CPPM does not rely on a periodic clock and can eliminate any trace of periodicity from the spectrum of the transmitted signal. Finally, these features makes CPPM an attractive low cost secure non-coherent chaos-based communication system [139].

*5) **Applications of coherent modulation schemes**:* Since the chaotic synchronization is still not ready to be applied in the wireless context, the research and the study of the application of coherent chaos-based communication systems in different wireless communication applications is limited. Table IV summarizes different works done in this area where the chaos coherent-based modulation schemes are used as part of a communication system.

IV. CHAOS-BASED NON-COHERENT MODULATION SCHEMES

The majority of chaos-based communication schemes with coherent receivers are still in their initial stage of applications facing many challenges in development and evolution. As long as coherent detection is concerned, robust synchronization between the chaotic systems at the transmitter and the receiver is of great importance, since it requires the availability of synchronized replicas of the chaotic signals at the receiver. When it comes to low signal-to-noise conditions, the applied chaos synchronization scheme to the communication system plays a vital role where coherent detection has shown to have significant challenges in low SNR conditions [142].

On the other hand, coherent communications dominate the state-of-the-art of the wireless communications domain. In fact, coherent receivers require perfect knowledge of channel state information at the receiver side to demodulate the received information without error. To reach this aim, training-based channel estimation methods using pilots are employed, as done for instance in current long term evolution (LTE)

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Coherent modulations	Applications
Analog modulations	- Chaotic masking for secure communication [140], [141]
Digital modulations	- Chaos shift keying with multiple acces communications [123], [142] - Chaos shift keying with cooperative communications [143], [144] - Chaos shift keying with MIMO systems [145], [146] - Chaos shift keying with mutli-carrier transmission [147] - Symbolic dynamics with MIMO systems [136] - Symbolic dynamics for secure transmission [148] - Symbolic chaos-based coded modulations [133], [149], [150] - Chaos-based free-space optic (FSO) communications [151]–[153]

TABLE IV: Applications of coherent modulations

systems. Therefore, such estimation techniques, however, involve a significant increase in both the receiver complexity and the signaling overhead. For this reason, coherent systems are often impractical in fast-fading scenarios, due to their short coherence time. On the other hand, in slow-fading channels, the transmitter will frequently send pilot symbols, leading to wasting some of the resources due to excessive pilot transmissions. Another major disadvantage of coherent communications is their degradation under channel estimation errors, which is especially dramatic under high mobility [154].

Hence, non-coherent detection which does not require any complex synchronization process between the transmitter and the receiver, has motivated many research communities in the field of chaos-based communication systems. In this part of the survey we will introduce numerous non-coherent systems, then we will compare several related metrics such as performance, complexity, data rate, security, multiple-access, etc. in order to offer the reader a clear idea about what is done and what is yet needed to be developed in future research works.

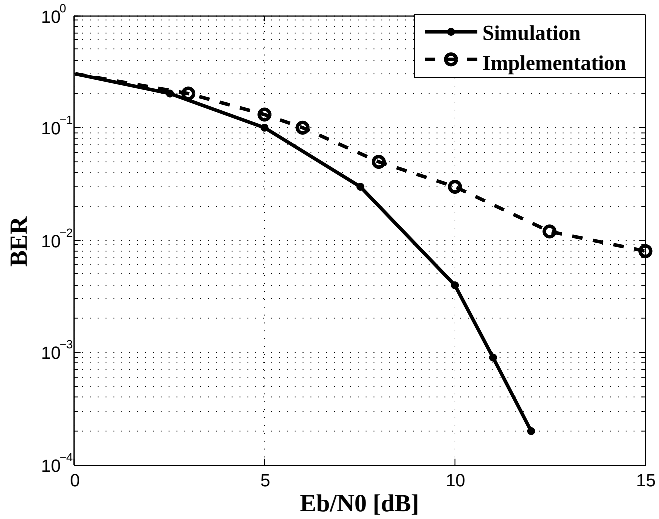

Fig. 13: The manifestation of estimation and threshold problems. Simulated noise performance of optimum and an implemented COOK system in a narrowband system [156]

A. *Non-coherent analog modulations*

*1) **Chaos Based On-Off Keying**:* The chaos on-off keying (COOK) modulation is first proposed in [155] and later discussed in several papers [3], [156]–[158]. In this scheme, the chaotic signal is transmitted for a period of time T when the bit is 1 and disabled for the bit 0 and at the receiver side, an envelope detector with a threshold is used to recover the data. As a matter of fact, several advantages are offered by such kind of modulation such as: the simplicity of modulation and the low complexity of the transceiver architecture, and the energy efficiency where 3 dB in terms of energy efficiency is gained compared to the pulse code modulation (PCM). In practice, a COOK system suffers from two problems, the autocorrelation and the cross correlation estimations that causes non-zero threshold problems [17], [121], [159]. In fact, in COOK the energy carried by the transmitted signal is not constant (i.e autocorrelation estimation) because of the non periodic nature of chaotic sequences [121] (i.e, see Fig. 7). This phenomena increases the variance of observation signal and, consequently, corrupts the the system performance in noisy channels. The second problem is that the optimum value of the decision threshold depends on the signal-to-noise ratio measured at the input of COOK detector. Both problems deteriorate the noise performance of the narrowband COOK system as shown in Fig 13, where the noise performance of an optimum COOK and an implemented COOK are shown for the wireless local area network in the 2.4 GHz industrial, scientific and medical (ISM) band.

To overcome these problems, many solutions were proposed and discussed [157], [158], [160]. It was shown in [159] that the estimation problem reduces as an inverse of the product of bandwidth and bit duration. On the other hand, the threshold problem may be solved either by using an adaptively controlled decision threshold, called soft decision demodulation, or by applying a preamble that is used to estimate the optimum value of the decision threshold. Furthermore, it has been shown in [157] that only a small size of preamble is required to achieve constant decision threshold for both low and high SNR scenarios.

In [160], a flexible chaotic ultra-wideband (UWB) communication system with an adjustable channel spectrum is proposed to perform in various communication environments. The proposed system can overcome the spectral inefficiency and RF power wastage that is typically observed in conventional methods like the COOK system by utilizing adjustable channel allocations. At the receiver side, the digital pulse shape is recovered by detecting the chaotic pulse at an envelope detector consisting of a nonlinear component and a low-pass filter. Finally, the decision levels of a comparator are determined by measuring the received signal power of previous packets

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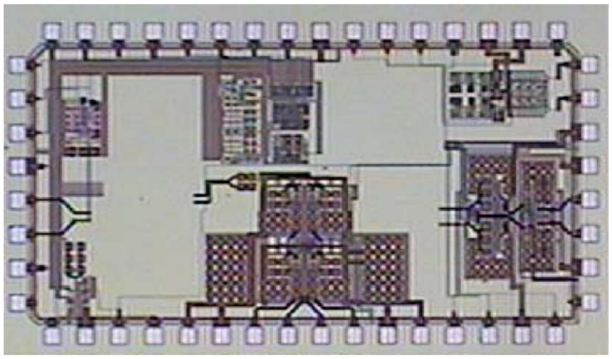

Fig. 14: Microphotograph of the CMOS RFIC for the flexible chaotic UWB system [160].

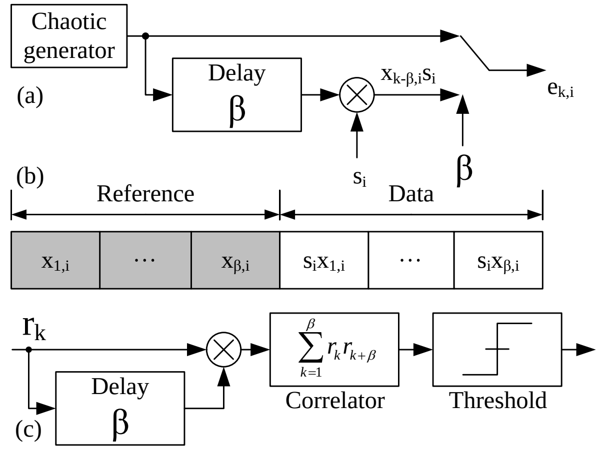

Fig. 15: Block diagram of the general structure of the DCSK communication system; (a) transmitter, (b) frame, and (c) receiver.

at the peak detector. The proposed transceiver design that is implemented in CMOS 0.18 μm technology and includes adjustable chaotic signal generation and adaptive detection is shown in Fig 14.

*2) **Chaotic parameter modulation**:* In almost all schemes, correlators or match filters are used for binary signal estimation at the receiver end. Another class of modulation named chaotic parameter modulation (CPM) approach is proposed in [161]. This approach is based on the ergodicity of chaotic signals as a simple technique to recover the transmitted data by estimating the chaotic parameters such as the mean value function under a noisy environment. An ergodic chaotic on-off keying (E-COOK) scheme can be considered as a direct application of this method for viable digital signal transmission.

B. Non-coherent digital modulations

*1) **Differential Chaos Shift Keying and its extensions**:* Differential chaos shift keying was first proposed in [29]. Indeed, among chaos-based modulation schemes, DCSK is one of most widely studied chaos-based communication systems [18], [162], [163]. Typically, a DCSK systems is easy to implement [164], [165] and encounters the problems of the COOK system. As shown in Fig. 15 (a) and (b), each bit duration in DCSK system is split into two equal slots where the first slot is allocated to the reference chaotic signal, and the second slot, depending on the bit being sent, is used to transmit either the reference signal or its inverted version. On the other hand, the feature of the DCSK system is that the reference signal is not generated at the receiver side but is transmitted via the same telecommunication channel as the information bearing signal. As illustrated in Fig. 15, the received signal r_k is correlated with a delayed version $r_{k+\beta}$ of itself, and accumulated over half the bit duration T in order to demodulate the transmitted bit. The received data is estimated through a thresholding operation, by computing the sign of the correlator output. Finally, various analytical bit error rate (BER) performance derivations of DCSK communication systems in fading channels have been analyzed for many scenarios in [166], [88], [89], [167] and [168].

This solution makes the DCSK radio system very robust against linear and nonlinear channel distortions and the demodulation process can be carried out without any knowledge of channel state information [163], [168]. However, serious drawbacks of the conventional DCSK design including weakened information security, low data rate, high energy consumption, non-constant bit energy, non supporting of mobility, and the use of wideband delay lines, which is very difficult to implement in the current CMOS technology [169], [170]. In addition, the reference and information bearing signals are corrupted by the channel noise and a noisy reference signal is correlated with a noisy information bearing signal at the receiver, consequently, this deteriorates the performance of the DCSK system.

A growing number of research is being conducted to overcome the mentioned weaknesses of the DCSK scheme. In [171] they introduce a frequency modulator after the chaotic generator in order to make the transmitted bits modulated by the chaotic waveform constant. This scheme named FM-DCSK has demonstrated its considerably high performance in enhancing communication quality over the multi-path channel under severe conditions without increasing the hardware complexity [18], [142], [172]. In [173], an optimized FM-DCSK UWB system is proposed to enhance the performance of the conventional FM-DCSK scheme in the IEEE 802.15.4a low-rate application.

Moreover, in another scheme analysed in [174] and named correlation delay shift keying (CDSK), the transmitted signal is the sum of a chaotic sequence x and of a delayed chaotic sequence multiplied by the information signal. Hence, CDSK overcomes the disadvantages of DCSK by replacing the switch by an adder, and the transmitted signal is never repeated. Another extension proposed in [175] called FM-CDSK is a combination of FM-DCSK and CDSK. This new system exhibits a superior performance compared to CDSK because of the use of FM modulators which leads to having a constant transmitted bit energy. Therefore, CDSK and FM-CDSK increase the security at the cost of BER performance.

In subsequent research, a generalized extension of the CDSK, called the GCDSK, is proposed in [177] and [176]. As shown in Fig. 16, a number of delayed chaotic signals

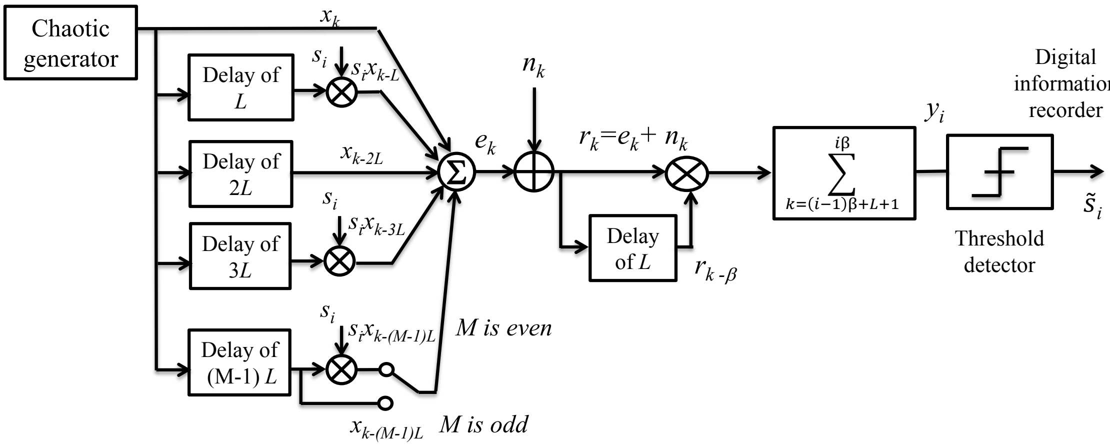

Fig. 16: Block diagram of a generalized CDSK communication system. [176]

are first produced, then some of them are modulated by the data being sent. Finally the delayed signals are added to the original chaotic signal and transmitted. Such a construction of the transmitted signal allows the transmission of more than one reference signal and more than one information-bearing signal simultaneously. The useful signal component, as well as the interference component, will be enhanced at the receiving side. Naturally, such schemes increase data rate and data security at the cost of BER performance degradation and the use of excessive delay circuits.

Many extensions are proposed either to enhance the spectral efficiency or the BER performance of DCSK systems. An M-ary DCSK (M-DCSK) system is proposed in [178] in which each n bits are converted to a symbol, then transmitted using the same DCSK modulation scheme. In [179], the authors use the same technique to transmit a spread spectrum QAM modulation.

Targeting similar objectives, a quadrature CSK is proposed in [180] to enhance the spectral efficiency of the conventional DCSK system. In QCSK modulation, the chaotic generator generates the reference chaotic signal x. This signal is then transformed into another (quadrature) chaotic signal $\tilde{x}$ by applying the Hilbert transform. A linear combination of these two independent orthogonal chaotic signals is used to map the transmitted bits in the form of $m_{k,i} = x_{k,i}s_i + \tilde{x}_{k,i}s_{i+1}$.

Analogous to DCSK, the reference signal in QCSK is transmitted in the first half period of the bit time while the data carrier signal $m_{k,i}$ is sent in the second half. At the receiver, the received reference signal correlates the data carrier m in order to decode s_i. Hilbert transform is then applied to the received reference signal to generate the orthogonal signal $\tilde{x}$ used to recover the bit s_{i+1}. Therefore, QCSK scheme doubles data rate by using the same frame time as DCSK scheme, but increases receiver complexity. In [181], with similar underlying ideas to QCSK, an Orthogonal Chaotic Vector Shift Keying (OCVSK) scheme is proposed. In this scheme, the Gram Schmidt method is used to generate an orthogonal chaotic function from the originally generated function. As mentioned in [181], the complex representation is derived from complex analysis, which employs inherent orthogonality

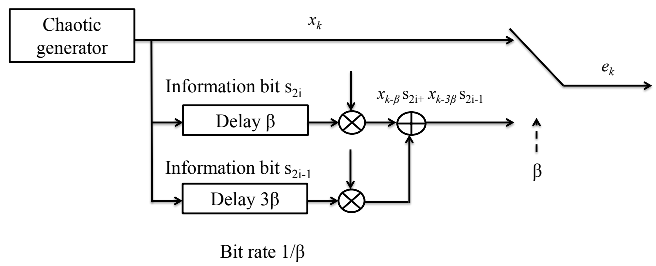

Fig. 17: Transmitter structure of HE-DCSK [183]

properties of the sine and cosine function representations. If symbols can be represented within a higher dimensional space, then their apparent dependence on inherent orthogonality can be discarded; the effective separation between the symbols can be increased and the effects of noise reduced. Compared to QCSK, the proposed OCVSK increases data transmission rates with greatly improved robustness. Recently, L. Wang et *al* proposed in [182] a new multiresolution (MR) M-ary differential chaos shift keying (DCSK) modulation scheme as extension to the QCSK scheme. The authors showed in this work that this new system provides better anti-multipath fading performance against various spreading factors, which inherits the advantages of the conventional DCSK system.

In order to reduce the wasted energy used to transmit the reference signal many systems have been proposed and evaluated. A high efficiency DCSK (HE-DCSK) is proposed in [183]. As shown in Fig. 17, the modulator recycles each reference slot, two bits of data can be carried in one data-modulated sample sequence. This doubles bandwidth efficiency and reduces retransmissions making the transmitted signal less prone to interception in comparison to DCSK. Therefore, as shown in the receiver and transmitter structures, this system requires four delay circuits and cannot perform in its actual frame design in fast fading channels where channel coefficients vary during three time slots.

The same authors improved the HE-DCSK by proposing another system named reference modulated (RM-DCSK) [183]. In this design which is shown in Figs 19 and 20, the chaotic

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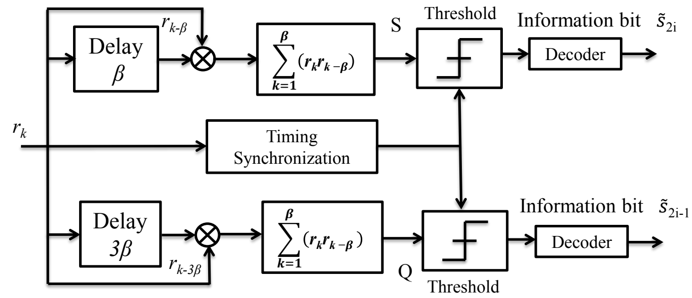

Fig. 18: Receiver structure of HE-DCSK [183]

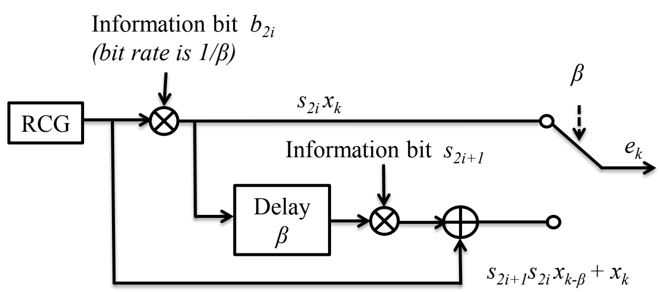

Fig. 19: Transmitter structure of RM-DCSK [183]

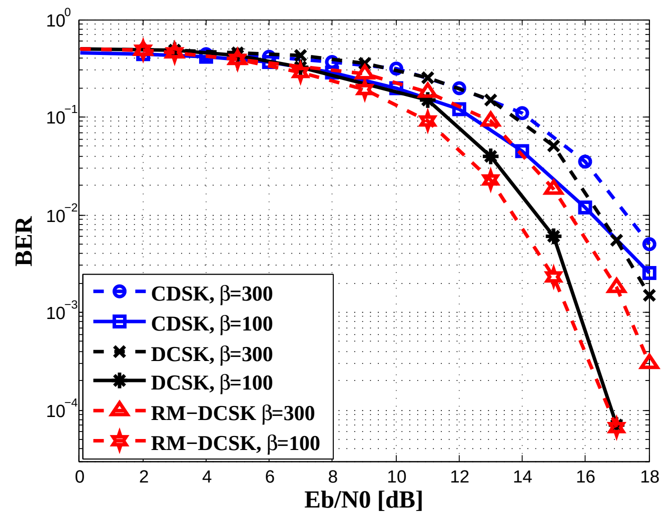

Fig. 21: BER over AWGN channel for different non-coherent systems and spreading factors β. [183]

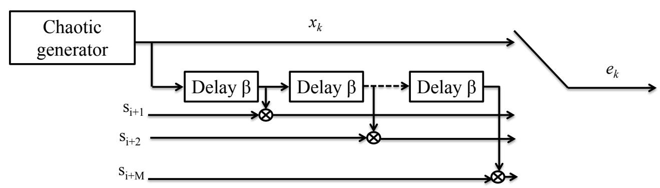

Fig. 22: Improved DCSK modulator configuration using a delay line having M tabs [186]

signal is sent in either the first or the second slot of each frame and not only carries one bit of data but also serves as the message bearer of the data bit transmitted in its subsequent time slot. Fig. 21 shows the BER performance of CDSK, DCSK and RM-DCSK versus E_b/N_0. It is observed in Fig. 21 that RM-DCSK outperforms CDSK and DCSK schemes under high signal-to-noise ratio levels for large spreading factors. In addition, this scheme requires less delay circuits than HE-DCSK. However, since parts of the signals overlap in time, this system can suffer from high interference in multi-path scenarios.

In the same vein, a simpler version of DCSK system named (DCSK/S), i.e FM-DCSK/S, is proposed in [184]. In this configuration, instead of using β chips per bit for both the reference signal and the information-bearing signal, each reference sequence of β chips is used to transmit M information-bearing bits as shown in Fig. 22. Hence, such a design reduces the bit energy for this class of modulation by a factor of $2M/(M+1)$. At the receiver side, this reference is used to recover the M transmitted bits. A similar concept is adopted in [8], [169], [170], [185] in which one reference is used to transmit more than one bit and the separation between the reference and the information-bearing signals is done in code, phase or frequency domains. As indicated earlier, the data is recovered with the majority of the proposed and enhanced *transmit reference* chaos-based communication receivers by performing a correlation between the information-bearing and the reference signals. However, none of the systems benefit from the correlation between the information-bearing signals. In order to enhance the performance and recover the transmitted data modulated using the DCSK/S frame, different receiver architectures have been proposed [186], [187]. The first receiver architecture known as (DCSK/AV)(i.e FM-DCSK/AV) is proposed first in [187]. This system aims to enhance the performance by denoising the reference signal. This process is achieved by using an averaging technique to estimate the reference signal from the noisy received signal, an operation can be modelled as

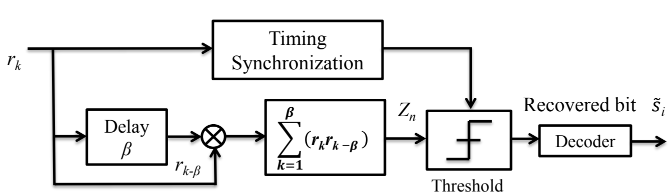

Fig. 20: Receiver structure of RM-DCSK [183]

$$\hat{r}_{1,k}=\frac{1}{M+1}\left\{\hat{r}_{1,k}+\sum_{i=1}^{M}2\left[\hat{P}_C(D_{1.l})-\frac{1}{2}\right]\text{sign}\left(D_{1.l}\right)\hat{r}_{i,k}\right\} \tag{4}$$

By observing equation (4), we can conclude that the denoising can perform efficiently if the modulation is extracted and removed correctly from the noisy signal $\hat{r}_{i,k}$. Therefore, the scalar weighting factor of $2\left[\hat{P}_C(D_{1.l})-1/2\right]$ is introduced by the authors to mitigate the problem of wrong decision. Later, the same research group have proposed a shortest path

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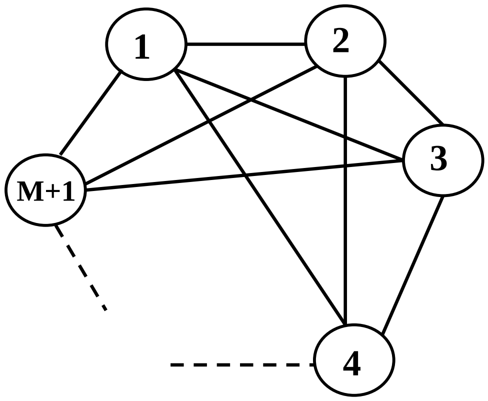

Fig. 23: Graph showing all possible decision paths for an enhanced DCSK signal having one reference and M information bearing signals. [172]

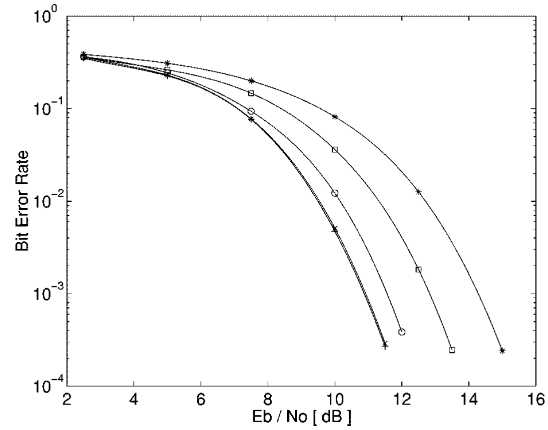

Fig. 24: Performance of different enhanced DCSK systems over AWGN. The curves for FM-DCSK/SP, FM-DCSK/ST, FM-DCSK/AV, and FM-DCSK/S are represented by '+','×', 'o' and '□' marks respectively. The performance of conventional FM-DCSK system (solid curve with '*' marks) is shown for comparison. [172]

algorithm named (DCSK/SP) to enhance the performance of the DCSK system [186]. This class of receivers use non-redundant error correction techniques based on the graph theory approach by exploiting the fact that every β chips are transmitted $M+1$ times. Fig. 23 shows the all possible decision paths in DCSK receivers where the vertices represent the received $M+1$ signal functions while the edges are the correlation between pairs of chips. Moreover, given the probability of correctness, a weight is assigned to each edge and the data is recovered based on the shortest path algorithm [172]. Another receiver based on minimum cost spanning tree algorithm is developed by *Jako et al*. This system which is named DCSK/ST yields a similar performance to DCSK/SP over AWGN channels but with less computation effort. A detailed analysis of this decoding algorithm is found in [172]. Fig. 24 compares the performance of FM-DCSK/S, FM-DCSK/AV, FM-DCSK/ST, and FM-DCSK/SP receivers for $M = 4$ and the same bandwidth $2B = 17$ Mhz over an AWGN channel. As shown in Fig. 24, the FM-DCSK/S system outperforms the conventional FM-DCSK. This improvement is due to the fact that the reference energy is shared among M bits and it means that for a high number of bits M, we need less energy to reach a given BER. Based on this principle We can also conclude that FM-DCSK/S and MC/FM-DCSK [8] give identical performance over AWGN channels. Therefore, a better performance is observed for FM-DCSK/SP and FM-DCSK/ST algorithms. This is due to the fact that the FM-DCSK/ST algorithm requires less computational charge then the FM-DCSK/SP. Besides, since the separation is done in time domain between the reference and the M data-bearing signals, tree receivers are very sensitive to time-varying signals. Moreover, the price to pay for the higher performance for DCSK/SP and DCSK/ST is the complexity in system configuration. Finally, the use of M delay lines makes the implementation of the proposed schemes in CMOS technology challenging [169].

In the same vein, the authors in [188] proposed a noise reduction DCSK (NR-DCSK) system as a solution to reduce the noise variance present in the received signal in order to improve performance. In this design, instead of generating β different chaotic samples to be used as a reference sequence, β/P chaotic samples are generated and then duplicated P times in the signal. At the receiver, each P identical samples are averaged and the resultant filtered signal is correlated to its time delayed replica to recover the transmitted bit. This averaging operation of size P reduces the noise variance and enhances the performance of the system.

Fig. 31 shows the BER performance of the proposed NR-DCSK system for different values of P as well as for DCSK, improved DCSK (I-DCSK) (i.e I-DCSK will be presented later in this survey) and DPSK schemes. The performance curves

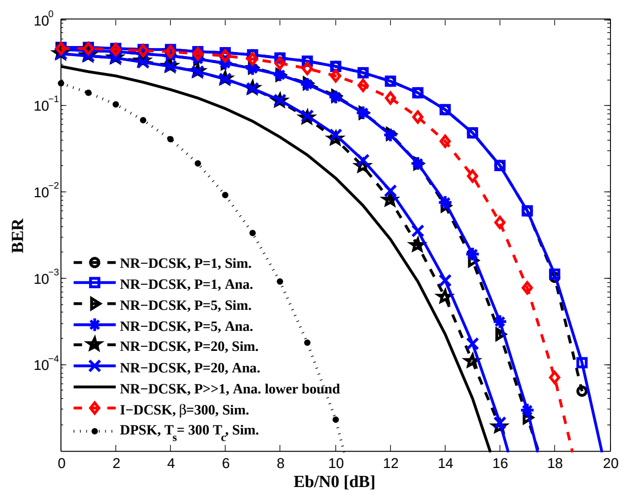

Fig. 25: Simulation, analytical and lower bound BER in AWGN channel of DPSK, DCSK (i.e $P = 1$), I-DCSK and NR-DCSK with a spreading factor of $\beta = 300$ for $P = 1$, 5 and 20.

shown in Fig. 31 reveals the extent to which simulation results perfectly validate the analytical BER expression provided in [188]. As expected, the achieved enhancement in the performance of NR-DCSK is well proportional to the value of P, i.e.

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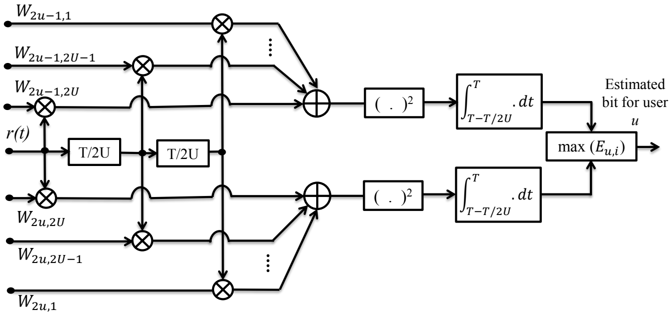

Fig. 26: Receiver structure of u^{th} user of DCSK-WC system [191]

the higher the value of P the better the performance of NR-DCSK. Note that the NR-DCSK with $P = 1$ reduces to the conventional DCSK. This enhancement is due to the averaging operation applied to the received signal which reduces the noise power. Therefore, for higher values of P the performance of NR-DCSK tends to the lower bound BER performance given by BER $= \frac{1}{2}\text{erfc}([4N_0/E_b]^{-\frac{1}{2}})$. Hence, from the lower bound performance shown in Fig. 31, the maximum gain that can be achieved by NR-DCSK is 10 dB. Moreover, as predicted, the DPSK system results in a better performance over AWGN channel but this latter outperforms DPSK system over multipath fading channel [188].

To solve the problem of multi-user access in chaos-based non coherent detection, many designs are proposed. In [189], a permutation transformation is performed on each DCSK time frame which destroys the similarity between the reference and data samples in a DCSK system is introduced, making the bit rate undetectable from the frequency spectrum and allowing multiple access communication by attributing different permutation functions for each user. Based on the same idea, an OFDM based DCSK scheme is proposed in [190] to enhance security, simplify equalization and allow multi-user access.

Kolumbán *et al* were the first to propose a multiuser FM-DCSK communication system based on *Walsh* functions [172]. In this design, Walsh codes are used to eliminate interference among users by creating an orthogonal set of signals. Hence, for this design, Walsh codes W^{2n} $(n = 0, 1, 2, ...)$ of 2U-order are used to accommodate U users. Later, this multiuser chaos-based system was analysed in [191] under multipath fading channels and in cooperative communication scenarios. As shown in Fig. 26, the demodulation process of multiple users based on the Walsh code is generalized such that a generalized maximum likelihood (GML) detection rule may be applied.

In [192] a novel differentially DCSK (DDCSK-WC) technique is proposed to save energy wasted on unmodulated references and support multiuser scenarios. To save energy, the proposed transmission algorithm is described as follows: the chaotic signal is sent at the beginning of transmission. Then, if the first bit is 1, the same chaotic sequence, which is a copy of the previous one, is sent; otherwise, the inverted copy is sent. Moreover, Walsh codes are used for multiple access scenarios. As shown in Fig. 27, the authors show that DDCSK-WC scheme improves the performance gain as compared with the conventional DCSK-WC [191], while retains its hardware complexity, i.e. keeps it unchanged.

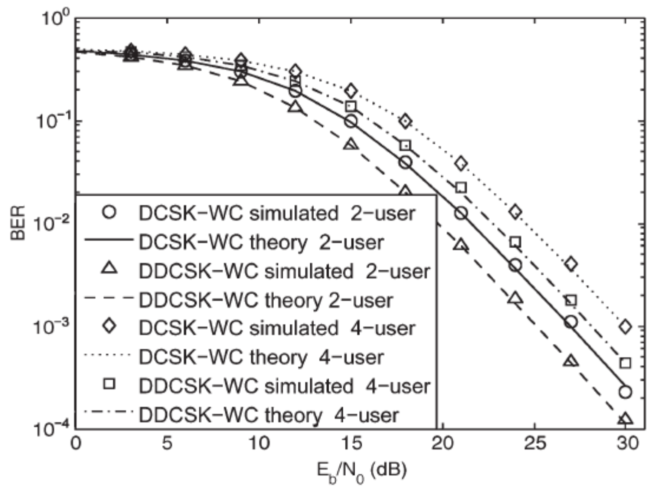

Fig. 27: Performance comparison between DCSK-WC and DDCSK-WC, including two-user and four-user systems, over two-ray fading channels [192]

In [8], the authors have proposed a multi-carrier DCSK (MC-DCSK) system that can support multi-user transmission [193]. As shown in Fig 28, the chaotic reference sequence is transmitted over a predefined subcarrier frequency while multiple modulated data streams are transmitted over the remaining subcarriers. The MC-DCSK scheme improves energy efficiency and increases data rate, but has large demands for bandwidth. Finally as for MC-DS-CDMA, this system can perform with a small number of subcarriers to avoid using a large number of match filters at the receiver.

In [194], the authors study the power allocation strategy on subcarriers of the MC-DCSK system [8]. Based on the BER expression, the optimal subcarrier power allocation strategy is obtained. Their results exhibit significant advantages of the optimal subcarrier power allocation when the number of subcarriers is large.

On the other hand, an Multi-User Orthogonal frequency division multiplexing DCSK (OFDM-DCSK) system was then proposed in [195] to reduce the usage of wide bandwidths. As shown in Fig. 29, in this system, the spreading operation is performed in time domain over the multi-carrier frequencies. To allow the multiple access scenario without using excessive bandwidth, each user has N_P predefined private frequencies from the N available frequencies to transmit its reference signal and share with the other users the remaining frequencies to transmit its M spread bits. In this new design, N_P duplicated chaotic reference signals are used to transmit M bits instead of using M different chaotic reference signals as done in DCSK systems. Moreover, given that $N_P << M$, the MU OFDM-DCSK scheme increases spectral efficiency, uses less energy and allows multiple-access scenario. Therefore, the use of OFDM technique reduces the integration complexity of the system where the parallel low pass filters are no longer

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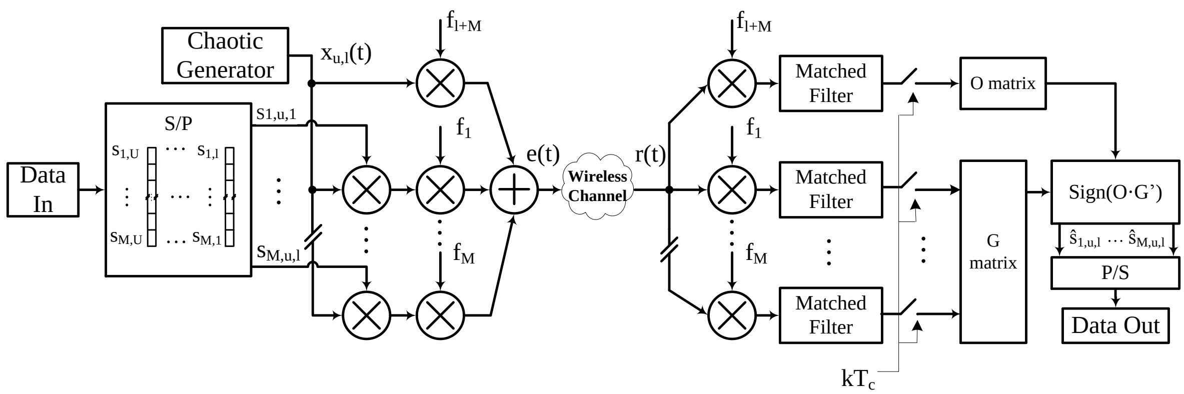

Fig. 28: Block diagram of the MC-DCSK system for the l^{th} user [193]

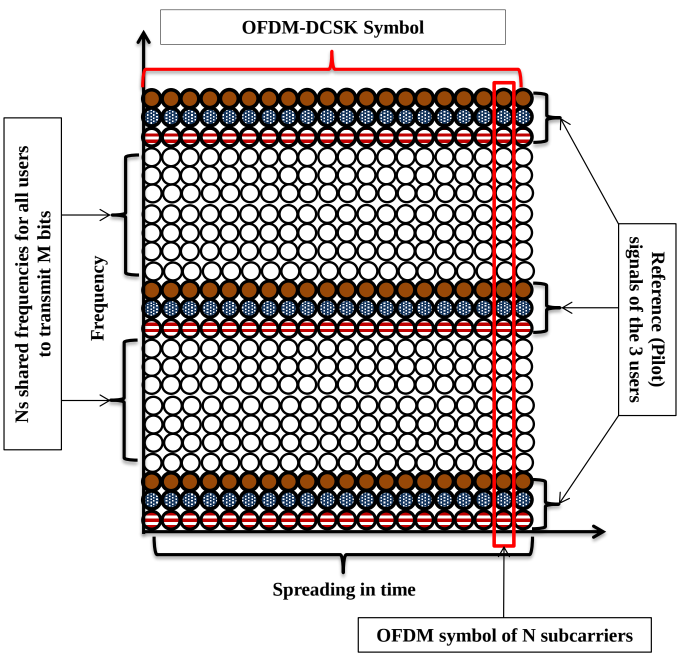

Fig. 29: Signal structure of MU OFDM-DCSK modulator with comb-type reference sequences for the p^{th} user.

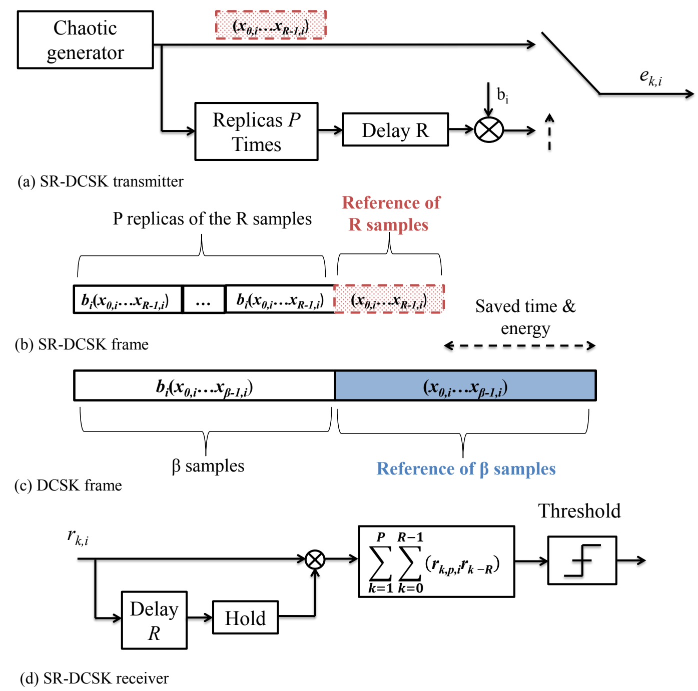

Fig. 30: (a) Block diagram of the general structure of the SR-DCSK transmitter; (b) SR-DCSK frame (c) DCSK frame and (d) SR-DCSK receiver.

needed to recover the transmitted data as in multi-carrier DCSK scheme.

To reduce or avoid the use of delay lines in DCSK, many non-coherent schemes were proposed. The main aim is to replace separation in time between reference and data carrier signals or to reduce it as used in the conventional DCSK system to avoid the use of wideband delay lines. This is because wideband delay lines are very difficult to implement in the current CMOS technology [169], [170].

In order to reduce the delay line, a *short reference* DCSK system (SR-DCSK) is proposed in [196]. As shown in Fig 30, the number of chaotic samples in SR-DCSK that constitute the reference signal is shortened to R such that it occupies less than half of the bit duration. To build the transmitted data signal, P concatenated replicas of R are used to spread the data. This operation increases data rate and enhances energy efficiency without imposing extra complexity onto the system structure. The receiver uses its knowledge of the integers R and P to recover the data. Performance results of SR-DCSK in AWGN channels for $\beta = 100$ and for various values of the reference signal length R is shown in Fig. 31. It is clearly observed that the optimized value of $R = 50$ results in a superior performance. Moreover, SR-DCSK system performance at $\beta = R = 100$ represents in fact the performance of conventional DCSK. In addition, SR-DCSK outperforms the DCSK system when $R = 20$ for E_b/N_0 values ≤ 15 dB. Eventually, by choosing $R = 20$ or $R = 50$, SR-DCSK delivers a better performance than DCSK and according to the different analysis done in this work, the SR-DCSK system boosts its data rate by 65% and 33% and saves 40% and 25% from the bit energy, respectively.

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Moreover, the application of the proposed short reference

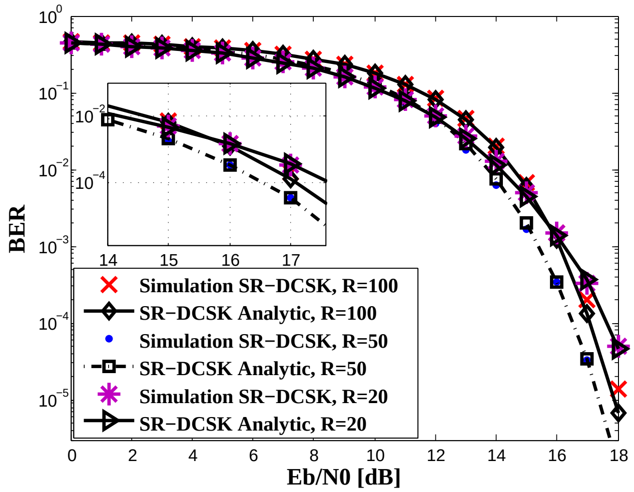

Fig. 31: Simulation and analytical BER performance of SR-DCSK and DCSK in AWGN channels for $\beta = 100$ and various R.

technique to the majority of transmit reference systems such as DCSK, multi-carrier DCSK, and quadratic chaos shift keying enhances the overall performance of this class of chaotic modulations and is, therefore, promising.

A system called code-shifted CS-DCSK is proposed in [169] in which reference and data sequences are separated by Walsh codes instead of time delay multiplexing. An extended version of this scheme is presented in [170] in which Walsh codes are replaced by different chaotic sequences to separate different data, and the reference signal is transmitted over an orthogonal frequency. The two mentioned methods increase data rate and improve BER but need the generation and the synchronization of chaotic or Walsh codes at the receiver, which affects the non-coherent nature of the DCSK system.

Recently, an improved DCSK system (I-DCSK) is proposed in [197] sharing the same concept of the systems proposed in [169] and [170] where the reference signal and the data carrier are transmitted in the same time slot. Therefore, the I-DCSK system does not affect the non-coherent nature of detection as in the previous systems, where any generation of chaotic or Walsh codes is required to recover the transmitted data. In this design and as illustrated in Fig. 32, the reference signal is time reverted and added to the data carrier signal. This operation creates an orthogonality between the reference signal and the data carrier. Moreover, the summation of these signals halves the transmitted symbol duration, which doubles the spectral efficiency of the I-DCSK system compared to conventional DCSK and avoids the use of wideband circuitry.

At the receiver, the received signal is correlated with its time reversed version and summed over a bit duration. The decoded bits are recovered by comparing the correlator output to a zero threshold. In this scenario, the receiver can perform without any need for complex channel estimators.

As shown in Fig 33, I-DCSK and QCSK manifest a close BER performance over AWGN channel but with lower complexity. In addition, an enhancement is achieved by both

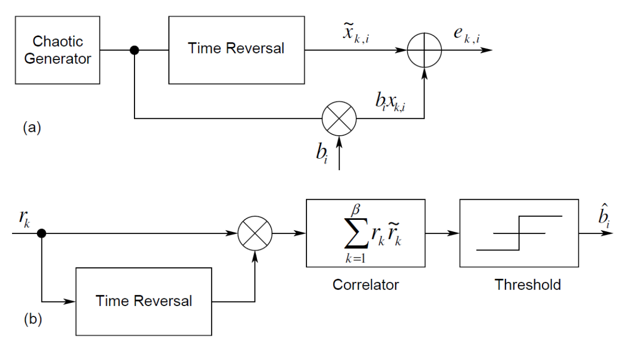

Fig. 32: Block diagram of the general structure of the I-DCSK communication system; (a) transmitter and (b) receiver. [197]

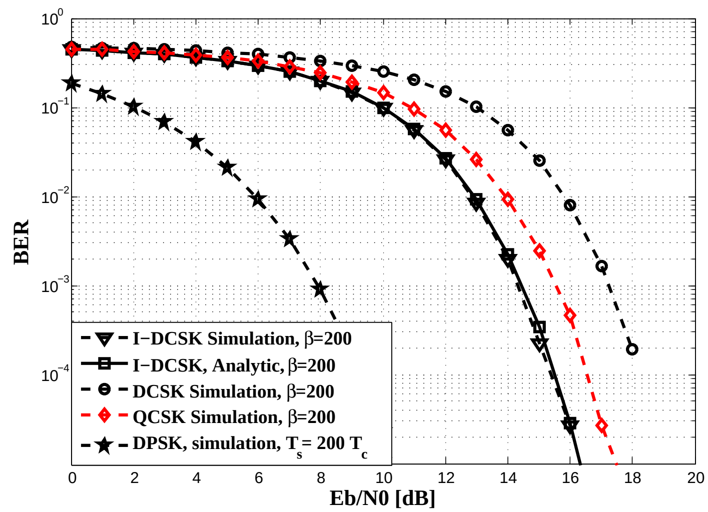

Fig. 33: Simulation and analytical BER in AWGN channel of I-DCSK, QCSK and DCSK systems for $\beta = 200$. [197]

systems compared to DCSK. The performance enhancement between QCSK and DCSK is explained in [180]. The performance behaviour of I-DCSK scheme over an AWGN channel can be explained as follows: even with cross terms, interferences emerging from the addition of the reference to the data carrier signal, the signal-to-noise ratio at the output of the correlator of I-DCSK system is higher than DCSK and QCSK. This is because the power of useful signals in I-DCSK is twice as large as the power in DCSK. Moreover, the spectral efficiency of I-DCSK system is two times higher than DCSK and is equal to QCSK.

A phase-separated differential chaos shift keying (PS-DCSK) modulation scheme is proposed in [185] as a simple delay-component-free version of DCSK modulation. In this scheme, the data carrier and reference signals are separated by orthogonal sinusoidal carriers rather than time delays, and transmitted simultaneously in parallel during the same time slot. As a result, PS-DCSK not only avoids the difficult-to-implement radio-frequency delay line problem but also achieves a doubled attainable data rate, enhanced communication security, and equivalent bit-error-rate (BER) performance with respect to DCSK. Fig.34 shows that the BER performance of PS-DCSK system outperforms CS-DCSK and HCS-DCSK2

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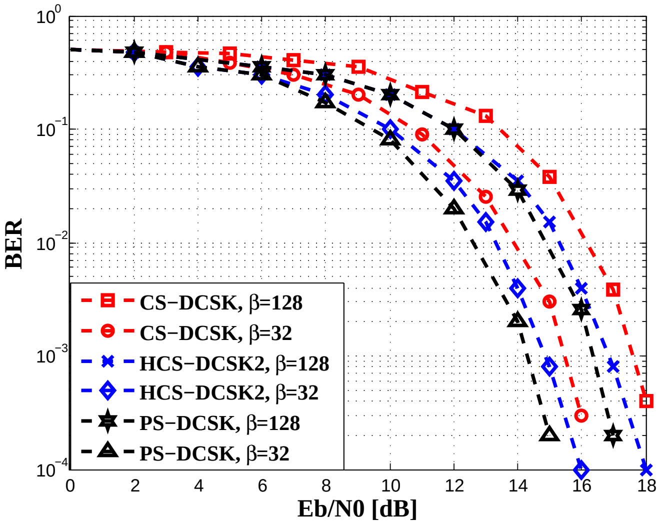

Fig. 34: Performance comparison between PS-DCSK, CS-DCSK and HCS-DCSK2 systems with different lengths of chaotic spreading sequences M under an AWGN channel [185]

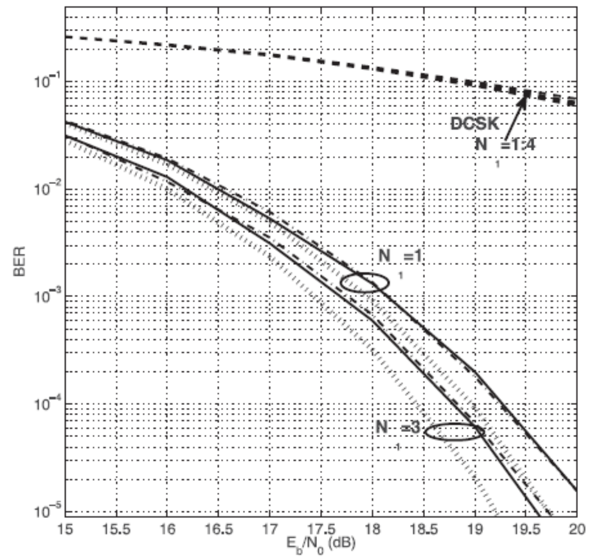

Fig. 35: CM-DCSK simulation results (continuous lines), numerically evaluated (dash-dotted lines), simplified bound (dotted lines), and simulation results for DCSK (dashed lines), for different N_1, $\beta = 100$, $K = 1$, $N_2 = 3$, $d_2 = 2$, $G2 = G13$ (i.e The system parameters are detailed in [198])

systems. As explained by the authors, this performance gain over HCS-DCSK2 system seems more and more evident as the spreading factor β shrinks. This is due to the fact that HCS-DCSK2 system uses chaotic sequences to separate the reference and information-bearing signals, which increases the uncertainty of the useful signal component in every correlator output, specifically in the case of small spreading sequence lengths.

On the other hand, conventional differential chaos-shift-keying systems (DCSK) are not the most suitable for supporting continuous-mobility scenarios. Therefore, the authors in [198] proposed an improved continuous-mobility differential chaos-shift-keying system (CM-DCSK) that provides greater agility and improved performance in fast fading channels without accurate channel estimation while still being simple compared to a conventional DCSK system. A new DCSK frame signal is designed to reach this goal. In the new frame design, each reference sample is followed by a data carrier sample. This modification of the system design reduces the hardware complexity of DCSK because it requires a shorter wideband delay line and significantly improves the performance over fast fading channels while keeping the non-coherent nature of the transmission system. As illustrated in Fig. 35, CM-DCSK system outperforms the DCSK one over multipath fast fading channel. Hence, the application of all these principles to DCSK in the form of CM-DCSK has shown a great performance enhancement compared to conventional DCSK. Considering the need and demand for future low rate continuous wireless non-coherent communications with minimal complexity, typical for the envisioned internet of things (IoT) pervading needs, the proposed CM-DSS system seems to be a promising alternative.

Table V summarizes different types of chaos-based non-coherent modulation schemes. As shown in this part of the survey, the proposed schemes try to overcome the major drawbacks of DCSK system such as the low spectral efficiency (taken as reference for comparison), delay line, security and the multiple access capacity. While some systems succeed in solving one or two drawbacks, others add extra complexity or require the generation of spreading code at the receiver side. In this table, all proposed systems are compared to the conventional DCSK system. The full non-coherent detection in this table refers to systems that can recover the transmitted data without any channel estimation or generation of local replica of the spreading code. A partial non-coherent detection means that the system requires the generation of the waveform at the receiver side. For comparison proposes, the fields spectral efficiency, complexity and security in the table are marked $high$ for systems having a higher spectral efficiency, complexity and security compared to DCSK. Finally, a time division multiple access (TDMA) is attributed to systems which do not support multiple users in the same band and at the same time. Otherwise, the multiple access protocol is implemented in frequency, permutation or code domains.

C. Implementation of non-coherent modulation schemes

The implementation of chaos-based communication systems received a part of attention in the last decade. On the one hand, most of the experimental demonstrations of chaos-based communication systems with coherent receivers have employed wired links as transmission channels to demonstrate the possibility of using chaos in the context of data transmission in order to avoid the problem of complex synchronization procedures that exist in wireless channels [199], [200]. On the other hand, the implementation and the proof-of-concept of non-coherent communication systems received more attention because of the chaotic synchronization-free procedures at

TABLE V: Comparison between different non-coherent modulation schemes

Modulations	Delay line	Non-coherent	Spectral efficiency	Complexity	Security	Multiple access
DCSK	Yes	Full	Low	Low	Low	TDMA
PMA-DCSK	Yes	Full	Low	Low	High	PDMA
FM-DCSK	Yes	Full	Low	Low	Low	TDMA
GCDSK	Yes	Full	High	High	High	TDMA
M-DCSK	Yes	Full	High	Low	Low	TDMA
QCSK	Yes	Full	High	Moderate	Low	TDMA
MR-QCSK	Yes	Full	High	Moderate	Low	TDMA
HE-DCSK	Yes	Full	High	High	Low	TDMA
RM-DCSK	Yes	Full	High	High	Low	TDMA
DCSK-WC	Yes	Partial	Low	High	Low	CDMA
DDCSK-WC	Yes	Partial	High	High	Low	CDMA
DCSK/S	No	Full	High	Low	Low	TDMA
DCSK/AV	No	Full	High	Low	Low	TDMA
DCSK/SP	No	Full	High	Moderate	Low	TDMA
DCSK/ST	No	Full	High	High	Low	TDMA
NR-DCSK	No	Full	Low	Low	Low	TDMA
CM-DCSK	No	Full	Low	Low	Low	TDMA
SR-DCSK	No	Full	Moderate	Low	Low	TDMA
CS-DCSK	No	Partial	High	High	High	CDMA
HCS-DCSK$_{1,2}$	No	Partial	High	High	High	CDMA
I-DCSK	No	Full	High	Low	Low	TDMA
PS-DCSK	No	Full	Low	Low	Low	TDMA
MC-DCSK	No	Full	High	High	Low	FDMA
OFDM-DCSK	No	Full	High	Low	Low	FDMA/CDMA

the receiver side. In [160], a flexible COOK ultra-wideband (UWB) communication system with an adjustable channel spectrum is proposed to perform in various communication environments. The transceiver design that is implemented in CMOS 0.18 μm technology and includes adjustable chaotic signal generation and adaptive detection is shown in Fig 14. In the same vein, a proof-of-concept of DCSK system is analyzed in [201]. In this paper, the authors use the generic architecture for the monolithic realization of the DCSK modem, and identify their basic building blocks. Moreover, the electronic implementation of two essential blocks of the DCSK modem; the chaotic generator and the delay blocks are detailed. The same authors in [202] realized a custom fabricated integrated circuit for the low frequency FM-DCSK system. As shown in Fig. 36, a mixed-signal application-specific integrated circuit (ASIC) for a frequency-modulated differential chaos shift keying (FM-DCSK) communication system is proposed. The operation of the ASIC is herein illustrated for a data rate of 500 Kbits/s and a transmission bandwidth in the range of 17 MHz. Additionally, an alternative implementation of FM-DCSK system is realized using FPGA circuit in [203]. The arrival of software defined radios (SDR) on the market facilitate and flourish many implementations of DCSK and FM-DCSK on these platforms. In fact, such platforms offer flexible, efficient, complete and cheap solutions for performance testing. Moreover, since the analog RF output and input circuitry of the transceivers are available, real field tests can be performed or even the system performance can be evaluated in a real operating network [204]. In [164], an experimental chaos radio system using DCSK is realized. The software design and implementation are proposed for the experimental DCSK system on Universal Software Radio Peripheral (USRP) platforms. Moreover, the code used in [164] is published under the GPLv3 license. With this open source contribution, the authors wish that this framework will spur further research in that field. Likewise, a universal software defined PXI platform is used for the performance evaluation of FM-DCSK communications system [205]. Finally, the advantages of using chaotic waveforms in wireless communications is discussed throughout this survey. As a matter of fact, in comparison to conventional communication systems, the difference and indeed the main challenge in implementing a chaos-based communication system is the implementation of the chaotic generator.

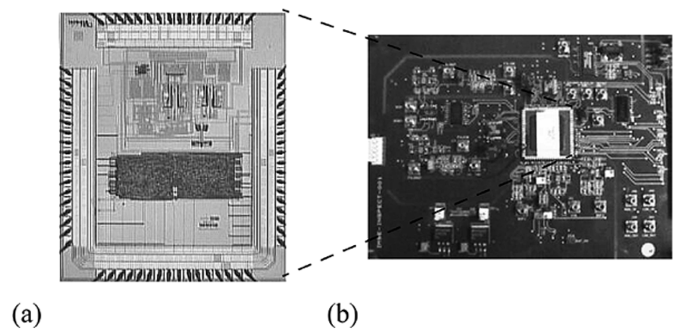

Fig. 36: (a) ASIC microphotograph. (b) FM-DCSK board [202]

The chaotic map implementation problem is addressed in subsection II-A of the survey where many proposed solutions are given to achieve this task. In addition, for coherent receivers, the chaotic synchronization is also another difficulty that faces the implementation stage. As discussed in subsection II-C, a huge effort is put as many research projects are studying different ways to improve the quality and the robustness of chaotic synchronization.

D. Applications of non-coherent modulation schemes

The research on non-coherent detection is just underway, but it has attracted lots of attention from industrial bodies and scholars [206], [207]. A quick glance through this survey can provide the reader critical perceptions about a significant number of research concerning non-coherent schemes and their applications. After presenting various non-coherent modulation schemes, in this part we will present a detailed review of several wireless applications that use non-coherent chaos-based communication as means of modulation at the physical layer. Throughout this part, we will discuss each application and we will highlight the advantages and limitations of each system.

1) ***Multiple antennas****:* The performance of SIMO and MIMO systems with non-coherent modulation are anlyzed in many papers [163], [208]–[213]. In [208], a SIMO FM-DCSK UWB system is introduced and the performance of this system is analyzed. In [211], the SIMO-DCSK employs orthogonal Walsh functions at the transmitter, with parallel substreams transmitted with a single antenna to help achieve a significant increase of the data rate. The authors show in the same paper that the proposed system with the decoding algorithm is more efficient than the DS-VBLAST scheme.

In [209] and [163], the authors analyze the use and the performance of DCSK modulation and the space-time block code (STBC) technique. In [163], they show that this combination of DCSK and STBC can remarkably suppress inter-transmit-antenna interference and achieve full diversity gain, because of the existence of very low correlation between different chaotic signals. In [212], an M-DCSK is used to transmit M-ary symbols instead of binary bits with MIMO systems. In [210], the authors propose a MIMO-DCSK scheme based on orthogonal multi-codes (OMCs) and equal gain combination (EGC). Simulation results show that full spatial diversity gain is achieved without channel estimation in MIMO-DCSK communications and that it outperforms multi-codes EGC for a large number of transmit antennas. The common point with the aforementioned papers is to see the advantages of DCSK systems to be the utilisation of marvellous correlation properties of chaotic signals and the dispense of channel estimators at the receiver side to recover the data. Finally, future research directions may consider chaos-based non-coherent modulation in conjunction with index modulation and massive MIMO.

2) ***Cooperative communications and network coding****:* The application of non-coherent schemes in cooperative networks has also received a particular attention. In [191], a differential chaos shift keying cooperative communication (DCSK-CC) system with two users is proposed. The cooperation is achieved through a decode-and-forward relay. The proposed scheme has an orthogonal subchannel in broadcast phase and cooperative phase through orthogonal Walsh code sequences as its multi-access scheme. Benefiting from the resistance of DCSK scheme in multipath channels, the proposed system outperforms conventional CDMA systems that have a single path correlation receiver.

The study is extended in [214] to evaluate the performance of FM-DCSK in cooperative networks. Later, a MIMO relay differential chaos shift keying cooperative diversity (DCSK-CD) system is proposed in [215]. It is shown that, with spatial diversity gains, the BER performance of the proposed system is remarkably better than the conventional DCSK non-cooperation (DCSK-NC) and DCSK cooperative communication (DCSK-CC) systems. In [216], a low-complexity amplify-and-forward relaying scheme for a differential chaos shift keying (DCSK) system in proposed. By transmitting the data carrier and the reference signals separately, the proposed protocol aims to minimize the processing load, the cooperative time and the energy for relaying symbols.

Recently, a DCSK system equipped with an automatic repeat request/cooperative (ARQ/CARQ) technique, called DCSK-ARQ/CARQ system is proposed in [217]. In this article the authors show that the DCSK-ARQ/CARQ system is remarkably superior to the existing DCSK non-cooperative/cooperative communication (DCSK-NC/CC) system.

The application of DCSK systems with network coding techniques are investigated in [193] and [218]. In [218], different network coding schemes for DCSK modulation are proposed and analyzed. The paper shows that Physical layer Network Coding (PNC) and Analog Network Coding (ANC) schemes are not suitable to be used with the DCSK scheme because of the high level of interference in the resultant signal originating from the cross product of the user signals at the relay's correlator, which severely degrades the system performance. Hence, in order to address this problem, the authors propose two coding schemes that separate user signals either in frequency or in time domains. Furthermore, the design and performance analysis of an ANC scheme for multi-user multi-carrier differential chaos shift keying (MC-DCSK) modulation is proposed in [193]. At the receiver end, each user mitigates the overall interference by subtracting its own data signal from the received combined signal before starting the decoding process. In addition, the conventional ANC-DCSK scheme is analyzed and compared to the proposed ANC-based MC-DCSK scheme to show the improvement in performance.

3) ***Channel coding*** *:* In general, the DCSK system shows poor performance over noisy channels. Degradation is mainly due to the additive noise on the reference and the data carrier slots. Therefore, the performance of such systems can be improved by designing appropriate channel codes [219], [220]. In [219] an FM-DCSK based on Woven convolutional code (WCC) is presented and the proposed system shows superior performance to that of the traditional code-based FM-DCSK system and the original FM-DCSK system over AWGN, Rayleigh and Ricean flat fading channels. Recently, an iterative receiver (IR) DCSK system is proposed with soft demapper suitable for non-coherent M-ary DCSK receiver [220]. The proposed system is analysed and their results show that the latter can work either with or without fading amplitude information.

*4) **Power line communications**:* The authors in [221], [222] investigated for the first time the application of non-coherent chaos based modulation techniques for power line communications (PLC). In [221], the authors proposed a differential chaos shift keying (DCSK) modulation scheme as a potential candidate for smart grid communication networks since this class of non-coherent modulation is very robust against linear and non-linear channel distortions. In their work, a simulator is developed to verify the performance of the proposed DCSK against direct sequence code division multiple access (DS-CDMA) and direct sequence differential phase shift keying (DS-DPSK). The results presented in this work proved the advantages of this low-cost non-coherent modulation technique for PLC systems over its rivals. In the same vein, a DCSK system with blanking device is proposed in [222] for PLC applications. The blanking method is used in order to mitigate the effects of impulsive noise present in the channel. the proposed system is compared to differential phase shift keying (DPSK) modulation to highlight the robustness of DCSK scheme against phase noise imperfection.

V. Future works and Conclusions

Since Carroll and Pecora proposed their method to synchronize chaos in 1991, communication techniques based on chaotic systems have been the subject of intensive study. In this paper, we provide a literature review of a large number of related studies, including chaotic coding, chaotic modulation/demodulation and multiple-access communication schemes. This survey offers a strong, transparent and a clear entry point into the topic. Further, we present a classification for different modulation techniques and provide a thorough discussion of their advantages and disadvantages. We also focus and elaborate on multiple-access methods and chaos-based non-coherent detection approaches. From what has been presented and discussed throughout this paper, we can extract the following points:

- There still exists a need for more research work targeting the problem of chaos synchronization techniques.
- The implementation of coherent detection is still a challenge because of the weak performance of chaotic synchronisation algorithms.
- Chaos-based symbolic dynamics is a promising class of coherent modulation exploiting the chaotic waveform.
- In order to benefit from the correlation properties of chaotic signals and to better utilize the features of chaotic sequences to enhance the capacity of communication systems, a carefully improved design of non-coherent chaos-based communication systems seems a necessity.
- Cognitive radio aspects are neither covered nor yet considered in any previous work. Many interesting scenarios such as interweave and underlay approaches benefiting from the correlation properties of chaotic signals may be proposed and evaluated, where the primary, the secondary both of the users utilize chaotic waveform.
- Various techniques that were proposed and implemented at the physical layer helped to combat the detrimental effects of wireless channels. Moreover, several fading mitigation techniques proposed for chaos-based communications work well, e.g. diversity, error control codes, noise cleaning, etc.
- Future research works must start considering modifications at the other layers such as the link layer, the transport layer or the network layer in order to improve the reliability of chaos-based communication systems.

Finally, this survey is aimed at providing the readers with valuable resources for understanding current research contributions in the growing area of chaos-based communication systems. This will contribute to trigger further research efforts for the design of next generation chaos-based wireless communication systems.

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