Accepted in IEEE Transactions on Circuits and Systems II: Express Briefs, vol. 62, no 9, 2015

I-DCSK: An Improved Non-Coherent Communication System Architecture

Georges Kaddoum*, *Member, IEEE,* Ebrahim Soujeri, *Senior Member, IEEE,* Carlos Arcila and Khaled Eshteiwi

***Abstract*—This paper presents the design and performance analysis of an Improved Differential Chaos Shift Keying (I-DCSK) system. Instead of sending reference and data carrier signals in two time slots as in conventional DCSK scheme, in the improved design, a time reversal operation is used to generate an orthogonal reference signal to the data carrier signal and then sum up these two sequences into one time slot, prior to transmission. This operation reduces the bit duration to half, which doubles data rate and enhances spectral efficiency. At the receiver, the received signal is correlated to its time reversed replica and is summed over the bit duration. The new system design proposed in this work replaces the delay circuit used in conventional DCSK systems by time reversal operations. Moreover, the theoretical bit error rate expressions for AWGN and multipath fading channels are analytically studied and derived. The proposed I-DCSK system is compared to the conventional DCSK and Quadrature Chaos Shift Keying (QCSK) schemes. Finally, to validate accuracy, simulation results are compared to relevant theoretical expressions.**

***Index Terms*—Non-coherent chaos based communication system, I-DCSK, High data rate, Performance analysis.**

I. Introduction

DUE to their advantageous features, chaotic signals have recently been impressively one of the main topics of many research groups in the field of wireless communications [1]–[7]. This is basically related to the inherent wideband characteristics of these signals that make them well suited for various spread spectrum modulation schemes [1], [2], [8]. Chaotic modulations have analogous advantages to other spread spectrum modulation techniques including reduction of fading effects and jamming resistance *exempli gratia*. Moreover, the low probability of interception (LPI) in chaotic signals makes them natural candidates for military scenarios [8]. Several chaos-based communication systems have been proposed and evaluated in the last decade [4], [8], [9]. Differential chaos shift keying (DCSK) [9]–[11] is the most studied system among chaos-based communication systems. In a typical DCSK system, each bit duration is divided into two equivalent slots; the first slot is allocated to the reference chaotic signal and depending on the transmitted bit, the second slot is used to transmit either the reference signal or its inverted version. Therefore, the common points between DCSK and differential phase shift keying (DPSK) modulations is that both are non-coherent schemes and do not require channel state information at the receiver to recover the transmitted data [11], [12]. However, DCSK system is more robust to multipath fading enviroment than the DPSK scheme and is suitable for ultra wide band (UWB) applications [7], [11]–[13]. Nonetheless, the major handicap of conventional DCSK is due to the repetition of chaos sequences caused by low data rate and the use of wideband delay lines which makes it hardly implementable in current CMOS technologies [14]. To overcome the mentioned deficiencies of the DCSK scheme, a growing number of research has been conducted to porpose new non-coherent systems. A quadrature chaos shift keying (QCSK) proposed in [15] uses the Hilbert transform to generate an orthogonal basis of chaotic functions allowing to transmit more bits with respect to DCSK, while occupying the same bandwidth. Also, high efficiency HE-DCSK [16], M-DCSK [13], and differential DDCSK [17] are proposed to improve the data rate of DCSK system at the cost of increased system complexity. To eliminate the use of delay lines in DCSK scheme, code-shifted CS-DCSK is proposed in [14] in which reference and data sequences are separated by Walsh sequences instead of time delay multiplexing. An extended version of this scheme is presented in [18] in which the Walsh codes are replaced by different chaotic sequences to separate different data, and the reference signal is transmitted over an orthogonal frequency. These two methods increase the data rate but need synchronization of the Walsh codes at the receiver, which influences the non-coherent structure of the DCSK system. Multi-carrier (MC-DCSK) is proposed in [7] in which a 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 offers increased data rates, but demands bandwidth.

Contributions: The majority of proposed schemes suffer from high system complexity. The main motivation of our paper is to propose a low complexity, non-coherent DCSK scheme that avoids the complex design and performs without the use of any channel estimator at the receiver. To reach this goal, we propose a new modulator in which the reference signal is time reverted, then added to the data carrier signal. This operation creates an orthogonality between the reference signal and the data carrier one. Moreover, the summation of these signals halves the transmitted symbol duration, which improves the spectral efficiency of the I-DCSK system 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. Finally the decoded bits are recovered by comparing the correlator

G. Kaddoum, E. Soujeri, C. Arcila and K. Eshteiwi are with University of Québec, ÉTS, LaCIME Laboratory, 1100 Notre-Dame west, H3C 1K3, Montreal, Canada (e-mail: georges.kaddoum@etsmtl.ca). E. Soujeri is also affiliated to the Dept. of E.E.Eng., European University of Lefke, Cyprus.

* This work has been supported by the NSERC discovery grant 435243 – 2013.

DOI: 10.1109/TCSII.2015.2435831

output to a zero threshold. In this scenario, the receiver can perform without any need to complex channel estimators. We derive the analytical bit error rate expressions over multipath fading and additive white Gaussian noise (AWGN) channels and we show the accuracy of our analysis by matching the numerical performance. Finally, we analyse and compare the performance of I-DCSK to those of DCSK and QCSK.

Paper Outline: The remainder of this paper is organized as follows: In section II, the conventional DCSK and QCSK are briefly presented and the architecture of the I-DCSK system is explained. Performance analysis of the I-DCSK scheme is done in section III. Simulation results and discussions are presented in section IV and concluding remarks are presented in section V.

II. NON COHERENT CHAOS-BASED COMMUNICATION SYSTEMS

A. DCSK Communication System

In the DCSK modulator [8], each bit $b_i = \{-1, +1\}$ is represented by two sets of chaotic signal samples, where the first is allocated to the reference, and the second to the carrying data symbols. If $+1$ is transmitted, the data-bearing sequence is equal to the reference sequence, and if -1 is transmitted, an inverted version of the reference sequence is used as the data-bearing sequence. The spreading factor in DCSK systems is defined as the number of chaotic samples used to spread each bit and is presented by 2β, where β is an integer. Moreover, $T_{DCSK} = 2T_b = 2\beta T_c$ is the DCSK frame time interval for each bit. During the i^{th} bit time interval, the discrete form of the discrete baseband signal sequence at the output of the transmitter $e_{i,k}$, can be given by

$$e_{k,i} = \begin{cases} x_{k,i} & \text{for } (1 < k \leq \beta) \\ b_i x_{k-\beta,i} & \text{for } (\beta < k \leq 2\beta) \end{cases}, \tag{1}$$

where $x_{k,i}$ is the chaotic sequence used as the reference signal and $x_{k-\beta,i}$ is its delayed version. In order to demodulate the transmitted bits, the received signal r_k is correlated to its delayed version $r_{k+\beta}$ and summed over the bit duration T_b where $T_b = \beta T_c$ and T_c is the chip time. The received bits are, then, estimated by computing the sign of the correlator output. In this system half of the bit time interval is spent on sending the non-information-bearing reference signal, thus, the data rate of this system is considerably reduced.

B. QCSK Communication System

In QCSK modulation [15], [19], the chaotic generator generates the reference chaotic signal x. This signal is then transformed into another (quadrature) chaotic signal $\tilde{x}$ by applying Hilbert transform. A linear combination of these two independent orthogonal chaotic signals is used to map the transmitted bits in the form of $m_{k,i} = x_{k,i}b_i + \tilde{x}_{k,i}b_{i+1}$. Hence, the transmitted signal $e_{i,k}$, can be given as

$$e_{k,i} = \begin{cases} x_{k,i} & \text{for } (1 < k \leq \beta) \\ m_{k,i} & \text{for } (\beta < k \leq 2\beta) \end{cases}, \tag{2}$$

Similar to DCSK scheme, the reference signal $x_{k,i}$ is transmitted in the first half period of bit time and 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 b_i. Hilbert transform is then applied to this received reference signal to generate the orthogonal signal $\tilde{x}$ used to recover the bit b_{i+1}. Therefore, QCSK scheme doubles data rate by using the same frame time as DCSK scheme does, i.e. $T_{QCSK} = T_{DCSK} = 2\beta T_c$, but increases complexity.

C. I-DCSK System Architecture

A block diagram of the general structure of I-DCSK communication system is shown in Fig.1. As illustrated in Fig.1, each bit b_i is first multiplied by the chaotic signal x_k. So, instead of being delayed, the reference signal is first time inversed, then is added to the data carrier signal. This operation (time inversion) aims at generating an orthogonal signal to the data carrier, to enable addition at a later stage. Our aim is limited to presenting different implementation aspects of the I-DCSK system for which the baseband discrete transmitted signal may be expressed as

$$e_{k,i} = b_i x_{k,i} + \tilde{x}_{k,i}, \tag{3}$$

where $\tilde{x}_{k,i}$ is the time reversed version of the chaotic signal $x_{k,i}$. Therefore, the frame time of each transmitted bit in the

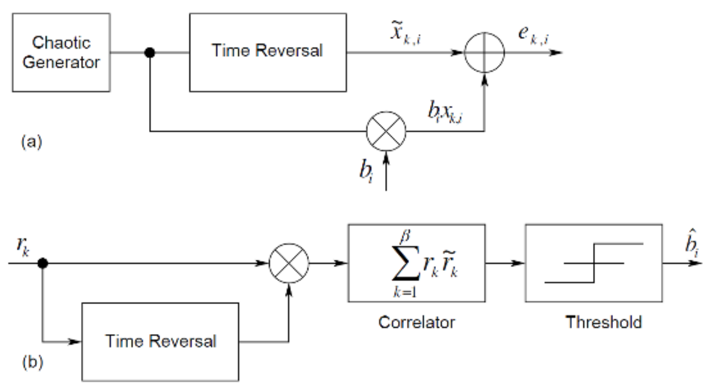

Fig. 1: Block diagram of the general structure of the I-DCSK communication system; (a) transmitter and (b) receiver.

I-DCSK is equal to the half of DCSK or QCSK systems where $T_{I-DCSK} = 0.5T_{DCSK} = 0.5T_{QCSK} = \beta T_c$. In this paper a commonly used channel with two independent paths called two-ray Rayleigh fading channel [12], [11] is considered. The channel coefficients and time delays between the two rays are denoted by α_1, α_2 and τ respectively. It should be noted that the channel coefficients follow the Rayleigh distribution and in this work, they are considered to be flat (i.e., static) over the transmission period of one frame. Therefore, the probability density function of the channel coefficient α in this case can be given as

$$f(\alpha|\,\sigma) = \frac{\alpha}{\sigma^2} e^{-\frac{\alpha^2}{2\sigma^2}}, \tag{4}$$

where $\sigma > 0$ is the scale parameter of the distribution representing the root mean square value of the received voltage signal before envelope detection.

The received signal could be written as

$$r_{k,i} = \alpha_1 b_i x_{k,i} + \alpha_2 b_i x_{k-\tau,i} + \alpha_1 \tilde{x}_{k,i} + \alpha_2 \tilde{x}_{k-\tau,i} + n_k, \quad (5)$$

where n_k is additive white Gaussian noise with zero mean and variance $N_0/2$. At the receiver side, the received signal r_k is correlated to its time inverted version $\tilde{r}_k$ and summed over the bit duration T_b. The decision variable at the output of the correlator becomes

$$\begin{aligned} D_i =& T_c \sum_{k=1}^{\beta} (\alpha_1 b_i x_{k,i} + \alpha_2 b_i x_{k-\tau,i} + \alpha_1 \tilde{x}_{k,i} + \alpha_2 \tilde{x}_{k-\tau,i} + n_k) \\ & (\alpha_1 b_i \tilde{x}_{k,i} + \alpha_2 b_i \tilde{x}_{k-\tau,i} + \alpha_1 x_{k,i} + \alpha_2 x_{k-\tau,i} + \tilde{n}_k) \cdot \end{aligned} \quad (6)$$

The decision variable may be further expanded as

$$\begin{aligned} D_i =& \\ & T_c \sum_{k=1}^{\beta} \Bigg(\underbrace{\alpha_1^2 b_i x_{k,i}^2 + \alpha_2^2 b_i x_{k-\tau,i}^2 + \alpha_1^2 b_i \tilde{x}_{k,i}^2 + \alpha_2^2 b_i \tilde{x}_{k-\tau,i}^2}_{U} + \\ & + \underbrace{2\alpha_1^2 \tilde{x}_{k,i} x_{k,i} + 2\alpha_2^2 x_{k,i} \tilde{x}_{k-\tau,i} + 2\alpha_1\alpha_2 \tilde{x}_{k,i} x_{k-\tau,i}}_{I_1} \\ & + \underbrace{2\alpha_1\alpha_2 (b_i \tilde{x}_{k,i} \tilde{x}_{k-\tau,i} + b_i x_{k,i} x_{k-\tau,i} + \tilde{x}_{k-\tau,i} x_{k,i})}_{I_2} \\ & + \underbrace{\alpha_1 b_i (\tilde{x}_{k,i} n_k + x_{k,i} \tilde{n}_k) + \alpha_2 b_i (\tilde{x}_{k-\tau,i} n_k + x_{k-\tau,i} \tilde{n}_k)}_{N_1} \\ & + \underbrace{(\alpha_1 x_{k,i} + \alpha_2 x_{k-\tau,i}) n_k + (\alpha_1 \tilde{x}_{k,i} + \alpha_2 \tilde{x}_{k-\tau,i}) \tilde{n}_k + n_k \tilde{n}_k}_{N_2} \Bigg) \end{aligned} \quad (7)$$

where U represents the useful signal, I_1 and I_2 are the interference components generated from the multipath channel and the chaotic sequence, and N_1 and N_2 designate interference emerging from Gaussian noise.

III. Performance Analysis of I-DCSK System

In this section, the performance of I-DCSK scheme is evaluated. Furthermore, the BER expressions under AWGN and multipath fading channels are analytically derived. To this end, the mean and the variance expressions of the decision variable D_i are determined. Different signal components U, I_1, I_2, N_1, and N_2 in (7) are independent because channel coefficients are independent of each other, of the chaotic sequences and of the Gaussian noise. In addition, the chaotic sequence is independent of its time reversed version and of the Gaussian noise as well [8]. In this work, the second-order Chebyshev polynomial function (CPF) is employed to generate chaotic sequences due to its easiness and good performance [20]. For simplicity, the chip time T_c is set to unity,

$$x_{k+1} = 1 - 2x_k^2 \cdot \quad (8)$$

The variance of the normalized chaotic map with zero mean is equal to one, i.e. $\mathrm{Var}(x) = \mathrm{E}[x^2] = 1$, where $\mathrm{E}[\,.\,]$ denotes the expected value operator. Therefore, for the i^{th} bit, the instantaneous mean of the decision variable is the mean of the useful signal given by

$$E\left[D_i\right] = b_1(\alpha_1^2 + \alpha_2^2)E_b, \quad (9)$$

where $E_b = 2\sum_{k=1}^{\beta} E\left[x_{k,i}^2\right]$ represents the transmitted bit energy. Equation (9) is significant because apart from the useful signal U, all other components described in (7) have zero mean. The conditional variance of the decision variable for the i^{th} bit may be expressed as

$$V\left[D_i\right] = V\left[I_1\right] + V\left[I_2\right] + V\left[N_1\right] + V\left[N_2\right], \quad (10)$$

The variances of I_1, I_2, N_1 and N_2 can be directly obtained from (7) in the following manner

$$V\left[I_1\right] = 2E_b\left(\alpha_1^4 + \alpha_2^4 + \alpha_1^2\alpha_2^2\right) \cdot \quad (11)$$

$$V\left[I_2\right] = 6E_b\left(\alpha_1^2\alpha_2^2\right) \cdot \quad (12)$$

The variance of I_1 and I_2 are obtained because the mean value of the squared product of two chaotic sequences (time inverted or shifted) can be equal to $\sum_{k=1}^{\beta} \mathrm{E}[(\tilde{x}x)^2] = \sum_{k=1}^{\beta} \mathrm{E}[x^2] = E_b/2$. This returns to the fact that the chaotic sequences are independent and have a unit variance.

$$V[N_1] = \frac{E_b}{2} N_0 \left(\alpha_1^2 + \alpha_2^2\right) \cdot \quad (13)$$

Similarly, the variance of N_2 can be expressed by

$$V[N_2] = \frac{E_b}{2} N_0 \left(\alpha_1^2 + \alpha_2^2\right) + \beta \frac{N_0^2}{4} \cdot \quad (14)$$

The add-up of the variance components above results in the variance of the decision variable, which becomes

$$\begin{aligned} & V\left[D_i\right] = \\ & 2E_b\left(\alpha_1^4 + \alpha_2^4\right) + 8E_b\left(\alpha_1^2\alpha_2^2\right) + E_b\left(\alpha_1^2 + \alpha_2^2\right)N_0 + \beta\frac{N_0^2}{4} \cdot \end{aligned} \quad (15)$$

Since bit energies (or chaotic chips) are deterministic variables, thanks to central limit theorem the decision variable at the output of the correlator follows a Gaussian distribution. Therefore, the bit error probability is represented by

$$\begin{aligned} \mathrm{BER} =& \tfrac{1}{2}\Pr\left(D_i < 0 \middle| b_i = +1\right) \\ & + \tfrac{1}{2}\Pr\left(D_i > 0 \middle| b_i = -1\right), \end{aligned} \quad (16)$$

which can be given as

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\left[\frac{2V\left[D_i\right]}{\mathrm{E}\left[D_i\right]^2}\right]^{-\frac{1}{2}}\right), \quad (17)$$

where $\mathrm{erfc}(x)$ is the well-known complementary error function defined as $\mathrm{erfc}(x) \equiv \frac{2}{\sqrt{\pi}}\int_x^{\infty} e^{-\mu^2} d\mu \cdot$ By virtue of equations (9) and (15) above, the BER for the I-DCSK scheme can be determined and stated as

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\left[\begin{array}{l} \frac{4\left(\alpha_1^4+\alpha_2^4\right)+16\alpha_1^2\alpha_2^2}{\left(\alpha_1^2+\alpha_2^2\right)^2 E_b} + \\ \frac{2N_0}{\left(\alpha_1^2+\alpha_2^2\right)E_b} + \frac{\beta N_0^2}{2\left(\alpha_1^2+\alpha_2^2\right)^2 E_b^2} \end{array}\right]^{-\frac{1}{2}}\right). \quad (18)$$

Equation (18) gives the theoretical BER benchmark of I-DCSK system over multipath fading channels. Based on this, it is essential to note that the channel keeps changing at every transmission instant, so the average BER expression becomes

$$\overline{BER} = \frac{1}{2}\int_0^{\infty}\int_0^{\infty} \mathrm{erfc}\left(\left[\begin{array}{l} \frac{4\left(\alpha_1^4+\alpha_2^4\right)+16\alpha_1^2\alpha_2^2}{\left(\alpha_1^2+\alpha_2^2\right)^2 E_b}+ \\ \frac{2N_0}{\left(\alpha_1^2+\alpha_2^2\right)E_b}+ \\ \frac{\beta N_0^2}{2\left(\alpha_1^2+\alpha_2^2\right)^2 E_b^2} \end{array}\right]^{-\frac{1}{2}}\right) f(\alpha_1)f(\alpha_2)d\alpha_1 d\alpha_2. \tag{19}$$

Equation (18) can be extended to AWGN channel case by choosing $\alpha_1 = 1$ and $\alpha_2 = 0$. Hence, the BER expression under AWGN would simplify to

$$\mathrm{BER} = \frac{1}{2}\mathrm{erfc}\left(\left[\frac{4}{E_b} + \frac{2N_0}{E_b} + \frac{\beta N_0^2}{2E_b^2}\right]^{-\frac{1}{2}}\right). \tag{20}$$

Finally, for high spreading factor, the transmitted bit energy E_b can be considered constant as in this paper. Therefore, for low spreading factor the energy variation must be taken into account and derived, as done in [20].

IV. Discussions and Simulation Results

In order to validate the performance of the I-DCSK scheme and compare it to existing chaos-based and conventional non coherent schemes, the computed BER expressions are verified and well justified by simulation results under AWGN and multipath fading channels. Fig. 2 shows performance results of the I-DCSK, QCSK and DCSK schemes for a spreading factor $\beta = 200$. In addition, the performance of the DPSK system is plotted for a symbol duration of $T_s = 200T_c$.

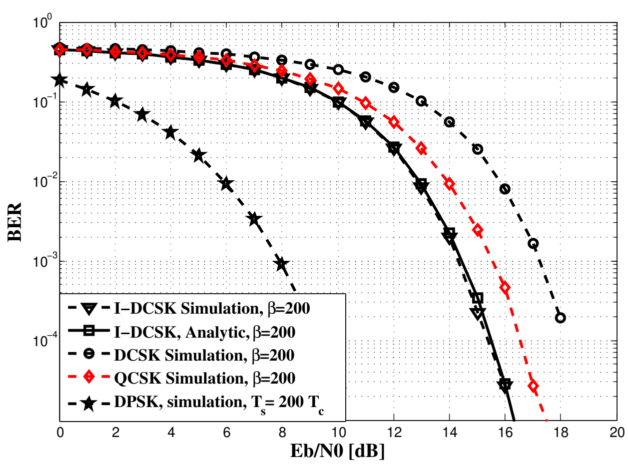

Fig. 2: Simulation and analytical BER in AWGN channel of I-DCSK, QCSK and DCSK systems for $\beta = 200$.

As can be seen in Fig. 2, simulation results perfectly validate the analytical BER expression given in (20). As depicted, I-DCSK and QCSK manifest a close BER performance but with lower complexity. In addition, an enhancement is achieved by both systems compared to DCSK. The performance enhancement between QCSK and DCSK is explained in [15]. On the other hand, 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 (see Equation (9)). Moreover, the spectral efficiency in I-DCSK system is two times higher than DCSK and is equal to QCSK. The derived BER expression represents the lower bound performance of the system. Therefore, if the orthogonality between the chaotic sequences (i.e reference and data carrier sequence $\sum_{k=1}^{\beta} x_k\tilde{x}_k << 1$) is not maintained (small spreading factor can affects time inverse operation) the performance will be degraded and the analytical BER expressions are no longer valid for such scenario. In addition, the selected chaotic sequence and its time inversion replica is this simulation respect the orthogonality property. Finally, as expected, DPSK modulation outperforms DCSK in AWGN channels. This is because DCSK spends half of the bit energy to transmit the reference signal, and AWGN influences both reference and data carrier signals [9], [12].

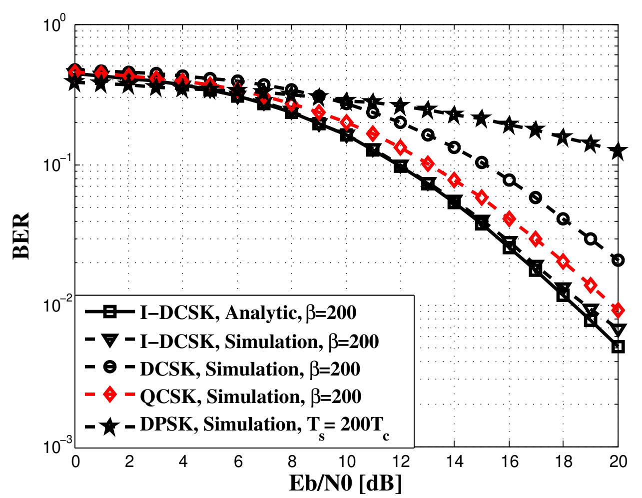

Fig. 3: Simulation and computed BER under multipath Rayleigh fading channels of I-DCSK, QCSK and DCSK systems for $\beta = 200$.

The obtained BER performance under multipath Rayleigh fading channel for a spreading factor $\beta = 200$ is shown in Fig. 3. The average power gains of the first and second paths are $E[\alpha_1^2] = 0.7$ and $E[\alpha_2^2] = 0.3$ respectively with a delay $\tau = 6T_c$ existing between the two paths. Simulation results endorse the accuracy of our BER expression given by (19).

As observed in Fig. 3, the proposed I-DCSK system outperforms DCSK and QCSK with a bit less gain than AWGN case. This can be interpreted in the following manner: The I-DSCK system has more cross terms interference emerging from the addition of reference to data carrier signals. In

AWGN channels, the higher power ratio of useful signals to interference signals (i.e twice the power of useful signals in DCSK) will compensate the interference power and lead to the aforementioned performance improvement. Therefore, the multipath channel significantly increases the number of cross terms interference in I-DCSK which degrades its overall signal-to-noise ratio. This is why the proposed system does not outperforms the other systems in the multipath channel. We can conclude that the proposed I-DCSK technique can be considered as a promising low complexity solution with high spectral efficiency. On the other hand, Fig. 3 shows that the conventional narrowband DPSK system is not suitable for the multipath fading environment, recommending I-DCSK as a suitable solution for UWB applications [12].

V. Conclusion

An improved spectrally efficient DCSK system has been proposed in this paper. At the transmitter, the reference signal is first time reversed, and then added to the data carrier signal. This operation aims at making the reference signal orthogonal to the data carrier signal, to allow summation and avoid the use of delay lines. In addition, this design reduces the frame duration to half, which doubles the total data rate of the system. The received signal is correlated at the receiver with the time inverted replica in order to recover the transmitted data. Moreover, the performance of the I-DCSK is analytically studied and the general bit error rate expression under multipath fading channels is derived. The analytical BER expression is then simplified to suit the AWGN channel scenario. Computer simulations are carried out to confirm the derived analytical results. Finally, simulation results show that our system outperforms DCSK and QCSK systems in AWGN channels and exhibits a closer performance to these systems in multipath fading channels dB but with less complexity. Taking BER, bandwidth and complexity into consideration, the overall performance of our proposed system is promising. Finally, future work will focus on a generalized M-ary I-DCSK system.

References

[1] A. P. Kurian, S. Puthusserypady, and S. M. Htut, "Performance Enhacment of DS-CDMA System Using Chaotic Complex Spreading Sequence," *IEEE Trans. Wireless Commun.*, vol. 4, no. 3, pp. 984 – 989, 2005.

[2] R. Vali, S. Berber, and S. K. Nguang, "Accurate Derivation of Chaos-Based Acquisition Performance in a Fading Channel," *IEEE Trans. Wireless Commun.*, vol. 11, no. 2, pp. 722–731, 2012.

[3] Y. Fang, L. W. J. Xu, and G. Chen, "Performance of MIMO Relay DCSK-CD Systems over Nakagami Fading Channels," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 60, no. 3, pp. 1–11, 2013.

[4] Y. Fang, L. Wang, and G. Chen, "Performance of a Multiple-Access DCSK-CC System over Nakagami-m Fading Channels," in *IEEE International Symposium on Circuits and Systems (ISCAS)*, 2013, pp. 277–280.

[5] W. Xu, L. Wang, and G. Chen, "Performance of DCSK Cooperative Communication Systems over Multipath Fading Channels," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 58, no. 1, pp. 196 –204, 2011.

[6] C.-C. Chong and S. K. Yong, "UWB Direct Chaotic Communication Technology for Low-Rate WPAN Applications," *IEEE Trans. Veh. Technol.*, vol. 57, no. 3, pp. 1527 – 1536, 2008.

[7] G. Kaddoum, F. Richardson, and F. Gagnon, "Design and Analysis of a Multi-Carrier Differential Chaos Shift Keying Communication System," *IEEE Trans. Commun.*, vol. 61, no. 8, pp. 3281 – 3291, 2013.

[8] F. C. M. Lau and C. K. Tse, *Chaos-Based Digital Communication Systems*. Springer-Verlag, 2003.

[9] M. P. Kennedy, G. Kolumbán, G. Kis, and Z. Jákó, "Performance Evaluation of FM-DCSK Modulation in Multipath Environments," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 47, no. 3, pp. 1702–1711, 2000.

[10] Z. Zhibo, Z. Tong, and W. Jinxiang, "Performance of Multiple-Access DCSK Communication over a Multipath Fading Channel with Delay Spread," *Circuits, Systems and Signal Processing*, vol. 27, no. 4, pp. 507–518, 2008.

[11] P. Chen, L. Wang, and F. Lau, "One Analog STBC-DCSK Transmission Scheme Not Requiring Channel State Information," *IEEE Trans. Circuits Syst. I, Reg. Papers*, vol. 60, no. 4, pp. 1027 – 1037, 2013.

[12] Y. Xia, C. K. Tse, and F. C. M. Lau, "Performance of Differential Chaos-Shift-Keying Digital Communication Systems over a Multipath Fading Channel with Delay Spread," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 51, no. 12, pp. 680 – 684, 2004.

[13] S. Wang and X. Wang, "M-DCSK-Based Chaotic Communications in MIMO Multipath Channels With No Channel State Information," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 57, no. 12, pp. 1001–1005, Dec 2010.

[14] W. K. Xu, L. Wang, and G. Kolumban, " A Novel Differential Chaos Shift Keying Modulation," *Int. J. Bifurcation Chaos*, vol. 21, no. 03, pp. 799 – 814, 2011.

[15] Z. Galias and G. M. Maggio, "Quadrature Chaos Shift Keying: Theory and Performance Analysis," *IEEE Trans. Circuits Syst. I, Fundam. Theory Appl.*, vol. 48, no. 12, pp. 1510–1519, 2001.

[16] H. Yang and G.-P. Jiang, "High-Efficiency Differential-Chaos-Shift-Keying Scheme for Chaos-Based Noncoherent Communication," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 59, no. 5, pp. 312 – 316, 2012.

[17] P. Chen, L. Wang, and G. Chen, "DDCSK-Walsh Coding: A Reliable Chaotic Modulation-Based Transmission Technique," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 59, no. 2, pp. 128–132, Feb 2012.

[18] G. Kaddoum and F. Gagnon, "Design of a High-Data-Rate Differential Chaos-Shift Keying System," *IEEE Trans. Circuits Syst. II, Exp. Briefs*, vol. 59, no. 99, pp. 1–5, 2012.

[19] Z. Galias and G. Maggio, "Quadrature chaos shift keying," in *The 2001 IEEE International Symposium on Circuits and Systems, ISCAS*, vol. 3, May 2001, pp. 313–316.

[20] G. Kaddoum, P. Chargé, D. Roviras, and D. Fournier-Prunaret, "A Methodology For Bit Error Rate Prediction in Chaos-Based Communication Systems," *Circuits, Systems and Signal Processing*, vol. 28, no. 6, pp. 925–944, 2009.