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Transmission System Using Chaotic Delays Between Lightwaves

Min Won Lee, Laurent Larger, and Jean-Pierre Goedgebuer

Abstract—We report a chaos-based transmission system that uses optical path differences between wavegroups produced by a short coherence source. Chaos synchronization is demonstrated in delay-differential equations involving optical delays larger than the coherence length of the source. The particular feature is all-optical chaos subtraction for message extraction and a very high masking efficiency.

Index Terms—Chaos, coherence modulation, encryption, unbalanced electrooptic Mach–Zehnder.

IN RECENT years, secure communication systems based on chaotic dynamics have known an increasingly interest in electronics [1], [2], optics [3], [4] and optoelectronics [5], [6]. Most investigations have focused on the problem of chaos synchronization [7] with low- and high-dimensional chaotic systems, and recently on the problem of anticipating chaos [8]. Also recently, all-optical chaos synchronization and signal encryption/decryption with signal bandwidths up to the gigahertz range have been demonstrated experimentally from chaotic lasers with external feedback [9], [10]. All of those investigations have been sustained by the need of exploring mechanisms by which coupled simple nonlinear elements can entrain one another, one of the last example in this area being the investigation of delay-coupled semiconductor lasers [11]. The basic idea behind the use of chaos to transmit messages is to mask a message within a chaotic carrier before transmission, which is a form of spread-spectrum communication, and makes the presence of the signal difficult to detect in either the time or frequency domain, although breaking methods have been recently proposed [12], [14]. The masking efficiency is typically -15 dB in most of the present-day chaotic systems.

Unlike optical chaotic encryption systems reported to date, where chaos synchronization has been observed in the chaotic behavior of laser wavelength and laser intensity, we report in this paper the demonstration of chaos synchronization based on an unusual dynamical variable, the optical path-difference (OPD) between wavegroups of light produced by a short coherence source in coherence-modulated systems. Recent studies of chaos in coherence modulation have shown specific routes to chaos, including forward and reverse Hopf bifurcations, and their fundamental relevance [16]. We present the synchronization process

Fig. 1. Experimental setup. SLD: super luminescent diode. MZ: unbalanced electrooptic Mach–Zehnder. PD: photodiode. TD: time delay. Amp: amplifier. LPF: low-pass filter.

between two such chaos generators and report numerical and experimental results about its dependence on the chaotic keys.

The encryption system (Fig. 1) consists of a transmitter (subscript 1) and a receiver (subscript 2), which are built symmetrically. The message to be transmitted is $m(t)$. The transmitter consists of a short coherence source [a superluminescent diode (SLD)], and an integrated unbalanced Mach–Zehnder modulator (MZ_1) driven by a feedback loop. The feedback loop is formed by a second unbalanced MZ (MZ'_1), a photodetector PD_1 , a delay line (time delay $T_1 = 512 \mu s$), an electronic amplifier (gain $K_1 = 20$ dB), and a low-pass filter LPF_1 with a time response $\tau_1 = 6.4 \mu s$ (which stands for the time constant of the setup and corresponds to a cut-off frequency f_c). The continuous wave (CW) SLD operates at $\lambda_0 = \sigma_0^{-1} \approx 1.28 \mu m$ and with a coherence length $L_c \approx 47 \mu m$. Due to its low temporal-coherence degree, its emission may be regarded as a random sequence of wavegroups of coherence length L_c and whose correlation function is related to the temporal coherence degree of the source [15, Ch. 10]. The interferometers MZ_1 and MZ'_1 have identical static OPDs, ($D_{01} = D'_{01} = 260 \mu m$) greater than the coherence length. The optical beam at the output of MZ_1 is therefore formed by random pairs of wavegroups that do not produce any detectable intensity modulation since their extension L_c is much smaller than the OPD D_{01} separating them (for more details about coherence modulation, we refer the reader to [16]). Electrooptically modulating MZ_1 results in OPD variations $\Delta D_1(t)$ around D_{01} that are linearly related to the modulation voltage $V_1(t)$ through $\Delta D_1 = V_1/(2V_{\pi 1}\sigma_0)$, where $V_{\pi 1} = 4.3$ V is the half-wave voltage of MZ_1 . The OPD at MZ_1 output is $D_1(t) = D_{01} + \Delta D_1(t)$, with $\Delta D_1(t) \ll D_{01}$.

M. W. Lee is with the University of Wales, Bangor, Gwynedd LL57 2UW, Wales, U.K.

L. Larger and J.-P. Goedgebuer are with the University of Franche-Comté, 25030 Besançon, France.

A part of this coherence-modulated beam is sent to the receiver, while the other part is launched in MZ'_1 . MZ'_1 then converts nonlinearly the optical delay $D_1(t)$ into a detectable output intensity modulation given by [16]

$$I_1(t) = P_1 \left\{ 1 + \frac{1}{2} \cos[2\pi\sigma_0(D_1(t) - D'_{10})] \right\} \quad (1)$$

where $P_1 \approx 600$ nW is the average optical power at MZ'_1 output. After detection by PD_1 , the signal is time delayed by T_1 through the electronic delay line, filtered by the low-pass filter LPF_1 and serves as the feedback signal applied to MZ_1 . The message $m(t)$ is added to the feedback signal [17] with its amplitude (300 mV) at least ten times smaller than $V_1(t)$ (8.6 V). The amplitude of the feedback voltage $V_1(t)$ is adjusted to be twice higher than $V_{\pi 1}$. Under these conditions, ΔD_1 can be expressed as the addition of the OPD $\delta D_1(t)$ induced by the feedback signal and the OPD $D_m(t)$ induced by $m(t)$: $\Delta D_1(t) = \delta D_1(t) + D_m(t)$ with $D_m = m(t)/2V_{\pi}\sigma_0 \ll \delta D_1(t)$. Then, the transmitter equation, which rules the fluctuations of the OPD of MZ_1 is a delayed differential equation (DDE) that can be shown to be [16]

$$\delta D_1(t) + \tau_1 \delta \dot{D}_1(t) = F_1[\Delta D_1(t - T_1), \beta_1, \Phi_1]. \quad (2)$$

In (2), F_1 is a nonlinear function derived from (1) and expressed as

$$F_1(D_1, \beta_1, \Phi_1) = \beta_1 \left[1 + \frac{1}{2} \cos(2\pi\sigma_0 D_1 + \Phi_1) \right] \quad (3)$$

where $\beta_1 = 2K_1 P_1 / \sigma_0 V_{\pi 1} = 8$ is the bifurcation parameter and $\Phi_1 = 2\pi\sigma_0(D_{01} - D'_{01})$. Finally, the message $m(t)$ is encrypted at the transmitter into a chaotic coherence-modulated beam formed by wavepackets separated by a chaotically modulated OPD $D_1(t) = D_{01} + \delta D_1(t) + D_m(t)$ larger than the coherence length L_c of the source. Under these conditions, we do not have any detectable intensity modulation in the transmitter beam.

We have already described the complicated dynamics and routes to chaos corresponding to (2), showing that forward and reverse Hopf bifurcations can be obtained [16]. For the parameters used in the transmitter, the solutions of (2) are hyperchaotic, with the Lyapunov dimension evaluated from Kaplan–Yorke’s conjecture [18], [19] found to be about 76.

The receiver is constructed from the same components as those in the transmitter. A part of the transmitted beam is sent into the loop of the receiver. This loop is formed by MZ'_2 , which features a static OPD $D'_{02} = D'_{01}$ and a coherence demodulation function F_2 , a delay line T_2 , an amplifier (gain K_2) and a low-pass filter LPF_2 (response time τ_2). The output electrical signal of the loop serves as the driving voltage of MZ_2 (OPD D_{02} , half-wave voltage $V_{\pi 2}$) and generates chaotic fluctuations δD_2 of the OPD of MZ_2 around D_{02} . Those chaotic fluctuations are ruled by a DDE that can be expressed as

$$\delta D_2(t) + \tau_2 \delta \dot{D}_2(t) = F_2[\Delta D_1(t - T_2), \beta_2, \Phi_2] \quad (4)$$

with $\beta_2 = 2K_2 P_2 / \sigma_0 V_{\pi 2}$, $\Phi_2 = 2\pi\sigma_0(D_{01} - D'_{02})$, $F_2 = \beta_2[1 + 1/2 \cos(2\pi\sigma_0 D_2 + \Phi_2)]$, and P_2 is the average optical power at MZ'_2 output. Assuming $F_2 = F_1$, $\beta_2 = \beta_1$, $\Phi_2 = \Phi_1$, $\tau_2 = \tau_1$, and $T_2 = T_1$, (4) leads to solutions $\delta D_2(t)$ identical to

Fig. 2. Spectrum of the synchronization error for various parameter mismatches. The contour line indicates a -40 dB noise level. (a) Response time τ mismatch. (b) Delay T mismatch.

the solutions $\delta D_1(t)$ of (2), when there is no message ($m = 0$, $D_m = 0$) at the transmitter, meaning that we have chaos replication in that case.

The other part of the transmitted coherence-modulated beam is launched in MZ_2 . MZ_2 operates as a coherence demodulator that features a chaotically modulated OPD $D_{02} + \delta D_2(t)$ with $D_{02} = D_{01} + \lambda_0/4$. That branch is aimed at *optically* carrying out a subtraction between the chaotic fluctuations $\Delta D_1(t) = \delta D_1(t) + D_m(t)$ in the transmitted beam and those $\delta D_2(t)$ produced by MZ_2 , to retrieve the original message $m(t)$. Noting that $\delta D_1(t) = \delta D_2(t)$ and $D_m(t)$ is small, the output intensity $I_2(t)$ of MZ_2 is given by

$$I_2(t) = P_2 \left\{ 1 + \frac{1}{2} \sin[2\pi\sigma_0 D_m(t)] \right\} \approx P_2 \left[1 + \frac{\pi}{2V_{\pi}} m(t) \right]. \quad (5)$$

The original message $m(t)$ is then directly retrieved at the receiver output. Since matching the transmitter and receiver parameters is one key condition, it is important to know its impact on the recovery of the message. For that, we first evaluated the sensitivity of the synchronization process from numerical simulations using (2) and (4), and introducing voluntarily mismatches between the different parameters at the receiver. The computations were done with no message ($D_m(t) = 0$) and evaluating the power spectrum of the synchronization error signal $\delta D_1 - \delta D_2$ (which is also chaotic), normalized to the rms level of the chaotic carrier ($\langle \delta D_1^2 \rangle_t$), as a function of the relative parameter mismatch expressed as a percent. Results of the simulations are plotted in Fig. 2 for mismatches ranging

Fig. 3. Experimental synchronization with a mismatch between T_1 and T_2 . (a) Receiver chaos versus emitter chaos for a 0.01% T -mismatch. (b) Same representation for a 1% T -mismatch.

from -2% to 2% for τ_2 and for T_2 . In Fig. 2, the magnitude of the decoding noise (expressed in decibels) is encoded into gray scales, where dark gray corresponds to a very small synchronization error (a good message recovery), whereas white indicates a very bad synchronization, and hence a bad message decoding. Typically, following the usual standards in telecommunications, a good decoding quality is obtained when the noise level is smaller than -40 dB that corresponds here to 20 dB for the signal-to-noise ratio and 20 dB for the chaos-to-signal ratio. A contour for those -40 dB is indicated in the figure. Computation shows that synchronization is very sensitive to a time delay mismatch [Fig. 2 (b)]. In that case, the decoding noise can reach 0 dB when the mismatch is a few percent, meaning that the message is completely altered by noise. In contrast, the synchronization process is much less sensitive to a τ -mismatch, as shown in Fig. 2 (a). Similar computations can be done for parameters β and Φ , showing that an intermediate sensitivity is obtained, compared to the one presented for parameters τ and T .

To confirm those numerical simulations, we then investigated experimentally the synchronization process by varying the value of the time delay mismatch, all the other parameters being closely matched one with each other. The results are shown in Fig. 3. Fig. 3(a) shows, for a 0.01% T_2 -mismatch, the Lissajou representation of the driving signals of MZ_1 and MZ_2 , which are linearly related to $\Delta D_1(t)$ and $\Delta D_2(t)$ at the transmitter and receiver, respectively. In spite of their multiple positive Lyapunov exponents [7], these signals show a very good synchronization, and the signal-to-noise ratio was then measured to be 36.5 dB from this figure. Fig. 3(b) corresponds to only a 1% T_2 -mismatch, resulting in a large synchronization error and non correlated chaotic signals. The fact that the most critical parameter to consider is the time delay in the feedback loop has already been observed with other chaotic schemes [20].

In a third step, we adjusted the parameters to meet the conditions of optimal matching (all the parameters matched to less than 1%), and we introduced a message $m(t)$ in the feedback loop of the transmitter. The encryption and decryption results are illustrated in Fig. 4. Fig. 4(a) shows the original and decoded message $m(t)$ in the case of a 1-kHz sine waveform. The driving voltage of MZ_1 thus obtained (lower trace), and the intensity of the coherence-modulated beam carrying the message

in the transmission line (upper trace), are shown in Fig. 4(b). The residual intensity modulation was measured to be smaller than 1% of the average intensity. This residual intensity modulation is due to the low mutual coherence degree of the wavegroups of light at MZ_1 output, and could be made even smaller by using an OPD D_{01} in MZ_1 greater than $260 \mu\text{m}$. We also show the spectrum of the residual intensity modulation of the coherence-modulated beam [Fig. 4 (c)], which provides information that an eavesdropper can detect when tapping the transmission fiber. No detectable peak at the 1-kHz message frequency can be seen in the spectrum, down to -70 dB, which is the masking efficiency (the masking efficiency in chaotic transmission systems is expressed as the message-to-chaos ratio in the transmitted signal). The message is therefore strongly hidden due to the chaotic coherence modulation encryption. Finally, the spectrum of the decoded message from the receiver is shown in Fig. 4 (d), in which the signal-to-noise ratio was measured to be 33 dB. In the case of a realistic broadband information message, we observed similar signal-to-noise ratio performances, which can be explained by the fact that the decoding noise does not depend significantly on the frequency inside the chaos generator bandwidth (see Fig. 2).

To summarize, we have reported for the first time the proofs of principle of an optical cryptographic system based on a chaotic coherence modulation. OPD fluctuations are used to mask an information message. The chaotic waveform exhibits a high Lyapunov dimension (≈ 76). Such a hyperchaos was successfully synchronized in a transmitter and receiver, and the impact of mismatches has been investigated numerically and experimentally. Encryption and decryption of a message was obtained experimentally with a 33-dB signal-to-noise ratio. Direct recovery of the message at the receiver was performed through a subtraction process performed optically (which seems to be specific to the coherence demodulation scheme), unlike other schemes in which an electronic subtractor is generally used. The system features an extremely high masking efficiency (-70 dB), a value which is the best performance reported with chaotic systems so far. The system could operate in the gigahertz range with high-speed components [9]. Another attractive feature of the system concerns the multiplexing capabilities of coherence modulation systems [21], in which each channel can be attached to a different OPD. Finally, the system can be potentially dedicated to optical telecommunications,

Fig. 4. Experimental encoding and decoding results. (a) Original and decoded 1-kHz sine-waveform. (b) Transmitted intensity and corresponding OPD fluctuations. (c) FFT of the transmitted intensity. (d) FFT of the recovered message.

since it makes use of fiber-based components and integrated Mach-Zehnder modulators.

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