Chaos Based Optical Communication

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Abstract—**Chaos based communication has been a very attractive research field from last couple of decades due to its potential of providing secure communication. In this paper, we reviewed principles and theory governing the field of chaos. We studied governing principles and different methods for chaotic signal generation and schemes used to modulate message signal with chaotic signal in optical fiber communication systems. We also reviewed the principal concepts governing chaos synchronization, types of chaos synchronization and some proposed techniques used for the synchronization of transmitter and receiver in optical fiber communication systems.**

***Index Terms*—Chaos, chaos communication, chaos generation, chaos masking, chaos modulation, chaos shift keying, chaos synchronization.**

I. Introduction

Chaotic optical communication systems have been very attractive field of research from last couple of decades. In this type of communication, the user message signal is transmitted using chaotic carrier signal and retrieved at receiver upon synchronization with transmitter. Chaos based communication is very hard to intercept, since it is very sensitive to the initial condition. The rest of the paper is divided into the four sections; Section-2 explains the basic principles governing chaos theory and chaotic signals followed by Section-3 where we explain theories and principles used in chaotic optical communication, includes chaos generation, chaotic transmission and chaotic synchronization. Finally the study is briefly summarized in Section-4, followed by Section-5 in which we identify the broad research areas in which groups around the world are working and contributing.

II. Introduction-Chaos Theory

Chaos theory, the field of study in mathematics and physics used to describe the behavior of dynamical systems that are highly sensitive to initial state of the system i.e. small perturbation in initial condition yields significantly varying behavior, also referred to as butterfly effect [1]-[2]. This implies that long term prediction is impossible even the system is deterministic, also known as deterministic chaos [1] -[2]. The dynamical system evolves its state with time that may exhibit dynamics [1]-[2]. Some dynamical systems exhibit chaotic behavior every where but in most cases the chaos exists only in a subset space, since a set of initial conditions may lead to same chaotic region e.g. a chaotic behavior may take place on an attractor [1]-[2].

An attractor is a set of states which a dynamical system attains after a long period of time, it may be set of points, a curve or a complicated fractal (strange attractor) [3]. Differential equations, partial differential equations and difference equations are used to describe the states of dynamical systems for short period of time [1]-[3]. Any attractor contains an infinite state of unstable orbits that leads to complicated and unpredictable roving over a long period of time [1]-[3]. Chaos is controlled using stabilization algorithms, based on small perturbation in the some of the unstable orbits e.g. OGY (Ott, Grebogi and Yorke) method, Pyragas continuous control [3].

A. Chaotic Signals in Communications

Chaotic signals are random noise like signals as shown in Figure1. Chaotic signals are used in communication systems to provide secure communication of data [1]. Communication based on chaotic carrier are hard to intercept and predict but can be if receiver is proper synchronized. It is one of the anti-jamming communication techniques. Chaotic signal is also used as wideband carrier leading to high data rate communication.

Chaotic signals are analog in nature but they can be used as carrier signal in analog as well as in digital communication. Chaotic carriers are like pseudo-random signals used in spread spectrum communication, but chaotic carriers are analog signals unlike pseudo-random signals used in spread spectrum communication as shown in Fig. 1.

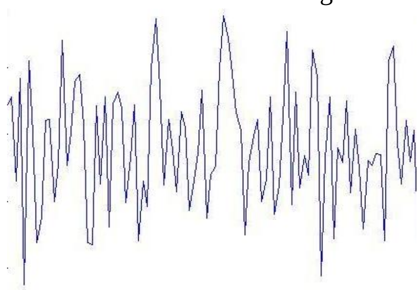

Fig. 1. Chaotic signal.

III. Chaos in Optical Communication

In this section, we will present a brief rationalization of methods used for optical chaotic carrier generation, followed by chaotic transmission and finally we will present some schemes used to synchronize transmitter and receiver.

A. Generation of Optical Chaotic Carrier

Optical chaotic carrier is generated by varying the intensity of laser diode (LD). The dynamic operating states of a laser can be achieved using different methods e.g. optical injection

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[4]-[5] optical feedback [6]-[7] and optoelectronic feedback [8].

Optical chaotic signal can be generated using integrated devises [9]. Hybrid integrated chaos generator is shown in Fig. 2 [9]. It can be divided into two major parts, integrated fiber cavity (IFC) and external distributed feed-back (DFB) laser. IFC comprises of a 90/10 coupler, thermally tunable variable optical attenuator (VOA), phase section (PS) and a reflector having reflectivity more then 95%. The dynamic behavior of generated signal is a function of feedback strength from IFC. VOA will vary the intensity of a laser. This varying strength depends on the voltage applied to VOA. A voltage of 0V means a loss of 40dB. The loss decreases gradually by increasing the voltage applied to VOA, thus the dynamic behavior of a signal depends on the VOA, leads to the generation of chaotic signal. PS does not contribute in the dynamics of the signal but used only to adjust the phase of the signal.

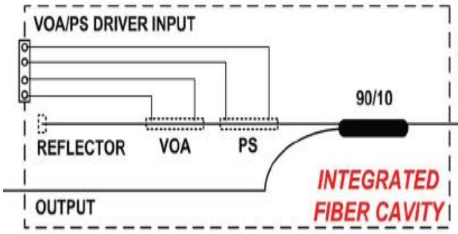

Fig. 2. Hybrid integrated chaos generator [9].

Optical chaotic signal can also be generated by using an optoelectronic feedback shown in Fig. 3. [8].

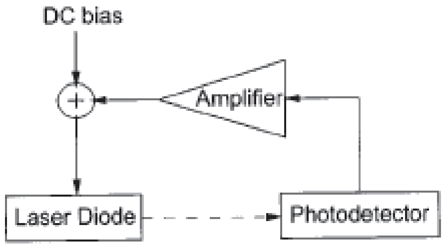

Fig. 3. Laser with optoelectronic feedback [8].

Similar to Hybrid integrated chaos generator, chaotic optical signal is a function of the variation in the intensity of a LD resulted by feedback in optoelectronic feedback. In optoelectronic feedback laser diode, photo detector (PD) is used to convert the optical signal to electrical signal, amplified by an amplifier and is then applied to LD after the addition of a DC bias voltage. The gain of an amplifier and DC bias plays an important role in generation of a chaotic signal. The resultant variations in optical signal depend on the gain and DC bias voltage. The configuration is known as optoelectronic feedback because electrical components are involved in the feedback.

Chaotic signal can also be generated using optical feedback. In this configuration setup, a mirror is used as feedback devise. The dynamics of the laser changes due to interference of the light reflecting from a mirror and a field inside a LD. It results in fluctuations in the output power resulted by the interference inside the cavity of LD, the resultant output signal is a chaotic signal. The effect of optical reflector on the output power is shown in Fig. 4. [6].

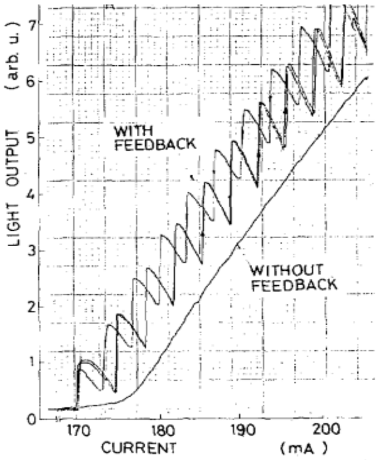

Fig. 4. Optical output with and without reflector [6].

B. Chaotic Transmission

In chaos based optical communication; generally following three schemes are used for chaos based transmission of data:

Chaotic masking/addition

Chaotic modulation

Chaos switching

In chaotic masking, message signal is simply added to the chaotic signal and is transmitted [1]. Schematic diagram for chaos masking is shown in Fig. 5 (a). The transmitted signal is a noise like signal depicted in Fig. 6 (a). Receiver recovers the message signal by subtracting locally generated chaos signal from received signal as shown in Fig. 5. (b). The recovered signal is shown in Fig. 6. (b).

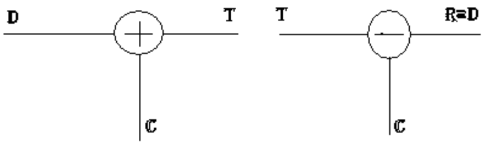

Fig. 5. (a) Transmitter setup (b) Receiver setup.

For error free recovery of message signal, the locally generated chaotic signal must be synchronized with the transmitter chaotic signal [1]. Let D(t) be a message signal and C(t) represents the locally generated chaotic signal, the transmitted signal T(t) can be modeled mathematically as

$$T(t) = D(t) + C(t) \tag{1}$$

The receiver recovers the message signal D(t) by subtracting chaos signal C(t) from the received signal as

$$\begin{aligned} R(t) &= T(t) - C(t) \\ R(t) &= (D(t) + C(t)) - C(t) \\ R(t) &= D(t) \end{aligned} \tag{2}$$

Fig. 6. (a) Transmitted signal.

Fig. 6. (b) decoded message.

Chaotic modulation is another method, based on the classical method of modulation i.e. multiplication of message signal with the chaotic carrier as shown in Fig. 7. Receiver retrieves the message signal using the same classical methods of demodulation using locally generated chaotic signal.

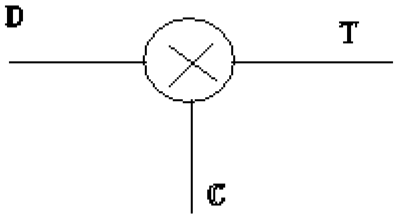

Fig. 7. Chaotic modulation (Transmitter).

Chaos switching is another scheme used mostly in digital communication [1]. In Chaos switching, similar to shift keying methods used in communication systems chaotic signals are generated for all symbols in the alphabet set. There is a 1-1 mapping between symbols and chaotic signal. Transmitter transmits a particular chaotic signal in a fashion shown in Fig. 8. [10].

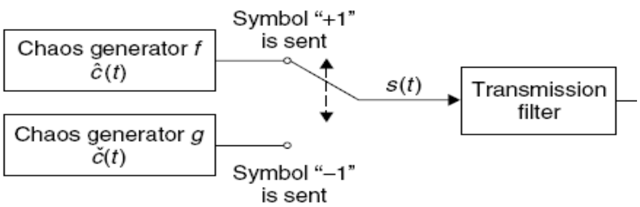

Fig. 8. Chaos switching [10].

The receiver recovers the signal by computing maximum correlation between the received signal and the set of locally generated chaotic signals [1]-[10]. Maximum correlation provides the corresponding message symbol. The chaos switching is also known as chaos shift keying.

C. Synchronization of Chaotic Carriers at Transmitter and Receiver

Two chaotic oscillators or transmitter and receiver in simpler terms are said to be synchronized when they are properly coupled. Synchronization of the chaos based transmitter and receiver plays a vital role in an error free communication between the two systems. Chaos synchronization can be classified into the following classes based on synchronization parameters:

Identical synchronization
Generalized synchronization
Phase synchronization
Anticipated and lag synchronization
Amplitude envelop synchronization

Identical synchronization is a form of synchronization where two identical chaotic oscillators are coupled mutually or either of the oscillators is driven by the other one. In this case the dynamical variables used to define the state of the systems are equal. When non-identical chaotic oscillators are coupled mutually, this results in the form of synchronization known as generalized synchronization [11]. In generalized synchronization, the dynamical variables, defining state of systems are affiliated with each other using a transform function φ such that after transformation, they are identical to each other. Phase synchronization is the case when two non-identical oscillators are coupled mutually with respect to phase and the amplitudes remain unsynchronized. Anticipated and lag synchronization is a form of synchronization where the synchronization state of the systems is related to each other by a time difference τ, described by delay differential equations. In this form, the dynamics of one oscillator follows the dynamics of the other one. Amplitude envelop synchronization is a soft form of synchronization in which neither phase nor amplitude is synchronized but the systems exhibit a periodic envelop having same frequency in the two systems [11].

In chaos based optical communication, chaos synchronization is realized either by complete synchronization (CS) or generalized synchronization (GS). In CS, two identical systems are said to be coupled mutually when all parameters of the systems are essentially matched [14]. On the other hand GS does not require the systems to have all parameters identical to each other i.e. some of the parameters in the systems are required to be in synchronous with each other.

In practice combination of CS and GS are used. There are different proposals defining systems based on the combination of CS and GS. Some of the systems uses single channel for synchronization as well as for data communication. In this configuration, the time delay between control packets, used to synchronize the two systems and data packets is significant for higher data rates. There is a trade off between acceptable delay and quality of the communication. Signal in this form of setup induces a synchronization error.

A different approach uses two identical pairs of chaos based master and slave systems, one at transmitter and the other at receiver [12] – [13]. The configuration uses two channels, one for CS between master system of the transmitter and receiver while the other channel is used by the slave system of the two ends to compare the trajectories. Binary message is encrypted using the coupling strength between master and slave systems in the transmitter. The message is recovered at the receiver by examining the error dynamics of the receiver. This method is the result of the modification in CSK with the major change of using two channels. A slightly different configuration uses GS on one of the channels. It has been found that in CSK based methods, the binary message intrinsically induces a synchronization error at higher data rates i.e. limiting the rate of communication, due to the synchronization time.

In another method, two channels are utilized with pair of lasers (master laser and slave laser) at both transmitter and receiver. Master laser (ML) and slave laser (SL) are not essentially identical but exhibit GS while ML at transmitter and receiver are identical (or nearly identical) to demonstrate CS. One possible implementation of the complete setup of the system is shown in Fig. 9.

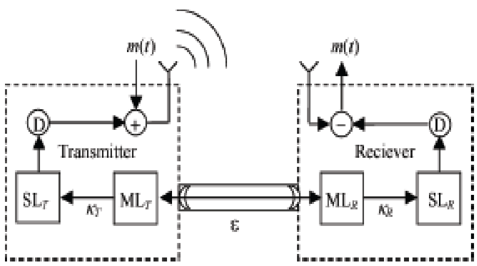

Fig. 9. System based on two channels using CS and GS in combination [12].

ML in transmitter and receiver can be coupled either in unidirectional or bidirectional manner. The main advantage of bidirectional coupling is the immunity against eaves dropper. Transmitter receives feedback from the receiver revealing its behavior. If some one was able to intercept the synchronization channel, he/she would try to use some of the power to synchronize his laser; this would result in power reduction entering into the receiver. The returning power to the transmitter can assist it to identify malicious activity in the channel. Another advantage of bidirectional coupling between ML of transmitter and receiver is the robustness against parameter mismatch i.e. small parameter mismatch does not affect communication quality [12]. The communication model is evaluated using Q-function, mathematically modeled as

$$Q = (P1 - P0) / (\sigma 1 + \sigma 0)$$

where P is the average power of bit 1 and 0, σ is corresponding standard deviation.

Chaos shift keying and chaos masking transmission methodologies are compared with each other in Fig. 10. Above the dashed line, the transmission quality is good. From the Fig it is quite clear that higher data rates (5Gbps) are not possible for chaos shift keying. Bit error ratio (BER) as a function of Q for both unidirectional and bidirectional coupling has been shown in Fig. 11.

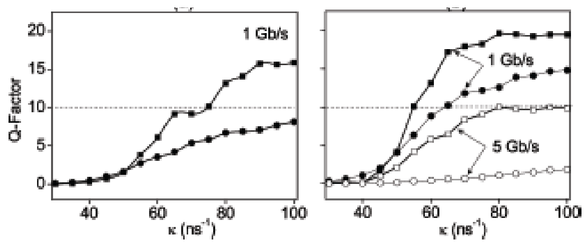

Fig. 10. Coupling parameter is set to Q-function (a) chaos shift keying (b) chaos masking, when ML of transmitter and receiver is unidirectionally coupled (dots) and bidirectionally coupled (squares) [12].

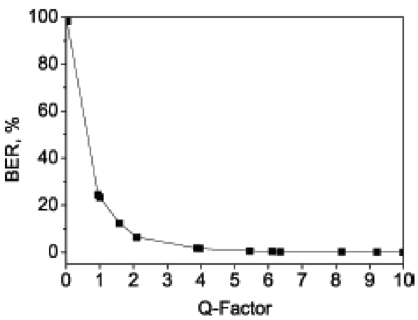

Fig. 11. BER for unidirectional and bidirectional coupling [12].

IV. Conclusion

In this paper we explained theory of chaos briefly and its application in optical fiber communication. We explicated briefly chaos as a field of research in optical fiber communication systems. Different techniques used to generate optical chaotic signals and schemes used for chaotic transmission are discussed briefly in this paper. Synchronization as the vital part of chaotic communication is conferred in this work. We briefly described types and different approaches used to synchronize transmitter and receiver.

Chaos masking has been reported a good chaos transmission mechanism in many papers. Also many papers proposed systems that use CS and GS in combination with each other and the results revealed a positive response for the configuration. In addition to that, bidirectional and unidirectional coupling of transmitter and receiver has been compared and bidirectional coupling has been found more robust against eavesdropper.

V. Future Work

Chaos communication as a field of research has been an attractive option from the last decade and a lot of work is currently going on in this field. The major fields in which research groups are currently contributing includes different approaches for synchronization between transmitter and receiver, schemes that can increase the communication security using chaotic carriers with more complex structures, keeping less complexity at transmitter and receiver. Consequently design of devices that can generate chaotic carriers with much more complex structures, difficult to predict. Work is also been done in comparison and performance evaluation of CDMA and chaos based systems in the context of security and entropy. Chaos based communication performance has been reported better than CDMA based systems in some papers.

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