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Fuzzy cellular automata and intuitionistic fuzzy sets applied to an optical frequency comb spectral shape

Javier F. Botía[a,c,*], Ana M. Cárdenas[a], Carlos M. Sierra[b,c]

[a] Grupo de Investigación en Telecomunicaciones Aplicadas (GITA), Faculty of Engineering, Dept. of Electronic Engineering, Universidad de Antioquia (UdeA), Calle 50 No. 73-21, Medellín, Colombia

[b] Grupo de Investigacion en Simulación y Comportamiento de Sistemas (SICOSIS), Faculty of Engineering, Dept. of Computer Science, Universidad de Antioquia (UdeA), Calle 50 No. 73-21, Medellín, Colombia

[c] Faculty of Engineering, Dept. of Computer Science, Universidad de Antioquia (UdeA), Calle 50 No. 73-21, Medellín, Colombia

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ABSTRACT

Optical frequency comb is an optical spectrum with equispaced frequency lines, used in different applications, for instance, in optical communications. In this application, when an optical spectrum is propagated in single-mode fiber, temperature fluctuations, normal dispersion, and mechanical vibrations can affect the peak power and phase of the comb lines. In consequence, compensation techniques are required to correct the spectral shape, distorted by non-flatness and phase shifts of the spectrum lines. In this research, a method for analyzing optical frequency comb behavior and the spectral shape in terms of phase and intensity is used. This approach is based on fuzzy cellular automata (FCA) to catch up the dynamic of spectrum behavior, fuzzy clustering methods to classify the measured data, and intuitionistic fuzzy entropy to validate the analysis. Two settings to generate optical frequency comb are considered in the experiments: two intensity Mach- Zehnder modulators and mode-locking laser (picosecond pulsed source). Both comb line spectra are propagated through 25 km of single- mode fiber. Using the pulse shaper at the optical link output, the spectrum is corrected in flatness and phase shift. The pulse shaper was controlled by a computer, where the proposed method was implemented as a control algorithm based on information obtained by the analysis results. In the experiment, inside the framework of FCA and intuitionistic fuzzy sets (IFSs), the evolution rules 27 (experiment 1) and 184 (experiment 2) were used to find the dynamic behavior of comb spectrum, chosen after a performance comparison with another evolution rules. The comparison was carried out through the calculation of mean and standard deviation of phase shift and power peak, periodicity of FCA, and computational cost. For the first experiment, the change of peak powers was reduced from 4.34 dBm to 1.78 dBm and the phase shift was minimized from −0.2901 rad to −0.2618 rad . Instead, the second experiment is observed a correction in flatness from 22.13 dBm to 19.89 dBm and the standard deviation of phase shift was reduced from 0.00067 rad to 0.000471 rad.

1. Introduction

As a response to the high bandwidth demand, optical frequency combs (OFC) appear as one of the most promising techniques for multiwavelength light sources (MWLs) to be used in low cost, broad-band and scalable optical dense wavelength division multiplexing (DWDM) networks (Kani, 2010). There are several techniques for generating OFC spectrum: mode- locking lasers (Delfyett et al., 2006), supercontinuum sources (Ohara et al., 2006), microresonator rings (DelHaye et al., 2007), and Mach- Zehnder modulators (MZMs) (Sakamoto et al., 2007a; Torres and Weiner, 2014; Sakamoto et al., 2007b). However, when this kind of OFC spectrum is propagated through single- mode fiber (SMF), linear and non- linear phenomena generate changes in peak power and phase shift of comb lines and, in consequence, spectral shape variation. Such distortions restrict the OFC usage in high capacity communication systems, which require good performance relative to spectrum flatness and phase stability (Sakamoto et al., 2007a; Alic et al., 2014). Thus, several compensation methods have been proposed for improving the power flatness and correcting phase shift in MWL systems in telecommunication applications.

In general, two compensation strategies of flatness and phase correction are used according to the stage where those strategies are applied: at generation or reception stage after OFC spectrum is

* Corresponding author at: Grupo de Investigación en Telecomunicaciones Aplicadas (GITA), Faculty of Engineering, Dept. of Electronic Engineering, Universidad de Antioquia (UdeA), Calle 50 No. 73-21, Medellín, Colombia.
E-mail addresses: javier.botia@udea.edu.co, botiavalderramaer@gmail.com (J.F. Botía), ana.cardenas@udea.edu.co (A.M. Cárdenas), carlos.sierra@udea.edu.co (C.M. Sierra).

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propagated in SMF. Considering the OFC generation stage, we found three main compensation techniques: manual adjustment, mathematical model of OFC behavior, and feedback loop control (FLC). These techniques are described as follows:

- *Manual adjustment*: flatness correction is carried out to manipulate the bias voltage and amplitude of radio frequency (RF) sources, in the specific case of OFC generated by MZMs. However, phase shift correction is not easy to get by using manual adjustment (Sakamoto et al., 2007b; Dai et al., 2013; Chen et al., 2014; Hraghi et al., 2014; Shang et al., 2014, 2015; Dou et al., 2011; Hmood et al., 2015).
- *Mathematical model of OFC behavior*: the technique is focused on the flatness and phase shift correction based on a transfer function model (Huang et al., 2006; Supradeepa and Weiner, 2012). To apply the model, a pulse shaper (PS) is programmed to compensate the spectrum shape.
- *Feedback loop control*: the FLC or adaptive control is a technique to search the optimal waveform through a stochastic optimization algorithm between desired and measured spectra (Weiner, 2011). The developed algorithm allows programming the PS. The FLC is useful to reduce the electrical field intensity variations and phase shift produced by OFC source generator (in that case, mode- locking lasers) (Gollub, 2008). Usually, the technique uses an optimal control (OC) to express the optimization model and to solve the model through genetic algorithms (GAs). The above is well- known as OC- GAs where the best model of solution identifies the amount of phase and/or intensity variations to be compensated in the spectrum, through a spatial light modulator (SLM). The FLC has been applied in several optical communication systems, at a relative short distance (Omenetto et al., 2002; Shemirani et al., 2010; Luo Wen et al., 2014). However, for long distance, the FLC has limitations when the measured spectrum needed for the optimization algorithm, presents more distortions than the perceived by receiver due to that OFC is propagated once again to return at generation side, where the control process is carried out.

Due to the limitation of FLC in optical communications, the open loop control (OLC) is another alternative of compensation at the reception stage. The OLC considers the desired output waveform, a reasonable knowledge of the input pulse, and the desired transfer function (if it is known) for constructing one simple program in the PS (Huang et al., 2006). Through an interactive compensation procedure, the transfer function of SLM is updated until to obtain the desired spectrum. The OLC was used to compensate group- velocity dispersion (GVD) in a propagation of sub- 500 fs pulses in 3 km SMF (Chang et al., 1998) and 50 km SMF (Jiang et al., 2005), where a dispersion compensation fiber (DCF) was included to mitigate the lowest order dispersion. Other experiments made by Sano et al. (2003) use one PS to compensate residual dispersion after DCF in optical links at 10 Gb/s and they allow compensating dispersion in an optical signal of continuous wave (CW) laser propagated through at 240 km of SMF (Lee et al., 2006). Other relevant work presented in Yousaf Hamza (2009) proposed an improvement of OLC by using GAs to mitigate GVD and self- phase modulation (SPM) effects. The used technique is called dispersion- and power- map co- optimization.

Although OLC has shown effectively in mitigate these effects, there are other non- linear phenomena affecting the propagated spectrum (Agrawal, 2013). Therefore, the optimization model must consider many physical variables, restrictions, and multiple fitness function. This increase of variables can generate high computational time for real- time applications. Considering the above, the use of historical experimental data could catch up the dynamic of the propagated OFC spectrum due to changing conditions of the transmission system. Using historical data, a novel compensation method is designed based on real OFC behavior, allowing an iterative automatic process to obtain the changes of power and phase in the temporal- domain. The method is developed through fuzzy sets (FSs) theory (Zadeh, 1965), fuzzy clustering methods (Botía et al., 2013; Jain, 2010; Bezdek et al., 1984; Chaira, 2011; Chaira and Panwar, 2014; Chaudhuri, 2015; Gustafson and Kessel, 1978; Egrioglu et al., 2011; Lee and Kwak, 2014; Škrjanc and Dovžan, 2015; Martín and de Mantaras, 1982; Carrete and Martín, 1991; Kempowsky et al., 2006; Isaza et al., 2014; Isaza, 2007; Uribe et al., 2010; Bedoya et al., 2014), and fuzzy cellular automata (FCA) (Flocchini and Cezar, 2008; Seth et al., 2008; Cattaneo et al., 1993, 1997; Mraz et al., 2000; Maji and Chaudhuri, 2005, 2007; Al-Ahmadi et al., 2009; Mantelas et al., 2010; Noei et al., 2012; Placzek, 2013; Mingarelli, 2006; Mingarelli and el Yacoubi, 2006; Betel, 2012; Maji, 2008; Yacoubi and Mingarelli, 2011a, 2011b; Leal-Ramirez et al., 2009; Atanassova and Atanassov, 2011; Dong and Zhang, 2013; Hu et al., 2015; Chai and Wong, 2015; Uguz et al., 2015; Azari et al., 2016; Martsenyuk and Seletkov, 2015; Ntinas et al., 2016).

Applying the method in the propagated OFC spectrum, FSs could provide a degree of power and phase distortions in terms of membership degrees, whilst the FCA method allows catching up the spatio-temporal dynamic of the OFC spectrum. Combining FCA, fuzzy clustering methods, and FSs in the case of study, it is possible to detect changes between comb lines at the same spectrum (spatio variations) and, at the same time, to find changes in a specific comb line among spectra taken in different times (temporal variations).

To work under the FSs framework, several steps are required to transform the data obtained by measurement instruments, such as optical spectrum analyzers (OSAs) and oscilloscopes, into a FS representation. The proposed method was tested in two different OFC generators: two intensity Mach- Zehnder modulators and mode-locking laser (in that case, picosecond pulsed source). Both experiments were integrated with the developed control algorithm in a pulse shaper (PS) which contain a liquid crystal spatial light modulator (LC-SLM). Based on open loop control strategy (Weiner, 2011), the PS could compensate flatness and phase of OFC spectrum propagated after 25 km of SMF. To evaluate the compensation quality of the comb lines (in phase and power), side – comb suppression ratio (SCSR), and phase shift correction were calculated.

The paper is organized as follows: in Section 2, the experiments setup with two cascaded intensity modulators (IMs)- MZMs and mode-locking laser are shown, where an OFC is generated and propagated through 25 km of standard single mode fiber (SSMF), and subsequently, the spectrum is compensated by a pulse shaper (PS). In Section 3, a general explanation regarding to the method for compensating flatness and phase OFC Distortion applying intuitionistic fuzzy sets (IFSs) and FCA is detailed by steps. In Section 4, the methodology used in the experimental set- up is explained. Discussion of the achieved compensation of the propagated OFC spectrum is presented in Section 5. Finally, conclusions and further works are mentioned.

2. Experimental setup

Since the proposed method is based on real data, the Sections 2.1 and 2.2 present the settings used to generate the OFCs. To show the repetitively and effectivity of our method, the propagation through SMF and control devices were the same in both cases.

2.1. Experiment 1: OFC spectrum generated by cascaded two intensity modulators

The general scheme implemented for compensating the comb generated by the cascaded MZM is shown in Fig. 1a, divided into three stages: OFC spectrum generation, propagation, and compensation. The OFC generation stage was deployed by a continuous wave (CW) laser fixed at 1550 nm, and it is connected to two cascaded IM - MZMs. To generate the best OFC spectrum, several parameters were configured as follows: the CW laser power was fixed at 5 mW at 1550 nm . The two IM-MZMs labeled as IM- 1 and IM- 2, are fed with two DC sources and two