

Secure Optical Communication Systems based on Chaotic Carriers

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Abstract. In this Thesis, the generation of a chaotic carrier by semiconductor lasers is theoretically studied. Three different encoding techniques are employed and the performance of an optical chaotic communications system for different receiver configurations is evaluated. It is proved that chaotic carriers allow the successful encoding and decoding of messages with up to 10 Gb/s bit rate. Focusing on the Chaotic Modulation encoding method it is shown that the normalized decoding method provides significantly different results in the estimation of the system's performance compared to the method of photocurrent subtraction, proposed in this study. Finally, the effects of transmission in optical fiber are studied for a chaotic communications system when CM and CSK encoding techniques are employed for various message bit-rates. The downgrading of the system's performance due to fiber transmission impairments is confronted by the employment of various dispersion management techniques.

Keywords: Chaotic Cryptography, Synchronization, Semiconductor Lasers, Optical fibers, Dispersion management, Secure Communications.

1 Introduction

The development of optical telecommunications systems has generated a particular interest in secure optical transmission [1], [2]. Owing to the high dimensionality and wide bandwidth of a chaotic signal, several optoelectronics and all-optical systems based on fast chaotic dynamics have been proposed as a possible alternative to classical encryption techniques relying on numerical algorithms. Chaotic cryptography performed in the physical layer rather than the application layer seems extremely attractive, since it exploits the deterministic nature of chaos, showing at the same time a strong dependence on minimal variations of the system's parameter values. Communication systems utilizing chaotic carriers are an extension of the conventional communication systems used today. While in a conventional communication system the message is modulated in the transmitter upon a periodic carrier, in chaotic systems an information message is transmitted using a chaotic

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signal as a broadband carrier. The chaotic carrier in which data is encrypted can be either electronic or optical using corresponding electronic [3], or optic oscillators working in the chaotic regime. In the case of the semiconductor laser-based oscillators the operation in the chaotic regime can be achieved by applying optical feedback [4], optoelectronic feedback [2], or optical injection [5], and their chaotic behavior appears either in the amplitude or in the wavelength regime. Concerning the encoding of the information in the chaotic carrier, the schemes that have been proposed are the chaotic masking (CMS), chaotic modulation (CM), chaotic shift-keying (CSK), On-Off shift keying (OOSK) and chaos shift-keying using chaos in wavelength [1], [6]. The philosophy of the decoding process however is always the same, based on a very good synchronization between the transmitter and the receiver system.

In this Thesis, the generation of a chaotic carrier by semiconductor lasers is theoretically studied. Three different encoding techniques (Chaotic Modulation, Chaotic Shift Keying, and Chaotic Masking) are employed and the performance of an optical chaotic communications system for different receiver configurations is evaluated. It is proved that chaotic carriers allow the successful encoding and decoding of messages with up to 10 Gb/s bit rate.

Focusing on the Chaotic Modulation encoding method, the performance of a back-to-back chaotic communications system is also studied when two different decoding methods are followed. In both closed- and open-loop configurations, the normalized decoding method that is widely used in literature provides significantly different results in the estimation of the system's performance compared to the more realistic method of photocurrent subtraction, proposed in this study.

Finally, the effects of transmission in optical fiber are studied for a chaotic communications system when CM and CSK encoding techniques are employed for various message bit-rates. The downgrading appearing to the system's performance due to fiber transmission impairments is confronted by the employment of various dispersion management techniques.

2 Numerical modeling

For the numerical analysis, the optical carrier is a chaotic signal generated by a Fabry-Perot semiconductor laser diode subjected to an external optical feedback (master laser - ML). This chaotic waveform is optically injected into another semiconductor laser diode (slave laser - SL) that operates at the exactly same conditions as the ML (fig. 1a), and forces it to synchronize with the ML, producing at its output a chaotic carrier identical to that of the ML. The above setup, representing a closed-loop scheme, is theoretically described by the well-known Lang-Kobayashi equations [2]

$$\begin{aligned} \frac{dE_{t,r}(t)}{dt} = & (1 - j\alpha_{t,r}) \left(G_{t,r}(t) - \frac{1}{\tau_{p,t,r}} \right) \frac{E_{t,r}(t)}{2} \\ & + \gamma E_{t,r}(t - \tau) e^{j\omega_0 \tau} + \kappa_r E_{ext}(t) + \sqrt{2\beta N_{t,r}(t)} \xi_{t,r}(t) \end{aligned} \quad (1)$$

$$\frac{dN_{t,r}(t)}{dt} = \frac{I}{e} - \frac{1}{\tau_{n_{t,r}}} N_{t,r}(t) - G_{t,r}(t) |E_{t,r}(t)|^2 \quad (2)$$

$$G_{t,r}(t) = \frac{g(N_{t,r} - N_{0,t,r})}{(1 + s|E_{t,r}(t)|^2)} \quad (3)$$

where $E_{t,r}(t)$ is the complex slowly varying amplitude of the electric field at the oscillation frequency ω_0 and $N_{t,r}(t)$ the carrier number within the cavity. The subscript symbols t,r refer to the transmitter and the receiver system, respectively. The two lasers were considered to be similar to each other and therefore most of the internal parameters are the same. The spontaneous emission process is also taken into account through a complex Gaussian white noise term $\xi(t)$ of zero mean value and correlation

$$\langle \xi_t(t) \cdot \xi_r^*(t') \rangle = 2\delta_{t,r} \delta(t-t') \quad (4)$$

The light propagation along the fiber connecting the transmitter and the receiver has been modeled by integrating the well known generalized non-linear Schrödinger equation [7],

$$j \frac{\partial E}{\partial z} = -\frac{j}{2} \alpha E - \gamma |E|^2 E + \frac{1}{2} \beta_2 \frac{\partial^2 E}{\partial t^2} + \frac{j}{6} \beta_3 \frac{\partial^3 E}{\partial t^3} \quad (5)$$

where E is the total field envelope at the pump wave optical frequency, α is the fiber attenuation coefficient, $\gamma = \frac{2\pi n_2}{\lambda A_{\text{eff}}}$ is the nonlinear coefficient of the fiber responsible

for Self Phase Modulation (SPM), where n_2 is the Kerr coefficient, λ is the carrier wavelength, and A_{eff} is the fiber cross section; and constants β_2 , β_3 are the second-order chromatic dispersion and the third-order chromatic dispersion respectively and are related to the zero-dispersion wavelength and dispersion slope of the fiber. The transmission module additionally consists of in-line EDFAs and Gaussian optical band-pass filters. The former have been modeled under the assumption that the gain profile of the amplifier is practically constant in the wavelength region of the propagating wave, while its value is set to $G = \exp(\alpha L_c)$ in order to compensate for the fiber loss in an amplification period. Additionally, Amplified Spontaneous Emission (ASE) noise is taken into account introducing noise power per unit frequency $P_n = n_{\text{sp}} (G - 1) h\nu$, where n_{sp} is the spontaneous emission factor. The optical band-pass filters, used to suppress the ASE noise added by the EDFAs, are selected to be Gaussian of 1.1 nm bandwidth.

3 Performance Characterization of High Bit-Rate Optical Chaotic Communication Systems in a Back to Back Configuration

A comparative study of three data encoding techniques in optical chaotic communication systems is presented in this chapter. The chaotic carrier is generated by a semiconductor laser with optical feedback and the data are encoded on it by Chaotic Modulation (CM), Chaotic Masking (CMS) or Chaotic Shift Keying (CSK) (fig.1). In all cases the receiver, which is directly connected to the transmitter,

consists of a semiconductor laser similar to that of the transmitter subjected to the same optical feedback. The performance of this back to back configuration is numerically tested by calculating the Q-factor of the eye diagram of the received data for different bit rates from 1 to 20 Gb/s.

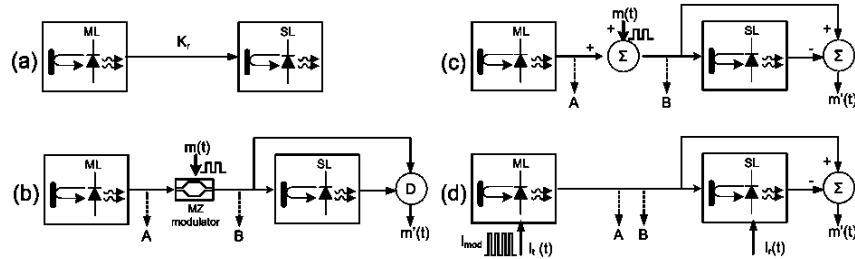


Fig 1. (a) The master laser (ML) output is optically injected to the slave laser (SL) and causes it to synchronize. (b) CM encryption method, (c) CMS encryption method, and (d) CSK encryption method.

Fig. 2 shows the Q-factor values calculated for different repetition rates, for the three encryption methods. These values are taken for the decoded message, as well as after filtering the decoded message with a fifth order Butterworth low-pass filter. Without any usage of filters, the CM encryption method has an obvious advantage over the other two methods. It exhibits very high Q-factor values (~ 18) at low values of bit-rate (1 Gb/s), while for higher bit-rates that end up to 20 Gb/s, the Q-factor value gradually decreases to 5. On the contrary, CMS method exhibits very low Q-factor values (~ 1.5), which remain practically constant as the bit-rate increases (fig. 2b). Finally, in the CSK method the Q-factor degrades in respect to the bit-rate increase, with values confined below 4.

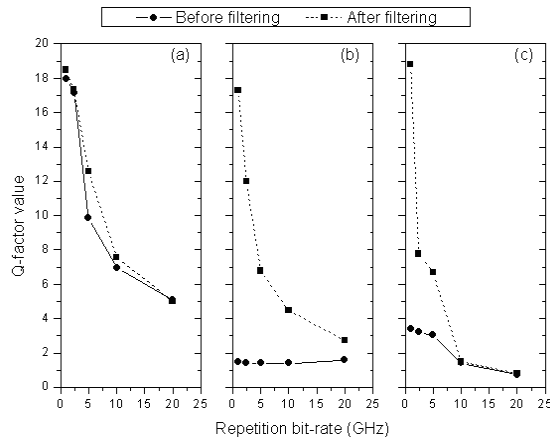


Fig 2. Estimation of Q-factor values for different repetition bit-rates of the decoded message, employing (a) the CM method, (b) the CMS method, and (c) the CSK method. The synchronization error of the master – slave system is set to 0.2%.

The higher Q-factor values extracted from the CM method in comparison to the other two methods can be explained by the nature of the encoding process. For the optical feedback system under investigation, complete synchronization entails not only synchronization of the laser field amplitude waveform, but also the synchronization of the laser field phase. In the CM method the message is being applied by modulating the transmitter's chaotic carrier itself, according to the expression: $(1 + m(t)) \cdot E_{ML} \cdot e^{i\phi_{ML}}$, resembling the typical coherent AM modulation scheme. Therefore, the phase of the chaotic carrier with the message encoded on it, which is injected to the receiver, is the same with that of the chaotic carrier without any information. Thus, the presence of signal on the chaotic carrier does not cause a significant perturbation in the synchronization process of the system. On the contrary, in the CMS method the message is a totally independent electric field, which is added to the chaotic carrier, according to the expression: $E_{ML} \cdot e^{i\phi_{ML}} + m_E(t) \cdot e^{i\phi_{message}}$. Therefore, the phase of the total electric field injected now to the receiver consists of two independent components. The phase of the message acts in this case as a perturbation in the phase matching condition of a well-synchronized system and thus, the phase difference between the transmitter and the receiver diverges from zero. In the CSK scheme with one receiver, although the phase exhibits the same behavior as in the CM method, the Q-factor values are degraded due to the synchronization error of the system, induced by the different injection currents between the ML and the SL. An additional drawback of the CSK method is that the laser cannot be modulated properly for frequencies above the relaxation oscillation frequency.

In order to improve the efficiency of the studied encoding schemes, a fifth-order Butterworth low-pass filter is employed. The cut off frequency of the filter is optimized for the different repetition bit-rate values of the encoding message. As it can be seen from fig. 2, for the 1 Gb/s bit-rate message all methods exhibit a similar behavior, providing a very high Q-factor value (17 to 19), since the high frequency oscillations have been entirely removed.

By increasing the synchronization error of the system to higher values, the Q-factor is found to be minimized in all three methods, even at low repetition bit-rates. The improvement caused by the filter usage is limited. For example, 5% synchronization error gives a Q-factor value of almost 6, in the CM method after filtering, while 30% error further limits the Q-factor value to a low value of 2.5. The above behavior proves that when the synchronization error is high, the message cannot be recovered at all. Thus, it is crucial to maintain the system well synchronized in order to achieve a fully recovered message with a high Q-factor value [8].

4 Influence of the Decoding process on the Performance of Chaos Encrypted Optical Communication Systems

Two different decoding methods of an all-optical chaotic communication system are investigated when Chaotic Modulation (CM) encoding format is employed. The transmitter consists of an external cavity semiconductor laser generating thus a chaotic carrier, modulated using an external modulator. The receiver is either a solitary semiconductor laser diode identical to that of the transmitter or a laser diode

coupled to an external cavity, forming an open or a closed-loop configuration respectively (fig. 3). The performance of the system is then evaluated by means of calculating the Q-factor extracted by the eye diagram of the recovered data when two different approaches of the decoding process for the receiver are adopted. The first decoding method relies on the normalized to receiver's amplitude output, difference of the two lasers' optical amplitude outputs, while the second one corresponds to a more realistic case by subtracting the electrical current outputs of two p-i-n photodiodes coupled to the transmitter and receiver laser correspondingly. By comparing the numerical results extracted by the two decoding methods and for various cases of interest, such as employing open- or closed-loop configuration for several message bit-rates and different laser's driving current, it was shown that, under certain circumstances, the two decoding methods result to significantly different results.

The encryption method considered in the present work is chaotic modulation (CM) (fig. 3). In this method the message encoding is carried out by modulating the chaotic carrier of the ML using an external Mach-Zehnder modulator, according to:

$$|E_t^{\text{mod}}(t)| = |E_t(t)|(1 + m(t)) \quad (6)$$

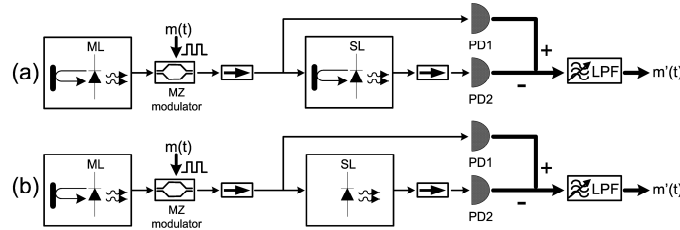


Fig. 3. a) Closed-loop, b) Open-loop configuration

where $m(t)$ is a 1-5Gb/s pseudorandom bit sequence forming a codeword with length $2^{11}-1$. The modulation depth engaged for the simulations was chosen to be no more than 5% so that the message not only was totally indistinguishable from the chaotic carrier of the ML but caused limited distortion in the synchronization process of the system as well. The proposed decoding process, in many papers exhibiting numerical simulations, is of the form:

$$m'(t) = \sqrt{\frac{|E_t^{\text{mod}}(t)|^2}{|E_r(t)|^2}} - 1 \quad (7)$$

which actually, under perfect synchronization conditions, mathematically provides a replica of $m(t)$. To approximate a possible decoding procedure in real, laboratory conditions two photodiodes were adopted to provide a subtraction between the two chaotic outputs of the ML and SL, rather than the division used in the first method. The equation describing this function is

$$I_{dec} = I_t - I_r \quad (8)$$

where $I_{t,r}$ denotes the photocurrent created by the optical injection of the output waves of the ML and SL into the photodiodes PD1 and PD2 respectively.

In fig. 4 the Q-factor value in respect to the normalized injection strength for the two different decoding methods is presented. The results correspond to the case of a

closed-loop scheme when 1 Gb/s message is embedded on the chaotic carrier. Two different regions can be easily discriminated in this figure.

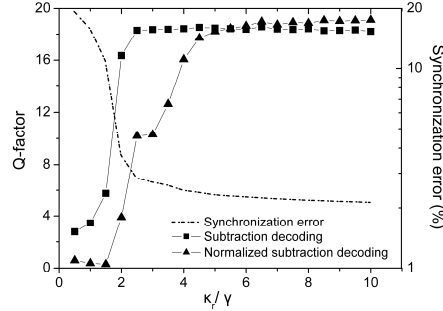


Fig. 4. Q-factor and synchronization error as a function of the normalized injection strength for 1Gb/s message bit-rate and closed-loop configuration.

In the first one, for normalized injection strength values κ_r/γ greater than 5, the two decoding methods provide similar performance results. On the other hand, for κ_r/γ values less than 5, a significant difference in the measured Q-factors appears. In detail the behavior of each decoding method can be discussed as follows:

A. Normalized difference of Electric fields

By using the normalized decoding method according to eq. 7 (which for simplicity will be further called first method), a significantly lower estimation of the system's performance is observed. The normalized difference between the two methods for low values of the injection strength exceeds 90% and gradually diminishes to zero as the injection strength increases. The synchronization error of the system (defined in [9]), also plotted in the same figure, provides a possible explanation of the observed behavior. It is evident that the Q-factor curve concerning the first method directly follows (in the opposite obviously direction) the synchronization error curve. This is somewhat mathematically expected since $m(t)$ becomes identical to $m(t)$ under perfect synchronization conditions as indicated by equations (6), (7).

B. Subtraction of Photocurrents

For the subtraction based decoding method according to eq. 8, (which for simplicity will be further called second method) there is a major difference. Mathematically, under perfect synchronization conditions and in the absence of every added by the photodiodes noise terms, the decoded photocurrent follows the relation $I_{dec} \sim m(t)|E(t)|^2$. This means that in the second decoding method the quality of the decoded signal not only depends on a good synchronization between ML and SL but on the chaotic carrier of the transmitter itself. Therefore the spectrally wider the transmitted chaotic wave is, the worse performance is expected for the second decoding method. Moreover, it is well known that chaos spectrally grows up around the relaxation oscillation frequency of the laser. Consequently, a deterioration of the system performance is expected as more frequency components of the chaotic carrier are included in the decoded message after the filtering procedure. This could happen for example if higher message bit-rate was employed. For the 1 Gb/s message bit-rate though, a good decoding quality is expected since the electrical filter utilized has a cut-off frequency of 600MHz, eliminating the higher spectral components of the

chaotic carrier. By observing fig. 4, it can also be pointed out that for high values of synchronization error the synchronization quality is the dominant factor deteriorating the performance calculated using the second decoding method, while at moderate injection parameter values ($\kappa_r/\gamma=2-4$), the calculated Q-factor values are at a constant high level, despite the corresponding synchronization improvement. Therefore, according to the second decoding method, a floor on the best achievable performance is expected.

To further verify the dependence of system's performance mainly from the spectral characteristics of the transmitted chaotic carrier using the second decoding method, and exclusively from the degree of synchronization using the first method, the performance of the same setup is evaluated for 2.4 & 5 Gb/s message bit-rates (fig. 5). It is evident that when the first decoding method is used, a direct relation between the Q-factors and the synchronization degree is observed. In fact the Q-factor curve resembles a mirror image of the corresponding synchronization error curve with slight differences, basically due to the fact that the synchronization error was calculated in the whole spectral region while the Q-factor was calculated after filtering the remaining high frequency non-synchronized spectral components. Concerning the first decoding method, a system's performance degradation is also observed relative to the low message bit-rate. This result, depicted in fig. 5, can be attributed to the fact that when higher message bit-rates are employed, output filters with increased bandwidth are used. This allows the higher non-synchronized spectral components to be part of the filtered decoded message, deteriorating the performance. On the other hand this is not solely the case for the second decoding method. Significant performance degradation, especially when compared to the first decoding method, is observed in fig. 5 which cannot be attributed exclusively to the increased filter's bandwidth. As already mentioned, there is an enhancement of the chaotic carrier's spectral components around the relaxation oscillation frequency ($\sim 4.5\text{GHz}$) of the laser. Since the frequency components of the message bit-streams come closer (2.4 Gb/s) or even exceed (5 Gb/s) the relaxation oscillation frequency, the decoding quality, which depends on the chaotic carrier, is degraded even in the presence of a filter. Compared to the first decoding method, synchronization degree only confines its effect on the high synchronization error region since in all the other cases, although the synchronization error of the system decreases, the Q-factor stabilizes to a certain value.

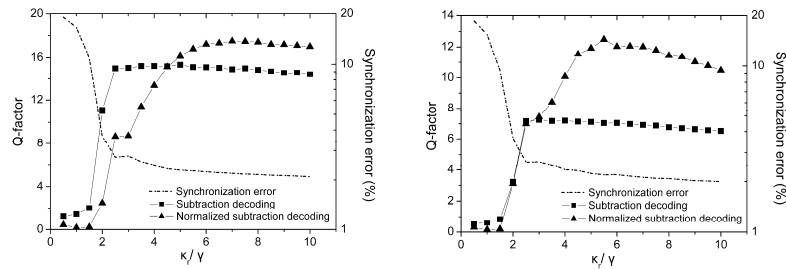


Fig. 5. Q-factor and synchronization error as a function of the normalized injection strength for 2.4Gb/s (left) and 5Gb/s (right) message bit-rate and closed-loop configuration.

To generalize the conclusions derived so far an analogous study was performed in the case of an open-loop scheme. From the study performed it was evident that the two different decoding methods exhibit similar performance behavior compared to the corresponding closed-loop cases confirming the generality of the conclusions derived for the closed-loop scheme [10].

5 Numerical Investigation of Fiber Transmission of a Chaotic Encrypted Message using Dispersion Compensation Schemes

A detailed numerical investigation of the transmission properties of all-optical chaotic communication systems is finally presented for two data-encoding techniques and for various dispersion compensation maps. A semiconductor laser subjected to optical feedback generates the chaotic carrier and the data is encoded on it by CM or CSK methods. The complete transmission module consists of different types of fiber, in-line amplifiers and Gaussian optical filters. Different dispersion maps based on either Non-zero Dispersion Shifted Fibers (NZ-DSFs) or combinations of Single Mode Fibers (SMF) along with Dispersion Compensating Fibers (DCF) were considered (fig. 6). The system's performance is numerically tested by calculating the Q -factor of the eye diagram of the received data for 1 and 2.4Gb/s. The influence of the optical power launched into fiber and the transmission distance to the quality of the decoded message has been investigated.

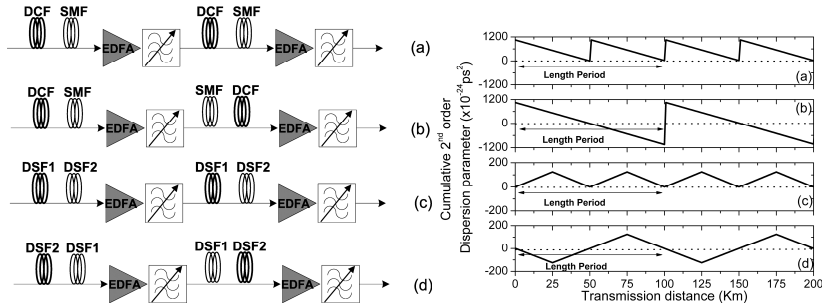


Fig. 6. Cumulative second-order chromatic dispersion parameter in respect to the transmission distance (right) for a) Pre-compensation map, b) Symmetrical map, c) One-step map, d) two-step map.

By utilizing a NZ-DSF of a small value of second order dispersion parameter ($1\text{ps}^2\text{Km}^{-1}$) in the link between master and slave laser, it was found that for distances that exceed 10 Km no message extraction is possible. Consequently, dispersion management techniques should be appointed, so that adequate message quality is derived for longer transmission spans.

In order to identify the upper limits of the transmission maps employed, in terms of the maximum distance achievable for acceptable message quality (Q factor values higher than 6), the optimum value of the launched optical power from the transmitter to the transmission module should be determined. It is well known that Self Phase

Modulation (SPM) induced impairments are enhanced as the optical power propagating through the fiber increases. On the other hand as the optical power of the transmitted signal reduces, the gain, and in consequence the ASE noise added by the in line EDFAs, increases. Therefore, the optimum value of the optical power injected into the fiber from the transmitter results from a trade-off between the non-linear effects of the fiber, and the added by the in-line amplifiers ASE noise.

The performance of the transmission maps proposed (utilizing DCF-1 in the corresponding dispersion compensation maps), by means of the Q-factor values in respect to the launched optical power, is presented in fig. 7 for a total transmission period length of 100 Km and for both modulation formats. As expected, the curves for each map have a peak corresponding to the optimum value of the launched optical power. It is also evident that the maps utilizing the NZ-DSFs (fig. 6c and 6d) appear to be more insensitive to injected optical power, sustaining high Q-factor values for a wide range of power values. On the other hand, symmetrical and pre-compensation map show strong dependence from the optical power, due to the enhanced SPM phenomena related to the DCF fibers employed.

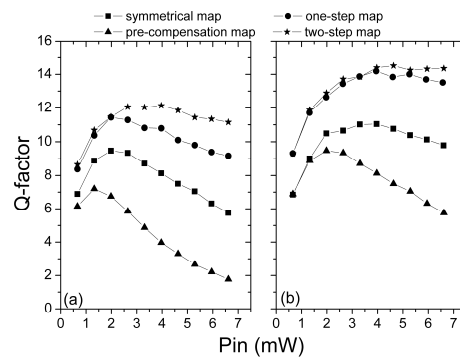


Fig. 7. Q-factor values, for 1 Gb/s bit-rate and 5% modulation depth, as a function of the launched optical power for all transmission maps proposed and for a) CM method, b) CSK method.

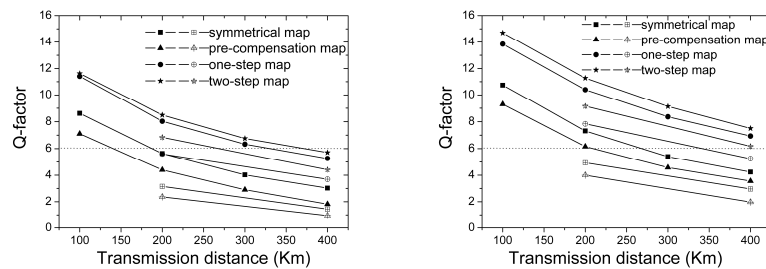


Fig. 8. Q-factor values, for CM method (left) and CSK method (right), as a function of the transmission distance for all maps proposed and for a) 100 Km map period length (solid symbols), b) 200 Km map period length (blank with crosses symbols).

For the optimum power values extracted from fig. 7, system's performance was investigated in respect to the transmission distance. The latter extends from 100 to

400 Km by simply utilizing multiple periods of the initial, 100 Km length, maps proposed. In fig. 8 the calculated Q-factor is shown versus the transmission distance, for all the maps used and for both message encoding methods. The strong degradation of the system performance, in respect to the transmission distance, is caused by the accumulated nonlinearity and ASE noise effects. The contribution of these two phenomena distorts the phase and amplitude characteristics of the chaotic carrier, degrading severely the synchronization quality in the receiver and thus the system performance. For both modulation formats, the dispersion maps based on NZ-DSFs (fig. 6c and 6d) appear to be more efficient than the other two based on DCF as dispersion compensating element. An evident performance improvement is also observed between the symmetrically constructed maps (two-step map and symmetrical map) and the corresponding (by means of the different types of fiber employed) non-symmetrical maps.

In order to investigate the performance of the system at higher bit-rates, a 2.4 Gb/s message bit-stream with a modulation depth of 5% was applied to the chaotic carrier. The curves extracted by simulations, were similar with the ones presented for the 1 Gb/s message bit-rate case (fig. 8), indicating that the inherent properties of the maps used (the type of fibers employed, the way they are placed along the whole map and the spacing between the EDFAs), mainly determine the optimum power level for each map.

In order to improve the performance of the system for the 2.4 Gb/s case, the modulation depth of the message applied to the chaotic carrier was increased. The value of 7% chosen not only improves the decoded message quality but keeps the high level security of the system as well. It was found that in CM method the upper distance limits are about 190 and 230 Km for both the one and two-step map respectively, while for the dispersion compensation maps the corresponding values, for the symmetrical and pre-compensation map, are 150 and 140 Km [11]. On the other hand, CSK method appear to have quite improved performance, since the upper distance limits determined, were 280 and 300 Km for the one and two-step map respectively, and less than 200 Km for both the symmetrical and pre-compensation map.

6 Conclusions

A performance comparison by means of Q-factor calculations between the three encoding methods was demonstrated in the above analysis. It has been shown that the CM method has an obvious advantage over the other two methods, due to the fact that the message carries the phase of the chaotic carrier. However, after filtering the chaotic high frequency oscillations, all methods result satisfactory Q-factor values for low repetition bit-rates up to 2.4 Gb/s. By increasing the bit-rate to 10 Gb/s, only CM method could be characterized as a sufficient encoding scheme, while at 20 Gb/s the best Q-factor value extracted is almost 5 and is referred to the CM method, also.

Then a performance analysis by means of Q-factor calculation was also conducted for CM codification scheme and two possible decoding methods in a back-to-back chaotic communication setup. For both closed and open loop configurations, it was

shown that the first decoding method provided performance results strictly dependent on the degree of the synchronization between ML and SL. On the other hand, the performance results extracted with the second decoding method proved to be strongly determined by the complexity of the chaotic carrier itself.

Finally it was shown that the CSK method has an obvious advantage over the CM method in all the transmission maps proposed. In order to explore the upper limits of the system, by means of the maximum distance achievable for acceptable message quality, the optimum value of the launched optical power has been determined. The maps utilizing NZ-DSFs appear to be more robust to variations in the injected optical power, compared to the dispersion compensation maps for both the message bit-rates employed. When 1 Gb/s bit-rate is used, dispersion management maps, though less practical, proved to provide better results. When a 2.4 Gb/s message is applied to the chaotic carrier the corresponding in each case, Q-factor values are decreased because of the residual spectral components of the chaotic oscillations in the higher frequency regime. However, by increasing the modulation depth of the message, improved results can be obtained.

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