Analysis of the effects of linear and non-linear distortions on QPSK modulated signals for optical channels

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***Resumen*— En este artículo se presenta algunos de los alcances logrados de la tesis de pregrado titulada “Analysis of the effects of linear and non-linear distortions on QPSK modulated signals for optical channels” desarrollado por los dos primeros autores. La pertinencia de este trabajo radica en que, actualmente, el procesamiento digital de señales ha tomado un importante lugar en las comunicaciones, en particular, en comunicaciones ópticas. Los sistemas actuales de transmisión son soportados por dispositivos con DSP para tareas de filtración y ecualización. En el caso de la filtración, la primer paso es interpretar la distorsión y, en el mejor de los casos, obtener un modelo. En este trabajo se presenta un breve estado del arte de las distorsiones lineales y no lineales en canales de fibra óptica desarrolladas en los últimos trece años. También se presenta un marco teórico concreto y útil acerca de distorsiones y formatos de modulación digital orientado a las comunicaciones ópticas. En tanto a las distorsiones se da una definición y se estudia el efecto sobre la constelación de representación. Para los formatos de modulación digital se presenta un diagrama de bloques y ecuaciones generalizadas. También, se introduce un modelo de distorsión lineal para el formato QPSK.**

***Palabras clave*— Distorsión lineal, fibra óptica, modulación digital.**

Abstract— In this paper, we present some achievements of the degree thesis entitled “Analysis of the effects of linear and non-linear distortions on QPSK modulated signals for optical channels” developed by the two first authors. The pertinence of this work lies in that digital signal processing have currently taken an important place in Communications, in particular, Optical Communications. Current transmission systems are supported by DSP based devices to carry out filtering and equalization tasks. For filtering, the first stage is to understand the distortion and establish a model (when possible). In this work, we present a brief state of the art of linear and non-linear distortions in optical channels developed in the last thirteen years. Also, we present an useful and specific theoretical background about distortions and digital modulation formats oriented to optical communications. Distortions are defined and the effect over representation constellation is studied. For each digital modulation format, we present a block diagram and generalized equations. Additionally, a linear distortion model for QPSK format is introduced.

Keywords—Linear distortion, optical fiber, digital modulation.

I. INTRODUCTION

The optical fiber was born due to the need of high-performance channels. Basically, there exist two transmission modes for optical fiber: single-mode and multi-mode. Also, there exist many fabrication types for it; among the most recent we found the dispersion shifted fiber (DSF). Since it was installed the first optical line in 1977, the expectative was that the best transmission channel, in terms of efficiency, according to the theory was achieved. Next, some experiments shown the fiber has certain distortion that can be attributed to fabrication material and transmission mode. But, because it was a new material that is not affected for electromagnetic interferences and attenuations for material resistance, fiber cannot be associated with known distortion in that time.

According to the background on optical theory, the transmission through optical fiber does not have attenuations for material resistance because of their physical properties. In fact, distortions are null because fiber does not present electromagnetic interferences and, as an important advantage, its fabrication cost is significantly low. However, transmission through fiber presents both distortions and attenuations that are related to channel, source and optical detector properties. It is evident that such distortions affect the quality of power transmission and bit error rate (BER) causing loss of information in the reception system, whereas attenuations cause optical power loss [1]-[3]. In literature, we can find some mathematical models that describe some kind of fiber distortion and devices employed in optical transmission [1, 2].

In this work, the description of some fiber and transmission devices distortions is presented, that is supported by scientific literature in the last thirteen years. In addition, some basic digital modulation schemes are also studied and a linear distortion model is introduced.

The present paper is composed by four parts: state of the art, theoretical background, results and final remarks. The state of the art is presented in section II. Background and results are presented in sections III and IV, respectively. At the end, we present final remarks and future work in section V.

II. STATE OF THE ART

In this section, some linear distortions and their main effects in optical data transmission are presented. In order to increase the data transmission rate of optical fiber and improve the propagation performance, a lot of investigations about the optical transmission systems and their impairments have been made. The results of this research show that the problem is bigger than that was really considered at the beginning because the optical fiber present great limitations in band width, velocity of transmission and BER (Bit error rate). In [2] it is discussed how the need of providing higher data throughput in digital communications systems has prompted the use of higher order modulation schemes such as M-QAM (M-ary quadrature amplitude modulation). These schemes were studied on performance evaluation for QAM-Code division multiple access (QAM-CDMA) transmission taking into account that the system performance is degraded by nonlinear distortions, mainly, fading channel and nonlinear distortion.

For M-PSK and M-QAM formats, in [4] the transmission is investigated over optically and electronically compensated link, with duty cycles varying in an appropriate range. The nonlinear effects are identified by using the nonlinear threshold (NLT) [6] as a performance measure, which estimates the susceptibility of a given modulation format to nonlinear distortion. Furthermore, links with optically and electronically compensated are used for all M-PSK and M-QAM formats showing a favorable results for M-QAM, which presented a higher NLT in links optically compensated in comparison with electronically compensated ones, as long as M-PSK formats presented a lower NLT in the same comparison. Moreover in [7], a simple method of equalization to compensate for the nonlinear distortion is proposed. This method uses proper saturation levels in the receiver for compensating decision regions and improving numerical accuracy to compute the error probability. This technique of compensation performs well when the saturation level is increased. Also, it was probed that the use of modified decision regions by the receiver performs better than a 16-PSK modulation technique in terms of average symbol energy to noise ratio. In [6], M-QAM systems are studied that have the effect of linear distortion caused by imperfect filters and selective fading, and nonlinear distortion mainly caused by data transmission through high power amplifier (HPA). In [6], an analytical procedure for estimating the upper bound of BER performance is proposed, which shows that the M-QAM signals under linear and nonlinear effects simultaneously have a lower bound of BER.

In digital transmission systems it is necessary to amplify modulated signals because of the low input power. The amplification of these signals with nonlinear amplifiers caused attenuation on the signal and data distortion. In [1], a method to compensate for nonlinear distortion is proposed. The method is based on determining the decision regions defined by received symbols 16QAM. Symbol Error Probability (SEP) is calculated from the decision region. Then, the compensator is designed based on such SEP. In this work a valid expression for calculating the error SEP is found and verified by simulation.

The compensation of the distortion in DSF fiber is shown and described in [2]. Such paper shows that the distortion on the DSF fiber is associated with FWM phenomenon and other less important distortion types. The FWM works as follows. A continues pump wave propagates at frequency w1 while a modulated co-propagates at frequency w2 interact producing a new conjugated wave at frequency w3. Proposed mathematical expressions are simulated and compared with a transmission system simulation.

For optical fiber-based transmission system, the digital modulation schemes take place because the light source can be represented as a sinusoidal wave and the data to be transmitted are digital (bits). For this reason some works related to optical fiber communications that are focused on digital modulation issues. For example, in [9], taking into consideration the recently proven theorem about the statistical properties of nonlinearly distorted phase-shift keyed (PSK) signals, it is shown that the theorem holds not only for PSK sequences but that can be directly extended for -QAM sequences constructed from independent quaternary PSK and binary PSK sequences.

In other work [10], M-QAM modulation is considered in order to find an analytical expression for Bit Error Rate (BER) under the effect of nonlinear distortion caused by the nonlinear transmit high power amplifier (HPA). This is achieved by introducing a model of the system in which the HPA is followed by the Tx filter. In this paper, a procedure for estimating an upper bound of BER under the simultaneous effects of linear and nonlinear distortions, timing and phase errors is analyzed and presented.

In the Table I is shown some distortion types with their parameters

TABLE I
DISTORTIONS OF OPTICAL CHANNELS

Type of Distortion / Model	Parameters	Ref.
Soft limiter $f(\rho)=\begin{cases}\rho & if\lvert\rho\rvert<\rho_{sat}\\ \rho_{sat}sign(\rho) & if\lvert\rho\rvert\geq\rho_{sat}\end{cases}$	$\rho_{sat}:HPA$ amplitud saturation	[7]
Limited Transmitter band width It is modeled whit fifth-order Bessel filter $H(s)=\dfrac{\theta_n(0)}{\theta_n(s/\omega_0)}$	$\theta_n(s/\omega_0)$: Reserve Bessel polynomial ω_0 : Cut-off low pass frecuency	[5]
Nonlinear amplifier distortion $u(t)=F_A(\rho)e^{jF_p\rho(t)}e^{j\phi(t)}$ $F_A(\rho)=\dfrac{A_{sat}^2\rho}{\rho^2+A_{sat}^2}$ $F_P(\rho)=\dfrac{\pi}{3}\dfrac{\rho^2}{\rho^2+A_{sat}^2}$	$F_A(t)$: AM/AM Function $F_P(t)$: PM/PM Function A_{sat} : Input Voltage Saturation of TWT amplifier	[4]
Fading Channel $h(t)=\sum_{k=1}^{K}\beta_k e^{(j\gamma_k)}\delta(t-\tau_k)$	$k:k-th$ path of fading channel γ : phase delay τ : propagation delay β : gain path whit Rayleigh PDF	[4]

III. THEORITICAL BACKGROUND

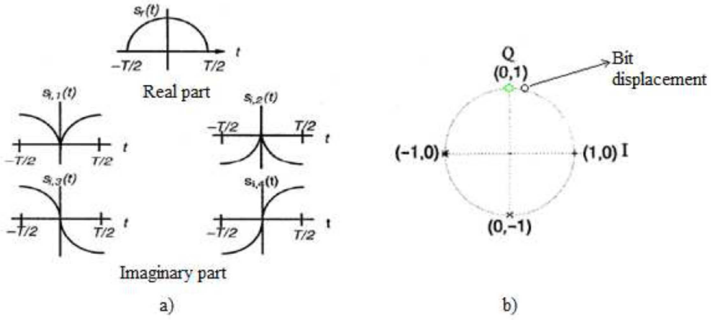
A. *Optical Fiber and Distortion*

The fiber availability with high attenuation rate limits high performance system communication developments. Distortions are from different origin and they are directly related with the optical source, transmission channel, and receptor affecting the new transmission system develops. By knowing the origin of these distortions it can be possible the design of a compensator that makes the system more efficient. Some distortions are described below.

Bandlimiting

The "Bandlimiting" is a phenomenon that suppresses sharp transitions in the signal phasor trajectory. This sharp transition (as shown in figure 1) are caused by the change of direction associated with signals $s_1(t)$ and $s_2(t)$. This phenomenon generates a displacement of the signal phase and therefore of the received constellation. The displacement of the received constellation is generated due to synchronism time of the optical receiver.

FIG. 1. SIGNAL WAVEFORM FOR SOME TRAJECTORIES



a)

b)

Linear Distortion

The linear distortion is considered in case of the signal amplitude presents polarity changes. In Fig. 1, signals $s_3(t)$ and $s_4(t)$ suffer distortions. Such distortion generates a displacement that locates constellation points inside or outside of the unit circle. Signals $s_1(t)$ and $s_2(t)$ are not affected by this distortion, but they can be affected by Bandlimiting distortion. The points inside of the unity circle represent that its corresponding signal has been amplified. By the other hand, the points out of the unity circle correspond to some signal attenuation.

Linear Amplitude

The linear amplitude distortion is considered when the amplitude signals have polarity changes. In figure 1, the signals that suffers distortions are $s_3(t)$ and $s_4(t)$. This distortion generates the displacement inside or outside of the unit circle. The signals $s_1(t)$ and $s_2(t)$ are not affected by this distortion, but do be affected by the Bandlimiting distortion. The points that are inside of the unity circle under the amplification signal. By the other hand, the points that are outside of the unity circle where the attenuation of signal occurs.

Parabolic Amplitude

The parabolic amplitude distortions causes that all points are located out of the unity circle for positive parabolic amplitude. On the other hand, for negative parabolic amplitude distortion, all the trajectories suffer some attenuation, i.e., all points are to be inside unity circle.

Parabolic Phase

In parabolic phase phenomenon, negative frequencies are delayed as long as positive frequencies are advanced, i.e., if the phase is positive the first point in the received constellation is to be inside the unity circle, the second point is to be on the unity circle, and the third point is to be outside of the unity circle. The opposite effect occurs when negative parabolic phase is considered.

Cubic Phase

Distortion cubic phase is an effect similar to Bandlimiting and therefore there is no difference in the scatter plot between positive and negative polarities.

Residual Amplitude and Phase

The residual amplitude causes that the constellation seems to be a random dispersion of the samples. This can be explained by the theory of paired echoes in which ripples in the frequency-domain result from echoes, or intersymbol interference in the time-domain that is known to cause dispersion of the constellation points [1]. Combined effects of parabolic phase and residual amplitude are obtained from the residual distortion and the clusters rotation caused by parabolic phase distortion [1].

B. Digital Modulation

In this work, three different modulation formats were considered, namely, QPSK, OQPSK y MSK, Next they are briefly described.

Quadrature Phase Shift Keying

Quadrature Phase Shift Keying (QPSK) is a digital modulation that can be expressed as follows:

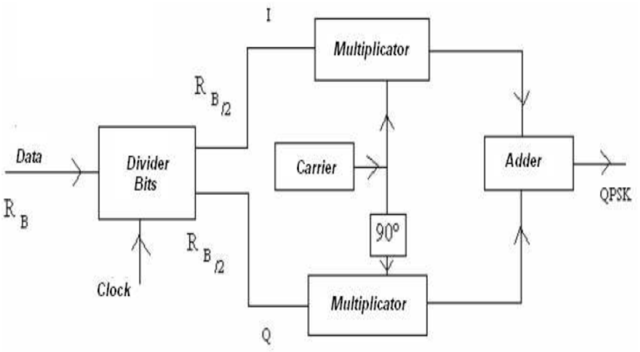
$$\begin{aligned} v(t) &= A\left\{\sum_k \cos(w_o t+\phi_k) * h(t-kT)\right\} \\ &= I(t)\cos(w_0 t) + Q(t) sin(w_o t) \end{aligned} \quad (1)$$

QPSK modulation scheme is divided into two parts: one part is signal $I(t)$ that is zero phased, and the other part is a signal $Q(t)$ with a phase displacement at 90º. Also the equation (1) can be represented as the equation 2, separating the real and imaginary part of the complex of d_k:

$$\begin{aligned} I(t) &= \sum_k real\{d_k\} * h(t-kT) \\ Q(t) &= \sum_k imag\{d_k\} * h(t-kT) \end{aligned} \quad (2)$$

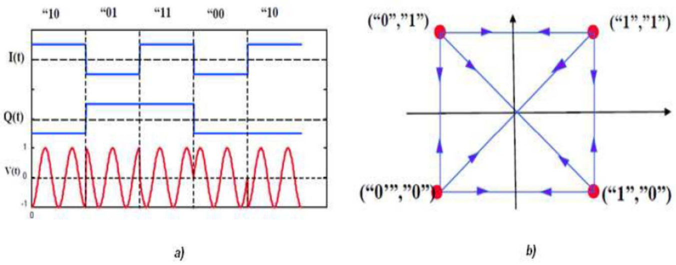
In figure 2 a block diagram modulator is shown, which illustrates the divider bits and the displacement signal.

FIG. 2. BLOCK DIAGRAM FOR QPSK MODULATION



In figure 3: a) shows an example of a QPSK modulated sequence and b) shows the zero crossing for the bit transmission ((1,0) to (0,1)) and the corresponding constellation.

FIG. 3. EXAMPLE OF A QPSK MODULATED SEQUENCE

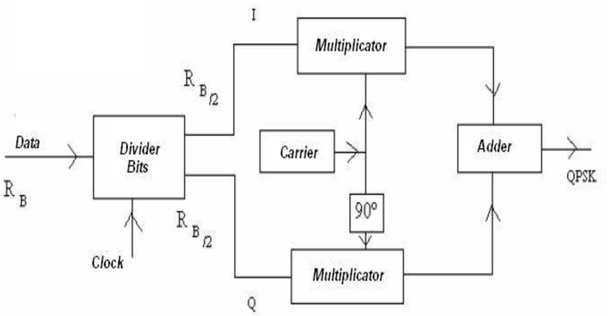


a) b)

Offset QPSK

In this modulation a time delay is added, denoted as Tb (also called offset) to suppress the zero crossing. The block diagram is shown in figure 4.

FIG. 4. BLOCK DIAGRAM FOR OQPSK MODULATION



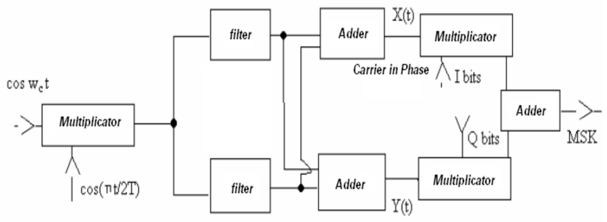
The equation that described such modulation is the same as the equation (1), excepting delay, as expressed in equation (3).

$$I(t)=\sum_k d_{2k} * rect_T(t-2kT_b)$$
$$Q(t)=\sum_k d_{2k+1} * rect_T(t-(2k+1)T_b) \qquad (3)$$

Minimum Shift Keying

Minimum Shift Keying (MSK) can be considered as an improvement of OQPSK, i.e., an offset QPSK adding a pulse made from a sinusoidal signal. This digital modulation reduces the Inter-symbol Interference (ISI) and eliminates phase discontinuities. Figure shows the block diagram of MSK modulation scheme.

FIG. 5. BLOCK DIAGRAM FOR MSK MODULATION



The equations that describe MSK modulation are the same as above given, but multiplied by a cosine function (a shaping pulse), so:

$$I(t)=\sum_k d_{2k} * rect_T(t-2kT_b) * \cos(\frac{\pi t}{T}) \qquad (4)$$
$$Q(t)=\sum_k d_{2k+1} * rect_T(t-(2k+1)T_b) * \sin(\frac{\pi t}{T})$$

IV. SIMULATIONS AND RESULTS

The OQPSK and QPSK signals were distorted using a linear distortion, which consist of a simple phase deviation by adding noise. This distortion is modeled as is shown in equation (6):

$$y(t)_d = y(t)_o + n$$
$$n = a + (b-a)K_{rand} \qquad (6)$$

where:

a: Lower limit of amplitude distortion.
b: Upper limit of amplitude distortion.
K_{rand}: A random scalar.

Following are shown some experimental results in figure 6 to 9.

FIG. 6. QPSK SIGNAL WITH 100 BITS AND NOISE IN [0.01, 0.1] RANGE

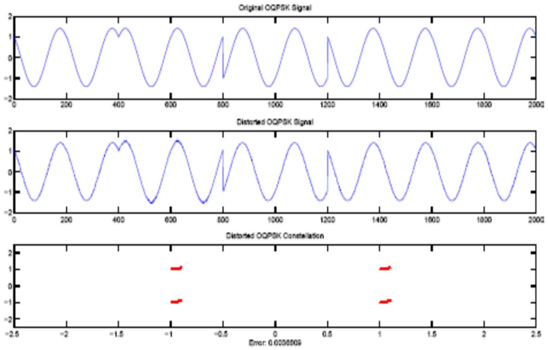


FIG. 7. QPSK SIGNAL WITH 100 BITS AND NOISE IN [0.1 ,0.8] RANGE

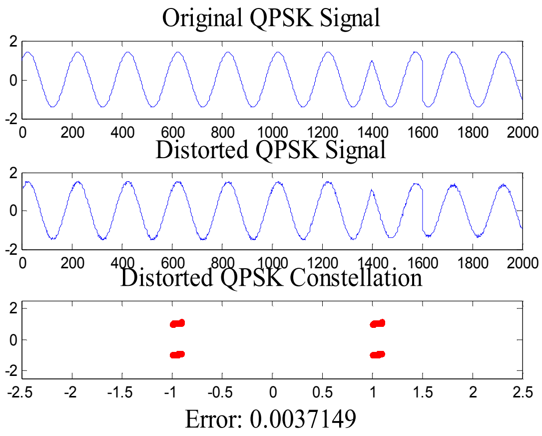


FIG. 8. QPSK SIGNAL WITH 100 BITS AND NOISE IN [0.01 ,0.1] RANGE

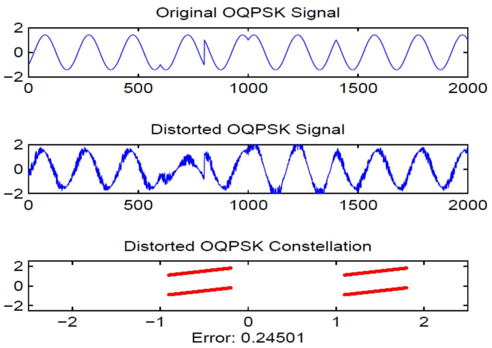
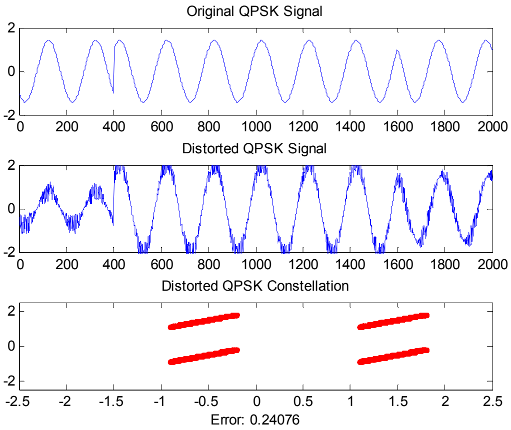


FIG. 9. QPSK SIGNAL WITH 100 BITS AND NOISE IN [0.1 ,0.8] RANGE



Results obtained from simulations show that the Mean Square Error (MSE) between the original data and distorted data for QPSK or OQPSK formats increases when the rate of bits or the nose magnitude increase. In the Table 2 are shown some experimental results for QPSK and OQPSK error.

TABLA I
MEAN SQUARE ERROR FOR QPSK AND OQPSK MODULATED SIGNAL

#BITS	MSE for OQPSK n ∈ [0.01, 0.1]	MSE for QPSK n ∈ [0.01, 0.1]	MSE for OQPSK n ∈ [0.1, 0.8]	MSE for QPSK n ∈ [0.01, 0.8]
30	0.00369	0.003681	0.24465	0.24247
100	0.00366	0.003714	0.24501	0.24076
5000	0.00370	0.003697	0.24379	0.24294

V. FINAL REMARKS

Because the optical pulses can be shaped as a sinusoidal waveform (by means of the inverse Fourier transform), the digital modulation formats (such as QPSK, OQPSK and MSK) take place for optical transmission. Optical distortions are inherent to material, transmission mode as well as the kind of fiber by which the optical transmission goes through. Therefore, in this work, we made a review of some related scientific studies in order to show some kind of distortion and their corresponding mathematical models.

We proved that a linear distortion model can be achieved via a heuristic method that localizes the constellation points as a line around the ideal locations according to a specific modulation format. With a proper parameters tuning, this approach can be useful for further analysis because a real distortion may be modeled.

As a future work, new linear and non-linear distortions are going to be studied in order to design properly filters that can be applied in real fiber distortions. In addition, distortions models for both fiber and transmission devices will be explored and implemented for further real time applications in optical transmission.

REFERENCES

[1] G. Chrisikos and M.Z. Win. Performance of quadrature amplitude modulation with nonlinear transmit amplifiers inr ayleigh fading. In Radio and Wireless Conference, 2000. RAWCON 2000. 2000 IEEE, 2000.

[2] J. Herrera, F. Ramos, and J. Marti. Nonlinear distortion generated by dsf-based optical-phase conjugators in analog optical systems. Lightwave Technology, Journal of, 20(9):1688–1693, September 2002.

[3] L. Giugno, M. Luise, and V. Lottici. Adaptive pre- and post compensation of nonlinear distortions for high-level data modulations. Wireless Communications, IEEE Transac-tions on, 3(5):1490 – 1495, 2004.

[4] G. Chrisikos. Analysis of 16-qam over a nonlinear channel. In Personal, Indoor and Mobile Radio Communications, 1998. The Ninth IEEE International Symposium on, volume 3, pages 1325–1329 vol.3, September 1998.

[5] C. Behrens, R.I. Killey, S.J. Savory, M. Chen, and P. Bayvel. Nonlinear distortion in transmission of higher order modulation formats. Photonics Technology Letters, IEEE, 2010.

[6] C. Behrens, R.I. Killey, S.J. Savory, M. Chen, and P. Bayvel. Reducing the impact of intrachannel nonlinearities by pulse-width optimization in multi-level phase-shift-keyed transmission. In Optical Communication, 2009. ECOC '09. 35th European Conference on, pages 1–2, 2009.

[7] G. Chrisikos. Analysis of 16-qam over a nonlinear channel. In Personal, Indoor and Mobile Radio Communications, 1998. The Ninth IEEE International Symposium on, volume 3, pages 1325–1329 vol.3, September 1998.

[8] Nguyen Thanh Bien. Estimation of an upper bound of ber under the efects of linear and nonlinear distortions, timing and phase errors in m-qam systems. In Advanced Technologies for Communications, 2008. ATC 2008. International Conference on, pages 84–87, 2008.

[9] N.Y. Ermolova. Corrections to num: 8220;on the statistical properties of specially con- structed –qam sequences in nonlinear radio channels num 8221;. Communications Letters, IEEE, 8(8):547–547, 2004.

[10] Nguyen Thanh Bien. Estimation of an upper bound of ber under the effects of linear and nonlinear distortions, timing and phase errors in m-qam systems. In Advanced Tech-nologies for Communications, 2008. ATC 2008. International Conference on, volume 9, pages 84–87, 2008.