Abstract

Polarization Mode Dispersion induces polarization dependent propagation. Consequently it generates a multiple imaging of the light pulse carrying the information. Its first order appears as a dual path fading channel of Maxwellian statistics. It results in harmful impairments that prevent the upgrade and installation of high bit-rate systems. The random process PMD exhibits strong frequency dependence, so that its amelioration requires channel by channel, non-linear, adaptive mitigation. Electronic mitigation appears as a very attractive solution to overcome the limit set by the PMD. Consequently, we considered the implementation of these solutions at the receiver in the electrical domain. We verified that these linear and non-linear equalization techniques can greatly reduce the power penalty due to PMD. Equalization's performance depends highly on the type of systems considered. For the two main types of systems: thermal noise limited systems and systems exhibiting ASE (systems using optical amplifiers), we demonstrated and quantified the induced improvement (measured as power penalty reduction). The most sophisticated technique that we considered (NLC+FDE) handles any kind of first order PMD within a 4 dB margin in the thermal noise limit. This extended to a 11 dB margin in the presence of ASE. This comes from the limitation set by the signal dependence of the noise. In fact, these DSP techniques do a better job at reducing very high penalty. Consequently, for a power and ISI limited link, it may be required to associate to electronic solutions optical compensation in order to reach acceptable performance. On the other hand, for links having large power margin or exhibiting reasonable PMD, electronic techniques appear as an easy, inexpensive and convenient solution. We derived in this work the bounds to NLC performance in the presence of ASE. Therefore, we extended the usual results of the thermal noise limit to the particular case of signal dependent noise. We also made clear that optical systems, because of their noise specificities cannot be studied or designed as others links. Notions such as eye opening, SNR and ISI need to be carefully defined and adapted to this case. We have provided in this work PMD dependent power penalty map for known systems. Given the link's statistics and characteristics, one can determine, following our structure, which mitigation techniques allow upgrade.
Index

1 **Polarization Mode Dispersion** ........................................................................................................... 7

1.1 **Birefringence in fibers** .................................................................................................................. 7
  1.1.1 Propagation of light in a medium ............................................................................................... 8
  1.1.2 Concept of polarization states .................................................................................................. 11
  1.1.3 Anisotropic propagation in a fiber ............................................................................................. 15
  1.1.4 Short fibers, Hi Bi fibers ............................................................................................................. 16

1.2 **Representation of polarization** .................................................................................................... 19
  1.2.1 Representation of polarization states ......................................................................................... 19
  1.2.2 Representation of anisotropy, retardors, rotators ..................................................................... 26

1.3 **Properties of PMD** ......................................................................................................................... 31
  1.3.1 Correlation length ....................................................................................................................... 31
  1.3.2 Coupled-power Model ................................................................................................................ 32
  1.3.3 Principal States of Polarization model ....................................................................................... 33
  1.3.4 Statistical properties of PMD ...................................................................................................... 37
  1.3.5 Consequence on a communication system ................................................................................ 45

1.4 **Numerical Simulation of PMD** ....................................................................................................... 48
  1.4.1 Jones matrix simulation .............................................................................................................. 48
  1.4.2 Poincaré sphere simulation ......................................................................................................... 50

1.5 **Experimental measurements of PMD** .......................................................................................... 54
  1.5.1 Pulse delay measurement ............................................................................................................ 54
  1.5.2 Interferometric method ............................................................................................................... 55
  1.5.3 Poincaré method ......................................................................................................................... 55
  1.5.4 Jones Matrix method ................................................................................................................. 55
  1.5.5 Fixed Analyzer method .............................................................................................................. 56

2 **Non Linear Cancellation and Mitigation Techniques** ........................................................................ 57

2.1 **Introduction** .................................................................................................................................... 57

2.2 **Non Linear Canceller** .................................................................................................................. 59
  2.2.1 Principle ...................................................................................................................................... 59
  2.2.2 Implementation ............................................................................................................................ 64
  2.2.3 Adaptive NLC ............................................................................................................................. 68

2.3 **Feed forward Equalizer** .................................................................................................................. 72
  2.3.1 Principle ...................................................................................................................................... 72
  2.3.2 Implementation ............................................................................................................................ 73
  2.3.3 Performance .................................................................................................................................. 74
  2.3.4 Adaptation .................................................................................................................................... 75

2.4 **Experiments/simulations** .................................................................................................................. 77
  2.4.1 Experimental setup ....................................................................................................................... 77
  2.4.2 Devices ........................................................................................................................................ 78
  2.4.3 Simulations ................................................................................................................................... 80
  2.4.4 Results/interpretations ................................................................................................................ 81

2.5 **performance degradation in optically amplified systems** ................................................................. 93
  2.5.1 Noise processes in fiber optic communication systems ............................................................. 94
2.5.2  Theoretical bounds to digital electronic mitigation ________________________________ 99
2.5.3  Experimental verification __________________________________________________ 103
2.5.4  Conclusion______________________________________________________________ 107

2.6  Hybrid solutions____________________________________________________ 109
2.6.1  PSP launched and spectrum shaping _________________________________________ 109
2.6.2  Diversity techniques ______________________________________________________ 110
INTRODUCTION

Fiber optic technology has exhibited one of the most impressive developments. The transmission capacity of commercial systems doubles every six months. Fiber optics support today’s information based explosion. Backbones of communication networks, transoceanic communication and even large Local Area Network (LAN) employ optical communication system.

Indeed fiber optic technology created the only communication systems able to support Terabit/s transmission that some of the aforementioned systems require. Many advancements have allowed this achievement. First, manufacturing processes dropped fiber loss down to 0.2 dB/km. Then chromatic dispersion (frequency dependent propagation speed) was ameliorated using dispersion compensation techniques. Non-Linearities were reduced using dispersion map management. Finally, the cost effective development of Wavelength Division Multiplexing (WDM) was allowed by the creation of optical amplifiers. It is possible, from this technology to transmit tens of channels at 10 Gb/s over thousands of kilometers. However, Polarization Mode Dispersion (PMD) limits system design to this value.

PMD is the manifestation of the remaining birefringence (anisotropy) of the fiber. Because of the imperfect circular symmetry of the fiber, there exist, in the propagation medium, preferential wave orientations. A lightwave, depending on the direction of its electric field, called polarization, has different propagation speed. This polarization dependence of the propagation constant induces dispersion of the pulses. Its main approximate effect is to duplicate the pulse into two copies propagating at different
speed. This dual imaging affects so strongly systems that a 40 Gb/s system requires very low PMD fiber. Furthermore, it prevents many installed systems to be upgraded from 2.5 Gb/s to 10 Gb/s. Giving up these networks represents a very large waste, since deploying a mile of fiber costs $100,000. Consequently, PMD has become one of the main topics of the fiber optic research, in recent years.

PMD was first studied by C.D. Poole [1]. Its model, based on the existence of two special polarizations, called the principal states of polarization (PSP) is the basis of all studies. In the first part of this thesis, we recall the origins of PMD in fibers and the formalism of polarization effects in fibers to derive his concept. Then, we verify by simulations some characteristics of PMD.

The second part of this thesis is devoted to the amelioration of PMD effects on optical transmission. According to PMD characteristics and consequences, we considered electronic solutions implemented at the receiver. This means that we do not try to overcome the polarization effects by ‘inverting’ them in the optical domain (optical solutions). We rather try to mitigate PMD consequences by processing the received electrical signal. Therefore, we study the performance of equalization techniques at the receiver: Non-Linear Cancellation (NLC) (or Decision Feedback Equalization (DFE)) and Feed Forward Equalization (FDE) (Transversal Filter (TF)). We recall their principles; we verify their performance in case of thermal noise. Then we derive a new model to estimate the performance degradation in the presence of Amplified Spontaneous Emission (ASE). We also discuss a high-speed adaptive implementation of these techniques.
The global goal of this thesis is to derive the range of PMD over which a given technique provides acceptable link performance.