Contributors/ acknowledgments

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Background literature investigation (Intro) Version 1

Experimental setup

I have only considered a single channel with assumed Gaussian pulses. In the simulations, a 64 QAM processing technique is used.

Why does it happen? What is SPM?

Self-phase modulation occurs because the physical properties of the electromagnetic waves and the nature of fiber materials exhibit a relationship known as the Kerr effect. The Kerr effect is a describes the nonlinear relationship between light and fiber. Physically, the Kerr effect is the change of refractive index instantaneously and locally with dependant on the intensity. Since fiber transmission is foundationally dependent on the refractive index, changes the refractive index can cause degradation to the signal. The Kerr effect categorizes the non-linear effects into three responses; self-phase modulation (SPM), cross phase modulation (XPM), and four-wave mixing (FWM). \\

SPM is an intra-symbol nonlinearity, meaning that a single pulse causes the nonlinear effects to itself. The effect of SPM is a nonlinear phase shift which increases over longer fiber lengths, appearing as a phase modulation. SPM can case effects that appear as multiplicative noise (---define), and intensity to phase modulation conversion (---define). \cite{slidesOct---}. Multiplicative noise is ---

When does it happen?

SPM is more prominent for higher power signals and increases for longer path length. Furthermore, SPM accumulates over amplifiers used to compensate for optical loss \cite{slidesOct---} \cite{text64-65}.

How does it happen?

The intensity of a given channel causes a non-linear (recall the Kerr effect generally is intensity dependent) shift of the phase of the channel. This phase shift corresponds to an introduced nonlinear up-chirp (the chirp coefficient is C$>0$). Chirp is a frequency changes as a function of time \cite{slidesOct---}.

What problems does it cause?

SPM limits the performance of optical systems since it increases with power. A mitigation technique would be to decrease input power; however, this is disadvantageous for other system considerations such as SNR \cite{text64-65}. This also limits the number of channels that can be used, for example in subcarrier multiplexing systems \cite{text273}. \\

By inducing up-chirp, and the combined effects with GVD, SPM alters the shape of a propagating pulse in the optical fiber that leads to pulse broadening. This broadening requires more bandwidth to maintain performance when more than one signal is transmitted, which adds a limit to the performance of a system \cite{text64-65}. \\

Amplifiers are used in telecommunication links to reduce power loss along a link. SPM poses a problem for these long-haul systems since it is not reduced through amplifiers, instead it accumulates across them \cite{text194-195}.\\

Dispersion compensating fiber (DCF) is also used in telecommunications to reduce the impact of dispersion on a signal. However, this fiber type has a smaller effective area, increasing the effect of nonlinearities, including SPM \cite{text194-195}. SPM is related to the effective area of a fiber by

\begin{equation}

SPM relation to Aeff

\end{equation}

--- include how this is harmful to long reach systems

--- include Ahmed’s paper info (here or in mitigation)

How do we mitigate its effects?

Modulation techniques have been developed where the input signal is down -chirped to try and mitigate the up-chirp effect on the signal at the output of the system. These modulation techniques include CRZ \cite{text194-195}. Another technique proposed in optical phase conjugation (OPC). This technique is capable of compensating SPM and GVD simultaneously.

The effect of Dispersion (particularly GVD)

GVD is the dispersion can be considered a phase to intensity modulation conversion. Initially, it appears that dispersion could potentially completely compensate for SPM. SPM cannot be compensated by dispersion where chromatic dispersion is evident (--- verify, maybe include equation or plot and why chromatic dispersion causes problems) \cite{slidesOct---}. In the case of a situation where dispersion coefficient is greater than zero, so dispersion is evident, and there is no chromatic dispersion, $\beta\_2< 0$ from the propagation equation below \cite{slidesOct---} one can achieve compensations for SPM using GVD. \cite{slidesOct---}

\begin{equation}

\beta (\omega) = --- complete this line

\end{equation}

This is effective because SPM will work to compress the pulse by red-shifting the leading edge of the pulse and blue-shifting the trailing edge. Meanwhile, GVD affects the pulse by broadening it. This concept is the basis for self -reinforcing wave packets known as solitons \cite{wikiSolitons}. \\

---include why this is not realistic for communication systems (can we not remove chromatic dispersion? Simply because we have other channels and info to send?)

About the software

This program calculates coefficients for the non-linearity effects for each channel. These coefficients are calculated using the NLSE (---verify) which can account for dispersion and SPM interacting simultaneously \cite{text194-195} \cite{text335}. The input signals have the coefficients applies to them to determine the output signal will look like. The coefficients are dependant on the fiber type and length. The program used was developed by Ahmed and Prof Cartledge in 2018 (---?) at Queen’s university optics lab(---?). \cite{Ahmed}

Background version 2

Thoroughness, suitability, demonstrates understanding of technological trends.

* The Kerr effect is when the refractive index of a fiber instantaneously and locally changes in the presence of a wave. The change in refractive index is dependant on the intensity of the excitation. The Kerr effect includes several non-linear effects including self-phase modulation (SPM), cross-phase modulation (XPM), and four-wave mixing (FWM) which degrade a signal being transmitted.
* SPM is
* Impairment on fiber transmission include --- effects
* This is a problem because
* Solutions include
* Past solutions/ experiments have been done to
* Next step for technology is ahmed’s paper and Aazar’s

Explain the significance of the referred work and put it in context with current state-of-the-art technology

* need for more bandwidth
* reduce time for approximate simulations of new patters before testing reduces time spent testing patters that will not work
* further advancements through machine learning to determine optimal transmission constellation spatters (geometry and probability shaping’s ----verify)
* see if Aazar has a paper on her research that I could possibly include a reference to since ML in the routers would be another cool advancement to include

Novelty

Advantage of current research

Ahmed’s

* Current research includes using QAM constellations are sued with probabilistic shaping to reduce the affects of non-linearities and with the intent of improving achievable information rates\cite{ahmed}. ---Lower intensity variation will reduce the amount of non-linear interference indicating that constant modulus techniques would be preferable\cite{ahmed}. Constellations allow
* This program provides an efficient computational method to estimate the performance of novel constellations in fully loaded systems.
* Novel technique of utilizing genetic algorithms to optimize the constesllation for QAM
* “Using this methodology, different variations of a known power and polarization balanced(PPB)constellation(4bits/8Dsymbol)as well as polarization-balanced polarization-switched QPSK (PB-PSQPSK, 6 bits/8D symbol) can be obtained by optimizing the 8D QPSK subset selection at an appropriate constellation entropy (CE,bits/multidimensional symbol).Moreover, the results suggest that PPB constellation and its polarization unbalanced versions are the closest 8D QPSK subsets to the Shannon limit at 4 bits/8D symbol.”
* Performance evaluations compare non-linear tolerances for different constellations in information rates of fully loaded systems in DWDM systems.
* To improve efficiency using QAM formats is practical and rely simple to implement if using IQ modulators.
* Probabilistic shaping is beneficial for improving power efficiency in multi-level high carnality QAM constellations. Geometric shaping is useful for constant modulus and multilevel forms.

Cartledge

* Reduce peak to average power in order to reduce the nonlinear effects by restricting high energy symbols in a constellation. This resulted in lower NLIN power.
* Simulations and experiments showed that gains up to 400km are achievable with probabilistic shaping. This is achieved though “rate-matching the independent identically distributed input binary data to the speciﬁc MB PM”

Chandrasekhar

* Closely approach Shannon limit using constellations shaping, and most recently probabilistic shaping. This is useful do to its ability to more easily implement flexible transponders. These transponders are capable of “dynamically adapting the information rate to the desired system reach”. The transponders also use the system spectral efficiency to adapts the information rate.

Aazar

* ---read and complete

Discuss possible trade offs with existing technology

Cartledge

* Constellations reduce NLIN increase the SNR
* A minimum Euclidean distance was achieved in a lattice like constellations which recued the symbol error rate in linear AWGN channel, but performance is not maintained when non-linearities are included. ---maybe background
* Bit to symbol mapping is non-trivial ---maybe background
* “It was shown that the gains potentially exceed the ultimate shaping gain on an AWGN channel of 1.53 dB. Operating such systems at high spectral eﬃciency is non-trivial due to the complexity of the DSP at the receiver side”
* “Optimal detection generally requires that each possible input combination of symbols is evaluated, which generally results in an exponential increase in complexity both with the dimensionality time slots) and the spectral eﬃciency (cardinality) of the base modulation format (restricted to QPSK in[55]).”

Chandrasekhar

* Probabilistic shaping in particular has much higher complexity than existing systems. This is difficult to implement in electronic design ---contradictory with ahmed( for amplifications and at the transmitter and receiver) .
* A possible technique to reduce complexity while still increasing shaping techniques and facilitating flexible transponders has been proposed “…a novel, low-complexity PS scheme based on prefix codes to achieve close-to-optimum shaping performance while requiring only simple look-up table searches and allowing for highly parallelized application specific integrated circuit (ASIC) implementation.”

Discuss innovation

Ahmed’s

* Machine learning techniques used to optimize the constellations
* Include some results

Chandrasekhar

* Experimentally demonstrate a system utilizing flexible transponders and probabilistic shaping with reduced complexity and forward error correction (FEC) decoding on polarization-division multiplexing (PDM) 256-QAM in dense WDM system. The results are shown for 50km to 4000km and have record spectral efficiency (SE) performance.

Aazar

* ---read and complete

Methodology – evaluated on correctness

Theory/simulation/experiment to demonstrate innovation due to proposed research

Optilux

* Parameters initialization including number of bits, samples, number of channels, roll off, extinction ratio, and wavelength. Link parameters also initialized including the span and fiber parameters (attenuation, effective area, nonlinear index, dispersion, slope)
* Length of required compensating dispersion fiber calculated and gamma index and amplifier gain.
* Non-linear index is a quantity that indicated the Kerr effect in a medium. (https://www.rp-photonics.com/nonlinear\_index.html)
* Gamma index is nonlinear coefficient related to fiber nonlinear index by $\gamma = \dfrac{2\i n\_2}{\lambda\_0 A\_{eff}} $

(<http://optilux.sourceforge.net/Documentation/optilux_doc/NLSE.html>)

* Uses Fourier step method to calculate effects along desired fiber length.
* The transmitter is simulated by setting up a “WDM optical field whose channels are saved into columns of” a matrix. A pseudo random pattern is generated form a De Bruijn sequence form which is where an additional 0 added to the longest sequence of zeros. [optilux function definition]
* The modulation technique used is on-off keying (OOK) which is implemented using to optilux functions. An ideal modulator is simulated by choosing the method where all channels are combined to account for FWM, however, since the simulations done for this report include only 1 channel to explore SPM only this does not impair the results.
* The link is modeled by solving the NLSE with the use of a Fourier algorithm that calculates step by step transmission. The calculation neglects polarization effects.
* Finally, the program applies an ideal optical amplification to the signal with ASE noise

Ahmed’s code

* Similarly, this program initializes the same parameters, and includes some others such as an up-sampling rate, and a scaling actor that is used to normalize ---.
* Assumes negligible PMD, and weak non-linearity. It \cite{ahmed} the intent was to explicitly model the modulation format properties and neglect undesired parameters.
* Fully loaded system modeled
* “intra-channel nonlinearities are calculated according to the time domain first order perturbation solution of Manakov equations”.
* Pseudo random sequence is still used to produce a symbol sequene, as in the optilux program. Intra-channel non-linearities are considered first, and phase and amplitude pertbations are applied to the symbols. This is done using a additive-multiplicative model.
* After the pertibations have been applies the symbol x-polerization can be decribed by $A\_{0,x}^{out} = (A\_{0,x}^{in} + \DeltaA\_x)e^{j\Delta \phi\_x}$ at time index 0.
* “where, Ain 0,x and Aout 0,x are the input and output symbols, respectively. The amplitude and phase nonlinear perturbations ΔAx and Δφx are approximate solutions of the single-channel Manakov equations.”
* This solution is proportional to th launch power nad symbol sequence and nonlinear pertibation coeffects found through the peribation analysis. (---equation in paper if want to add) The coefficients are normalized using the nonlinear coeffient $\gamma$, over a given length and pulse shape, assuming mathc ed filtering. The coeffients are give by $C\_{m, n}(L) = j\dfrac{8}{9}\gamma ---$ where ---.
* The y-polarization is also taken into account by the same method.
* The third stage of this model is used to apply the OSNR to the signals after the linear propagation. Periodic amplifier noise is also included in this stage and the OSNR s caluated by $OSNR = 58 + P\_0 - \alpha - NF - N$ where ---.
* The code is extended to consider inter-channel NLIN which includes cross phase modulation and four wave mixing. However, these abilities were not uslized for modeling since SPM was of primary interest.

**My progression**

optilux

* Explored the length at which SPM becomes significant in uncompensated fiber.
* Included additional fiber length calculated by $ \dfrac{Din – \dfrac{Dc\*Lf}{1\times 10^3}}{Dc\_2}(1\times 10^3)$ of dispersion compensating fiber (DCF) to visually explore the benefits. (---- why this equation, where does it come from?)
* Explored the variation of power on the SPM effect with and without DCF. ---what power level does it start to take effect at? Does this start power change for the addition of DCF? Why is this?

Ahmed’s code

* Explored length span effect on --- (want to compare SPM effect when using constellation, but if not then compare variation of lengths with constellations) INCLUDE GVD sine I do in optilux
* %(with only) With and without dispersion effects ---
* With and without probabilistic shaping

**Optilux 64QAM\***

* Compare the BER of uniform and PS 64 QAM for different lengths and input powers. Dispersion not included.
* Plot results