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.

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?)

Background version 2

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 patterns before testing reduces time spent testing patterns that will not work

Thoroughness, suitability, demonstrates an understanding of technological trends.

The Kerr effect is when the refractive index of a fiber instantaneously and locally changes in the presence of an electric field. 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\cite{slide}. \\

Non-linearities can be grouped as either inter-channel or intra-channel non-linearities. SPM is an intra-symbol nonlinearity which means that the channel will be affected by this non-linearity even if it is the only channel in the fiber. Intra-channel non-linearities can be thought of as the channel inducing nonlinearities onto itself. SPM is a nonlinear phase shift of the original signal being transmitted on a channel. The phase shift is a non-linear up-chirp (the chirp coefficient is C$>0$). Chirp is a frequency changes as a function of time\cite{slide}. SPM increases over longer fiber lengths and with higher input power. SPM can appear to be an intensity to phase modulation conversion and or multiplicative noise\cite{slide}. \\

SPM poses a limiting factor to fiber communication systems \cite{text} \cite{stolen}. SPM limits the performance of optical systems since it increases with power, introduces chirp, and accumulates across amplifiers \cite{text}. Increasing input power can help improve the signal to noise ratio (SNR), however, if SPM is evident then increasing the power will increase the non-linearity effects. In such a case it the non-linearity effects can become the dominant limiting factor and another method should be used to increase the SNR \cite{slide}\cite{text}. Limiting the input power also limits the number of channels that can be used, for example in subcarrier multiplexing systems \cite{text}. \\

SPM also introduces up-chirp to the signal which in combination with GVD, which is evident in all real fibers, broadens a propagating pulse in the optical fiber. This broadening requires more bandwidth to maintain performance when more than one signal is transmitted\cite{text}. Dispersion compensating fiber (DCF) is used in telecommunications to reduce the impact of dispersion; however, this fiber has a smaller effective area, increasing the effect of nonlinearities, including SPM \cite{text}. SPM is related to the effective area of a fiber by the non-linear parameter given by \cite{text}

\begin{equation}

\gamma = \dfrac{2\pi n\_2}{\lambda A\_{eff}}

\end{equation}

Where $n\_2$ is the refractive index of the cladding, $\lambda$ is the wavelength of the signal, and $A\_{eff}$ is the effective area of the fiber. Lastly, SPM accumulates over amplifiers which are used in telecommunication links to reduce power loss along a link. These effects indicate some of the main reasons SPM limits performance of long-haul fiber optics communication systems \cite{text}.\\

Reducing the impact of SPM on communication systems can be achieved by mitigating the effects or by improving the system’s tolerance to SPM and other nonlinearities\cite{cartledge}. To mitigate the effects of SPM modulation techniques such as CRZ have been developed where the input signal is down-chirped to try and reduce the SPM up-chirp effect on the signal at the output of the system. Another technique proposed in optical phase conjugation (OPC) which is capable of compensating SPM and GVD simultaneously\cite{text}. More recently techniques including constellation shaping and machine learning techniques are being researched to improve system tolerance to non-linearity effects\cite{cartledge}\cite{ahmed}\cite{chand}. \\

%---Novelty/background of novelty

Novelty

Constellation shaping is a dynamic digital signal processing (DSP) technique that can help increase the capacity of a system and reduce the impact of nonlinearities\cite{cartledge}\cite{ahmed}\cite{chand}. Constellation shaping is a step towards future optical networks that are moving towards being flexible, dynamic, and accommodating to various modulation formats and bit rates\cite{aazar}. Both the geometry of points in the I/Q plane (geometric shaping) and the probabilities of the points (probabilistic shaping) are considered in constellation shaping. Increasing the dimensionality of constellations increases the flexibility which allows for improvements in power efficiency and for relationships between dimensions to be introduced that reduce non-linear effects. Geometric shaping is useful for constant modulus and multilevel forms. Probabilistic shaping is beneficial for improving power efficiency in multi-level high carnality QAM constellations \cite{ahmed}.\\

Geometric shaping is performed with the goal of limit high-energy symbols to a lower peak-to-average power ratio in the constellation. This can be useful in mitigating non-linear effects and reducing the non-linear interference noise (NLIN) by restricting high energy symbols in a constellation. Symbol sequence has a direct impact on the NLIN, but NLIN is also affected by the system configurations, including but not limited to the length of transmission and amplification type. Thus, NLIN can be a good indication of constellation shaping systems performance\cite{ahmed}. It has been shown that for short ranges of approximately 50km NLIN is strongly affected by the geometry shaping of the transmitted signal\cite{ahmed}. An example of geometric shaping achieved reduced symbol error rate in linear AWGN channel by achieving a minimum Euclidean distance in a lattice-like constellation. Unfortunately, performance was not maintained when non-linearities are included and the bit to symbol mapping is complex\cite{cartledge}. \\

%---Polarization balanced from cartledge

Probability shaping (PS) is one of the latest concepts being explored in fiber optic communications. It has attracted a significant amount of interest for communications since it extracts shaping gain and enables flexible transponders for dynamic information rate allocation\cite{chand}. For systems that are highly dependant on entropy, probabilistic shaping can be used to reduced entropy of the system and improve spectral efficiency by improving the mutual information. This is possible through optimization of the probability mass function of the input signal. When a system is close to capacity it is more dependant on effective SNR than on entropy, and thus a non-uniform probability mass function is more effective for optimization. PMF typically used include the Maxwell-Boltzmann, however, a modified Blahut-Arimoto algorithm has also been used recently and demonstrated the probabilistic shaping outperforms geometric shaping in some cases\cite{cartledge}. Simulations and experiments have shown that gains up to 400km are achievable with probabilistic shaping. Iterative approaches are currently used to optimize the geometry and probability distributions of constellations\cite{cartledge}.\\

Although these advancements are excellent, it requires high computation and implementation complexities\cite{cartledge}. \\

Simulation tools that are accurate and modest computational effort are beneficial to provide fast estimates of new proposed designs. A novel technique of utilizing genetic algorithms to optimize the constellation for QAM fully loaded systems has been proposed in \cite{ahmed}. The procedure makes some well-established approximations including negligible PMD and weak non-linearities. It also assumes that the receiver functions operate near ideally, in which case the systems’ modulation format can be considered to be affected by the Kerr non-linearities and ASE noise. The procedure is used to evaluate the performance and compare non-linear tolerances for different constellations in information rates of fully loaded systems in DWDM systems. The implementation of genetic algorithms is useful particularly in cases when the iterative approach is infeasible. For example, a case where there is 4bits/8D symbol with 16 point subsets therein lies an optimal solution subset. In order to iteratively find the solution set the number of possible combinations will be on the order of 10$^25$. Genetic algorithms do not always find a global minimum, so in order to determine an optimal solution for several initial conditions. In the example provided above, several SNR values will be used for the genetic algorithm to minimize the following function\cite{ahmed}

\begin{equation}

S\_{opt} = min\_s[E – AIR(X;Y)\_{@SNR}]

\end{equation}

Where $S\_{opt}$ is the optimal solution subset, AIR is the attainable information rate, and X and Y indication the polarizations. Though this process, the subset closest to the Shannon limit is chosen\cite{ahmed}.\\

%In this report the details will only be explored for intra-nonlinearity effects since SPM is the topic of interest.

Discuss possible trade offs with existing technology

There are a couple of disadvantages to the proposed research discussed above. The first is that the simulation process is not as accurate as models that are more computationally intensive but go through the fiber in segments to determine the effects on the pulses. For example, an open source toolbox called Optilux is more accurate. Optilux uses the Fourier step method to calculate effects on the signal along the desired fiber length. However, as an estimation of performance, the process suggested is sufficient for the application proposed in \cite{ahmed}. \\

The second disadvantage is the system computation and implementation constellation shaping complexities. Computational complexities include the modelling of the signal propagation along the optical fiber. This is complex due to the combination of effects including SPM, dispersion and many others that need to be considered to have an accurate model. There are several mathematical approaches to modelling optical channels to include the required effects. Computational complexities can also be expanded to searching for an optimal solution of a constellation shaping in a design project. A novel solution to this dimension of computational complexity is genetic algorithms. The process for using genetic algorithms to determine optimal constellations shaping is discussed in \cite{ahmed}. This method is both time and computationally efficient as the issue of modelling a complex system of optical transmissions is also simplified. \\

The implementation complexity is the complexity of the hardware that will be relied upon to realize the constellation shaping in optical communication links. In order to reduce the complexity required for transponder implementation \cite{chand} proposed a simple look-up table method that is utilized to implement low-complexity PS with near optimum shaping performance is achieved. This method is implemented on an integrated ASCI circuit.

Methodology – evaluated on the correctness

Theory/simulation/experiment to demonstrate innovation due to the 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.
* The 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 from 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 modelled 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 factor that is used to normalize ---.
* Assumes negligible PMD, and weak nonlinearity. It \cite{ahmed} the intent was to explicitly model the modulation format properties and neglect undesired parameters.
* The fully loaded system modelled
* “intra-channel nonlinearities are calculated according to the time domain first-order perturbation solution of Manakov equations”.
* The pseudo-random sequence is still used to produce a symbol sequence, as in the Optilux program. Intra-channel non-linearities are considered first, and phase and amplitude perturbations are applied to the symbols. This is done using an 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 is 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 the launch power and symbol sequence and nonlinear perturbation coeffects found through the perturbation analysis. (---equation in the paper if want to add) The coefficients are normalized using the nonlinear coefficient $\gamma$, over a given length and pulse shape, assuming matched filtering. The coefficients 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 calculated 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 utilized for modelling 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 to 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 the variation of lengths with constellations) INCLUDE GVD since 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
* discuss