Impact of Fiber Parameters on Nonlinear Fiber Capacity

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Abstract: We present the impact of varying the fiber loss and nonlinear coefficients and the chromatic dispersion on the nonlinear capacity limit estimates of fibers. The results suggest that a relative change in fiber loss or nonlinear coefficients have greater impact on the fiber nonlinear capacity limit estimate than a similar relative change in chromatic dispersion.

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1. Introduction

The silica-based optical fiber had been foreseen by Charles K. Kao in the mid-1960's as a medium that could radically change optical communication. This was mainly due to the potential of fibers for achieving ultra-low loss (below 20 dB/km) [1]. By the late 1970's, optical fibers with loss coefficients well below one dB/km (in the 1550 nm region) had been fabricated. The availability of such ultra-low-loss fibers unleashed a quest for increasing capacity which was only possible through tremendous advances in *optical* technologies, such as lasers, modulators, photodetectors, optical filters, optical amplifiers as well as *electronic* technologies such as broadband electronics, digital signal processing (DSP) and forward error correction (FEC). Given the tremendous advances in these fields, it has become useful to evaluate the capacity limit of fiber-optic communication systems due to Kerr nonlinearity considering the ultimate performance of optical and electronic technologies. Such a study has been performed in Ref. [2] that provided a nonlinear fiber capacity limit estimate, hereafter simply referred to as *nonlinear fiber capacity*, for standard single-mode fiber (SSMF). This study follows the procedure outlined in [2] and looks at the impact of three fiber parameters: the loss coefficient, α, the nonlinear coefficient, γ, and the chromatic dispersion, β_2. We are ignoring in this study the possible tradeoffs required between these fiber parameters as well as the possible impact on other fiber properties such as resistance to bending loss and onset of multimode operation.

2. Nonlinear Fiber Capacity

Shannon considered the rate at which information can be transported reliably (i.e., with arbitrary low bit error rate) through a medium that adds noise [3]. For the additive white Gaussian noise (AWGN) channel, Shannon found that the capacity (C) per unit of channel bandwidth (B) or the spectral efficiency (SE) is given by $C/B \equiv \mathrm{SE} = \log_2(1+\mathrm{SNR})$, where SNR is the signal-to-noise ratio. The SNR relates to the optical SNR (OSNR) used in optical communication [2] by $\mathrm{OSNR} = pR_S\,\mathrm{SNR}/(2B_{\mathrm{ref}})$ where p is the number of polarization states of the signal, R_S is the symbol rate, and B_{ref} is a reference bandwidth commonly taken to be 0.1 nm, or 12.5 GHz at 1550nm.

The fundamental principles of information theory laid out by Shannon have been applied to calculate the capacity of a variety of channels beyond AWGN. Such calculations are often based on a representation of a channel by a set of discrete transition probabilities between M input states of X and Q output states of Y as represented in Fig. 1. For a channel represented by a set of transition probabilities $P_{Y|X}(b|a)$, the capacity for an input signal power $P \equiv \mathscr{E}[|X|^2]$ is given by [3, 4]

$$\frac{C}{B} = \max_{X:\,\mathscr{E}[|X|^2]\leq P} \sum_{a,b} P_{Y|X}(b|a)\,P_X(a)\,\log_2 \frac{P_{Y|X}(b|a)}{P_Y(b)}\ . \tag{1}$$

The calculation of fiber capacity estimates is based on Eq. (1) with additional constraints listed in the next paragraph. The waveform channel is represented by pre-equalization at the transmitter, nonlinear propagation over fibers followed by digital signal processing and matched filtering at the receiver (see [2] for more details). X and Y are taken at the input and output of the waveform channel, respectively. We evaluate the impact on nonlinear fiber capacity of three fiber parameters: α, γ, and β_2.

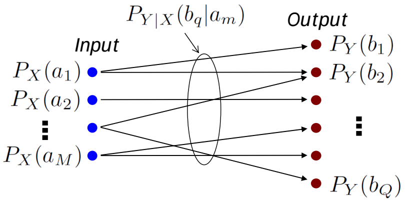

Fig. 1: Channel model.

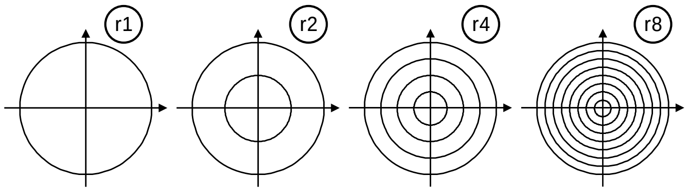

Fig. 2: Ring constellations used for capacity limit estimate calculations.

The main features of the nonlinear fiber capacity calculations are 1) near-Nyquist signaling, 2) ring constellations with rings equally spaced in optical field amplitude and with equal frequencies of occupation, 3) coding that can recover the mutual information, 4) ideally distributed Raman amplification (IDRA), 5) pseudo-linear transmission (highly dispersive transmission regime) 6) back-propagation at the receiver or at the transmitter, 7) optically-routed networks (ORNs) using near-rectangular filtering at reconfigurable optical add-drop multiplexers (ROADMs) located every 100 km. An example of the nonlinear fiber capacity calculated for different numbers of rings is shown in Fig. 3. The distance $L = 2000$ km and the fiber parameters are $\alpha_{\text{dB}} = 0.15$ dB/km, $\gamma = 0.847$ (W - km)$^{-1}$, and $D = 17$ ps/(nm-km). One observes that all capacity curves of Fig. 3 exhibit a maximum due to the growth of distortions with power from fiber nonlinearity. As the number of rings in the constellation increases, this “maximum capacity” converges to statistically identical values when the number of rings is sufficiently large ($\sim$16 rings here). Therefore, the nonlinear fiber capacities are calculated based on a large number of rings.

3. Transmission Fiber Capacity

For a given optical networking scenario and optical amplification scheme, the nonlinear fiber capacity depends mainly on the fiber parameters and system length. We assume here an ORN where there is no access to neighboring wavelength-division multiplexed (WDM) channel fields. Nonlinear fiber capacities when varying the three fiber parameters are shown below. The results here have been obtained with back-propagation at the receiver but statistically identical results were obtained with back-propagation at the transmitter. Only single-polarization results are reported here.

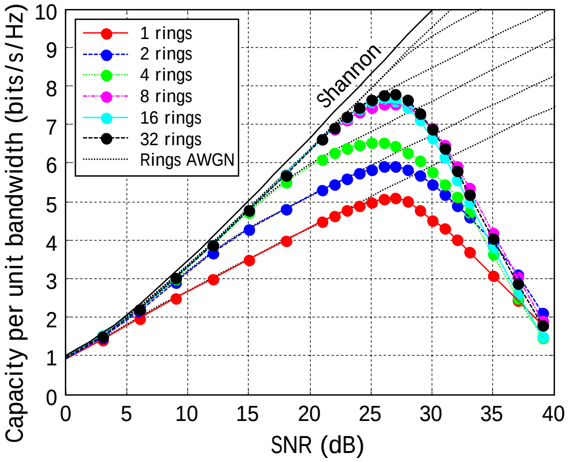

Fig. 3: Typical nonlinear capacity limit estimate curves for an increasing number of rings. The dashed lines are the capacity curves for additive white Gaussian noise (AWGN) only.

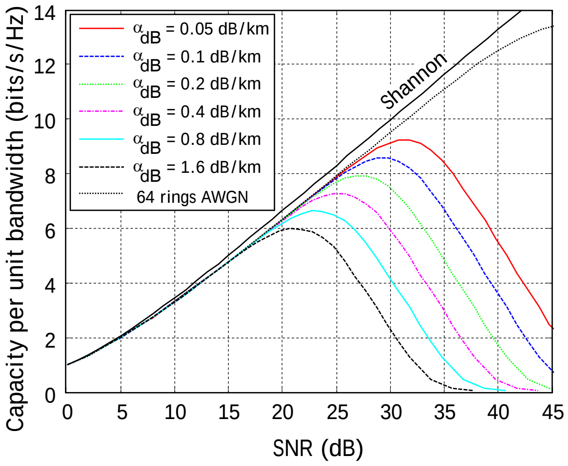

Fig. 4: Effect of fiber loss coefficient α on the nonlinear capacity limit. $L = 1000$ km, $\gamma = 1.27$ (W - km)$^{-1}$, and $D = 17$ ps/(nm-km).

Fiber Loss: Figure 4 shows the dependence of the nonlinear fiber capacity on the fiber loss coefficient α_{dB}. The Shannon and the 64-ring constellation capacity for the AWGN channel are also shown as references. One observes

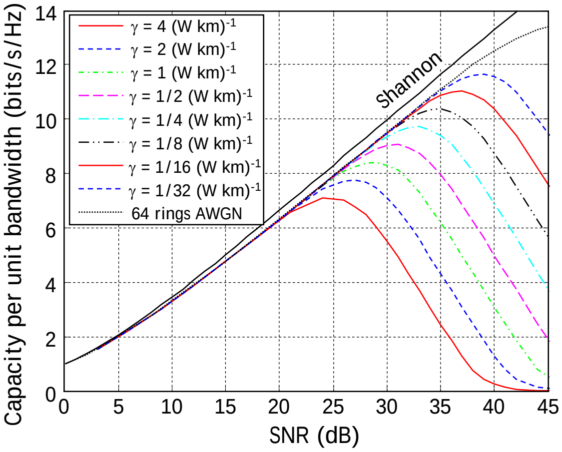

Fig. 5: Effect of fiber nonlinear coefficient γ on the nonlinear capacity limit. $L = 1000$ km, $\alpha_{\text{dB}} = 0.15$ dB/km and $D = 17$ ps/(nm-km) (64-ring constellations)

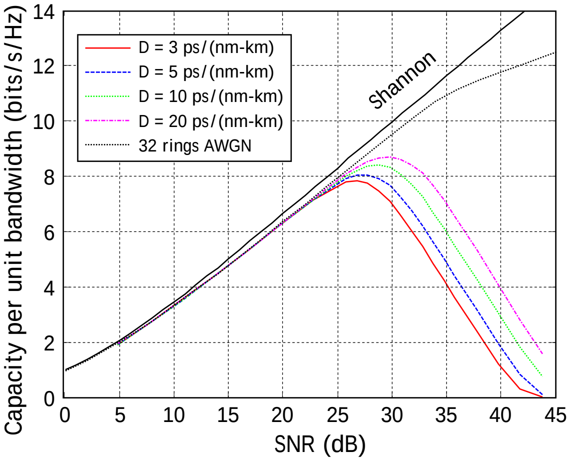

Fig. 6: Effect of fiber chromatic dispersion on capacity on the nonlinear capacity limit. $L = 500$ km, $\alpha_{\text{dB}} = 0.2$ dB/km, $\gamma = 1.27$ (W - km)$^{-1}$ (32-ring constellation).

that the nonlinear fiber capacity does not increase dramatically with a reduction in fiber loss. For instance, reducing α_{dB} from 0.2 to 0.05 dB/km increases capacity only from $\sim$8 to $\sim$9 bits/s/Hz. One should point out, however, that a decrease of α_{dB} (presumably for both the signal and Raman pump wavelength) could be a great benefit by either increasing the distance between pump stations or by reducing pump powers requirements.

Fiber Nonlinear Coefficient: The nonlinear coefficient of silica fiber can be made to vary by a change of material or material properties or through advances in fiber designs. The impact of varying the nonlinear coefficient γ on the nonlinear fiber capacity is shown in Fig. 5. A reduction of the fiber nonlinear coefficient has similar effect on capacity as a reduction in the fiber loss coefficient. However, in contrast to a loss reduction, a nonlinear coefficient reduction increases the Raman pump power requirement. Even though challenging, the perspective of a reduction of the fiber nonlinear coefficient appears more achievable than the same reduction in the fiber loss coefficient.

Fiber Dispersion: Figure 6 shows the impact of varying fiber chromatic dispersion on nonlinear fiber capacity. The range covers the chromatic dispersion of most commercial fibers. A relatively small variation of the maximum capacity is observed for that range. These results suggest that, in proportion, a variation of chromatic dispersion has a lower impact on capacity than the fiber loss or nonlinear coefficient.

4. Acknowledgment

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