The Information Capacity of the Fiber-Optic Channel: Bounds and prospects

Mark Shtaif [(1)], Cristian Antonelli [(2)], Antonio Mecozzi[(3)] and Xi Chen[(3)]
(1) School of EE, Tel Aviv University, Tel Aviv, Israel (2) University of L'Aquila, 67100 L'Aquila, Italy
(3) Nokia Bell Labs, Murray Hill, NJ 07974 USA
shtaif@tauex.tau.ac.il

Abstract: We discuss the challenges in assessing the theoretical limits to the throughput of fiber-optic communications systems and argue that the uncertainty of available information capacity limits is within a range of 1.17 bit/s/Hz. We show that record experiments are within 20 to 30 percent from these limits in terrestrial single-mode fiber systems for metro to long-haul transmission. It appears that the continued scaling of optical communications will have to rely on parallelism and space-division multiplexed fiber transmission

1. Introduction

Since their very beginning in the 1980's, the information throughput of fiber communication systems has been growing steadily to satisfy the never ending appetite for data transmission. Since the beginning of this millennium, the transmitted information rates on a single-mode terrestrial fiber increased by two orders of magnitude from ~ 1 Tb/s [1] to ~100 Tb/s [2], with most of the growth realized before 2015, i.e. 9 years ago. Since then, the increase in the per-fiber information rates slowed down considerably, as predicted in [3], and in the past few years the rate increase seems to be gradually diminishing. Shannon's information capacity specifies the highest possible information transmission rate and its assessment for the fiber-optic channel is necessary in order to understand whether the observed saturation of transmission rates is fundamental or not. The relevance of this question concentrates in particular on the case of terrestrial metro to long-haul transmission systems for which the information throughput is limited by the available fiber bandwidth, whereas in the case of very short (data-center), or very long (trans-oceanic) systems, throughput limitations are primarily dictated either by transceiver performance, or power consumption, respectively.

The main challenge in relating to the capacity of the fiber-optic channel lies in the fact that in the general case, the concept of signal bandwidth cannot be uniquely defined, as it may change considerably during the signal's propagation owing to the intrinsic nonlinearity of the optical fiber. Another difficulty stems from the fact that the evolution of the signal waveform along the fiber can only be evaluated numerically, so that no acceptably accurate analytical input-output relation exists. This difficulty is considerably exacerbated when considering ultra-broad-band transmission containing the S+C+L frequency bands, where numerical solutions become unrealistically slow and where Raman effects and the frequency dependence of the various fiber parameters need to be taken into account. In this regime substantial extensions of existing models are necessary [4], as well as semi-analytical tools that can reliably replace split-step simulations [5,6].

In this paper we explore ways of assessing the information capacity, focusing on metro to long-haul point-to-point links. In our study we take advantage of the fact that in essentially all systems that are considered of practical relevance, nonlinear propagation phenomena are accurately accounted for by a perturbation analysis in which only nonlinear contributions up to first order in the nonlinear coefficient, are considered [7]. We discuss the methodology of obtaining bounds for the information capacity, while illuminating important considerations and critical pitfalls that may lead to incorrect results. We address the potential benefit of equalization and show that the uncertainty in the assessment of capacity is fixed and equal to 1.17 bit/sec/Hz. We also relate to the potential and implications of space-division multiplexing (SDM) in the context of information capacity, pointing to their advantage in terms integration and weaker effective nonlinearity. Examination of hero experiments reveals that the potential increase in spectral efficiency of systems based on single-mode-fiber (SMF) is limited to the order of 20 to 30 percent. Hence, the path to achieving the continued growth in throughput seems to pass through parallelism, as provided by SDM.

2. Capacity estimates and bounds

One of the most important ideas is that the capacity of an arbitrary channel with a given average input power is lower-bounded by the capacity of an auxiliary additive white Gaussian noise (AWGN) channel whose noise has a correctly prescribed variance and which is appropriately scaled. While the details are outside our scope (see [2,8] and references

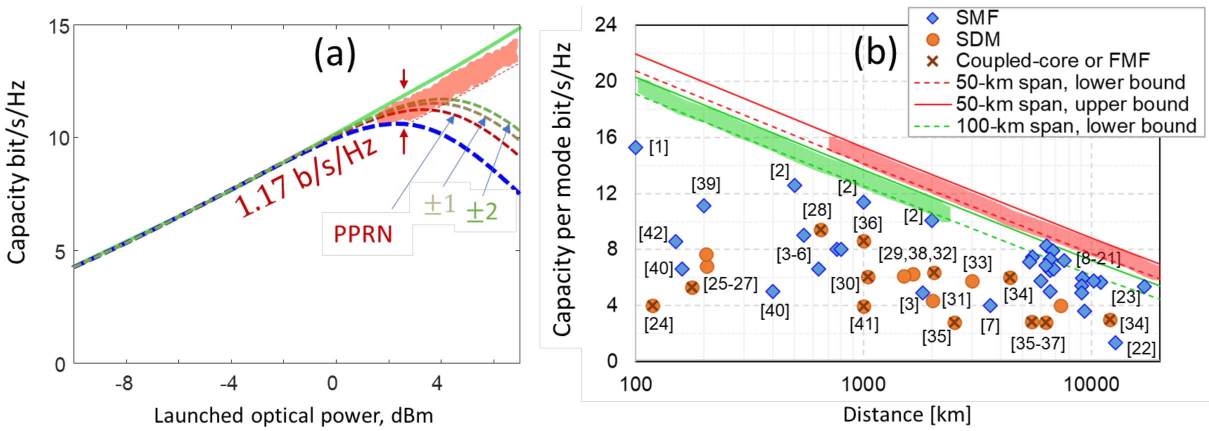

Figure 1: (a) Capacity vs. power upper-bound (green solid) and lower-bounds (dashed) without nonlinearity compensation (blue) and when ideally equalizing the 0^{th} to $\pm 2^{\text{nd}}$ ISI orders induced by NLIN. (b) Capacity vs. reach. Dashed and solid curves show lower and upper bounds, respectively. Green and red are for 100 km and 50 km amplifier spacings, respectively. Experimental points are labeled by reference numbers in [12]. Data points should be compared with the green curves for short-reach and with the red curves for long reach, as shown qualitatively by the red and green stripes.

therein), the underlying principle is quite intuitive. Since the Gaussian distribution possesses the largest entropy for a given variance, Gaussian noise is the 'noisiest' noise possible, and hence the capacity of any channel is at least as large as the capacity of an AWGN channel with the same second-order statistics. For a fiber-optic channel, this statement translates into

$$C \geq 2\log_2(1 + \mathrm{SNR}_{\mathrm{eff}}), \tag{1}$$

where C is the capacity and $\mathrm{SNR}_{\mathrm{eff}}$ is the effective SNR defined as the ratio between the average input signal power and the mean-square-average of the received signal after the (appropriately scaled) input signal has been subtracted from it. Within the first-order perturbation analysis the effective SNR is given by [9]

$$\mathrm{SNR}_{\mathrm{eff}} = P/(\sigma_{ASE}^2 + \xi P^3)\,, \tag{2}$$

where σ_{ASE}^2 is the variance of the amplification noise and ξP^3 is known as the variance of the nonlinear interference noise (NLIN) [10]. Here P is the average signal power, and ξ is a coefficient determined by the entire set of the fiber, link, and channel parameters, including the modulation format [8,10]. Equation (2) is universal and covers all fiber-optic systems within the first-order perturbation analysis. The exact choice of system parameters, as well possible enhancements in the form of nonlinearity mitigation etc., manifest themselves only in the magnitude of ξ.

An important consequence of Eq. (2) is that $\mathrm{SNR}_{\mathrm{eff}}$ is maximized at $P = (\sigma_{ASE}^2/2\xi)^{1/3}$, where $\mathrm{SNR}_{\mathrm{eff}} = 0.53\xi^{-1/3}\sigma_{ASE}^{-4/3}$, and hence the substitution of this value into Eq. (1) yields the capacity lower-bound at the optimal transmission power. An important caveat that illuminates a common pitfall in many reported estimates of capacity, is ***that for Eq. (1) to be a legitimate lower-bound***, ξ ***must be evaluated in the case of Gaussian modulation***. That is so because the derivation of the bound relies on the assumption that the auxiliary channel is Gaussian.

An upper-bound for the fiber-optic channel capacity operating with average input power P, is given by Eq. (1) with $\mathrm{SNR}_{\mathrm{eff}}$ replaced by the linear SNR obtained by setting $\xi = 0$, as proven in [11]. The gap between the upper and lower bounds in the relevant regime of $\mathrm{SNR}_{\mathrm{eff}} \gg 1$ is readily seen to be $\Delta C = 2\log_2(1 + \xi P^3/\sigma_{ASE}^2)$, which equals 1.17 bits when $P = P_{\mathrm{opt}}$. We stress once again that this result is general to all fiber communications systems, whereas the details distinguishing one system from another play a role only in setting the value of ξ, and hence also the value of the optimal input power P_{opt} and the capacity.

Approaches for increasing the capacity of fiber-optic systems often rely on equalization that is applied at the receiver in order to correct for nonlinear distortions introduced during propagation. The idea is based on the notion that a large fraction of the NLIN can be represented as linear time-dependent inter-symbol-interference (ISI) [5]. In this framework the nonlinear perturbation imposed on the received j-th symbol of the channel of interest is expressed as

$$\Delta\vec{a}_j = i\sum_{n=0}\mathbf{R}_n(j)\vec{a}_{j-n}, \tag{3}$$

where $\vec{a}_j$ is the transmitted j-th symbol-vector, whose two components are the correspond to the two orthogonal polarization channels, and $\mathbf{R}_n(j)$ are 2×2 time-dependent ISI matrices of the n-th order, whose elements are determined by the parameters of the link and by the interfering WDM channels. The idea behind NLIN equalization is that ISI contributions can be reduced by exploiting the temporal correlations of the ISI matrices [5].

Figure 1a shows the capacity as a function of input power of a 10-span WDM system with 51 WDM Gaussian-modulated channels spaced by 80 GHz with ideal Nyquist pulses, at a symbol rate of 75 Gbaud and with the channel of interest being in the middle. The system is implemented over standard SMF with a span-length of 100 km and assuming amplifiers with a noise figure of 5 dB. The solid curve shows the capacity upper bound whereas the four dashed curves show the capacity lower bounds for an unequalized system, and for systems where ISI is ideally equalized up to the zeroth, first (i.e. ± 1) and second (± 2) orders. The zeroth-order NLIN contribution is also known as the phase and polarization rotation noise or PPRN. The gain in the capacity lower-bound from the equalization ranges between 0.6 bit/s/Hz with 0-th order equalization to 1.1 bit/s/Hz when all order up to ± 2 are ideally equalized. Notice that the upper bound increases correspondingly, so that the gap between lower and upper bound is always 1.17 bit/s/Hz. This range of 1.17 bit/s/Hz is indicated by the red strip in the figure.

Finally, we note that Fig. 1a assumes relatively narrowband C-band transmission, whereas addressing broadband C+L or S+C+L systems as the ones considered today requires accounting for additional phenomena such as Raman and the frequency dependence of the various system parameters.

3. Experimental state of the art

In Fig. 1b we show the upper and lower capacity bounds per-mode as a function of system reach together with results of hero experiments. This figure is an updated version of the figure originally presented in [2], and the numbers indicated on the various experimental points correspond to the references appearing in [12]. The two sets of bounds shown by the green and red curves in the figure correspond to span lengths of 100 km and 50 km, respectively, and hence the short-reach experiments should be compared with the green curves, whereas the very long-reach experiments should be compared with the red curves, as indicated qualitatively by the green and red stripes in the figure. While the comparison between the experiments, as well as between the experiments and the theoretical bounds is somewhat limited in validity because of the variability of system settings, it provides valuable insights as to the current state of the art. Evidently, the gap to capacity appears to be in the range of 20% to 30% in most cases suggesting that no substantial increase in throughput should be anticipated in single-mode fiber systems.

Figure 1b also contains results obtained in SDM systems, where the per-mode throughput is seen to be lower than in single-mode fiber as can be expected in view of the greater maturity of single-mode technology. Nonetheless, the SDM systems using strongly coupled modes are characterized by weaker NLIN than SMF systems [13], and hence their per-mode capacity is bound to be higher. This argument combined with the intrinsic parallelism of SDM transmission makes these systems the best candidates for future optical communications.

4. Conclusions

We have shown that the per-mode capacity of fiber-communication systems is well estimated within an uncertainty range of 1.17 bit/s/Hz and it is independent of system parameters and of the presence of nonlinearity mitigation schemes. Hero experiments in metro to long-haul systems report information throughput values that are only 20% to 30% below what appears to be the channel capacity limit, thereby suggesting that the observed saturation in the growth of system throughput in recent years follows from fundamental reasons. Consistently with [1,3], the only path to the continued scaling of future communication systems appears to require reliance on spatial multiplexing.

[1] P. J. Winzer et al., "Fiber-optic transmission and networking: the previous 20 and the next 20 years," Opt. Express 26, 24190 (2018).
[2] M. Shtaif et al., "Challenges in Estimating the Information Capacity of the Fiber-Optic Channel," Proc. of the IEEE 110, 1655 (2022).
[3] A. R. Chraplyvy, "The coming capacity crunch," European Conf. on Optical Comm. (ECOC), Vienna, Austria, Plenary Session (2009).
[4] T. Hoshida et al., "Ultrawideband Systems and Networks: Beyond C + L-Band," Proc. of the IEEE 110, 1725 (2022)
[5] O. Golani et al., "Modeling the Bit-Error-Rate Performance of Nonlinear Fiber-Optic Systems," JLT 34, 3482 (2016).
[6] D. Dahan et al., "Universal Virtual Lab: A Fast and Accurate Simulation Tool for Wideband NL DWDM Systems," JLT 40, 2441 (2022).
[7] A. Mecozzi and R. -J. Essiambre, "Nonlinear Shannon Limit in Pseudolinear Coherent Systems," JLT 30, 2011 (2012).
[8] M. Secondini, "Chapter 20 - Information capacity of optical channels," in Opt. Fiber Telecomm. VII (Academic Press, 2020).
[9] P. Poggiolini et al., "Analytical modeling of non-linear propagation in uncompensated optical transmission links," PTL 23, 742 (2011).
[10] R. Dar et al., "Properties of nonlinear noise in long, dispersion-uncompensated fiber links," Opt. Express 21, 25685 (2013).
[11] M. I. Yousefi et al., "Upper bound on the capacity of the nonlinear Schrödinger channel," CWIT 2015.
[12] M. Shtaif, C. Antonelli, A. Mecozzi, and X. Chen "The Information Capacity of the Fiber-Optic Channel: Bounds and prospects." Optica Open. Preprint. https://doi.org/10.1364/opticaopen.24864648.
[13] C. Antonelli et al., "Modeling of nonlinear propagation in space-division multiplexed fiber-optic transmission," JLT 34, 36 (2016).