Capacity Limits of Optical Fibre Based Communications

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Abstract: We discuss the nonlinear capacity limits imposed by inter-channel nonlinearities and signal-noise interaction, and investigate their impacts on the performance of coherent-detection based optical systems using high-level formats and electronic dispersion or intra-channel nonlinearity compensation.
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1. Introduction
Recent advances in microelectronics have enabled a series of key technologies including digital-signal-processing based coherent detection, and consequently the practicality of near-ideal compensation of deterministic impairments such as chromatic dispersion, the use of high-level formats to optimize the signal constellation, and high-speed multi-carrier systems with minimized channel spacing etc. These innovations greatly facilitate system designs intended to approach the channel limit. In this paper, we will discuss the fundamental capacity limits imposed by inter-channel nonlinearities and signal-noise interaction, and their impacts on the performance of optical systems.

2. Nonlinear Capacity Limit from Inter-channel Nonlinearities
In optical fibre based communications, in addition to the noise-imposed capacity limit of a generic linear communication channel [1], the systems are characterised by distributed non-linear effects in the fibre, such as self-phase modulation (SPM), crosstalk-phase modulation (XPM), and four-wave mixing (FWM) [2]. In theory, deterministic and reversible impairment would not cause information loss provided that appropriate signal processing can be performed to compensate these impairments. However, despite recent proposals of intra-channel nonlinearity compensation techniques, including digital back-propagation, it is currently impractical to implement full optical-band impairment compensation such that inter-channel effects result in an effective loss of channel capacity. The information spectral density (C/B) limit for coherent detection can be obtained from the condition [3]:

\[
\frac{C}{B} \geq \frac{B}{\Delta f} \log_2 \left(1 + \frac{P_{ave} \exp(-I_{ave}/I_{non})^2}{P_n + (1 - \exp(-(I_{ave}/I_{non})^2))P_{ave}} \right)
\]

where \(P_{ave}\) is the average signal power per channel, \(P_n\) is the total ASE noise power and is equal to \(N_a(G-1)n_o\nu\nu B\), with \(N_a\), \(G\), \(n_o\), \(\nu\nu\); \(B\) being the number of spans, the amplifier gain, the spontaneous emission noise factor, the photon energy, and the channel bandwidth respectively. \(\Delta f\) is the channel spacing. \(I_{non}\) is the nonlinear intensity scale, and has different expression for XPM and FWM-limited cases [4-5].

Table 1: Parameters of the system for simulation and analytical calculation for quadrature amplitude modulation (QAM)

<table>
<thead>
<tr>
<th>Format</th>
<th>PM-4QAM</th>
<th>PM-16QAM</th>
<th>PM-64QAM</th>
<th>PM-256QAM</th>
<th>Loss (dB/km)</th>
<th>Dispersion (ps/nm/km)</th>
<th>Nonlinearity (1/W/km)</th>
<th>Length per span (km)</th>
<th>Noise Figure (dB)</th>
<th>Number of channels</th>
</tr>
</thead>
<tbody>
<tr>
<td>Baud rate</td>
<td>28Gbaud</td>
<td>14Gbaud</td>
<td>9.33Gbaud</td>
<td>7Gbaud</td>
<td>0.2</td>
<td>20</td>
<td>1.5</td>
<td>80</td>
<td>4.5</td>
<td>9</td>
</tr>
<tr>
<td>Channel spacing</td>
<td>50GHz</td>
<td>25GHz</td>
<td>10GHz</td>
<td>7.5GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>MUX</td>
<td>30GHz</td>
<td>15GHz</td>
<td>10GHz</td>
<td>7.5GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DeMUX</td>
<td>50GHz</td>
<td>25GHz</td>
<td>16.667GHz</td>
<td>12.5GHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Simulated bits</td>
<td>32,768</td>
<td>65,536</td>
<td>98,304</td>
<td>131,072</td>
<td></td>
<td></td>
<td></td>
<td></td>
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</tr>
</tbody>
</table>

Equation (1) implicitly suggests that the capacity of a fibre-based system does not grow infinitely with the increasing signal power, but has a maximal value. Recently developed multi-carrier systems such as no-guard-interval OFDM [6] and coherent WDM [7] allow \(B/\Delta f = 1\) while advanced modulation formats and coding methods enable the optimal signal constellation distribution to be approached. More importantly, the capacity of a fibre-based system, in contrast to a linear channel, depends on \(I_{non}\), and consequently the fibre parameters, e.g. dispersion and nonlinear coefficient, and system configurations, e.g. channel number and spacing. In both XPM and FWM-limited systems, a higher in-line dispersion value would increase \(I_{non}\), and results in improved channel capacity. Fig. 1(a) illustrates the capacity limit as a function of length for a dispersion value of 20ps/nm/km (dashed) and 2ps/nm/km (dotted). Other parameters are listed in Table 1. The figure implies that the use of electronic dispersion compensation (EDC) techniques [8] to compensate the accumulated impairments at the transmitter or receiver not
only avoids the need for in-line dispersion compensation, but also, in turn, reduces the degradation due to inter-channel nonlinearity. We simulated the performance of 112Gbit/s polarization multiplexed (PM) m-QAM WDM systems using the parameters listed in Table 1, and the results are shown in Fig. 1(a). In the simulation, continuously interleaved BCH FEC was assumed [9], (9.35dB gain, 1Mbit latency and 7% overhead). The results show that even under both dispersion and intra-channel nonlinearity compensation using digital back propagation (DBP), the transmission reach of 256-QAM was limited to below 200km by inter-channel nonlinearities, while for long-distance WDM transmission over 2000km, 16, 64 and 256 QAM formats are not suitable.

Fig. 1(a). Theoretical nonlinear capacity limit versus the transmission distance when the in-line dispersion is 20ps/nm/km (dotted line) and 2ps/nm/km (dashed line), and the simulated maximum achievable distance of 4-, 16-, 64-, 256-QAM WDM system for dispersion compensation only (triangles) and single-channel digital back-propagation (DBP) including both dispersion and intra-channel nonlinearity compensation (circles). (b) The maximum achieved Q-factor (dB) versus the fiber length by using single-channel back-propagation for DBP in the scenarios of WDM system (open) and single channel (closed). (c) Performance as a function of the signal launch power for a single-channel 112Gbit/s PM-QPSK after 4800km with EDC only (circles) and DBP with in-line noise loading (triangles) and with receiver-side noise loading (squares).

3. Performance Limit from Signal-Noise Interaction

Fig. 1(a) compares the maximum reach of four different PM-QAM formats in a WDM system to the theoretical nonlinear capacity limits [3-5]. There is a penalty in reach of approximately 1dB when compared to the theoretical nonlinear limit with the same dispersion. One reason for this penalty is that the modulation formats and the coding schemes are not optimal. Fig. 1(b) shows the maximum achieved Q-factor at the optimum signal launch power versus the transmission distance for single-channel (closed symbols) and WDM (open symbols) transmission, with both cases using DBP to compensate dispersion and intra-channel nonlinearities. It can be seen that even for the single-channel case where inter-channel nonlinearities, are fully compensated, the transmission distance cannot be increased arbitrarily. We may conclude that for the single channel case, a signal-noise interaction which cannot be compensated by back propagation must limit the performance, however, the nature of this limitation has, until recently [10], been unknown. To illustrate the cause of this capacity limitation, Fig. 1(c) shows the performance of QPSK at a transmission distance of 4,800km versus the signal launch power for the single-channel case, and it is seen that optimal signal launch power exists for not only EDC but also DBP even after intra-channel nonlinearity compensation if noise is loaded along the amplifier chain rather than just at the receiver. In [10], it is shown that this increase in noise with signal power is mainly caused by FWM between the signal and noise fields, where the simulated amplified noise evolution is consistent with analytical predictions.

4. Conclusions

We have investigated inter-channel nonlinearities and signal-noise interaction, and the limits they impose on the channel capacity of state-of-the-art optical communication systems, where coherent detection with high-level modulation formats and advanced FEC, and near-ideal compensation for dispersion and intra-channel nonlinearities have been enabled by recent rapid advances in optical technologies.

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References