Ultimate capacity of WDM transmission systems and networks

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Abstract: We derive analytic expressions for the ultimate capacity of WDM transmission systems and networks limited by stimulated Raman scattering.

It is generally acknowledged that stimulated Raman scattering (SRS) and amplified spontaneous emission (ASE) ultimately limit the capacity of WDM transmission systems. An analytic formula for the ultimate capacity of transmission system has been derived in ref. [1] and it was refined considering the statistical nature of the modulated data [2]. These results were based on the allowable degradation level of optical signal-to-noise-ratio (ONSR) due to SRS. However, the choice of degradation level is not unique and they may underestimate the system capacity. In this paper, we derive analytic expressions for the ultimate capacity of WDM systems/networks limited by SRS based on the maximum achievable ONSR at the receiver.

When we transmit N equally spaced WDM channels (channel spacing Δf) through a transmission fiber, SRS induces power depletion in blue side channels and power amplification in red side channels. Then, the fractional power depletion of the shortest wavelength channel is given by exp[−C_k P_{IN}], where P_{IN} is the signal power and C_k is a random variable describing the statistics of SRS effect [2]. In most WDM systems, C_k converges to a delta function [3] and its average value equals to g B_o N L_{eff} / 4 A_{ref}, where g is the slope of Raman gain spectrum, L_{eff} and A_{ref} are effective length and area of the fiber, respectively, and B_o is the total system bandwidth (πΔf (N-1)). Taking into account SRS induced signal and ASE power depletion, ONSR of the worst channel (the shortest wavelength channel) is given by

\[ OSNR = K P_{IN} e^{-2\sigma_{exp}^{\alpha} / L_o} (1 - e^{-2\sigma_{exp}^{\alpha} / L_o}) (1 - e^{-\sigma_{exp}^{\alpha} / L_o})^{-1} \]

(1)

where 2σ_{exp} is the amplifier noise figure, hν is the photon energy, B_o is the optical bandwidth, α is the fiber loss, L_o is the total transmission distance, and L_a is the amplifier spacing.

To obtain the maximum achievable ONSR by differentiating Eq. (1) with respect to P_{IN}. It is 0.65 K L_o^{2} / C_g L^{2} in WDM systems/networks, where C_g is the maximum achievable ONSR for a fiber. The system capacity (C), link throughput (bit rate B_o) × channels (N)) × transmission distance, is given by

\[ C = L_o \sqrt{\frac{2.6 A_{ref}}{g L_a} T (K / B_o) (R_o / B_o)} \]

(2)

where T is the link throughput. We use the following parameters to calculate the system capacity: A_{ref}=50 μm^2, g=4.6×10^{-7} m/Hz, α=0.075 dB/km, B_o=25.6 nm, 2σ_{exp}=5 dB, B_a=12 GHz. We assume that the signal bit rate is 2.5 Gb/s. It may be noted that the ultimate system/network capacity is independent of signal bit rate.

Fig. 1 shows the system capacity as a function of the link throughput when the amplifier spacing is 80 km. The analytic results (solid lines) agree well with the numerical results (dashed lines). The ultimate capacity of transmission system is of the order of 10^5 Gb/s/km and proportional to the square root of the link throughput. We also show the capacity obtained from the analytic formula in ref. [2] as a comparison with dashed lines. It underestimates the system capacity.

The system capacity can be increased by suppressing SRS induced depletion. We consider the suppression method proposed in ref. [3], i.e., SRS induced ONSR degradation was mitigated by the power equalizers at each amplifier. In general case, the equalization would be done at every M amplifier in the transmission route. In this case, the system capacity is given by

\[ C = L_o \cdot T \cdot F_{max} / R_o \]

(3)

where \( F_{max} \) denotes the maximum value of \( F \), \( I \) is the insertion loss of the equalizer, and \( L_o \) is the distance between power equalizer locations, i.e., \( L_{eq} = M L_o \).

Fig. 2 shows the relative system capacity increased by SRS suppression when the required ONSR is 12 dB and \( M = 1 \). The capacity improvement depends on the system parameters. Generally, the improvement increases as we decrease the amplifier spacing and/or the link throughput.

To investigate the capacity of all-optical transport networks, we considered a simple regular network shown in Fig.3, where \( L_G \) is the OXC loss, \( G_a \) is the in-line amplifier gain, \( G_p \) is the gain of the node pre-amplifier, and \( G_b \) is the gain of the node booster amplifier. We assume that input signal power of each fiber span is a constant, i.e., \( e^{-\alpha d} G_a = 1 \) and \( e^{-\alpha d} G_p L_G G_a = 1 \). Then, ONSR of the worst channel is identical to the first equation of Eq. (1). However, the expression for \( K \) changes with the operation condition of the optical amplifiers. There are two possible conditions, i.e., the constant output mode and the constant input mode. In the former mode, the output signal power of all amplifiers is a constant. Then, the node pre-amplifier compensates for the fiber loss \( e^{-\alpha d} G_a = 1 \) and the node booster amplifier compensates for the OXC loss \( L_G G_b = 1 \).
The ultimate capacity of the WDM transmission systems is limited by SRS. The analytical results agreed well with the numerical results. From Eqs. (2), (4) and (5), the network capacity $(N_C)$, node throughput $(N_T) \times$ transmission distance, is given by

$$N_C = L_N \sqrt{(2.6 A_0 / g L_{de})(N_x N_y K/B_0)(R_s)^4},$$

where $N_x$ is the number of input/output fibers per node, $N_T$ equals $N_x N_y B_0$, and $L_N$ is distance between two adjacent nodes. Fig. 4 shows the network capacity obtained from the analytic solution (solid lines) and that of numerical simulations (filled diamonds) when the network is constant output mode. Here, $L_A=80$ km, $L_N=240$ km, $N_x=8$, $L_o=20$ dB. The ultimate network capacity is of the order of $10^9$ Gb/s km and proportional to the square root of the node throughput.

Fig. 5 shows the network capacity for a specific node throughput of 1.28 Tb/s when the required OSNR is 12 dB. In constant output mode, there exists an optimum amplifier spacing that maximizes the network capacity, while the shorter amplifier spacing gives the more network capacity in constant input mode. The optimum amplifier spacing is a function of the OXC loss. For example, the optimum amplifier spacing is 30 km for the OXC loss of 15 dB and it is 60 km for the OXC loss of 25 dB.

In all-optical transport network, the SRS induced OSNR degradation can be mitigated by using power equalizers at each node. Then, the analytic expression for network capacity can be obtained similarly. The network capacity increases up to 10 times with SRS suppression and it becomes independent of the node throughput. Details of these results will be given at the conference.

In summary, we derived analytic expression for the ultimate capacity of the WDM transmission systems/networks limited by SRS. The analytical results agreed well with the numerical results.

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References