Modeling of Guided Acoustic Waveguide Brillouin Scattering Impact in Long-Haul Fiber Optic Transmission Systems

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Abstract *We perform analytical modelling of the GAWBS effect impact in long-haul coherent transmission systems for quasi- and deeply linear power regimes, with inclusion of Tx/Rx penalties. We show that beyond effective area, GAWBS SNR penalty depends on propagation distance, span length and fiber attenuation.*

Introduction

Recently there has been a growing interest in understanding the effect of Guided Acoustic Waveguide Brillouin Scattering (GAWBS) in coherent optical communications[1]–[4]. This effect leads to additional uncompensated phase noise of transmitted signals. The effect may be included in system modeling as an additional noise term in the Gaussian Noise model of fiber-optic transmission system, together with amplified spontaneous emission (ASE) noise, nonlinear interference (NLI) noise[5]-[7] and other impairments. The noise power depends approximately linearly on channel power, propagation distance and effective area (A_{eff}). In [2] a slightly nonlinear dependence on A_{eff} was given.

In terms of system effects, GAWBS has been studied relatively little to date, perhaps because the impact is generally small: typical values of GAWBS noise are on the order of -30 dB per 1000 km relative to signal power. However, a recent study [2] showed a Q penalty up to 0.6 dB for a large A_{eff} fiber that was distance-independent. This raises a question of whether smaller A_{eff} optical fibers in the context of linear-power operated submarine transmission systems would suffer more from the GAWBS effect, given that GAWBS noise power varies inversely with fiber A_{eff}. This question seems relevant in the context of maximizing power efficiency, or capacity per unit of power consumption. This tends to drive submarine transmission toward more linear operation at lower SNR and larger numbers of fiber pairs, and further away from the previous practice of operating at the nonlinear optimum channel power to maximize SNR[8],[9]. However, as a counterpoint, it was recently reported[10] that submarine SDM system cost optimization results in channel power operation only slightly below the nonlinear optimum, typically 1 dB to 3 dB below the nonlinear optimum depending on link length.

Here, we extend the investigation of GAWBS noise impact on long-haul submarine SDM transmission systems. We analytically model the impact of GAWBS noise inclusion for three fiber types used for long haul submarine systems and consider two power regimes – deeply linear regime (aiming at power-efficiency maximization) and quasi-linear regime (aiming at cost/bit minimization) for various transmission distances and span lengths. We also include the effects of realistic transponder implementation penalties and fiber A_{eff} and attenuation.

Model description

We calculate GAWBS noise power as it is described in [2] for total link distance L, channel power P_{ch} and GAWBS noise coefficient β_{GAWBS}

Tab. 1: Fiber parameters for SNR modeling

	Corning® Vascade® EX2000 fiber	Corning® Vascade® EX3000 fiber	Corning® SMF-28® ULL fiber	Units
Attenuation	0.150	0.150	0.158	dB / km
Nonlinear refractive index	2.1	2.1	2.1	10^{-20} m^2 / W
Effective area	115	153	82	μm^2
Dispersion	20.2	20.9	16.5	ps / nm / km
GAWBS coefficient	-30.8	-32	-29.3	dB / 1000 km

(1/km) as:

$$P_{GAWBS} = P_{ch} \cdot L \cdot \beta_{GAWBS} \quad (1)$$

The dependence on fiber effective area of the coefficient β_{GAWBS} is assumed to follow previous results based on calculations of the overlap of the optical mode intensity and acoustic mode distributions[2, Fig. 2].

For SNR calculation we employ a recently proposed generalized droop formalism described in [11]-[12] which accounts for span-by-span power transfers from the signal component into noise components for constant output power amplifiers. We compute NLI noise using the GN-model [5] with an applied modulation format-dependent correction term [7], using the modulation-format factor for QPSK. A complete set of fiber parameters used for modeling in this paper is given in Tab. 1. We define GAWBS SNR penalty as the difference between SNR calculated with GAWBS noise turned off and SNR with GAWBS effect included at the same power:

$$GAWBS\ penalty = SNR^{dB}_{No\ GAWBS} - SNR^{dB}_{GAWBS} \quad (2)$$

For all transmission modeling, we assumed polarization-multiplexed signals modulated at 69 GBaud, with 75 GHz channel spacing populating the full C-band (53 channels). The GAWBS penalty was evaluated over a wide range of link lengths for fixed span length (80 km), and over a wide range of span lengths at fixed link distance (10 Mm) for all fiber types.

We performed the calculations in two power regimes: deeply linear and quasi-linear. We define the deeply linear power regime as the minimum power required to obtain a link SNR of at least 5 dB[13]. The quasi-linear regime assumes operation at 2 dB below the nonlinear optimum launch power, i.e. the channel power with maximum SNR. For inclusion of implementation penalty, we used the gap-to-Shannon data as given in[13] for a real-time transponder, and we fit the SNR penalty as a function of link SNR to a third-order polynomial, as shown in Fig. 1.

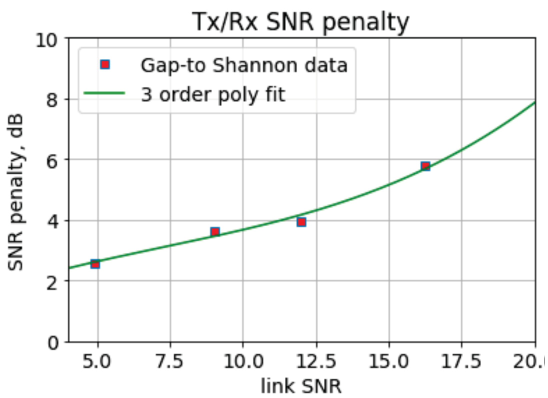

Fig. 1: Transponder implementation penalty applied in this paper. Transponder is assumed to operate error-free at maximum information rate possible.

Results

We first assessed GAWBS penalties as a function of total propagation distance for fixed 80 km spans as shown in Fig. 2(a). The quasi-linear power regime results without Tx/Rx penalty agree with those reported in [2] for nonlinear optimum operation showing independence of the GAWBS penalty from distance. Such behavior is observed because the operating power is almost fixed in the quasi-linear regime, and thus the power-dependent GAWBS penalty does not change with distance. In the deeply linear regime however, as the operating power is increased for longer distances to obtain the minimum required

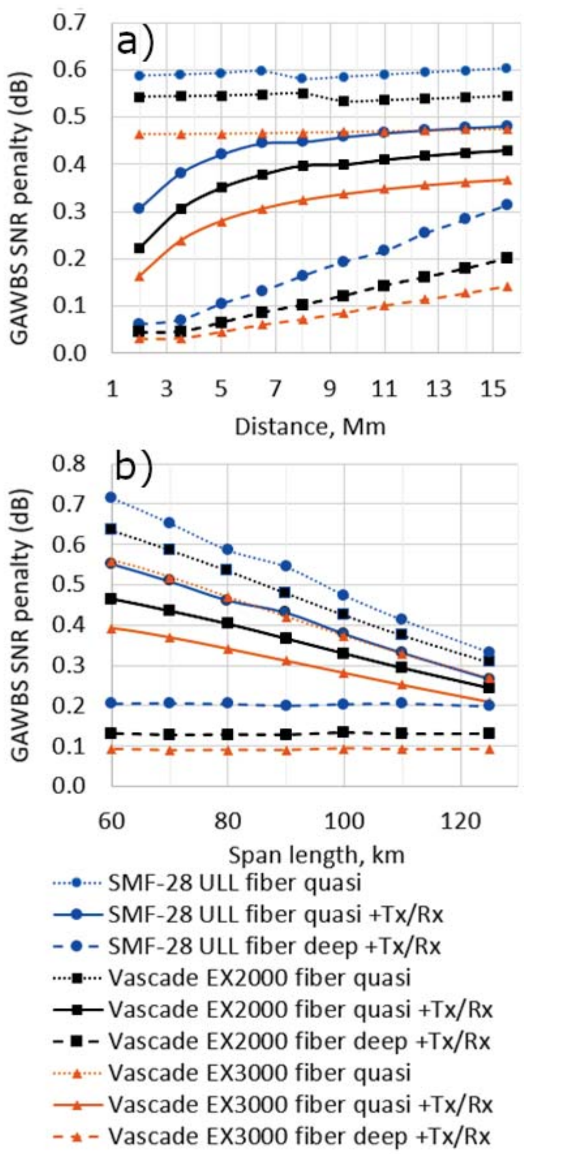

Fig. 2: GAWBS SNR penalty (a) vs. distance, span length is 80 km; (b) vs. span length, the propagation distance is 10 Mm. 'Deep' stands for deeply linear power regime – lowest power for SNR>5 dB, and 'quasi' stands for quasi-linear power regime, 2 dB below nonlinear optimum. '+Tx/Rx' curves account for Tx/Rx penalty.

SNR, the GAWBS noise is increased with distance. With inclusion of transponder implementation penalty in the quasi-linear regime, the GAWBS penalty starts to have a dependence on transmission distance with a reduction of GAWBS impact at smaller distances. Moreover, we note that the impact of an SNR penalty may also be less critical at shorter link lengths due to higher operating SNRs. In Fig. 2, the GAWBS penalty data for deeply linear transmission without implementation penalty are not shown but are similar to the results including the transponder penalty with slightly increased slope, reaching the maximum value of 0.43 dB for SMF-28 ULL fiber.

The penalty dependence on span length results are given in Fig. 2(b). The total propagation distance is fixed at 10 Mm. Here we observe that the GAWBS penalty significantly depends on span length in the quasi-linear power regime: shorter span lengths lead to higher GAWBS penalties, with 60 km spans resulting in 0.4-0.7 dB as was reported for nonlinear optimum operation in [2],[14]. We observe this behavior both when implementation penalty is included and not included, while inclusion of the implementation penalty reduces the penalty by up to 0.15 dB for all fiber types. This may be explained as follows. ASE noise is power-independent but depends on span length through EDFA gain required to compensate for span loss. Conversely, GAWBS noise is span length-independent but depends on the operating power. In the quasi-linear regime, the EDFA gain is smaller for shorter spans compared to longer spans. This leads to reduced ASE noise, more pronounced GAWBS noise and, hence, larger GAWBS penalty at shorter spans. In the linear regime the dependence of GAWBS penalty vs span length is modest (0.1 – 0.2 dB, depending on fiber type). The throughput penalties induced by the GAWBS SNR penalties in Fig. 2 are in the range from 0.4% to 4% for the deeply linear regime and from 1% to 6% for the quasi-linear regime with included transponder penalty. That said, we conclude that the GAWBS effect has minor but quantifiable system effects that should be considered during transmission systems design, for example when choosing the FEC overhead value in steps of 5%. We also emphasize that the A_{eff} of the fiber is not the only factor that impacts the level of GAWBS penalty, and that fiber attenuation (which defines EDFA gain and the relationship between ASE and GAWBS noises) can also play a small role. For fiber with lower attenuation, the GAWBS penalty will generally be slightly larger than for higher attenuation fiber with the same A_{eff}. However, the absolute SNR values obtained with lower attenuation fiber will still be greater than with higher attenuation fiber. The dependence of effective SNR penalty from GAWBS on A_{eff} and attenuation is shown more generally in Fig. 3 for a 10Mm link in the quasi-linear regime and including transponder implementation penalty.

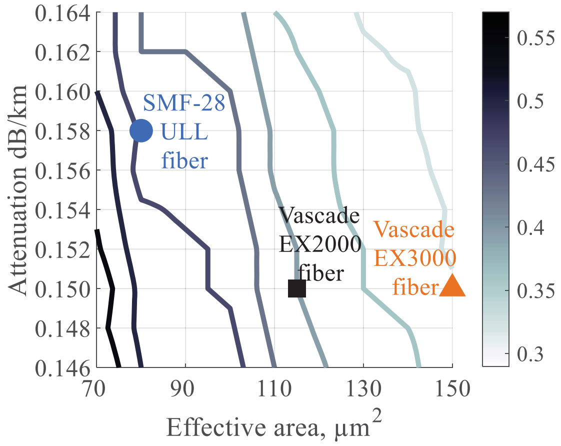

Fig. 3: GAWBS SNR penalty vs. effective area and attenuation. Dispersion is varied together with effective area between 16 to 21 ps/nm/km.

Conclusion

We have investigated the impact of GAWBS noise on long-haul fiber optic systems in both quasi- and deeply linear transmission regimes. We showed that in the quasi-linear power regime the GAWBS SNR penalty depends on propagation distance (when transponder implementation penalty is included) and span length. In the deeply linear power regime, however, there is no dependence of GAWBS SNR penalty on span length, but the GAWBS penalty has a significant distance dependence and reaches more meaningful values at ultra-long distances. Also, we found that for the different A_{eff} fibers studied here, the differences in SNR penalty due to GAWBS in quasi-linear transmission are less than 0.2 dB and may also depend on fiber attenuation.

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