Narrowband and Low-Noise Brillouin Amplification for Coherent Communications

Mark Pelusi, Takashi Inoue, Shu Namiki
National Institute of Advanced Industrial Science and Technology (AIST), Tsukuba, Ibaraki, Japan.
m.pelusi@aist.go.jp

Abstract: Advantages of Brillouin amplification for phase noise sensitive 64-QAM coherent communications are described. The limits of narrowband gain enhancing the carrier-to-noise ratio of noisy pilot tones for high performance optical signal carrier recovery are shown. © 2020.

1. Introduction

Brillouin amplifiers having wide ranging applications of its uniquely narrow gain bandwidth. Examples are optical clock frequency transfer [1], [2], high resolution optical spectroscopy [3], [4], optical frequency comb line extraction [5], [6], and microwave photonics [7]. Its potential for coherent communications has also been explored, including as a pre-amplifier of spectral lines in phase sensitive amplifiers for signal regeneration [8], and suppressing background noise from optical frequency combs as carrier sources for 64-QAM signals [9]. Another is aiding pilot tone extraction from the signal for low noise optical carrier recovery at the receiver [10-13], as a potential alternative to using a conventional local oscillator (LO) laser for intradyne detection. All examples benefit from large Brillouin gain with moderate pump powers. Of greater significance, Brillouin amplification of spectral lines can also be sufficiently low noise for low signal distortion in application to 64-QAM communications [9], [12]. Moreover, it can even boost performance by enhancing the carrier to noise ratio (CNR) relative to unamplified out of band noise [9].

This work describes such performance benefits of Brillouin amplification in application to spectral lines for 64-QAM communications. The main factors considered are both the practically achievable largest enhancement of CNR dictated by the narrowness of the Brillouin gain bandwidth, and the largest output CNR dictated by Brillouin noise. From this, the minimum tolerable input CNR for attaining the maximum output CNR is determined. The predicted limits are tested in various experiments of pilot tone carrier recovery from 64-QAM signals. The noise characteristics of the Brillouin amplifier itself are also evaluated by method of coherent detection and offline digital signal processing, revealing the limited range of launch powers that ensure lowest noise with large gain ≥≈26 dB.

2. Estimated CNR enhancement predictions

Figure 1 illustrates the schematic of CNR enhancement by narrowband gain. The input is in this case an optical frequency comb of spectral lines, each a delta function of power, P_C and background white noise of spectral power density, S_C. Amplification by gain, G adds noise that is approximated for the purpose of this analysis as also white but with a spectral power density S_B limited to within a bandwidth Δ_B centered at each spectral line frequency. Thus, noise power added to each line is $\approx S_B \cdot G \cdot \Delta_B$. Notably, Δ_B for Brillouin gain is around tens of megahertz and thus far narrower than the typical signal channel width of tens of gigahertz (Δ_S) in optical communications. By integrating the total noise power before and after applied gain, the respective CNR of CNR_{IN} and CNR_{OUT} are obtained [9]. The CNR enhancement factor follows as $\Delta CNR = CNR_{OUT}/CNR_{IN}$ and has the upper limit $\Delta CNR_{LIM} \rightarrow \Delta_S/[(1+(S_B/S_C))\cdot\Delta_B]$ for very large G. For practical conditions with a noisy input spectral line such that $S_C \gg S_B$, then $\Delta CNR_{LIM} \approx\rightarrow \Delta_S/\Delta_B$. The point being, a narrower gain bandwidth equates to an inversely proportional larger upper limit on ΔCNR.

Calculations in [14], [15] gave insight into the approximate achievable ΔCNR via narrowband gain. For realistic Δ_S =10 GHz and practical Brillouin amplifier parameters in standard single mode fiber (SSMF) having Δ_B = 30 MHz [9], then $\Delta CNR \rightarrow \Delta CNR_{LIM} \approx 25$ dB at $G \approx\geq 35$ dB in the case of $S_B/S_C \ll 1$, such as for a noisy spectral line with low $CNR_{IN} \approx\leq 0$ dB/0.1 nm. For $G = 30$ dB, this is predicted to translate to $CNR_{OUT} \approx 24$ dB/0.1 nm, which is near the minimum spectral line CNR needed to ensure its use with 64-QAM signals achieves low bit error rate (BER) below the hard decision FEC limit [15]. On the other hand, for rising $CNR_{IN} \approx>20$dB/0.1 nm where S_B/S_C is no longer ≪1, Brillouin noise comes into play and caps CNR_{OUT} for any G to near ≈40 dB/0.1 nm. Such high CNR_{OUT} corresponds to minimal degradation of 64-QAM signal BER and is predicted reached for $CNR_{IN} \approx\geq 20$ dB/0.1 nm with $G \approx 30$ dB.

3. Low noise Brillouin amplification

Operating Brillouin amplifiers for lowest noise output is required for most applications. Figure 1 illustrates a typical schematic using a backward propagating pump to drive gain, G in a gain medium for an input spectral line. Here, the pump is sourced from the input itself by a coupler as reported in [16]. This favorably eliminates use of a dedicated pump laser. Moreover, it avoids the need for sophisticated frequency locking [17] to suppress the otherwise relative random frequency drift between both lasers from being near enough to the narrow Brillouin gain bandwidth to cause gain fluctuations. The self-frequency aligning pump has been observed effective even for poor CNR_{IN} ≈0 dB/0.1 nm [15]. Maximizing the gain requires the pump be frequency up-shifted by δf_B, determined by the gain medium parameters. This is 10.83 GHz at 1555 nm in SSMF and can be easily applied by electro-optic modulation [18], [19].

Noise for Brillouin amplification is also sensitive to operating conditions making its characterization important. A typical method is heterodyne beat signal analysis [1]. A recent alternative used coherent detection and digital signal processing [20], related to measuring laser noise [21-23]. This allowed evaluating amplitude and phase noise as well as Q^2-factor degradation. Low distortion with large Brillouin gain ≥26 dB in a 4.46 km SSMF was found constrained to launch powers of between ≈-13 to -6 dBm for the input and ≈14~20 dBm for the pump. Both optimum δf_B and state of polarization for maximum gain were also crucial. These parameters were targeted in Section 4 tests.

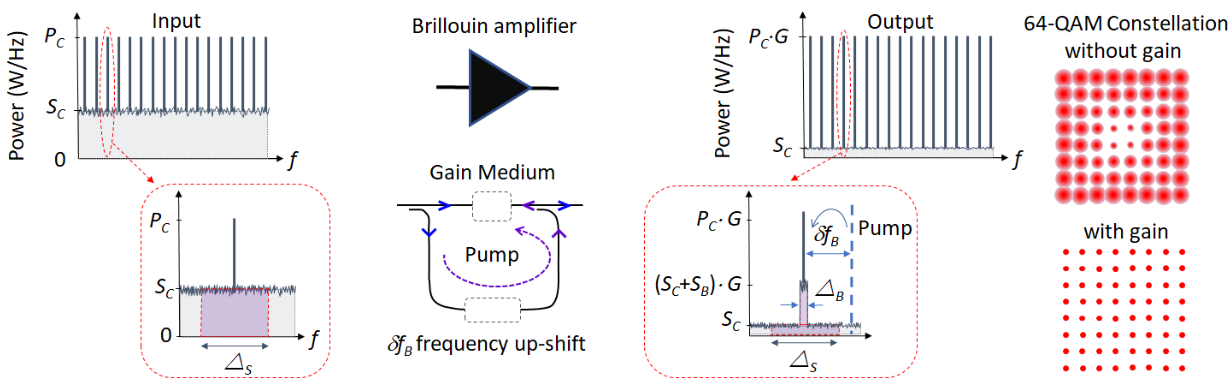

Fig. 1. Schematic of Brillouin amplifier applying gain G to optical frequency comb lines. The CNR of each spectral line is enhanced by suppression of out of band noise with respect to the narrow gain bandwidth, Δ_B and signal channel width, Δ_S. (Right inset): Applying the lower noise spectral line as a signal carrier or local oscillator for coherent detection of 64-QAM signals translates to a lower distortion signal constellation.

4. 64-QAM pilot tone carrier recovery limits

The benefit of Brillouin gain for optical carrier recovery in coherent detection of 64 QAM signals was also evaluated for testing the limits in Section 2 [15]. The BER was measured after transmission through a 80 km link of SSMF for a 48 Gb/s 64-QAM signal containing a polarization multiplexed pilot tone. Brillouin amplification was performed in a 4.46 km long SSMF at the receiver and applied to only the pilot tone that served as the LO for coherent detection.

The robustness of Brillouin gain in aiding pilot tone carrier recovery was evaluated for wide ranging power ratio of the pilot to signal (PSR). Decreasing the PSR degraded the pilot tone CNR_{IN} at the receiver due to increased amplified spontaneous emission noise (ASE) added mainly from the receiver EDFA. Brillouin gain countered this to enhance the overall CNR before coherent detection. The signal BER reached a minimum for PSR ≈>-16 dB corresponding to a measured pilot tone CNR_{IN} >≈19 dB/0.1 nm. This is consistent with the Section 2 prediction that CNR_{IN} ≈ >20 dB/0.1 nm gives a CNR_{OUT} of around ≈40 dB/0.1 nm, where the BER degradation of 64-QAM signals becomes minimal. By extrapolation from the linear trend of measured CNR_{IN} versus PSR, the minimum tolerable PSR for achieving a BER below the hard decision FEC limit [24] was deemed as being ≈-30 dB. That was by extrapolating CNR_{IN} down to ≈0 dB/0.1 nm, which Section 2 predicted would give CNR_{OUT} ≈24 dB/0.1 nm. This is notably well below the typical PSR ≈-10 dBm used for carrier recovery by the optical injection locking method [25].

The CNR improvement limits were also tested for wide ranging launch power (P_{IN}) to the 80 km link. In this case, decreasing P_{IN} degraded both the optical signal to noise ratio (OSNR) and pilot tone CNR_{IN} at the receiver due to ASE added by the receiver EDFA. Performance was compared to using a conventional LO for coherent detection for a signal without a pilot tone. For high P_{IN} where signal BER degradation was dominated by the nonlinear Kerr effect in the 80 km link, performance was close to the reference case. This was consistent with predictions for $G \approx 30$ dB since the measured pilot tone CNR_{IN} exceeded 20 dB/0.1 nm, corresponding to predicted CNR_{OUT} being around ≈40 dB/0.1 nm, that equates to a minor impact on the BER. On the other hand, performance was worse in the low P_{IN} region where degradation was dominated by EDFA ASE. This was again consistent since measured CNR_{IN} ≈< 15 dB/0.1 nm corresponded to predicted CNR_{OUT} below ≈40 dB/0.1 nm due to insufficient ΔCNR limited by Δ_B.

The limits were similarly consistent for a WDM 3×48 Gb/s signal [15] using the same Brillouin amplifier for delivering ≈30 dB gain to 3 tone pilot tones, verifying the validity of the predictions for more advanced schemes.

5. Summary

Brillouin amplifiers offer performance benefits to phase noise sensitive coherent communications with 64-QAM signals. Its capability to reduce signal distortion by enhancing spectral line CNR, such as for optical frequency comb carriers or pilot tone carrier recovery is greatest for noisier spectral lines where Brillouin noise has less impact. In this case, the performance boost is limited by the narrowness of the Brillouin gain bandwidth. On the other hand, for less noisy spectral lines, Brillouin noise comes into play, even in low noise operating conditions and caps the highest achievable CNR to around 40 dB/0.1 nm at 30 dB gain level. Nevertheless, such large CNR is enough to ensure low distortion impact on 64-QAM signals. These characteristics were also shown favorably scalable to WDM operation.

6. References

[1] O. Terra, G. Grosche, and H. Schnatz, “Brillouin amplification in phase coherent transfer of optical frequencies over 480 km fiber”, Opt. Express, vol. 18, pp. 16102-16111, 2010.

[2] C. Lisdat, et al., “A clock network for geodesy and fundamental science”, Nat. Commun., vol. 7, 12443, 2016.

[3] H. Al-Taiy, N. Wenzel, S. Preußler, J. Klinger, and T. Schneider, “Ultra-narrow linewidth, stable and tunable laser source for optical communication systems and spectroscopy”, Opt. Lett., vol. 39, pp. 5826-5829, 2014.

[4] J. Subías, C. Heras, J. Pelayo, and F. Villuendas, “All in fiber optical frequency metrology by selective Brillouin amplification of single peak in an optical comb”, Opt. Express, vol. 17, pp. 6753-6758, 2009.

[5] F. Rohde, E. Benkler, and H. Telle, "High contrast, low noise selection and amplification of an individual optical frequency comb line", Opt. Lett., vol. 38, pp. 103-105, 2013.

[6] J. Galindo-Santos, A.V. Velasco, A. Carrasco-Sanz, and P. Corredera, “Brillouin filtering of optical combs for narrow linewidth frequency synthesis”, Opt. Commun., vol. 366, pp. 33-37, 2016.

[7] A. Loayssa, D. Benito, and M. José Garde, “Applications of optical carrier Brillouin processing to microwave photonics”, Opt. Fiber Technol., vol. 8, pp. 24-42, 2002.

[8] A. Almaiman et al., “Experimental demonstration of phase-sensitive regeneration of a binary phase-shift keying channel without a phase-locked loop using Brillouin amplification”, Opt. Lett., vol. 41, pp. 5434-5437, 2016.

[9] M. Pelusi, A. Choudhary, T. Inoue, D. Marpaung, B.J. Eggleton, K. Solis-Trapala, H. Nguyen Tan, and S. Namiki, “Low noise frequency comb carriers for 64-QAM via a Brillouin comb amplifier”, Opt. Express, vol. 25, pp. 17847-17863, 2017.

[10] A. Lorences-Riesgo, M. Mazur, T.A. Eriksson, P.A. Andrekson, and M. Karlsson, “Self-homodyne 24x32-QAM superchannel receiver enabled by all-optical comb regeneration using Brillouin amplification”, Opt. Express, vol. 24, pp. 29714-29723, 2016.

[11] Y. Cao et al., “Pilot-tone-based self-homodyne detection using optical nonlinear wave mixing”, Opt. Lett., vol. 42, pp. 1840-1843, 2017.

[12] M. Pelusi, T. Inoue and S. Namiki, “64-QAM signal carrier recovery from low power pilot tone by narrowband Brillouin amplification before coherent detection”, in proc. 44th European Conference on Optical Communication (ECOC), paper We2.48, Rome, Sept. 23-27, 2018.

[13] Q. Zhang, B. Zheng, and C. Shu, “Kramers-Kronig detection with Brillouin-amplified virtual carrier”, Opt. Lett., vol. 43, pp. 1367-1370, 2018.

[14] M. Pelusi, T. Inoue, and S. Namiki, “Carrier to noise ratio improvement by Brillouin amplification for 64-QAM coherent communications”, in proc. Optical Fiber Communication Conference (OFC) paper M1B.7, San Diego, 2019.

[15] M. Pelusi, T. Inoue and S. Namiki, "Enhanced carrier to noise ratio by Brillouin amplification for optical communications," J. Lightwave Technol., doi: 10.1109/JLT.2019.2948226, 2019.

[16] M. Niklés, L. Thevenaz and P.A. Robert, “Brillouin gain spectrum characterization in single-mode optical fibers”, J. Lightwave Technol., vol. 15, pp. 1842-1851, 1997.

[17] Y. Souidi, F. Taleb, J. Zheng, M. Lee, F. Burck, and V. Roncin, “Low-noise and high-gain Brillouin optical amplifier for narrowband active optical filtering based on a pump-to-signal optoelectronic tracking”, Appl. Opt., vol. 55, pp. 248-253, 2016.

[18] A. Loayssa, R. Hernández, D. Benito, and S. Galech, “Characterization of stimulated Brillouin scattering spectra by use of optical single-sideband modulation”, Opt. Lett., vol. 29, pp. 638-640, 2004.

[19] T. Tanemura, Y. Takushima, and K. Kikuchi, “Narrowband optical filter, with a variable transmission spectrum, using stimulated Brillouin scattering in optical fiber”, Opt. Lett., vol. 27, pp. 1552-1554, 2002.

[20] M. Pelusi, T. Inoue and S. Namiki, “Noise characterization of Brillouin amplified narrowband carriers for coherent communications”, in proc. 44th European Conference on Optical Communication (ECOC) paper Tu3A.4, Sept. 23-27, 2018.

[21] K. Kikuchi, "Characterization of semiconductor-laser phase noise and estimation of bit-error rate performance with low-speed offline digital coherent receivers," Opt. Express, vol. 20, pp. 5291-5302, 2012.

[22] T.N. Huynh, L. Nguyen and L.P. Barry, "Phase noise characterization of SGDBR lasers using phase modulation detection method with delayed self-heterodyne measurements," J. Lightwave Technol., vol. 31, pp. 1300-1308, 2013.

[23] T. Duthel, G. Clarici, C.R.S. Fludger, J.C. Geyer, C. Schulien and S. Wiese, "Laser linewidth estimation by means of coherent detection," in IEEE Photonic Tech L., vol. 21, no. 20, pp. 1568-1570, 2009.

[24] F. Chang, K. Onohara and T. Mizuochi, “Forward error correction for 100G transport networks”, IEEE Commun. Mag., vol. 48, pp. S48-S55, 2010.

[25] T. Kan, K. Kasai, M. Yoshida, and M. Nakazawa, “42.3 Tbit/s, 18 Gbaud 64 QAM WDM coherent transmission over 160 km in the C-band using an injection-locked homodyne receiver with a spectral efficiency of 9 bit/s/Hz”, Opt. Express, vol. 25, pp. 22726-22737, 2017.