Optical Single-Sideband Direct Detection Transmissions: Recent Progress and Commercial Aspects

S. T. Le[1, *], K. Schuh[2], F. Buchali[2], T. Drenski[3], A. Hills[3], M. King[3] and T. Sizer[1]

[1]Nokia Bell Labs, NJ, USA, *son.thai_le@nokia-bell-labs.com;

[2]Nokia Bell Labs, Stuttgart, Germany

[3]Socionext Europe GmbH, Concorde Park, Concorde Road, SL64FJ, UK

Abstract *We discuss recent progress and commercialization of optical single-sideband direct detection systems with data rate of 100 Gb/s and beyond. Critical hardware requirements and signal processing challenges, especially for the cancellation of signal-signal beat interference, are reviewed.*

Introduction

Intensity modulation direct detection (IM/DD) has been considered as the primary technology for short-reach optical transmission systems [1] because of its simplicity and low cost. Due to the dispersion-induced power fading effect, the reach of an IM/DD system is inversely proportional to the square of symbol rate [2]. As a result, the reach in the C-band (without optical dispersion compensation) is limited to only ~ 10 km for commercial 50 Gb/s PAM4 modules [3] and the total system capacity in the O-band is unlikely to reach 800 Gb/s (for 10 km of reach [4]).

One attractive possibility for overcoming these issues is to leverage coherent detection schemes for short-reach applications. However, beside its high cost, the size and power consumption of full-coherent receivers are still not fully suitable for client-optics hot-pluggable form factors (e. g. QSFP, SFP+). Therefore, alternative dispersion-tolerant schemes which are less complicated than full-coherent detection have been actively investigated.

One potential scheme is the single-sideband (SSB) [5-16] or vestigial sideband (VSB) DD schemes [17-18] as shown in Fig. 1, where the information bearing signal is placed at one side of a referenced optical tone. This scheme is free of chromatic dispersion (CD), but it suffers from the signal-signal beat interference (SSBI) when frequency gap between the optical tone and the information bearing signal is smaller than the signal's bandwidth. Over the last 5 years, many DSP techniques have been investigated for mitigating the SSBI which have successfully

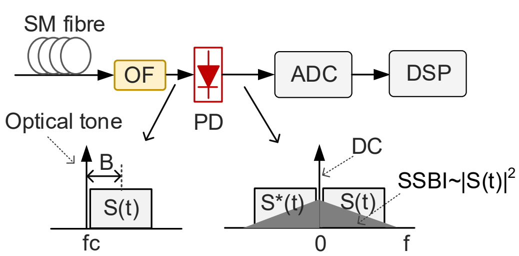

Fig. 1. Schematic of SSB or VSB DD receivers

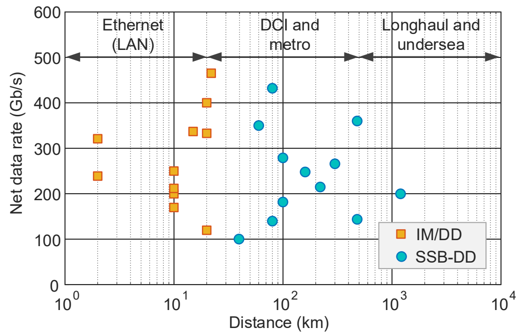

Fig. 2. Reported net data rate versus distance for single-polarization systems using a single-ended PD

pushed the data rate of single-polarization SSB DD transmission beyond 400 Gb/s (Fig. 2). However, there are still several challenges that hinder the commercial success of this scheme. These challenges and recent progress of SSB DD are discussed in this paper.

Principle

In SSB or VSB DD transmissions, the signal at the input of photodiode (PD) can be written as:

$$E_{rx}(t) = A + S(t)e^{2\pi jBt}, \qquad (1)$$

where A is the amplitude of the optical tone, $S(t)$ is the information bearing signal distorted by the CD, and B is the frequency gap between the optical tone and the information bearing signal. When the signal spectrum is confined within the frequency range of $[-B;\, B]$ the transmission scheme is called SSB otherwise the scheme is called VSB [17-20]. VSB signal is usually created

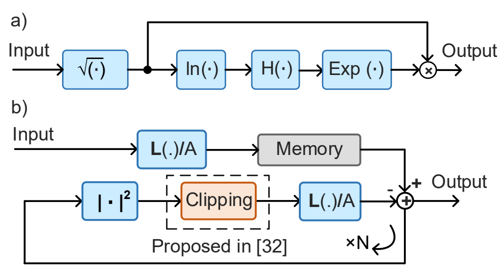

Fig. 3. Bock diagrams of KK (a) and iterative SSBI cancellation scheme (b); **L**() – SSB filter

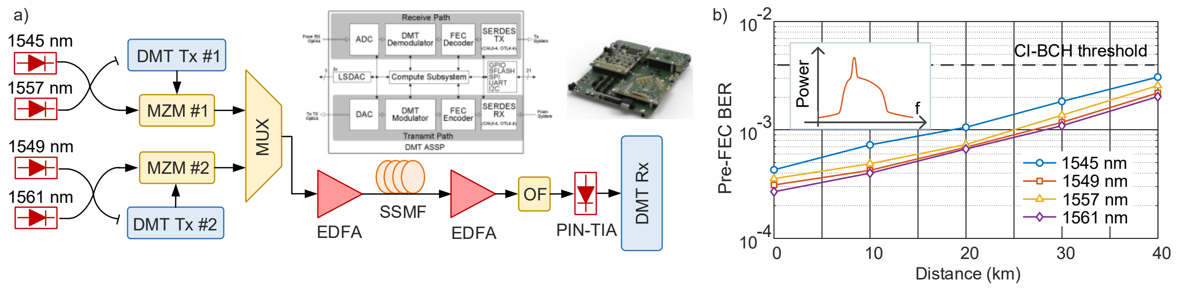

Fig. 4a – Experimental setup of 400 Gb/s real-time VSB DD transmission over up to 40 km in C-band; b) – overall transmission result for all channels when the received signal power was set to – 1 dBm.

by passing an IM signal through an optical filter (OF) (either at the Tx or Rx), where a part of the signal is still present on the other side of the optical carrier due to the limited steepness of OF. The generation of SSB signals usually requires more sophisticated approaches, including: *i*) – using an IQ modulator [5,8-9]; *ii*) – make use of an additional laser source or a frequency comb [10,11,13,21]; *iii*) – using a dual-driver MZM modulator [22] and *iv*) – utilizing cascaded or segmented modulators [23-24].

The detected signal after PD is expressed as:

$$I(t) = |A|^2 + 2\Re(AS(t)e^{2\pi jBt}) + |S(t)|^2, \qquad (2)$$

where the second term is the useful detected signal and the third term is the SSBI.

When the optical tone power is large enough such that the complex optical signal in Eq. 1 becomes minimum-phase [6-7], the SSBI can be effectively removed using the Kramers-Kronig field reconstruction technique [7] or iterative SSBI cancellation techniques [8-9] as shown in Fig. 3. However, effective SSBI cancellation requires accurate Optical/Electrical (O/E) front-end characterization [9,12] and sufficient DSP processing. This performance versus complexity trade-off should be considered carefully when developing practical SSB transmission systems.

4×100 Gb/s real-time VSB DD transmission

For 100 Gb/s transport, VSB DD is a more suitable solution compared to SSB DD with SSBI mitigation due to its lower complexity in both hardware and DSP. For VSB DD systems, Discrete Multi-Tone (DMT) is a very attractive modulation format as the joint impact of CD and O/E response can be mitigated using a single-tap equalization [17-20]. Fig. 4a shows a 4×100 Gb/s real-time VSB DD transmission setup in C-band using a commercially available 16 nm CMOS DMT ASIC [25,26]. The ASIC incorporates a complete single channel DMT transmission PHY for up to 100 Gb/s data rates, supporting various client interfaces, including CPRI-10, 100 GbE (IEEE CAUI-4 compliant) and OTL4.4. The ASIC generates double-sideband (DSB) DMT signals with a sampling rate up to 71 GS/s using an iFFT size of 512 where 256 subcarriers are modulated with adaptive QAM-format with 2-8 bits per subcarrier. In this experiment, the DMT ASIC was used to modulate two interleaved optical carriers (either 1545 nm with 1557 nm or 1549 nm with 1561nm) using a Mach-Zehnder Modulator (MZM). After multiplexing, the WDM signal was amplified and fed into a single span of SSMF with span length from 0 km to 40 km. When 100 Gb/s DSB DMT signal is transmitted in the C-band, the reach is limited to only ~ 2 km due to the power fading effect. To increase the reach by using the VSB scheme, we used a tunable optical filter at the Rx to remove one sideband. The OF bandwidth was set to 0.7 nm and the offset between the filter center and optical carrier was ~ 0.32 nm. The transmission performances for all 4 channels is shown in Fig. 4b. The Pre-FEC BER was below the Continuously Interleaved BCH (CI-BCH) FEC threshold and the post-FEC BER was zero, confirming that a reach of 40 km in the C-band can be achieved. This result represents a 20-fold increase in reach compared to the 100 Gb/s DSB DMT transmission scheme.

Beyond 100 Gb/s SSB DD transmission

For systems with data rate per channel beyond 100 Gb/s, SSBI mitigation becomes crucial. It has been shown in many publications [8-15] that both KK and iterative SSBI cancellation schemes are

Tab. 1. Hardware comparison of SSB DD with full coherent detection; BPD – balanced PD; B – half symbol rate; PBS – polarization beam splitter; capacity and power are normalized to values of full coherent detection system.

	Laser	Mod	DAC	ADC	PD	WDM Cap	Front-end	Power [28]
Full Coherent	1	DP-IQ	4@B	4@B	4 BPD@B	1	90° hybrid	1
SSB type 1 [9]	1	IQ	2@2B	1@4B	1 PD@4B	< 0.25	No	~0.8
SSB type 2 [10]	1	DP-IQ	4@B	2@2B	2 PD@2B	~1	2 PBS	~1.1

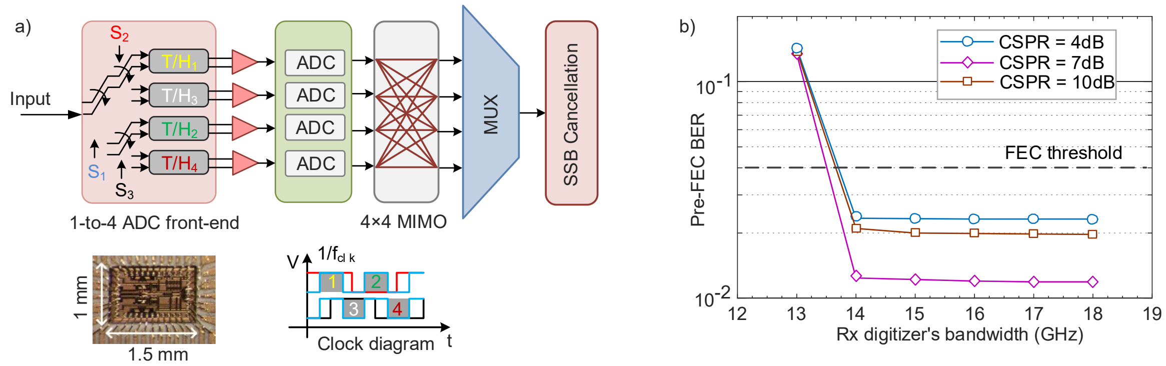

Fig. 5a – Block diagram of SSB Rx with 112 GS/s 1-to-4 ADC front-end, insets show a picture of the die and clock diagram of the ADC front-end; b) – Digitizer's bandwidth requirements for 200 Gb/s SSB transmission using 112 GS/s ADC front-end

very effective. As shown in Fig. 2, net data rates of 400 Gb/s over 80 km [11] and 200 Gb/s over 1200 km [27] have been achieved. However, for a commercial success, SSB DD must compete directly with the full coherent solution for DCI and metro applications. As discussed before, the optical tone in SSB DD transmission can be added at the Tx (SSB type 1) or at the Rx [9] (SSB type 2). We assume that both the full coherent and SSB type 2 schemes require only one laser which serves as both Tx laser and LO. The power consumption estimation was adjusted from [28] considering the laser split option. In Table 1, one can observe that the hardware requirement and total achievable WDM capacity of the full-coherent and SSB type 2 schemes are quite similar. Due to the complexity of SSBI cancellation schemes, the total power consumption of a SSB type 2 module is somewhat even higher than those of a full coherent module (at 200 Gb/s). In addition, with recent advances in photonics integration, the relative cost of PDs and coherent front-ends is decreasing rapidly. These two reasons strongly restrict the practical aspects of the SSB type 2 scheme. On the other hand, an SSB type 1 scheme can still bring several advantages over the full coherent scheme such as simpler Tx architecture (using only IQ modulator and 2 DACs + 2 drivers) and a lower total module power (a reduction of 20%-33% for 200 Gb/s [28]). However, the SSB type 1 scheme also has two significant challenges to overcome, namely *i*) – it employs only one ADC at the Rx but the digitizer's bandwidth requirements is 4 times higher than those of the full-coherent system; *ii*) – due to the co-transmission of the optical tone, the total number of WDM channels which can be supported by a single EDFA reduces significantly. Solving these two problems is crucial for the commercialization of SSB DD transmission. Following, we review two potential technologies for addressing these problems.

A. 1-to-4 ADC analog front-end

The digitizer's bandwidth requirement in an SSB type 1 scheme can be relaxed by employing a high-speed ADC front-end and parallel digitization at lower speed. In [29], a 112 GS/s 1-to-4 SiGe HBT BiCMOS ADC frontend has been developed. This ADC front-end exploits a charge-sampling architecture to perform track-and-hold (T/H) operations of the input signal (Fig. 5a), providing better SNR performance against clock jitter for fast-varying input signals over conventional voltage sampling architecture. Using this ADC front-end, high-bandwidth SSB signal can be digitized in parallel by 4 ADCs at quarter speed. A 4x4 MIMO algorithm was proposed in [30] for accurately combining the outputs of 4 ADCs before SSBI cancellation. For a 200 Gb/s SSB DD transmission over 80 km, it was shown in [30] that only 14 GHz of digitizer's bandwidth was required. This value is comparable to those of a 200 Gb/s full coherent detection system at the same spectral efficiency. This result is promising, but the integration of SiGe ADC frontend with CMOS ADCs and the complexity of 4x4 MIMO must be further investigated.

B. Iterative SSBI cancellation with clipping

For SSB type 1 transmission, by reducing the carrier to signal power ratio (CSPR), the number of WDM channels can be increased. However, when the CSPR is too low, e.g. below 6 dB, existing SSBI cancellation schemes suffer from significant performance penalties [31]. Most reported SSB type 1 experiments so far employ CSPR values of 10 dB or even higher. To address this issue, an iterative SSBI cancellation scheme with clipping was proposed in [32] (Fig. 3b). With this scheme, a CSPR value as low as 5 dB can be used for a 30 Gbaud SSB DD transmission even with 128 QAM format. On the other hand, this algorithm requires up to 10 iterations for achieving the best performance, which increases the complexity. This issue should be also further investigated.

Conclusion

100 Gb/s VSB DD can be achieved using a commercial DMT ASIC. Beyond 100 Gb/s, the

most realistic data rate target for SSB DD systems with SSBI cancellation would be 200 Gb/s. However, with recent advances in photonics integration, packaging and CMOS technologies which significantly reduce the cost, size and power consumption of conventional coherent transceivers, it is not clear if 200 Gb/s SSB DD transmission will ever be commercialized.

References

[1] https://standards.ieee.org/standard/802_3-2018.html

[2] J. Song and C. Fan, "A simplified dispersion limit formula for IM/DD systems and its comparison with experimental results," in Journal of Lightwave Technology, vol. 13, no. 3, 1995.

[3] https://www.inphi.com/products/colorz/

[4] IEEE P802.3db 100 Gb/s, 200 Gb/s, and 400 Gb/s Short Reach Fiber Task Force. https://www.ieee802.org/3/db/index.html

[5] M. S. Erkılınc¸ et al., "Spectrally-efficient WDM Nyquist-pulse-shaped 16-QAM subcarrier modulation transmission with direct detection," J. Lightwave Technol., vol. 33, pp. 3147-3155 (2015).

[6] Robert J. Davies, "Minimum phase dispersion compensator", US patent US5949926A, 1997

[7] A. Mecozzi, C. Antonelli, and M. Shtaif., "Kramers–Kronig coherent receiver." Optica 3, 1218-1227 (2016).

[8] Z. Li et al., "SSBI Mitigation and Kramers-Kronig Scheme in Single-Sideband Direct-Detection Transmission with Receiver-based Electronic Dispersion Compensation." JLT 35 (2017).

[9] S. T. Le et al, "1.72-Tb/s virtual-carrier-assisted direct-detection transmission over 200 km", J. Lightwave Technol. 36 (2018).

[10] Xi Chen et al, "Kramers–Kronig Receivers for 100-km Datacenter Interconnects," J. Lightwave Technol. 36, 79-89 (2018)

[11] S. T. Le et al, "5× 510 Gbps Single-Polarization Direct-Detection WDM Transmission over 80 km of SSMF", in OFC 2019, paper Tu2B. 1

[12] S. T. Le, K. Schuh, R. Dischler, F. Buchali, L. Schmalen and H. Buelow, "Beyond 400 Gb/s Direct Detection Over 80 km for Data Center Interconnect Applications," in Journal of Lightwave Technology, vol. 38, no. 2, pp. 538-545, 15 Jan.15, 2020.

[13] I. Sackey et al, "Distributed aggregation and reception of a 400-Gb/s net rate Superchannel in a single-photodiode 110-GHz Kramers-Kronig receiver," in Optical Fiber Communication Conference Postdeadline Papers, paper Th4C.7.

[14] Tianwai Bo and Hoon Kim, "Kramers-Kronig receiver operable without digital upsampling," Opt. Express 26, 13810-13818 (2018)

[15] K. Schuh, S. T. Le, R. Dischler, F. Buchali, "Transmission of 90 Gbd 32 QAM over 480 km of SSMF with Kramers-Kronig Detection", in OFC 2019, paper Tu2B. 3, pp. 1-3.

[16] C. Füllner et al, "Transmission of 80-GBd 16-QAM over 300 km and Kramers-Kronig Reception Using a Low-Complexity FIR Hilbert Filter Approximation," in OFC 2018, paper W4E.3, 2018

[17] A. Dochhan, H. Griesser, N. Eiselt, M. Eiselt and J. Elbers, "Optimizing Discrete Multi-tone Transmission for 400G Data Center Interconnects," Photonic Networks; 17. ITG-Symposium; Proceedings of, Leipzig, Germany, 2016, pp. 1-6

[18] A. Dochhan, H. Griesser, N. Eiselt, Michael H. Eiselt, and J. Elbers, "Solutions for 80 km DWDM Systems," J. Lightwave Technol. 34, 491-499 (2016)

[19] P. Dong, J. Lee, Y. Chen, L. L. Buhl, J. H. Sinsky and K. Kim, "Four-channel vestigial sideband discrete multi-tone modulation using silicon photonic integrated circuits," 2015 European Conference on Optical Communication (ECOC), Valencia, 2015

[20] F. Li, X. Li, J. Zhang and J. Yu, "Transmission of 100-Gb/s VSB DFT-Spread DMT Signal in Short-Reach Optical Communication Systems," in IEEE Photonics Journal, vol. 7, no. 5, pp. 1-7, Oct. 2015.

[21] C. Antonelli, A. Mecozzi, M. Shtaif, X. Chen, S. Chandrasekhar and P. J. Winzer, "Polarization Multiplexing with the Kramers-Kronig Receiver," J. Lightwave Technol. 35, pp. 5418-5424, (2017).

[22] K. Schuh, E. Lach, B. Junginger and B. Franz, "53.5 Gbit/s NRZ-VSB modulation applying a single Mach-Zehnder modulator and transmission over 21 km SSMF with electronic dispersion compensation," OFC 2009

[23] Tianwai Bo and Hoon Kim, "Generalized model of optical single sideband generation using dual modulation of DML and EAM," Opt. Express 28, 28491-28501 (2020)

[24] M. Chagnon, "Optical Communications for Short Reach," in Journal of Lightwave Technology, vol. 37, no. 8, pp. 1779-1797, 15 April15, 2019

[25] https://www.eu.socionext.com/assets/downloads/37/DMT-ASSP-V06.pdf

[26] S. T. Le et al, "400Gb/s Real-time Transmission Supporting CPRI and eCPRI Traffic for Hybrid LTE-5G Networks," in Optical Fiber Communication Conference Postdeadline Papers 2020, (Optical Society of America, 2020), paper Th4C.4.

[27] S. T. Le, K. Schuh, M. Chagnon, F. Buchali, and H. Buelow, "1.6 Tb/s Virtual-Carrier Assisted WDM Direct Detection Transmission Over 1200 km," J. Lightwave Technol. 37, 418-424 (2019).

[28] T. Bo and H. Kim, "Coherent versus Kramers-Kronig Transceivers in Metro Applications: A Power Consumption Perspective," in Optical Fiber Communication Conference (OFC) 2019

[29] X. Du et al., "A 112-GSa/s 1-to-4 ADC front-end with more than 35-dBc SFDR and 28-dB SNDR up to 43-GHz in 130-nm SiGe BiCMOS," IEEE Radio Frequency Integrated Circuits (RFIC) Symposium, 2019, pp. 1-4

[30] S. T. Le et al., "Single Sideband Transmission Employing a 1-to-4 ADC Frontend and Parallel Digitization," in Journal of Lightwave Technology, vol. 38, no. 12, pp. 3125-3134, 15 June15, 2020

[31] C. Sun, D. Che, H. Ji, and W. Shieh, "Towards Low Carrier-to-Signal Power Ratio for Kramers-Kronig Receiver," in OFC 2019, paper M1H.6, pp. 1-3.

[32] S. T. Le, V. Aref, K. Schuh and H. N. Tan, "Power-Efficient Single-Sideband Transmission With Clipped Iterative SSBI Cancellation," in Journal of Lightwave Technology, vol. 38, no. 16, 2020.