Nanosecond-Latency IM/DD/DSB to Coherent/SSB Converter

Arthur Lowery[(1)], Bill Corcoran[(1)]

[(1)] Electro-Photonics Laboratory, Department of Electrical and Computer Systems Engineering, Monash University, Clayton, VIC 3800, Australia arthur.lowery@monash.edu

Abstract *We demonstrate an all-analogue converter from intensity modulated direct-detection double-side-band to field-modulation coherent single-sideband, which is based on the Weaver SSB method. This is designed to interface short-haul datacentre links to coherent metro/long-haul links.*

Introduction

Intensity Modulation Direct-Detection (IM/DD) has long enabled compact transmitters based on directly modulated lasers (DML) and single-photodiode receivers. Although it can have high electrical spectral efficiency, to make the most of the electrical and optoelectronic components' bandwidths, its optical spectral efficiency is not usually a concern, as only single-wavelength or coarse wavelength division multiplexing is used. Suitable modulation formats to increase the capacity of IM/DD include Pulse-Amplitude Modulation, Discrete Multi-tone Modulation, and Optical Orthogonal Frequency Division Multiplexing (OFDM) [1, 2].

Although IM/DD systems provide an attractive solution for short-haul links, in the O-band high fibre attenuation limits the transmission distance, while in the C-band, the transmission distance is severely limited by fibre chromatic dispersion (CD), which causes nulls in the baseband signal due to the double-sideband spectrum. Coherent optical communications systems avoid this dispersion-induced fading by effectively using a single-sideband, which also enables equalization of the CD and supports high optical spectral efficiency.

Currently, interfaces between short-haul IM/DD links and long-haul coherent optical links rely on reception, decoding and re-encoding before re-transmission. While this provides full flexibility in terms of format conversion, removing the digital processing stages will dramatically reduce latency.

In this paper, we propose using a format converter to extend the range of short-haul IM/DD links, to make their signals compatible with long haul, coherent links, as illustrated in Fig. 1. In a few nanoseconds, it converts an intensity modulated (so DSB) optical signal to a carrierless field-modulated (single-sideband supressed carrier, SSB-SC) signal, which we will illustrate with a Nyquist-shaped QAM signal frequency offset from a carrier. Of course, this conversion could be achieved with a sufficiently narrow-band optical filter, if a sufficiently wide spectral guard-band were to be left between the carrier and sidebands (as in direct-detection optical OFDM [3]); however, such a system would require wavelength stabilised and chirp-managed transmitters for the short-haul link. Our solution is input wavelength agnostic, but can output a precise wavelength suitable for dense WDM. Furthermore, our solution converts intensity modulation (where the optical and electrical spectra are not 1:1 mapped), to a field-modulated signal, with 1:1 mapping to support the equalisation of linear channel impairments, such as CD. The converter has almost zero latency, apart from the lengths of its wires, as it uses only analogue signal processing.

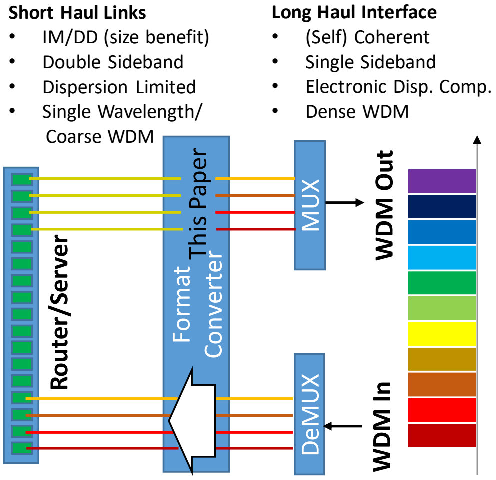

Fig. 1: Concept of format conversion to support long-haul transmission from short-haul interfaces.

Format Conversion Method

The Weaver (or 'third') method [4] of generating RF-wireless SSB-SC signals was developed in 1956, using two pairs of double-balanced RF mixers. The first pair took a single-input such as an audio signal, (of single-sided bandwidth B), and mixed it with 0-degrees and 90-degree versions of an oscillator centred at $B/2$. This down-converted the audio-band into two paths (inphase & quadrature, I and Q) centred on DC, which are a Hilbert pair. Each path was low-pass-filtered (LPF) to just above $B/2$, and sent to a second pair of mixers, with quadrature local oscillators to upconvert to RF SSB-SC. This 'third method' proposed by Weaver neither required sharp-transition RF filters at the carrier frequency to remove one sideband (the first or 'filter' method), nor a multi-octave phase-shift network at baseband to approximate a Hilbert transform (the second or 'phasing' method). The Weaver method was particularly good at supressing out-of-band (OOB) emissions even with IQ imbalances, so was neighbourly for the crowded radio spectrum, and so should be suitable for high spectral efficiency optical multiplexing.

Fig. 2 shows our optical implementation. The first pair of RF mixers take the output of the IM/DD link and mix it with 0° and 90° versions of an RF signal centred on the information band of the DD/IM link. This produces I/Q signals that are a Hilbert pair, without the need for broad-band phase-shifting networks. These are low-pass filtered and amplified, to remove the sum mixing products. To generate an optical signal, Weaver's second pair of RF mixers is replaced by an optical SSB modulator ('complex MZI'), biased at its nulls to produce a signal with voltage to field mapping, suitable for coherent reception.

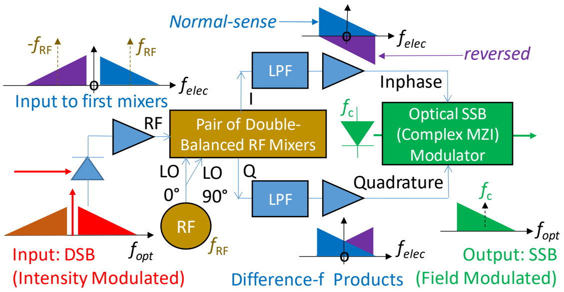

Fig. 2: Optical Weaver SSB generator. The two RF mixers are usually a single component with I and Q outputs.

Spectrally, the double-sided optical input is converted to a double-sided electrical spectrum by the photodiode. The first mixer pair (and LPFs) produce superimposed spectra in each of the I and Q paths. These can also be thought of as normal-sense and frequency-reversed spectra, shown in blue and purple, respectively. As I and Q are a Hilbert pair, the optical SBB (CMZI) modulator substantially cancels the frequency reversed spectrum, to produce a signal suitable for a coherent optical receiver. The mathematical derivation is identical to the Weaver method [4].

Experimental demonstration

Fig. 3 shows the experimental setup. One channel of a Keysight 62-GS/s Arbitrary Waveform Generator provides the input to the system, which drives a directly-modulated Gouch and Housego 1310-nm DFB laser biased at 25 mA and driven by a 7-mA p-p 5-Gbaud QPSK or 16-QAM Nyquist signal (10% roll-off) centred around a 6-GHz offset from the optical carrier. This frequency offset enables phase-encoded QPSK/QAM signals to be transmitted over an intensity-modulated channel. The Weaver method allows smaller offsets (dependent on the sharpness of the LPFs that separate the sum and difference mixing products); however, we were constrained by our 'on-hand' RF mixer, which had a minimum LO frequency of 6 GHz.

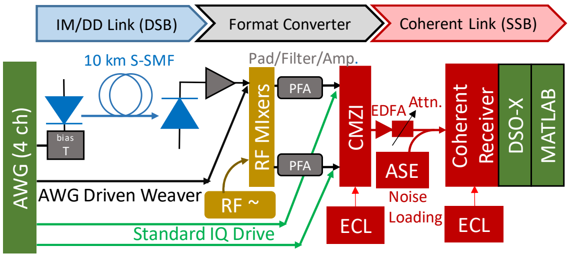

Fig. 3: Experimental signal paths to identify impairments.

The output of the DM laser traverses 10 km of standard single-mode fibre, and is detected by a Discovery DSO-X-9280A photoreceiver, whose output is amplified by an SHF807 amplifier. The received optical power is around 0 dBm, and the output of the amplifier is about 2 $V_{p\text{-}p}$. A Marki M06225 dual double-balanced mixer, with a 15-dBm, 6-GHz local-oscillator converts this to I and Q signals centred around DC (a Hilbert pair). Although the mixer's IF outputs have sharp low-pass cutoffs at 5 GHz, MiniCircuits LPF5000 5-GHz low-pass filters were added to remove breakthrough of the local oscillator and its higher harmonics. These filters were preceded by 2-dB pads to reduce reflections into the mixer's IF ports. The I and Q signals were then amplified by SHF807 amplifiers, which feed a 20-GHz bandwidth Sumitomo SBX1.5-20P DQPSK 'complex' modulator, with a 1552.4-nm input from a tunable external cavity laser (ECL: Keysight N7714A) with linewidth <100 kHz, to provide a SSB-SC signal suitable for coherent reception.

The coherent signal is amplified by an EDFA, attenuated and noise loaded. A U^2T coherent receiver with another similar ECL local oscillator (set to 1552.4-nm) provides electrical signals to a Digital Storage Oscilloscope (Keysight DSO-X92804A) with an 80-GS/s sampling rate. Finally, the captured samples were analysed by off-line DSP. The DSP flow is similar to that used for Nyquist-shaped QPSK signals. Frequency offset compensation using a spectral-peak search allows for optical f_C-LO and RF AWG-f_{RF} drifts. Next are frame synchronisation, RRC matched filtering, equalization using the constant modulus algorithm, phase estimation using a training-aided maximum-likelihood algorithm, then demodulation and error counting.

Results

Fig. 4a plots the Q^2-factors for QPSK versus OSNR (0.1-nm noise bandwidth, dual polarization), for: (●) the full system with directly-modulated (IM/DD) and coherent link; (▲) the format converter fed from the AWG via an

SHF807; (🟩) the CMZI driven by 2-channels of the AWG (a standard coherent link). There is a sensitivity penalty of 1.1 dB at 7% FEC threshold for both the full system and the format converter driven directly from the AWG, compared to the coherent system alone ("standard IQ drive"). These penalties increase for higher Q values, with the DM-link-driven Weaver increasing its penalty before the AWG-driven Weaver.

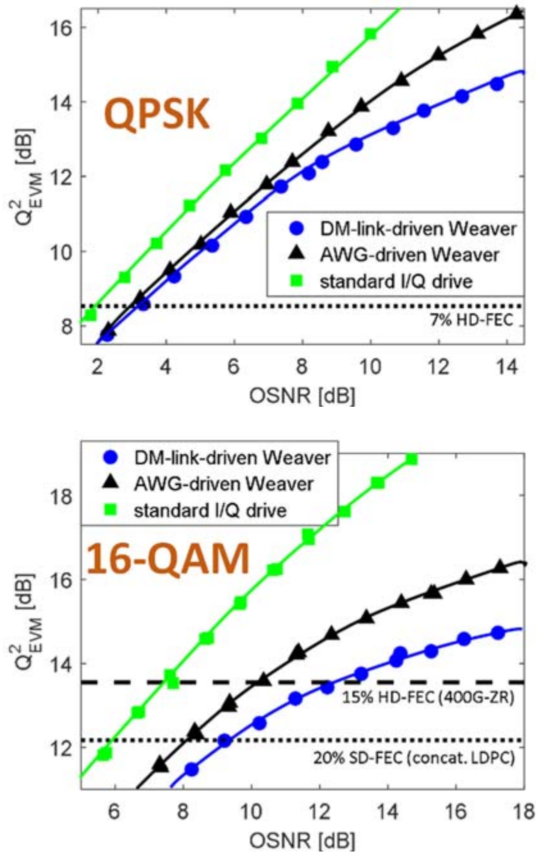

Fig. 4: Q^2-factors for noise-loaded optical back-to-back.

Fig. 4b shows that because 16QAM requires a higher signal quality for the same error-rates, the penalties are larger than for QPSK. From back-to-back experiments *without noise loading*, the AWG-driven Weaver transmitter provided 17.5 dB Q^2, while the Weaver transmitter fed by the IM/DD link provided just over 15 dB Q^2. This asymptotically limits the achievable BER, resulting in an error floor for the 16QAM link. The penalties are 2 dB and 3.2 dB for AWG-driven and DM-link Weaver respectively, compared with the standard I/Q drive at an indicative 20% SD-FEC threshold (for concatenated LDPC code at 0.026 BER). These increase to 2.9 dB and 4.9 dB for AWG-driven and DM link Weaver respectively, compared with a standard I/Q drive at 15% HD-FEC threshold (for 400G-ZR staircase FEC).

The penalty of the IM/DD link can be attributed to many factors, including the frequency response of the laser (the laser's RIN peak was only slightly beyond the maximum modulation frequency) and the dynamics of the laser (though a high bias and low peak-peak drive was used to avoid turn-off so avoid turn-on jitter).

The causes of the format converter's penalty are currently under investigation. These could include: imperfections in the frequency response of the mixers (which showed up in the equalisation curve); intermodulation distortion in the mixer; phase imbalances in the I/Q drive paths, including from the amplifiers, low-pass filters and CMZI; and nonlinearity of the MZI itself.

The latency of the system is mainly due to the interconnecting coaxial cables between the photodetector, mixers and CMZI. This latency could be made insignificant by closer integration.

Conclusions

In this paper, a proof-of-concept ns-latency format converter has been presented and experimentally demonstrated. It takes a double-sideband intensity-modulated signal of arbitrary wavelength, and converts it to a SSB-SC field-modulated signal suitable for coherent reception and electronic dispersion compensation. The converted signal is very spectrally efficient, and suitable for the formation of superchannels. While we used a Nyquist-shaped intensity-modulated QAM signal as a basis for this demonstration, in principle this method should also work for the wider range of IM/DD formats, including OFDM and DMT.

The methods we demonstrate here can form the basis of many other techniques for packing several IM/DD signals into dense-WDM systems. Using state-of-the-art RF mixers, sidebands could be placed tens of GHz away from the optical carriers. This provides the opportunity to form multi-subcarrier systems to aggregate multiple IM/DD channels onto the one WDM channel, or potentially onto a superchannel.

The reverse direction conversion would need to add a carrier to the 'coherent' signal, possibly derived from a pilot tone via injection locking.

Acknowledgements

Australian Research Council's Laureate Fellowship (FL130100041) scheme.

References

[1] M. H. Eiselt *et al.*, "Direct detection solutions for 100G and beyond," Proc. OFC, Tu3I.3, Los Angeles (2017).

[2] M. Morsy-Osman & D.V. Plant, "A comparative study of technology options for next generation intre- and inter-datacentre interconnects," OFC, We4E.1 (2018).

[3] B.J.C. Schmidt, A. J. Lowery, L.B. Du, "Low sample rate transmitter for direct-detection optical OFDM," Proc. OFC, OWM.4, (2009)

[4] D.K. Weaver, "A third method of generation and detection of SSB signals," Proc. I.R.E, vol. 44, pp.1703-1705 (1956)