Digital Signal Processing: Enabling a Revolution in Optical Networking

Seb J. Savory
UCL Electronic & Electrical Engineering, Torrington Place, London, WC1E 7JE, UK

Paper Summary
Over the last decade, digital signal processing has revolutionized the design and operation of optical networks. In this tutorial we chart this revolution, discussing the key algorithms and technologies before speculating on future research directions.

The Start of the Revolution
Optical networking has undergone a revolution over the last decade due to the application of digital signal processing (DSP) to optical transmission systems. In this tutorial we aim to chart the evolution that has occurred, reflecting on the key advances that progressed the field.

The application of DSP to optical networking began in earnest a decade ago, when the first application specific integrated circuit (ASIC) implementing advanced DSP algorithms appeared [1]. At that time, the application of DSP to 10GBd optical line rates, could be anticipated, due to the emergence of 20 GSa/s analogue to digital converters (ADC) in real-time oscilloscopes. Off-line processing of data captured by a real-time oscilloscope allowed DSP to be applied to sufficiently long sequences such that the pre-FEC BER could be measured in the region of the FEC limit. This facilitated research into DSP for optical receivers without the need to either design an ASIC or develop an FPGA based prototype. As such before moving on, it is illustrative to consider the development of ADCs in test equipment, since this facilitated many of the proof of principle experiments that led to subsequent ASIC development.

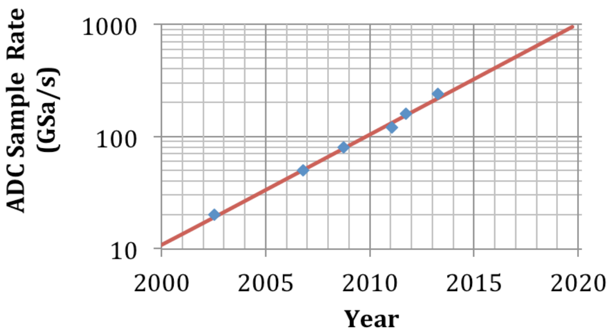

Fig. 1: ADC rates in commercial test equipment

As can be seen in Fig. 1 in the course of a decade the ADC sample rates in oscilloscopes increased by an order of magnitude, with the current rate of increase corresponding a ten-fold increase every ten years. A decade ago, when the ADC sampling rate was 20 GSa/s, this allowed for 10 Gbit/s MLSE to be investigated [1], or 40 Gbit/s using 10 GBd PDM-QPSK [2]. As the sampling rates increased 100 GbE was demonstrated using PDM-QPSK [3], then subsequently 400 GbE using PDM-16QAM[4]. With sampling rates of 240 GSa/s now being reported a 1 TbE superchannel could be processed, enabling a hundred-fold increase in the data rates being processed in just over a decade, thereby causing a revolution in the design of optical networks.

The Driver for using DSP
The first application of DSP for optical transmission systems was chromatic dispersion compensation. Given however a single optical element could compensate the chromatic dispersion across the C-band the value proposition for DSP was not strong. In contrast for polarization mode dispersion (PMD) its stochastic nature resulted in the PMD being different for each WDM channel such that the complexity was equivalent to having a PMD compensator per WDM channel. By using a phase and polarization diverse receiver with appropriate linear filtering it was shown not only could chromatic dispersion be compensated, but more critically all orders of PMD could be mitigated [5]. Given the PMD of the legacy fiber, this created a strong value proposition for using DSP with coherent detection.

DSP as an Enabling Technology
When DSP was combined with spectrally efficient modulation formats and coherent detection a symbiotic relationship emerged. The DSP made the coherent detection of spectrally efficient modulation formats a practical proposition. DSP not only minimized the need for adaptive optical subsystems, but also allowed for linear transmission impairments, in particular chromatic dispersion and PMD to be mitigated. Given that PMD was a severe limitation for 40 Gbit/s systems using direct detection, digital coherent receivers enabled 40 Gbit/s to be transmitted over links that previously could not support 10 Gbit/s due to PMD. In essence DSP made coherent detection a robust and attractive proposition for deployment of 40 Gbit/s, in a stark contrast to the conventional direct detection 40 Gbit/s systems, which could not be deployed over much of the installed fibre [6]

First Generation of Digital Coherent Transceivers

The first commercially deployed digital coherent transceiver was the Nortel 40 Gbit/s ASIC (QREW) that included two key DSP subsystems: digital chromatic dispersion compensation and digital PMD compensation [7]. While the exact algorithms employed were not published, given the size of the finite impulse response (FIR) filter required for chromatic dispersion compensation a frequency domain is generally optimal, to convert direct convolution rather than circular convolution using the fast Fourier transform (FFT). Digital PMD compensation was realized using a set of four FIR filters each consisting set using of complex taps. These were updated to allow 50 kHz polarization fluctuations to be tracked [8] albeit it was not revealed if the update algorithms were phase invariant (such as the constant modulus algorithm) or required the phase to be recovered. In addition to the equalization algorithms various algorithms for synchronization of the receiver with the transmitter were employed, including carrier phase and frequency estimation and correction, timing recovering and interpolation being based on conventional techniques [8].

Second Generation of Digital Coherent Transceivers

The second generation of digital coherent transceivers targeted 100 GbE as a data rate using PDM-QPSK. Much of the equalization and demodulation algorithms were similar to the first generation, however the FEC changed to being integrated with the DSP on a single ASIC. The integration of the DSP and the FEC was key to implementing soft decision FEC which was needed to allow long-haul transmission of 100 GbE [9].

Third Generation of Digital Coherent Transceivers

The third generation of digital coherent transceivers employed both transmitter and receiver based DSP with the associated DAC and ADC respectively. DSP at the transmitter permitted both more complex modulation formats such as PDM-16QAM to be realized, permitting the same transceiver operating at ~ 32 GBd to be used for either 100 Gbit/s (PDM-QPSK) or 200 Gbit/s (PDM-16QAM). The transmitter based DSP also allowed for pulse shaping such as root raised cosine filtering to be applied in order to control the spectrum, enabling a 400 GbE channel to be realized using a dual carrier technique.

Digital Coherent Transceivers for Elastic Networks

We are at the cusp of the next generation of digital coherent transceivers that will cause the most significant impact at the network level as transceivers move away from having a fixed data rate or symbol rate [10]. The technology is emerging for optical transceivers that are able vary their modulation format, FEC overhead, symbol rate and bit rate according to the network demands and the available signal to noise ratio (SNR). Rather than operate unconstrained, it is useful to consider as in [10] two distinct options: fixed symbol rate or fixed data rate. The case of fixed symbol rate requires variable data rates on the client side however it has the benefit that each transceiver would require a fixed amount of optical spectrum, thereby simplifying the challenge of spectrum assignment. In contrast for a fixed data rate the client side is fixed and the spectrum required varied. This has the obvious benefit of simplifying the client side but increasing the complexity of spectrum assignment. While both approaches increase the overall complexity this may be necessary to fully exploit the available network resources at the physical layer.

In addition to being elastic in terms of data or symbol rate, future transceivers could be cognitive, sensing for example the maximum SNR and the bandwidth available from which a strategy to best utilizes these resources is elected. Given the flexibility afforded by elastic transceivers, this causes significant interactions between the physically layer and the networking layers. Hence while it may be possible to accurately virtualize the elastic transceivers for a software-defined network, the strong interaction may require a more holistic approach.

Future Research Directions for DSP

Herein we have focused on DSP for the core network since this is where DSP has currently been extensively deployed. For core networks, in addition to the research required to make elastic cognitive transceivers a reality, a key area of research is nonlinear and multichannel DSP be this for a superchannel or for a multimode/multicore fibre [11]. A key consideration for both multichannel and nonlinear DSP is the superlinear scaling of complexity and hence power consumption, with the number of channels processed resulting in prohibitive power requirements. As such reduced complexity DSP is emerging as a fruitful area of research, not only for the core network but also for the access/metro networks as it becomes evident that just as with wireless networks, DSP will move to the very edge of the network.

Concluding Remarks

DSP has caused a revolution in the design of optical networks. New functionalities and opportunities from DSP are continuing to emerge as DSP permeates all parts of the optical network, thereby continuing the revolution.

References

1. A. Färbert et al, Proc. ECOC 2004, paper Th4.1.5A
2. S. Tsukamoto et al, Proc. OFC 2005, paper PDP29
3. C. R. S. Fludger et al, JLT vol. 26, pp. 64–72 (2008)
4. P.J. Winzer et al, Proc. ECOC 2010, paper PD2.2
5. S.J. Savory, Opt. Express, vol. 16, pp. 804-817 (2008)
6. D. Breuer et al, Proc. LEOS Summer Topical Meetings, paper MB2.1 (2003)
7. H. Sun et al, Opt. Express, vol. 16, pp. 873-879 (2008)
8. C. Laperle et al, JLT, vol.26, pp.168-175, (2008)
9. L. E. Nelson et al, JOCN, vol.4, pp.B131-B141 (2012)
10. D. McGhan et al, Proc. OFC 2012, paper OW4C.7
11. IEEE Signal Proc. Mag., vol. 31, no. 2, pp. 15-117 (2014)