6.3 Advanced modulation.

PON access systems have been commercially deployed for about two decades. Virtually all deployed PONs have used TDM PON technology. Throughout this history, commercially deployed TDM PON bit rates have consistently doubled every two years [1], recently reaching 10 Gb/s. At each increase in speed, TDM PON has needed to overcome three main challenges without resorting to WDM: (1) higher speed optics and electronics, (2) more optical transmit power and improved receiver sensitivity to sustain signal-to-noise ratio (SNR), and, since GPON, (3) mitigation of chromatic dispersion (CD).

While it may be possible to achieve the next step in speed with NRZ transmission, ~~P~~penalties resulting from increasing line rate could be offset to some extent by using more advanced, non-NRZ modulation schemes that allow more than one bit to be encoded into a single baud. ~~While a~~A number of more spectrally efficient modulation schemes have been proposed to-date [references needed]~~], the level of their technical maturity at this time would likely not allow for their immediate application into the optical access network, primarily because of the resulting cost and complexity of optical modules, specifically on the ONU side~~.

[1] E. Harstead, R. Sharpe, “Future Fiber-To-The-Home bandwidth demands favor Time Division Multiplexing Passive Optical Networks”, IEEE Communications Mag., Nov. 2012.

6.3.1 Duobinary modulation.

Compared to higher multi-level modulation schemes, duobinary implementations for modulation and for demodulation are relatively simple. As described in [2], duobinary data can be generated by sending NRZ-OOK data through an electrical "delay-and-add" filter, creating a 3-level signal. This filter has a z-transform of $1+z^{-1}$, which can be approximated by a low-pass filter (LPF) in the electrical domain. (Duobinary coding is a *correlative* coding method, so to avoid error propagation, pre-coding of the data at the transmitter is needed[3]). An example of a simple duobinary decoder is an electrical circuit that includes a splitter, 2 comparators and an XOR gate [3].

The duobinary signal generated by a LPF is compared to NRZ in the time and frequency domains in Figure 6.3.1-1.

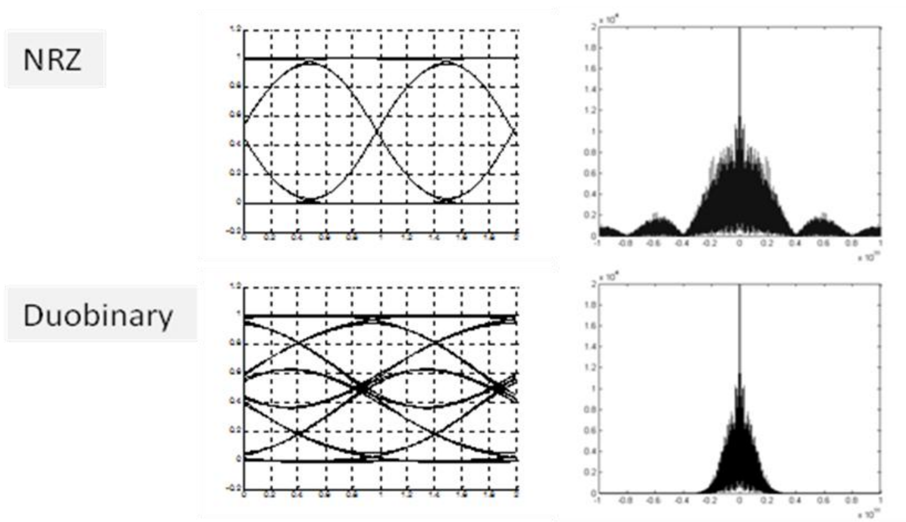

Figure 6.3.1-1. NRZ and duobinary (LPF) signals in the time and frequency domains.

The payoff for these simple electronic circuits is, compared to NRZ, a reduction in signal spectrum of approximately 60% and an increase in CD tolerance by approximately a factor of 2. These characteristics of duobinary mitigate the need for higher speed components and increased dispersion tolerance, while SOA post-amplifiers, where required, can answer the needs for higher power.

The duobinary LPF encoding can be realized by the bandwidth roll-off of either the transmitter or the receiver. The required bandwidths of the LPF are shown in Table 6.3.1-1.

Table 6.3.1-1. Duobinary LPF encoding bandwidths compared to NRZ.

Modulation	10 Gb/s	25 Gb/s	40 Gb/s
NRZ	7 GHz	17.5 GHz	28 GHz
Duobinary	(not in scope)	7 GHz	11 GHz

To cost-optimize a TDM PON, the lowest bandwidth components should be placed in the ONU, i.e. the duobinary encoding should be done by the ONU receiver for downstream, and by the ONU transmitter for upstream, as indicated by Figure 6.3.1-2. The values in the table indicate that a 25 Gb/s symmetric ONU only requires a 10 Gb/s transmitter and receiver, the same kinds of components already commercially available in 10G EPON NRZ systems. A 40 Gb/s symmetric ONU only requires 25 Gb/s components (which are actually overkill and would need to have their bandwidth reduced in the electrical domain). These components might be leveraged from the 25 Gb/s components in 802.3ba 100GBASE-ER4 Ethernet systems.

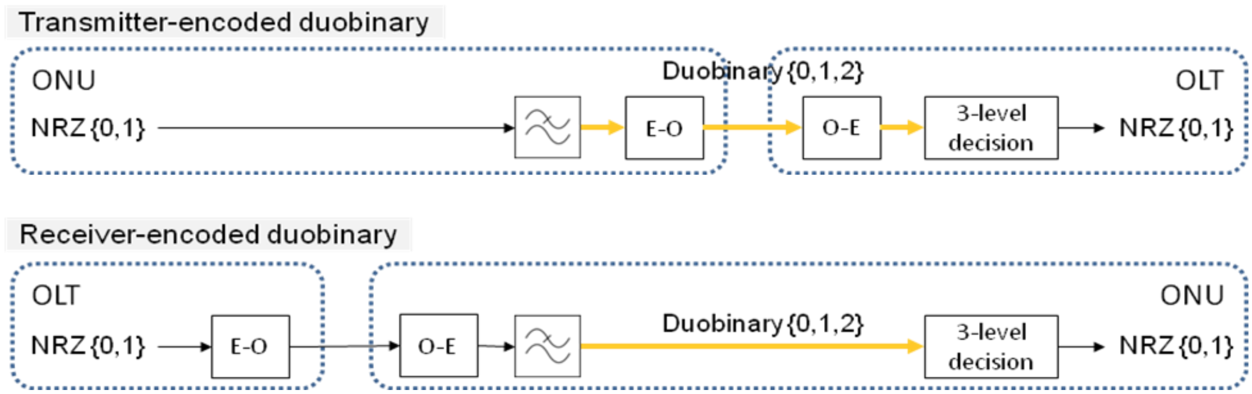

Figure 6.3.1-2. Partitioning duobinary functions in TDM PON.

In the OLT, full-rate 25 or 40 Gb/s components are required, but their higher cost is shared.

To summarize,

- 25 Gb/s symmetric NG EPONs can be implemented with low cost 10 Gb/s optical components in the ONU
- 40 Gb/s symmetric NG EPONs can be implemented with 25 Gb/s components in the ONU
- Asymmetric PONs, 25/10, 40/10, and 40/25, will further reduce the cost of the ONU transmit and OLT receiver optics.

Experimental confirmation of receiver-encoded duobinary downstream PON transmission at 26 Gb/s [4] and 40 Gb/s [5] are reported. Upstream duobinary burst-mode transmission remains to be experimentally verified.

While increasing the bit rate from 10 Gb/s to 25 Gb/s reduces the CD tolerance by a factor of 6, and to 40 Gb/s by a factor of 16, duobinary encoding provides partial mitigation by increasing the dispersion tolerance to CD by a factor of approximately 2 compared to NRZ. There are multiple paths to gaining the further required reductions in CD.

1. If both upstream and downstream transmission in the O-band, no dispersion compensation is required. Duobinary transmission up to 25 Gb/s can be achieved with DML lasers. Co-existence with 10G EPON , GPON and EPON simultaneously is possible, if EPON upstream transmission is constrained to the same 1310 +/- 20 nm as GPON, using a DFB laser.

2. If the O-band is not available, then transmission must be placed in the E, S, C, or L bands. No dispersion compensation is required for up to 10 Gb/s duobinary with DMLs, and up to 25 Gb/s duobinary with EMLs.

3. 40 Gb/s transmission above the O-band will require dispersion compensation (DC). DC fiber is low-loss (<3 dB) and low cost, although bulky. FBG DCs for PON applications might be possible; they would be smaller but possibly more expensive. Electronic DC may be possible, but the improvement in dispersion tolerance for duobinary modulation has not yet been determined.

The (estimated) usable spectrum for a 20 km G.652 (SSMF) fiber that can be used without dispersion compensation for the considered bit rates, laser sources and encoding are summarized in Figure 6.3.1-3.

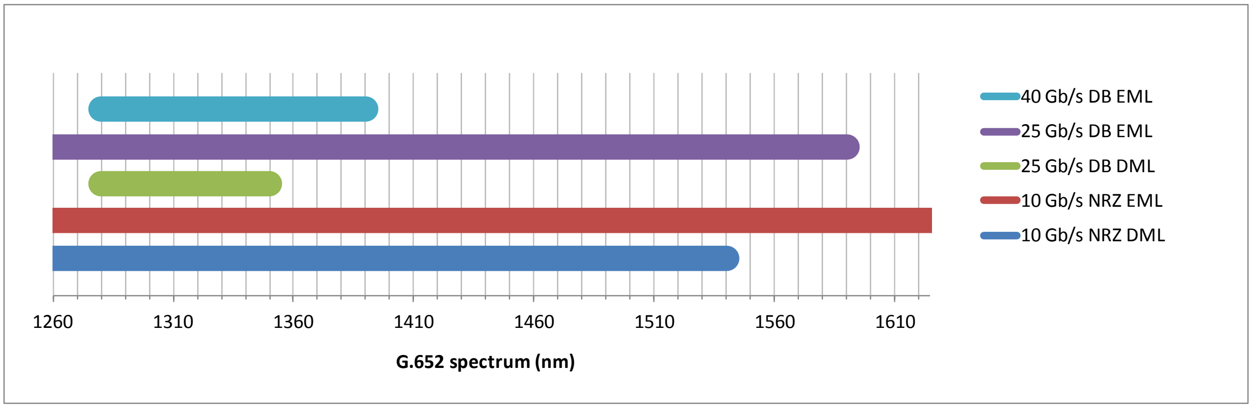

Figure 6.3.1-2. Estimated usable SSMF spectrum (20 km) without DC.

References

[2] A. Lender, “The Duobinary Techniques for High-Speed Data Transmission”, IEEE Trans. Consumer Electronics, vol. CE-82, pp. 214–218, May 1963.

[3] J. Sinsky et al., “High-Speed Electrical Backplane Transmission Using Duobinary Signaling”, IEEE TRANSACTIONS ON MICROWAVE THEORY AND TECHNIQUES, VOL. 53, NO. 1, JANUARY 2005, p.152

[4] D. van Veen, V. E. Houtsma, P. Winzer, and P. Vetter, "26-Gbps PON Transmission over 40-km using Duobinary Detection with a Low Cost 7-GHz APD-Based Receiver," in *European Conference and Exhibition on Optical Communication*, OSA Technical Digest (online) (Optical Society of America, 2012), paper Tu.3.B.1

[5] V. Houtsma, D. van Veen, A. Gnauck and P. Iannone, "APD-Based DuoBinary Direct Detection Receivers for 40 Gbps TDM-PON”, 2014, unpublished.

[The following text is not specific to duobinary, but to any advanced modulation technique]

6.3.x High speed bit interleaving.

To date, TDM PON ONUs have had to fully process the aggregate downstream signal at line rate, regardless of how much traffic was actually being sent to the ONU. This is a source of inefficiency leading to higher power consumption compared to dedicated signals. A dynamic bit-interleaving protocol has been proposed [6], wherein a decimator in the clock-data recovery (CDR) circuit extracts only a small proportion of the downstream bits containing the ONU payload, which avoids the need for wide parallel buses, significantly reducing the size of the ONU digital circuitry and its power consumption. In particular, the relatively intensive FEC processing can be done at the user rate.

ONUs cost-optimized for residential services might be limited to a fraction of the downstream bit rate, say 10 Gb/s. ONUs optimized for business services might be designed to have access to the full line rate, say 25 or 40 Gb/s. Both ONUs could be mixed on a PON and their bandwidths allocated dynamically, analogously to dynamic bandwidth allocation protocols already used in the upstream direction.

A simpler static bit interleaving could also be devised. In this case the decimator ratio would be fixed, and its bit phase would be configured for each ONU. For example, a 40 Gb/s downstream/ 10 Gb/s upstream OLT and ONU could be implemented with 10G EPON logic, as shown in Figure 6.3.x-1. The down-side of static bit interleaving is that the ONU maximum downstream bandwidth is limited to the fixed decimation ratio (10 Gb/s in this example). This static implementation is analogous to wavelength-stacking in TWDM PONs, except a single OLT transceiver provides the full aggregate bandwidth and no wavelength agility or management is required.

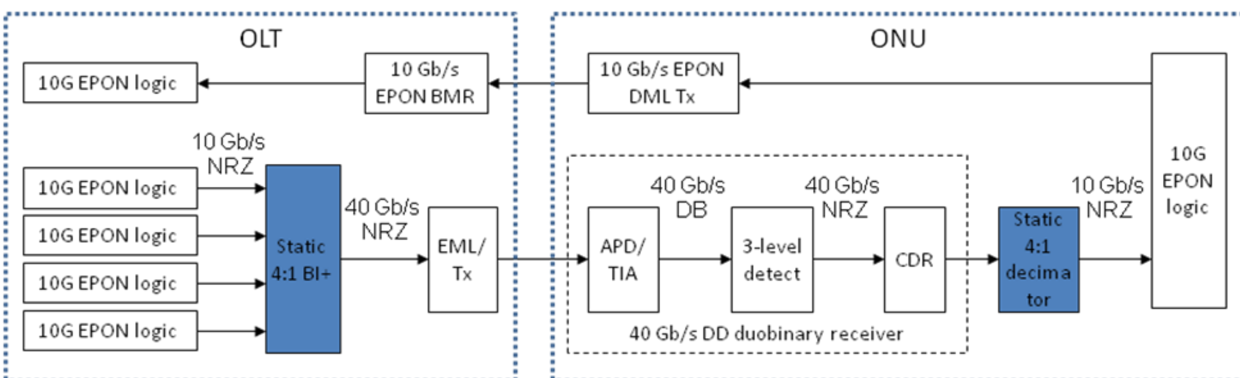

Figure 6.3.x-1. Forecasted demand vs. the number of aggregated subscribers

Upstream burst mode bit interleaving is more complex and remains to be investigated.

[6] D. Suvakovic, H. Chow, D. van Veen, J. Galaro, B. Farah, N. P. Anthapadmanabhan and P. Vetter, "Low Energy Bit-Interleaving Downstream Protocol for Passive Optical Networks", 2012 IEEE Online Conference on Green Communications (GreenCom), p.26-p31 (2012).